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MEASUREMENT AND COMPOUND NUCLEUS ANALYSIS
OF THE
ELASTIC SCATTERING OF ALPHA PARTICLES BY BERYLLIUM-9

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

John Douglas Goss, B.S., M.S.

* * * * * *

The Ohio State University
1970

Approved By

S. Leslie Black
Adviser
Department of Physics
The author wishes to dedicate this thesis to his parents whose sacrifices over the years made this work possible.
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PUBLICATIONS


FIELD OF STUDY

Major Field: Physics
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Energy levels of light nuclei have been studied for many years and our present understanding of the nucleus has been enhanced by comparison of experimental measurements and theoretical models. However, many gaps in experimental information still exist, as, for example, in the case of the level structure of $^{13}$C. Though the level structure of $^{13}$C has previously been investigated by many reactions, in the region of excitation above 11 MeV very little information is available concerning level parameters. In this laboratory, the region of excitation of $^{13}$C from 11 to 14 MeV may be studied with the 6 MeV (type CN) Van de Graaff accelerator by reactions involving alpha particles on $^{9}$Be. In the present work, the level structure of $^{13}$C has been investigated by the measurement of the elastic scattering of alpha particles by $^{9}$Be for bombarding energies from 1.7 to 6.2 MeV. In a previous measurement of the elastic scattering of alpha particles by $^{9}$Be which was done by Taylor\(^{(1)}\) for bombarding energies from 4 to 20 MeV, the data below 6 MeV is incomplete and his analysis was concerned primarily with the data
Present information concerning the properties of the levels in $^{12}\text{C}$ from 11 to 14 MeV has come primarily from the preliminary analyses of the $^9\text{Be}(\alpha, n)$ reactions.\(^{(2, 3, 4)}\) From these analyses, there appears to be a strong contribution from compound nucleus formation, which is also evident from the fluctuations in the excitation curves of the elastic scattering data. In the present work, the elastic scattering data is analyzed with compound nucleus theory. Up to the present, most analyses of this type have been attempted only for the elastic scattering of spin 0, or spin 1/2 projectiles from closed shell nuclei. The more complex case studied here thus required extensive new calculations and the writing of a special computer program to perform the analysis. The results of the compound nucleus analysis of the $^9\text{Be}(\alpha, \alpha)^9\text{Be}$ elastic scattering data are presented below and are further compared for consistency with the $^9\text{Be}(\alpha, n_0)$ cross section data of Weil \textit{et al.}\(^{(5)}\)
CHAPTER II
EXPERIMENTAL

A helium-four beam from the Ohio State University Van de Graaff CN Accelerator was magnetically analyzed to provide an energy spread of about 10 keV. The elastic scattering data were measured simultaneously by four silicon surface barrier detectors mounted in a 23-inch scattering chamber. With a bias of 100 V the depletion depth was approximately 300 microns for each detector. The position of the detectors and their collimators are shown schematically in Fig. 2 and a schematic of the scattering chamber is shown in Fig. 1. A fifth detector was used for determining 0° by measuring yields on either side of the beam axis. The solid angles at forward angles were smaller than those at backward angles so counting rates in all detectors would be approximately the same. The solid angles of each detector and the angular acceptance of each are presented in Table 1. Except for purposes of checking symmetry about the beam axis, 0°, the target was positioned with its normal at 40° to the beam direction so that all detectors could "view" the beam spot. The platform on which the detectors were mounted could be rotated remotely with an angular uncertainty for each of the detectors with
Figure 1. Scattering Chamber in a schematic cross sectional view.
Figure 2. Detector Positions on Rotatable Plate.
### TABLE 1

**Solid Angles and Angular Acceptance**

<table>
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<tr>
<th>Detector Number</th>
<th>$\Delta \Omega$ (Steradian)</th>
<th>Angular Acceptance</th>
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<tr>
<td>1</td>
<td>$2.58 \times 10^{-4}$</td>
<td>$0^\circ 46'$</td>
</tr>
<tr>
<td>2</td>
<td>$2.62 \times 10^{-4}$</td>
<td>$0^\circ 46'$</td>
</tr>
<tr>
<td>3</td>
<td>$5.56 \times 10^{-8}$</td>
<td>$0^\circ 19'$</td>
</tr>
<tr>
<td>4</td>
<td>$9.18 \times 10^{-8}$</td>
<td>$0^\circ 34'$</td>
</tr>
<tr>
<td>Symmetry</td>
<td>$6.51 \times 10^{-8}$</td>
<td>$0^\circ 16'$</td>
</tr>
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respect to the beam axis of 0.2°.

The beam was collimated by two "slit-boxes" on the beam pipe and entered the chamber through a 0.041 inch diameter circular aperture. No steering or focusing was used on the beam pipe to assure that the beam would pass through the center of rotation of the scattering chamber. The beam was collected in a Faraday cup and integrated by a Brookhaven Model 1000 current integrator.* The current integrator was checked for accuracy at this laboratory and the accuracy was found to be 0.2%. Experimentally it was found that electrostatic or magnetic suppression was not necessary. Typically the currents used in measuring the data were of the order of 0.1 to 0.5 microamp.

The linear signals from each of the four detectors were routed into four quadrants of a 512 channel Nuclear Data pulse height analyzer. Several electronic configurations were used during the course of the experiment, one of which is shown schematically in Fig. 3. With this configuration the noise of each detector is isolated from the noise of the others.

The preparation of pure thin beryllium targets (i.e., 15 to 50 keV for 5 MeV alpha particles) presented considerable difficulty. Sturdy and rugged self-supporting beryllium foils can be made,

Each linear and routing signal is derived as above.

Figure 3. Electronics Block Diagram. The following abbreviations are used: amplifiers (AMP), detector (DET), and single channel analyzer (SCA).
however they are of the order of 100 keV for 5 MeV alpha particles. Because thin films of beryllium become brittle and crack, the targets actually used in this experiment were made by vacuum evaporation of beryllium metal onto a thin film of formvar. The targets made this way ranged from 5 to 24 keV for 5 MeV alpha particles. Unfortunately, the oxygen and carbon in the formvar added unwanted contaminants and also made target thickness measurements more difficult. Kinematically the elastically scattered alpha particles from $^9$Be, $^{12}$C and $^{16}$O are unresolved for angles smaller than $25^\circ$ lab, preventing analysis of measurements at forward angles. Typical spectra of alpha particles on the formvar-backed $^9$Be target are shown in Fig. 4. Background was estimated by averaging counts on either side of the $^9$Be peak yield. For further details concerning the experimental apparatus, see Appendix A.
Figure 4. Particle Spectra of Alpha Particles on $^9$Be Target with Formvar Backing. The bombarding energy is 3.85 MeV and the target is approximately 24 keV.
CHAPTER III
EXPERIMENTAL RESULTS

Excitation curves (shown in Figs. 5 and 6) were measured at various center of mass angles including those for which the Legendre polynomials of order 2, 3, 4, and all odd-$\ell$ are zero. The solid lines show the results of compound nucleus calculations discussed in Chapter IV. The excitation curves in Figs. 5 and 6 were taken in 50 keV steps with several targets, all approximately 24 keV thick for 4.29 MeV alpha particles. The relative uncertainty in the cross section is about 5% for all data presented and was determined from the reproducibility of the data. This uncertainty includes statistical errors, background uncertainties, angular uncertainties and errors due to target non-uniformity. An absolute target thickness was measured experimentally for one of the targets and the remaining were determined by comparison of yields over an energy range and at various angles. This was done in order to minimize sources of error due to the different target thicknesses.

Two independent experiments were performed in determining the absolute target thickness. The target thickness was unfolded
Figure 5. Excitation Curves of $^9\text{Be}(\alpha,\alpha)^9\text{Be}$ at $85.8^\circ$, $90.0^\circ$, $106.8^\circ$, $115.9^\circ$ and $116.7^\circ$ c.m. The solid lines are the results of compound nucleus calculations for the set of level parameters given in Table 2.
Figure 6. Excitation Curves of $^9$Be($\alpha$, $\alpha$)$^9$Be at 125.2°, 140.6°, 149.6°, 156.0° and 167.2° c.m. The solid lines are the results of compound nucleus calculations for the set of level parameters.
from the shift of the excitation curve over the 4.28 MeV resonance in the $^{12}\text{C}(\alpha, \alpha)^{12}\text{C}$ reaction for the carbon on the front of target (built up during beam bombardment) and for the carbon in the formvar backing. In the second method a deuterion beam was used, and the observed yields were normalized to the elastic scattering data of Renken. Both measurements agree well within the experimental uncertainty and give a target thickness of $1.79 \times 10^{18}$ atoms/cm$^2$ with an uncertainty of 10%.

Errors due to charge collection, solid angle uncertainties, analyzer dead time corrections, and routing errors, are less than or equal to 1%.

An excitation curve at 137.9° c.m. taken with a thinner target is shown in Fig. 7. The data were taken in 10 keV steps and the target was approximately 5 keV for 5 MeV alpha particles. No absolute normalization has been made and the cross section plotted is in arbitrary units. When compared to the data taken with the 24 keV targets (Figs. 5 and 6) additional fluctuations do appear; however, the general structure is the same and none of the resonance features are further resolved.

Special attention to the analysis of the region near 5 MeV has been made because of the large fluctuation in the excitation curves there. Angular distributions near 5 MeV are shown in Fig. 8.
Figure 7. Thin Target Excitation Curve of $^9$Be($\alpha, \alpha$)$^9$Be at 137.9° c.m.

The target was approximately 5 keV for 5 MeV alpha particles.
Figure 8. Angular Distributions of $^9\text{Be}(\alpha, \alpha)^9\text{Be}$ at 5.00, 5.05, 5.10, 5.15, and 5.5 MeV. The solid lines are the results of compound nucleus calculations for the set of level parameters given in Table 2.
The solid lines are again compound nucleus predictions discussed in Chapter IV. Thicker targets were used in measuring the angular distributions, than used in measuring the excitation curves in Figs. 5 and 6 (50 to 150 keV for 4.29 MeV alpha particles). The relative uncertainty is about 5% for the data and the uncertainty due to target thickness is about 15%.

For further details concerning the target thickness measurements or errors associated with the cross section, refer to Appendix B.
CHAPTER IV

COMPOUND-NUCLEUS ANALYSIS

a. Theory

A formula for the differential cross section for the elastic scattering of charged particles has been given explicitly by Blatt and Biedenharn\(^\text{(7)}\) for an isolated level of the compound nucleus. It is evident from the present data that to explain the cross section in the energy region of interest, several levels must be included. As a first approximation, one might first make the assumptions that all the levels to be included are of different spins and parities, and that the contributions from "distant-levels" are negligible.

The formula of Blatt and Biedenharn may then easily be extended to a multiple level theory or the "single-level" approximation. Using the formalism and notation of Blatt and Biedenharn, the formula for the differential cross section for the elastic scattering of charged particles in the "single-level" approximation is
\[ \frac{d \sigma}{d \Omega} \alpha, \alpha = \frac{x_0^2}{(2 \eta + 1)(2 \eta + 1)} \sum_{\eta, f, L} \sum_{n} R^l(\alpha, \alpha) P_l(\cos \theta) \]

\[ + \gamma^2 \cos \theta \left( \theta/2 \right) \]

\[ - 2 \frac{x_0}{\alpha} \int_0^\infty (2 \eta + 1) \sin \theta \cos \left[ 2 \eta \ln (\sin \theta/2) + 2 \psi_0 + \frac{\theta}{\eta} \right] \]

\[ \times \cosec \left( \theta/2 \right) \frac{P_l}{\alpha} \cos \theta \]

\[ + \frac{x_0^2}{\alpha} \sum_{\eta, f, L} \sum_{n} \frac{\eta!}{(2 \eta + 1)(2 \eta + 1)} \left[ (\eta_0' \eta_0 \eta_0) \right]^2 \sin \theta \frac{\sin \frac{\theta}{2}}{\cos \left( \frac{\theta}{2} \right) - \frac{\psi_0}{\eta} + \frac{\theta}{\eta}} \times \]

\[ \times \cosec \left( \theta/2 \right) \frac{P_l}{\alpha} \cos \theta \]

\[ + \frac{x_0}{\alpha} \sum_{\eta, f, L} \sum_{n} \frac{\eta!}{(2 \eta + 1)(2 \eta + 1)} \frac{J_{n+1}}{J_{n} \cdot L_{\eta} L_{\eta}} \frac{P_{n+1}}{P_{n} \cos \left( \theta/2 \right)} \times \]

\[ \sin \left[ 2 \eta \ln (\sin \theta/2) + 2 \psi_0 + 2 \psi + \frac{\theta}{\eta} \right] \frac{P_l}{\alpha} \cos \theta \]

\[ - \frac{x_0^2}{\alpha} \sum_{\eta, f, L} \sum_{n} \frac{\eta!}{(2 \eta + 1)(2 \eta + 1)} \frac{J_{n+1}}{J_{n} \cdot L_{\eta} L_{\eta}} \frac{P_{n+1}}{P_{n} \cos \left( \theta/2 \right) \eta! \cdot L_{\eta} \cdot L_{\eta}} \left[ (\eta_0' \eta_0 \eta_0) \right]^2 \]

\[ \times \sin \theta \frac{\sin \frac{\theta}{2}}{\cos \left( \frac{\theta}{2} \right) - \frac{\psi_0}{\eta} + \frac{\theta}{\eta}} \frac{P_l}{\alpha} \cos \theta \]

where
\[ R'_L(\alpha, \alpha) = \sum_{S'} \sum_{S} R'_L(\alpha S', \alpha S) \]

and

\[ R'_L(\alpha S', \alpha s) = \left( \frac{-1}{4} \right)^{J_{m} - S} \frac{J_{h} + S}{|J_{h} - S|} \frac{J_{m} + S'}{|J_{m} - S'|} \frac{J_{h} + S'}{|J_{h} - S'|} \frac{J_{m} + S}{|J_{m} - S|} \]

\[ \mathcal{Z}(l_{J} l_{J}; s_{J} s_{J}; s'_{J} s'_{J}) \mathcal{Z}(l'_{J} l'_{J}; s'_{J} s'_{J}) \frac{1}{|\epsilon_{n}|^2} \]

\[ \left[ G_{\alpha \alpha} + G_{\alpha \beta} + G_{\beta \alpha} + G_{\beta \beta} \right] \left[ S_{\alpha \alpha} + S_{\alpha \beta} + S_{\beta \alpha} + S_{\beta \beta} \right] \]

In eq. IV-1, sums over \( J_{n} \) and/or \( J_{m} \) are sums over the levels to be included in the calculation; \( \alpha \) and \( s \) are the channel index and channel spin respectively. The channel index \( \alpha \) defines the type of incoming particle and the state of the target nucleus and the channel spin \( s \) is the total spin angular momentum in the channel and is formed by vector addition of the intrinsic spin \( i \) of the incoming particle and the spin \( I \) of the target nucleus. The other quantities which appear in the above equations are defined as follows:

1) \( \phi_{n} = -\arctan \frac{F_{n}(R)}{G_{n}(R)} \), (hard sphere phase shift).
where $F_l$ and $G_l$ are the regular and irregular Coulomb functions respectively, evaluated at the channel radius $R$ which is the sum of the radii of the target nucleus and the incident particle.

2) $\psi_l = \sigma_l - \sigma_l^0$, (modified Coulomb phase shift),

where $\sigma_l$ is the ordinary Coulomb phase shift.

3) $\delta_l = \psi_l + \sigma_l + \sigma_l^0$,

where the index $\alpha$ has been dropped for convenience.

4) $\gamma = Z_1 Z_2 e^2 / 2 \mu \nu^2$,

where $Z_1$ and $Z_2$ are the atomic numbers of the incident particle and target nucleus, respectively, and $\mu$ is the reduced mass for the relative motion in the center of mass.

5) $\eta = Z_1 Z_2 e^2 / \pi \nu$.

6) $|E_n| = \left[ (E - E_n)^2 + \left( \frac{\Gamma_n}{2} \right)^2 \right]^{1/2}$,

where $E_n$ is the observed resonance energy of the level with spin $J_n$, and $\Gamma_n$ is the total width of level $J_n$. 
7) $\Gamma_{m} = \sum_{\alpha} \Gamma_{n \alpha}$ and $\Gamma_{n} = \sum_{\alpha} q_{n \alpha}$,

where $J_{n}$ serves only to identify the level.

8) $g_{\alpha \delta} = \pm \left( \Gamma_{\alpha \delta} / 2 \right)$,

where both $g_{\alpha \delta}$ and $\Gamma_{\alpha \delta}$ are functions of the channel energy through the usual penetration factor.

9) $\bar{Z}(l_{1} J_{1} l_{2} J_{2} ; S L) = (2l_{1} + 1) (2l_{2} + 1) (2J_{1} + 1) (2J_{2} + 1) \times$

$W(l_{1} J_{1} l_{2} J_{2} ; S L) (l_{1} l_{2} 0 0 | L 0 )$,

where $W$ is the Racah coefficient defined in reference 6, and $(l_{1} l_{2} 0 0 | L 0 )$ is a Clebsch-Gordan coefficient.

and

10) $\beta_{n} = \arctan \left( E_{n} / E_{n} \right) / \sqrt{2} \Gamma_{n}$

The interpretation of the terms in the cross section formula are as follows: The first term is pure resonance scattering, and restrictions on the sum over $L$ are determined from the selection rules for non-vanishing $\bar{Z}$ coefficients. For two levels of opposite parity $L$ may have odd values as well as even values whereas for the case of an isolated level where the sum over $J_{m}$ and $J_{n}$ disappear, $L$ may have only even values. The next term is pure
Rutherford scattering from a point charge and the following two
terms represent the correction to this due to the finite size of the
nucleus. These three terms together are the potential scattering
and as assumed by Blatt and Biedenharn the potential scattering is
scattering from a charged hard-sphere. The Rutherford scattering
has been separated explicitly from the potential scattering so that
the potential scattering may be written as rapidly convergent sums.
In the analysis these sums have been truncated at \( \ell \) equal to six.

For a given \( J_n \) the next to last term is the interference between
resonance scattering and pure Rutherford scattering, while the
last term is the finite nuclear size correction to this interference
term. The range of summation over \( \ell \) in these last two terms is
such that the three angular momenta \( \ell, i, \) and \( I \) can combine by
the vector addition rules to give a total angular momentum \( J_n \).
The conservation of parity further restricts the sum over \( \ell \) to
either even or odd \( \ell \) values.

Besides the assumption of hard-sphere potential scattering,
it has been assumed that the level shift is negligible and may be
omitted. This approximation is good only for narrow states and
may introduce up to a 10\% uncertainty in the width of broad levels.
In a first order approximation, the formula for the elastic
scattering cross section given above may also be used to calculate
the cross section when several of the levels have the same spin and parity if these levels are sufficiently separated. Additional terms must be included in the above formula when this condition is not met. For this purpose such terms (not written out above) have been included in our analysis which allow an approximate calculation of the cross section when either two or three levels of the same spin and parity are included. The approximations used are good, however, only if these levels are separated by at least a full level width. For details concerning the derivation of the "single-level" formula and the additional terms which must be included for "two- and three-level" calculations see Appendix C.

b. Application to $^6\text{Be}(\alpha, \alpha)^6\text{Be}$

A computer code has been written by the present author to evaluate the elastic scattering cross section as discussed above. In addition the code allows one to calculate the differential cross section for the $^6\text{Be}(\alpha, n)$ reactions in the "single-level" approximation. The elastic scattering data were compared to calculations by minimization of the quantity $\chi^2$ given by

$$\chi^2 = \sum_{i=1}^{N} \left[ \frac{(\sigma_{\text{exp}} - \sigma_{\text{calc}})^2}{(\Delta \sigma_{\text{exp}})^2} \right]_i$$
Here N is the number of data points, \( \sigma_{\text{exp}} \) and \( \sigma_{\text{cal}} \) are the measured and calculated cross section, respectively. A search routine\(^{(9)}\) incorporated in the code minimized \( \chi^2 \) by varying the reduced partial widths and the total width of each level. The observed resonance energy of each level was held constant during a search. The level parameters given in Table 2 are the results of simultaneous "fits" to five of the experimental excitation curves.

The analysis has been primarily concerned with the energy region from 3.5 to 5.5 MeV. In this region, levels have been observed from \(^8\text{Be}(\alpha, n)\) reactions\(^{(10,11,12)}\) at the bombarding energies of 4.00, 4.18, 4.50, 5.00 and 5.40 MeV. The levels at 4.2 and 4.50 MeV have been assigned spins and parities of 5/2\(^+\) (1) and 3/2\(^+\) (3) respectively, by DeMartini et al.\(^{(3)}\) and are in agreement with the work of Darden\(^{(4)}\) and Risser\(^{(2)}\). (The number in parenthesis is the dominant \( l_{\alpha} \)-value.) These assignments have been incorporated into the present work, though \( l \)-mixing has also been allowed. Information concerning the spin and parity assignments of the remaining observed levels in this region is sketchy, though from the fits of the polarization data near 5 MeV of the ground state neutrons\(^{(3)}\) of the \(^9\text{Be}(\alpha, n_0)\) reaction, there appears to be a significant contribution from a 5/2\(^-\) (4) state. In the elastic scattering data, a negative parity state would show a "differentiation" pattern at
TABLE 2

Resonance Parameters for $^6$Be($\alpha$, $\alpha$)$^6$Be

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$E_\alpha$ (MeV)</th>
<th>$\Gamma_{c.m.}$ (keV)</th>
<th>$\Gamma_{c.m.}$ (keV)</th>
<th>$J^\pi$</th>
<th>$\Gamma_{a\ell pseudoc.m.}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Work</td>
<td>Other Work</td>
<td>Present Work</td>
<td>Present Work</td>
<td></td>
<td>$t_1$</td>
</tr>
<tr>
<td>3.80</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>343</td>
<td>$3/2^-(0,2)$</td>
</tr>
<tr>
<td>4.00</td>
<td>4.00</td>
<td>60</td>
<td>58</td>
<td>9/2$^-(4,6)$</td>
<td>15</td>
</tr>
<tr>
<td>4.20</td>
<td>4.18</td>
<td>570</td>
<td>685</td>
<td>5/2$^+(1,3)^b$</td>
<td>284</td>
</tr>
<tr>
<td>4.50</td>
<td>4.50           ≈350</td>
<td>247</td>
<td>3/2$^+(1,3)^b$</td>
<td>37</td>
<td>44</td>
</tr>
<tr>
<td>5.00</td>
<td>5.00           ≈200</td>
<td>75</td>
<td>5/2$^-(2,4)$</td>
<td>0</td>
<td>61</td>
</tr>
<tr>
<td>5.075</td>
<td>---</td>
<td>---</td>
<td>73</td>
<td>7/2$^+(3,5)$</td>
<td>46</td>
</tr>
<tr>
<td>5.50</td>
<td>5.40±.10</td>
<td>260</td>
<td>400</td>
<td>5/2$^+(1,3)$</td>
<td>199</td>
</tr>
</tbody>
</table>

a) Number in parenthesis refers to the $\ell$-values of the incoming $\alpha$ particle; $t_1$ refers to the lower value.

b) Agrees with previous assignment references 2, 3, and 4.
90° c.m. and such a pattern is evident at 5.0 MeV. The inclusion of a 5/2− (4) level at 5.00 MeV is consistent with the elastic scattering data for angles back to 149° c.m., but it and all other negative parity states up to 9/2− are unable to reproduce the elastic scattering data at 156.0° and 167.2° c.m. Failure of a positive parity state to reproduce the data at 5.0 MeV led to the conclusion that the resonance feature must be due to contributions from at least two levels. With a 5/2− (4) state at 5.00 MeV, a "best-fit" was obtained with a 7/2+ (3) level at 5.075 MeV. Other combinations of spins and parities were tried for these two levels and another possible assignment is a 7/2− (4) level at 5.00 MeV and either a 3/2+ (3), 5/2+ (3), or 7/2+ (3) level at 5.075 MeV.

The narrow level at 4.00 MeV seen in the 9Be(α,n,γ4.43)12C reaction has a natural width of approximately 60 keV in the center of mass and is also evident in the elastic scattering data. Such a narrow level though cannot explain the broad structure just below 4 MeV. In order to even qualitatively fit the data below 4 MeV, it was necessary to assume a level at 3.8 MeV and a "best-fit" was obtained with a 3/2− state. Attempts to fit the narrow 4.00 MeV level directly with the computer code were not successful. The most probable reason being that the broad levels at 3.8 and 4.2 MeV influence the cross section so strongly at 4 MeV that data in 50 keV
steps is insufficient for a satisfactory search. The spin and parity for this level for which no previous assignments have been made was therefore obtained, instead, by comparison of isolated theoretical resonance shapes for many $J^\pi$ values at all the angles for which data was taken. The results of this comparison indicate that $9/2^-$ is probably the most likely assignment.

Broad structure is evident near 5.7 MeV which seems to resonate at different energies as a function of angle, suggesting that several states make up this broad feature. In a first attempt to fit the data above 5 MeV, various spin and parity assignments were tried and a "fit" was obtained with either a $5/2^+$ (1) or $3/2^+$ (1) assignment at the resonance energy 5.5 MeV. The $5/2^+$ (1) assignment has tentatively been chosen over the $3/2^+$ (1) assignment because of better agreement in the analysis of the ground state neutron from the $^6$Be$(\alpha,n\alpha)$ reaction. Because of the lack of information on even the number of levels in the region from 5.5 to 6.2 MeV, analysis has been extremely difficult and the results of the fitting of this region are not presented.

The solid lines shown in Figs. 5, 6 and 7 are the compound nucleus calculations obtained with the level parameters given in Table 2. These parameters were found by fitting simultaneously the excitation curves at 106.8°, 125.2°, 140.6°, 156.0° and 167.2° c.m.
The calculated cross section has not been energy averaged over the target thickness. To further verify the level parameters found from the analysis of the elastic scattering data, analysis of the ground state neutron data of Weil et al. (5) of the $^6\text{Be}(\alpha,n_0)$ reaction has been initiated. In the analysis of this data the only parameter allowed to vary is the neutron partial width, the alpha width and total width of each level assumed to be known from the elastic scattering data analysis. Preliminary results of this analysis are shown in Fig. 9. The solid lines are calculated from theory and the level parameters are given in Table 3.
Figure 9. Angular Distributions of $^9\text{Be}(\alpha, n_0)^{12}\text{C}$. The data was taken by Weil et al. The solid lines are the results of compound nucleus calculations for the level parameters given in Table 3.
### TABLE 3

Resonance Parameters for $^9\text{Be}(\alpha,n)^9\text{Be}$

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$J^\pi$</th>
<th>$l_n$</th>
<th>$\Gamma_{\text{c.m.}}$ (keV)</th>
<th>$\Gamma_{\alpha(\text{c.m.})}$ (keV)</th>
<th>$\Gamma_{\nu_n}$</th>
<th>$g_1 g_2$ $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.20</td>
<td>$5/2^+$</td>
<td>2</td>
<td>685</td>
<td>296</td>
<td>374</td>
<td>-+</td>
</tr>
<tr>
<td>4.50</td>
<td>$3/2^+$</td>
<td>2</td>
<td>247</td>
<td>81</td>
<td>32</td>
<td>-+</td>
</tr>
<tr>
<td>5.00</td>
<td>$5/2^-$</td>
<td>3</td>
<td>75</td>
<td>61</td>
<td>3</td>
<td>+-</td>
</tr>
<tr>
<td>5.50</td>
<td>$5/2^+$</td>
<td>2</td>
<td>400</td>
<td>199</td>
<td>39</td>
<td>++</td>
</tr>
</tbody>
</table>

(a) The signs of the $g$'s for the incoming alpha particles are tabulated. The subscript 1 refers to the smaller of the $l_\alpha$ - values. It is assumed that the $g$ for the outgoing neutron is positive.
CHAPTER V
CONCLUSIONS

The assignments of $5/2^+$ (1) and $3/2^+$ (3) for the levels at 4.20 and 4.50 MeV respectively, seem to be entirely consistent with the elastic scattering data, though there is a significant contribution of p-wave, not included by DeMartini et al. (3), for the $3/2^+$ level.

An assignment of $5/2^-$ (4) for the level at 5.00 MeV is consistent with the work of DeMartini et al. (3) and the preliminary analysis done by the present author of the $^9\text{Be}(\alpha,n\alpha)$ data indicates a slight preference for this assignment. However, as mentioned earlier an assignment of $7/2^-$ (4) cannot be ruled out on the basis of the analysis of the elastic scattering data. With an assignment of $5/2^-$ (4) at 5.00 MeV a good fit to the elastic scattering data is obtained only with an additional $7/2^+$ (3) level at 5.075 MeV. (Fig. 10 shows results of fits in this region using only a single level.)

The assignment of the spin of the second level depends critically on the assignment of the level at 5.00 MeV, however the dominant $t_{\alpha}$ value for this state appears to be 3. Because the data were taken in 50 keV steps and because the levels at 5.00 and 5.075 MeV
Figure 10. "Fits" to $^9\text{Be}$(α, α)$^9\text{Be}$ with a Single Level at 5.0 MeV.

Except for the levels at 5.00 and 5.075, the level parameters are those given in Table 2.
overlap strongly, the exact position of the resonance at 5.075 MeV is uncertain to at least 25 keV. Due to the fact that \( \Gamma_{\alpha} \approx \Gamma_{T0T} \) for the positive parity level, there is little neutron width. Thus the \(^9\text{Be}(\alpha, n_0)\) data is insensitive to this level. The large \( \ell \)-value (\( \ell_n = 4 \)) needed for the outgoing neutrons explains the small \( \Gamma_n \) in this case. Earlier calculations of the cross section with an assignment of \( 9/2^- \) for the narrow level at 4.00 MeV were in much better agreement with the experimental cross section than the calculations shown now in Figs. 5 and 6. However, it was necessary to include a significant \( \ell_\alpha = 6 \) contribution to the state. Since the reduced width obtained for this channel was much larger than the Wigner limit, this state was not physically realistic. Therefore complete knowledge of this state is still in doubt. In the \(^9\text{Be}(\alpha, n_0)\) cross section, this state does not seem to play a very important role. If the state is \( 9/2^- \), then for the ground state neutrons \( \ell_n \) would be 5 and this may explain the very small contribution to this cross section.

A level at an excitation energy of 13.3 MeV in \(^{13}\text{C}\) which corresponds to an alpha bombarding energy of 3.83 MeV has previously been observed in neutron decay\(^{(13)}\) of \(^{13}\text{C}\). The quoted width is \( 5 \pm 1 \) MeV and if this is the same level as seen in the elastic scattering data at 3.8 MeV, there is considerable discrepancy
in the width. The level seen in the elastic scattering data may be another level since the analysis of the elastic scattering data is not sufficiently sensitive to the resonance energy of the level to determine the position to closer than 50 keV. In addition there are indications that the resonance structure at 3.8 MeV may be due to contributions from more than one level. Without knowledge of the number of strongly contributing levels, it becomes virtually meaningless to try to fit the data by including more and more levels in the calculation. The results of the search do indicate strong \( \ell_\alpha = 0 \) and \( \ell_\alpha = 2 \) contributions in this region. Thus it seems certain then that at least one of the levels contributing to the resonance structure at 3.8 MeV has an assignment of \( 3/2^- \) since only this assignment allows s-wave contributions.

The assignment of \( 5/2^+ (1) \) for a level at 5.50 MeV is consistent with the elastic scattering data and is preferred over a \( 3/2^+ (1) \) state by the \(^9\text{Be}(\alpha,n_0)\) data. The exact resonance energy, however, may prove to be different when contributions from higher-lying levels are included. But there appear to be several overlapping levels in the region above 5 MeV and without additional information meaningful analysis is very difficult.

A comparison of the total width of each level found from the elastic scattering data analysis with previously quoted widths is
presented in Table 2. The numerical value of the total width and partial widths of each level, however, are quite sensitive to the contributions to the cross section from nearby levels. Also because of the neglect of the level shift and the contributions of distant levels the widths must be considered as only approximate. At angles near 90° c.m. the calculations appear qualitatively correct though the magnitude is wrong. At this point the limitations of the present analysis prevent a good fit to the magnitude: contributions from distant levels have been neglected, and any contributions from direct reactions have been replaced by the assumption of hard sphere scattering.

Although there may be more levels in this energy region than those included in the present analysis, it appears that the $^9\text{Be}(\alpha,\alpha)^9\text{Be}$ excitation curves and angular distributions, together with the $^9\text{Be}(\alpha,n_0)$ data, present a strong case for the presence of at least the 7 levels in $^{13}\text{C}$ included in the analysis reported above.
APPENDIX A

APPARATUS

The experimental apparatus used to perform the measurements of the elastic scattering data is discussed in more detail below. The errors associated with the measurement are presented in Appendix B.

Scattering Chamber

The 23 inch diameter brass scattering chamber, shown schematically in Fig. 1, Chapter II, has an aluminum base plate and lid, both vacuum-sealed by conventional o-rings. The depth of the chamber is 6 inches while the lid and the base plate are each 1 inch thick. The base plate is bolted to a steel supporting table which is in turn secured to the floor by "dogs". To gain access to the scattering chamber, the lid is hoisted upward by a block and tackle located above the center of the chamber.

There are five ports on the brass shell of the scattering chamber, four of which are $90^\circ$ apart. The beam-entrance port is 1 inch in diameter; the faraday cage or beam-collecting port, the high vacuum port, and the viewing port are all 3 inches in diameter.
The fifth port is 2 inches in diameter and by-passes the beam entrance port and both connect to the beam pipe. The viewing port is covered during experimental runs to prevent light from entering the chamber since the solid state detectors used are sensitive to light.

The pressure in the chamber was measured by a type DG-2 Veeco Cold Cathode Discharge Gauge placed on the 2 inch beam pipe approximately one foot before the chamber. Typically the pressure attained by the 2 inch pumping system (with liquid nitrogen cold trap) was $2 \times 10^{-6}$ mm Hg.

Four surface-barrier silicon detectors manufactured by Ortec were used to measure yields at four angles simultaneously. For a detector bias of 100 V they had a depletion depth of 300 microns, sufficient to stop 20 MeV alpha particles. Each detector and its collimator was positioned in a dove-tail groove on a 15 inch diameter rotatable aluminum plate. The arrangement of the detectors and their collimators is shown schematically in Fig. 2., Chapter II. A fifth detector was used to check symmetry about 0°. The detector arrangement of two detectors 40° apart in the backward quadrant and two 40° apart in the forward quadrant allows one to measure angular distributions with only a few settings of the aluminum plate.

In order to have similar count rates in all detectors, solid angles
are smaller in the forward quadrant than in the backward quadrant.
The solid angles of each detector are tabulated in Table 4, Appendix B.

The aluminum plate can be positioned remotely by a variable-speed d.c. motor to 0.1 degree. A selsyn connected directly to the drive shaft of the motor is used to drive a selsyn in the control room which is read by a vernier scale graduated in 0.1 degree. The aluminum plate itself is scribed every degree. There is a vernier in the chamber which allows the position of the plate to be read to the nearest tenth of a degree, allowing comparisons of the angle set from the control room and the actual angle to which the plate has rotated. The system is calibrated at 0° first, by viewing with a telescope the alignment of the beam entrance collimator and each detector collimator. The beam entrance collimator is a tantalum slit with a circular hole 41 mils in diameter. Once the optical zero has been established, the beam is allowed to enter the chamber and zero degrees is determined by symmetry of scattering yields on either side of 0°.

Besides the beam entrance collimator, there are two slit-boxes positioned along the beam pipe to control the entrance of the alpha particle beam into the chamber. This is to assure that the beam will pass directly through the center of the chamber. The slit boxes were aligned optically.
Electronics

The pulses from each detector were fed to separate Tennelec Model TC133 low-noise preamplifiers located beneath the scattering chamber. The signals from each preamp were then amplified by an Ortec linear amplifier. The linear signals from each of the four detectors were ultimately routed into four quadrants of a 512 channel Nuclear Data analyzer. Several electronic configurations were used during the course of the experiment to accomplish this, but the best configuration is shown schematically in Fig. 3, Chapter II. With this configuration the noise of each detector is isolated from the noise of the others. Other configurations were used, however, before all four linear gates were available. With the addition of the IBM 1800 computer and Northern Scientific ADC to the facilities of the laboratory, the same electronic configuration shown in Fig. 3 can be used but instead of routing to the Nuclear Data 512 channel analyzer the pulses are routed to the computer. However, most of the elastic scattering data presented in this work were taken before the acquisition of these facilities.

Targets

The preparation of pure thin $^9$Be targets (i.e., thicknesses of 15 to 50 keV to 5 MeV alpha particles) presented considerable
difficulty. Sturdy and rugged beryllium foils can be made but the targets are of the order of 100 keV. Because thin films of beryllium become brittle and crack, targets were finally made by vacuum evaporation of beryllium metal onto a thin film of formvar. Molybdenum boats were found to be better suited for evaporation than tantalum because the beryllium metal seemed to form some compound or alloy with the tantalum boats making evaporation very difficult. The oxygen and carbon in the formvar added unwanted contaminants and also made target thickness measurements difficult (e.g., target thickness could not be determined by weight). The method of target thickness determination is presented in Appendix B. Typical spectra of alpha particles on the formvar backed $^9$Be target are shown in Fig. 4, Chapter II. The errors in determining the yield of alpha particles elastically scattered by $^9$Be is discussed in Appendix B.

The beam was collected in the faraday cup which is approximately 30 inches from the target. From the faraday cup the beam was integrated by a Brookhaven Model 1000 current integrator. Electrostatic suppression of backscattered electrons could be used, but was found to be unnecessary. Errors associated with the charge collection are discussed in Appendix B.
APPENDIX B

Experimental Uncertainties

The uncertainties associated with the measurement of the elastic scattering data are considered in this section. Discussions of the errors associated with solid angles, angular uncertainties, target thicknesses, and the reduction of yields of alpha particles elastically scattered by $^9$Be are presented. The experimental cross sections themselves are tabulated in Appendix G.

Solid Angles

The experimental data were measured simultaneously by four detectors each with its own collimator. The collimators were constructed of aluminum and the important dimensions of each are tabulated in Table 4. The collimators are numbered the same as the detectors are numbered in Fig. 2 in Chapter II with the exception that the collimator of the symmetry detector is listed as number 5. The diameter of the circular entrance aperture in each collimator was larger than the minimum diameter which would just allow the entire beam spot be seen by each detector. The mean diameter of each exit aperture was measured by a travelling microscope which allowed determination to within 0.01 mil. The
mean diameters of each exit aperture are also tabulated in Table 4. Another important consideration is the thickness of the exit aperture. At forward angles, small-angle scattering from the aperture presents some difficulties. To reduce this the thickness of each aperture is less than the mean diameter of the aperture.

The solid angles calculated from the area of each exit aperture and its distance from the center of the chamber were checked experimentally. Though experimentally one cannot easily measure an absolute solid angle, the ratio of the solid angles may be checked by comparison of yields when two detectors are at the same angle. The ratios of the various solid angles determined experimentally were the same as the ratios determined from the calculated solid angles to within the statistical error associated with the yield measurements. Except for detector 3 and the symmetry detector, all solid angles are known to better than 1%.

Angular Uncertainties

The collimators are arranged on the rotatable platform as shown in Fig. 2, Chapter II. The positioning of each collimator was accomplished by using a telescope at 0°. The beam entrance collimator was removed so that each collimator could be viewed at 0° and 180°. Since the angle of the rotatable platform could be read
TABLE 4

Detector Collimation

Detector Collimators

![Diagram of detector collimators with labels: d_i, T_i, C_i, D_i, and δC_i, δD_i.]

<table>
<thead>
<tr>
<th>Col.</th>
<th>d_i (in.)</th>
<th>T_i (in.)</th>
<th>C_i (in.)</th>
<th>δC_i (in.)</th>
<th>D_i (in.)</th>
<th>δD_i (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0.1098</td>
<td>0.025</td>
<td>2.984</td>
<td>+0.002</td>
<td>3.067</td>
<td>+0.002</td>
</tr>
<tr>
<td>#2</td>
<td>0.1094</td>
<td>0.021</td>
<td>2.926</td>
<td>+0.002</td>
<td>3.063</td>
<td>+0.002</td>
</tr>
<tr>
<td>#3</td>
<td>0.0164</td>
<td>0.013</td>
<td>2.946</td>
<td>+0.002</td>
<td>3.209</td>
<td>+0.002</td>
</tr>
<tr>
<td>#4</td>
<td>0.0656</td>
<td>0.021</td>
<td>2.982</td>
<td>+0.002</td>
<td>3.083</td>
<td>+0.002</td>
</tr>
<tr>
<td>#5</td>
<td>0.0179</td>
<td>0.013</td>
<td>2.974</td>
<td>+0.002</td>
<td>3.238</td>
<td>+0.002</td>
</tr>
</tbody>
</table>
\[ \Delta \Omega = \frac{A_i}{R_i^2} \], where \( R_i = C_i + D_i \)

<table>
<thead>
<tr>
<th>Col</th>
<th>( A_i ) (in( ^2 ))</th>
<th>( \frac{\delta A_i}{A_i} ) %</th>
<th>( \frac{\delta R_i}{R_i} ) %</th>
<th>( \Delta \Omega ) (str)</th>
<th>( \frac{\delta \Delta \Omega}{\Delta \Omega} ) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>( 9.463 \times 10^{-3} )</td>
<td>0.2</td>
<td>( 6.051 )</td>
<td>(&lt; 0.1 )</td>
<td>( 2.58 \times 10^{-4} )</td>
</tr>
<tr>
<td>#2</td>
<td>( 9.398 \times 10^{-3} )</td>
<td>0.2</td>
<td>( 5.989 )</td>
<td>(&lt; 0.1 )</td>
<td>( 2.62 \times 10^{-4} )</td>
</tr>
<tr>
<td>#3</td>
<td>( 2.11 \times 10^{-4} )</td>
<td>1.2</td>
<td>( 6.155 )</td>
<td>(&lt; 0.1 )</td>
<td>( 5.56 \times 10^{-6} )</td>
</tr>
<tr>
<td>#4</td>
<td>( 3.377 \times 10^{-3} )</td>
<td>0.3</td>
<td>( 6.065 )</td>
<td>(&lt; 0.1 )</td>
<td>( 9.18 \times 10^{-6} )</td>
</tr>
<tr>
<td>#5</td>
<td>( 2.52 \times 10^{-4} )</td>
<td>1.1</td>
<td>( 6.212 )</td>
<td>(&lt; 0.1 )</td>
<td>( 6.51 \times 10^{-8} )</td>
</tr>
</tbody>
</table>
to the nearest $0.1^\circ$ with an accuracy of $0.05^\circ$, the position of each collimator with respect to $0^\circ$ is known to no better than this uncertainty. Considerable care was taken to assure that the centers of each exit aperture of the various collimators were the same height above the platform.

The remote angle indicator was graduated to $0.1^\circ$, but the graduations are so close that they are very difficult to read. In addition the remote angle indicator had to be calibrated to the actual angles through which the platform rotated when the angles were set remotely. To avoid random errors the angle set remotely was always set in the direction of increasing angles so that any error in the angle would be systematic. The largest error associated with this system is in the actual reading of the remote angle indicator; the setting cannot usually be read to better than $0.2^\circ$.

The beam entrance collimator is a circular aperture with an 0.041 inch diameter. The target was set $40^\circ$ to the normal to the beam so that detectors 1 through 4 could "see" the target spot. If we let "a" be the diameter of the beam entrance collimator, $\theta$ be the angle of the target to the beam normal, and $\gamma$ the angle of the detector to the beam, we may write that the maximum angle $\theta$ for an off-axis alpha particle (dotted-dashed line in Fig. 11) which may be detected is
\[
\tan \theta = \frac{d' + \gamma \cos \varphi}{C + D} + \frac{\mu}{C + D},
\]

where \( C, D \) and \( d \) are tabulated in Table 4, and

\[
\varphi = \varphi - \bar{\varphi},
\]

\[
\gamma = \frac{a_h}{\cos \bar{\varphi}},
\]

and

\[
\lambda = \frac{y^2 \sin \varphi \cos \varphi}{[C + D - \frac{d'}{\tan \theta} - y \sin \varphi]}.
\]

It can be shown by evaluation of this expression that in the present work \( h \) is negligible since \( \theta \approx 1^\circ \), so that

\[
\tan \theta = \frac{d'}{C + D}.
\]

Bl. 1

The angular resolution of each detector using equation Bl. 1 is tabulated in Table 5. If the projection of the target spot to the normal of the collimator was less than the half the beam diameter the angular resolution was calculated using half the beam diameter. Also the angular resolution for the symmetry detector was calculated for the case when the target was normal to the beam \( i.e., \bar{\varphi} \) is zero. The angular resolution for all detectors is less than 1\(^\circ\).
Figure 11. Target Collimator Geometry.

\[
\tan \theta = \frac{d/2 + g + h}{C+D}
\]

\[
\tan \theta' = \frac{h + g}{C+D - d/2}
\]

\[
\psi = \psi - \phi
\]

\[
y = \frac{a/2}{\cos \phi}
\]

\[
g = y \cos \psi
\]

\[
I = y \sin \psi
\]

\[
h = I \tan \theta'
\]
Table 5

Angular Resolution

\[ \frac{a/2}{\cos 40^\circ} = 0.0267 \]

<table>
<thead>
<tr>
<th>Angle</th>
<th>Col.</th>
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</tr>
</thead>
<tbody>
<tr>
<td>165°</td>
<td>#1</td>
<td>0° 46'</td>
</tr>
<tr>
<td>130°</td>
<td>#1</td>
<td>0° 46'</td>
</tr>
<tr>
<td>130°</td>
<td>#2</td>
<td>0° 46'</td>
</tr>
<tr>
<td>90°</td>
<td>#2</td>
<td>0° 43'</td>
</tr>
<tr>
<td>15°</td>
<td>#3</td>
<td>0° 18'</td>
</tr>
<tr>
<td>50°</td>
<td>#3</td>
<td>0° 19'</td>
</tr>
<tr>
<td>50°</td>
<td>#4</td>
<td>0° 34'</td>
</tr>
<tr>
<td>90°</td>
<td>#4</td>
<td>0° 31'</td>
</tr>
<tr>
<td>10°</td>
<td>#5</td>
<td>0° 16'</td>
</tr>
<tr>
<td>20°</td>
<td>#5</td>
<td>0° 16'</td>
</tr>
</tbody>
</table>
**Charge Collection**

Located approximately 1 inch before the faraday cage was a tantalum disk with a 2-inch diameter circular hole. Voltages of 300 V or 600 V could be applied to the disk to electrostatically suppress backscattered electrons. Experimentally it was found that the data taken with such applied potentials were the same within statistical uncertainties as the data taken without suppression. Magnetic deflection was also tried and no discernible difference was measured in the experimental data. For these reasons, neither magnetic deflection or electrostatic suppression were used while taking the majority of the data presented in this work. Current on the tantalum disk could be monitored and was never more than 1% of the total beam.

Leakage from the faraday cup was checked by using a Dymec Voltage-to-frequency converter as a current integrator. The input resistance of the Dymec Voltage-to-frequency converter is one megohm and the input of the Brookhaven current integrator is a virtual ground. Data measured with both were the same within statistical uncertainties (1%) and it was thus concluded that error due to leakage currents were negligible. The Brookhaven current integrator was used in measuring the data because of its low input impedance.
Below two approximate calculations are presented to 1) check the amount of beam deflected by the target and thus not be collected in the Faraday cage, and 2) to check the amount of beam elastically backscattered from the Faraday cage.

1) For the sake of calculation, let us assume that scattering from the target on the average is Rutherford. The number of particles scattered by the target which do not enter the Faraday cage is

$$\gamma = \frac{TQ}{Q} \int d\sigma,$$

where $T$ is the target thickness in number of atoms per cm$^2$, $Q$ is the total charge striking the target, $q$ is the charge per particle striking the target, and the limits of integration exclude a cone determined by the size of the opening of the Faraday cage. The angle of the cone is designated as $\gamma$.

The charge not collected in the Faraday cage because of Rutherford scattering is

$$Q' = \gamma Q = TQ \int d\sigma. \quad \text{B1.2}$$

Substitution of $d\sigma$ into B1.2 we have

$$\frac{Q'}{Q} \approx T (\frac{1.296}{E}) \left( \frac{Z_1 Z_2}{E} \right)^2 \int_0^{\gamma} \int_{\frac{m_1^2}{m_2}}^{\frac{m_1^2}{m_2}} \left[ \frac{m_1^2}{m_2} \theta - 2 \left( \frac{m_1}{m_2} \right) \theta \right] d\theta d\phi. \quad \text{B1.3}$$
where we have used only the first two terms in the expansion of Rutherford scattering cross section, \( E \) is in MeV and the cross section is in mb/sterad. From the dimensions of the scattering chamber, \( \gamma \) is 4.8°. Performing the integrations in Bl. 3 we have

\[
\frac{Q'}{Q} = T (1.296) \left( \frac{Z_1 Z_2}{E} \right)^2 2\pi \left[ \frac{-2}{\alpha m_1^2} \left| \phi \right| + 2 \left( \frac{m_1}{m_2} \right)^2 \cos \theta \left| \frac{\pi}{\phi} \right| \right],
\]

Bl. 4

Let us evaluate this for \( E \) equal to 1.7 MeV. The other quantities have the following values:

\[
T = 1.79 \times 10^{18} \text{ particles/cm}^2,
\]

\[
Z_1 = 2,
\]

\[
Z_2 = 4,
\]

\[
m_1 = 4,
\]

and \( m_2 = 9. \)

We have

\[
\frac{Q'}{Q} \approx (1.79 \times 10^{18}) (28.7 \times 10^{-27}) 2\pi \left[ 568 \right]
\]

or

\[
\frac{Q'}{Q} \approx 0.02\%.
\]

We can conclude that this effect is negligible if the scattering is Rutherford. Even if the scattering were three or four times that which you expect from Rutherford scattering the error is still negligible.
2) To estimate the amount of beam which scatters from the Faraday cup. We assume Rutherford scattering again. From the dimensions of the chamber the beam can escape if it scatters from 176.2° to 180°. We use equation B1.4 again, changing the limits of integration and the values of the quantities associated with the reaction. To achieve an order of magnitude calculation, an effective target thickness of the tantalum beam stop must be estimated. Since the beam stop is "thick" enough to stop the entire beam, the effective target thickness is taken to be that thickness which would degrade an 8 MeV alpha particle beam to 4 MeV. From range calculations we find that the target thickness is approximately 5.7 x 10^{19} atoms/cm^2. The other quantities have the following values:

\[ Z_1 = 2, \quad Z_2 = 73, \quad m_1 = 4, \quad m_2 = 181. \]

We again evaluate at the energy 1.7 MeV and find that

\[ \frac{Q'}{Q} \approx 10^{-6} \% . \]

We find this effect even smaller than the first. Of the errors which we have considered, the largest seems to be the beam which was read on the suppressor ring. We take this to be the upper limit of the error associated with charge collection, approximately 1%.
Target Thickness

Several targets were used during the course of the experiment. An absolute target thickness determination was made for only one of these. The other data were then normalized to the data taken with this target which we shall denote as F. The thickness of target F was measured using two independent experiments.

The first method took advantage of the carbon which was on both sides of the target. The $^{12}\text{C}(\alpha,\alpha)^{12}\text{C}$ cross section has a very marked resonant fluctuation at 4.28 MeV bombarding energy, corresponding to the $4^+$ level at an excitation energy of 10.36 MeV in $^{16}\text{O}$. This level has a natural width of 27 keV. The $^9\text{Be}$ target thickness was unfolded from the shift in the excitation curves of the carbon on the front of the target and the carbon in the backing over this resonance. The data were taken at 157.3° lab. and are shown in Fig. 12. From the cross section data\textsuperscript{13} for alpha particles elastically scattered by $^{12}\text{C}$ and from energy loss calculations from Whaling\textsuperscript{14} the carbon on the front of the target was found to be approximately 2.7 keV. From similar calculations\textsuperscript{15} the amount of $^{16}\text{O}$ present in the target was estimated to be 4.5 µg/cm². Assuming half of the total $^{16}\text{O}$ yield is from the front of the target it was calculated that the alpha particle beam at
Figure 12. Excitation Curve of $^{12}\text{C}(\alpha,\alpha)^{12}\text{C}$ at 157.3° lab. The lower excitation curve was measured for the carbon which was on the front of the target, the second for carbon in the target backing.
4.92 MeV loses 3.7 keV passing through the oxygen. The two resonance curves are shifted approximately 30 keV from each other and so the shift due to the $^9$Be target is about 23.6 keV. If the estimates of the carbon and oxygen thickness were off by 50%, the error in the determination of $^9$Be target thickness would be 15%. From this method we find the $^9$Be target thickness of target $F$ to be $1.77 \times 10^{18}$ atoms/cm$^2$ with an upper limit of 15% uncertainty.

From the elastic scattering of deuterons by $^9$Be and normalizing to the data of Renken$^6$ at 1.2 MeV and 163.5 c.m. the thickness of target $F$ was measured to be $1.81 \times 10^{18}$ atoms/cm$^2$. Renken$^6$ quotes an uncertainty of 6.7%. Because of background in the present measurement of the deuteron yield, there is an additional uncertainty of about 4% in the present result. The two independent measurements of target $F$ agree much closer than the quoted uncertainties but this may be fortuitous. Taking an average of the two measurements, the $^9$Be target thickness is found to be $1.79 \times 10^{18}$ atoms/cm$^2$ with an uncertainty of 10%.

The target thickness of each of the other targets used in the experiment is given in Table 6 along with the uncertainty due to normalization. The normalizations were done over several energies and at various angles. Except for targets $A$ and $B$ the targets are the same thickness within 20%. Target $A$ was a self-
supporting $^9$Be foil and was approximately 150 keV thick for 4.29 MeV alpha particles. Normalizations of this target and target B which were used for taking angular distributions around 5.0 MeV are rather uncertain (~15%) because of the significant difference in target thickness compared to target F.

The reproducibility of the data at all angles indicates a relative uncertainty of 5% even though the statistical uncertainties for all data presented are between 1 and 3%. The discrepancy may be due to several causes. The uncertainty of the position of the platform on which the four detectors are mounted relative to the beam will cause systematic differences between the yields measured at these four angles relative to those yields when the platform is at a slightly different setting. The uncertainty introduced in the measurements depends on how fast the cross section is varying at the different angles. In the present experiment such systematic variation in yields is observed but cannot easily be corrected.

Another source of error is background subtraction which varies from 1 to 10%. A significant contribution to background is from alpha particles elastically scattered by $^{12}$C. The $^{12}$C($\alpha$, $\alpha$)$^{12}$C cross section is rapidly changing with energy in the region from 1.7 to 6.0 MeV. Kinematically at low energies or forward angles,
the elastically scattered alpha particle groups from $^9$Be and $^{12}$C are not entirely resolved. Depending on how the background is averaged, uncertainties of 2 or 3% may result.

Another possible source of error is target non-uniformity. To reduce errors of this type the beam is tightly collimated and the beam spot is 0.041 inches in diameter. It is difficult to estimate the uncertainty due to target non-uniformity; however, from the observed reproducibility of the data, it must be less than 5% over the target spot.

Electronic routing of the four detector signals into the Nuclear Data analyzer may also produce errors. Routing errors were constantly checked and were always less than 1%. Corrections due to analyzer dead time were negligible, less than 0.5%. The energy resolution and reproducibility of the Van de Graaff accelerator is another possible source of uncertainty. The energy reproducibility was approximately 10 keV for a 5 MeV alpha particle beam. This was determined experimentally by observing the shifts in the excitation curves which were taken in 10 keV steps with a 5 keV target for 5 MeV alpha particles. This data is not presented in Appendix G but appears in the Chapter III of the text.

The overall error associated with the experimental measurements is presented in Table 7. The uncertainty in the cross
The cross section is calculated from

\[
\left( \frac{\Delta \sigma}{\sigma} \right)_{\text{LAB}} = \left[ \left( \frac{4 Q}{q} \right)^2 + \left( \frac{4 Y}{Y} \right)^2 + \left( \frac{4 T}{T} \right)^2 + \left( \frac{4 \Omega}{\Omega} \right)^2 + \left( \frac{4 \theta}{\theta} \right)^2 \right]^{1/2}
\]

where \( Q \) is the total charge collected, \( Y \) is the experimental yield, \( T \) is the target thickness in number of atoms per cm\(^2\), \( \Omega \) is the solid angle, and \( q \) is the effective charge per particle (see Appendix E, CONVR). The largest errors associated with the cross section measurement are the absolute target thicknesses.
<table>
<thead>
<tr>
<th>Target</th>
<th># atoms/cm²</th>
<th>Normalization uncertainty %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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</tr>
<tr>
<td>B</td>
<td>$3.08 \times 10^{18}$</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>$1.87 \times 10^{18}$</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>$2.06 \times 10^{18}$</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>$2.17 \times 10^{18}$</td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>$1.79 \times 10^{18}$</td>
<td></td>
</tr>
</tbody>
</table>
# TABLE 7

Cross Section Uncertainty

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<tr>
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<th>ΔΩ/Q</th>
<th>ΔY/Y</th>
<th>ΔT/T</th>
<th>ΔC/Ω</th>
<th>Δq/q</th>
<th>Δσ/σ</th>
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<td>Normalization</td>
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<td></td>
<td></td>
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<tr>
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<td>1%</td>
<td>5%</td>
<td>15%</td>
<td>10%</td>
<td>1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>B</td>
<td>1%</td>
<td>5%</td>
<td>15%</td>
<td>10%</td>
<td>1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>C</td>
<td>1%</td>
<td>5%</td>
<td>4%</td>
<td>10%</td>
<td>1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>D</td>
<td>1%</td>
<td>5%</td>
<td>5%</td>
<td>10%</td>
<td>1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>E</td>
<td>1%</td>
<td>5%</td>
<td>7%</td>
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<td>1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>F</td>
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<td>5%</td>
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<td>11%</td>
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</tbody>
</table>
APPENDIX C

Development of Elastic Scattering and Reaction Cross Section Formulae

As mentioned earlier, the cross section for the elastic scattering of alpha particles by $^9$Be appears to have a large contribution due to compound nucleus formation. In the following sections, the formulae for the elastic scattering and reaction cross sections are developed assuming compound nucleus formation. The formalism and approach follows closely that of Blatt and Biedenharn. In Section 1 passages of Blatt and Biedenharn are quoted to introduce the notation to be used. The purpose of each section is outlined below.

Section 1. Starting from the Hamiltonian and the definition of the scattering matrix $S$ (or collision matrix $U$) the cross section is defined in terms of a reaction amplitude $q$.

Section 2. The sums over magnetic quantum numbers are separated out from the cross section defined in Section 1. The sums over the magnetic quantum numbers are performed in Section 9 and the resulting cross section formula presented in Section 2.

Section 3. The scattering matrix elements are presented and discussed.
Section 4. Using the scattering matrix elements presented in Section 3 the reaction cross section is evaluated.

Section 5. In this section the elastic scattering of neutral particles is evaluated. A short discussion of why this formula is not suited for the elastic scattering of charged particles is presented.

Section 6. The elastic scattering of charged particles is evaluated by separating out Rutherford scattering and comparison with the results derived in Section 5.

Section 7. In Sections 4, 5, and 6, only levels with different spin and parity were allowed to contribute to the cross section. In this section terms are evaluated for the case of two levels of the same spin and parity. The various approximations used are discussed.

Section 8. In this section terms are evaluated for the case of three levels of the same spin and parity. This was done with the analysis of the $^{12}\text{C}(d, d)^{12}\text{C}$ data particularly in mind. In this reaction there are three levels of $J^\pi$ equal to $4^+$ and to $4^-$ quoted in the energy region of interest.

Section 9. The sum over magnetic quantum numbers is performed. See Section 2.
1. INTRODUCTION

In order to develop the expression for the elastic scattering or reaction cross sections, it is necessary to develop an expression for the scattering amplitude \( f(\theta) \). The differential cross sections are then related to \( f(\theta) \) by

\[
\frac{d\sigma}{d\Omega} = |f(\theta)|^2
\]

For the case of pure elastic scattering of spinless particles, one has the well-known result that

\[
f(\theta) = \kappa \sum_{\ell=0}^{\infty} (2\ell+1)e^{i\delta_{\ell}} \sin \delta_{\ell} \mathcal{P}_{\ell}(\cos \theta)
\]

where \( \kappa \) is the de Broglie wave length divided by \( 2\pi \), \( \mathcal{P}_{\ell}(\cos \theta) \) are the Legendre Polynomials, and \( \delta_{\ell} \) are the phase shifts.

It is the purpose of the following sections to derive an expression for \( f(\theta) \) dropping the assumptions of pure elastic scattering and spinless particles.

Let us consider the reaction

\[
a + x = b + y
\]
where particle \( a \) collides with the target nucleus \( x \) and (in the center of mass \([c.m.]\)) particle \( b \) emerges, after the collision, at some angle \( \theta \) relative to the beam and the residual nucleus \( y \) recoils in the opposite direction. We wish to solve the Schroedinger equation for \( \psi \) describing this system. Once we have \( \psi \), then using the definition of the scattering or collision matrix we can finally solve for \( f(\theta) \).

Since the total angular momentum \( J \) of the system is preserved during the collision, it is natural that we wish to express the solution in the \([JM] \) representation where \( M \) is the projection of \( J \) along some quantitization axis (usually chosen along the beam direction).

Before we can write the solution, there are several other quantities associated with the system which must be defined.

The system before the collision is described by three numbers: the channel index \( \alpha \), the channel spin \( s \) and the orbital angular momentum (in the center of gravity system) \( \ell \).

The channel index \( \alpha \) defines the type of incoming particle (neutron, proton, \( \alpha \)-particle, etc.) and the state of the struck nucleus (usually the ground state). The channel spin \( s \) is the total spin angular momentum in the channel; it is formed by vector addition of the intrinsic spin \( i \) of the incoming particle and the spin \( I \) of the struck nucleus. The state of the system after the collision is described by the channel coordinate \( \alpha' \) (which includes specification of the outgoing particle and of the quantum state of the residual nucleus), channel spin \( s' \)
(which is formed by vector addition of the intrinsic spin $i'$ of the outgoing particle and of the spin $I'$ of the residual nucleus in whatever quantum state it is left), and the outgoing orbital angular momentum $\ell'$.

$J$ is formed by vector addition of $\ell$ and $s$ and since $J$ is conserved, it must also be equal to the vector addition of $\ell'$ and $s'$.

To solve for $\psi$ we must solve the Schroedinger equation,

$$H\psi = E\psi$$ \hspace{1cm} \text{(C1.4)}$$

where $E$ is the total energy and $H$ is the Hamiltonian of the system.

In R-matrix theory\textsuperscript{(16), (17)} the configuration space is divided into two regions; an external region and an internal region. In the external region, the separation of the two nuclear fragments is large enough that there are no nuclear forces acting and if the particles are charged, the only interaction considered is the Coulomb force. However, in the internal region, the nuclear fragments are close enough to experience strong nuclear forces, and thus may temporarily form an unstable compound nucleus. It is sufficient for our purposes now to consider only the wave function in the external region after a reaction has occurred.
Let us consider the experimental situation that a reaction is initiated in only one channel $\alpha$ with channel spin $s$. Furthermore we shall consider only those channels $\alpha$ which are "open" at the energy in question, i.e. for which $k_\alpha$, the channel wave number, is real.

The Hamiltonian in the external region corresponding to channel $\alpha, s$ is given by

$$H = H_a + H_x + h_\alpha$$

where $H_a$ and $H_x$ are the Hamiltonians for the internal motion of the respective nuclei $a$ and $x$, and $h_\alpha$ is the Hamiltonian for the relative motion of the centers of mass of $a$ and $x$.

The wave function $\psi_{\alpha s}$ is a complete set of eigenfunctions which have the product form

$$\psi_{\alpha s} = \chi(r_\alpha) \psi_a \psi_x,$$

where

$$h_\alpha \chi(r_\alpha) = E_\alpha \chi(r_\alpha),$$

$$H_a \psi_a = E_a \psi_a,$$

$$H_x \psi_x = E_x \psi_x,$$

and $E = E_\alpha + E_a + E_x$, and
where $\psi_a$ and $\psi_x$ are the internal wave functions of nuclei $a$ and $x$ appropriate to specification $\alpha, \beta$. The wave function $\chi(r_\alpha)$ is that of relative motion of the nuclear pair and can be further factorized into radial and angular functions:

$$
\chi(r_\alpha) = \frac{U_{\alpha \ell}(k_\alpha r_\alpha)}{\sqrt{\nu_\alpha r_\alpha} \ r_\alpha} \left[ i^{\ell} \gamma_{\ell, m_\ell}^{+}(\theta, \phi) \right], \quad \text{Cl. 5}
$$

where $\nu_\alpha$ is the relative velocity in channel $\alpha$ and $Y_{\ell, m_\ell}(\theta, \phi)$ is the spherical harmonic with relative angular momentum $\ell$ and $z$ component $m_\ell$.

The factor $i^{\ell}$ is included in the above equation because

$$
i^{\ell} Y_{\ell, m_\ell}(\theta, \phi) \text{ satisfies the time-reversal relation proposed by Huby}^{(\text{a})}
$$

$$
K(i^{\ell} Y_{\ell, m_\ell}) = (-)^{\ell-m_\ell} (i^{\ell} Y_{\ell, -m_\ell})
$$

The radial function $U_{\alpha \ell}$ satisfies the radial Schroedinger equation

$$
\left[ \frac{d^2}{dr_a^2} - \frac{l(l+1)}{r_a^2} + \frac{\hbar^2}{\alpha} - \frac{2\mu_a}{\hbar^2} V(r_\alpha) \right] U_{\alpha \ell}(k_\alpha r_\alpha) = 0, \quad \text{Cl. 6}
$$

where for chargeless particles $V(r_\alpha) = 0$, while charged particles have

$$
V(r_\alpha) = Z_a Z_x e^2/r_\alpha.
$$

The quantity $\mu_a$ is the reduced mass of the relative motion in channel $\alpha$. 
For positive $E_\alpha$, there are two linearly independent solutions for equation C1.6. Let us denote these solutions by $I_{\alpha l}$ and $O_{\alpha l}$ since for large $r$ they have the form of an ingoing and outgoing spherical wave. Let us separate out the spin function $\chi_{s',m_s}$ and define $\mathcal{F}_{as}$, the product of the wave function of the nucleus $x$ and the particle $a$, by

$$\psi_a \psi_x = \mathcal{F}_{as} \chi_{s',m_s} \quad \text{C1.7}$$

The complete channel wave functions can then be written as

$$I_{\alpha s'l,m_s l} = i^l \gamma_{l,m_l} \frac{I_{\alpha l}}{\sqrt{r_a}} \mathcal{F}_{as} \chi_{s',m_s} \quad \text{C1.8}$$

$$O_{\alpha s'l,m_s l} = i^l \gamma_{l,m_l} \frac{O_{\alpha l}}{\sqrt{r_a}} \mathcal{F}_{as} \chi_{s',m_s} \quad \text{C1.8}$$

Before continuing let us change from the $\xi_{as'l,ms'm_s}$ representation to the $\xi_{aslJM}$ representation and separate out the spin-angle dependence in the function $\psi_{Jls}^M$. Using the Clebsch-Gordon coefficients which couple $l$ and $s$ and $m_s$ and $m_l$ to $J$ and $M$, we have

$$\psi_{Jls}^M = \sum_{l=1}^{l} \sum_{m_s = -s}^{s} \langle lsm_l m_s | JM \rangle \gamma_{l,m_l} (\theta, \phi) \chi_{s,m_s} \quad \text{C1.9}$$

The most general solution for $\psi$ is a superposition of the wave functions given in equation C1.8. We thus have

$$\psi = \sum_{J,M} \sum_{l} \mathcal{F}_{J,M} \psi_{aslJM} \quad \text{C1.10}$$
The coefficients \( A_{\text{JM}} \) and \( B_{\text{JM}} \) are not independent of each other. The relation between them defines the scattering matrix

\[
B_{\alpha' s' l'} = \sum_{\alpha' s' l'} S^J_{\alpha' s' l'} A_{\text{JM}}^{\alpha s l}.
\]

Thus in terms of the scattering matrix, we have

\[
\psi = \sum_{JM} A_{\text{JM}}^{\alpha s l} \frac{1}{r} (\frac{\nu}{\alpha})^\nu \psi_{JM}^{\alpha s l} \left[ A_{\text{JM}}^{\alpha s l} I_{\alpha l} - \sum_{J} S^J_{\alpha' s' l'} A_{\text{JM}}^{\alpha' s' l'} O_{\alpha l} \right].
\]

We must now evaluate the coefficients \( A_{\text{JM}}^{\alpha s l} \). In order to determine \( f(\theta) \) we want to write

\[
\psi = \psi_{\text{inc}} + \psi_{\text{reac}}.
\]

where \( \psi_{\text{inc}} \) (the incident wave in channel \( \alpha, s \)) is a plane wave. Thus \( \psi_{\text{inc}} \) is given by \( \exp(i k_{\alpha} z_{\alpha}) \chi_s m_s \) since we have chosen the \( z \) axis along the beam direction. To evaluate \( A_{\text{JM}}^{\alpha s l} \) requires some algebra but the first step involves decomposing the plane wave

\[
\exp(i k z) = (4\pi)^{\frac{1}{2}} \sum_{l=0}^{\infty} \frac{1}{(2l+1)^{\frac{1}{2}}} J_l(kr) Y_l^0(\theta).
\]

For large \( r \), the spherical Bessel functions have the asymptotic form
\[ j_l (r) \sim \left[ \sin (kr - \frac{1}{2} l \pi) \right] / kr \quad \text{C1.15} \]

And again using C. G. coefficients we can write

\[ \gamma_{\alpha l} (\theta) \chi_{3, m_s} = \sum_{s} \sum_{M=-J}^{J} \left( \langle s \text{om} |JM \rangle \right) \frac{1}{k_a r_a} \quad \text{C1.16} \]

Thus using equations C1.14, C1.15, and C1.16 we have for large

\[ r_a \]

that

\[ \exp (i k_a J_\alpha) \chi_{3, m_s} \mathcal{F}_{\alpha S} \sim \frac{i (\pi)}{k_a r_a} \sum_{s} \sum_{M=-J}^{J} \left( \langle s \text{om} |JM \rangle \right) \frac{1}{k_a r_a} \quad \text{C1.17} \]

\[ \left( \langle s \text{om} |JM \rangle \right) \frac{1}{k_a r_a} \left[ e^{-i (k_a r_a - \frac{1}{2} l \pi)} - e^{i (k_a r_a - \frac{1}{2} l \pi)} \right] \]

The properties of the C. G. coefficient allow us to interchange \( \ell \) and \( J \) in the first two sums in equation C1.17 without changing the result. Since for large \( r_a \)

\[ l_\alpha \sim e^{-i (k_a r_a - \frac{1}{2} l \pi)} \quad \text{and} \quad o_\alpha \sim e^{i (k_a r_a - \frac{1}{2} l \pi)} \quad \text{C1.18} \]

we can easily evaluate the \( A_{\alpha s l}^{JM} \) coefficients by comparing the asymptotic form of equation C1.12 with C1.17 for the ingoing wave.

\[ A_{\alpha s l}^{JM} = \frac{i (\pi \nu_a)^{\frac{1}{2}}}{k_a} \left( \langle s \text{om} |JM \rangle \right) (2l + 1)^{\frac{1}{2}} \quad \text{in channel } \alpha, s \quad \text{C1.19} \]

\[ A_{\alpha s l}^{JM} = 0 \quad \text{in other channels.} \]
Using equation C1.11 and the above results we find that

\[ B^J_M = \sum_{s'} l_s |s'| \frac{i}{k_l} (\pi v_d) \frac{1}{2} \left( \text{som}_s |J_M \rangle (2l+1)^{\frac{1}{2}} \psi_{a's'l'} \right). \]  

C1.20

Notice that there is no sum over \( \alpha \) or \( s \) in C1.20. This corresponds to the fact that there are no ingoing spherical waves in any channels other than the entrance channel \( \alpha, s \).

Expressing equation C1.17 in terms of \( A^J_M_{\alpha s} \) we have

\[ \psi_{inc} = \frac{\sum_{s'} \mathcal{L}_M}{r_d(v_d)} \sum_{J, M} A^J_M_{\alpha s} \left( f \frac{e^{i(k \alpha r_{\alpha} - \frac{1}{2} l \pi)}}{l_{s'} \alpha s \lambda} \right). \]  

C1.21

Returning to equation C1.10 and using equations C1.18 and C1.21, we now separate \( \psi \) into the incident part and the reaction part. Since \( A^J_M_{\alpha s} \) is zero except for channel \( \alpha, s \) we obtain

\[ \psi = \psi_{inc} + \sum_{J, M} \frac{\mathcal{L}_M}{r_d(v_d)} \sum_{J, M} A^J_M_{\alpha s} \left( f \frac{e^{i(k \alpha r_{\alpha} - \frac{1}{2} l \pi)}}{l_{s'} \alpha s \lambda} \right) \]  

C1.22

To make substitution into equation C1.22 less confusing, let us interchange the order of the sums over primed and unprimed quantities (one sum is in \( B^J_M_{\alpha s l} \)) and relabel. Also we know that

\[ i'e^{-i\frac{\Delta \pi}{2}} = 1, \]

so we may rewrite equation C1.22 as
\[ \psi = \psi_{\text{me}} + \sum_{\text{JM}} \sum_{\alpha's'} \frac{s_{\alpha's'}}{r_{\alpha}(\nu_{\alpha})^{1/2}} \mathcal{F}_{\text{JM}}^{M} \mathcal{J}_{\text{JM}}^{\alpha's'} (s_{s's's's'} s_{ll'}a_{JM}^{T}) \]

\[ -B_{\alpha's'l'}^{JM} e^{i(k_{\alpha},r_{\alpha})} \]

If we define

\[ \psi = \sum_{\alpha's'} \psi_{\text{me}} (\alpha's') \]

we see from equation C1.23 that

\[ \psi_{\text{me}} (\alpha's') = \sum_{\text{JM}} \sum_{\alpha's'} \frac{s_{\alpha's'}}{r_{\alpha}(\nu_{\alpha})^{1/2}} \mathcal{F}_{\text{JM}}^{M} \mathcal{J}_{\text{JM}}^{\alpha's'} (s_{s's's's'} s_{ll'}a_{JM}^{T}) - B_{\alpha's'l'}^{JM} e^{i(k_{\alpha},r_{\alpha})} \]

Substituting for \( A_{\alpha's'l'}^{JM} \) and \( B_{\alpha's'l'}^{JM} \), we have

\[ \psi_{\text{me}} (\alpha's') = \frac{s_{\alpha's'}}{r_{\alpha}(\nu_{\alpha})^{1/2}} \sum_{\text{JM}} \mathcal{F}_{\text{JM}}^{M} \mathcal{J}_{\text{JM}}^{\alpha's'} e^{i(k_{\alpha},r_{\alpha})} \]

\[ = \left\{ (2l+1)^{1/2} \frac{i}{k_{\alpha'}} \left( \text{some J} \right) s_{s's's's'} s_{ll'}a_{JM}^{T} - \sum_{l} \frac{i(\pi\nu_{\alpha})^{1/2}}{k_{\alpha}} \right\} \]

\[ \left( \text{some J} \right) (2l+1)^{1/2} \sum_{\alpha's'l'\alpha's'l'} \mathcal{F}_{\text{JM}}^{T} \]
Using C1.9 to decompose the spin-angle-function $\psi^M_{\mathcal{J} \mathcal{L}', \mathcal{S}'}$, in C1.27 we write $\psi_{\text{react}}(\alpha's')$ in the form

$$\psi_{\text{react}}(\alpha's') = i \chi(\frac{\mathcal{V}_\alpha}{\mathcal{V}_\alpha'})^\frac{i}{2} \frac{e^{i(\hat{\mathcal{H}} \cdot r_{\alpha'}}}{r_{\alpha'}^*} \bar{\Xi}_{\alpha's'} X.$$  

where $q$, the reaction amplitude, is given by

$$q_{\alpha's'm_s'j \alpha sm_s}(\Theta, \Phi) = \sum_{\mathcal{J}, \mathcal{L}' \mathcal{J}' \mathcal{S}' \mathcal{S}} \sum_{\mathcal{J}, \mathcal{L} \mathcal{S}'} \frac{1}{(2\mathcal{J} + 1)(2\mathcal{J}' + 1)} (\mathcal{L} \mathcal{S}' \mathcal{J}' \mathcal{S}') X_{\alpha's'm_s'}.$$  

The quantity $q$ defined in C1.29 can properly be called the reaction amplitude for the reaction $\alpha sm_s \rightarrow \alpha's'm_s$. The differential cross section corresponding to known spin directions $m_s$ and $m_s'$ in the incident and outgoing channels respectively, for a collision in which the final particle emerges within the solid angle element $d\Omega$ in the direction $\Theta, \Phi$ with respect to the incident
beam is given in terms of the reaction amplitude \( q \) as

\[
\frac{d\sigma_{\alpha's'm_s';j \alpha s m_s}}{d\Omega} = \chi^2 \left| \delta_{\alpha's'm_s';j \alpha s m_s}(\Theta, \phi) \right|^2.
\]

The collision amplitude \( q \) depends on the angle \( \phi \) since the spin directions \( m_s \) and \( m_s' \) are specified. Experimentally, detectors select particles traveling in a given direction \( \Theta, \phi \), but are unable to differentiate among particles corresponding to various values of the channel spin \( s' \) and spin directions \( m_s' \). Also in the present work the incident beam was unpolarized so the cross section for the \( \alpha - \alpha' \) collision is obtained by averaging over the incident channel spin \( s \) and spin directions \( m_s \) and summing the spins \( s' \) and spin directions \( m_s' \):

\[
\frac{d\sigma_{\alpha's'm_s';j \alpha s m_s}}{d\Omega} = \sum_{s'=-s}^{s+s'} \sum_{m_{s'}=-s}^{s} \frac{1}{(2I+1)(2I'+1)} 
\]

In C.1.31 the sums over \( s \) and \( s' \) cannot be simplified by geometrical considerations. However, the sums over \( m_s \) and \( m_s' \) are purely geometrical in nature. In the next section we shall perform the sums over \( m_s \) and \( m_s' \), it being understood that the sums over \( s \) and \( s' \) must be performed on the final expression before comparison can be made with experiment. Notice that the scattering amplitude \( f(\phi) \) which we were originally trying to evaluate
is the same as the collision amplitude $q$ times $\chi$. Thus dropping the assumption of spinless particles has added a $\phi$ dependence to the scattering amplitude. However, the averaged cross section (C1.31) is independent of the angle $\phi$, even though individual terms depend upon it.
2. REDUCTION OF THE DIFFERENTIAL CROSS SECTION

In this section we shall perform the operations indicated in Cl. 30 and perform the sums over $m_\alpha$ and $m_{\alpha'}$ in Cl. 31. Let us define for convenience:

$$\frac{d\sigma_{\alpha's',\alpha}}{d\Omega} = \frac{1}{(2S+1)} \sum_{m_\alpha m_{\alpha'}} \frac{d\sigma_{\alpha's'm_{\alpha'}j s m_\alpha}}{d\Omega} ,$$

C2.1

so that

$$\frac{d\sigma_{\alpha'\alpha}}{d\Omega} = \sum_{s'1} \frac{d\sigma_{\alpha's';\alpha}}{d\Omega} \frac{d\sigma_{\alpha's'm_{\alpha'}j s m_\alpha}}{d\Omega} \frac{(2S+1)}{(2I'+1)(2I+1)} \frac{d\sigma_{\alpha's',\alpha}}{d\Omega} .$$

Doing the indicated operations we have

$$\frac{d\sigma_{\alpha's',\alpha}}{d\Omega} = \frac{\lambda_\alpha^2}{(2S+1)} \sum_{l_1} \sum_{l'_1} \sum_{l_2} \sum_{l'_2} \sum_{l_3} \sum_{l'_3} \times$$

$$\left( S_{\alpha\alpha'} S_{S'S'} f_{l_1 l'_1} - S_{\alpha's'l'_1}{,\alpha s l_1} \right)^* \times C2.2$$

$$\left( S_{\alpha\alpha'} S_{S'S'} f_{l_2 l'_2} - S_{\alpha's'l'_2}{,\alpha s l_2} \right) K(J_{1l_1 l'_1} J_{2l_2 l'_2} j s s') ,$$

where we have separated out the sums over magnetic quantum numbers and $K$ is defined as

$$K(J_{1l_1 l'_1} J_{2l_2 l'_2} j s s') = \frac{1}{(2J_1+1)} \frac{1}{(2J_2+1)} \prod \sum_{m_5 m_6} \sum_{m_7 m_8} \mu_1 \mu_2 \times$$

$$C2.3$$

$$\left( \left| \langle \frac{1}{2} \frac{1}{2} | \frac{1}{2} \frac{1}{2} | J M \rangle \right| \langle \frac{1}{2} \frac{1}{2} | \frac{1}{2} \frac{1}{2} | J'M' \rangle \left( \frac{1}{2} s' \mu_1 m_5 | \frac{1}{2} s' \mu_1 m_5 | J M \rangle \right) \times$$

$$\langle \frac{1}{2} \frac{1}{2} | \frac{1}{2} \frac{1}{2} | J'M' \rangle Y_{1l_1 l'_1}^{\mu_1}(\theta, \phi)^* Y_{2l_2 l'_2}^{\mu_2}(\theta, \phi) .$$

The sums over $J_\alpha$ and $J_{\alpha'}$ in C2.2 refer to sums over the various levels.
The factor $K$ may be simplified by performing the indicated sums. This reduction is rather tedious and is therefore presented separately in Section 9. After simplification we have

$$K = \frac{(-)^{s-s'}}{4} \sum_L \Xi \left( \begin{array}{c} l \ J \ l' \ J' \ 1 \ 2 \ 1 \ 2 \ \ s \ L \end{array} \right) \Xi \left( \begin{array}{c} l' \ J' \ l \ J \ 1 \ 2 \ 1 \ 2 \ \ s' \ L \end{array} \right) P(\omega \Theta), \quad C2.4$$

where $\Xi$ is given by

$$\Xi \left( \begin{array}{c} l \ J \ l' \ J' \ 1 \ 2 \ 1 \ 2 \ \ s \ L \end{array} \right) = (2l+1)^{\frac{1}{2}} (2l'+1)^{\frac{1}{2}} (2J+1)^{\frac{1}{2}} (2J'+1)^{\frac{1}{2}} \times \quad C2.5$$

$$W(\begin{array}{c} l \ J \ l' \ J' \ 1 \ 2 \ 1 \ 2 \ \ s \ L \end{array}) (\begin{array}{c} l \ J \ l' \ J' \ 1 \ 2 \ 1 \ 2 \ \ s' \ L \end{array}) = W$$

where $W$ is a Racah coefficient. ($\alpha \omega$)

Substituting equation C2.4 for $K$ into equation C2.2 we have

$$\frac{d \sigma_{\alpha's',\alpha s}}{d \omega} = \frac{\hbar^2}{(2S+1)} \sum_{L=0}^{\infty} \frac{1}{L} \frac{1}{L'} \frac{1}{L''} \frac{1}{L'''} B(\alpha's';\alpha s) P(L \omega \Theta)$$

where

$$B(\alpha's';\alpha s) = \frac{(-)^{s-s'}}{4} \frac{\Xi}{l} \frac{\Xi}{J} \frac{\Xi}{l'} \frac{\Xi}{J'} \times$$

$$= \Xi \left( \begin{array}{c} l \ J \ l' \ J' \ 1 \ 2 \ 1 \ 2 \ \ s \ L \end{array} \right) \Xi \left( \begin{array}{c} l' \ J' \ l \ J \ 1 \ 2 \ 1 \ 2 \ \ s' \ L \end{array} \right) \times \quad C2.6$$

$$\left( \delta_{\alpha \alpha'} \delta_{ss'} \delta_{l'1} \delta_{l1} \delta_{l'1} \delta_{l1} \right) \left( \delta_{\alpha \alpha'} \delta_{ss'} \delta_{l'1} \delta_{l1} \delta_{l'1} \delta_{l1} \right).$$
Equation C2.6 is the result we have been seeking and shall use in the next sections to derive formulae for elastic scattering and reaction cross sections assuming single-level dispersion theory.

The sum in C2.6 all extend from zero to $\infty$ but in practice only one of these sums is really infinite (say the sum over $J_1$). The other sums are finite because of the selection rules for nonvanishing $\tilde{Z}$ coefficients. A more detailed discussion of these selection rules shall be given later.
3. SCATTERING MATRIX ELEMENTS

The derivation of the differential cross section in the last section is based on the scattering matrix S (frequently called the collision matrix U) which provides the asymptotic form of the wave function of a pair of nuclei. The connection between this and a set of parameters related directly to the various states of the compound nucleus system is accomplished by use of R-matrix theory. It is not the purpose of the present author to present R-matrix theory but only the results which are pertinent to our needs.

For convenience let us define an index c which stands for:

\[ c = \{as, \ell \} \]  

The results of R-matrix theory \(^{(a1)}\) give

\[ U^{J}_{c'c} = e^{i(\Omega_{c} + \Omega_{c'})} \left[ 2i P^{\frac{1}{2}}_{c} P^{\frac{1}{2}}_{c'} \sum_{\mu, \lambda} \gamma^{\mu}_{c'} \gamma^{\lambda}_{c} A^{\mu \lambda}_{c} \right], \]

where:

\[ P_{c} = \frac{k}{(F^{2}_{c} + G^{2}_{c})}, \]

\[ \Omega_{c} = \sigma_{c} - \sigma_{0} + \phi_{c}, \]

\[ \phi_{c} = -\tan^{-1}(F_{c}/G_{c}), \]

and \( \sigma_{c} \) is the regular Coulomb phase, \( \gamma^{2}_{\mu, \lambda} \) is the reduced width, and \( A^{\mu \lambda}_{c} \) is an element of the "level" matrix A whose dimensionality equals the number of levels of the same spin and parity. The \( F_{c} \) and \( G_{c} \) are the conventional regular and irregular solutions of the
radial wave equation outside the nuclear surface, i.e. in the external region. In our case the phases outside the square brackets in C3.2 are modified somewhat because in our derivation of the differential cross section for charged particles, we included the phase \(-\eta_c \ln 2\rho_c + \sigma_{co}\) as part of the scattering matrix, i.e. we said that \(I_c\) and \(O_c\) had the asymptotic forms given in equation C1.18 on page 71. This is true for neutral particles, but in the case of charged particles, the asymptotic forms of \(I_c\) and \(O_c\) also contain the phase \(-\eta_c \ln 2\rho_c + \sigma_{co}\), where \(\eta_c\) is

\[
\eta_c = Z_a Z_x e^{a/h\nu_c}
\]

Note that this extra phase is zero for neutral particles, so including this phase in the definition of \(U^J_{c,c'}\) in equation C3.2 we have

\[
U^J_{c,c'} = e^{i \left( \xi_{\alpha'\ell'} - \eta_\alpha \ln 2\rho_\alpha + \frac{5}{2} \rho_\alpha \ln 2\rho_\alpha - \eta_\alpha' \ln 2\rho_\alpha' \right)} \times
\]

\[
\left[ \xi_{c,c'} + 2i \rho^\frac{1}{2}_{c'} \rho^\frac{1}{2}_c \sum_{\mu,\lambda} \gamma_{\mu c'} \gamma_{\lambda c} A_{\mu\lambda} \right],
\]

where

\[
\rho_\alpha = \frac{\hbar}{\alpha} r_c
\]

\[
\frac{5}{\alpha} l' = \sigma_{\alpha l'} + \phi_{\alpha l'} = \text{Coulomb phase and hard sphere phase},
\]

and we have assumed that the channel radius \(r_c\) is independent of channel spin \(s\), thus allowing us to index with \(\alpha\ell\) instead of \(c\).

Up to the present point the formula for \(U^J_{c,c'}\) in C3.4 is rigorous, but the sums over \(\mu\) and \(\lambda\) run over many (perhaps,
infinite) levels of the same spin and parity. In practical computations, some approximations have to be made so that the summations include only those levels which have the greatest influence on the nuclear reactions in the energy range of interest. It is, therefore, assumed in the present work that there are no more than three levels of the same spin and parity in the region of interest. However, it may be true that there exist many more levels of the same spin and parity remote from the energy of interest. We thus would have a contribution from "distant" levels which could be approximated by adding a term $U^0_{ic}$ to equation C3.4. It is further assumed in the present work that this term is negligible. This is the so-called "few level" approximation and has been used by others to analyze elastic scattering data.

For our present purposes, let us assume that we have only one level of a given spin and parity in the region of interest. The matrix element $A_{\mu\lambda}$ is given by E. P. Wigner\(^{(33)}\) as

$$A_{\mu\lambda} = \frac{1}{\mu} \sum_{\lambda} \frac{1}{\mu'} \Gamma_{\mu'} \left( E - E_{ic} \right)$$

C3.5

where dropping the $\mu$ for convenience we have

$$\Gamma = \sum_{\mu} \Gamma_{\mu} = \sum_{\mu} \frac{1}{\mu} \Gamma$$

(total width at half maximum)

$$\Gamma_c = 2\Gamma_c\Gamma_c^2$$

(Partial width)
and \( \Delta \lambda = -\frac{1}{c} \sum_{S \in C} (S - B) \frac{C^2}{\lambda C} \) (the level shift).

The level shift has been defined since it is usually included in the denominator of C3.5. However, without knowledge of the reduced widths \( \gamma^a_{\lambda C} \) for all other channels \( c \), an accurate evaluation of the level shift is difficult. In this work, the level shift has been neglected.

Substituting \( A_{11} \) into equation C3.4 and converting to the notation of Blatt and Biedenharn, we have

\[
S_{a's'l',asl}^{J_0} = e^{i(\xi_{a'-l'} - \gamma_{a'} ln 2\rho_{a'} + \xi_{a' l') - \gamma_{a'} ln 2\rho_{a'})} \times \\
\left[ \begin{array}{c} S_{a'a'} S_{s's} S_{l' l'} + \frac{i g_{a'sl} g_{a's'l'}}{E_0 - E - \frac{1}{2} i \Gamma} \end{array} \right] \quad \text{FOR } J=J_0, \pi=\pi_0,
\]

where \( g_{a'sl}^{J_0} = \pm \sqrt{g_{a'sl}} \) and \( \Gamma_{a'sl} \) is defined in equation C4.6. For \((J, \pi) \neq (J_0, \pi_0)\) then \( g_{a'sl}^J \) is zero, and we have the matrix element for potential scattering:

\[
S_{a's'l',asl}^{J_\pi} = S_{a'a'} S_{s's} S_{l' l'} e^{2i(\xi_{a'l} - \gamma_{a'} ln 2\rho_{a'})} \quad \text{FOR } J, \pi \neq J_0, \pi_0.
\]
The expressions for the scattering matrix C3.7 and C3.8 certain factors \( \exp (-i\pi \ln 2kr) \) where \( r \) is a screening radius for the electrostatic field of the nucleus. In practice the effect of screening on the angular distribution of elastically scattered particles is negligible at all angles except for very small-angle forward scattering (where the screening effect prevents the cross section from becoming infinite). We can therefore ignore these factors.

We are now ready to derive expressions for the differential cross sections for elastic scattering and reactions. As mentioned earlier a contribution from no more than three levels of the same spin and parity has been assumed in the analysis of the \(^9\text{Be}\) elastic scattering data and we shall return to this case in a later section.
4. REACTION CROSS SECTION

In this section we develop a formula for the reaction cross section using single-level dispersion theory. This formula will be used to analyze the $^9$Be$(\alpha, n)$ reactions. Later when we develop elastic scattering formulae we will also be able to identify certain terms which are closely related to this cross section.

For a reaction we assume that either $\alpha' \neq \alpha$ or $s' \neq s$ or both. We see immediately that for $(J, \pi) \neq (J_0, \pi_0)$ that the scattering matrix elements in equation C3.8 are zero and for $(J, \pi) = (J_0, \pi_0)$ reduces to

$$S_{J_0, \alpha' s' l', \alpha s l} = \iota \exp \left( i\left( \xi_{\alpha l} + \xi_{\alpha' l'} \right) \right) \frac{\tau_{\alpha s l} \tau_{\alpha' s' l'}}{E - E - \frac{1}{2} i \Gamma_0} .$$ C4.1

For convenience let us write

$$(i) \left[ E_j - E - \frac{1}{2} i \Gamma_j \right] = |\epsilon_j| e^{-i\beta_j} ,$$

where

$$t_{mn} \beta_j = (E - E_j)/\frac{1}{2} \Gamma_j \quad \text{and} \quad |\epsilon_j| = \left[ (E_j - E)^2 + \frac{\Gamma_j^2}{4} \right]^{1/2} .$$ C4.2

Substituting C4.1 into equation C2.6 we have

$$B_L(\alpha' s; \alpha s) = \left(-\frac{s' s}{4}\right)^{\frac{3}{2}} \sum_{J_1} \sum_{J_2} \sum_{l_1} \sum_{l_2} \sum_{l_1'} \sum_{l_2'} \overline{Z} \left( \frac{l_1 J_1 l_2 J_2 s L}{l_1 l_2 J_1 J_2 s L} \right) \times$$

$$\overline{Z} \left( \frac{l_1' J_1' l_2' J_2' s' L}{l_1 l_2 J_1 J_2 s L} \right) \frac{\tau_{\alpha s l_1} \tau_{\alpha' s' l'_1}}{|\epsilon_j|} e^{i\beta_1} \frac{\tau_{l_1} \tau_{l_2}}{|\epsilon_j|} e^{i\beta_2} \times C4.3$$

$$e^{i\left( \xi_{\alpha l} + \xi_{\alpha' l'} - \xi_{\alpha l} - \xi_{\alpha' l'} \right)} .$$
The above expression is real since the imaginary part changes
sign when \( J_1 \) and \( J_2 \), and \( J_1' \) and \( J_2' \), and \( \ell_1' \) and \( \ell_2' \) are interchanged.

This is best seen using the property that

\[
\Xi_{11112222} (l J l J ; s L) = \Xi_{221111} (l J l J ; s L) .
\]

Thus

\[
B_L (\alpha' s' ; \alpha s) = \frac{(-)^{S'-S}}{4} \Xi_{1} \Xi_{1} \sum_{1} \sum_{2} \sum_{l} \sum_{l'} \sum_{J} \sum_{J'} \Xi_{11112222} (l J l J ; s L) \times
\]

\[
\Xi_{11112222} (l' J' l' J' ; s' L) \delta_{\alpha s \ell} \delta_{\alpha' s' \ell'} \delta_{\alpha s \ell} \delta_{\alpha' s' \ell'} \times C4.4
\]

\[
\cos (\xi_{\alpha} - \xi_{\alpha} + \xi_{\alpha} - \xi_{\alpha} + \beta - \beta) / |\ell_1 \ell_2| \quad \text{FOR} (\alpha, S \neq \alpha', S') .
\]

The reaction cross section is after summing over \( s \) and \( s' \) equal to

\[
\frac{d \sigma_{\alpha' \alpha}}{d \Omega} = \frac{\chi^2}{(2 I+1)(2 I+1)} \sum_{S} \sum_{S'} \sum_{L} B_L (\alpha' s' ; \alpha s) \ p (\cos \theta) \quad C4.5
\]

For use in later sections let us define the quantity in equation C4.4 as

\[
R_L (\alpha' s' ; \alpha s) \equiv B_L (\alpha' s' ; \alpha s) . \quad C4.6
\]
The expression in C4.4 can be simplified with the use of the restrictions on the various sums imposed by the selection rules for nonvanishing $\overline{Z}$ coefficients and also by the restrictions due to the conservation of parity.

Selection Rules for Nonvanishing $\overline{Z}$

Since the $\overline{Z}$ contain Racah coefficients some of the selection rules come from the properties of the Racah coefficients. The Racah coefficient $W(t_1J_1t_2J_2,SL)$ vanishes unless the four triads

$$(t_1J_1S), (t_2J_2S), (t_1t_2L), \text{ and } (J_1J_2L)$$

are satisfied. From these we get the following restrictions on $t_1$, $t_2$ and $L$ and since four similar triads must be satisfied for $t_1'$, $t_2'$ and $s'$ we have the following selection rules.

1. $|J_1-s| \leq t_1 \leq J_1+s$
2. $|J_2-s| \leq t_2 \leq J_2+s$
3. $|t_1-t_2| \leq L \leq t_1+t_2$
4. $|J_1-J_2| \leq L \leq J_1+J_2$
5. $|J_1-s'| \leq t_1' \leq J_1+s'$
6. $|J_2-s'| \leq t_2' \leq J_2+s'$
7. $|t_1'-t_2'| \leq L \leq t_1'+t_2'$
If we denote the parity of channel $\alpha$ by $\pi_\alpha$, that of channel $\alpha'$ by $\pi_{\alpha'}$ and of the compound nucleus by $\pi_J$, we have from the conservation of parity the further restrictions that

\[ (-)^{l_1} = \prod_{\alpha} \prod_{\Delta J_l}, \quad (-)^{l_1'} = \prod_{\alpha'} \prod_{\Delta J_{l_1}'}, \quad (-)^{l_2} = \prod_{\alpha} \prod_{\Delta J_2}, \quad \text{and} \quad (-)^{l_2'} = \prod_{\alpha'} \prod_{\Delta J_{l_2}'} . \]  

C4.9

In addition there are two more restrictions on $l_1$, $l_2$, $l_1'$ and $l_2'$ which come from the Clebsch-Gordan coefficient in the $\overline{Z}$ coefficient.

From $(t_1 t_2 00 | L0)$ and $(t_1' t_2' 00 | L0)$ we have

\[ l_1 + l_2 - L = \text{even} \]  

C4.10

\[ l_1' + l_2' - L = \text{even} \]

We shall return to the restrictions in C4.8, C4.9 and C4.10 when we specialize to the case of alpha particles incident on $^9\text{Be}$.

We shall now concern ourselves in simplifying the expression for $B_L$ in equation C4.4.

If we write $\cos \left( \xi_{a_1 l_2} - \xi_{\alpha_1 l_1'} + \xi_{\alpha_1' l_1'} - \xi_{\alpha_2 l_2'} + \beta - \beta' \right)$ as

\[
\cos (\beta - \beta') \left[ \cos (\xi_{a_1 l_2} - \xi_{\alpha_1 l_1'}) \cos (\xi_{a_2 l_2'} - \xi_{\alpha_2' l_1'}) - \sin (\xi_{a_1 l_2} - \xi_{\alpha_1 l_1'}) \sin (\xi_{a_2 l_2'} - \xi_{\alpha_2' l_1'}) \right] + \\
- \sin (\beta - \beta') \left[ \cos (\xi_{a_1 l_2} - \xi_{\alpha_1 l_1'}) \sin (\xi_{a_2 l_2'} - \xi_{\alpha_2' l_1'}) + \sin (\xi_{a_1 l_2} - \xi_{\alpha_1 l_1'}) \cos (\xi_{a_2 l_2'} - \xi_{\alpha_2' l_1'}) \right],
\]

C4.11
and substitute it into equation C4.4, we see that the sums over \( l_1 l_2 \) separate from the sums over \( l_1' l_2' \). Let us further define the four quantities \( A, B, C, \) and \( D \):}

\[
A = \sum \sum \Xi(l_1, J, l_2, J; s, L) \, \mathcal{J}_1^{J_1} \, \mathcal{J}_2^{J_2} \, \cos(\xi_{\alpha_1} - \xi_{\alpha_2}) ,
\]

\[
B = \sum \sum \Xi(l_1, J, l_2, J; s, L) \, \mathcal{J}_1^{J_1} \, \mathcal{J}_2^{J_2} \, \sin(\xi_{\alpha_1} - \xi_{\alpha_2}) , \tag{C4.12}
\]

\[
C = \sum \sum \Xi(l_1', J', l_2', J'; s', L) \, \mathcal{J}_1'^{J_1'} \, \mathcal{J}_2'^{J_2'} \, \cos(\xi_{\alpha_1'} - \xi_{\alpha_2'}) ,
\]

\[
D = \sum \sum \Xi(l_1', J', l_2', J'; s', L) \, \mathcal{J}_1'^{J_1'} \, \mathcal{J}_2'^{J_2'} \, \sin(\xi_{\alpha_1'} - \xi_{\alpha_2'}) .
\]

With the definition of \( A, B, C, \) and \( D \) in C4.12 we can write

\[
B(\alpha's; \alpha s) = \left( - \right)^{S - S} \sum \sum \cos(\beta_2 - \beta_1) \, \left\{ AC - BD \right\} - \frac{\sin(\beta_2 - \beta_1)}{\left| \xi_1 \right| \left| \xi_2 \right|} \left\{ BC - AD \right\} . \tag{C4.13}
\]

Furthermore when \( J_1 = J_2, B \) and \( D \) are both zero, the "self-terms" are given as

\[
B(\alpha's; \alpha s) = \left( - \right)^{S - S} \sum \frac{AC}{\left| \xi_1 \right|^2} . \tag{C4.14}
\]
Thus the expression in C4.13 is used only when $J_1$ is not equal to $J_2$ while the expression in C4.14 is used for the "self-terms". We see that, in theory, the reaction cross section should be straightforward to calculate if the parameters of the levels are known.

From the selection rules in C4.9 and C4.10 we see that if we have levels of different parity we will have odd-$L$ Legendre polynomials contributions and thus the angular distributions need not be symmetric about $90^\circ$ c.m.
5. ELASTIC SCATTERING OF NEUTRAL PARTICLES

Before we develop the formula for the elastic scattering of charged particles it is quite instructive to do neutral particles. We will consider the case where there is no spin flip, i.e. \( s = s' \).

As before we shall use the single level approximation.

We first break up the sums over \( J_1 \) and \( J_2 \) in equation C2.6. So as to avoid confusion, let us denote the sums over the various resonances of different spins and parities as sums over \( J_n \) and \( J_m \).

We thus obtain that

\[
\begin{align*}
\frac{\epsilon \cdot x}{J_n} & \rightarrow \frac{\epsilon \cdot x}{J_m} \left( \frac{\epsilon \cdot x}{J_n} \right) + \frac{\epsilon \cdot x}{J_m} \left( \frac{\epsilon \cdot x}{J_n} \right) \\
& \quad + \frac{\epsilon \cdot x}{J_m} \left( \frac{\epsilon \cdot x}{J_n} \right) + \frac{\epsilon \cdot x}{J_n} \left( \frac{\epsilon \cdot x}{J_m} \right) \\
& \quad \text{C5.1}
\end{align*}
\]

The first indicated sum in C5.1 is the most complicated so we shall start with it first. Remembering that \( \alpha = \alpha' \) and \( s = s' \) and substituting the scattering matrix elements C3.7 into C2.6 we have

\[
\begin{align*}
\frac{1}{4} \sum_{J_n} \sum_{J_m} \sum_{J_1} \sum_{J_2} \overline{Z}(J_1, J_2, J_n, J_m, j_s l) \overline{Z}(J_1', J_2', J_n, J_m, j_s l') & \times \\
\left( \delta_{J_1', J_1} - \delta_{J_1', J_1} e^{i(\xi_{\alpha_1} l_1 + \xi_{\alpha_1} l_1')} + \frac{J_n}{\partial \alpha_1 \partial \alpha_1'} \frac{J_n'}{\partial \alpha_1 \partial \alpha_1'} e^{-i(\xi_{\alpha_1} l_1 + \xi_{\alpha_1} l_1')} \right) & \times \\
\left( \delta_{J_2', J_2} - \delta_{J_2', J_2} e^{i(\xi_{\alpha_2} l_2 + \xi_{\alpha_2} l_2')} + \frac{J_m}{\partial \alpha_2 \partial \alpha_2'} \frac{J_m'}{\partial \alpha_2 \partial \alpha_2'} e^{-i(\xi_{\alpha_2} l_2 + \xi_{\alpha_2} l_2')} \right) & \text{C5.2}
\end{align*}
\]
Since \( \alpha = \alpha' \) and \( s = s' \) let us drop these subscripts. Further let us define

\[
\Xi(l \mid J \mid J ; sL) = \bar{\Xi}(l \mid J) ,
\]

\[
\Xi(l' \mid J \mid J' ; sL) = \bar{\Xi}(l' \mid J') ,
\]

\[
\xi_{\alpha l} - \xi_{\alpha' l} = \theta
\]

and

\[
\xi_{\alpha l} - \xi_{\alpha' l} = \theta'.
\]

Performing the indicated operations in C5.2 we obtain as one of the sums

\[
\frac{1}{4} \sum_{J} \sum_{J} \frac{\Xi(l \mid J) \Xi(l' \mid J) \frac{J_{n} J_{n} J_{n} J_{m}}{|\epsilon_{n}| |\epsilon_{m}|} \cos(\theta + \theta' - \beta - \beta')}{|\epsilon_{n}| |\epsilon_{m}|} ,
\]

which we recognize as \( R_{\Xi}(\alpha s, \alpha s) \) in equation C4.4. The other terms we have are

\[
\frac{1}{4} \sum_{J} \sum_{J} \frac{\Xi(l \mid J) \Xi(l \mid J) (1 - e^{2i \xi_{l_{1}}})(1 - e^{2i \xi_{l_{2}}})}{|\epsilon_{n}| |\epsilon_{m}|} ,
\]

\[
+ \frac{1}{4} \sum_{J} \sum_{J} \frac{\Xi(l \mid J) \Xi(l' \mid J') (1 - e^{2i \xi_{l_{1}}})(1 - e^{2i \xi_{l_{2}}}) \frac{J_{m} J_{m}}{|\epsilon_{m}|} e^{i(\xi_{l_{x}} + \xi_{l_{y}} + \beta_{m})}}{\epsilon_{m}} ,
\]

C5.3
and

\[ \frac{1}{4} \sum_{n, m} \sum_{l, l'} \mathcal{Z}(l, l') \mathcal{Z}(l', l) (1 - e^{2i\xi_{n,l}}) \frac{J_n J_{l'}}{|\xi_n|} e^{i(\xi_{n,l} \xi_{l', l} \beta_n)}. \] C5.7

Doing the next indicated sum we observe that we would get pure hard-sphere scattering by using C3.8 for all values of \( J \) and \( \pi \) including those \( (J, \pi) \) equal to \( (J_n, \pi_n) \). It is therefore advantageous to add and subtract the cross section for hard sphere scattering.

\[ \frac{1}{4} \sum_{n, m} \sum_{l, l'} \mathcal{Z}(l, l') \mathcal{Z}(l', l) (1 - e^{2i\xi_{n,l}}) (1 - e^{2i\xi_{l', l}}). \] C5.8

and

\[ -\frac{1}{4} \sum_{n, m} \sum_{l, l'} \mathcal{Z}(l, l') \mathcal{Z}(l', l) (1 - e^{2i\xi_{n,l}}) (1 - e^{2i\xi_{l', l}}). \] C5.9

We see that the expression in C5.5 cancels the expression in C5.9.

We also have

\[ -\frac{1}{4} \sum_{n, m} \sum_{l, l'} \mathcal{Z}(l, l') \mathcal{Z}(l', l) (1 - e^{2i\xi_{n,l}}) (1 - e^{2i\xi_{l', l}}). \] C5.10

and
\[ -\frac{1}{4} \sum_{J} \sum_{J_h} \sum_{L} \Z \left( J, J_h, \frac{1}{2} \right)^2 \left( 1 - e^{2i\xi_l} \right) \left( 1 - e^{2i\xi_l} \right) . \]  

The expression in C5.8 can be rewritten as

\[ \sum_{J} \sum_{J_h} \sum_{L} \Z \left( J, J_h, \frac{1}{2} \right)^2 \left( 1 - e^{2i\xi_l} \right) \left( 1 - e^{2i\xi_l} \right) \cos (\xi_l - \xi_l') . \]  

We use the sum rule for the \( \Z \) coefficients. (a)

\[ \sum_{I} \overline{Z}(a,b,c,d,e,f) \overline{Z}(a,b',c',d',e',f) = \delta_{e,e'} (2a+1)(2d+1) \left[ \frac{(a + 1)}{(a - 1)} \right] . \]

We see that in C5.12, \( a = \xi_1, \ b = J_1, \ c = c' = \xi_2, \ d = J_2, \ e = s, \)
\( f = L \) so that C5.12 can be simplified to

\[ \sum_{J} \sum_{J_h} \sum_{L} (2J+1)(2J'+1) \left[ (L\ell J, \ell_0) L_0 \right] \left[ (\ell_0) \right] \cos (\xi_l - \xi_l') . \]

However hard-sphere (potential) scattering is by assumption independent of the channel spin \( s \). This assumption comes from the fact that we assumed that the channel radius was independent of \( s \).

(Eq C3.8 page 83). Thus we decouple \( \xi_2 \) and \( s \) and we have

\[ \sum_{J} (2J+1) \approx (2s+1)(2J_2+1) . \]
Thus equation C5.13 becomes

\[(2a+1) \, H_L(\alpha, \alpha),\]

WHERE

\[H_L(\alpha, \alpha) = \sum_{l=0}^{\infty} \sum_{i=1}^{l} (2l+1)(2l+1) \left[ (\frac{1}{1-i} |1-l|)^2 \right] \sin \xi_i \sin \xi_i \chi \]

\[C5.15\]

\[\cos (\xi_i - \xi_i) \]

We see that the contribution \(H_L(\alpha, \alpha)\) is exactly what we would get if we used equation C1.2 with \(\delta_\ell\) replaced with \(\xi_\ell\). The factor \(2a+1\) merely serves to cancel the corresponding factor in C2.2.

Performing the sum over \(J_1(\neq J_n)\), sum over \(J_n (J_2 = J_n)\) we have the following terms.

\[\frac{1}{4} \sum_{\ell} \sum_{j} \sum_{l} \bar{Z}(\ell j l l'; s\ell) \bar{Z}(l j l' l'; s\ell) (1-e^{-2i \xi_{l'}}) \chi \]

\[C5.16\]

\[\frac{g_l g_{l'}}{|\epsilon_n|} \, e^{i (\xi_{l'} + \xi_{l'}) \beta_n}, \]

and

\[-\frac{1}{4} \sum_{l} \sum_{j} \sum_{l} \bar{Z}(l l') \bar{Z}(l l') (1-e^{-2i \xi_{l'}}) \frac{g_l g_{l'}}{|\epsilon_n|} \, e^{i (\xi_{l'} \xi_{l'} \beta_n)}, \]

\[C5.17\]
and

\[ + \frac{1}{4} \sum_{J} \sum_{J'} \sum_{J''} \sum_{J'''} \Xi \left( \sum_{l} \left( \sum_{n} \sum_{\xi} \sum_{\xi'} \sum_{\xi''} \sum_{\xi'''} \ \Xi \left( J, J', J''; SL \right) \right)^2 \left( 1 - e^{2i \xi \xi} \right) \left( 1 - e^{2i \xi' \xi''} \right) \right) \]

We see that the expression in equation C5.17 cancels the expression in equation C5.6 and that the expression in C5.18 cancels C5.11. Performing the last sum indicated in C5.1 we have

\[ \frac{1}{4} \sum_{J} \sum_{J'} \sum_{J''} \sum_{J'''} \Xi \left( \sum_{l} \left( \sum_{n} \sum_{\xi} \sum_{\xi'} \sum_{\xi''} \sum_{\xi'''} \ \Xi \left( J, J', J''; SL \right) \right)^2 \left( 1 - e^{2i \xi \xi} \right) \left( 1 - e^{2i \xi' \xi''} \right) \right) \times \]

\[ \frac{J_n}{|\xi_n|} \left( \frac{J_n}{|\xi_n|} \right) e^{-i(\xi_n \xi_n + \xi' \xi')} \]

C5.19

\[ \left( \sum_{l} \left( \sum_{n} \sum_{\xi} \sum_{\xi'} \sum_{\xi''} \sum_{\xi'''} \ \Xi \left( J, J', J''; SL \right) \right)^2 \left( 1 - e^{2i \xi \xi} \right) \left( 1 - e^{2i \xi' \xi''} \right) \right) \frac{J_n}{|\xi_n|} \frac{J_n}{|\xi_n|} e^{-i(\xi_n \xi_n + \xi' \xi')} \]

C5.20

and

\[ + \frac{1}{4} \sum_{J} \sum_{J'} \sum_{J''} \sum_{J'''} \Xi \left( \sum_{l} \left( \sum_{n} \sum_{\xi} \sum_{\xi'} \sum_{\xi''} \sum_{\xi'''} \ \Xi \left( J, J', J''; SL \right) \right)^2 \left( 1 - e^{2i \xi \xi} \right) \left( 1 - e^{2i \xi' \xi''} \right) \right) \]

C5.21
Note that expression C5.21 cancels C5.10 and that expression C5.20 cancels C5.7. This leaves us with only the expressions in C5.4, C5.15, C5.16 and C5.19. Using the sum rule, equations C5.16 and C5.19 may be simplified to

\[
\frac{1}{4} \sum_{n} \sum_{l} (2l+1)(2J+1) \left( \mu_l \mu_0 |L_0 \right)^2 (1 - e^{-2i\xi_{l_1}^n}) x \sum_{l}^{T} \frac{e^{i(2\xi_{l_1}^n + \beta_n)}}{|e_n|}, \quad \text{C5.22}
\]

and

\[
\frac{1}{4} \sum_{n} \sum_{l} (2l+1)(2J+1) \left( \mu_l \mu_0 |L_0 \right)^2 (1 - e^{2i\xi_{l_1}^n}) x \sum_{l}^{T} \frac{e^{-i(2\xi_{l_1}^n + \beta_n)}}{|e_n|}, \quad \text{C5.23}
\]

respectively. If we interchange \( t_1 \) and \( t_2 \) in C5.23 we see that it is the complex conjugate of equation C5.22. Thus C5.22 and C5.23 combine to give

\[
-\sum_{n} (2J+1) \sum_{l} (2l+1)(2J+1) \left( \mu_l \mu_0 |L_0 \right)^2 \sum_{l}^{T} \frac{\sin \xi_{l_1} \sin(2\xi_{l_2}^n + \beta_n)}{|e_n|}, \quad \text{C5.24}
\]

The expression in C5.24 we shall call \( I_n (\alpha, \alpha) \) since it represents the interference term in the cross section.

To review: starting with expression C2.2 and using C5.1 we were able to break the cross section up into three terms; one which repre-
ents the resonance scattering, one which represents the potential scattering, and one which represents the interference between the resonance and potential scattering. We thus can write \( B_L(\alpha s, \alpha s) \) as,
\[
B_L(\alpha s, \alpha s) = R_L(\alpha s, \alpha s) + (2s+1)H_L(\alpha s, \alpha s) + I_L(\alpha s, \alpha s),
\]
where \( R_L(\alpha s, \alpha s) \) is given in equation C5.4, \( H_L(\alpha, \alpha) \) is given in equation C5.15 and \( I_L(\alpha, \alpha) \) is given in C5.24.

Substituting \( B_L \) into C2.6 and C2.1 we have for the elastic scattering of neutral particles where spin flip is allowed that
\[
\frac{d\sigma_{\alpha'i', \alpha}}{d\Omega} = \frac{\pi^2}{(2\pi h)^2} \sum_{l=0}^{\text{LMAX}} R_L(d, d) P_L(\cos \theta) + \sum_{l=0}^{\text{LMAX}} H_L(d, d) P_L(\cos \theta) - \sum_{l=0}^{\text{LMAX}} \sum_{l'=1}^{l_{\text{min}}} \sum_{l''=l-1}^{l+1} \left[ (2l'+1)(l''00|l0)^2 \right. \times C5.26
\]
\[
\frac{\Gamma_n}{\Gamma_{\alpha'i', \alpha}} = \frac{\sin \xi_{l'} \sin (2\xi_{l'} - \xi_{l'} - \beta_n) P_L(\cos \theta),
\]
where
\[
R_L(\alpha'i', \alpha) = \sum_{s'|l-i'}^{l+i} \sum_{s|l-i}^{l-i} R_L(\alpha's', \alpha s),
\]
\[
\Gamma_n = \sum_{\alpha'sl} \Gamma_n
\]
and LMAX and \( l_{\text{min}} \) are determined by the selection rules C4.8, C4.9, and C4.10.

Though equation C5.26 is the cross section for the elastic scattering of neutral particles, we would obtain the same result for
for the elastic scattering of charged particles with the only exception being that of the phase \( \xi_{\alpha l} \) would be evaluated differently. The difficulty of using C5.26 for charged particle elastic scattering is the sums in \( H_L \) and the interference term converge very slowly for charged particles. For neutral particles the phase shifts \( \xi_{\alpha l} \) approach zero as \( l \) becomes large, so that we have no such problem of convergence. In the next section we shall treat the elastic scattering of charged particles by first separating out the Coulomb scattering from \( H_L \) and \( I_L \).
6. ELASTIC SCATTERING OF CHARGED PARTICLES

In the last section we derived an expression for the elastic scattering of neutral particles. As was mentioned then, the expressions derived are still correct for the elastic scattering of charged particles but are not useful in practical computations because the sum over \( L \) converges very slowly. Thus we must treat the Coulomb scattering explicitly in order to get usable expressions. The potential scattering is now scattering by a charged hard sphere which can be written as scattering by a point charge plus correction terms to take into account the finite nuclear radius. For purposes of illustration we shall first investigate the scattering of spinless charged particles by a nucleus of zero spin \((I = i = 0)\).

For spinless particles on a spin zero nucleus, the reaction amplitude \( q \) derived in Section 1, simplifies considerably. For this case, \( q \) is the same as \( f(\theta) \) and \( J = l \). For elastic scattering since \((s = s' = 0)\), and \( \alpha = \alpha' \), we have for \( f(\theta) \) that

\[
 f(\theta) = \hat{\mathbf{t}} \sum_{L=0}^{\infty} \sum_{\mu=-L}^{L} \sum_{\mu'=-L}^{L} \frac{1}{(2L+1)^{1/2}} \langle 000|LM \rangle \chi_{\mu} \gamma_{\mu'}(\theta, \phi).
\]
From $(\ell'000|\ell M)$ we see that $M$ is zero and from $(\ell'0\mu'0|\ell M)$ that $\mu'$ is also zero. Using the following property of C.G. coefficients

$$(1000|l'o) = \delta_{ll'},$$

we further simplify the expression $f(\theta)$ in equation C6.1.

We have on substitution of C6.2 that

$$f(\theta) = \pi \sum_{l=0}^{\infty} \frac{1}{l(2l+1)} \left(1-S_{(l')o(l'o)}\right) \gamma_{l'o}(\theta).$$

We shall again use single level dispersion theory and use the scattering matrix elements given in equations C3.7 and C3.8, remembering that we are neglecting the screening factors $\exp(-i\eta \ln(2kr))$. As in Section 5 we shall add and subtract the cross section for potential scattering. We thus obtain:

$$f(\theta) = \pi \sum_{l=0}^{\infty} \frac{1}{l(2l+1)} \left(1-e^{2i\xi_{l'n}}\right) \gamma_{l'o} -$$

$$\pi \sum_{l=0}^{\infty} \frac{1}{l(2l+1)} \left(1-e^{2i\xi_{l'n}}\right) \gamma_{l'n,0} +$$

$$\pi \sum_{l=0}^{\infty} \frac{1}{l(2l+1)} \left[\left(1-e^{2i\xi_{l'n}}\right)\gamma_{l'n,0} + \frac{\beta_n}{|\xi_n|} e^{(2i\xi_{l'n}+\beta_n)}\right] \gamma_{l'n,0},$$
where we have defined $\beta_n$ and $\epsilon_n$ in equation C4.2, and the sum over $\ell_n$ represents the sum over the various levels of different spin and parity. On investigation of expression C6.4, we see that the second sum and the first part of the third sum cancel. Substituting for $\xi$, (equation C3.4) we have

$$f(\theta) = i \pi^{\frac{1}{2}} \sum_{F=0}^{\infty} (2F+1)^{\frac{1}{2}} (1-e^{2i(\phi_0 + \sigma_0)}) Y_{F,0} +$$

$$i \pi^{\frac{1}{2}} \sum_{k_n} (2k_n+1)^{\frac{1}{2}} \frac{\Pi_n}{|\epsilon_n|} e^{i(2(\phi_{k_n} + \sigma_{k_n}) + \beta_n)} Y_{k_n,0}.$$  

Let us investigate the first sum in expression C6.5. We know for pure Coulomb scattering of spinless point particles, that we may use equation C1.2 with $\xi_\ell$ replaced by $\sigma_\ell$ to obtain $f(\theta)$ for Coulomb scattering. Rewriting $f(\theta)$ given in equation C1.2 to match our present notation, we have $f_c(\theta)$ is

$$f_c(\theta) = i(\pi)^{\frac{1}{2}} \sum_{F=0}^{\infty} (2F+1)^{\frac{1}{2}} (1-e^{2i\delta F}) Y_{F,0}(\theta).$$  

Let us multiply expression C6.5 by $i$ since

$$|i f(\theta)|^2 = |f(\theta)|^2,$$

and add and subtract $f_c(\theta)$ to the expression in C6.5. We obtain

$$f(\theta) = f_c(\theta) + i \pi^{\frac{1}{2}} \sum_{F=0}^{\infty} (2F+1)^{\frac{1}{2}} e^{2i\delta F} (1-e^{2i\phi_0}) Y_{F,0}(\theta) +$$

$$i \pi^{\frac{1}{2}} \sum_{k_n} (2k_n+1)^{\frac{1}{2}} \frac{\Pi_n}{|\epsilon_n|} e^{i(2(\phi_{k_n} + \sigma_{k_n}) + \beta_n)} Y_{k_n,0}.$$
From Messiah\(^{(10)}\) an alternative expression for \(f_c(\theta)\) is

\[
\langle f_c(\theta) \rangle = -\mathcal{G} \cos \frac{\theta}{2} e^{-i2\ln(\sin \frac{\theta}{2}) + 2i\sigma_0},
\]

WHERE

\[
\mathcal{G} = \frac{Z_rZ_e e^2}{2\mu \alpha^2}.
\]

Substituting the expression for \(f_c(\theta)\) in equation C6.8 into equation C6.7 and factoring out \(e^{2i\sigma_0}\) we have

\[
\langle f(\theta) \rangle e^{-2i\sigma_0} = \langle f'(\theta) \rangle = \langle f_c(\theta) \rangle + \sum \langle R\ell_n(\theta) \rangle,
\]

WHERE

\[
\langle f_c(\theta) \rangle = -\mathcal{G} \cos \frac{\theta}{2} e^{-i2\ln(\sin \frac{\theta}{2})},
\]

\[
\langle f_{CH}(\theta) \rangle = i \pi \frac{1}{\xi_0} (2l+1) \xi e^{2i\Phi} (1-e^{2i\Phi}) \gamma_{l0}(\theta),
\]

\[
\langle R\ell_n(\theta) \rangle = i \pi \frac{1}{\xi_0} (2l+1) \xi e^{i(2\Psi_{l0} + \Phi_{l0} + \beta_{l0})} \gamma_{l0}(\theta),
\]

and \(\psi_l = \sigma_c - \sigma_0\). Note that \(f_{CH}(\theta)\) is the difference between the scattering amplitude from a charged hard sphere and Coulomb scattering by a point charge. The scattering amplitude \(f_{R\ell_n}(\theta)\) is the nuclear resonance scattering amplitude.

The cross section for elastic scattering is given by C1.1, i.e.

\[
\frac{d\sigma}{d\Omega} = \left| \langle f_c(\theta) \rangle + \langle f_{CH}(\theta) \rangle + \sum \langle R\ell_n(\theta) \rangle \right|^2
\]

\[
= \left[ \left| \langle f_c(\theta) \rangle \right|^2 + 2R.P.\left( \langle f_c^* f_{CH} \rangle + \langle f_{CH} f_c \rangle \right) \right] + \left[ \sum \left( 2R.P.\left( \langle f_c^* f_{R\ell_n} \rangle + \sum \left( 2R.P.\left( \langle f_{CH}^* f_{R\ell_n} \rangle + \sum \langle f_{R\ell_n}^* f_{R\ell_m} \rangle \right) \right) \right) \right].
\]
Performing the indicated operations in order of appearance in the first square bracket, we have

\[ |l_{cL}^2| = \frac{\rho}{2} \cosec \frac{\rho}{2}, \]  

C6.11

\[ 2 \mathcal{R} \mathcal{P} \left( l_{cL}^* \right) = -2 \pi \gamma \cosec \frac{\rho}{2} \sum_{l=0}^{\infty} (2l+1) \sin \alpha \cos (2\phi_{l} \sin \frac{\rho}{2}) + \]

\[ 2 \gamma_{l} \gamma_{l'} \times P_{l} (\cos \theta), \]  

C6.12

where we have used

\[ \gamma_{l,0} (\theta) = \sqrt{\frac{2l+1}{4\pi}} P_{l} (\cos \theta), \]  

C6.13

and

\[ |l_{cL}^2| = \frac{\pi^{2}}{2} \sum_{l=0}^{\infty} (2l+1) \left( \frac{1}{2l+1} \right) \frac{1}{2} e^{2i(\gamma_{l} - \gamma_{l'})} \times \]

\[ (1-e^{-2i\phi_{l}})(1-e^{-2i\phi_{l'}}) \gamma_{l,0} (\theta) \gamma_{l,0}^* (\theta). \]  

C6.14

Using equation C9.1 and C6.13 we may write

\[ \gamma_{l,0} (\theta) \gamma_{l,0}^* (\theta) = \sum_{L=0}^{\infty} \frac{(2l+1)^{\frac{1}{2}}(2l'+1)^{\frac{1}{2}}}{4\pi} (\mathbb{P}^{\alpha}_{L} | 00 \rangle)^{2} P_{l} (\cos \theta). \]  

C6.15
Substituting equation C6.15 into equation C6.14 we obtain,

\[ |_{\text{CH}}^2 = \sum_{l=0}^{L_{\text{ch}}} \sum_{l'=0}^{L_{\text{ch}}'} \frac{L_{\text{ch}}}{\pi (l+1)(l'+1)}(2l+1)(2l'+1) \frac{\sum_{m} \sum_{m'} \phi_l \phi_{l'} \cos(2\psi_l + \phi_l - 2\psi_{l'} - \phi_{l'})}{P(\cos \Theta)} \cdot \]  

C6.16

Before we continue, we see that expressions C6.11, C6.12, and C6.16 reduce to the differential cross section for potential scattering of neutral particles if we set \( z = \psi_{l'} = 0 \) and \( \phi_{l'} = \phi_{l} \).

(See equation C5.15 page 95). The interference term between resonance and potential scattering is equal to

\[ \sum_{l=0}^{\infty} 2 \text{R.P.} \left( \int_{\text{CH}}^{l} \right \text{R}_{l} \cdot \frac{2 \text{R.P.} \left( \int_{\text{CH}}^{l} \right \text{R}_{l} \cdot}{\int_{\text{CH}}^{l} \text{R}_{l}} \right) \]

C6.17

\[ = 2 \sum_{l=0}^{\infty} (2l+1) \frac{\sum_{m} \sum_{m'} \cos^2 \frac{\phi_l}{2} \sum_{m} (2g_{ln} \sum m_0 + l(\psi_l + \phi_{l}) \beta_{l}) P(\cos \Theta) + \]  

\[ 2 \text{R.P.} \left\{ \frac{\sum_{l=0}^{\infty} (2l+1)^2}{\int_{\text{CH}}^{l}} \frac{1}{\int_{\text{CH}}^{l}} e^{2i\psi_l} \left(1-e^{-2i\phi_l}\right) e^{i(\psi_{l} + \phi_{l}) \beta_{l}} \right\} \times \right \} \]

C6.18
Again using C6.15, expression C6.18 simplifies to

\[-X^2 \sum_{I_n} \left( \sum_{L=0}^{L_n} \sum_{|L-I_n|} \frac{L_n!}{|L-I_n|!} \right) \frac{\sin \phi_n \sin \left( \frac{2l_n+1}{2} \right) \sin \phi_n - \sin \left( \frac{2l_n+1}{2} \right) \sin \phi_n}{|l_n|} \]

\[\times \left( l_n l_{oo} | L_0 \right)^2 \quad P_L (\cos \theta) \quad \text{C6.19} \]

Finally, the pure resonance scattering cross section in the absence of spins is given by

\[\sum_{I_n} \sum_{l_m} 2 \text{R.P.} \left( \sum_{R_{l_n} R_{l_n}} l_{R_{l_n} R_{l_n}} \right) = X^2 \sum_{I_n} \sum_{|l_m|} \left( \sum_{L=0}^{L_n} \sum_{|L-I_n|} \frac{L_n!}{|L-I_n|!} \right) \frac{\sin \phi_n \sin \left( \frac{2l_n+1}{2} \right) \sin \phi_n - \sin \left( \frac{2l_n+1}{2} \right) \sin \phi_n}{|l_n|} \]

\[\times \left( l_n l_{oo} | L_0 \right)^2 \quad \times \quad \text{C6.20} \]

\[\cos \left[ 2 \left( \frac{\psi_{\phi_m} - \beta_m - \beta_n}{2} \right) - 2 \left( \frac{\psi_{\phi_n}}{2} + \phi_n \right) \right] \quad P_L (\cos \theta) \]

We may easily check to see if we have properly identified the expression in equation C6.20 as the pure resonance scattering term by reducing to the case of neutral particles. We set \( z = \psi_{\phi} = 0 \) and \( \phi_{\phi} = \epsilon_{\phi} \) in expression C6.20. We then use the property that:

\[\mathbb{H} (1 J l J \cdot 0 L) = \delta_{l_1 l_2} \delta_{l_1 l_2} \left[ \frac{(2l_n+1)(2l_m+1)}{2} \right]^\frac{1}{2} \left( l_{oo} l_{oo} | L_0 \right) \]
and substitute into the expression for $R_L(a, s, α, s)$, equation C5.4.

Substituting $R_L(a, s, α, s)$ into equation C2.22 and comparing we see that the two expressions are identical and equal to

$$\mathcal{X}^{2} \sum_{L} \sum_{l} \sum_{l'} \left(\begin{array}{c} l+1 \\ l' \\ l \end{array}\right) \left(\begin{array}{c} l+1 \\ l' \\ l \end{array}\right) \left(\begin{array}{c} \infty \\ \infty \\ \infty \end{array}\right)^2 \frac{\Gamma_i \Gamma_{l'} \Gamma_{l}}{\left|\varepsilon_i\varepsilon_{l'}\varepsilon_{l}\right|}$$

$$\cos(2\xi_1 - 2\xi_2 \beta_1 - \beta_2) P_L(\cos\theta),$$

where we have changed notation from $\Gamma^{J_n}$ to $\Gamma_{ln}$ and $l_n$ to $l_1$ etc.

Formulas C6.11, C6.12, C6.16, C6.17, C6.19, and C6.20 give the elastic scattering cross section for the special case $i = I = 0$. They can be used directly to analyze the elastic scattering of alpha particles by even-even nuclei. The more general case $i \neq 0, I \neq 0$ can be obtained from these expressions and the results for the elastic scattering of neutral particles by simple inspection. As has been mentioned the results obtained for the elastic scattering of neutral particles are also correct for the elastic scattering of charged particles except that some of the terms converge very slowly. Returning to the results for the elastic scattering of neutral particles (see equation C5.26) we see that the expression for pure resonance scattering can be used as it stands even in the presence of Coulomb fields, since the sums over $L$ and $l_1, l_2, s', s'$,
are finite and no question of convergence arises. Thus for the case of $I \neq 0$, $i \neq 0$, we replace equation C6.20 by the first line of C5.26. The potential scattering term (second line of C5.26) is replaced by expressions C6.11, C6.12, and C6.16 since the only difference is that these expressions involve rapidly convergent sums. Finally we consider the last line of equation C5.26, the interference between resonant and potential scattering. We observe that the statistical factor $(2J_n+1)/(2I+1)(2i+1)$ reduces to $(2\ell_n+1)$ for the case $I = i = 0$, and the sum over $J_n$ reduces to a sum over $\ell_n$.

Thus for the interference term the only effect of the spins consists in the multiplication by the usual statistical factor, and in the need for summing over the many possible values of $\ell$ consistent with $J_n$ and $\pi_n$. Thus for the case of $I \neq 0$, $i \neq 0$ we replace $(2\ell_n+1)$ by $(2J_n+1)/(2I+1)(2i+1)$ in expressions C6.17 and C6.19 and also replace the sum over $\ell_n$ by a sum over $J_n$ and add a sum over $\ell$ consistent with $J_n$ and $\pi_n$.

Putting together all this information, we arrive at the following formula for the elastic scattering of charged particles.
\[
\frac{d^2 \sigma_{\alpha \alpha}}{d \Omega_d} = \frac{\lambda^2}{(2 \pi m) (2 \pi n)} \sum_{L=0}^{\infty} \frac{R_L (\alpha, \alpha) P_L (\cos \theta)}{\cos^2 \theta} + 3 \frac{\csc \theta}{\pi} \\
- 2 g \cos^2 \theta \sum_{L=0}^{\infty} \frac{(2 \pi n) (2 \pi m) (2 \pi L) \sin \phi \cos (2 \pi m \sin \theta + 2 \pi n + \phi) P_L (\cos \theta)}{\cos \theta} \\
+ \frac{\lambda^2}{(2 \pi m) (2 \pi n)} \sum_{L=0}^{\infty} \frac{2^{L+2+1} \sum_{L=0}^{\infty} \frac{\csc \theta}{\pi} \sin \left[ 2 \pi m \sin \theta \right] P_L (\cos \theta)}{\csc \theta}
\]

\text{C6.21}

where it is understood that \( \lambda \) is \( \lambda_\alpha \).

To review, we repeat the interpretation of the various terms in this formula. The first term is pure resonance scattering where \( R_L (\alpha, \alpha) \) is given by C5.4 and C5.26. The next term is Rutherford scattering of point charged. The following two terms represent the correction due to the finite size of the nucleus. The next to the last term is the interference between resonance scattering and pure Rutherford scattering, while the last term is the finite nuclear size.
correction to this interference term. The sums over J_n represent
the sum over the levels of different spin and parity which contribute
in the energy region of interest. We have also neglected the contri-
bution from "distant-levels" and so we have what is called "single-
level" dispersion theory. In the next section we shall investigate what
happens if we have two levels of the same spin and parity in the
energy region of interest.
7. APPROXIMATE TWO LEVEL FORMALISM

In developing the elastic scattering cross section for charged particles we used the matrix elements C3.7 and C3.8 which were obtained by using the "single-level" approximation (i.e. we set \( \mu = \lambda = 1 \) in expression C3.4 for the scattering matrix element.)

If we have two levels of the same spin and parity then the sums over \( \mu \) and \( \lambda \) extend to two. Thus the scattering matrix element for the two levels of the same spin and parity is

\[
S_{c',c}^J = e^{i\left(\xi_{\alpha 1} - \gamma_{\alpha 1} \ln 2\rho_{\alpha} + \xi_{\alpha 1} ' - \gamma_{\alpha 1} ' \ln 2\rho_{\alpha}' \right)} \times \nonumber
\]

\[
\left[ \delta_{c',c}^2 + \frac{1}{2} \mathcal{E}_{\mu 1} \mathcal{P}_{\mu 1} \mathcal{P}_{\lambda 1} \mathcal{A}_{\mu \lambda} \right],
\]

where the various quantities are defined as in equation C3.4.

The \( A_{\mu \lambda} \) are given by E. P. Wigner\(^\text{(a3)}\) as

\[
A_{\mu \lambda} = \frac{1}{E_{\mu} - E_{\lambda} - \frac{i\Gamma}{2}}
\]

and

\[
A_{\mu \lambda} = \frac{1}{(E_{\mu} - E_{\lambda} - \frac{i\Gamma}{2}) (E_{\mu} - E_{\lambda} - \frac{i\Gamma}{2})} \quad (\mu \neq \lambda),
\]

\[
\Gamma_{\mu \lambda} = \sum c \mathcal{P}_{\mu \lambda} \mathcal{P}_{\lambda \mu}
\]

where again the level shift has been assumed negligible and the expressions in C7.2 are good only if the energy differences are larger than the widths \( \Gamma \). In the first order approximation, one
considers $A_{\mu\lambda}$ small compared to $A_{\mu\mu}$ and we would have exactly the same result for the elastic scattering of charged particles as we have in expression C6.21 except that the sum over $J_\pi$ is not restricted to levels of different spin and parity. As a second order approximation we do not neglect the $A_{\mu\lambda}$. We thus have for the matrix element for two levels of the same spin and parity

$$S_{c'c}^{J} = e^{i(\xi_\alpha' l + \xi_\alpha l')} \left[ \delta_{c'c} - \left\{ \frac{g^{(1)}}{g^{(2)}} \frac{e^{i\beta_1}}{|\epsilon_1|} \right\} \right]$$

where the 1 and 2 denote the two levels and $g$, $|\epsilon_j|$, and $\beta_j$ are defined as before. It is now our task to evaluate the new terms which now have to be included in the elastic scattering formula C6.21.

For convenience let us call the terms in the curly brackets of C7.3 $F_{12}(c', c)$. Returning to the expansion of the sums over $J_1$ and $J_2$ in equation C5.1, let us assume that the sum over $J_\pi$ includes the case where we have two levels of the same spin and parity, $J_0$, $\pi_0$. Separating out this case we have the following new terms, where we have yet to substitute the results into equation C4.5 to obtain the experimental cross section:
\[
\begin{align*}
\left. \frac{1}{2} \sum_{\mathbf{J}_0} \sum_{\mathbf{J}_1} \overline{Z}(l J_1 J'_1 ; \mathbf{J}_0) \overline{Z}(l' J_1 J'_1 ; \mathbf{J}_0) x \right|_{\mathbf{J}_0} \\
2 \text{R.P.} \left\{ \left( g_{\alpha_{\mathbf{J}_0}} \overline{g}_{\alpha_{\mathbf{J}_0}} \right) \right. && (F_{l}(l' J'_1)) \\
\left. \sum_{\mathbf{J}_1} \sum_{\mathbf{J}_2} \overline{Z}(l J_1 J_2 ; \mathbf{J}_0) \overline{Z}(l' J'_1 J'_2 ; \mathbf{J}_0) \right|_{\mathbf{J}_0} \\
(F^*(l' J'_1)) (F_{l2}(l' J'_2)) \\
\text{and} \\
2 \text{R.P.} \left\{ \left. \frac{1}{2} \sum_{l} \left( 2 l + 1 \right) \left( 2 J + 1 \right) \left( l \ell_{\mathbf{o}} \ell_{\mathbf{o}} \right) \overline{\mathbf{F}}(l \ell_{\mathbf{o}} \ell_{\mathbf{o}}) \right. \right. \\
\left. \left( 1 - e^{2i\xi_{\mathbf{j}}} \right) \left( 1 - e^{2i\xi_{\mathbf{i}}} \right) \right. \\
\text{Substituting for } F_{l2} \text{ we have that } C7.4 \text{ becomes:} \\
\left. \sum_{\mathbf{J}_1} \sum_{\mathbf{J}_2} \overline{Z}(l J_1 J_2 ; \mathbf{J}_0) \overline{Z}(l' J'_1 J'_2 ; \mathbf{J}_0) \overline{g}_{\alpha_{\mathbf{J}_0}} \overline{g}_{\alpha_{\mathbf{J}_0}} \right|_{\mathbf{J}_0} \\
\left. \left( \xi_{\mathbf{j}} - \xi_{\mathbf{j}} - \xi_{\mathbf{i}} - \xi_{\mathbf{i}} + \rho_{\mathbf{j}} - \rho_{\mathbf{j}} \right) \right. \\
\text{C7.7}
\end{align*}
\]
We notice that the expressions in C7.9 and C7.10 are small compared to C7.7 and C7.8 because of the extra factor of $|e_j|^{-1}$.

Evaluating equation C7.5 we have the following sums:

$$\frac{1}{2} \sum_{J, J', I, I'} \overline{Z}(J, J'; sl) \overline{Z}(J', J'; sl) \frac{J_n}{|\epsilon_n|} \frac{J_n}{|\epsilon_n|} x$$

C7.8

$$g_{\alpha \gamma}^{(2)} g_{\alpha \gamma}^{(2)} \cos (\xi^2 - \xi^0, \xi^0, -\xi^0, +\beta - \beta_n)$$

and

$$-\frac{1}{2} \sum_{J, J', I, I'} \overline{Z}(J, J'; sl) \overline{Z}(J', J'; sl) \frac{J_n}{|\epsilon_n|} \frac{J_n}{|\epsilon_n|} x$$

C7.9

$$g_{\alpha \gamma}^{(2)} g_{\alpha \gamma}^{(1)} \cos (\xi^2 - \xi^0, +\xi^0, +\xi^0, +\beta + \beta - \beta_n)$$

C7.10

$$g_{\alpha \gamma}^{(1)} g_{\alpha \gamma}^{(2)} \cos (\xi^2 - \xi^0, +\xi^0, +\xi^0, +\beta + \beta - \beta_n)$$

C7.11
\[
\begin{align*}
\frac{1}{2} & \sum I \sum I \sum \sum \sum \bar{X}(I\bar{J}\bar{J};s)L \bar{X}(I\bar{J}\bar{J};s)L_{(2)}^{(2)}_{(2)}_{(2)} x \left| \varepsilon_{x} \right|^{2} \\
\cos(\xi_{p} - \xi_{q} + \xi_{r} - \xi_{s})_{2 \ 2 \ 2 \ 2} \\
\frac{1}{2} & \sum I \sum I \sum \sum \sum \bar{X}(I\bar{J}\bar{J};s)L \bar{X}(I\bar{J}\bar{J};s)L_{(2)}^{(2)}_{(2)}_{(2)}_{(2)} x \left| \varepsilon_{x} \right|^{2} \\
\frac{\Gamma_{12}^{2}}{2 \left| \varepsilon_{x} \right|^{2}} & \cos(\xi_{p} - \xi_{q} + \xi_{r} - \xi_{s})_{2 \ 2 \ 2 \ 2} \\
\frac{1}{2} & \sum I \sum I \sum \sum \sum \bar{X}(I\bar{J}\bar{J};s)L \bar{X}(I\bar{J}\bar{J};s)L_{(2)}^{(2)}_{(2)}_{(2)}_{(2)} x \left| \varepsilon_{x} \right|^{2} \\
\frac{\Gamma_{12}^{2}}{2 \left| \varepsilon_{x} \right|^{2}} & \cos(\xi_{p} - \xi_{q} + \xi_{r} - \xi_{s})_{2 \ 2 \ 2 \ 2}
\end{align*}
\]
\[ -\frac{i}{4} \sum_{I, I', L} \sum_{I, I', L} \sum_{l, l'} \sum_{l', l''} \sum_{s, s'} \sum_{s, s''} \sum_{s', s''} \sum_{s', s''} \frac{\Xi(I'J'I'; sL) \Xi(I'J'I'; sL)}{\Xi(IJ; sL) \Xi(IJ; sL)} \gamma_{a^s l^s}^{(1)} \gamma_{a^s l^s}^{(1)} \gamma_{d^s l^s}^{(2)} \gamma_{d^s l^s}^{(2)} \gamma_{d^s l^s}^{(1)} \gamma_{d^s l^s}^{(1)} \gamma_{d^s l^s}^{(1)} \gamma_{d^s l^s}^{(1)} \times C7.15 \]

\[ \frac{\Gamma_{ix}}{|\varepsilon_1|^2 |\varepsilon_2|} \cos \left( \xi_1 - \xi_1' + \xi_2 - \xi_2' + \beta_2 \right). \]

\[ + \frac{1}{4} \frac{2}{|\varepsilon_1|^2 |\varepsilon_2|} \sum_{I, I', L} \sum_{I, I', L} \sum_{l, l'} \sum_{l', l''} \sum_{s, s'} \sum_{s, s''} \sum_{s', s''} \sum_{s', s''} \frac{\Xi(I'J'I'; sL) \Xi(I'J'I'; sL)}{\Xi(IJ; sL) \Xi(IJ; sL)} \times C7.16 \]

\[ \gamma_{a^s l^s}^{(1)} \gamma_{a^s l^s}^{(1)} \gamma_{d^s l^s}^{(2)} \gamma_{d^s l^s}^{(2)} \cos \left( \xi_1 - \xi_1' + \xi_2 - \xi_2' + \beta_2 - \beta_2 \right). \]

\[ -\frac{i}{4} \sum_{I, I', L} \sum_{I, I', L} \sum_{l, l'} \sum_{l', l''} \sum_{s, s'} \sum_{s, s''} \sum_{s', s''} \sum_{s', s''} \frac{\Xi(I'J'I'; sL) \Xi(I'J'I'; sL)}{\Xi(IJ; sL) \Xi(IJ; sL)} \gamma_{a^s l^s}^{(1)} \gamma_{a^s l^s}^{(1)} \gamma_{d^s l^s}^{(1)} \gamma_{d^s l^s}^{(1)} \gamma_{d^s l^s}^{(2)} \gamma_{d^s l^s}^{(2)} \times C7.17 \]

\[ \frac{\Gamma_{ix}}{|\varepsilon_1|^2 |\varepsilon_2|} \cos \left( \xi_1 - \xi_1' + \xi_2 - \xi_2' + \beta_2 \right). \]
Before we proceed to evaluate C7.6, let us investigate the terms from C7.11 to C7.19. We see that C7.11 and C7.12 are the "self-terms" for pure resonance scattering of levels one and two respectively. We will therefore concentrate on the remaining terms.

Let us define the following quantities
Since the ranges of $t_1'$ and $t_2'$ are identical to those of $t_1$ and $t_2$, we may also use the quantities defined in C7.20 when the sums are over $t_1'$ and $t_2'$. Decomposing the cosine terms and factoring we have that equation in C7.13 becomes

$$\frac{1}{8} \frac{\Gamma_{1,2}^2}{|\epsilon_1|^2 |\epsilon_2|^2} \mathcal{C} \mathcal{D}; \quad \text{and}$$

C7.21

equation C7.14 becomes

$$\frac{1}{4} \frac{\Gamma_{1,2}^2}{|\epsilon_1|^2 |\epsilon_2|^2} (A^2 + B^2).$$

C7.22

Equations C7.15 and C7.17 combine and we have

$$\frac{1}{4} \frac{(-2 \Gamma_{1,2})}{|\epsilon_1|^2 |\epsilon_2|^2} \left[ \mathcal{C} (A \cos \beta - B \sin \beta) \right].$$

C7.23

Likewise equation C7.18 and C7.19 are equal and we have

$$\frac{1}{4} \frac{(-2 \Gamma_{1,2})}{|\epsilon_1|^2 |\epsilon_2|^2} \left[ \mathcal{D} (A \cos \beta + B \sin \beta) \right].$$

C7.24
and finally we may write equation C7.16 as

\[
\frac{1}{4} \frac{2}{|\epsilon_1||\epsilon_2|} \left[ (R^2 - B^2) \omega_{\alpha}(\beta - \beta) - 2 \omega_{\alpha}(\beta - \beta) R B \right].
\]

We see that by defining the quantities in equation C7.20 we have simplified our work considerably. If we neglect the contributions given by equations C7.9 and C7.10 and include the levels of the same spin and parity in the sum over single levels for the cross section given in C6.21 we see that the additional terms we need to this point are C7.21, C7.22, C7.23, and C7.24. The sums C7.7, C7.8, C7.11, C7.12, and C7.25 are already included in the sum over single levels in C5.4.

We have yet to evaluate C7.6. Performing the indicated operations we have

\[
-(2J+1) \sum_{\ell, L, \lambda} (\ell \ell \parallel 0 \downarrow 0 \uparrow)^2 \frac{\Gamma^{(1)}_{\alpha\beta\lambda}}{|\epsilon_1|} \omega_{\alpha} \omega_{\beta} (\beta \beta_\lambda - \beta_\lambda), \quad C7.26
\]

\[
-(2J+1) \sum_{\ell, L, \lambda} (\ell \ell \parallel 0 \downarrow 0 \uparrow)^2 \frac{\Gamma^{(2)}_{\alpha\beta\lambda}}{|\epsilon_2|} \omega_{\alpha} \omega_{\beta} (\beta \beta_\lambda - \beta_\lambda), \quad C7.27
\]
In their present form the last three expressions are not suitable for practical computations for the elastic scattering of charged particles. Using the same procedure as in Section 6, we separate out Rutherford (point charge) scattering. Without going through the computation, we have that C7.26 and C7.27 give us the same contributions as given in equation C5.24 for levels of different spin and parity. However we have two additional contributions to the cross section from equation C7.28 which are

\[
\frac{2}{(2I+1)(2I'+1)} \sum_{l=0}^{\infty} \frac{F_{+}^{2} \Gamma_{+}^{2}}{l^{|l-I-1|}} (2I+1)_{l} l^{|l-l-1|} (2I'+1)_{l} l^{|l-l-1|} (\beta_{+}^{2} + 2\gamma_{l}^{2} \beta_{-}^{2} - 2\gamma_{l} \beta_{-})
\]

\[
\times \frac{g_{(x)}^{(2)} g_{(z)}^{(1)}}{|\epsilon_{1}||\epsilon_{2}|} \frac{[\ell(\ell'_{00}|L_{0})^{2}]}{P_{L}(\cos \theta)}
\]
and \[
\frac{-\frac{3}{2} (2I+1) \Gamma_{1z}}{(2I+1) (2I+1)} \sum_{l} \frac{\frac{3}{2} l+I+1}{l+1} \frac{(\epsilon)}{(\epsilon)} \cos \left(\frac{\theta}{2}\right) \times \\
\sum_{\frac{l}{2}} \left(2 \gamma \ln \sum_{\frac{l}{2}} + 2 \phi_{l} + 2 \phi_{l}^* + \beta^* \beta \right) P_{l}(\cos \theta),
\]
where in the case of spin flip we must sum over $s$ in C7.29 and C7.30.

In review, if we neglect contributions to the cross section from the expressions given in equations C7.9 and C7.10 we have that the additional terms to be included in equation C6.21 for the use of two levels of the same spin and parity are C7.21, C7.22, C7.23, C7.24, C7.29, and C7.30. (It being understood that the first four expressions must be substituted into equation C4.5.) We see that in the second order approximation, besides modifying the resonance scattering term, we have an additional interference term between resonance scattering and Coulomb scattering and a finite nuclear size correction to this interference term.

We have made several approximations which we should now investigate in more detail. The $A_{\mu \lambda}$ are given by Lane and Thomas as
\[ A_{11} = \frac{\varepsilon_2}{D}, \]
\[ A_{12} = A_{x1} = \frac{\xi_{12}}{D}, \]
\[ A_{22} = \frac{\varepsilon_1}{D}, \]

where
\[ D = \varepsilon_1 \varepsilon_2 - \xi_{12}^2, \]
\[ \xi_{12} = -\Delta_{12} + \frac{1}{2} i \Gamma_{12}, \]

and
\[ \varepsilon_\lambda = \varepsilon + \Delta_\lambda - \frac{1}{2} i \Gamma_\lambda. \]

From C7.31 we see that the \( A_{\mu\lambda} \) for the two level case reduce to those quoted from E. P. Wigner\(^{(23)}\) if we set \( \Delta_{12} \) equal to zero and in \( D \) neglect the factor \( \xi_{12}^2 \) in comparison to \( \varepsilon_1 \varepsilon_2 \). In addition we have again set the level shift \( \Delta_\lambda \) equal to zero, and as before we have neglected the contribution from "distant-levels". The expressions we have developed are good only if the two levels of the same spin and parity are separated by at least a full level width and the assumption is justified that contributions from "distant-levels" are negligible.
8. THREE LEVEL APPROXIMATION

To derive expressions for the elastic scattering of charged particles when we have three levels of the same spin and parity in the energy region of interest we shall use the $A_{\mu \lambda}$ given by E. P. Wigner\(^{23}\) as we did in Section 7. The sums over $\mu$ and $\lambda$ in the scattering matrix element now extend to three. The procedure for evaluating the additional terms is the same as was outlined in Section 7. Without going through the details we shall present the additional terms that must be included in equation C6.21 for this case.

First we shall define the following quantities:

$$\mathcal{A} = \sum_{I_1} \sum_{I_2} \mathcal{Z}(lJ_l I_o I_0; sL) g^{(1)}_{\alpha s I} g^{(2)}_{\alpha s I_2} \cos (\xi_{l I} - \xi_{I_2})$$

$$\mathcal{B} = \sum_{I_1} \sum_{I_2} \mathcal{Z}(lJ_l I_o I_0; sL) g^{(1)}_{\alpha s I} g^{(2)}_{\alpha s I_2} \cos (\xi_{l I} - \xi_{I_2})$$

$$\mathcal{C} = \sum_{I_1} \sum_{I_2} \mathcal{Z}(lJ_l I_o I_0; sL) g^{(1)}_{\alpha s I_1} g^{(1)}_{\alpha s I_2} \cos (\xi_{l I} - \xi_{I_2})$$

$$\mathcal{D} = \sum_{I_1} \sum_{I_2} \mathcal{Z}(lJ_l I_o I_0; sL) g^{(2)}_{\alpha s I_1} g^{(2)}_{\alpha s I_2} \cos (\xi_{l I} - \xi_{I_2})$$

$$\mathcal{E} = \sum_{I_1} \sum_{I_2} \mathcal{Z}(lJ_l I_o I_0; sL) g^{(3)}_{\alpha s I_1} g^{(3)}_{\alpha s I_2} \cos (\xi_{l I} - \xi_{I_2})$$

$$\mathcal{F} = \sum_{I_1} \sum_{I_2} \mathcal{Z}(lJ_l I_o I_0; sL) g^{(1)}_{\alpha s I_1} g^{(3)}_{\alpha s I_2} \cos (\xi_{l I} - \xi_{I_2})$$
We shall now list the additional terms which are included in the resonance scattering term.

\[ \frac{1}{8} \frac{\Gamma_{12}^2}{|\epsilon_1|^2|\epsilon_2|^2} \cos \beta \sigma \]  
C8.2

\[ \frac{1}{2} \frac{1}{|\epsilon_1||\epsilon_2|} \left[ (A^2 B^2) \cos (\beta \cdot \beta) - 2 \sin (\beta \cdot \beta) \mathcal{R} \mathcal{B} \right] \]  
C8.3

\[ -\frac{1}{2} \frac{\Gamma_{12}^2}{|\epsilon_1|^2|\epsilon_2|^2} \left[ (A^2 \cos \beta + B^2 \sin \beta) \sigma \right] \]  
C8.4

\[ -\frac{1}{2} \frac{\Gamma_{12}^2}{|\epsilon_1|^2|\epsilon_2|^2} (A^2 B^2) \]  
C8.5

\[ \frac{1}{8} \frac{\Gamma_{12}^2}{|\epsilon_1|^2|\epsilon_2|^2} (A^2 B^2) \]  
C8.6
\[
\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1|^2 |\epsilon_3|^2} (H^2 + \Delta^2) C \in \xi , \\
C8.9
\]

\[
\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1|^2 |\epsilon_3|^2} \left[ \sigma \left( H \cos \beta_3 - \Delta \sin \beta_3 \right) \right] ,
C8.10
\]

\[
\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1|^2 |\epsilon_3|^2} \left[ \varepsilon \left( H \cos \beta_3 + \Delta \sin \beta_3 \right) \right] ,
C8.11
\]

\[
\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1|^2 |\epsilon_3|^2} (H^2 + \Delta^2) C \in \xi , \\
C8.12
\]

\[
\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1|^2 |\epsilon_3|^2} \left[ (H^2 + \Delta^2) \cos (\beta_3 - \beta_1) - 2 \Delta \sin (\beta_3 - \beta_1) \right] , C8.13
\]
\[-\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1^2| |\epsilon_3|} \left[ \mathcal{E} \left( F \cos \beta + \mathcal{H} \sin \beta \right) \right], \quad \text{C8. 14}\]

\[-\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1^2| |\epsilon_3|} \left[ \mathcal{E} \left( F \cos \beta - \mathcal{H} \sin \beta \right) \right], \quad \text{C8. 15}\]

\[\frac{1}{6} \frac{\Gamma_3}{|\epsilon_1^2| |\epsilon_3|^2} \left( \mathcal{F}^2 + \mathcal{H}^2 \right), \quad \text{C8. 16}\]

\[-\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1||\epsilon_2||\epsilon_3|} \left[ \mathcal{A} \left( F \cos \beta' - \mathcal{H} \sin \beta' \right) - B \left( \mathcal{H} \cos \beta' + F \sin \beta' \right) \right], \quad \text{C8. 17}\]

WHERE \( \beta' = \beta_2 + \beta_3 - \beta_1 \).

\[-\frac{1}{2} \frac{\Gamma_3}{|\epsilon_1||\epsilon_2||\epsilon_3|} \left[ \mathcal{H} \left( \mathcal{A} \cos \beta'' + \mathcal{B} \sin \beta'' \right) - \mathcal{A} \left( \mathcal{H} \cos \beta'' - \mathcal{B} \sin \beta'' \right) \right], \quad \text{C8. 18}\]

WHERE \( \beta'' = \beta + \beta_3 - \beta_1 \).

\[-\frac{1}{2} \frac{\Gamma_2}{|\epsilon_1||\epsilon_2||\epsilon_3|} \left[ \mathcal{H} \left( \mathcal{F} \cos \beta' + \mathcal{H} \sin \beta' \right) + \mathcal{F} \left( \mathcal{H} \cos \beta' - \mathcal{F} \sin \beta' \right) \right], \quad \text{C8. 19}\]

WHERE \( \beta' = \beta_1 + \beta_2 - \beta_3 \).
One will immediately recognize the first five terms as those which we had for the two level case. Again it is understood that the above results are to be substituted into equation C4.5. Listing the new interference terms with Coulomb and their correction terms due to finite nuclear size, we have

$$\frac{1}{4} \frac{\Gamma_2 \Gamma_3}{|\epsilon_1| |\epsilon_2| |\epsilon_3|^2} \left[ (B^+ + A^+ + B^2) \cos \beta' - (B^+ + A^+ + B^2) \sin \beta' \right],$$  \hspace{1cm} \text{C8.20}

WHERE $\beta' = \beta_3 - \beta_1$.

$$+ \frac{1}{4} \frac{\Gamma_2 \Gamma_3}{|\epsilon_1| |\epsilon_2| |\epsilon_3|^2} \left[ (A^+ + B^+ + C^2) \cos \beta' + (B^+ + A^+ + C^2) \sin \beta' \right],$$  \hspace{1cm} \text{C8.21}

WHERE $\beta' = \beta_3 - \beta_2$.

and

$$\frac{1}{4} \frac{\Gamma_3 \Gamma_3}{|\epsilon_1| |\epsilon_2| |\epsilon_3|^2} \left[ (A^+ + B^+ + C^2) \cos \beta' + (B^+ + A^+ + C^2) \sin \beta' \right],$$  \hspace{1cm} \text{C8.22}

WHERE $\beta' = \beta_2 - \beta_1$.
\[
\frac{-X \pi (2I+1) \Gamma_2}{(2I+1)(2I+1)} \sum_{I=1}^{I_{\text{min}}} \frac{\mathcal{G}_{\text{ast}} \mathcal{G}_{\text{ast}}}{|\epsilon \epsilon_{\text{I}}|} \frac{(2)}{(1)} \frac{1}{\sin^{2}\beta _{I}} \sin \left( 2 \gamma_{I} \theta_{I} \sin \frac{\epsilon_{I}}{2} + \gamma_{I} \beta_{I} \right) \sin \left( 2 \gamma_{I} \theta_{I} \sin \frac{\epsilon_{I}}{2} + \gamma_{I} \beta_{I} \right)
\]

\[X \mathcal{P} (\cos \theta) \]

C8.24

\[
\frac{-X \pi (2I_{0}+1) \sum_{I=0}^{\infty} \frac{\mathcal{G}_{\text{ast}} \mathcal{G}_{\text{ast}}}{|\epsilon \epsilon_{I}|} \frac{(1)}{(3)} \frac{}{}}{(2I+1)(2I+1)} \frac{}{\frac{1}{(200L_{0})}} \mathcal{P} (\cos \theta)
\]

\[C8.25\]

\[
\frac{-X \pi (2I_{0}+1) \frac{1}{(2I+1)(2I+1)} \frac{\mathcal{G}_{\text{ast}} \mathcal{G}_{\text{ast}}}{|\epsilon \epsilon_{I}|} \frac{(1)}{(3)} \frac{1}{\sin^{2}\beta _{I}} \sin \left( 2 \gamma_{I} \theta_{I} \sin \frac{\epsilon_{I}}{2} + \gamma_{I} \beta_{I} \right) \sin \left( 2 \gamma_{I} \theta_{I} \sin \frac{\epsilon_{I}}{2} + \gamma_{I} \beta_{I} \right) \frac{}{}}{X \mathcal{P} (\cos \theta) \frac{}}
\]

C8.26
Actually for the case when there is the possibility of spin flip
the terms C8.24 to C8.28 must be summed over s. We recognize
C8.23 and C8.24 as two of the additional terms we had for the two level
case. All the approximations and assumptions made for the two
level case apply here also. (See Section 7.) In Appendix D
we shall describe the program which has been written to evaluate
the elastic scattering cross section and point out any additional
assumptions which may have been used in the program.
9. REDUCTION OF K

In the next few pages, the expression for K given in equation C2.3 is reduced to a simple form. The first step is to use the fact that a product of two spherical harmonics can be expressed as a linear superposition of spherical harmonics:

\[ Y_{l_1^{'}} \ell_1^{'|}(\theta, \phi) \cdot Y_{l_2^{'}} \ell_2^{'|}(\theta, \phi) = (-)^{l_1^{'}} \frac{L^{l_1^{'}}}{L^{l_1^{'}}} \frac{L^{l_2^{'}}}{L^{l_2^{'}}} \frac{1}{4\pi (2L+1)} \left[ \frac{(2l+1)(2l^{'}+1)}{4\pi (2L+1)} \right]^{\frac{1}{2}} \times \]

\[ (l_1^{'}, l_2^{'}) \left| L_1^{|M|} \right| (l_1^{'}, l_2^{'}) \left| L_2^{|M|} \right| \right) Y_{LM}(\theta, \phi). \]

Substituting C9.1 into C2.3 we obtain

\[ K = \frac{\pi (2l+1)}{(4\pi)^{\frac{1}{2}}} \frac{1}{(2L+1)} \frac{1}{(2L^{'}+1)} \sum_{M} \sum_{M} \sum_{M} \sum_{M} \left[ \left( \frac{1}{2L+1} \right)^{\frac{1}{2}} \times \right. \]

\[ (l_1^{'}, l_2^{'}) \left| L_1^{|M|} \right| (l_1^{'}, l_2^{'}) \left| L_2^{|M|} \right| \] \left( (l_1^{'}, l_2^{'}) \left| L_1^{|M|} \right| (l_1^{'}, l_2^{'}) \left| L_2^{|M|} \right) \right) Y_{LM}(\theta, \phi) \times \]

\[ \left\{ \sum_{M} \sum_{M} \sum_{M} (-)^{\ell_1^{'}} \left( \frac{1}{2L+1} \right)^{\frac{1}{2}} \times \right. \]

\[ \left( (l_1^{'}, l_2^{'}) \left| L_1^{|M|} \right| (l_1^{'}, l_2^{'}) \left| L_2^{|M|} \right) \right) \left( (l_1^{'}, l_2^{'}) \left| L_1^{|M|} \right| (l_1^{'}, l_2^{'}) \left| L_2^{|M|} \right) \right) \right\} \times \]
The next step is to perform the sums in the curly brackets using a Racah sum rule \(^\text{(a)}\) which is
\[
\sum_{\beta} (abc\beta|abc\alpha\beta) (ed\alpha\beta\gamma\alpha\beta|ed\gamma\alpha) = \frac{1}{(2\ell+1)(2\ell'+1)} (a\ell\gamma-a\ell\gamma) \times C_{9.3}
\]
\[
W(abcde;ef),
\]
where \(W\) is a Racah coefficient. \(^\text{(a8)}\) Before we can continue we also need a few symmetry properties of C. G. coefficients. \(^\text{(a9)}\)

\[
(j_1,j_2,m_1,m_2|JM) = (-)^{j_1+j_2-J} (j_1,j_1,m_1,m_1|JM),
\]
\[
= (-)^{j_1-j-M} (j_2,j_2,M-j_2,j_2) \frac{1}{2j_2+1} (j_1,j_1,M,j_1M), \quad C_{9.4}
\]
\[
= (-)^{j_2-J-M} (j_1,j_1,J-m_1,J,m_1) \frac{1}{2j_1+1} (j_2,j_2,J-M,j_2M),
\]
\[
= (-)^{j_1+j_2-J} (j_1,j_2,J-m_1,J-m_2|JM).
\]

Using the symmetry properties of C. G. coefficients \((C9.4)\) we rewrite
\[ ( \ell' s' \mu_1^m s' \mid J M ) = (-)^{s'-J-\mu_1^i} \left( \frac{2J+1}{2s'+1} \right)^{\frac{1}{2}} \left( \ell' J - \mu_1^i M \mid s' m_3' \right), \]

\[ = (-)^{s'-J-\mu_1^i} (-)^{\ell' s' - s'} \left( \ell' J - M \mu_1^i \mid s' m_3' \right) \left( \frac{2J+1}{2s'+1} \right)^{\frac{1}{2}}, \]

\[ = (-)^{J_1 - \mu_1^i - s'} \left( \frac{2J+1}{2s'+1} \right)^{\frac{1}{2}} \left( \ell' J - M \mu_1 \mid s'-m_3' \right). \]

and

\[ ( \ell' s' \mu_2^m s' \mid J M ) = (s' \ell' - m' - \mu_2^i \mid J - M ), \]

\[ ( \ell' s' \mu_1^i \mu_2^i \mid L M ) = (-)^{\ell' s' - L} ( s' \ell' \mu_1^i - \mu_2^i \mid L - M ). \]

Substituting C9.5 and C9.6 into the curly brackets of C9.2 we have

\[ (-)^{J_1 - s' + \ell' s' - L} \sum_{\mu_1^i} \sum_{\mu_2^i} \left( \frac{2J+1}{2s'+1} \right)^{\frac{1}{2}} \left( \ell' J - M \mu_1^i \mid s' m_3' \right) \times \]

\[ \left( s' \ell' - m' - \mu_1^i \mid J - M \right) \left( \ell' s' \mu_1^i - \mu_2^i \mid L - M \right). \]

Now the three sums in C9.7 are not independent because of the C. G. coefficients. Let us perform the sum over \( \mu_1^i \) then

\[ m_3' = M - \mu_1^i, \]

\[ \mu_1^i = M + \mu_1^i, \]

\[ \mu_2^i = M + \mu_2^i, \]
and substituting these into C9.7 we get

\[- \frac{J_1 + J_2 - L + \mathbf{J} - \mathbf{S}}{(2J_1 + 1)\frac{1}{2}} \sum_{\mu_1} (J_1 - \mu_1 | s_1^2 \mu_2^2 - M) \times C9.9\]

\[(s_1^2 \mu_2^2 - (M + \mu_2^2) | J_1 - M) (J_1^2 \mu_2^2 - (M + \mu_2^2) | L - M).\]

Now comparing C9.9 with C9.3 we see that

\[a = J_1, \quad b = \mu_1^2, \quad c = J_2, \quad d = \mu_2^2, \quad e = s_1^2, \quad f = L, \quad \alpha = -M_1.\]

\[\beta = \mu_1^2, \quad \text{and} \quad \gamma = -M_2.\]

Using the values in C9.10 we see that the sums in the curly brackets of C9.2 are equal by using C9.3 to

\[- \frac{J_1 - J_2 - s_1^2 + \mathbf{J}_1^2 + \mathbf{J}_2^2}{(2J_1 + 1)\frac{1}{2}} \times C9.11\]

\[(J_1 M M_1 | J_1 M_1) W(J_1^1 J_1^2 s_1^2 L).\]

Substituting C9.11 into C9.2 and collecting terms we have
where

\[ K = \frac{1}{\pi (2J+1)^2} \left( \frac{1}{4\pi} \right)^2 \frac{1}{(2L+1)^2} \left( \frac{1}{2L+1} \right)^2 \sum_{LM} \frac{1}{(2L+1)^4} (-)^{2J-J'-S^I-L'}. \]

and

\[ (2J+1)^2 (2L+1)^2 W(1J'1J'1s'1L') \left( \begin{array}{ccc} J' & 00 & L0 \end{array} \right) Y_L^M(\theta, \phi) \times \]

\[ \left\{ \sum_{LM} \sum_{M} \left( l_{s} \text{om} | J M \right) \left( l_{s} \text{om} | J' M \right) \left( J L M M | J' M \right) \right\}. \]

We perform next the indicated sums in the curly brackets of C9.12. As before we must rewrite the C. G. coefficients before we can use the Racah sum rule.

\[ \left( l_{s} \text{om} | J M \right) = (-)^{l-J+M_{s}} \left( \frac{1}{2L_{s}+1} \right)^{\frac{1}{2}} \left( S J m - M | l o \right), \]

\[ \left( l_{s} \text{om} | J M \right) = (-)^{S-J} \left( \frac{2J_{s}+1}{2S+1} \right)^{\frac{1}{2}} \left( l \text{om} | S m \right), \]

and

\[ \left( J L M M | J' M \right) = (-)^{J-M} \left( \frac{2J_{s}+1}{2L_{s}+1} \right)^{\frac{1}{2}} \left( J M - M | L-M \right). \]

Also from C9.13 we see that \( m_s = M_1 = M_s \) so we may rewrite the sums in the curly brackets of C9.12 as
As before we again compare C9.14 to the Racah sum C9.3 and we find that

\[ a = l_1, \quad b = J_1, \quad c = l_2, \quad e = S, \quad f = J, \quad \alpha = 0, \quad \beta = m_{\gamma} \]

and \( \gamma = -M = 0 \). Using the Racah sum rule we have that C9.14 becomes

\[
(-)^{J - J_z + S} \frac{(2J + 1)(2J_z + 1)^{\frac{1}{2}}}{(2L + 1)^{\frac{1}{2}} (2S + 1)^{\frac{1}{2}} (2L_z + 1)^{\frac{1}{2}}}
\sum_{m} (J \gamma_{J \gamma} m | S m) \times \text{C9.14}
\]

\[
(s J m - m | \gamma_0) (J J_z m - m | L - M).
\]

And we find that

\[ a = l_1, \quad b = J_1, \quad c = l_2, \quad e = S, \quad f = J, \quad \alpha = 0, \quad \beta = m_{\gamma} \]

and \( \gamma = -M = 0 \). Using the Racah sum rule we have that C9.14 becomes

\[
(-)^{L - J_z + S} \frac{(2J + 1)(2J_z + 1)^{\frac{1}{2}}}{(2L + 1)^{\frac{1}{2}} (2S + 1)^{\frac{1}{2}} (2L_z + 1)^{\frac{1}{2}}}
\sum_{m} (J \gamma_{J \gamma} m | S m) \times \text{C9.15}
\]

\[ \text{OR} \]

\[
(-)^{L - J_z + S} \frac{(2J + 1)(2J_z + 1)^{\frac{1}{2}}}{(2L + 1)^{\frac{1}{2}} (2S + 1)^{\frac{1}{2}} (2L_z + 1)^{\frac{1}{2}}}
\sum_{m} (J \gamma_{J \gamma} m | S m) \times \text{C9.15}
\]

where \( M = 0 \).

Substituting C9.15 into C9.12 for the sums in the curly brackets, \( K \) becomes

\[
K = \frac{\pi (2L + 1)^{\frac{1}{2}} (2J_z + 1)^{\frac{1}{2}} (2J + 1)^{\frac{1}{2}} (2L_z + 1)^{\frac{1}{2}}}{(4 \pi)^{\frac{1}{2}}}
\sum_{L M} (2J + 1)(2J_z + 1)
\times \text{C9.16}
\]

\[
W(J I', J I'; S L) (I' \gamma_{I' \gamma} | I \gamma) W(I \gamma_{I \gamma} | L \gamma_{L \gamma} | LM) W(L J \gamma_{J \gamma} | J J_z) \times \text{C9.16}
\]

\[
(-)^{S \gamma_{S \gamma} I' \gamma_{I' \gamma} J \gamma_{J \gamma} + L} \frac{1}{(2L + 1)^{\frac{1}{2}}}
\gamma_{LM} (\theta, \phi).
\]
Defining

\[ \mathcal{Z}(\ell J \ell' J'; SL) = (2\ell+1)(2\ell'+1)(2J+1)(2J'+1)^{-\frac{1}{2}} \]

and using the fact that

\[ W(\ell J \ell' J'; SL) (\ell \ell' 0 0 | L0), \]

and

\[ Y_{L0}(\theta) = \frac{\sqrt{2L+1}}{4\pi} P_{L}(\cos \theta), \]

equation C9.16 simplifies to

\[ K = \frac{1}{\pi} (-)^{S-S'} \sum_{L} \mathcal{Z}(\ell J \ell' J'; SL) \mathcal{Z}(\ell' J' \ell'' J''; SL') P_{L}(\cos \theta). \]

Notice in C9.18 the factor \((-)^{\ell_1' + \ell_2' + L}\) is missing as well as a sum over \(M\). Because of \((\ell_1 \ell_2 00 | LM)\), \(M\) can have only one value which is zero. Likewise from \((\ell_1' \ell_2' 00 | L0)\) we know that \(\ell_1' + \ell_2' + L\) must be even so that \((-)^{\ell_1' + \ell_2' + L}\) is equal to one. It should also be pointed out that the \(\mathcal{Z}\) defined in equation C9.17 differs by the factor \(i^{L - \ell_1 + \ell_2}\) from the \(Z\) defined in Blatt and Biedenharn\(^{(7)}\), who were wrong because of their neglect of the Huby time reversal convention\(^{(18)}\).
APPENDIX D

Discussion of Program EORCS to Calculate
Elastic Scattering and Reaction Cross Section

In Appendix C we developed a formula for the reaction cross section using single-level dispersion theory and a formula for the elastic scattering cross section in the "few-level" approximation. In this section the computer program which calculates these is presented. The program has been specialized to the case of alpha particles on \(^9\)Be. However, the modifications necessary to do other reactions will be pointed out. The program has also been used to investigate the following reactions: \(^{12}\)C(d, d)\(^{12}\)C, \(^{24}\)Mg(p, p)\(^{24}\)Mg, and \(^{12}\)C(\(^3\)He, \(^3\)He)\(^{12}\)C. Among the various options, the user may choose to do a minimum \(\chi^2\) search or simply calculate the cross section for a given set of levels. The various options at the user's disposal are discussed in detail later.

The program has been divided into a main program called EORCS and several subroutines. For purposes of clarification, each is described, in a separate section. The main program is discussed in Section 1. The subroutines are discussed in Sections 2 to
11, and modifications necessary for doing other reactions are discussed in Section 12. Data cards are discussed in Section 13. Listings of the program and subroutines are given on pages 235 to 288.
1. EORCS

The program EORCS calculates some of the cross section terms but is mainly a calling program. The program reads input data from cards; from the options chosen, it decides which subroutines to call and the form the output should take. We start by describing in alphabetical order the variables which are read from cards. Depending on the options chosen, however, only some of these are read at any one time.

Variables Read from Cards

COMP2(K, 1, 1): Center of mass angles, in degrees, for angular distributions of reactions.

COUPH(I, L): The modified Coulomb phase shifts and $\eta$ calculated in HSPS (Appendix E, Section 5), are stored in this variable. I, which may have a maximum value of forty-one, specifies the energy at which they are evaluated and L specifies the order $\ell$, i.e., $\text{COUPH}(I, L) = \psi_{\ell-1} = \sigma_{\ell-1} - \sigma_0$, for $L \leq 7$, and $\text{COUPH}(I, 8) = \eta = Z_1Z_2e^2/\hbar\nu$. 
DELTA (I, L): This variable contains the hard sphere phase shifts and \( \gamma \), calculated in HSPS (Appendix E, Section 5). \( I \) (maximum value of 41) specifies the energy at which they are evaluated and \( L \) specifies the \( l \).

\[
\text{DELTA} (I, L) = \phi_{L-1} = -\tan^{-1} \frac{F_{L-1}}{G_{L-1}},
\]

and \( \text{DELTA} (I, 8) = \gamma \).

EIN: When the program does a \( \chi^2 \) search it reads experimental data. \( \text{EIN} \) specifies the initial laboratory energy in MeV of the experimental excitation curve to be read into the program.

EFIN: \( \text{EFIN} \) is the final laboratory energy in MeV for the experimental excitation curve to be read into the program.

ELABB: Laboratory energy in MeV of experimental angular distribution.

ER: \( \text{ER} \) is the resonance energy in MeV in the laboratory system.
ERESL(NJE): This variable stores the laboratory resonance energies in MeV for up to eight levels. If more levels are desired, the dimension of this variable must be increased. The value of NJE specifies which level we are considering.

GSIGN(NJE,2): This variable stores the sign of the g's of the incoming channel for each level. For alpha particles on $^6$Be there are usually two possible incoming $t$ values for each level of a given spin and parity and the second variable specifies to which the sign belongs. If more levels are desired the dimension of eight must be increased.

GR: GR is the resonance width in the laboratory system in MeV.

I1SN: Sign of $g^{J_{ct1}}$, either +1 or -1.

I2SN: Sign of $g^{J_{ct2}}$, either +1 or -1.
<table>
<thead>
<tr>
<th>IFINS:</th>
<th>IFINS is the spin of the state of the final nucleus and is used for reaction cross sections. It is assumed that the outgoing reaction product has a spin of 1/2 and the final states are either $0^+$ or $2^+$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIMAX:</td>
<td>Has a value from one to forty-one. Used to tell program the maximum value of $I$ in the variables COUP($I, L$), DELTA ($I, L$), $T(I, L)$, PENTRA($I, L$) and ZELTA ($I, L$).</td>
</tr>
<tr>
<td>IMAX:</td>
<td>The laboratory energies in MeV are stored in $T(I, 8)$. IMAX specifies the maximum energy desired in the calculation, i.e., $E_{\text{max}} = T(\text{IMAX}, 8)$.</td>
</tr>
<tr>
<td>IMIN:</td>
<td>IMIN specifies the minimum energy desired in the calculation. $E_{\text{min}} = T(\text{IMIN}, 8)$.</td>
</tr>
<tr>
<td>INTF3:</td>
<td>INTF3 is a control variable which has two values, either zero or one.</td>
</tr>
</tbody>
</table>
For the value one, terms for the three-level approximation are included; if the value is zero, they are not included.

**INTFR:** Control variable used to tell the program if two-level approximations are to be used. If all levels have INTFR = zero, single-level dispersion theory is used.

**INTFS (NJE):** This variable stores the value of INTFR for each level.

**IPAR:** IPAR is the parity of the level, either +1 or -1.

**IPITY (NJE, JOHN):** This variable specifies the parity of each level. In the search routine, one is allowed to change the parity and the variable JOHN specifies which value is to be used.

**ISERH:** In reaction cross section, the sign of $g$ is very important. ISERH equal to one calculates reaction
cross sections for up to three
levels, with all possible signs of the
g's and plots the results. If ISERH
equal to zero, this option is omitted.

**IVAL(J):**
This variable stores the I value
which corresponds to the energy
at which an angular distribution is
to be calculated. i.e. \( E = T(IVAL(J), 8) \).

**JAKE:**
If it has the value one, the program
reads the angles at which the
angular distribution is to be calcu-
culated. If JAKE is zero, the
program assumes 5° steps in the
laboratory system for elastic
scattering or 5° steps in the center
of mass system for reactions.

**JMAX:**
JMAX is the number of angular
distributions to be calculated. If
none use the value one.

**KCASE:**
Used to specify either 1/2+ or 1/2-
level when doing a single level search
only. KCASE equal to zero, program calculates $1/2^+$ level, equal to one $1/2^-$ level.

**KKMAX:**

KKMAX is the number of excitation curves to be calculated. If none use the value one.

**KMAX:**

KMAX may have values from one to thirty-three and specifies the maximum angle to be calculated in an angular distribution. The maximum angle in degrees is KMAX times five.

**MAX:**

This variable serves a dual purpose. When more than one level is included in the calculation of the cross section, MAX is the number of levels. For a calculation which involves only one level, MAX determines the last spin of the level to be considered. The spin is MAX minus one-half.
MIN: When there is more than one level in the calculation MIN is set equal to one. For a calculation which involves only one level, MIN determines the first spin of the level to be considered. The spin is MIN minus one-half.

MIPAR: This variable may have the value of either one or two. If more than one level is involved in the calculation MIPAR is set to one. For a single-level calculation if MIPAR is equal to one, the parity is determined by the value of IPAR. If MIPAR is equal to two then both parities are calculated. The option is included so one may generate the shapes of isolated levels of different spin and parity, the spins being determined from MIN and MAX.

MJSAVE(NFIT): Stores the identification of each level the program is to search on.
**MSAVE(NJE):** This variable stores the number of different spin and parity cases that are to be tried by the search routine for each level. i.e. A number from one to four.

**MXCAL:** MXCAL specifies the number of levels to be involved in the calculation.

**MXR:** This variable is used to control the length of time spent in the search routine. The variable tells the search routine how many written outputs are allowed. Usually one gives this variable a value from seventy-five to one hundred.

**N1SN:** Sign of \( g^J_{\alpha'S'_{\ell_1}} \), either +1 or -1.

**N2SN:** Sign of \( g^J_{\alpha'S'_{\ell_2}} \), either +1 or -1.

**NCAL:** This variable tells the program whether one or more levels are involved in the calculation. If NCAL is set equal to zero, then only one level is involved. If it is set equal to
one, two or more levels are included in the calculation.

**NE1SN:** Sign of $g^J_{\alpha'S''}\ell_1$, either +1 or -1.

**NE2SN:** Sign of $g^J_{\alpha'S''}\ell_2$, either +1 or -1.

**NE3SN:** Sign of $g^J_{\alpha'S''}\ell_3$, either +1 or -1.

**NFIT:** NFIT may have a value from zero to four. For a given level if it is zero, the program does no search on the level. If it is equal to one, it is the first level to be searched. If it is two, it is the second level to be searched and so on.

**NFSAV(NJE):** The value of NFIT for each level is stored in this variable.

**NN:** The value zero for this variable specifies that the program is to calculate angular distributions, the value one, excitation curves.

**NOPT:** For the value one the program does a minimum $\chi^2$ search. For the value zero, the program calculates the cross section with the given
level parameters.

**NPPIN:** If NPPIN is equal to zero, there is output on the line printer. If NPPIN is equal to one, the output is also punched on cards.

**NREAT:** For a value of one, reaction cross sections are calculated; zero, elastic scattering cross sections are calculated.

**NSPMX:** The variables specifies the number of spin and parity cases for each level that the search is to try. A maximum of four are allowed.

**NTRACE:** For the value zero, one does not get trace of $\chi^2$ search; for the value one the trace is included.

**OEW1(NJE, 2):** The values of $\Gamma_{a'S'_{a_1}}$ and $\Gamma_{a'S'_{a_2}}$ are stored for each level. (In MeV in the laboratory system).

**OEW2(NJE, 3):** The values of $\Gamma_{a'S'_{a_1}}$, $\Gamma_{a'S'_{a_2}}$, and $\Gamma_{a'S'_{a_3}}$ are stored for each level. (In MeV in the laboratory system).
OSPN(NJE, 2): 
Signs of $g^J_{\alpha'S'\ell_1}$ and $g^J_{\alpha'S'\ell_2}$ are stored for each level.

OSPPN(NJE, 3): 
Signs of $g^J_{\alpha'S''\ell_1}$, $g^J_{\alpha'S''\ell_2}$, and $g^J_{\alpha'S''\ell_3}$ are stored for each level.

OWE1: 
The value of $\Gamma_{\alpha'S'\ell_1}$ in MeV in the laboratory system.

OWE2: 
The value of $\Gamma_{\alpha'S'\ell_2}$ in MeV in the laboratory system.

OWEE1: 
The value of $\Gamma_{\alpha'S''\ell_1}$ in MeV in the laboratory system.

OWEE2: 
The value of $\Gamma_{\alpha'S''\ell_2}$ in MeV in the laboratory system.

OWEE3: 
The value of $\Gamma_{\alpha'S''\ell_3}$ in MeV in the laboratory system.

PENTRA(I, L): 
The neutron penetrabilities calculated in NHPS (see Appendix E, Section 7) are stored in this variable. $I_{\text{max}}$ specifies the energy at which they were calculated.

i.e. $\text{PENTRA}(I, L) =$

$$
\frac{2\rho}{(\rho j_{L-1})^2 + (\rho \eta_{L-1})^2} |E=T(I, \theta)|
$$
PSII: The initial angle in degrees for the experimental angular distribution to be read into the program.

PSIF: The final angle in degrees for the experimental angular distribution to be read into the program. The program assumes the angular step is 5° from PSII to PSIF. The angle is the laboratory angle for elastic scattering and the center of mass angle for reactions.

REW(NJE, 2): This variable stores the values of \( \Gamma_{\alpha S t_1} \) and \( \Gamma_{\alpha S t_2} \) respectively for each level.

SAM1: The value of \( \Gamma_{\alpha S t_1} \) in MeV in the laboratory system.

SAM2: The value of \( \Gamma_{\alpha S t_2} \) in MeV in the laboratory system.

SPIN(NJE, JOHN): The spin of each level is stored in this variable. The variable JOHN specifies the various spins which the user may wish to try for each level.
The penetrabilities for alpha particles calculated in HSPS (see Appendix E, Section 5) are stored in this variable. I (maximum value of 41) specifies which energy they were calculated.

\[ T(I, L) = \frac{2\rho}{F_{L-1}^2 + G_{L-1}^2}, \quad L \leq 7. \]

and

\[ T(I, 8) = E \, (\text{Lab}). \]

TAMMA(NJE): This variable stores the total width, \( \Gamma \), for each level. (in MeV in the laboratory system).

TH(KK): The center of mass angles in degrees at which the excitation curves are to be calculated.

THETA: The center of mass angle in degrees for the experimental excitation curve to be read into the program.

YEXP(I, J): The experimental data is stored in this variable. The variables I and J specify the energy and angle respectively if excitation curves are read.
in, and vice versa for angular
distributions.

**YSIG(KP):**
The experimental data times one
hundred is read into this variable.
The factor of one hundred is for
plotting purposes.

**ZELTA(I, L):**
This variable stores the hard
sphere phase shifts for neutrons
calculated in NHPS (see Appendix
E, Section 7). \(I\) (maximum value of
41) specifies the energy at which
they were evaluated.

\[
\text{ZELTA}(I, L) = -\tan^{-1} \frac{J_{L-1}}{\eta_{L-1}} \bigg| E = T(I, \delta) .
\]

**NOTE:** When a variable above is specified by \(\ell_1, \ell_2, \ell_1', \text{ etc.}\)
it is assumed that \(\ell_1\) is the smallest \(\ell\) value necessary to
form a level of a given spin and parity, \(\ell_2\) is the next
largest, and so on; the same being true for the primed \(\ell\)
values which are the \(\ell\) values of the exit channel. Also \(S\)
refers to the entrance channel, \(S'\) to the smallest channel
spin of the exit channel, and \(S''\) to the next largest channel
spin.
VARIABLES CALCULATED INTERNALLY IN EORCS

In this section the formula for the elastic scattering cross section is specialized to the case of alpha particles on $^9\text{Be}$. Instead of listing all the variables in alphabetical order, most are presented as they pertain to the various terms in equation C6.21 for the elastic scattering cross section.

Since the Legendre polynomials $P_L(\cos \theta)$ are included in every term of equation C6.21, they are calculated for the various angles to be considered and stored before the cross section is actually evaluated. There are several other quantities which are also handled in this fashion:

CGE(LELAR, LESMA, LEPRM): This variable stores the values of the Clebsh-Gordan coefficients which appear in C6.21. The C. G. coefficients are of the form $(\ell, \ell' 00 \mid L0^2$ and are always accompanied by the factor $\sin \phi_\ell$. Since the sums over $\ell'$ extend to $\infty$, it is necessary to terminate the sums for some $\ell$.

The hard sphere phases $\phi_\ell$ approach zero rapidly as $\ell'$ increases and for $\ell'$ equal to six the value of the hard sphere phase is approximately a thousandth of the value for $\ell'$ equal to zero. The sums over $\ell'$ have, therefore, been terminated at $\ell'$ equal to six.
Thus we have

\[ \text{CGE(LELAR, LESMA, LEPRM)} = (t \ t'00 \mid L0)^2 \]

for \( t' \leq 6 \) and equal to zero for \( t \geq 6 \), where we have

\[ t = \text{LESMA-1}, \]
\[ t' = \text{LEPRM-1}, \]

and

\[ L = \text{LELAR-1}. \]

**COU (I, JMM):** This variable stores the values of the modified Coulomb phase shifts \( \psi \)\_i. Since we have terminated the sums over \( t' \) or \( t \) at six, we have

\[ \text{COU (I, JMM)} = \psi_{\text{JMM-1}} = \text{COUPH(I, JMM)}, \text{ for JMM} \leq 7, \]

and equal to zero for JMM greater than seven.

**DIL (I, JMM):** This variable stores the values of the hard sphere phase shifts, and as for COU (I, JMM) we have

\[ \text{DIL}(I, JMM) = \phi_{\text{JMM-1}} = \text{DELTA}(I, JMM), \text{ for JMM} \leq 7, \]

and equal to zero for JMM greater than seven.

**PLALL(K, L):** The values of the Legendre polynomials are stored in this variable, \( L \) specifies the order and \( K \) the angle, i.e.
\[ \text{PLALL}(K, L) = P_{L-1} \cos \theta_K. \]

**SINN(K):** The variable is defined by,

\[ \text{SINN}(K) = \sin \left( \frac{\theta_K}{2} \right), \] where \( K \) specifies the angle.

**SS(I, JMM):** This variable stores the values of \( \sin \phi_{JMM} \), and is given as

\[ \text{SS}(I, JMM) = \sin(\text{DIL}(I, JMM)) = \sin \phi_{JMM-1}. \]

We are now ready to evaluate the various terms in equation C6.21. We will describe in general what the program does for the case of elastic scattering when more than one level is included in the calculation. It is instructive first, however, to investigate the \( \ell \) values for the incoming channel for the case of alpha particles on \( ^9\text{Be} \). The ground state of \( ^9\text{Be} \) is \( 3/2^- \). The possible \( \ell \) values are tabulated in Table 8. As we can see, for levels with spins greater than or equal to \( 3/2 \) there are two possible \( \ell \) values for a given parity for the incoming channel. In the program the smallest of these is equal to \( LK-1 \), the other to \( LJ-1 \). The program begins by treating each level to be included in the calculation as if it were the only level. The second, third and fourth terms of equation C6.21
(the potential scattering terms) are included in the cross section just once. The values of $L_K$ and $L_J$ for each level are determined, and the contribution $R_L(a, a)$ is calculated in subroutine RSUM for the "self-term" (i.e. $J_n=J_m$). The remaining terms of C6.21 are then evaluated in EORCS. Once the contributions of the last level have been included, the contributions from the "cross-terms" between the levels in $R_L(a, a)$ are calculated in subroutine EXTRA. Note that the major change needed for doing other reactions, such as $^{12}\text{C}(d, d)^{12}\text{C}$, is to change the part of the program which determines $L_K$ and $L_J$ since these are determined for the particular case of alpha particles on $^9\text{Be}$.

We now investigate the quantities calculated in EORCS associated with $R_L(a, a)$:

**BETA:** BETA is $\beta$ and is defined as

$$\beta = \tan^{-1} \left( \frac{E-E_0}{\Gamma/2} \right).$$

**ERCM:** This variable is the resonance energy in ergs in the center of mass.

**FRCM:** When two levels have the same spin and parity, FRCM is the center of mass resonance energy in ergs for one level, ERCM the resonance energy for the other.
TABLE 8

The entrance channel \( \ell \)'s are tabulated for alpha particles (0\(^+\)) on \(^9\text{Be}(3/2)^-\). The reactions studied are \(^9\text{Be}(\alpha, n_0), \(^9\text{Be}(\alpha, n_1)\) and \(^9\text{Be}(\alpha, n_2)\). The \( n_0 \) and \( n_2 \) reactions go to 0\(^+\) states of \(^{12}\text{C}\). The \( n_1 \) reaction goes to a 2\(^+\) state. The \( S' \) and \( \ell' \) refer to the exit channel and are also tabulated.

<table>
<thead>
<tr>
<th>( J^\pi ) (compound nucleus)</th>
<th>( S )</th>
<th>( \ell )</th>
<th>( S' )</th>
<th>( \ell' )</th>
<th>( S' )</th>
<th>( \ell' )</th>
<th>( S' )</th>
<th>( \ell' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2(^-)</td>
<td>3/2</td>
<td>2</td>
<td>1/2</td>
<td>1</td>
<td>3/2</td>
<td>1</td>
<td>5/2</td>
<td>3</td>
</tr>
<tr>
<td>1/2(^+)</td>
<td>3/2</td>
<td>1</td>
<td>1/2</td>
<td>0</td>
<td>3/2</td>
<td>2</td>
<td>5/2</td>
<td>2</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>3/2</td>
<td>0,2</td>
<td>1/2</td>
<td>1</td>
<td>3/2</td>
<td>1,3</td>
<td>5/2</td>
<td>1,3</td>
</tr>
<tr>
<td>3/2(^+)</td>
<td>3/2</td>
<td>1,3</td>
<td>1/2</td>
<td>2</td>
<td>3/2</td>
<td>0,2</td>
<td>5/2</td>
<td>2,4</td>
</tr>
<tr>
<td>5/2(^-)</td>
<td>3/2</td>
<td>2,4</td>
<td>1/2</td>
<td>3</td>
<td>3/2</td>
<td>1,3</td>
<td>5/2</td>
<td>1,3,5</td>
</tr>
<tr>
<td>5/2(^+)</td>
<td>3/2</td>
<td>1,3</td>
<td>1/2</td>
<td>2</td>
<td>3/2</td>
<td>2,4</td>
<td>5/2</td>
<td>0,2,4</td>
</tr>
<tr>
<td>7/2(^-)</td>
<td>3/2</td>
<td>2,4</td>
<td>1/2</td>
<td>3</td>
<td>3/2</td>
<td>3,5</td>
<td>5/2</td>
<td>1,3,5</td>
</tr>
<tr>
<td>7/2(^+)</td>
<td>3/2</td>
<td>3,5</td>
<td>1/2</td>
<td>4</td>
<td>3/2</td>
<td>2,4</td>
<td>5/2</td>
<td>2,4,6</td>
</tr>
<tr>
<td>9/2(^-)</td>
<td>3/2</td>
<td>4,6</td>
<td>1/2</td>
<td>5</td>
<td>3/2</td>
<td>3,5</td>
<td>5/2</td>
<td>3,5,7</td>
</tr>
<tr>
<td>9/2(^+)</td>
<td>3/2</td>
<td>3,5</td>
<td>1/2</td>
<td>4</td>
<td>3/2</td>
<td>4,6</td>
<td>5/2</td>
<td>2,4,6</td>
</tr>
</tbody>
</table>
GAM1: GAM1 is the partial width for $\ell_1$ of the incoming channel. i.e.,

$$\text{GAM1} = \Gamma_{\alpha S \ell_1}, \quad \text{where } \ell_1 = LK-1.$$ 

GAM2: GAM2 is the partial width for $\ell_2$ of the incoming channel, i.e., $\text{GAM2} = \Gamma_{\alpha S \ell_2}$, where $\ell_2 = LJ-1$.

Note that in the elastic scattering of alpha particles, there is no spin flip so we have $\Gamma_{\alpha S \ell_1} = \Gamma_{\alpha \ell_1}$, etc.

GRCM: GRCM is the center of mass resonance width divided by two (in units of ergs).

HRCM: When three levels have the same spin and parity,

HRCM is the center of mass resonance energy, (in units of ergs) for the third level.

JO: For purposes of computation, we define $JO = 2J$.

LMAX: In Appendix C, Section 4, the selection rules for non-vanishing $Z$ coefficients were tabulated. For the case of elastic scattering by alpha particles, we have for the "self-terms" that

$$LMAX \leq 2\ell_{\text{max}},$$

$$LMAX \leq 2\ell'_{\text{max}},$$

and

$$LMAX \leq 2J.$$

LMAX is the smallest of these conditions. The last condition has been used in the program since if one of
the other two conditions actually gave a smaller LMAX, 
the subroutine which calculates the $\tilde{Z}$'s will give zero 
anyway for $L$ larger than this LMAX. Since for the 
"self-term" only even $L$ are allowed we define 
LMAX as

$$LMAX = \frac{(2J-1)}{2} + 1$$

where the sum over $L$ now extends from one to LMAX and we are actually summing over $2L$.

PCON1: When one does a two or three level calculation one 
needs a value for the variable $\Gamma_{\lambda\mu} = \sum_c g_c^{(\lambda)} g_c^{(\mu)}$ where 
c stands for a sum over all channels $\alpha$, a sum over all 
s, and a sum over all $t$. We know that $\Gamma = \sum_c \Gamma_c$ and 
$g_c = \pm \sqrt{\Gamma_c}$. To estimate the magnitude of $\sum_c \Gamma_c$ for 
channels other than the elastic scattering channels 
we define $PCON1 = \Gamma - \Gamma_{\alpha \lambda_1} - \Gamma_{\alpha \lambda_2}$, where the $\alpha$ refers 
to the elastic scattering channel. We will then use the 
approximation that $g_c$ is equal to $\sqrt{PCON1}$ for $c$ 
not equal to the elastic scattering channel. The 
value of $\Gamma_{\lambda\mu}$ found this way is exact only if the total 
width is entirely due to elastic scattering. However, 
without more information about the other channels, this
seems to be the most reasonable first order approximation to use.

PCON2: This variable is the same as PCON1 except it is evaluated with total width and partial widths for elastic scattering for the second level of the same spin and parity.

PCON3: See PCON1. This variable is evaluated for the third level of the same spin and parity.

PRCM: PCRM is the center of mass resonance width divided by two (in units of ergs) for the first level of two levels of the same spin and parity.

PW1: In a two level calculation, PW1 is the reduced width for $I = \frac{LJ-1}{LJ-1}$ for the first level. i.e., $PW1 = \sqrt{2LJ-1}$.

PW2: In a two level calculation, PW2 is the reduced width for $I = LK-1$ for the first level.

QRCM: In a three level calculation, QRCM is the center of mass width divided by two (in units of ergs) for the third level.

QW1: In a three level calculation QW1 is the reduced width for $I = LK-1$, for the third level.

QW2: In a three level calculation QW2 is the reduced width for $I = LJ-1$, for the third level.
RES: This variable is defined as

\[ \text{RES} = \frac{1}{\sqrt{(E-E\phi)^2 + \frac{\Gamma^2}{4}}} \]

ZZ(L, 2, 2): This variable stores the values of the \( \bar{Z} \) coefficients for the "self-terms" in \( R_L (\alpha, \alpha) \) for the case of elastic scattering. i.e.,

\[ ZZ(L, 1, 2) = \bar{Z} (t_1 J_n, t_2 J_n, SL') \], where

\[ t_1 = LK-1, \]
\[ t_2 = LJ-1, \]

and \( L' = 2L-2 \).

We next define other variables associated with the remaining terms in equation C6.21.

ANG1 = \( 2\eta \ln \sin \theta/2 + 2\psi_{t_1} + 2\phi_{t_2} + \beta \), where \( t_1 = LK-1 \).

ANG2 = \( 2\eta \ln \sin \theta/2 + 2\psi_{t_2} + 2\phi_{t_2} + \beta \), where \( t_2 = LJ-1 \).

ANGG = \( 2\eta \ln \sin \theta/2 + 2\psi_{L-1} + \phi_{L-1} \).

ANM = \(-2\psi_{L'} -1 + \phi_{L'} -1\).

AN1 = \( \beta + 2\psi_{t_1} + 2\phi_{t_1} \), where \( t_1 = LK-1 \).

AN2 = \( \beta + 2\psi_{t_2} + 2\phi_{t_2} \), where \( t_2 = LJ-1 \).

ANZ = \(-2\psi_{L-1} + \phi_{L-1} \).
COMP1(I, K, KOOL): This variable stores the contributions to
the cross section associated with the level specified
by KOOL.

\[
\text{CONST} = \frac{\pi (2J+1) \cosec^2 \theta / 2}{4 \sqrt{(E-E_0)^2 + (L_1^2/2)^3}}.
\]

\[
\text{CS} = \cos (\phi_{l_1} + \phi_{l_2} - \phi_{l_3} - \phi_{l_4}), \text{ where } l_1 = LK-1, \text{ and } l_2 = LJ-1.
\]

FETA: In a two or three level calculation FETA is \(\beta_1\).

\[
\text{GAM12} = \Gamma_{12} \text{ (in units of ergs)}.
\]

\[
\text{GAM13} = \Gamma_{13} \text{ (in units of ergs)}.
\]

\[
\text{GAM23} = \Gamma_{23} \text{ (in units of ergs)}.
\]

\[
\text{CTERM} = z^2 \cosec^4 (\theta/2). \text{ (Rutherford scattering).}
\]

PEW1: In a two level calculation, \(\text{PEW1} = \Gamma_{0S_{l_1}} \text{ for level one.}\)

PEW2: In a two level calculation, \(\text{PEW2} = \Gamma_{0S_{l_2}} \text{ for level one.}\)

PUMP: This variable is calculated in subroutine EXTRA, and
is the contributions of the cross terms between levels.

PUMP1(KAGE): This variable stores the cross terms between
the level specified by KAGE and all other levels in the
calculation.

QETA: In a three level calculation, QETA is \(\beta_3\).

QES: In a three level calculation, \(\text{QES} = \frac{(E-E_0)^2 + (L_1^2/2)^3}{(E-E_0)^2 + (L_1^2/2)^3}^{-1/3},\)

for level three.

QEWF: In a three level calculation, \(\text{QEWF} = \Gamma_{0S_{l_1}} \text{ for level three.}\)
QEW2: In a three level calculation, \( QEW2 = \Gamma_{\alpha S\ell_2} \) for level three.

\[
\text{RES13} = \frac{1}{|\epsilon_1| |\epsilon_3|} \quad \text{where} \quad |\epsilon_i| = \left[ (E - E_i)^2 + \left( \frac{\Gamma_i}{2} \right)^2 \right]^{-1/2}.
\]

RSUM1: This variable stores the value of the "self-term" for elastic scattering and is calculated in subroutine RSUM.

RSUM3: This variable stores the extra terms for two and three level calculations associated with \( R_L(\alpha, \alpha) \). The value is calculated in subroutine RSUM.

\[
\text{SUFIN} = \chi^2 \sum \sum \sum_{L \ell \ell'} \frac{(2\ell+1)(2\ell'+1)}{(l \ell' 00 | L0)} l^{2} \sin \phi_{\ell} \cos (2\psi_{\ell} + \phi_{\ell} - 2\psi_{\ell'} - \phi_{\ell'}) \times P_L(\cos \theta).
\]

SUMAD: In a three level calculation, this variable stores the values of the terms in equations C8.26 and C8.28. (i.e. the interference terms between resonance scattering and Coulomb scattering.)

\[
\text{SUMFN} = -2\chi z \sum_{\ell=0}^{\infty} (2\ell+1) \sin \phi_{\ell} \cos (2\eta \ln \sin \theta/2 + 2\psi_{\ell} + \phi_{\ell}) \cos^2(\theta/2) P_L(\cos \theta).
\]
\[
SUMIF = \frac{2z(2J+1)}{(2i+1)(2i+1)} \sum_{l}^{J_{0}+l+1} \frac{\Gamma_{\alpha l} I_{\text{min}}}{[(E-E_{0})^{2}+(\frac{l}{2})^{2}]^{1/2}} \cosec^{2}\theta/2 \times \\
\sin(2\pi ln \sin \theta/2 + 2\psi_{\alpha} + 2\phi_{\alpha} + \beta) P_{\alpha l}(\cos \theta).
\]

SUMI1: This variable stores the value of equation C8.24 for a three level calculation.

SUMI2: This variable stores the value of equation C8.26 for a three level calculation.

SUMI3: This variable stores the value of the terms in equation C8.28 for a three level calculation.

SURFN =

\[
\frac{x^{2}(2J+1)}{(2I+1)(2I+1)} \sum_{L} \sum_{l}^{(2I+1)} \left[(\Omega_{c}\Omega_{l})^{2}\sin^{2} \phi_{l} \Gamma_{\alpha l} \right] x
\]

\[
\frac{1}{[(E-E_{0})^{2}+(\frac{l}{2})^{2}]^{1/2}} \sin(2\psi_{\alpha} + 2\phi_{\alpha} + \beta) P_{\alpha l}(\cos \theta)
\]

SURF1: This variable stores the value of the expression in equation C8.23 for a two or three level calculation.

SURF2: This variable stores the value of the expression in equation C8.25 for a three level calculation.

SURF3: This variable stores the value of the expression in equation C8.27 for a three level calculation.
SW = \sin \phi_{L'-1}.
SX = \sin \phi_{L'-1}.
SY = \sin \phi_{L'-1}.

TES: In a two or three level calculation, TES is \(|e_1|\).

(See QES).

WO = \frac{-k^2(2J+1)}{4 \left[ \left( E-E_0 \right)^2 + \frac{\sigma^2}{4} \right]^{1/2}} \text{ where I and i have been set}
equal to 3/2 and 0 respectively.

WW = 2\lambda z \csc^2(\theta/2).

We now list internally generated control variables.

I3: When I3 is zero "three-level" terms are not calculated,
when it is one, they are.

ISTED: Used in setting up levels for the search routine. When
ISTED is equal to one, no two or three level terms are
calculated in EORCS.

JJ: When JJ has the value zero terms which do not depend
on angle are calculated, but when the program is
calculating an angular distribution JJ is set equal to
one at various times to skip terms which are in-
dependent of angle.

LPEX: This variable has several values and is used to
calculate SURF1, SURF2, and SURF3 in a "three-
level" calculation.
LES: When this variable is zero no "two-level" terms are calculated, when it is one "two or three-level" terms may be included.

MJOK: When MJOK is equal to one, the potential scattering terms are included in the cross section, when MJOK is equal to two they are not.

MULE: When the program is ready to go into the search routine, MULE is set differently from zero, so that only terms associated with the level to be searched on are calculated.
2. RSUM

In this subroutine the "self-terms" of $R_L(\alpha, \alpha)$ are calculated for the case elastic scattering and if a two or three level calculation is to be done the extra terms associated with $R_L(\alpha, \alpha)$ are included.

In Appendix C, Section 5 we found that

$$R_L(\alpha S, \alpha S) = \frac{1}{4} \sum_{n} \sum_{m} \sum_{J} \sum_{J'} \frac{Z^2}{1} \sum_{J} \sum_{J'} \sum_{L} \sum_{L'} \frac{Z(1, J, J', S L) Z(I', J', J, S L)}{1} \sum_{n} \sum_{m} \sum_{J} \sum_{J'} \sum_{L} \sum_{L'}$$

with

$$J_n, J_m, J_l, J_l'$$

$$\cos(\xi_n - \xi_m) \cos(\xi_n' - \xi_m') \cos(\xi_n - \xi_m') \cos(\xi_n' - \xi_m)$$

We found in Appendix C, Section 4 that if we define the quantities $A, B, C, \text{and} D$ in equation C4.12 we may write $R_L(\alpha S, \alpha S)$ as,

$$R_L(\alpha S, \alpha S) = \frac{1}{4} \sum_{n} \sum_{m} \frac{\cos(\beta_n - \beta_m)}{|\epsilon_n| |\epsilon_m|} \left\{ AC - BD \right\} - \frac{\sum_{n} \sum_{m} (\beta_n - \beta_m)}{|\epsilon_n| |\epsilon_m|} \left\{ BC + AD \right\}$$

In the case of elastic scattering of alpha particles by $^9\text{Be}$ there is no spin-flip and $S = S' = 3/2$, so that $R_L(\alpha, \alpha) = R_L(\alpha S, \alpha S)$.

We now break up the sums over $J_n, J_m$ as follows

$$\sum_{n} \sum_{m} \sum_{J} \sum_{J'} \sum_{L} \sum_{L'} \frac{Z(1, J, J', S L) Z(I', J', J, S L)}{1} \sum_{n} \sum_{m} \sum_{J} \sum_{J'} \sum_{L} \sum_{L'}$$

with

$$J_n, J_m, J_l, J_l'$$

$$\cos(\xi_n - \xi_m) \cos(\xi_n' - \xi_m') \cos(\xi_n - \xi_m') \cos(\xi_n' - \xi_m)$$

We have been designating the terms of the first sum the "self-terms" and the terms of the second sums as the cross terms. For the "self-terms" we can easily see from equation C4.12 that for the case
of elastic scattering that $A$ is equal to $C$ and $B$ and $D$ are equal to zero. Thus we have for the "self-terms" that

$$R_L(a, \alpha) = \frac{A^2}{4|\epsilon_n|^2}.$$ D2.2

We now define the variables used in RSUM.

**AAA:** This variable is equal to $A$ given in equation C7.20 or C8.1.

**AIAA:** This variable is equal to $I$ given in equation C8.1.

**BAA:** This variable is equal to $B$ given in equation C7.20 or C8.1.

**CAA1:** This variable is equal to $C$ given in equation C7.20 or C8.1.

**DAA1(L):** This variable is equal to $D$ given in equation C7.20 or C8.1 when the two g's have opposite sign.

**DAA2(L):** This variable is equal to $D$ given in equation C7.20 or C8.1 when the two g's have the same sign.

**EAA1:** This variable is equal to $E$ given in equation C8.1.

**FAA:** This variable is equal to $F$ given in equation C8.1.

**GAA:** This variable is equal to $G$ given in equation C8.1.

**HAA:** This variable is equal to $H$ given in equation C8.1.

**QBC1:** This variable is equal to the expression in equation C8.12.
QFG1: This variable is equal to the expression in equation C8.14.

QHJ1: This variable is equal to the expression in equation C8.15.

QKK: This variable is equal to the expression in equation C8.16.

PBC1: This variable is equal to the expression in equation C8.7.

PFG1: This variable is equal to the expression in equation C8.9.

PHJ1: This variable is equal to the expression in equation C8.10.

PKK: This variable is equal to the expression in equation C8.11.

RAA1(L): The variable stores the value of the expression in D2.2 when the two g's have opposite signs.

RAA2(L): The variable stores the value of the expression in D2.2 when the two g's have the same signs.

RBB1(L): This variable stores the two or three level terms for a given L.

RBC1: This variable stores the value of the expression in equation C8.2.

RFG1: This variable stores the value of the expression in equation C8.4.
RHJ1: This variable stores the value of the expression in equation C8.5.

RKK: The variable is equal to the expression in equation C8.6.

RQQ1: The variable stores the sum of three level terms different from the two-level terms.

RSUM1: The contribution to the cross section for the "self-term" is stored in this variable.

RSUM3: The contribution to the cross section for the two or three level" terms are stored in this variable.

THJ1: The variable is equal to the expression in equation C8.17.

THJ2: The variable is equal to the expression in equation C8.18.

THJ3: The variable is equal to the expression in equation C8.19.

TMM1: The variable is equal to the expression in equation C8.20.

TQQ1: The variable is equal to the expression in equation C8.21.

TSS1: The variable is equal to the expression in equation C8.22.
3. ZBARM

This subroutine calculates $\Xi$ coefficients for the cross-terms either for elastic scattering or one of the following reactions, $^9$Be($\alpha$,n$_1$), $^9$Be($\alpha$,n$_2$), $^9$Be($\alpha$,n$_3$), or $^{24}$Mg(p,p$_1$). The one variable necessary to define is

$$ \Xi_{ZZZZ}(L,1,2,\text{IEXTR},\text{MOPE}) = \Xi(L',t_1,t_2,J_2,SL'), $$

where $L'$ is $L-1$, one specifies $t_1$, two specifies $t_2$, IEXTR specifies $J_1$, JEXTR specifies $J_2$ and MOPE specifies $S$. 
4. EXTRA

In this subroutine the "cross-terms" (See equation D2.1) are calculated either for elastic scattering or for one of several reactions. As was mentioned earlier, these terms are evaluated only when the contributions of the last level to be included in the calculation are also being evaluated. The subroutine also has another purpose. For a reaction cross section the signs of the "cross-terms" depend upon the signs of the g's involved. When the option is chosen, the subroutine calculates the "cross-terms" with all possible signs of the g's. The resulting cross sections are then calculated in the subroutine FUGS and the results plotted on the line printer. A more detailed discussion of the option is postponed until the discussion of subroutines FUGS and PLOT.

Variables Calculated in EXTRA

CODE(L, 16, 1): This variable is used when the $^9\text{Be}(\alpha, n_1)$ or $^{24}\text{Mg}(p, p_1)$ reactions are being studied. Appropriate modifications for doing other reactions are discussed later. In these reactions spin flip is possible and there is more than one exit channel spin. The value one specifies that the variable is equal to one of sixteen possible values of C defined in equation C4.12 for
s' equal to 5/2, when all possible signs of the g's are considered.

CODE(L, 16, 2): This variable is equal to one of the possible values of D defined in equation C4.12 for s' equal to 5/2.

CORE(L, 8, 1, INDEX): This variable is used to store one of eight possible values of A defined in equation C4.12 when all possible signs of the g's are considered. The variable INDEX specifies which "cross term" it is (i.e., between level one and three, etc.).

CORE(L, 8, 2, INDEX): The value of the third variable, two, specifies that this variable is equal to one of the possible values of B defined in equation C4.12.

CORE (L, 8, 3, INDEX): The three specifies that the variable is equal to one of the possible values of C defined in equation C4.12.

CORE (L, 8, 4, INDEX): The four specifies that the variable is equal to one of the possible values of D defined in equation C4.12.

FI (INDEX, 2): The variable is used to store the value of \( \cos(\beta_i - \beta_j) \) or \( \sin(\beta_i - \beta_j) \) depending on the second index.
INDEX: The variable specifies which "cross-terms". For the value one it is the $X_{12}$ term, for two it is the $X_{13}$ term and for three it is the $X_{23}$ term.

WAA: The variable is equal to the expression A given in equation C4.12 for $s$ equal to 3/2.

WBB: The variable is equal to the expression B given in equation C4.12 for $s$ equal to 3/2.

WCC: The variable is equal to the expression C given in equation C4.12 for $s'$ equal to 1/2 or 3/2.

WCCP: The same as WCC except $s'$ equal to 5/2.

WDD: The variable is equal to the expression D given in equation C4.12 for $s'$ equal to 1/2 or 3/2.

WDDP: The same as WDD except $s'$ equal to 5/2.

WETZ (JZTO, IEXTR, JEXTR): The variable is equal to the expression given in C4.13. The variable JZTO specifies $L$, IEXTR specifies $J_1$ and JEXTR specifies $J_2$. 
5. FUNK

Once the cross section is calculated in EORCS, the user may choose to do a search on the level parameters of each level so as to obtain a "best-fit." The search routine used is a general search routine called STEPIT. In the application used here, the input parameters to STEPIT are the level parameters. The purpose of STEPIT is to minimize CHISQ by varying the input parameters. "STEPIT works by using a complex variation of a direct search method for finding local minimums on a hypersurface." For a complete description of STEPIT see reference 9. Once STEPIT has changed the level parameters, it is the purpose of FUNK to recalculate the cross section and to calculate CHISQ. The value of CHISQ is returned to STEPIT and is used as an indication of how well the search is going.

In EORCS the search has been set up so that up to five excitation curves or five angular distributions may be fit simultaneously. However, the level parameters of only one level are varied at one time, though the level parameters of up to four levels may be searched on consecutively. For each level four spin and parities may be tried and the program uses that spin and parity which gives the smallest CHISQ. The level parameters which are searched on are the reduced widths and the total width, it being assumed that the
position of each level is known. As an aid to anyone using the program, the following description of the variables set by the user, from the 360 STEPIT, A USER'S MANUAL, (9) is provided:

ACK: The ratio by which the step-size is increased, usually after a successful step. A good value to choose is 2.0. If your hypersurface is relatively free of valleys and ridges, a larger ACK may speed convergence to a solution. Remember, when you change ACK, you must change RATIO accordingly.*

COLIN: COLIN is the criterion for colinearity of two directions of the search. It is independent of NV. COLIN must lie between one and zero. The probability that two randomly chosen directions could satisfy this criterion is 1/2(1-COLIN). COLIN is used to determine COMPAR. If your X(I)s are not orthogonal, set COLIN low. If they are approximately orthogonal, set COLIN near one.*

DELMIN(I): DELMIN(I) should be set to reflect the expected error in the corresponding X(I). DELMIN(I) is the smallest step-size allowed for the corresponding X(I), and thus should be about three orders of magnitude smaller than the expected error. You may set DELMIN to zero. The program will probably then be terminated by MAXR. Setting DELMIN smaller than the truncation error will result in unneeded running time.

DELTAX(I): DELTAX should be set to reflect your confidence in your estimate of X(I). The smaller your confidence is, the larger
the DELTAX should be. A good value is between X(I)/10 and X(I)/100. DELTAX is made the starting step-size.

**KW**: KW is the logical I/O unit. Usual output is on the on-line printer. For this, KW should be set to 3.

**MASK(I)**: If you want a particular X(I) held constant during a run, set its mask not equal to zero; otherwise, be sure to set it to zero.

**MATRIX**: If MATRIX is non-zero and all MASK(I)s are zero, the error matrix will be calculated. If you want the error matrix calculated, set MATRIX between 100 and 110. MATRIX is returned zero if the error matrix is singular and negative if a diagonal element of the error matrix is negative. Be sure to reset MATRIX before every entry into STEPIT. (If \(X^2\) is not a quadratic function of X's, MATRIX should probably be set to zero.) If you do not know how to use the error matrix, set MATRIX to zero.

**MAXR**: MAXR should be set to maximum number of output records allowed by the computer center minus the number you have used in your calling program. The purpose of MAXR is to terminate the search before it is interrupted by the computer.

**MOSQUE**: MOSQUE should be set to the number of steps you wish to save during pattern search. The maximum is fifteen. (If you have more than twenty variables, STEPIT has to be recompiled and MOSQUE means a quicker, faster
convergence unless the surface is irregular. The more irregular the surface is, the smaller MOSQUE should be.

**NTRACE:** If trace of search is desired, set NTRACE not equal to zero. *

**NV:** Set NV to the number of X(I)s for which you are searching. The maximum is twenty. If you need more than twenty, STEPIT will have to be recompiled. MOSQUE should then be set to two and MATRIX to zero.

**RATIO:** RATIO is the ratio by which the step-size is decreased after a minimum has been found. If ACK is increased, RATIO should be increased. A good value is 10.0. *

**X(I):** The X(I)s are the values that STEPIT adjusts to minimize the output of FUNK which is called CHISQ. Set X(I)s to your best estimate. X(1) should be the one that affects the output of FUNK the most, etc. To confirm that the minimum that STEPIT finds is the best local minimum, start your X(I)s at different values and start the search again. *

**XMAX(I):** XMAX is the higher constraint on X(I). It should be set to exclude only the regions where the function (FUNK) becomes undefined. It is not to be used to exclude unreasonable values of X(I). *

**XMIN(I):** XMIN is the lower constraint on X(I). The same rules apply to XMIN as to XMAX. If XMIN(I) = XMAX(I), then XMAX(I) is set to HUGE and XMIN(I) to -HUGE. *
If you are unsure of how to set these variables, set them to zero. STEPIT will then set them to standard values when you call STEPIT. Remember, all the variables in PART A have to appear in the standard COMMON statement and must be given some value in your calling program.

In addition we define clearly what the X(I)'s are in our application:

\[
\begin{align*}
X(1) &= \gamma^2_{LJ-1} \quad \text{in MeV in the center of mass.} \\
X(2) &= \Gamma \quad \text{in MeV in the laboratory system.} \\
X(3) &= \gamma^2_{LJ-1} \quad \text{in MeV in the center of mass.} \\
X(4) &= \gamma^2_{\alpha' S' \ell_1} \quad \text{(in MeV in the center of mass.)} \\
X(5) &= \gamma^2_{\alpha' S' \ell_2} \quad \text{(in MeV in the center of mass.)} \\
X(6) &= \gamma^2_{\alpha'' S'' \ell_1} \quad \text{(in MeV in the center of mass.)} \\
X(7) &= \gamma^2_{\alpha'' S'' \ell_2} \quad \text{(in MeV in the center of mass.)} \\
X(8) &= \gamma^2_{\alpha'' S'' \ell_3} \quad \text{(in MeV in the center of mass.)}
\end{align*}
\]
6. LDETM

The reaction cross section given in equation C4.4 is calculated in the following subroutines: LDETM, SETOW, ZBARM, EXTRA and REACS. The subroutines ZBARM and EXTRA have been discussed earlier. The program has been specialized to calculate the reaction cross section for the following reactions, \(^9\)Be\((\alpha, n)_0\)\(^{12}\)C, \(^9\)Be\((\alpha, n)_1\)\(^{12}\)C\(^*\), and \(^9\)Be\((\alpha, n)_2\)\(^{12}\)C\(^*\). Modifications necessary to do other reactions such as \(^{24}\)Mg\((p, p)_1\)\(^{24}\)Mg\(^*\) are discussed in Section 12.

The \(n_0\) and \(n_2\) reactions go to \(0^+\) state of \(^{12}\)C. The \(n_1\) and \(p_1\) reactions go to \(2^+\) states of \(^{12}\)C and \(^{24}\)Mg respectively. The \(n_0\) and \(n_2\) reactions are specified by setting the variable IFINS equal to zero, the remaining two reactions by setting IFINS equal to two. The exit channel spins and the outgoing \(l\)-values for these reactions are tabulated in Table 8 Section 1 of Appendix D. It is the purpose of LDETM to select the outgoing \(l\)-values possible to form a state of the compound nucleus with spin \(J\) and parity \(\pi\). Let us call the smallest \(l\)-value that is possible to form the state \(J^\pi\), \(l_{\text{min}}\). For \(s'\) equal to either 1/2 or 3/2, \(l_{\text{min}}\) is set equal to JG1LK-1, for \(s'\) equal to 5/2, \(l_{\text{min}}\) is set equal to JG2LK-1. It is also the purpose of LDETM to calculate \(\bar{Z}\) coefficients for the "self-terms" and the values are stored in the variable ZZZZ, i.e.,
\[
\mathbb{Z} (L', 1, 2, 1) = \mathbb{Z} (\ell_1, \ell_2, \ell_3, s', L')
\]

where \( L' = 2L - 2 \), and the values of the second and third indices specify \( \ell_1 \) and \( \ell_2 \) respectively and the last index specifies the value of \( s' \).
7. SETOW

Once \( \ell_{\text{min}} \) has been determined in LDETM, it is the purpose of SETOW to estimate the reduced widths of the outgoing channels. For purpose of the search routine, SETOW also sets up XMAX(I), XMIN(I), DELMIN(I), DELTAX(I), and MASK(I), for I equal to four to eight. (See Section 5). If the partial widths of the exit channels for a given level have been initially set equal to zero by the user, the program estimates the reduced widths by setting them equal to each other and letting the sum of the outgoing partial widths equal to fifty percent of the total width. Also the variables OEW1, and OEW2 are reset from their original values to the values of the reduced widths.

VARIABLES IN SETOW

- \( \text{OEW1}(\text{MJE}, 1) = \gamma^2 JG1LK-1 \) in units of ergs in the center of mass), where MJE specifies the level and \( s' \) equals 1/2 or 3/2.

- \( \text{OEW1}(\text{MJE}, 2) = \gamma^2 JG2LJ-1 \) (in units of ergs in the center of mass), where MJE specifies the level, JG1LJ-1 equal to \( \ell_{\text{min}} \) plus two, and \( s' \) equals 1/2 or 3/2.

- \( \text{OEW2}(\text{MJE}, 1) = \gamma^2 JG2LK-1 \) (in units of ergs in the center of mass), where MJE specifies the level and \( s' \) is equal to 5/2.
$OEW_2(MJE, 2) = \gamma_{JG2LJ-1}$, (in units of ergs in the center of mass), where MJE specifies the level and $s'$ is equal to $5/2$.

$OEW_2(MJE, 3) = \gamma_{JG2LM-1}$, (in units of ergs in the center of mass), where MJE specifies the level, $JG2LM-1$ equals $\lambda_{\text{min}}$ plus four, and $s'$ equals $5/2$.

$OW_1(JG1LJ) = \gamma_{JG1LJ-1}$, (ergs), $s' = 1/2$ or $3/2$.

$OW_1(JG1LK) = \gamma_{JG1LK-1}$, (ergs), $s' = 1/2$ or $3/2$.

$OW_2(JG2LJ) = \gamma_{JG2LJ-1}$, (ergs), $s' = 5/2$.

$OW_2(JG2LK) = \gamma_{JG2LK-1}$, (ergs), $s' = 5/2$.

$OW_2(JG2LM) = \gamma_{JG2LM-1}$, (ergs), $s' = 5/2$. 
8. REACS

The "self-terms" for the reactions cross section (eq. C4.14) are evaluated in subroutine REACS. The cross section is given by equation C4.5, and is stored in the variable RSUM1. Let us investigate the expression for the cross section in more detail.

\[
\frac{d\sigma_{\alpha'\alpha}}{d\Omega} = \frac{\kappa^2}{(2I+1)(2i+1)} \sum_{s'} \sum_{L} B_L(\alpha's',\alpha s) P_L(\cos \theta) \quad \text{D8.1}
\]

where \(B_L(\alpha's',\alpha s)\) is given by equation C4.4.

For the reactions we have selected to study, \(s\) has only one value, so we are left with a sum over \(s'\) in equation D8.1. For the \(^{9}\text{Be}(\alpha,n_0)\) and \(^{9}\text{Be}(\alpha,n_2)\) reactions, \(s'\) has only one value and is equal to 1/2. For these reactions then we are left only with a sum over \(L\) in equation D8.1. However, for the \(^{9}\text{Be}(\alpha,n_1)\) and \(^{24}\text{Mg}(p,p_1)\) reactions, \(s'\) may have either the value of 3/2 or 5/2. In these cases we must sum over \(s'\). In the program the contribution for \(s'\) equal to 3/2 is stored in RSUM1 and the contribution for \(s'\) equal to 5/2 is stored in RSUM3 and before the subroutine returns, the two are added together. Note, however, that the overall sign is correct only for the \(^{9}\text{Be}(\alpha,n)\) reactions and the final result should be multiplied by minus one for the \(^{24}\text{Mg}(p,p_1)\) reaction. In subroutine EXTRA the "cross-terms" were evaluated. For the case
of more than one exit channel spin, the contributions were handled in a slightly different fashion than in REACS. We were able to write the "cross-terms" as

$$B_L(\alpha^\prime \beta^\prime, \alpha \beta) = \frac{(-)^{s_1 s_2}}{J_1 J_2} \sum_{i,j} \frac{\cos(\beta^\prime_i - \beta_i)}{|E_i| |E_j|} \left[ \frac{A - B D}{E_i} \right] - \frac{\sin(\beta^\prime_i - \beta_i)}{|E_i| |E_j|} \left[ \frac{B + A D}{E_i} \right]$$

where $$A$$, $$B$$, $$C$$, and $$D$$ are defined in equation C4.12.

If we let $$C$$ and $$D$$ be the contributions for $$s'$$ equal to 3/2 and define similar quantities $$C'$$ and $$D'$$ with $$s'$$ equal to 5/2 and perform the sum over $$s'$$, we have for the special case of $$s$$ equal to 3/2 that:

$$\frac{d\sigma_{\alpha^\prime \alpha}}{d \Omega} = \frac{1}{16} \sum_{J_1 J_2} \frac{\cos(\beta^\prime_i - \beta_i)}{|E_i| |E_j|} \left[ \frac{A(C - C') - B(D - D')}{E_i} \right] - \frac{\sin(\beta^\prime_i - \beta_i)}{|E_i| |E_j|} \left[ \frac{B + A D'}{E_i} \right] \cdot D8.2$$

$$\left\{ (B(C - C') + A(D - D')) \right\} P_L(\cos \Theta)$$,

where $$J_1 \neq J_2$$.

The "cross-terms" for the case of more than one exit channel spin were evaluated in EXTRA using the expression D8.2. The subroutine REACS also stores values of $$A$$, $$C$$ and $$C'$$ for the "self-terms" for each level, for the option where the cross section is calculated with all possible signs of the g's.
VARIABLES IN REACS

\[ \text{COMP}_1(L, MJE, 1) = \frac{A}{4 |\epsilon_{\text{MJE}}|^{3}} \text{A}, \text{ for } s = 3/2, \text{ where } A \]

is defined in expression C.12 and MJE specifies the level. For the cases we are considering there
are two possible values for A depending on the sign of the g's. When the last index is equal to one, the
g's have opposite signs; when the last index is equal to two, they have the same sign.

\[ \text{COMP}_1(L, MJE, 3) = C, \text{ for } s' = 1/2 \text{ or } 3/2. \text{ C is defined in expression C.12 and MJE specifies the level.} \]

For the last index equal to three the g's have opposite signs and when the last index is equal to
four they have the same sign.

\[ \text{COMP}_2(L, MJE, 4) = C, \text{ for } s' = 5/2, \text{ where MJE specifies one of four possible values C may have when all} \]

possible signs of the g's are considered.

\[ \text{DAA}_1(L) = A, \text{ for } s = 3/2, \text{ and the signs of the g's are opposite.} \]

\[ \text{DAA}_2(L) = A, \text{ for } s = 3/2, \text{ and the g's have the same signs.} \]

\[ \text{RAA}_1(L) = C, \text{ for } s' = 1/2 \text{ or } 3/2, \text{ and the g's have opposite signs.} \]

\[ \text{RAA}_2(L) = C, \text{ for } s' = 1/2 \text{ or } 3/2, \text{ and the g's have the same signs.} \]
\[ \text{RBB1}(L) = C, \text{ for } s' = 5/2. \]

\textbf{RSUM1:} This variable stores the contributions to the cross section for the "self-term" for \( s' \) equal to 1/2 or 3/2.

\textbf{RSUM3:} This variable stores the contribution to the cross section for the "self-term" for \( s' \) equal to 5/2.
9. FUGS

The signs of the "cross-terms" in the reaction cross section depend upon the signs of the g's involved. Unless one has some knowledge of the signs, calculations become rather tedious for not only must one determine the J\(^\pi\) of each level, but also the signs of the g's. It is the purpose of this subroutine to give the user the option of calculating the reaction cross section for limited cases when all possible signs are considered. The subroutine evaluates the reaction cross section for one angular distribution for a calculation which involves two or three levels. For the \(^9\text{Be}(\alpha, n_0)\) and \(^9\text{Be}(\alpha, n_2)\) reactions up to three levels may be included; for the \(^9\text{Be}(\alpha, n_2)\) reaction only two levels are allowed. From the output which is plotted on the line printer, it is hoped that the user may gain some knowledge about the relative signs of the g's involved.

We first investigate the possible combinations we may have for the case of two levels for either the \(^9\text{Be}(\alpha, n_0)\) or \(^9\text{Be}(\alpha, n_2)\) reactions. We have been able to factor R\(\_L(\alpha, \alpha)\) into terms which depend only on the incoming channel and terms which depend only on the outgoing channel. For these two reactions, there is only one outgoing \(t\)-value allowed for each state of a given spin J and parity \(\pi\), and thus only one g associated with the outgoing channel.
Its sign may either be plus or minus. However, for the incoming channel there may be two $t$-values involved and two $g$'s. We write out $A$ and $B$ explicitly for $J_1 \neq J_2$ and denote $t_{\text{min}}$ by $t_1$ and the other allowed $t$-value by $t_{11}$. For level 2 let us denote $t_{\text{min}}$ by $t_2$ and the other allowed $t$-value by $t_{22}$. We have for $A$ that,

$$A = \bar{Z} \left( t_1 t_2 J_1 J_2; SL \right) g_{\alpha s t_1}^{(J_1)} g_{\alpha s t_2}^{(J_2)} \cos (\xi_{\alpha} t_2 - \xi_{\alpha} t_1)$$

$$+ \bar{Z} \left( t_1 t_2 J_1 J_2; SL \right) g_{\alpha s t_1}^{(J_1)} g_{\alpha s t_{11}}^{(J_2)} \cos (\xi_{\alpha} t_2 - \xi_{\alpha} t_{11})$$

$$+ \bar{Z} \left( t_1 t_2 J_1 J_2; SL \right) g_{\alpha s t_2}^{(J_1)} g_{\alpha s t_{22}}^{(J_2)} \cos (\xi_{\alpha} t_{22} - \xi_{\alpha} t_1)$$

$$+ \bar{Z} \left( t_1 t_2 J_1 J_2; SL \right) g_{\alpha s t_{11}}^{(J_1)} g_{\alpha s t_{22}}^{(J_2)} \cos (\xi_{\alpha} t_{22} - \xi_{\alpha} t_{11}).$$

For $B$ we would have the same quantities in D9.1 except the cos is replaced by a sin. Let us denote the terms of each line of D9.1 as 01, 02, 02, and 04 respectively. For convenience let us change notation and let:

$$g_{\alpha s t_1}^{(1)} = g_{\alpha s t_1}^{(J_1)},$$

$$g_{\alpha s t_{11}}^{(1)} = g_{\alpha s t_{11}}^{(J_1)},$$

$$g_{\alpha s t_{2}}^{(2)} = g_{\alpha s t_{2}}^{(J_2)},$$

$$g_{\alpha s t_{22}}^{(2)} = g_{\alpha s t_{22}}^{(J_2)}.$$
The possible combinations we may have for A and B are tabulated in Table 9, where we let 0 stand for a plus sign and 1 stand for a minus sign. The sign associated with 01 et. is only that associated with the signs of the g's. The various combinations are stored in the variable CORE(L, M, N, INDEX) as follows.

The variable M specifies one of the eight possible combinations of A and B. For the variable N equal to one, the value of \( \frac{A}{4 |c_1||c_2|} \) is stored, and for N equal to two, the value of \( \frac{B}{4 |c_1||c_2|} \) is stored. The variable INDEX specifies which "cross-term" is being evaluated. For the two level case, there is only one "cross-term" between level 1 and level 2 and the value of the variable INDEX is one. For three levels there would be three "cross-terms" and the value of INDEX equal to two denotes the "cross-term" between level 1 and level 3, and the value of INDEX equal to three denotes the "cross-term" between level 2 and level 3.

If we denote the "self-terms" as 1, if the signs of the g's of a given level are different, and, 2 if the signs are the same we see that the cross section calculated for set 8 and set 9 of signs would be identical if the same set of signs of the outgoing g's were used in both cases. The cross sections calculated for the other sets of signs below the dashed line are also the same as would be calculated for the sets above the dashed line. For purposes
TABLE 9

Possible combinations of A and B when all signs of g's are considered for the case of two levels. (See text for definition of quantities.)

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<th>03</th>
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</table>
of calculation then we need not now concern ourselves with all sets of signs but only with the first eight sets. For the reactions we are considering at the present, D is zero and C may either by plus or minus. Thus it would appear that we must also calculate the cross section for each of the eight sets of signs of the incoming g's with either plus or minus the "cross-term" which we would calculate with A and B specified by M. However, for example, we see that A and B for M equal to one are equal respectively to the negative of the A and B specified by M equal to four. Since the "self-terms" are going to be the same no matter what the signs of the outgoing g's, we have that calculating the cross section with minus C and A and B specified by M equal to one would be the same as we would calculate if we used the cross section with plus C and used A and B specified by M equal to four. Other such relationships exist and we may calculate all the possible values of the cross section by considering the outgoing g's as positive and using the first eight sets of signs for the incoming g's.

The various cross sections are plotted on the line printer in the same order as tabulated in Table 10 where the "cross-term" is given the same number as the number which specified A and B.

These calculations do not specify the sign of a particular g but only its sign relative to the other g's involved. For the con-
venience of the user the various possible sets of signs for the g's of each level are tabulated in Table 11 for the eight possible different values of the cross section given in Table 10. The variable $g_s^{(1)}$ and $g_s^{(2)}$ are the outgoing g for level 1 and 2 respectively.

For the case where three levels are involved, things become a little more complicated. There would be $2^9$ cases if one considered all possible signs of the g's. In actuality, there are only thirty-two different ways to calculate the cross section and thus there are sixteen sets of signs for the g's for each of these thirty-two. The "cross-terms" are designated by a number from one to eight as in the case of two levels and are defined the same. The output is labeled by the "self-terms" and "cross-terms" as tabulated in Table 12. One possible set of g's for each of these is tabulated in Table 13.

For the $^9$Be($\alpha,n_1$) reaction, the exit channel spin may either be $3/2$ or $5/2$. When all signs are considered, the number of ways to calculate the cross section for two levels may be as high as $2^{14}$. However, there are only 1024 different combinations and thus there are sixteen sets of signs for the g's for each of these 1024. We do not tabulate the 1024 combinations but suggest how they are calculated. For the exit channel spin of $3/2$ there are
Eight different values of the cross sections which may be calculated for two levels when all possible sets of signs of the g's are considered.

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<th>( \frac{d\sigma}{d\Omega} )</th>
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<th>Level 2 &quot;Self-Term&quot;</th>
<th>X-term</th>
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TABLE 11

Possible sets of signs of the g's for two levels, for each of the eight possible values of the cross section.

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**TABLE 11 (cont.)**

**LEVEL 1**

**LEVEL 2**
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TABLE 12

Thirty-two possible values of the cross section which may be calculated for three levels when all possible sets of signs of the g's are calculated.

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<th>Level 3 &quot;Self-Term&quot;</th>
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One possible set of $g$'s for each of the thirty-two possible values of the cross section for three levels when all possible signs of $g$'s are considered.

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eight possible values of C and D for the "cross-term" and for
the "self-terms" there are two values of C for each level. For $s'$
equal to 5/2, for the "cross-term" there are sixteen possible
combinations of C and D which in Section 8 we denoted as C' and D'.
There are four possible values of C' for the "self-term". Let
us denote the "self-term" quantities by small letters. The cross
section is calculated with the quantities shown in Table 14. The
possible combinations of A and B are the same as defined for the
$^8\text{Be}(\alpha, n)$ or $^8\text{Be}(\alpha, n_2)$ reactions. The values of C and D are those
which one obtains using the specified signs of the g's. The primed
and double primed g's refer to the g's of the exit channel with $s'$
equal to 3/2 and $s'$ equal to 5/2 respectively.
TABLE 14
Calculated Cross Section Values for $^9$Be($\alpha$, $n$)\textsuperscript{12}C$^*$

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$s' = 3/2$ Components

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### TABLE 14 (cont.)

$s' = 3/2$ Components

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$s'' = s' = 5/2$ Components

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TABLE 14 (cont.)

\[ s'' = s' = 5/2 \text{ Components} \]

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<th>X-Term ( C', D' )</th>
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10. PLOT

Once a possible value of the cross section has been evaluated in FUGS, the subroutine PLOT plots the results on the line printer. The plot is of an angular distribution in ten degree steps starting at 5°. The maximum and minimum values of the cross section are printed out at the top of each graph.
11. OTHER SUBROUTINES

There are several subroutines used in this program which were written or were modified from existing programs by George Marr. The subroutines are used in the present program to calculate Legendre polynomials Clebsch-Gordon coefficients, and $\bar{Z}$ coefficients.

These subroutines are listed below. For more detailed explanations see reference 24.

BICO: BICO calculates Binary coefficients.

COFCG: This subroutine calculates Clebsch-Gordon coefficients.

COFJU: The subroutine calculates 6-J symbols.

COFJ: This subroutine is essentially a calling program for the other subroutines listed in this section. It is used in the present program to calculate Clebsch-Gordon coefficients and $\bar{Z}$ coefficients as follows.

$$\bar{Z}(l J J; s L) = COFJ(\theta, l, l, l, J, J, S, o.o, o.o, o.o)$$

and

$$\langle l l l | o o l \rangle = COFJ(1, l, 1, l, L, o.o, o.o, o.o, o.o, o.o, o.o, o.o)$$

COF9J: This subroutine calculates 9-J symbols.

FEG: This subroutine calculates first and second order Legendre polynomials. In the present program we need only first order Legendre junctions which are specified as: $P_{L-1}$

$$(\cos \theta) = FEG(1, L, THETA), \text{ when } THETA \text{ is in degrees.}$$
12. Suggested Modifications for Doing Other Reactions

The part of the program which calculates the elastic scattering has been specialized to the case of $^6\text{Be}(\alpha, \alpha)^6\text{Be}$. The modification necessary for doing other elastic scattering reactions of $0^+$ projectiles on $3/2^-$ targets are minor. The variables $T_M$ and $P_M$, which are the target mass and the projectile mass respectively in amu, must be changed from their present values to the proper values for the reaction under study. These variables are located at the beginning of each subroutine in which they are needed. The hard sphere phases, etc. which are calculated in HSPS must be calculated for the new reaction under study.

For the case for which the program was written, there is no possibility of spin flip. Other elastic scattering reactions where there is no possibility of spin flip such as $^{12}\text{C}(^{3}\text{He}, ^3\text{He})^{12}\text{C}$ and $^{24}\text{Mg}(p, p)^{24}\text{Mg}$ may be handled by making only a few modifications to the program. However, any elastic scattering reaction where spin flip is allowed would require considerable modification of the program. The changes necessary in each subroutine for the case of no spin flip are discussed below.

**EORCS**: The major modification in EORCS is to determine $\lambda_{\text{min}}$ for a state of a given spin $J$ and parity $\pi$. This is
done in EORCS from statement number 2653 to statement number 47. The statement numbers 2653 and 47 must remain in the program, though the contents of statement 2653 may be changed. The value of \( l_{\text{min}} \) is stored in the variable LL. Because \( l_{\text{min}} \) may be zero we define the variable \( LK = LL + 1 \). For the \(^{9}\text{Be}(\alpha, \alpha)\) reaction there were in most cases two possible \( \ell \)-values for the incoming channel and the second was denoted by \( LJ = LL + 3 \). Two reduced widths were defined and indexed by \( LK \) and \( LJ \).

If for the reaction which is being studied, there is only one allowed \( \ell \)-value for a state of a given spin and parity then \( RW(LJ) \) must be set equal to zero. The values of \( RW(LK) \) and \( RW(LJ) \) are determined in the program from statements 8041 to 6143.

At the beginning of EORCS the variables TM, PM, and s must be changed to the proper values for the reaction under study. The variable \( s \) is the entrance channel spin. The only other modification necessary in EORCS have to do with the factor \( 1/(2I+1)(2i+1) \). In the program this factor has been given the value 0.25. For other reactions this must be changed, but the number of placed it appears would make the necessary changes quite tedious. It is easier to define a quantity such as AAY,
\[ \text{AAY} = \frac{4}{(2I+1)(2i+1)}, \text{ where } I \text{ and } i \text{ have the values appropriate to the new reaction.} \]

The following statements in the program are then modified to:

\[ 6802 \quad \text{COMP1}(I, K, 1) = (\text{RSUM1} + \text{SUMIF} + \text{SURFN}) \times \text{AAY} \times 1.0 \times 10^2 + 27 \]

\[ 2629 \quad \text{COMP1}(I, K, \text{KUFT}) = (\text{RSUM3} + \text{SUMI1} + \text{SURF1}) \times \text{AAY} \times 1.0 \times 10^2 + 27 + \text{COMP1}(I, K, \text{KUFT}) \]

\[ 6152 \quad \text{COMP1}(I, K, \text{KOOK}) = (\text{RSUM1} = \text{SUMIF} + \text{SURFN}) \times \text{AAY} \times 1.0 \times 10^2 + 27 \_ \text{SIG1}(I, K) + \text{PUMP} \times \text{AAY} \]

\[ 1017 \quad \text{SIG1}(I, K) = (\text{RSUM1} + \text{SUMIF} + \text{SURFN}) \times \text{AAY} \times 1.0 \times 10^2 + 27 + \text{SIG1}(I, K) + \text{PUMP} + \text{AAY} \]

\[ 1015 \quad \text{SIG1}(I, K) = \text{RSUM1} + \text{SUMIF} + \text{SURFN}) \times \text{AAY} \times 1.0 \times 10^2 + 27 + (\text{CTERM} + \text{SUMFN} + \text{SUFFN}) \times 1.0 \times 10^2 + 27 \]

\text{EXTRA: Only change is TM and PM.}

\text{FUNK: In FUNK we must change TM and PM and defining AAY as above, the following statements become:}

\[ 6142 \quad \text{SIG1}(I, K) = \text{SIG1}(I, K) - \text{COMP1}(I, K, \text{KUUL}) + (\text{RSUM1} + \text{SUMIF} + \text{SURFN}) \times \text{AAY} \times (1.0 \times 10^2 + 27 + \text{PUMP} \times \text{AAY}) \]

\[ \text{COMP1}(I, K, \text{KUUL}) = (\text{RSUM1} + \text{SUMIF} + \text{SURFN}) \times \text{AAY} \times 1.0 \times 10^2 + 27 \]
ZBARM: In ZBARM the only change is statement 9107.

The value of parameter SO is set equal to value of
the entrance channel spin appropriate to the reaction
under study.

The modifications necessary to calculate reaction cross
sections other than for the $^6$Be($\alpha$,n$_0$), $^6$Be($\alpha$,n$_1$), and $^6$Be($\alpha$,n$_2$)
reactions depend on whether the outgoing $\ell$-values calculated in
LDETM still apply since they were determined for the case of
a 1/2$^+$ outgoing reaction particle and a 0$^+$ or 2$^+$ final state of
the residual nucleus. One reaction which may be calculated with a
minimum of change is $^{24}$Mg(p,p$_1$)$^{24}$Mg$^*$. The first excited state of
$^{24}$Mg is a 2$^+$ state. To calculate the reaction cross section, the vari-
able IFINS is set equal to two. If the changes discussed above
have been made, the additional changes are:

REACS: The statement:

1F (IFINS-2) 8064, 8065, 8065

which is at the end of the subroutine should be changed to

1F (IFINS-2) 8065, 8064, 8064

SETOW: The variables TM and PM must be changed to
their appropriate values.

EXTRA: The following statements are changed to:
\[ WCC = WCC + WCCP \]
\[ WDD = WDD + WDDP \]

Of course it is assumed that the outgoing penetrabilities and other phases have been evaluated in either HSPS or NHPS for the appropriate reaction.
13. DATA CARDS FOR VARIOUS OPTIONS

The first few cards are the same no matter what option is being used. They are as follows:

CARD 1: IIMAX  IIMAX is a number from one to forty-one used to tell program how many cards are to be read next.

CARD 2 to CARD N: N is equal to 6 IIMAX + 1. The quantities calculated in HSPS are read into the program. The quantities are

\[ \frac{P}{l}, E, \phi = \frac{F_l}{G_l}, \lambda, \gamma = \sigma - \sigma \]

The variable \( l \) goes from zero to six.

CARD N+1: This card is called the "option card" and controls what the program calculates and what data is read next. The card contains values for the following variables: KMAX, IMIN, IMAX, NN, JMAX, KKMAX, NOPT, MIN, MAX, IPAR, MIPAR, NTRACE, NCAL, MXCAL, KCASE, NPPIN, INTF3, NREAT, ISERH, and JAKE. Several of these variables have different functions depending on what values other of the variables have. For this reason, the values of the variables are discussed below for several options.
A description of each of these variables is also
given in Section 1 of Appendix D.

The main control variables on the "option card"
are NN, NOPT, NCAL, and NREAT. These variables
determine whether angular distributions or excitation
functions are being calculated, whether the program
is to do a search on the level parameters of various
levels, whether more than one level is to be included
in the calculation, and finally, whether elastic
scattering cross sections or reactions cross sections
are to be calculated.

Main Control Variables on "Option Card"

NN: Equal to zero, angular distributions are calculated.

   Equal to one, excitation curves are calculated.

NOPT: Equal to zero, no search is done. Equal to one, a

   search is to be done.

NCAL: Equal to zero, only one level is included in the cal-

   culation. Equal to one, more than one level is included
   in the calculation.

NREAT: Equal to zero, elastic scattering cross section is

   calculated. Equal to one, reaction cross section is cal-
   culated.
The only control variable which does depend directly or indirectly on the values of these four variables is \( NPPIN \).

\( NPPIN \): Equal to zero, the output is on the line printer. Equal to one, the output is also punched on cards.

**Variables on "Option Card" Controlled by NN**

1) \( NN = 0 \)

\( KMAX \): A number from one to thirty-three which specifies the maximum angle of the angular distribution,\n
\[ \theta_{MAX} = KMAX \times 5^\circ \]

The angular distributions are calculated from \( 5^\circ \) to \( \theta_{MAX} \) in \( 5^\circ \) steps. For elastic scattering cross sections the angles are laboratory angles and for reaction cross sections, if \( JAKE \) is equal to zero, the angles are center of mass angles.

\( IMIN \): Set \( IMIN \) equal to one.

\( IMAX \): Set \( IMAX \) equal to one.

\( JMAX \): This is the number of angular distributions to be calculated. A maximum of five are allowed at one time.

\( KKMAX \): Set equal to one.

2) \( NN = 1 \)

\( KMAX \): Set \( KMAX \) equal to \( KKMAX \).
IMIN: IMIN is a number from one to IIMAX and specifies the beginning laboratory energy in MeV of an excitation curve as

\[ E_{\text{min}} = T(IMIN, 8). \]

To specify \( E_{\text{min}} \) it is thus necessary for the user to know the energy stored in \( T(1, 8) \). The program has been written so that the excitation curves are calculated in 50 keV steps.

IMAX: (See IMIN). IMAX specifies the maximum energy of the excitation curve.

JMAX: Set JMAX equal to one.

KKMAX: This is the number of excitation curves to be calculated. A maximum of five are allowed. If NREAT is equal to one and JAKE is equal to one, set KKMAX equal to one.

Variables on "Option Card" Controlled by NREAT

1) \( \text{NREAT} = 0 \)

INTF3: If there are three levels of the same spin and parity included in the calculation, and if the three-level approximation is desired, set INTF3 to one, otherwise set equal to zero.
ISERH: Set equal to zero.

JAKE: Set equal to zero.

2) \( \text{NREAT} = 1 \)

NCAL: Set equal to one.

INTF3: Set equal to zero.

ISERH: If the user desires the option discussed in FUGS set ISERH equal to one, NN equal to zero, KMAX equal to thirty-three, KKMAX equal to one, JMAX equal to one, NOPT equal to zero, JAKE equal to zero, and MXCAL equal to two or three.

JAKE: If the experimental data for an angular distribution was taken at center of mass angles other than every five degrees, set JAKE equal to one and KKMAX equal to one.

Variables on "Option Card" Controlled by NOPT and NCAL

1) \( \text{NOPT} = 0 \) and \( \text{NCAL} = 0 \)

MIN: The cross section is calculated for an isolated level with different values of spin. The first value of spin considered is

\[ J = \text{MIN}-1/2. \]

MAX: The last value of spin considered is,

\[ J = \text{MAX}-1/2. \]
IPAR: Set equal to one.

MIPAR: If MIPAR is equal to one, the program calculates the cross section for the isolated level for a plus parity for each value of spin between or equal to those specified by MIN and MAX. If MIPAR is equal to two, the cross section is calculated for both plus and negative parities.

NTRACE: Set equal to one.

MXCAL: Set equal to one.

KCASE: Set equal to zero.

INTF3: Set equal to zero.

NREAT: Set equal to zero.

2) NOPT = 1 and NCAL = 0

MIN: Same as Section 1 above.

MAX: Same as Section 1 above.

IPAR: This variable specifies the parity of the level. The variable has the value one for plus parity, and minus one, for negative parity.

MIPAR: If the variable has the value one, only the parity specified by IPAR is used. If MIPAR is equal to two, both parity cases are considered.
NTRACE: Set equal to one if the user wants intermediate steps of search printed out. Set equal to zero if this option is not desired.

MXCAL: Set equal to one.

KCASE: Set equal to zero. This variable is now set internally in the present version of the program.

INTF3: Set equal to zero.

NREAT: Set equal to zero.

3) NOPT = 0 and NCAL = 1

MIN: Set equal to one.

MAX: Set equal to MXCAL.

IPAR: Set equal to one.

MIPAR: Set equal to one.

NTRACE: Set equal to one.

MXCAL: This variable is the number of levels to be included in the calculation. MXCAL has a maximum value of eight.

KCASE: Set equal to zero.

INTF3: See Variables Controlled by NREAT.

NREAT: May have either the value zero or one depending on whether elastic scattering or reaction cross sections are to be calculated.
4) \textbf{NOPT} = 1 and \textbf{NCAL} = 1

\textbf{MIN:} Set equal to one.
\textbf{MAX:} Set equal to \textbf{MXCAL}.
\textbf{IPAR:} Set equal to one.
\textbf{MIPAR:} Set equal to one.
\textbf{NTRACE:} See Section 2 of Variables Controlled by NOPT and NCAL.
\textbf{MXCAL:} See Section 3 above.
\textbf{KCASE:} Set equal to zero.
\textbf{INTF3:} Set equal to zero.
\textbf{NREAT:} See Section 3 above.

\textbf{CARD N+2:} This card contains the values of \textit{MASK}(1), \textit{MASK} (2), and \textit{MASK} (3). If the value is non-zero, the variable \textit{x(I)} is held fixed in search routine \textit{STEPIT}.

\textbf{CARD N+3:} This card depends on the value of \textbf{NREAT}. We discuss separately this card and the data cards following this card for both values of the variable \textbf{NREAT}.

\textbf{I. NREAT EQUAL TO ZERO}

\textbf{CARD N+3:} \textbf{MXR} A number used to control length of search.
Set equal to a number from seventy-five to one hundred.

Card is read even if no search is desired.

CARD N+4: ER, GR. The resonance energy ER and the total width $\Gamma$ in the laboratory system in MeV for an isolated level. If NCAL is equal to one, the program will read this card but disregard the values read.

CARD N+5: I1SN, I2SN, N2SN, NE1SN, NE2SN, NE3SN.

These variables have the value either plus one or minus one and are the signs of the g's involved. (See Section 1 of Appendix D.) These values are supplied for the case of an isolated level and are disregarded if NCAL is equal to one.

CARD N+6: This card depends on the value of NCAL, and NOPT.

a) NCAL = 0 and NOPT = 0

CARD N+6: TH(KK) The center of mass angles at which the excitation curves are to be calculated. The number of angles read is controlled by the variable KKMAX. If one is calculating an angular distribution there is one angle on this card, however, the program disregards it.
CARD N+7: IVAL (J) The values of I which specify
the energies for which angular distribution are
to be calculated. The number of values of I
read is controlled by the variable JMAX. If
excitation curves are being calculated there is
one number on this card. However, will be ignored
by the program.

CARD N+8: /*

LAST CARD: //

b) NCAL = 0 and NOPT = 1

1) NN = 0

CARD N+6: PSII, PSIF, ELABB The initial and final
angle in degrees of an experimental angular distri-
bution taken in 5° steps at the bombarding energy
ELABB in MeV.

CARD N+7 to CARD M: These cards contain the experi-
mental data. For elastic scattering the program
assumes the data is the ratio to Rutherford times
one hundred.

CARD M+1: /*

LAST CARD: //
2) **NN= 1**

CARD N+6: EIN, EFIN, THETA. The initial and final laboratory energies in MeV of an experimental excitation curve taken in 50 keV steps at the center of mass angle THETA.

CARD N+7 to CARD M: These cards contain the experimental data. The data is the center of mass cross section times one hundred.

CARD M+1: /*

LAST CARD: //

c) **NCAL = 1 and NOPT = 0**

CARD N+6: ER, GR, SAM1, SAM2, NSPMX, NFIT, INTFR

(See Section 1, Appendix D). We call this card the "level card". ER and GR are the laboratory resonance energy and total width in MeV. SAM1 and SAM2 are estimated partial widths for the incoming channel. If they are both zero, the program estimates values as follows. For the case when there are two possible incoming \( t \)-values, the reduced widths for each are set equal to each other and the sum of the partial widths is set equal to the total width. The variable NSPMX has the
one to four and specifies how many spin and parity cases are to be tried in the search. For the case we are considering now NSPMX has the value one. The variable NFIT specifies whether the level is to be fit. Here, the variable has the value zero.

The last variable INTFR specifies whether "two or three-level" approximations are to be included in the calculation. However, whether these terms are included or not also depends upon the position of the next "level card". For two levels of the same spin and parity, the value of INTFR is set equal to zero on the first card and on the next "level card" which is the card for the other level of the same spin and parity, the variable INTFR is set equal to one.

If there are three levels of the same spin and parity and if the "three-level" terms are desired, the first two level cards are the same as for the "two-level case" and the level card for the third level of the same spin and parity must follow these and have INTFR equal to zero. If the "level cards" for levels of the same spin and parity are not consecutive or if INTFR is equal to zero on all "level-cards" the
The program uses the "single-level" approximation only.

CARD N+7: I1SN, I2SN. The signs of the g's of the incoming channel, either plus one or minus one.

CARD N+8: RJO, IPAR. The spin and parity of the level.


CARD N+10: Same as Card N+7.

CARD N+11: Same as Card N+8. There are three cards like N+6, N+7, and N+8 for each level to be included in the calculations. The number of set of these cards is controlled by MXCAL.

CARD M: TH(KK), where M = N+6 +3 MXCAL. (See Part I, Section a) for discussion).

CARD M+1: IVAL(J). (See Part I, Section a)).

CARD M+2: /*

LAST CARD: //

d) NCAL = 1 and NOPT = 1

CARD N+6: The cards here are the same to Card M as described above in Section c). However, if NSPMX
is greater than one, there are as many RJO, IPAR cards as the number NSPMX. Note also the value of NFIT specifies which level is to be fit first, second and so on.

**CARD M:** Starting from this card the remaining cards are same as those discussed in Part I, Section b) i.e.,

**CARD M:** PSII, PSIF, ELABB or EIN, EFI, THETA.

Note, however, the number of sets of cards (ID card and data cards) which are read depend on the value of JMAX or KKMAX. The /* and // cards are included only once and come at the very end.

The various sets of data read are fit simultaneously by the search routine. For example, one may wish to fit four excitation curves at various angles simultaneously. One sets NN equal to one, KKMAX equal to four, KMAX equal to four, and then has four sets of cards which include one ID card and the experimental data for each angle.
II. NREAT EQUAL TO ONE

CARD N+3: IFINS. To specify the $^9\text{Be}(\alpha, n_0)$ or $^9\text{Be}(\alpha, n_2)$ reactions set IFINS equal to zero. To specify $^9\text{Be}(\alpha, n_1)$ reaction set IFINS equal to two.

CARD N+4 to CARD M: M is equal to N + 4 + 4 IIMAX.

These cards contain the penetrabilities and phase shifts of the outgoing channel. For the neutron reaction they were calculated in NHPS. The quantities are stored in the variable PENTR and ZELTA. Note that these should be evaluated for the same projectile energies as the penetrabilities and phase shifts of the incoming channel.

CARD M+1: MXR (See Part I).

CARD M+2: ER, GR (See Part I).

CARD M+3: I1SN, I2SN, N2SN, NE1SN, NE2SN, NE3SN (See Part I).

CARD M+4: "Level-card" (See Section c of Part I).

CARD M+5: I1SN, I2SN (See Section c of Part I).

CARD M+6: RJO, IPAR (See Section c of Part I).

CARD M+7: OWE1, OWE2, OWEE1, OWEE2, OWEE3. These are the partial widths of outgoing channels in MeV in the laboratory. These variables have been discussed in Section 1 of Appendix D.
CARD M+8: N1SN, N2SN, NE1SN, NE2SN, NE3SN. These variables are the sign either plus one or minus one for the g's associated with the outgoing channels. See Section I of Appendix D.

CARD M+9: There are as many sets of cards from CARD M+1 to CARD M+8 as there are levels to be included in the calculation. Note that on the "level-card" always set INTFR equal to zero.

CARD K: K equals M + 4 + 5 MXCAL. If JAKE is zero, this card and the remaining data cards are the same as in Part I, Section a) or Part I, Section b) with the exceptions discussed in Section d of Part I. i.e., K.

CARD K: TH(KK); or PSII, PSIF, ELABB; or EIN, EFIN THETA depending on the values of NN and NOPT. Note also that for angular distributions the experimental data is not the ratio to Rutherford but just the center of mass cross section times one hundred. If NOPT equals one, JAKE equals one, and NN equals zero we have

CARD K: NTIME, ELABB. NTIME is the number of experimental data points and ELABB is the laboratory bombarding energy in MeV.
CARD K+1 to CARD Q: Q equal to K + NTIME. Each card contains the center of mass angle and the center of mass cross section at that angle.

CARD Q+1: */

LAST CARD: //

As an example, the data cards starting with the "option card" are presented for a calculation of the elastic scattering cross section which includes seven levels, 2 of which are of the same spin and parity and a search on two levels which are of different spin and parities. We shall fit five excitation curves simultaneously.
**Sample Data Cards**  
**Starting with Option Cards**

<table>
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<tr>
<th>Card Numbers</th>
<th>Data (in millimeters)</th>
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<tr>
<td>000000</td>
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<td></td>
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<td>Sample Data Cards (cont.)</td>
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### Sample Data Cards (cont.)

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<td>5449.</td>
<td>6059.</td>
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<td>3305.</td>
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<td>9018.</td>
<td>9432.</td>
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<td>9175.</td>
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<td>1.70</td>
<td>5.60</td>
<td>167.2</td>
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<td>2603.</td>
<td>1809.</td>
<td>900.</td>
<td>1713.</td>
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<td>1684.</td>
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<td>4135.</td>
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<td>3504.</td>
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<td>10380.</td>
<td>8280.</td>
<td>16720.</td>
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<td>5772.</td>
<td>4457.</td>
<td>3515.</td>
<td>3105.</td>
<td>2998.</td>
<td>3403.</td>
<td>4085.</td>
<td>5380.</td>
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</tbody>
</table>

/*
//
DIMENSION PENTR(41,8), ZELTA(41,8), ZZZ(63,3,2), OEW1(8,2), OEW2(18,3)
DIMENSION O11(8), O2(8), GSIGN(8,2)
DIMENSION CODE(8,16,2), CORE(9,8,4,3), OSPN(8,2), OSPN(8,3)
DIMENSION T(41,8), COUPH(41,8), DELTA(41,8), TH(7), SINN(315)
1PLALL(10,33), RY(8), TVAL(7), SIGI(14,105), ZZ(6,2,2)
2RAA16), RAA2(6), DIL(41,13), COU(41,13), CCE(7,7,13), COMP(14,5,4)
3COMP(41,5,4), COMSY(41,5,4), SS(41,13), YEXP(41,5), XXX(3,2), YSIG(100)
41+SPINN(8,4), ERESL(8), TAMMA(8), IPITY(8,4), REW(8,2), NSAVE(8), NFSAV(8)
5+NSAV(4), LSAVE(4), YSAVE(3,4), FSAVE(5), F1(5,4)
DIMENSION LSAVE(8), LPSV(8,2), PUMP(14), ZZZ(9,3,3,6,8,3)
DIMENSION VEC(20), VEC(20), VSAVE(20), CHI(20), CHI(20), SECOND(2,2)
STEP0005
DIMENSION DAA(26), DAA(26), RBB1(6), INTFS(08)
DIMENSION OLDVECE(20), SALVO(20), XOSC(20,15), CHOSC(15)
DIMENSION MASK(20), X(20), XMAX(20), MAX(20), DELTA(20), DELMIN(20), STEPO005
ERR(20,20)
COMMON KWSV, VNTRAC, MASKL, XMAX, XMIN, DELTA, DELMIN, MATRIX
STEP0007
COMMON ERR, CHISQRATIO, COLIN, NCOMP, ACK, MAKR, MOSQUE
STEP0008
COMMON NPRIN, KGACE, LOAD, IPAR, MZERO, MIN, MAX, KKKS, KMIN, NN, JO, LL
COMMON KMAX, RJO, ER, KUUL, JULIE, IGMIN, IDMAX, JMAX, FISAV
COMMON IVAL, TCDUPLH, DELTA, SINN, SS, CCE, ZZ, PALL, YEXP
COMMON COU, O11, O2, SIG1, INCAL, COMP, COUP, COMSY
COMMON PCON1, PCON2, PW1, PW2, LES, LFSAVE, FRAC, PRCM
COMMON GAM1, GAM2, CS, RES, ECM, QW1, QD2, PCON3, HRCM, ORCM, BETA, NOPT
COMMON INF3, J3, 1L, LK, LMAX, K, JJ, ALAM, ERESL
COMMON RA1, RA2, RBB1
COMMON RSUM, RSUM3, MJE, MJJE
COMMON TES, OES, RES2, RES3, RES23, GEW1, GEW2, PEW1, PEW2, QETA, FETA
COMMON GAM12, GAM13, GAM23, GSIGN, ISERH
COMMON O11, O2, PENTR, OEW1, OEW2, ZELTA, ZZZ
COMMON IZ, IZF, JGILK, JGILJ, JG2ILK, JG2ILJ, JG2ILM, IFINS
COMMON NTIM, GRM, NREAT
COMMON NULX, MXCAL, IPITY, LISAIV, LPSV, JUNE, INF35, NSAV, NFSAV
COMMON SPINN, TAMMA, REW, PUMP, PUMP, ZZZZ, CODE, CORE, OSPN, OSPN
FORMAT(41E12.4)
401 FORMAT(7F10.2)
402 FORMAT((7I2)
403 FORMAT((7I2)
404 FORMAT((1X, B11E12.4, 2X))
405 FORMAT((6X, 4HSG1G+10X, 4HSG1G+6X, 12HSIN(THETA/2)/1)
406 FORMAT((6X, 4HSIG1G+10X, 4HSIG1G+6X, 12HSIN(THETA/2)/1)
407 FORMAT((6X, 4HSIG1G+10X, 4HSIG1G+6X, 12HSIN(THETA/2)/1)
408 FORMAT((6X, 7I12.4+2X+1X+12I12.4))
409 FORMAT((6X, 4HSIG1G+6X, 12HSIN(THETA/2)/1)
410 FORMAT((6X, 4HSIG1G+12X, 4HELAB/1)
411 FORMAT((6X, 5HRW(L), 8X, 7HRW(L), 29X, 2HJO, 10X, 5GGAMMA, 11X, 2HER, 11X,
14HGM1, 10X, 4HGAM2, 10X, 4HELAB/1)
412 FORMAT((6X, 5HRW(L), 8X, 7HRW(L), 29X, 2HJO, 10X, 5GGAMMA, 11X, 2HER, 11X,
14HGM1, 10X, 4HGAM2, 6X, 12HSIN(THETA/2)/1)
413 FORMAT((6X, 5HRW(L), 8X, 7HRW(L), 29X, 2HJO, 10X, 5GGAMMA, 11X, 2HER, 11X,
14HGM1, 10X, 4HGAM2, 8X, 4HELAB/1)
414 FORMAT((6X, 5HRW(L), 8X, 7HRW(L), 29X, 2HJO, 10X, 5GGAMMA, 11X, 2HER, 11X,
14HGM1, 10X, 4HGAM2, 8X, 4HELAB/1)
415 FORMAT((10I0))
416 FORMAT(1I1)
417 FORMAT((1X, IOERROR IN N/))
418 FORMAT((1X, ISERROR IN PARITY/))
420 FORMAT((7F10.2))
421 FORMAT((2X, 10F7.0))
423 FORMAT(1112)
C INITIALIZATION OF SOME PARAMETERS FOR STEPIT

NV=3
DO 501 NTEE=1+NV
MASE(NTEE)=0
XMAX(NTEE)=1.0
XMIN(NTEE)=0.0
DELM(NTEE)=1.0E-05
501 CONTINUE

C READ IN OF E+LAMBDA+ETA+P(L)+DELTAL+COUPH(L)
READ(5,42311)MAX
DO 1 L=1,11MAX
READ(5,40011)IT(I+L),L=1,8)
READ(5,40011)DELTAL(I+L),L=1,8)
READ(5,40011)COUPH(I+L),L=1,8)
1 CONTINUE

C READ IN OF CONTROL CARDS AND ADDITIONAL DATA
READ(5,401)KMAX,MIN1MAX,NN,JMAX,KKMAX,NQPT,MINMAX,IPARMIPAR,
INRACE,NCAL+MXCAL+KCASE,NPPIN,INTF3,NREAT,ISERH,JAKE
READ(5,403)MASK(I),MASK(2),MASK(3)
IF(NREAT=183001,8002,8002
8002 READ(5,439)FINS
IF(NFINS=28090,8091,8091
8090 7ZM=7
DO 9043 I=1,1MAX
ZELTA(I+8)=0.0
ZETNTR(I+8)=1.0
9043 CONTINUE
GO TO 8093
8001 READ(5,430)MKR
     READ(5,431)ER,GR
     READ(5,401)11SN,12SN,N1SN,N2SN,N1SN,N2SN,N2SN
     GSIGN(1,1)=11SN
     GSIGN(1,2)=12SN
     OSPN(1,1)=N1SN
     OSPN(1,2)=N2SN
     OSPPN(1,1)=N1SN
     OSPPN(1,2)=N2SN
     OSMPN(1,3)=N3SN
     ECM=ER*(TM/(TM+PM))#1.60206E-06
     GRCM=GR/(2.0)*(TM/(TM+PM))#1.602060E-06
     ECHECK=1(Y=8)
     IF(INCAL=1)1003,1001,1001
1001 DO 1002 NJE=1,MXCAL
     READ(5,424)ER,GR,SAM1,SAM2,NSPMX,NFIT,INTFR
     READ(5,403)11SN,12SN
     GSIGN(NJE,2)=12SN
     GSIGN(NJE,1)=11SN
     ERESL(NJE)=ER
     TAMMA(NJE)=GR
     REV(NJE,1)=SAM1
     REV(NJE,2)=SAM2
     NSAVE(NJE)=NSPMX
     INTFS(NJE)=INTFR
     NFSAV(NJE)=NFIT
     IF(NFIT=6263)6263,6264
6264 MJSAV(NFIT)=NJE
     JUNE=JUNE+1
6265 DO 6130 JOHN=1,NSPMX
     READ(5,431)RJO,IPAR
     SPINN(NJE,JOHN)=RJO
     IPITY(NJE,JOHN)=IPAR
6130 CONTINUE
     IF(NREAT=1)11002,8046,8046
8046 READ(5,440)OEW1,OEW2,OEE1,OEE2,OEE3
     READ(5,442)11SN,12SN,N1SN,N2SN,N1SN,N2SN,N2SN
     OSPN(NJE,1)=N1SN
     OSPN(NJE,2)=N2SN
     OSPNN(NJE,1)=N1SN
     OSPNN(NJE,2)=N2SN
     OSPNN(NJE,3)=N3SN
     OEW1(NJE,1)=OEW1
     OEW1(NJE,2)=OEW2
     OEW2(NJE,1)=OEW1
     OEW2(NJE,2)=OEW2
     OEW2(NJE,3)=OEE3
1002 CONTINUE
     MIN=1
     MAX=MXCAL
     MIPAR=1
1003 IF(NOPT=1)857,858,858
857 READ(5,402)11,12,KK=1,KKMAX)
     READ(5,403)IVAL(J),J=1,JMAX)
     GO TO 859
858 IF(INN)660,660,661
660 ILOAD=1
     IF(JAKE=1)8675,8676,8676
8676 JMAX=1
8675 DO 868 NZE=1,JMAX
IF(JAKE-1)863,866,864
864 KKMIN=1
READ(5,443)NTIME,ELABB
MAX=NTIME
IVAL(IOAD)=(ELABB-ECHEK)/0.05+1.01
READ(5,444)(COMP2(KP=1+1),YSIG(KP),KP=1+NTIME)
DO 866 KP=1+NTIME
866 YSIG(KP)=YSIG(KP)*100.0
GO TO 866
863 READ(5,420)PSIF,ELABB
IF(PSIF-PSI1)1800.871.871
871 NTIME=(PSIF-PSI1)/5+1.01
IVAL(IOAD)=(ELABB-ECHEK)/0.05+1.01
KKMIN=(PSI1-5.0)/5+1.01
READ(5,421)(YSIG(KP),KP=1+NTIME)
NCHEK=NTIME+KKMIN-1
IF(NCHEK-KMAX)1865,866,867
865 KMAX=NCHEK
866 DO 862 MME=1,NTIME
K=MME+KKMIN-1
IVAL=IVAL(IOAD)
IF(K-KMAX)1863.867
863 YEXP(KP,IOAD)=YSIG(MME)/100.0
862 CONTINUE
867 IOAD=IOAD+1
866 CONTINUE
GO TO 859
861 KKMIN=1
KMAX=KKMAX
J=1
DO 870 NZE=1,KKMAX
READ(5,420)EIN,EFIN,THETA
IF(EFIN-EIN)1800.872.872
872 NTIME=(EFIN-EIN)/0.05+1.01
THJ=THETA
IF(EIN-ECHEK)1875.876.876
875 IMIN=(ECHEK-EIN)/0.05+1.01
J=1
ICHEK=IMIN+2
IZZK=IMIN
GO TO 877
876 IMIN=(EIN-ECHEK)/0.05+1.01
ICHEK=IMIN
IZZK=1
877 READ(5,421)(YSIG(KP),KP=1+NTIME)
NCHEK=NTIME+ICHEK-1
IF(NCHEK-KMAX)1873.874.874
873 ICHEK=NCHEK
874 DO 888 MME=1,NTIME
KP=MME+IZZK-1
J=IMIN+MME-1
IF(1-IMAX)1889,889.890
889 YEXP(KP+1,J)=YSIG(KP)/100.0
888 CONTINUE
890 J=J+1
870 CONTINUE
C CALCULATION OF CG COEF FOR CORRECTION TERMS
899 IF(NREAT=1)18004.8005.8005
8004 DO 605 LELAR=1.7
WL=LELAR-1
DO 606 LESMA=1.7
WLL=LESMA-1
LOWER=1ABS(LESMA-LELAR)+1
LUPPR=LESMALLELAR-1
DO 607 LEPRM=LOWL+LUPPR
WLP=LEPRM-1
IF (LEPRM<7) 620, 620, 621
620 CEGE=COPJ1(1+WLP+WL+0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0)
CEGE(LELAR,LESMALLEPRM)=CEGE#2
GO TO 607
621 CEGE(LELAR,LESMALLEPRM)=0.0
607 CONTINUE
606 CONTINUE
605 CONTINUE
800 DO 1000 IAD=1
C CALCULATION OF ANGLES TO BE USED, PL(THEATA)*SIN(THEATA/2)
DO 3 K=KKMIN,KMAX
PSI=PSI/57.29578
IF (NREAT<1) 9060, 9061, 9061
9061 THEATA=PSI
GO TO 9066
9060 Y=(PM*SIN(PW))/TM
Y=Y/ISRT(1.0-Y**2)
THEATA=PSI+ATAN(Y)
9066 THEATA=57.29578*THEATA
IF (NREAT<1) 8671, 8673, 8673
8673 IF(IAKE<1) 8671, 8672, 8672
8672 THEATA=COMP2(K+1*1)
THEATTHEATA/37.29578
8671 IF (NNA K<48*49)
49 THEATA=TH(K)
THEATA=THEATA/57.29578
48 ILLL=10
DO 23 KKL=1, ILLL
PLALL(KKL, K)=FEG(1+KKL, THEATA)
23 CONTINUE
SINN(K)=SIN(THEATA/2.0)
3 CONTINUE
C CALCULATION OF PHASES PAST U=6 AND SIN(DELTAL)
IF (NN>634, 634, 635
635 IPTMA=1MAX
IPMIN=IMIN
GO TO 637
634 IPTMA=JMAX
IPMIN=1
637 DO 636 IPT=IPMIN+IPTMA
I=IPT
IF (NN>638, 638, 639
638 I=IVAL(IPT)
639 DO 640 JMM=1, I+13
IF (JMM<7) 603, 604, 604
603 DIL(I+JMM)=DELLA(1+JMM)
COU(I+JMM)=COUPH(1+JMM)
GO TO 640
604 DIL(I+JMM)=0.0
COU(I+JMM)=0.0
640 SS(I+JMM)=SIN(DIL(I+JMM))
602 CONTINUE
636 CONTINUE
MJOK=1
JOK=1
ECHEN=T(1,18)
ISTED=0
NTIM=(ER-ECHEK)/0.05+1.01
6291 DO 60 MMK=MIN,MAX
MLB=1
ANMK=MMK
RIEO=0.5*ANMK
IF(NOPT>1)701:702
701 IPAR=1
702 JO=2*RIEO+0.01
IF(INCAL-11005:1006:1006
1006 NJE=MMK
RIEO=SPINN(MJJE+J0HN)
IPAR=IPITY(MJJE+J0HN)
GR=YAMMA(MJJE)
ER=ERESL(MJJE)
ERCH=ER#(TM/(TH+PM))#1*602060E-06
ERCH=GR/2.0#(TM/(TH+PM))#1*602060E-06
JO=2*ERO+0.01
INTFR=INTFS(MJJE)
ECMEK=T(1+8)
NTIN=(ER-ECMEK)/0.05+1.01
IF(ISTED=112614:1005:1005
2614 IF(INJE-11005:1005:2601
2601 MJJE=MJJE-1
JOE=JO
JOE=2*0.5*SPINN(MJJE+J0HN)+0.01
IP2=IPAR
IP1=IPITY(MJJE+J0HN)
IF(J0E=JO111005:2602:1005
2602 IF(IP1=IP2)1005:2603:1005
2603 LES=1
FRCH=ERESL(MJJE)#(TM/(TH+PM))#1*602060E-06
FRCH=YAMMA(MJJE)/2.0#(TM/(TH+PM))#1*602060E-06
PW1=REF(MJJE+1)
PW2=REF(MJJE+2)
NYIN=(ERESL(MJJE)-ECMEK)/0.05+1.01
PCON#2=0*PREF#(TNYIM*LJ)#PW1+TNYIM*LJ)#PW2)
13=0
IF(INTFJ=12606:3001:3001
3001 IF(NOPT=1)3009:2606:2606
3009 MJJE=MJJE+1
IF(MJJE=MXCAL)3004:3040:2606
3040 JOE=2*0.5*SPINN(MJJE+J0HN)+0.01
IP1=IPITY(MJJE+J0HN)
IF(J0E=JO12606:3002:2606
3002 IF(IP1=IP2)2606:3003:2606
3003 MRCH=ERESL(MJJE)#(TM/(TH+PM))#1*602060E-06
MRCH=YAMMA(MJJE)/2.0#(TM/(TH+PM))#1*602060E-06
NQIN=(ERESL(MJJE)-ECMEK)/0.05+1.01
IF(J0E=3)3004:3005:3005
3005 XX=QRCH/(TNYIM*LJ)+TNYIN*LJ))
Q1=XX#2+0
QW2=XX#2+0
GO TO 3006
3006 QW1=QRCH/(TNYIM*LJ)#2+0
QW2=0+0
3006 SUSN=(REF(MJJE+1)+REF(MJJE+2))#1*0E+04
IF(ISUM=3007:3008
3008 QW1=REF(MJJE+1)#(TM/(TH+PM))#1*602060E-06)/T(NQIM*LJ)
QW2=REF(MJJE+2)#(TM/(TH+PM))#1*602060E-06)/T(NQIM*LJ)
3007 PCON#2=2.0*QRCH#(T(NQIM*LJ)#QW1+T(NQIM*LJ)#QW2)
13=1
GO TO 2606
1005 MLB=1
2653 IF(J0=3162:76:76
62 IF(IPAR)=6001:998:6002
6001 L=2
GO TO 47
CALL ZBARM

C ENERGY DO LOOP
56 I=IN
KKS=K
IF(NN).NE.50 .AND. NN.LT.51
30 I=IVAL(IOADO)
51 ETA=COUPH(I+B)
ELAB=T(I+B)
ECH=ELAB*(PM+TM)*1.602050E-06
RES=1.0/SQRT(ECH-ERCM)*2+GRCM**2)
ZEE=ETA/(ETA+1.04430E-27)/SQRT(8.0*ECM+RM1)
ALAM=DELTA(I+8)
BETA=ATAN2((ECH-ERCM),GRCM)
CS=COS(COUPH(I+LK)+DELTA(I+LK)-COUPH(I+LJ)-DELTA(I+LJ))
SIN=COUPH(I+LK)*SIN(T(I+LK)*RW(IK))
ANG=COUPH(I+LJ)*SIN(T(I+LJ)*RW(IJ))

C ANGLE DO LOOP
70 ANG=2.0*ETA+ALOGS(SIN(K))+2.0*COUPH(1+LK)+2.0*DELTA(I+LK)+BETA
ANG2=2.0*ETA+ALOGS(SIN(K))+2.0*COUPH(1+LJ)+2.0*DELTA(I+LJ)+BETA
CONST=ALAM*ZEE*RES*(2.0*ROJO+1.0)/(4.0*(SIN(K)**2))

C CALCULATION OF SUMFN
IF(NRJAT.EQ.1).GO TO 8065
8066 CTERM=0.0
SUFN=0.00
SUNIF=0.0
SUNMF=0.0
SUFN1=0.0
SUMI=0.0
CALL REACS
GO TO 8068
8065 IF(NCAL.EQ.1007,6155,6155)
6155 IF(NJOK.EQ.1007,1007,1008)
1007 WW=-2.0*ALAM/ZEE/(SIN(K)**2)
SUMFN=0.0
DO 601 LM=1,7
ALAM=LM-1
ANGG=2.0*ETA+ALOGS(SIN(K))+2.0*COUPH(I+LM)+DELTA(I+LM)
SUMFN=SUMFN+(2.0*AL+1.0)*SS(I+LM)*COS(ANGG)*PLALL(LEPARM)
601 CONTINUE
SUMFN=WWW*SUMFN

C CALCULATION OF SUFFN
SUFFN=0.0
DO 608 LEVAR=1,7
DO 609 LEVAR=1,7
WLL=LESMA-1
SX=SS(I+LESMA)
ANN=2.0*COU(I+LESMA)+DIL(I+LESMA)
LOWER=ABS(LESMA-LEVAR)+1
UPPER=LESMA+LEVAR-1
DO 610 LEPRM=LOWER+1,UPPER
LP=LEPRM-1
ANM=2.0*COU(I+LEPRM)+DIL(I+LEPRM)
SY=SS(I+LEPRM)
SUFFN=SUFFN+(2.0*WLL+1.0)*2.0*(LP+1.0)*CGE(LEVAR,LESMA,LEPRM)*
SX*SY*COS(ANN+ANM)*PLALL(LEVAR)
610 CONTINUE
609 CONTINUE
608 CONTINUE
SUFFN=SUFFN*(ALAM**2)

C CALCULATION OF SURFN FOR JO
1008 V0=-1.0*(ALAM**2)*2.0*RJO+1.0)/4.0*RES
SURF4=0.0
IF (INTE=1) 3022, 3023, 3023
3023 IF (NLOPT=1) 3024, 3025, 3025
3024 IF (I3=1) 3022, 3025, 3025
3025 IF (LPEX=2) 3026, 3027, 3028
3026 SURF5=SURF1
ANE=ANE+OETA-BETA
AN1=AN1+OETA-BETA
GAM1=SORT(PEW1*OEW1)*GSIGN(MJJE1)*GSIGN(MJJE1)
GAM2=SORT(PEW2*OEW2)*GSIGN(MJJE2)*GSIGN(MJJE2)
LPEX=2
GO TO 2613
3027 SURF2=-(1*GAM1*RES131/RES131)*SURFN
ANE=ANE+OETA-FETA
AN1=AN1+OETA-FETA
GAM1=SORT(GSAV1*OEW1)*GSIGN(MJJE1)*GSIGN(MJJE1)
GAM2=SORT(GSAV2*OEW2)*GSIGN(MJJE2)*GSIGN(MJJE2)
LPEX=3
GO TO 2613
3028 SURF3=GAM23*OES*SURFN
SURF1=SURF5
SURF=3
SURF3+SURF2
3029 SURFN=SURFS+SURF1+SURF4
LPEX=0
GAM1=GSAV1
GAM2=GSAV2
C CALCULATION OF RUTHERFORD
2600 CTERM=(ZEE**2)/(S11N(N1**4))
C CALCULATION OF SIGMA
8068 CALL EXTRA
 IF (ISERN=1) 19123, 19123
9123 IF (NNO=16141) 6141, 6142
6141 IMUS=15
KMUS=K
I=KMUS
K=10AD
6142 IF (NCAL=1) 6801, 1016, 1016
6801 IF (NLOPT=1) 1015, 6802, 6802
6802 COMP1(I+K+1)=(SUM1+SUMIF+SURFN)*1.0E+27
GO TO 1015
1016 KOOI=NFSAV(MJJE)
 IF (LES=1) 12625, 2627, 2627
2627 IF (LISTED=1) 12628, 2625, 2625
2628 KUTF=NFSAV(MJJE)
 IF (KUTF=1) 2625, 2625, 2629
2629 COMP1(I+K+KUTF)=(SUM1+SUMIF+SURFIN)*1.0E+27+COMP1(I+K+KUTF)
2625 IF (KOOI=16153, 6153, 6152
6152 COMP1(I+K+KOOI)=(SUM1+SUMIF+SURFN)*1.0E+27+PUMP1(KOOI)
 SAVE (KOOI=JOHN)=LL
6153 IF (MJJO=11015, 1015, 1017
1017 SIG1(I+K)=(SUM1+SUMIF+SURFIN)*1.0E+27+SIG1(I+K)+PUMP
GO TO 641
1015 SIG1(I+K)=(SUM1+SUMIF+CTERM+SUMFN+SURFN)*1.0E+27
641 IF (NN)=54, 54, 57
54 I=IMUS
K=KMUS
 IF (K=1) 77, 706, 706
706 IF (NLOPT=1) 180, 710, 710
710 IF (NCAL=1) 1705, 821, 821
77 K=K+1
J=1
GO TO 70
57 IF (I=1) 183, 707, 707
707 IF (NLOPT=1) 184, 711, 711
XXX(3,2)=X(3)
NPPIN=1
NPRIN=1
CALL FUNK
K=LL+1
LJ=LL+3
GO TO (821,822,821,822,821,822)*MZERO
81IPAR=-IPAR
JJ=0
IF(NBLL)=MIPAR)2654,2655,2655
82654NBLL=NBLL+1
ISTED=0
GO TO 2653
2655IF(NCAL-1)7308,7309,7309
7309MJOK=2
7308IF(ISTED-1)2641,60,60
2641LES=0
60CONTINUE
IF(NOPT-1)800,6110,6110
6110IF(NCAL-1)800,6262,6262
6262IF(MULE-1)6703,6269,6269
6703IF(KUUL-JUNE)6280,6265,800
6265NPRIN=0
NPPIN=1
WRITE(6,436)
DO 2307MJ=1,MXCAL
WRITE(6,437)ERESL(MJE)*SPINN(MJE)*IPITY(MJE)*REV(MJE)*1
REV(MJE)*2)*TAMMA(MJE)
2307CONTINUE
8260KUUL=KUUL+1
MJE=MJSAV(KUUL)
GR=TAMMA(MJE)
ER=ERESL(MJE)
INTFR=INTFS(MJE)
LL=LSAVE(KUUL,JULIE)
RJO=SPINN(MJE,JULIE)
C CALCULATION OF ZBAR
A1=LL
A2=LL+2
LMAX=(2+0*RJO-1+1)/2+0+1
DO 4413L=1,LMAX
AL=2*L-2
ZZL(L+1,1)=COFJ(8,A1,A1,AL,RJO,RJO,S,0,0,0,0,0,0)
ZZL(L+1,2)=COFJ(8,A1,A2,AL,RJO,RJO,S,0,0,0,0,0,0)
ZZL(L+2,1)=COFJ(8,A2,A2,AL,RJO,RJO,S,0,0,0,0,0,0)
4413 CONTINUE
ECHEK=T(1,18)
NTIM=(ER-ECHEK)/0.05+1+21
IF(NREAT-1)8877,8878,8878
8878MULE=1
CALL LDETM
CALL SETOW
8877IF(INTRFR-1)2617,2618,2618
2618LK=LL+1
LJ=LL+3
RJO=2+0*RJO+0.01
IPAR=IPITY(MJE,JULIE)
DO 2619IPUP=1,MXCAL
INTFR=INTFS(IPUP)
IF(INTRFR-1)2619,2620,2620
2620RJO=SPINN(IPUP)*2+0+0.01
IP=1*IPITY(IPUP,1)
IF (JO-J01)2619,2621,2619
2621 IF (IPar-IP1)2619,2622,2619
2622 IF (MJE-NJU)2623,2619,2623
2623 MJE=IPU
GO TO 2624
2619 CONTINUE
INTFR=0
LES=0
GO TO 2617
2624 PRCH=ERESL(MJE)*(TM/(TM+PM))*1.602060E-06
PRCH=(TAMM(MJE)/2.0)*(TM/(TM+PM))*1.602060E-06
PW=REW(MJE,1)
PW=REW(MJE,2)
NYIN=ERESL(MJE)-CHECK)/0.05+1.01
PCON1=2.0*PRCH-(T(NYIN+LK)*PW+T(NYIN+LJ)*PW2)
PCON2=GR*(TM/(TM+PM)-1*(INTIM+LJ)*REW(MJE,1)+T(INTIM+LJ)*REW(MJE,21)).
PCON2=PCON2*1.602060E-06
LES=1
INTFR=1
2617 JT1ME=GRA/0.05+1.01
JOMIN=INTIM-.JTIME
JOMAX=INTIM+.JTIME
IF (JOMIN-JMIN)6930,6931,6931
6930 JOMIN=JMIN
6931 IF (JOMAX-JMAX)6932,6933,6933
6933 JOMAX=JMAX
6932 NSPMX=MSAVE(MJE)
6269 RJO=SPINN(MJE+JULIE1)
LL=LSAVE(KUL+JULIE1)
JO=2.0+RJO+0.01
X(1)=REW(MJE,1)/1.602060E-06
X(2)=GR
X(3)=REW(MJE,2)/1.602060E-06
DO 6268 MTEE=1.3
DELTA=MTEE)=X(MTEE/10.0
6268 CONTINUE
MEPPN=0
MPPIN=0
IPAR=IPITY(MJE+JULIE1)
MATRX=0
MULE=1
MAXX=MXR
CALL STEPIT
YSAVE(1+JULIE1)=X(1)
YSAVE(2+JULIE1)=X(2)
YSAVE(3+JULIE1)=X(3)
IF (INN)=6270,6270,6271
6271 DO 6272 IN=1,NMAX
DO 6273 K=KKMIN,KMAX
SIG1(K+1)=SIG1(K+1)-COMP1(K+KUUL)
6273 CONTINUE
6272 CONTINUE
GO TO 6717
6270 DO 6274 K=KKMIN,KMAX
DO 6275 1OAD=1,JMAX
SIG1(K+1OAD)=SIG1(K+1OAD)-COMP1(K+1OAD+KUUL)
6275 CONTINUE
6274 CONTINUE
6717 IF J1ULIE=NSPMX=6701,6702,6702
6701 JULIE=JULIE+1
INTFR=INTFS(MJE)
IF (INTFR=1)2635,2636,2636
6236 RJO=SPINN(MJE+JULIE1)
IPAR=IPITY(MJE+JULIE1)
J0 = 2*0*IPU + 0.01
DO 2630 IPUP = 1, MXCAL
INTFR = INTFS(IPUP)
IF(INTFR = 1) 2630, 2631, 2631
2631 J01 = 2*0*SPINN(IPUP = 1) + 0.01
IP1 = IPITY(IPUP = 1)
IF(J0 = J01) 2630, 2632, 2630
2632 IF(IPAR = IP1) 2630, 2633, 2630
2633 MJJE = IPUP
GO TO 2634
2634 CONTINUE
LES = 0
ISTED = 1
GO TO 2635
2635 CONTINUE
IF (J0 = J01) 2630, 2636, 2636
2636 CONTINUE
IF (J0 = J01) 2630, 2637, 2637
2637 CONTINUE
CONTINUE
IF (NJV .GE. 1) STOP
END
C 
CALCULATION OF CROSS SECTION TERMS

LJ = LJ + 1
J = J + 3
C 
ENERGY DO LOOP
IF (NCAL - 1) 1931: 805, 805
803 IF (NPIN) 5299, 5299, 5300
5299 IF (NPIN) 5301, 5301, 5300
5300 IF (NPIN) 5306, 5306, 5306
931 J = J - 3804 OEW (MJE . I) - X (4) * 1 * 602060E - 06
OEW (MJE . I) - X (4) * 1 * 602060E - 06
IF (INF - 2) 19403, 19402, 19402
19402 OEW (MJE . I) - X (4) * 1 * 602060E - 06
OEW (MJE . I) - X (4) * 1 * 602060E - 06
OEW (MJE . I) - X (4) * 1 * 602060E - 06
OEW (MJE . I) - X (4) * 1 * 602060E - 06
9403 CHEVY = 0, 0
CHURH = 0, 0
CMHH = 0, 0
GO TO 56
804 IF (KCASE) 829, 829, 830
829 LK = 2
OEW (LJ) = X (1) * 1 * 602060E - 06
OEW (LJ) = X (1) * 1 * 602060E - 06
CHURH = 0, 0
CHEVY = 0, 0
CMHH = 0, 0
GO TO 56
830 LK = 3
OEW (LJ) = X (1) * 1 * 602060E - 06
OEW (LJ) = X (1) * 1 * 602060E - 06
CHURH = 0, 0
CHEVY = 0, 0
CMHH = 0, 0
56 L = L + 1
K = KKK5
IF (NCAL - 1) 16939, 6940, 6940
6940 K = 1
10AD = 1
SURSV = SURFN
AN2 = AN2 + FETA
AN1 = AN1 + FETA
GSAV1 = GAM1
GSAV2 = GAM2
GAM1 = SQRT(GAM1 * PEW1)
GAM2 = SQRT(GAM2 * PEW2)
LPEX = 1
GO TO 2613

2612 SURF1 = GAM12 + TES * SURFN
SURFN = SURSV + SURF1
LPEX = 0
GAM1 = GSAV1
GAM2 = GSAV2

C CALCULATION OF SIGMA

2608 PUMP = 0.0
CALL EXTRA
IF(NIN) = 6141 + 6141 + 6142

6141 K = K + 1
KMUS = K
CTERM = 1.0E+27
IF(NREAT) = 1.9531 + 9532

9531 CTERM = 1.0

6142 SIG1(I*K) = SIG1(I*K) - COMPI(I*K + KUUL) + (RSUM1 + SUM1 F + SURFN) * 1.0E+27
1 + PUMP
COMPI(I*K + KUUL) = (RSUM1 + SUM1 F + SURFN) * 1.0E+27 + PUMP
IF(NIN) = 54.54.57

54 CHMH = CHMH + ((SIG1(I*K) / CTERM) * EXP(I*K)) / SIG1(I*K) * CTERM
COMSV(I*K + JULIE) = COMPI(I*K + KUUL)

6903 I = KMUS
K = KMUS
IF(K = KMAX) = 77, 69, 69

77 K = K + 1
J = J + 1
GO TO 70

97 CHMH = CHMH + ((SIG1(I*K) - EXP(I*K)) * CTERM) / SIG1(I*K)
COMSV(I*K + JULIE) = COMPI(I*K + KUUL)

6906 IF(I = 1) = 6934 + 6935
6935 IF(I = 10) = 6936 + 6934
6936 CHEVY = CHEVY + ((SIG1(I*K) - EXP(I*K)) * CTERM) / SIG1(I*K)
6934 IF(I = 10) = 83, 72, 72
83 I = I + 1
GO TO 51

C CHOICE OF RETURN

401 FORMAT(’(8X,2HRW,10X,5HGMMA,10X,4HSPIN,11X,2HER,7X,12HSIN(TMTHA/2),12X,1MP/)’)
402 FORMAT(’(52X,1E12,4,2X,112)’)
403 FORMAT(’(6X,6HRW(LK),8X,6HRW(LJ),8X,6HTGMMA,10X,1HF;12X,4HSPIN,11X,12HER,7X,12HSIN(TMTHA/2),6X,5HSIGN,5X,1MP/)’)
404 FORMAT(’(8(2X,1E12,4,2X,112)’)
405 FORMAT(’(6X,8CAL SIG1,6X,7EXP SIG,8X,4HELAB/)’)
406 FORMAT(’(J(2X,1E12,4))’)
407 FORMAT(’((X,7CH1SO= ,T1F0;12)’)
408 FORMAT(’(8X,2HRW,10X,5HGMMA,10X,4HSPIN,11X,2HER,11X,4HELAB,6X,1HP/)’)
409 FORMAT(’(6X,6HRW(LK),8X,6HRW(LJ),8X,6HTGMMA,10X,1HF;12X,4HSPIN,11X,12HER,11X,4HELAB,10X,5HSIGN,5X,1HP/)’)
410 FORMAT(’(6X,8CAL SIG1,6X,7EXP SIG,4X,12HSIN(TMTHA/2))’)
411 FORMAT(’(K0)’)
416 FORMAT(’(1H)’)
417 FORMAT(’(6X,2HER,12X,2HJO,9X,1MP,2X,12HSIN(TMTHA/2))’)
418 FORMAT(’(1X,21E12,4,2X,112,2X,1E12,4))
419 FORMAT(’(6X,2HER,12X,2HJO,9X,1MP,6X,4HELAB/)’
WRITE(6,406)
WRITE(6,402)X(1),XZZY+RJO+ER+T(I+B)+IPPR
WRITE(6,407)CHHH
WRITE(6,415)
GO TO 836

836 NZERO=3
GOSS=G$SIGN(1.1)+G$SIGN(1+2)
NTIM=(ER-T(I+B))/0.05+1.2
XZZY=X(2).#(TM1+TM1));
F=RTW(LJ1)1T(NTIM+LJ)+RTW(LK11T(NTIM+LK))/(2.0*GRCM)
XZW=RTW(LJ)/1.602060E-06
WRITE(6,409)
WRITE(6,404)X(1),XZZY,F +RJO+ER+T(I+B)+GOSS+IPAR
WRITE(6,407)CHHH
WRITE(6,415)

836 IF NCAL=12320+2321+2321
2321 I0AD=1
2322 IF (NPRINT2322+2323+2324
2324 WRITE(6,419)
IVAL(I0AD)
WRITE(6,418)ER+RJO+IPAR+T(I+B)
2320 WRITE(6,410)
WRITE(6,406)(SIGI(K1+I0AD)+YEXP(K1+I0AD)+SINN(K1+K1+KKMIN+KMAX)
WRITE(6,416)
2323 IF (NPRINT2326+2326+2327
2327 PUNCH406(S1G1(K1+I0AD)+YEXP(K1+I0AD)+SINN(K1+K1+KKMIN+KMAX)
WRITE(6,410)
IF (NCAL=12330+2331+2332
2331 IF (I0AD=JMAX12333+2330+2330
2333 I0AD=I0AD+1
GO TO 2322
2330 RETURN
END

SUBROUTINE SETOW

DIMENSION PENTR(41+8),ZELTA(41+8),ZZZ(63+3+2),OW1(82),OW2(83)
DIMENSION CODE(816+2),CORE(984+3),OSPPN(82),OSPPN(83)
DIMENSION OW1(8),OW2(8)+G$SIGN(82)
DIMENSION CERESL(8)
DIMENSION R(8)+RAA1(6)+RAA2(6)
DIMENSION IVAL(1),T(41+8)+COUPH(41+8)+DELTAt(41+8)+SINN(83)+SS(41)
DIMENSION CGE(771+13)+ZZ(162+2)+PLALL(10+3)+S1G1(851)
DIMENSION YEXP(41+06)+COU(41+13)+DIL(41+13)+COMP(41+54)+COMP2(41+54)
DIMENSION C1(1)+54)+FISAV(5)+F1+54)+
DIMENSION RAA2(6)+DAA1(6)+RBB1(6)
DIMENSION L1SAV(8)+L1PSV(82)+PUMP1(4)+ZZZ(93+3)+B,8,3)
DIMENSION SPINN(84)+IPITY(84)+TAMMA(8)+REW(82)+INTFS(8)+MJSAV(1)
14)+NFSAV(8)
DIMENSION VEC(20)+TRIAL(20)+XSACE(20)+CH1(20)+DX(20)+SECOND(22)
DIMENSION OLDVEC(20)+SAVOL(20)+XOSC(20+15)+CH1OSC(15)
DIMENSION MASK(20)+X2(20)+X3MAX(20)+X1MIN(20)+DELTAX(20)+DELMIN(20)
DIMENSION ERR(20,20)

COMMON KW,NTACE,MAKEX,MAKEX,MAX+,MAX+I,MAX+DELTA,DELMIN,MAX+M11AX
COMMON ERR,CHISQ,RATIO,COLN+NCOMP+ACK,MAX+MOUSE
COMMON NPRINT,KCASE,IOAD,IPAR+ZERO,MIN+MAX+1+MIN+NUM+KKS,MAX+NUM+NN+JO+LL
COMMON KMAX+RJO+ER+KU=2+JULIE+10M1+10MAX+JMAX+FISAV
COMMON IVAL+T+COU+DELTAL1S1G1+SS+C1+ZZ+PLALL+YEXP
COMMON COU+DIL+SIGN+F1+NPRINT+NCAL+COMP1+COMP2+COMSV
COMMON PCON1,PCON2,PAW2+PZ2+PLA+INTFR+FCRM+PRCM
COMMON GAI1+GAM2+CS+RES+ECM+W1+QW2+PSON+HRCM+GRCM+BE+NOPT
COMMON INTFS+3+11+LK+LJ+LMAX+K+J+J+ALAM+ERE1
COMMON RAA1+RAA2+RBB1
COMMON RSUM1+RSUM3+MJE+MJE
COMMON TES+DES+RES1+RES2+RES23+QEW1+QEW2+PEW1+PEW2+SETA+FETA
COMMON GAM1+GAM2+GAM3+GAM2+G$SIGN+ISRM
COMMON QW1+QW2+PENTR+QEW1+QEW2+ZELTA+ZZZ
COMMON 1ZE, 1ZF, JGILK, JGILJ, JG2LK, JG2LJ, JG2LM, IFINS
COMMON NTIM, GRCH, NTMRT
COMMON MULE, MXCAL, IPITY, LSAV, LIPSV, JUNT, INTFS, MJSAV, NFSAV
COMMON SPNN, TANMA, RE*, PUMP1, PUMP2, ZZZ, CODE, CORE, OSPN, OSPPN
TM=9.01219
PM=4.00026
IF (IFINS=2) 8042, 8043, 8043
8042 OWI (JGILK) = GRCH/PENTR(NTIM, JGILK)
MASK(4) = 0
OWI (JGILJ) = 0.0
MASK(5) = 1
MASK(6) = 1
MASK(7) = 1
MASK(8) = 1
GO TO 8044
8043 IF (1ZE=2) 8042, 8044, 8049
8049 XX = GRCH/(PENTR(NTIM, JGILK) + PENTR(NTIM, JGILJ))
OWI (JGILK) = XX/4.0
OWI (JGILJ) = XX/4.0
MASK(5) = 0
MASK(4) = 0
MASK(6) = 1
MASK(7) = 1
MASK(8) = 1
8044 SUM = (0E91(MJE+1)+0E91(MJE+2)) + 0E+04
IF (MULE=1) 4132, 4131 + 4131
4131 OWI (JGILK) = 0E91(MJE+1)
OWI (JGILJ) = 0E91(MJE+2)
GO TO 8047
4132 IF (ISUM) 8047, 8048, 8048
8048 OWI (JGILK) = (0E91(MJE+1)*(TM/(TM+PM)) + 602060E-06)/PENTR(NTIM, JGILK)
OWI (JGILJ) = (0E91(MJE+2)*(TM/(TM+PM)) + 602060E-06)/PENTR(NTIM, JGILJ)
8047 IF (IFINS=2) 8050, 8051, 8051
8051 IF (IFZ=1) 8052, 8053, 8053
8052 XX = GRCH/(PENTR(NTIM, JG2LK) + PENTR(NTIM, JG2LJ) + PENTR(NTIM, JG2LM))
OWI (JG2LK) = XX/6.0
OWI (JG2LJ) = XX/6.0
OWI (JG2LM) = 0.0
MASK(6) = 0
MASK(7) = 0
MASK(8) = 0
GO TO 8056
8052 IF (IFZ=2) 8057, 8058, 8058
8058 XX = GRCH/(PENTR(NTIM, JG2LK) + PENTR(NTIM, JG2LJ))
OWI (JG2LK) = XX/4.0
OWI (JG2LJ) = XX/4.0
OWI (JG2LM) = 0.0
MASK(6) = 0
MASK(7) = 0
GO TO 8056
8057 OWI (JG2LK) = GRCH/PENTR(NTIM, JG2LK)
OWI (JG2LJ) = 0.0
OWI (JG2LM) = 0.0
MASK(6) = 0
8058 SUM = (0E92(MJE+1)+0E92(MJE+2)+0E92(MJE+3)) + 0E+04
IF (MULE=1) 4133, 4134 + 4134
4134 OWI (JG2LK) = 0E92(MJE+1)
OWI (JG2LJ) = 0E92(MJE+2)
OWI (JG2LM) = 0E92(MJE+3)
GO TO 4135
4135 IF (ISUM) 8055, 8055, 8055
8059 OWI (JG2LK) = 0E92(MJE+1)*(TM/(TM+PM)) + 602060E-06)/PENTR(NTIM, JG2L
SUBROUTINE REACS
DIMENSION PENTR(4,8),OW2(17),OEW1(8,2),OEW2(8,3)
DIMENSION OW1(8),OW2(8),SSIGN(8,2)
DIMENSION CODE(8,16),CORE(9,8,3),OSP(8,2),OSPPN(8,3)
DIMENSION ERESL(8)
DIMENSION RW(8),RAA1(6),RAA2(6)
DIMENSION IVAL(7),T(41,8),COUPH(41,8),DELTA(41,8),SINN(33),SS(41,13),CGE(7,7,13),ZZ(6,2,2),PLALL(10,33),SIG(41,5,11)
DIMENSION EXP(41,13),COMPS(41,5,4),COMP1(41,5,4),COMP2(41,5,4)
DIMENSION VS(8,4),FISAV(15),FL(15,4)
DIMENSION DAR(6),DA(6),RB(16)
DIMENSION LS(8,15),LSV(16),PUMP(4),ZZZ(9,3,3,8,3)
DIMENSION SP(8,4),PITY(8,4),TAMMA(8),REW(8,2),INTFS(8),MJSAV(41,8)

END
IPTAV(8)
DIMENSION VEC(20),TRIAL(20),XSAVE(20),CHI(20),DX(20),SECOND(2,2)
DIMENSION OLOVEC(20),SALVO(20),XOSC(20,15),CH1OSC(15)
DIMENSION MASK(20),X(20),XMIN(20),DELTAX(20),DELMIN(20)

ERR(20,20)
COMMON KV,NV,NTRAC,MASK,XMAX,XMIN,DELTAX,DELMIN,MATRIX
COMMON ERR,CHI,RAI,TAT,COIN,NCOMP,ACK,MAX,MOSQUE
COMMON NPRIN,KCASE,LOAD,IPAR,MZERO,IMAX,KKS,KKIN,NN,JO,LL
COMMON KMAX,RJO,ER,JO,UL,EOMIN,OMAX,JMAX,FISAV
COMMON IVAL,TV,COUPN,DELTAX,SSN,SS,CGE,ZZ,PLALL,YEXP
COMMON RODIL,SG1,FL,PPIN,NCAL,COMP1,COMP2,COMPV
COMMON PCOM1,PCOM2,PK1,PW2,LES,INFR,FRM,PRCM
COMMON GAM1,GAM2,CS,RES,ECM,OQ1,OQ2,PCON3,COMP2,COMPV
COMMON INTF3,IL,LK,LJ,LMAX,K,LMX,ALAM,ERESL
COMMON RAA1,RAA2,RA81
COMMON RSUM1,RSUM3,MJE,MJE
COMMON TES,QES,RES2,RES13,RES23,GE1,GE2,PEW1,PEW2,GETA,FETA
COMMON GAM12,GAM13,GAM23,GSIGN,ISERH
COMMON OW1,OW2,PENTR,GE1,GE2,ZETRA,ZZZ
COMMON IE,12,F,JGILK,JGILJ,JG2LK,JG2LJ,JG2LM,INFNS
COMMON NTIM,GRCM,NNRTA
COMMON MULE,MCAL,IPAV,COUP,OSPN,OSPPN
COMMON IF<NCAL=117101,7202,7202

7101 MJE=1
7202 IF (NQPT=1) 8070,8071,8071
8071 OW1(JGILK)=X(4)*1.602060E-06
8072 OW1(JGILJ)=X(5)*1.602060E-06
8072 IF (INFNS=2) 8070,8072,8072
8073 OW2(JG2LK)=X(6)*1.602060E-06
8074 OW2(JG2LJ)=X(7)*1.602060E-06
8075 OW2(JG2LM)=X(8)*1.602060E-06
8070 GIS1=SORT_OW1(JGILK)*PENTR(1,JGILK)*OSPN(MJE=1)
8071 GIS1=SORT_OW1(JGILJ)*PENTR(1,JGILJ)*OSPN(MJE=2)
8072 IF (INFNS=2) 8053,8063,8053
8063 GIS2=SORT_OW2(JG2LK)*PENTR(1,JG2LK)*OSPN(MJE=1)
8064 GIS2=SORT_OW2(JG2LJ)*PENTR(1,JG2LJ)*OSPN(MJE=2)
8065 GIS2=SORT_OW2(JG2LM)*PENTR(1,JG2LM)*OSPN(MJE=3)
8066 CS12=COS(ZETA(1,JG2LK)-ZELTA(1,JG2LJ))
8067 CS13=COS(ZETA(1,JG2LK)-ZELTA(1,JG2LM))
8068 CS23=COS(ZETA(1,JG2LJ)-ZELTA(1,JG2LM))
8062 CSS=COS(ZELTA(1,JGILK)-ZELTA(1,JGILJ))
8063 IF (JG1JK) 78,78,79
78 DO 8 L=1,LMAX
80 DAA1(L,1)=GAM1*ZZZ(L,1,1)-2.0*(SORT(GAM1,GAM2))2ZZZ(L,1,2)*CS+GAM2*ZZZ(L,1,2)
80 DAA1(L,2)=GAM1*ZZZ(L,1,1)-2.0*(SORT(GAM1,GAM2))2ZZZ(L,1,2)*CS+GAM2*ZZZ(L,1,2)
80 RAA1(L,1),(G15**2)*ZZZ(L,1,1,-2.0*(G1S1**2)*G2S1*ZZZ(L,1,2)**1)
80 RAA1(L,2),(G15**2)*ZZZ(L,1,1,-2.0*(G1S1**2)*G2S1*ZZZ(L,1,2)**1)
80 RAA2(L,1),(G15**2)*ZZZ(L,1,1,-2.0*(G1S1**2)*G2S1*ZZZ(L,1,2)**1)
80 RAA2(L,2),(G15**2)*ZZZ(L,1,1,-2.0*(G1S1**2)*G2S1*ZZZ(L,1,2)**1)
80 IF (ISERH=1) 9105,9104,9104
9105 RAA1(L)=RAA2(L)
9106 IwOR=GSIGN(MJE,1)+GSIGN(MJE,2)+0.01
9107 IF (IwOR) 9109,9109,9101
9101 DAA1(L)=DAA2(L)
GO TO 9110
9104 COMP1(MJE)=DAA1(L)*0.25*RES**2
9105 COMP1(MJE)=DAA2(L)*0.25*RES**2
9106 COMP1(MJE)=RRA1(L)
9107 COMP1(MJE)=RRA2(L)
9110 IF (INFNS=2) 8060,8060,8060
8060 RERA=(G15**2)*ZZZ(L,1,1,-2.0*(G1S1**2)*G2S1*ZZZ(L,1,2)**1)
8064
```fortran
1 3 3 2 2
A12=2.0*G12*G22*ZZZ(L+1,2,2)*CS2
A13=2.0*G12*G32*ZZZ(L+1,3,2)*CS3
A23=2.0*G22*G32*ZZZ(L+2,3,2)*CS23
RBB1(L)=RERA+AI2+A13+A23
1*SERH=1189202,9202
9202 COMP2(L+MJE+2)=RERA+AI2-A13-A23
COMP2(L+MJE+3)=RERA+AI2+A13-A23
COMP2(L+MJE+4)=RERA-A12-A13+A23
COMP2(L+MJE+1)=RBB1(L)
8 CONTINUE
79 RSUM1=0.0
RSUM3=0.0
IF(SERH=119301*8065)8065
9301 DO 24 L=1,LMAX
MM=2*L-1
RSUM1=DAAI(L)+RAAI(L)+PLALL(MM,K)+RSUM1
IF(IFINS=2)24,8061,8061
8061 RSUM3=DAAI(L)+RBB1(L)+PLALL(MM,K)+RSUM3
24 CONTINUE
RSUM1=0.25*(RES**2)*RSUM1+(ALAM**2)*0.25
RSUM3=0.25*(RES**2)*RSUM3+(ALAM**2)*0.25
RSUM1=RSUM1-RSUM3
IF(INS=2)8064,8065,8065
8064 RSUM1=-RSUM1
8065 RETURN
END
SUBROUTINE LDETM
DIMENSION PENTR(41,8),ZELTA(41,8),ZZZC6.3.3.2),EWE1(8,2),EWE2(8,3)
DIMENSION CODE(8,16,2),CORE(9.8+4.3),OSPN(8.2),OSPPN(8,3)
DIMENSION GW(8),OW2(8),GSIGN(8,2)
DIMENSION ERESL(8)
DIMENSION Rw(8),RAA1(6),RAA2(6)
DIMENSION IVAL(7),T(4,8),COUPH(4,1,8),DELTAL(41,8),SINN(33),SS(41,13)
DIMENSION CGE(7,7,13),ZRE(2,2,2),PLALL(10,33),SIG1(4,1,5)
DIMENSION VEXP(4,4),COU(4,1,13),DIL(4,1,13),COMP1(41,5,4),COMP2(41,5,4)
DIMENSION COMSV(41,5,4),FSAV15,FSAV15
DIMENSION DAA2(6),DA1(6)+RBB1(6)
DIMENSION LSIV(8),LPSV(8,2)+PUMP(4),ZZZ9,3,8,8,3)
DIMENSION SPINN(8,4)+LITY(8,4),TAMM(8),REW(6,2)+INTFS(8),MJSAV(14)+NFSAV(8)
DIMENSION VEC(20),TRIAL(20),XSAVE(20),CH(20),DX(20),SECOND(2,2)
DIMENSION OLDEVE(20),SAVO(20),XOSC(20,15),CHI(20,15)
DIMENSION MASK(20),XMAX(20),XMIN(20),MAXR(20),DELMIN(20),XMAX(20),DELMIN(20)
1ERR(20,20)
COMMON KMW,NTRAC,MASK,X,XMAX,XMIN,DELTA,DELMIN,MATRIX
COMMON ERR+CHISO,RATIO,COLIN,NCOMP,ACK+MOSQ,MOUSE
COMMON INPRIN,KCASE,LOAD,IPAR,MZERO,MIN+MAX,KKK5,KKM5,NN,J0,L1
COMMON KMAX,+RO+ER+KUUL2,JULIE+1OMIN,1OMAX,JMAX,FISAV
COMMON IVAL+COUPH+DELA+SINN,SS,CGE,ZZ,PLALL,YEXP
COMMON CoupH+DELTA+SINN,SS,CGE,ZZ,PLALL,YEXP
COMMON COMSV(41,5,4),FSAV15,FSAV15
COMMON PCON1,PCON2,P1,W2,LES,IFR+FRM,PRM
COMMON GAM1+GAM2,CS,RES,ECM,G1,G2,PCON3,HRM,ORCMBETA,NOPT
COMMON INTFS(13,1,1,1,1),LJ+LMAX+X,K,JJ,ALAM,ERESL
COMMON RAA1,RAA2,RBB1
COMMON RSUM1,RSUM3,MJE+MJJE
COMMON RES,RES,RES,RES,RES,RES,REW1,REW2,PEW1,PEW2,PEW3,PEW2,PEW3,PEW3
COMMON GAM1,GAM2,GAM3,SSIGN,ISERH
COMMON OW1,OW2,PENTR,OW1,REW2,ZETAL,ZZZ
COMMON IZE+IZE,JG1,JG1L,JG2L,JG2L,JG2LM,IFINS
COMMON NTIM+GRSM,REX
COMMON MILE+MXCOL+LITY+LISA+LPSV+JUNE+INTFS,MJSAV,NFSAV
COMMON SPINN,TAMM,REW,PUMP1,PUMP,ZETAL,ZZZ,CODE,CORE,OSPN,OSPPN
SP2=2.5
```
```
IF(IFINS=2)B018,B019,B019
B018 SPI=0.50
GO TO B007
B019 SPI=1.5
IF(JO=3)B006,B007,B007
B006 IF(IPAR)B008,B009,B009
B008 JOG=1
IZE=1
GO TO B010
B009 JOG=2
IZE=1
GO TO B010
B007 LLMIN=RJO-SP1+0.01
LTEST=(LLMIN/2)*2
N=LLMIN-LTEST
IF(N)B011,B011,B012
B011 IF(IPAR)B013,B013,B014
B013 JOG=LLMIN+1
IZE=2
GO TO B010
B014 JOG=LLMIN
IZE=2
GO TO B010
B012 IF(IPAR)B015,B015,B016
B015 JOG=LLMIN
IZE=2
GO TO B010
B016 JOG=LLMIN+1
IZE=2
B010 AP1=JOG
AP2=JOG+2
JG1LK=JOG+1
JG1LJ=JOG+3
(1PSVIMG.E-1)=JG1LK
IF(IFINS=2)B021,B022
B021 DO 8023 L=1,LMAX
AL=24L-2
ZZZIL(1,1,1)=CDFJB (AP1,AP1,AL+RJO,RJO,SP1+0.0,0.0,0.0,0.0)
ZZZIL(1,2,1)=CDFJB (AP1,AP2,AL+RJO,RJO,SP1+0.0,0.0,0.0,0.0)
ZZZIL(2,2,1)=CDFJB (AP2,AP2,AL+RJO,RJO,SP1+0.0,0.0,0.0,0.0)
B023 CONTINUE
GO TO B020
B022 IF(JO=5)B024,B025,B025
B024 IF(JO=3)B026,B027
B026 IF(IPAR)B028,B028,B029
B028 JOG=3
IZE=1
GO TO B030
B029 JOG=2
IZE=1
GO TO B030
B030 IF(IPAR)B031,B031,B032
B031 JOG=1
IZE=2
GO TO B030
B032 JOG=2
IZE=2
GO TO B030
B033 JOG=3
LTEST= LLMIN=2
N=LLMIN-LTEST
IF(N)B033,B033,B034
B034 IF(IPAR)B035,B035,B036
```
FUNCTION FEG(L, L, Y)
DIMENSION P(40)
C FEG CALCULATES 1ST AND 2ND ORDER LEGENDRE FUNCTION
C L = (L-1) DEGREE OF LEGENDRE FUNCTION
C LL = (LL-1) ORDER OF LEGENDRE FUNCTION
C X = THETA IN DEGREES
X=903*41592654/180
GO TO (21,22),LL
21 M=1
P(M)=1.0
IF(LM-6+10+6
6 M=2
P(M)=COS(X)
IF(LM-1+1+10+7
7 M=M+1
FM=M-1
P(M)=((2*MFM-1)*COS(X)*P(M-2)-(FM-1)*(FM-2))/FM
IF(LM-1+1+10+7
22 M=2
P(M)=SIN(X)
IF(LM-1+1+10+1
1 M=3
P(M)=3*SIN(X)*COS(X)
IF(LM-1+1+10+2
2 M=M+1
FM=M-1
P(M)=((2*MFM-1)*COS(X)*P(M-2)-(FM-1)*P(M-1))/(FM-1)
IF(LM-1+1+10+2
10 FEG=P(M)
RETURN
END
FUNCTION COFJ(J,A,B,C,X,Y,Z,A1,B1,C1)
  MODIFIED FROM TOBOCMAN COFJ BY GEORGE MARR
GO TO (1,2,3,4,5,6,4+4)J
1 D=COFCG(A,B,C,X,Y,Z)
  COFJ=D
GO TO 7
2 D=COFCG(A,B,C,X,Y,Z)
  COFS3J=1+0
  M=AJ+B-Z
  COFS3J=COFS3J*(-1)+M+D/SORT (2+0*C+1+0)
  COFJ=COFS3J
GO TO 7
3 H=COFJU(A,B,C,X,Y,Z)
  COFJ=H
GO TO 7
4 H=COFJU(A,B,C,X,Y,Z)
  COFS5J=1+0
  H=A+B*X+Y
  COFS5J=COFS5J*(-1)+M/SORT ((2+0*C+1+0)*(2+0*X+1+0))
  COFJ=COFS5J
  K=J-3
GO TO (7,7,7,8,9)K
8 KK=A+B*X+Y
  COFJ=COFJ*(-1)+KK
GO TO 7
  9 KK=A+B*X+Y
  RT=SORT((2+0*X+1+0)*(2+0*X+1+0)*(2+0*Y+1+0))
  COFJ=COFJ*(-1)*KK+RT*COFCG(A,B,C,X,Y,Z)
GO TO 7
5 R=COF9J(A,B,C,X,Y,Z,A1,B1,C1)
  COFJ=R
GO TO 7
6 R=COF9J(A,B,C,X,Y,Z,A1,B1,C1)
  COFS9J=1+0
  COFS9J=COFS9J/R/SORT ((2+0*X+1+0)*(2+0*Z+1+0)*(2+0*A1+1+0)*(2+0*B1+1+0))
  COFJ=COFS9J
7 RETURN
END
FUNCTION BICO (A,B)
  FUNCTION BICO CALCULATES BINARY COEFFICIENTS
X=A-B
IF(X)201,202,203
201 BICO =0
  GO TO 207
202 BICO =1
  GO TO 207
203 IF(B)201,202,204
204 Y=MINI(B,X)
  IF (Y-1+1)208,208,209
208 BICO=A
  GO TO 207
209 BICO=A/Y
  J=FIX(Y-1+1)
  DO 205 L=1+1,J
    U=FLOAT(1)
  205 BICO=BICO*(A-U)/(Y-U)
  RETURN
END
FUNCTION COFCG(A,B,C,X,Y,Z)
  FUNCTION COFCG CALCULATES CLEBSCH GORDAN COEFFICIENTS
IF(C-A-B)301,301,302
302 COFCG=0.0
GO TO 399
301 IF (A-B-C) 303, 303, 302
303 IF (B-A-C) 304, 304, 302
304 IF (Z-X-Y) 302, 305, 302
305 NMAX= MIN1 (C-A+B+C+Z) +1
NMIN= MAX1 (O-B+Z-A+2)
SUM=0
COFCG=1
YY=ABS(X)+ABS(Y)*100.0
ICHEK=YY+0.01
IF (ICHEK=1) 701, 702, 702
701 K=C+A+B+0.01
K2=(K/2)+2
IF (K-K2) 703, 702, 703
703 COFCG=0.0
GO TO 399
702 XI=A+X
Y1=B+Y
Z1=C+Z
X2=A-X
Y2=B-Y
Z2=C-Z
Z3=C+2+C+1
R=A+B+C+1+0
S=C+B+X
T=B+C-A
J=IFIX (Y)
DO 306 I=NMIN, NMAX
K=K+1
U=FLOAT (I) 1-1.0
IFIX) 11, 12, 13
306 SUM=SUM(-1.0)*K*BICO (Z1+U)*BICO (S-U+X1)*BICO (X2+U, Y)
SUM=(-1.0)*J*SUM
IFIX) 11, 12, 13
11 G=1/BICO (X2, X1)
L=1
' GO TO 14
12 G=1.
L=1
GO TO 14
13 G=BICO (X1, X2)
L=1
14 IF (Y) 15, 16, 17
15 G=G/BICO (Y2, Y1)
L=L-2
GO TO 18
16 G=G+1.
L=L+2
GO TO 18
17 G=G+BICO (Y1, Y2)
L=L+2
18 IF (Z) 19, 20, 21
19 G=G+BICO (Z2, Z1)
L=L-3
GO TO 22
20 G=G+1.
L=L+1
GO TO 22
21 G=G/BICO (Z1, Z2)
L=L+1
22 L=16+L/2
GO TO (23+24, 25, 26, 27, 28)*L
23 G=G+BICO (-2, Z2, -2, X)
GO TO 307
24 G=G/BICO (-2, Y, -2, Z)
FUNCTION COFJU (A, B, C, X, Y, Z)
COFJU CALCULATES 6-J SYMBOLS
IF (C < A - B) GO TO 402
402 COFJU = 0.0
GO TO 499
401 IF (A - B < C) GO TO 403
403 IF (B - C < A) GO TO 404
404 IF (C - X < Y) GO TO 405
405 IF (X - Y < C) GO TO 406
406 IF (Y - X < C) GO TO 407
407 IF (Z - X < B) GO TO 408
408 IF (X - Z < B) GO TO 409
409 IF (B - X < Z) GO TO 410
410 IF (Z < A - Y) GO TO 411
411 IF (A - Z < Y) GO TO 412
412 IF (Y - Z < A) GO TO 413
413 NM1X = MIN1 (A + B + C + X + Y + Z - 2 + B + X + Z + 1)
NM1N = MAX1 (0 + A - C + X - Z - B + C + Y - Z + 1)
SUM = 0.0
COFJU = 1.0
X3 = A + B + X + Y + Z + 1
Y3 = C + X + Y + Z + 1
Z3 = 2 + C + Z + 1
X4 = A + C + X - Z + 1
Y4 = A + B + X + Y - 2 + Z + 1
Z4 = B + X - Z + 1
R1 = A + B + C + 1
T1 = B + C - A
Z5 = 2 + Z + 1
R2 = X + Y + Z + 1
R3 = A + Y + Z + 1
T2 = Y + C - X
T3 = Y + Z - A
DO 414 I = NM1N,NM1X
K = I - 1
U = FLOAT (I - 1)*0
414 SUM = SUM + (-1)**K*BICO (X3-U,Y3)*BICO (Y3,Z3-U)*BICO (Z3-U,X4)*BICO (X4-U,Z4)*BICO (Z4-U+1)*U+1)
COFJU = COFJU*SUM*SQRT (Z3*Z5/(BICO (R-1 -Z+C)*BICO (2+C,T)*R*BICO (R1-1 -Z+C)*BICO (2+C,T)*R*BICO (R2-1 -Z+C)*BICO (2+C,T)*R*BICO (R3-1 -Z+C)*BICO (2+C,T)*R))
499 RETURN
END
FUNCTION COF9J (A, B, C, X, Y, Z, A1, B1, C1)
FUNCTION COF9J CALCULATES 9-J SYMBOLS
A2 = ABS (A - C1)
B2 = ABS (B - Z)
C2 = ABS (X - B1)
G1 = AMAX1 (A2, B2, C2) + 1.0
G2 = AMIN1 (A1 + C1, B + Z + B1) + 1.0
NG1 = G1
**C AUTHOR**

*JO. CHANDLER 4. PHYSICS DEPT. BLOOMINGTON, IND.

**SUBROUTINE STEP**

END

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! I CMAT (1)/ (1+0.4)
C MAIN DO LOOP FOR CYCLING THROUGH THE VARIABLES.
C FIRST TRIAL STEP WITH EACH VARIABLE IS SEPARATE.

200 
NACK=0 
DO 1050 I=1,NV 
OLDVEC(I)=VEC(I) 
VEC(I)=0.0 
TRIAL(I)=0.0 
KK=1 
IF(MASK(I))1050,10,1050 
1050 
NACK=NACK+1 
XSAVE(I)=X(I) 
IF(ISIGNIF(ABS(DX(I))<ABS(X(I))))360,360,220 
220 
X(I)=XSAVE(I)+DX(I) 
NFLAG=1 
JF (X(I)<XMIN(I))240,230,230 
STEP0035 
STEP0034 
STEP0033 
STEP0036 
STEP0037 
STEP0038 
STEP0039 
STEP0040 
STEP0041 
STEP0042 
STEP0043 
STEP0044 
STEP0045 
STEP0046 
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STEP0050 
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STEP0070 
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STEP0087 
STEP0088 
STEP0089 
STEP0090 
STEP0091 
STEP0092 
STEP0093 
STEP0094 
STEP0095 
STEP0096
230 IF(X(1)-XMAX(1))250+250+240
240 NFLAG=NFLAG+3
GO TO 270
250 CALL FUNK
NF=NF+1
CHIME=CHISO
IF(CHISO-CHIOLD)400+260+270
260 NFLAG=NFLAG+1
270 X(1)=XSAVE(1)-DX(1)
IF(X(1)-XMIN(1))370+280+280
280 IF(X(1)-XMAX(1))290+290+370
290 CALL FUNK
NF=NF+1
IF(CHISO-CHIOLD)390+300+310
300 NFLAG=NFLAG+1
310 IF(NFLAG=3)320+360+370
320 TRIAL(1)=DX(1)+0.5*(CHISO-CHIME)/(CHIME-2.0*CHIOLD+CHISO)
IF(TRIAL(1))330+370+330
330 VEC(1)=TRIAL(1)/ABS(DX(1))
X(1)=XSAVE(1)+TRIAL(1)
CALL FUNK
NF=NF+1
IF(CHISO-CHIOLD)340+350+350
340 CHIOLD=CHISO
GO TO 380
350 TRIAL(1)=0.0
VEC(1)=0.0
GO TO 370
360 VEC(1)=0.0
370 X(1)=XSAVE(1)
380 NCIRC=NCIRC+1
IF(NCIRC=NACTIV)470+1120+1120
390 DX(1)=DX(1)
C A BIGER VALUE HAS BEEN FOUND. HENCE THIS VARIABLE WILL CHANGE.
400 NCIRC=0
DEL=DX(1)
410 CHIME=CHIOLD
CHIOLD=CHISO
VEC(1)=VEC(1)+DEL/ABS(DX(1))
TRIAL(1)=TRIAL(1)+DEL
DEL=ACK*DEL
XSAVE(1)=X(1)
X(1)=XSAVE(1)+DEL
X(1)=XSAVE(1)+CINDER*DEL
420 IF(X(1)-XMIN(1))60+420+420
430 CALL FUNK
NF=NF+1
IF(CHISO-CHIOLD)410+440+440
440 CINDER=0.5*ACK*(ACK+2*CHIME-(ACK+2-1.0)*CHIOLD-CHISO)/
X(ACK+CHIME-(ACK+2-1.0)*CHIOLD+CHISO)
X(1)=XSAVE(1)+CINDER*DEL
CALL FUNK
NF=NF+1
IF(CHISO-CHIOLD)450+460+460
450 CHIOLD=CHISO
TRIAL(1)=TRIAL(1)+CINDER*DEL
VEC(1)=VEC(1)+DEL/ABS(DX(1))
GO TO 470
460 X(1)=XSAVE(1)
470 IF(INZIP=1)1040+480+480
480 IF(ABS(VEC(1))-ACK)520+490+490
490 DX(1)=ACK*ABS(DX(1))
VEC(1)=VEC(1)/ACK
OLDVEC(1)=OLDVEC(1)/ACK
DO 500 J=1:NOSQUE
500 ERR(I,J)=ERR(I,J)/ACK
IF(INTRACE).LT.510,520,510
510 WRITE(*,501) I,DX(I)
NR=NR+1
IF(NR-MAXR).LE.1520,1800,1800
520 SUMO=0.0
SUMV=0.0
DO 530 J=1,NV
SUMO=SUMO+OLDVEC(J)**2
530 SUMV=SUMV+VEC(J)**2
IF(SUMO+SUMV).LE.1040,1040,1040
540 SUMO=SQRT(SUMO)
SUMV=SQRT(SUMV)
COSINE=0.0
DO 550 J=1,NV
COSINE=COSINE+OLDVEC(J)/SUMO*VEC(J)/SUMV
IF(INZIP).LT.11040,560,570
560 IF(ACK-NACTIV).LT.590,590,590
570 IF(NACTIV-MAXR).LE.1590,600,600
580 IF(INZIP-NCOMP).LT.1590,600,600
590 IF(COSINE-COMPAR).LE.1040,600,600
C SIMON SAYS: TAKE AS MANY GIANT STEPS AS POSSIBLE...
600 IF(INTRACE).LE.610,620,610
610 WRITE(*,525) CHIOLD+VEC(J)*J=1:I
NR=NR+1
IF(NR-MAXR).LE.1620,1800,1800
620 NGIANT=0
NRETRY=0
K=1
NOSC=NOSC+1
IF(NOSC-MOSQUE).GT.650,650,630
630 NOSC=MOSQUE
DO 640 K=2:NOSQUE
CHIOSC(K-1)=CHIOSC(K)
DO 640 J=1,NV
XOSC(J,K-1)=XOSC(J,K)
640 ERR(J,K)=ERR(J,K)
650 DO 660 J=1,NV
XOSC(J,NOSC)*X(J)
660 ERR(J,NOSC)=VEC(J)/SUMV
CHIOSC(NOSC)=CHIOLD
IF(NOSC-3).LT.670,670,670
C SEARCH FOR A PREVIOUS SUCCESSFUL GIANT STEP IN A DIRECTION MORE...
C NEARLY PARALLEL TO THE DIRECTION OF THE PROPOSED STEP THAN WAS THE...
C IMMEDIATELY PREVIOUS ONE.
670 COXCOM=0.0
DO 680 J=1,NV
680 COXCOM=COXCOM+ERR(J,NOSC)*ERR(J,NOSC-2)
N=NU+2
NTRY=0
DO 710 K=KL,N
NRETRY=NU+K
COSINE=0.0
DO 700 J=1,NV
700 COSINE=COSINE+ERR(J,NOSC)*ERR(J,K)
IF(COSINE-COXCOM).LE.1710,710,730
710 CONTINUE
720 CHIAB=CHI(1)
GO TO 770
730 NTRY=1
KL=K+1
IF(INTRACE).LE.740,750,740
740 NT=NOSC-K
    WRITE(KW.645) NT
    NR=NR+1
    IF(NR-MAXR)1750.1800.1800
750 DO 760 J=1+NV
    SALVO(J)=TRIAL(J)
760 TRIAL(J)=(X(J)-XOSC(J+K))/ACK
    CHIBAK=CHIOLD+(CHIOLD-CHIOLD)/ACK
770 DO 790 J=1+NV
    XSAVE(J)=X(J)
    TRIAL(J)=ACK*TRIAL(J)
    IF(MASK(J)>.1790.780.790
780 X(J)=MAXI(MINI(X(J)+TRIAL(J)+XMAX(J)))+XMIN(J))
790 CONTINUE
    CALL FUNK
    NF=NF+1
    IF(NGIANT-CHILO)800.820.820
800 CHIBAK=CHIOLD
    CHIOLD=NGIANT+1
    IF(INTRACE)810.770.810
810 WRITE(KW.725) CHISO,(X(J)+J=1+NV)
    NR=NR+1
    IF(NR-MAXR)1770.1800.1800
820 IF(NRETRY)840.840.830
830 IF(INTRACE)890.890.840
840 CINDER=0.5*ACK*(ACK+2)*CHIBAK-(ACK+2-1.0)*CHOLD-CHISO)/
     X(ACK+CHIBAK-(ACK+2+1.0)*CHIOLD+CHISO)/
     DO 860 J=1+NV
    IF(MASK(J)>.1860.850.860
850 X(J)=MAXI(MINI(XSAVE(J)+CINDER*TRIAL(J)+XMAX(J)))+XMIN(J))
860 CONTINUE
    CALL FUNK
    NF=NF+1
    IF(NGIANT-CHIOLD)990.870.870
870 IF(INTRACE)910.860.910
880 IF(NTRY)980.910.900
890 DO 900 J=1+NV
    TRIAL(J)=SALVO(J)
900 X(J)=XSAVE(J)
    GO TO 910
910 DO 920 J=1+NV
    TRIAL(J)=TRIAL(J)/ACK
920 X(J)=XSAVE(J)
930 IF(INTRACE)940.950.940
940 WRITE(KW.825) CHIOLD+NGIANT
    WRITE(KW.856) (X(J)+J=1+NV)
    WRITE(KW.897)
        NR=NR+3
    IF(NR-MAXR)1950.1800.1800
950 IF(INTRACE)1960.960.1010
960 IF(NRETRY)970.970.690
970 IF(INTRY)980.970.980
980 NTRY=0
    GO TO 720
990 CHIOLD=CHISO
    IF(INTRACE)1000.1010.1000
1000 STEPS=NGIANT
    STEPS=STEPS+CINDER
    WRITE(KW.915) CHIOLD+STEPS
    WRITE(KW.856) (X(J)+J=1+NV)
    WRITE(KW.897)
        NR=NR+3
    IF(NR-MAXR)11010.1800.1800
1010 IF(NTER)1020.190.1020
1020 NOSC=0
1030 GO TO 190
1030 NOSC=MAXD(NOSC-1,0)
1040 CHI(1)=CHIOLD
1050 CONTINUE

C ANOTHER CYCLE THROUGH THE VARIABLES HAS BEEN COMPLETED.
C PRINT ANOTHER LINE OF TRACES.
   IF(NTER)11060.1060.1060
1060 WRITE(KW=525) CHIOLD*(VEC(J)+1.*NV)
      NR=NR+1
      IF(NR-MAXR)1080.1800.1800
1080 IF(NZP)1110.1090.1110
1090 IF(NTER)11100.1110.1110
1100 WRITE(KW=856) (X(J)+1.*NV)
      WRITE(KW=1015)
      NR=NR+2
      IF(NR-MAXR)1110.1800.1800
1110 NZP=NZIP+1
      GO TO 200

C A MINIMUM HAS BEEN FOUND: PRINT THE REMAINING TRACES.
1120 IF(NTER)1130.1140.1130
1130 WRITE(KW=525) CHIOLD*(VEC(J)+1.*KK)
      NR=NR+1
      IF(NR-MAXR)1140.1800.1800
1140 IF(NTER)1150.1160.1150
1150 WRITE(KW=856) (X(J)+1.*NV)
      WRITE(KW=897)
      NR=NR+2
      IF(NR-MAXR)1160.1800.1800
1160 CONTINUE

C DECREASE THE SIZE OF THE STEPS FOR ALL VARIABLES.
1170 NOSC=0
   DO 1180 I=1,NV
      IF(MASK(I))1220.1200.1220
1180 CONTINUE
   GO TO 1270
1190 NGATE=1
   DO 1220 I=1,NV
      IF(MASK(I))1220.1200.1220
1200 IF(AbsDX(I))=ABSDELMIN(I))1220.1210.1210
1210 NGATE=0
1220 DX(I)=DX(I)/RATIO
   IF(NGATE)1230.1230.1270
1230 IF(NTER)1240.190.1240
1240 WRITE(KW=1175) (DX(I)+1.*NV)
      WRITE(KW=1176)
      NR=NR+2
      IF(NR-MAXR)1190.1800.1800
1800 WRITE(KW=1805)
1270 CHISQ=CHIOLD
      WRITE(KW=1205) NF
1280 IF(ABS(MATRIX-100))=ABSDELMIN(I))1290.1290.1700
1290 IF(NACTIV-NV)1700.1300.1700

C COMPUTE THE STANDARD ERRORS AND THE CORRELATIONS.
1300 FAC=RATIO**MATRIX-100)
      ESUM=0.0
   DO 1360 I=1,NV
      IF(DELMIN(I))1310.1320.1310
1310 DX(I)=ABS(FAC*DELMIN(I))
   GO TO 1330
1320 DX(I)=ABS(FAC*DX(I))
1330 IF(DX(I))1700.1700.1340
1340 XSAVE(I)=X(I)
DO 1350 J=1+2
   X(1)=XSAVE(1)+DX(1)
   CALL FUNK
   NF=NF+1
   SECOND(J)=CHISO
1350 DX(I)=DX(I)
   ERR(I+1)=SECOND(I+1)-2.0*CHIOLD+SECOND(I+2)/DX(I)**2
1360 ESUM=ESUM+ABS(ERR(I+1))
DO 1390 J=2,NV
   IM=I-1
   DO 1380 K=I+2
      X(I+1)=XSAVE(I+1)+DX(I)
      DO 1370 L=I+2
         X(J)=XSAVE(J)+DX(J)
      CALL FUNK
      NF=NF+1
      SECOND(K+L)=CHISO
      X(J)=XSAVE(J)
1370 DX(J)=DX(J)
X(I+1)=XSAVE(I)
1380 DX(I)=DX(I)
   ERR(I+J)=0.25*(SECOND(I+1)-SECOND(I+2)-SECOND(2+I)+SECOND(2+2))
   X/ABS(DX(I+1))
   ESUM=ESUM+ABS(ERR(I+J))
1390 ERR(I+J)=ERR(I+J)
   WRITE(KW*1325)
   WRITE(KW*1326) (DX(J)+J=1,NV)
   WRITE(KW*1327)
   DO 1400 J=1,NV
1400 WRITE(KW*1326) (ERR(I+J),J=1,NV)
   ESAVE=NV**2
   BRAAA=ABS(ESUM)/ESAVE
   NGRAPE=0
   DO 1420 J=1,NV
      DO 1420 J=1,NV
         IF(ERR(I+J)>1420*14 10,1420,1420 STEP0401
1410 NGRAPE=1
1420 ERR(I+J)=ERR(I+J)/BRAAA
   IF(NGRAPE)1440,1440,1430
1430 WRITE(KW*1364)
C INVERT THE SCALING MATRIX USING SYMINV2 (COMM OF THE ACMM. 6 67)
1440 DET=1.0
   DO 1450 J=1,NV
1450 SALVO(J)=I+1
      DO 1600 K=1,NV
         BISAJ=I+1
         DO 1480 J=1,NV
            IF(SALVO(J))1460,1480,1460
1460 IF(ABS(ERR(I+J))>BIGA J J)1480,1480,1470
1470 BIGA JJ=ABS(ERR(I+J))
   K=J
1480 CONTINUE
   IF(BIGA JJ)1500,1490,1500
1490 DET=0.0
   GO TO 1610
1500 SALVO(K)=0.0
   DET=DET*ERR(K,K)
   TRIAL(K)=I+1/ERR(K,K)
   ERR(K,K)=0.0
   XSAVE(K)=I+1
   M=K-1
   IF(M)1540,1540,1510
1510 DO 1530 J=1,M
   272
XSAVE(J)=ERR(K,J)
TRIAL(J)=ERR(K,J)*TRIAL(K)
IF(SAVE(J))=1490,1530,1520
1520 TRIAL(J)=TRIAL(J)
1530 ERR(K,J)=0
1540 N=N+1
IF(M=NV)1550,1550,1590
1550 DO 1580 J=M,NV
XSAVE(J)=ERR(J,K)
IF(SAVE(J))=1490,1560,1570
1560 XSAVE(J)=XSAVE(J)
1570 TRIAL(J)=ERR(J,K)*TRIAL(K)
1580 ERR(J,K)=0
1590 DO 1600 J=1,NV
DO 1600 K=J,NV
1600 ERR(K,J)=ERR(K,J)+XSAVE(J)*TRIAL(K)
IF(DET)1620,1610,1630
1610 WRITE(KW,1545)
MATRIX=0
GO TO 1690
1620 WRITE(KW,1555)
1630 WRITE(KW,1565) DET=BRAAK
DO 1660 J=1,NV
DO 1660 K=J,NV
ERR(K,J)=ERR(K,J)+2.0/BRAAK
1640 ERR(J,J)=ERR(J,J)
IF(ERR(J,J)=1,1659,1650,1660
1650 WRITE(KW,1585) ERR(J,J)
1660 XSAVE(J)=SIGN(SORTABS(ERR(J,J),ERR(J,J))
WRITE(KW,1955)
WRITE(KW,1326) (XSAVE(J),J=1,NV)
WRITE(KW,1956)
DO 1680 J=2,NV
1680 M=J-1
DO 1690 J=1,M
1690 WRITE(KW,1205)
CONTINUE
1700 CALL FUNK
1720 WRITE(KW,1655)
WRITE(KW,1326) (X(J),J=1,NV)
WRITE(KW,1656)
CHISO
RETURN
01 FORMAT(1X=24H ENTER SUBROUTINE STEPIT)
02 FORMAT(10H MASK = 10(6+6X)/(4X,10(12)1)
03 FORMAT(10H X = 10E12*(4X,10E12+4))
04 FORMAT(10H XMAX = 10E12*(4X,10E12+4))
05 FORMAT(10H XMIND = 10E12*(4X,10E12+4))
06 FORMAT(10H DELTAM = 10E12*(4X,10E12+4))
07 FORMAT(10H DELLMIN = 10E12*(4X,10E12+4))
08 FORMAT(/10H,13+10H VARIABLES+13+8H ACTIVE+10X,8HMATRIX+14+10X:
16HCOMP = 12/8H RATIO = F5+10X,4HACK=F5+1,10X,7HCOLIN=F6,3:
210X=8HCMR = 16,3//8H CHISO = E15+8)
09 FORMAT(10H,25X,9HMAXSQ = +110+12H MAXR = +110)
12 FORMAT(/10H,13+10H TRACE HAP)
32 FORMAT(16HCHISO = E15+8/8H X(1) 10(1X,1E12+8))
856 FORMAT(8H X(1).... 10(I*E12.5))
857 FORMAT(/)
915 FORMAT(8H CHISO = E15.8.7H AFTER F6.1+12H GIANT STEPS)
1015 FORMAT(1H)
1175 FORMAT(5012H A//26H STEP SIZES REDUCED TO //..... 10(I*E12.5))
1176 FORMAT(/)
1205 FORMAT(/X.15.E2H FUNCTION COMUTATION//)
1235 FORMAT(4M lSIZES OF INCREMENTS TO BE USED BELOW//)
1236 FORMAT(10(I*E12.5))
1237 FORMAT(/45H MATRIX OF THE SECOND PARTIAL DERIVATIVES//)
1264 FORMAT(/45H THE ABOVE MATRIX CONTAINS ONE OR MORE ZEROS.
1616 A LARGER VALUE OF MATRIX SHOULD BE TRIED TO SEE IF THEY ARE.
212H LEGITIMATE.)
1545 FORMAT(/49H ERROR MATRIX IS SINGULAR. MATRIX SHOULD PROBABLY.
113H BE INCREASED //)
1555 FORMAT(/49H ERROR MATRIX IS NEGATIVE DEFINITE. MATRIX SHOULD.
122MPROBABLY BE DECREASED.)
1565 FORMAT(/3H DETERMINANT OF SCALED MATRIX = E12.5+10X.
1117SCALING FACTOR = E12.5+1H))
1585 FORMAT(/50H NEGATIVE OR ZERO MEAN SQUARE ERROR ENCOUNTERED....
13X+ E15.8/37H MATRIX SHOULD PROBABLY BE DECREASED.)
1595 FORMAT(/19H STANDARD ERRORS..)
1596 FORMAT(/44H LOWER TRIANGLE OF THE CORRELATION MATRIX//)
1655 FORMAT(/24H FINAL VALUES OF CHISO = E15.8//)
1685 FORMAT(/14H MAX RECORD COUNT EXCEEDED, RUN TERMINATED)
1900 FORMAT(14H *21H FUNCTION COMPUTATION.//)
END
SUBROUTINE EXTRA

DIMENSION WETZ(9*8*8)
DIMENSION PENTR(4 1 * 8 ).ZELTA(4 1 * 8 1* ZZZ16*3*3*2)*OW1 (8*2)*OW218*3)
DIMENSION CODE(8*16*2).CORE(9*8*4*3).OSPN(8*2).0SPPN(8*3)
DIMENSION OGI(6).OWZ(8).GSIGN(8,2)
DIMENSION ORES(6)
DIMENSION RW1(8).RAAU6).RAA2(6)
DIMENSION L1SAV(8).L1PSV(8*2).PUMP1(4).ZZZZ(9*3*8*8.3)
DIMENSION OLDVEC(20).SALVO(20).XOSC(20.15).CHIOSC(1 5) S

ERR(20.20)
COMMON KW,NV,INTRACL,MASSX,MNXHIN,DELTA,DELMIN,MATRIX
COMMON ERR=CHISO,RATIO,COLIN,NCOMP,ACK,MAXR,MOSUE
COMMON NPRIN,KCASE,10AD,1PAR,1ZERO,1IN1,1MAX,1KKS,1KMIN,NN,JO,LL
COMMON KMAX,RJO,EKUUL,JKL.1OMIN.1OMAX.1OMAX,1JMAX,FISA
COMMON IVAL,T.1OUPH.DELTA,SSINN,CGE,ZZ,PLALL,YEXP
COMMON COUOL,SIGFI,10PPIN,NCAL,COMP1,COMP2,COMSV
COMMON PCON1,PCON2,P1,PW2,LE5,INTFR,FRCM,PRCH
COMMON GAMI,GAM2,CS,RES,ECN,W1,W2,PON3,HRCM,QRCH,BETA,NOPT
COMMON INTFS,13,1x1L.1LX1L,JJ,1LAM,1ERE3L
COMMON RAA1,RAA2,RBU
COMMON RSUM1.1SUM3,1UE,1MJE
COMMON TES+OE5,RES3+RES13+RES23+OEW1.9OEW2.9PEW1.9PEW2.QETA+FETA
COMMON GAM12,GA13,GA23,GSIGN1.1SERH
COMMON OW1,0W2,PENTR+OEW1.9OEW2+ZELTA+ZZZ
COMMON I2E+IZF,12FLG,12ILJ,12ELK.12LJ+12LM+IFINS
COMMON NT1M,GRCM,NREAT
COMMON MULE, MXCAL, I PITY, L1SAV, LIPS V, JUNE, INTFS, MJSAV, NFSAV
COMMON SPINN, TAMMA, REW, PUMP1, PUMP, ZZZZ, CODE, CORE, OSPN, OSPPN
JOHN=JULIE
TM=9.01219
PM=4.0026
IFUG=0
PUMP=0.0
IF(INCAL=1)9131+9132+9133
IF(MJE-MXCAL)9131+9132+9133
9133 Mohn=1
IEXMN=1
JEXMX=MXCAL
IEXMN=MXCAL
GO TO 9142
9162 IF(NJE=1)9240+9241+9241
9240 IEXMN=MJE
Mohn=JOHN
IEXMX=MJE
GO TO 9142
9241 IEXMN=1
Mohn=1
IEXMX=MJE
9142 DO 9135 IEXTR=IEXMN+IEXMX
IF(JJ9135=9135+916
9315 J1=2+0.0001*(IEXTR+Mohn)+0.01
AMY=0.002060E-06
E1=EREAL(IEXTR)*AMY
VAM=TAMMA(IEXTR)*AMY/2.0
ZEX1=0.0/SORT(ECH-E1)**2+VAM**2)
BE1=TAN2(ECH-E11)*VAM
L1=LSAV(IEXTR)
L1=L1+2
GL1=SORT(REW(IEXTR+1)*T(1+L1))*GSIGN(IEXTR+1)
GL2=SORT(REW(IEXTR+2)*T(1+L1))*GSIGN(IEXTR+2)
IF(NREAT=1)9201+9202
9202 LPI=LI2PSV(IEXTR+1)
LPI=LI2PSV(IEXTR+1)
GLP1=SORT(REW(IEXTR+1)*PENTR(1+LPI))*OSPN(IEXTR+1)
GLP2=SORT(REW(IEXTR+2)*PENTR(1+LPI))*OSPN(IEXTR+2)
IF(IFINS=2)9201+9202
9203 LS1=LSAV(IEXTR+1)
LS1=LSAV(IEXTR+1)
GSL1=SORT(REW(IEXTR+1)*PENTR(1+LS1))*OSPPN(IEXTR+1)
GSL2=SORT(REW(IEXTR+2)*PENTR(1+LS1))*OSPPN(IEXTR+2)
GSL3=SORT(REW(IEXTR+3)*PENTR(1+LS3))*OSPPN(IEXTR+3)
9201 IF(MJE=1)9242+9243+9244
9242 IEXMN=IEXTR+1
Mohn=1
IEXMX=MXCAL
IF(JEXMN-MXCAL=1)9137+9137+9126
9243 IF(MJE=1)9242+9242+9247
9247 IF(IEXTR=MJE)9246+9311+9216
9311 IF(IFUG=1)9316+9316+9242
9316 Mohn=JOHN
IFUG=1
GO TO 9315
9246 IEXMN=MJE
Mohn=JOHN
IEXMX=MJE
9137 DO 9136 JEXTR=JEXMN+JEXMX
LXMAX=4+LSAV(IEXTR)+LSAV(IEXTR)
IF(LXMAX=9)9283+9283+9284
9284 LXMAX=9
SUBROUTINE ZBARM
DIMENSION PENTR(41,8),ZELTA(41,8),ZZZ(9,3,6,3,2),OEW1(8,2),OEW2(8,3)
DIMENSION CODE(8,16,2),CORE(9,8,4,3),OEPN(8,2),OEPNN(8,3)
DIMENSION OW1(8),OW2(8),GSIGN1(8,2)
DIMENSION ERESL(8)
DIMENSION RW(8),RRA1(6),RRA2(6)
DIMENSION JVAL(7),T(41,8),COUPH(41,8),DELTA(41,8),SINN(33),SS(41,113),CGE(7,7,13),ZZ(6,2,2),PLALL(10,33),SIGI(41,5,1),2YEXP(41,0,5),COU(41,13),DIL(41,13),COMK(41,5,4),COMP2(41,5,4)
DIMENSION OAA2(6),OAA1(6),RBB1(6)
DIMENSION L1PSV(8,2),PUMP1(4),ZZZ(9,3,6,3,2)
DIMENSION SPNN(8,4),IPITY(8,4),TAMMA(8),REW(8,2),INTFS(8),MJSAV(14),PFSAV(8)
DIMENSION VEC(20),TRIAL(20),XSAVE(20),CHI(20),DX(20),SECOND(2,2)
DIMENSION OLOVEC(20),SALVO(20),XOSC(15),CMISC(15)
DIMENSION MASK(20),X(20),XMAX(20),XMIN(20),DELTA(20),DELMIN(20)
DIMENSION OLDVEC(20),SALVO(20),XOSC(20),CHIOSC(15)
DIMENSION X(20),XMAX(20),XMIN(20),DELM(20),STEPO007
COMMON KW,NV,NTRACL,MASK*X,XMAX*XMIN*DELTA*DELMIN*MATRIX
COMMON ERR,CHISQ,RATID,COLIN,NCOMP,ACK,MASK,MOSQUE
COMMON NPRINT,NCASE,IOAD,IPARM,ZERO,IMIN,MAX,KKKS,KKMIN,NN,J0,LL
COMMON KMAX,RJO,ER,KUUL,JEUL,10MIN,10MAX,JMAX,XSAV,EFSAV
COMMON IVAL,T,COUPH,DELTA,SS,CGE,ZZ,PLALL,YEXP
COMMON COU,DIL,SIG1,F1,NPRIN,NCAI,COMI,COMP2,COMPV
COMMON PCON1,PCON2,PF1,PW2,LES,INTFR,FRCM,PRCM
COMMON GAM1,GAM2,CS,RES,ECW,OW2,PCON3,HRCM,QRCM,BETA,NOPT
COMMON INTF3,13,1,LL,LJ,LMAX,K*,ALAM,ERESL
COMMON RAA1,RAA2,RBB1
COMMON RSUM1,RSUM3,MJE,MJE
COMMON TES, OES, RES2, RES1, RES3, GEW1, GEW2, PWE1, PWE2, G3TA, FETA
COMMON GAM12, GAM13, GAM23, GSIGN, ISENM
COMMON OW1, OW2, PENTR, OEW1, OEW2, ZELTA, ZZZ
COMMON IZEF, JG1LK, JG1LJ, JG2LK, JG2LJ, JG2LM, IFINS
COMMON NTIM, GRCM, NREAT
COMMON MULE, MXCAL, IMPITY, LISA, LIKSV, JUNE, INTFS, MJSBV, NFSAV
COMMON SPINN, TAMMA, REV, PUMP1, PUMP2, ZZZZ, CODE, CORE, OSPN, OSPPN
COMMON MULE, MXCAL, IMPITY, LISA, LIKSV, JUNE, INTFS, MJSBV, NFSAV
COMMON SPINN, TAMMA, REV, PUMP1, PUMP2, ZZZZ, CODE, CORE, OSPN, OSPPN
JOHN = JULIE
IFAG = 0
IF(NCAL = 1) 9114, 9103, 9103
9103 IF(MULE = 1) 9280, 9281, 9281
9281 IF(MJE = 1) 9282, 9282, 9283
9282 IF(MJE = MJE) 9114, 9105, 9105
9105 NOP = 1
NOP = 1
GO TO 9106
9283 IFMN = MJE
MN = JOHN
MOP = 1
MOP = 1
GO TO 9106
9280 IF(MJE = MJC) 9114, 9105, 9105
9106 IF = 0
DO 9087 IEXTR = IEXMN, IEXMX
9322 RJ = SPINN (IEXTR, MHN)
IF(MOP = 2) 91907, 9108, 9109
9108 IF(IFINS = 2) 91919, 9120, 9120
9119 S0 = 0, 5
GO TO 9121
9120 S0 = 1, 5
9121 L1 = LPSV (IEXTR + 1)
AL1 = L1 - 1
AL1 = AL1 + 2, 0
GO TO 9110
9109 S0 = 2, 5
L1 = LPSV (IEXTR + 2)
AL1 = L1 - 1
AL1 = AL1 + 2, 0
AL1 = AL1 + 2, 0
GO TO 9110
9107 S0 = 1, 5
L1 = LPSV (IEXTR)
AL1 = L1 - 1
AL1 = AL1 + 2, 0
9110 IF(MJE = 1) 9285, 9286, 9286
9286 IF(MJE = 1) 9285, 9285, 9288
9289 IF(IEXTR = MJE) 9289, 9310, 9090
9310 IF(IFUG = 1) 9321, 9321, 9285
9321 IFUG = 1
MN = JOHN
GO TO 9322
9289 JEXMN = MJE
JEXMN = MJE
MN = JOHN
GO TO 9089
9285 JEXMN = IEXTR + 1
JEXNX=XCAL
NONN=1
IF(JEXNN-XCAL)9089,9089,9090
9089 DO 9088 JEXTR=JEXMN+JEXMX
RJ2=SPINN(JEXTR+NONN)
9291 IF(MOPE=2)9123,9124,9125
9123 L2=L1SAV(JEXTR)
AL2=AL2-1
AL2=AL2+2*0
GO TO 9126
9124 L2=L1PSV(JEXTR+1)
AL2=AL2-1
AL2=AL2+2*0
GO TO 9126
9125 L2=L1PSV(JEXTR+2)
AL2=AL2-1
AL2=AL2+2*0
AL32=AL22+2*0
9126 LMAX=+L1SAV(1EXTR)+L1SAV(JEXTR)
IF(LMAX-9)9294,9294,9295
9295 LMAX=9
9294 DO 9091 JZTO=1,1,LMAX
AL=JZTO-1
ZZZZ(JZTO+1,1,1EXTR,JEXTR,MOPE)=COFJ(B,AL1,AL2,AL+RJ2,RJ1+SO,0,0)*
10+0*0*0
ZZZZ(JZTO+2,1,1EXTR,JEXTR,MOPE)=COFJ(B,AL1,AL2,AL+RJ2,RJ1+SO,0,0)*
10+0*0*0
ZZZZ(JZTO+3,1,1EXTR,JEXTR,MOPE)=COFJ(B,AL1,AL2,AL+RJ2,RJ1+SO,0,0)*
10+0*0*0
ZZZZ(JZTO+4,1,1EXTR,JEXTR,MOPE)=COFJ(B,AL1,AL2,AL+RJ2,RJ1+SO,0,0)*
10+0*0*0
ZZZZ(JZTO+5,1,1EXTR,JEXTR,MOPE)=COFJ(B,AL1,AL2,AL+RJ2,RJ1+SO,0,0)*
10+0*0*0
ZZZZ(JZTO+6,1,1EXTR,JEXTR,MOPE)=COFJ(B,AL1,AL2,AL+RJ2,RJ1+SO,0,0)*
10+0*0*0
ZZZZ(JZTO+7,1,1EXTR,JEXTR,MOPE)=COFJ(B,AL1,AL2,AL+RJ2,RJ1+SO,0,0)*
10+0*0*0
9091 CONTINUE
9088 CONTINUE
9087 CONTINUE
9090 IF(INREAL=1)9114,9130,9130
9130 IF(IFINS=2)9111,9112,9112
9111 IF(IFAG=19113,9113,9114
9113 HOP=2
IFAG=1
HOP=2
GO TO 9106
9112 IF(IFAG=19301,9302,9302
9301 IFAG=1
HOP=2
HOP=2
HOP=1
GO TO 9106
9302 IF(MOPE=2)9303,9303,9304
9303 HOP=4
HOP=3
HOP=1
GO TO 9106
9114 RETURN
END
SUBROUTINE PLOT
DIMENSION LINES(17)
DIMENSION PENTR(41,8),ZELTA(41,8),ZETA(6,3,3,2),OEW1(8,2),OEW2(8,3)
DIMENSION CODE(8,16,2),CORE(9,8,4,3),OSPN(8,2),OSSPN(8,3)
DIMENSION OW(8),OW2(8),GSIGN(8,2)
DIMENSION ERESL(8)
DIMENSION RV(8),RAA1(8),RAA2(8)
DIMENSION IVAL(7,7,7,4,18),COUPH(41,8),DELTA(41,8),SINV(33,5),SINV(41,13),
      ZZ(7,7,13),ZZZ(10,33),SIG1(41,5),
VVEXP(41,05),COU(41,13),DIL(41,13),COMPL(41,5,4),COMPL(41,5,4),
CCOMSV(41,5,4),FISA(5,1,5,4)
DIMENSION DAA2(6),DAA1(6),RAA1(6)
DIMENSION SPINN(8,4),PIHITY(8,4),TAMMA(8),REW(8,2),INTFS(8),MJSAV(14),NFSAV(8)
DIMENSION VEC(20),TRIAL(20),XSAVE(20),CH(20),DX(20),SECOND(2,2)
DIMENSION OLDVEC(20),SALVO(20),XOSC(120,15),CHIOSC(120,15)
DIMENSION MASK(20),XMAX,XMIX,DELTAX,DELMIN,MATRIX
DIMENSION ERR1(20,20)
COMMON KN,TV,NG,NU,TRACEL,MAKEX,MAXMIN,DELTAX,DELMIN,MATRIX
COMMON ERF,RATIO,COLN,NCOMP,AC,MAX,MOSQUE
COMMON NPNR,KASE,LOAD,IPAR,MZERO,MINLMAX,KKKS,JKKM,NN,JO,LL
COMMON KMAX,RO,JERO,KUUL,JULIE,IONIN,IONMAX,IONMAX,FISAV
COMMON IVAL,T,COUH,DELTSINN,SS,CEGZZ,PLALL,YEXP
COMMON COUH,T,COUH,DELTA,SINN,SS,CEGZZ,PLALL,YEXP
COMMON PCON1,PCON2,PCON3,PCON4,LE3,INFR,FRCM,PRCM
COMMON SANI,GAM2,CS,RES,ECM,OW1,OW2,PCON3,HRM,GRM,GRM,BETA,NOPT
COMMON NTIF3,133,1LJ,LUK,MAX,IKJU,KKJAM,EREIL
COMMON RAA1,RAA2,RAA1
COMMON RSLM1,RSUM3,MJE,MJE
COMMON TES,TOES,RES,RES,RES,RES,RES,RES,OEW1,OEW2,PEW1,PEW2,PEW3,PEW4
COMMON GAMZ,GAMZ,GAMZ,GAMZ,GAMZ,GAMZ,GSIGN,ISERH
COMMON OW1,OW2,PENTR,OEW1,OEW2,DELTA,ZZZ
COMMON IZE,IZEF,IGILK,IGILJ,IGILK,IGILJ,IGILK,IGILJ,IFIN5
COMMON NTIM,GRM,NREAT
COMMON MULE,XXCAL,IPITY,LISAV,LPSV,JUNE,INTFS,MJSAV,NFSAV
COMMON SPINN,TAMMA,REW,PUMP1,PUMP2,PUMP3,PUMP4,ZZZ,CODE,CORE,OSPN,OSPPN
DATA IBLNK,1STAR/---*/
YMAX,SIGI(1,1)
YMIN,SIGI(1,1)
DO 100 K=1,30,2
YTEST=SIGI(K+1)
YTOR=SIGI(K+1)
IF(YMAX-YTEST)101,102,102
101 YMAX=YTEST
102 IF(YMIN-YTOR)103,103,104
104 YMIN=YTOR
103 CONTINUE
WRITE(6,452)YMAX,YMIN
452 FORMAT(2X,6HYMAX=+E16.8,2X,6HYMIN=+E16.8)
SPACE=1YMAX-YMIN)/120
DO 107 JV=1,13
AJV=JV
Y2=YMAX-SPACE*AJV-0.000001*SPACE
Y1=YMAX-SPACE*(AJV-1.0)+0.000001*SPACE
DO 105 IY=1,17
105 LINES(IY)=IBLNK
IY=0
DO 110 K=1,33,2
IY=IY+1
YTEST=SIGI(K+1)
IF(Y1-YTEST)110,109,109
109 IF(Y2-YTEST)111,111,110
SUBROUTINE FUGS
DIMENSION IORE(8), IOAR(16), ICOR(16)
DIMENSION PENTR(4*8), ZELTA(4*8), ZZ(6*3*2), OEW1(8*2), OEW2(8*3)
DIMENSION CODE(8*16*2), CORE(9*8*4*3), OSPN(8*2), OSPAN(8*3)
DIMENSION JW(8), OW2(8), TAX(8)
DIMENSION ERESL(8)
DIMENSION NW(8), RAA1(6), RAA2(6)
DIMENSIONIVAL(7), Y(4*8), COUPH(4*8), DELTA(4*8), SINF(3*3), SS(4*1)
DIMENSION CGE(7*7*13), ZZ(6*2*2), PLALL(10*33), SIGI(4*1.5), YEXP(41*0.5), COU(41*13), DIL(41*13), COMPL(41*5*4), COMPL2(41*5*4)
DIMENSION COSYV(41*5*4), FISAV(51*5*4)
DIMENSION DAA2(6), DAAI(6), RBB1(6)
DIMENSION LISA8(8), LIPS(8*2), PUMPl(4), ZZ(9*3*8*3)
DIMENSION SPINN(8*4), IPITY(8*4), TAMPAI(8), REV(8*2), INTFS(8), MSJAV(8), NFSAV(8)
DIMENSION VEC(20), TRIAL(20), XSSAVE(20), CHI(20), DX(20), SECOND(2*2)
DIMENSION OLV(20), SALVO(20), XDIS(20, 15), CHIOSC(15)
DIMENSION MASK(20), XMAX(20), XMIN(20), DELTA(20), DMIN(20)
DIMENSION KEY(20, 20)
COMMON NCV, NTRAC, MASK, XMAX, XMINT, DELTAX, DELMIN, MATRIX
COMMON ERR, CHISO, RATIO, COLIN, NCOMP, ACK, MAX, MOSQUE
COMMON NPRINT, CASE, I0AD, IPAR, NZERO, MIN, MAX, XMAX, XMIN, JO, LL
COMMON PMAX, RIO, ER, KUUL, JULIE, NOMIN, IOAMX, JMAX, FMAS
COMMON IVAL, Y, COUPH, DELTA, SINF, SS, CGE, ZZ, PLALL, YEXP
COMMON COU, DIL, SIGI, FI, NPRI, NCAL, COMPL, COMPL2, COMSV
COMMON PCON, PCON2, PW2, LEG, LFR, FRIC, PRM
COMMON GAMS, GAMS2, ES, ECM, OW1, OW2, PCON3, HRCM, ORCM, BETA, NOPT
COMMON INF3, LK, LJ, LMAX, K, JJ, ALAM, ERESL
COMMON RAA1, RAA2, RBB1
COMMON RSUM1, RSUM2, MJE, NJJE
COMMON TES, OES, RES2, RES13, RES23, OEW1, OEW2, PEW1, PEW2, QETA, FETA
COMMON GAM12, GAM13, GAM23, GSIGN, ISERH
COMMON OW1, OW2, PENTR, OEW1, OEW2, ZELTA, ZNZ
COMMON IZEL, JG, JGLK, JGJLJ, JGJLK, JGJ2LJ, JGJ2LM, IFINS
COMMON NTHI, GRCM, NRET
COMMON MULE, MXCAL, IPITY, LISA8, LIPS, JUNE, INTFS, MSJAV, NFSAV
COMMON SPINN, TAMPAI, REV, PUMPl, PUMP2, ZZ, CODE, CORE, OSPN, OSPAN
IORE(1) = 2
IORE(2) = 1
IORE(3) = 1
IORE(4) = 2
IORE(5) = 2
IORE(6) = 1
IORE(7) = 1
IORE(8) = 2
IF (MCNACAL - 3) 101, 102, 800
101 IF (FIN5 = 2) 103, 104, 105
103 LM1 = 2*OSPN(11)/2 + 0 + 0
LM2 = 2*OSPIN(21)/2 + 0 + 0
DO 2 K = 1, 33, 2
SELF1 = 0 + 0
SELF2 = 0 + 0
DO 3 L = 1, LM1
N = 2*LM1
SELF1 = COMPL(L + 1) + COMPL(L + 1) + PLALL(MM + K) + SELF1
SELF2=COMPI(L+1)*COMPI(L+2)*PLALL(MM+1)*SELF2
3 CONTINUE
COMSV(K+1)=SELF1
COMSV(K+2)=SELF2
SELF1=0
SELF2=0
DO 4 L=1,L2
MM=2*L-1
SELF1=COMPI(L+1)*COMPI(L+2)*PLALL(MM+1)*SELF1
SELF2=COMPI(L+2)*COMPI(L+3)*PLALL(MM+1)*SELF2
4 CONTINUE
COMSV(K+1)=SELF1
COMSV(K+2)=SELF2
2 CONTINUE
DO 1 LP=1,8
IF(LP<10) GO TO 201,501,502
501 IH=2
GO TO 503
502 IH=1
503 IG=10(RE(LP)
!XMAX=4*L0SAV(1)+L0SAV(2)
IF(LXMAX<9) GO TO 105,105,106
106 LXMAX=9
105 DO 701 K=1,2
XTERM=0
DO 5 L=1,LXMAX
WAA=CORE(L+LP+1)
WBB=CORE(L+LP+2)
WCC=CORE(L+LP+3)
WDD=CORE(L+LP+4)
CPRE=F1(K1)
SPRE=F1(K1-1)
XTERM=(CPRE*(WAA*WCC-WBB*WDD)-SPRE*(WBB*WCC+WAA*WDD))*PLALL(L+K)+
XTERM
5 CONTINUE
SIG1(K1)=2*SIG1(K1)*330*(XTERM+COMSV(K+1)*IH+C3M(K+2)
110))
701 CONTINUE
CALL PLOT
1 CONTINUE
GO TO 800
104 DO 329 LEV=1,8
IF(LEV<10) GO TO 330,330,331
330 IH=2
GO TO 332
331 IH=1
332 IG=10(RE(LEV1)
!XMAX=4*L0SAV(1)+L0SAV(2)
IF(LXMAX<9) GO TO 43,43,43
43 LXMAX=9
42 DO 356 LP=1,8
IF(LP<10) GO TO 341,341,342
341 UC=4
GO TO 345
342 UC=3
345 IV=10(RE(LP)+2
MGG=0
DO 348 MN=1,4
DO 349 MG=1,4
MGG=MGG+1
LM=(2.0*5PINN(1+1)-1.0)/2+1+00
LM=(2.0*5PIN(2+1)-1.0)/2+0+10
DO 353 K=1,33+2
SELF1=0
201,501,502
DO 350 L=1+LM1
RH=2*LI-1
SELF1=COMP1(L+1)*H*(COMP1(L+1)+U)=COMP2(L+1)*MN)#PLALL(MM=3)+SELFI
1F1
350 CONTINUE
SELF2=0.0
DO 351 L=1+LM2
RH=2*LI-1
SELF2=COMP1(L+2)*G*(COMP1(L+2)+IV)=COMP2(L+2)*MG)#PLALL(MM=K)+SELF
1F2
351 CONTINUE
XTERM=0.0
DO 352 L=1+LXMAX
WAA=CORE(L+LEV1+1)
WBB=CORE(L+LEV1+2)
WCC=CORE(L+LP+3)-CODE(L+MGG+1)
WDD=CORE(L+LP+4)-CODE(L+MGG+2)
CPRE=F1(1.1)
SPRE=F1(1,2)
XTERM=(SPRE*(WBB=WCC=WBB=WCC+WAA=WDD))#PLALL(L=K)+
1XTERM
352 CONTINUE
SIG1(K+1)=(1.0E+27)*(ALAN=2)*0.25*(XTERM+SELF1+SELF2)
353 CONTINUE
CALL PLOT
349 CONTINUE
348 CONTINUE
356 CONTINUE
329 CONTINUE
GO TO 800
102 IF(FINS=2)111,800,800
111 DO 121 JV=1+4
10AR(JV)=2
N=JV+12
10AR(N)=2
NG=JV+4
N=JV+8
10AR(NG)=1
10AR(N)=1
121 CONTINUE
DO 120 JV=1+16
11 JF(JV)=15+116,118
119 N=JV
GO TO 117
116 N=8
GO TO 117
118 N=N-1
117 ICOR(JV)=N
120 CONTINUE
LMH2=4+L15AV(1)+L15AV(2)
1F(LMH2=9)162,164,162
625 LMH2=9
624 NG=0
1Z=0
1P=0
LM1=(2.0*SPIN(1.1)-1.0)/2.0=0.01
LM2=(2.0*SPIN(2.1)-1.0)/2.0=0.01
LM3=(2.0*SPIN(3.1)-1.0)/2.0=0.01
DO 621 K=1+33,2
SELF1=0.0
SELF2=0.0
DO 620 L=1+LM1
MM=2*LI-1
SELF1=COMP1(L=1)+COMP1(L=3)#PLALL(MM=K)+SELF1
SELFZ=COMP1(L+1,2)*COMP1(L+1,3)*PLALL(MM,K)+SELF2
620 CONTINUE
COMSV(K+1,1)=-SELF1
COMSV(K+1,2)=-SELF2
SELF1=0.0
SELF2=0.0
DO 622 L=1,LM2
MM=2*L-1
SELF1=COMP1(L+2,1)*COMP1(L+2,3)*PLALL(MM,K)+SELF1
SELF2=COMP1(L+2,2)*COMP1(L+2,3)*PLALL(MM,K)+SELF2
622 CONTINUE
COMSV(K+2,1)=-SELF1
COMSV(K+2,2)=-SELF2
SELF1=0.0
SELF2=0.0
DO 623 L=1,LM3
MM=2*L-1
SELF1=COMP1(L+3,1)*COMP1(L+3,3)*PLALL(MM,K)+SELF1
SELF2=COMP1(L+3,2)*COMP1(L+3,3)*PLALL(MM,K)+SELF2
623 CONTINUE
COMSV(K+3,1)=-SELF1
COMSV(K+3,2)=-SELF2
621 CONTINUE
LXM23=4+L1SAV(2)+L1SAV(3)
IF(LXM23-9)626,626,627
627 LXM23=9
626 LXM13=4+L1SAV(1)+L1SAV(3)
IF(LXM13-9)628,628,629
629 LXM13=9
628 DO 131 LP=1,6
DO 132 MN=1,4
MG=MG+1
IF(MG-161617.617.618
617 IH=2
GO TO 619
618 IH=1
619 IF(LP-8)610,612,612
612 IP=0
610 IP=IP+1
IX=10RE(IP
IF(IP-16)615,616,616
616 IZ=0
615 IZ=IZ+1
IA=10AR(IZ)
IC=ICOR(IZ)
441 FORMAT(2X,9(15.2X1)
IF(LP-4)601,601,602
601 MGG=NN
GO TO 603
602 MGG=MN+4
603 WRITE(6,441)LXM12,LXM13,LXM23,IH,1A,1X,LP,1C,MGG
DO 793 K=1,33+2
XTM12=0.0
DO 630 L=1,LXM12
WAA=CORE(L,LP+1,1)
WBB=CORE(L,LP+2,1)
WCC=CORE(L,1,31)
WDD=CORE(L,1,41)
CPRE=F1(1,1)
SPRE=F1(1,2)
XTM12=(CPRE*(WAA+WCC-WBB+WDD)-SPRE*(WBB+WCC+WAA+WDD))*PLALL(L,K)+
1XTM12
630 CONTINUE
XTM23=0.0
DO 631 L=1*LXM23
  WAA=CORE(L+1*C+1*3)
  WBB=CORE(L+1*C+2*3)
  WCC=CORE(L+1*3*3)
  WDD=CORE(L+1*4*3)
  CPRE=FI(3,1)
  SPRE=FI(3,2)
  XTM23=(CPRE*(WAA*WCC-WBB*WDD)-SPRE*(WBB*WCC+WAA*WDD))*PLALL(L*K)+
  IXTM23
631 CONTINUE
DO 632 L=1*LXM13
  WAA=CORE(L+MGG,1+2)
  WBB=CORE(L+MGG,2+2)
  WCC=CORE(L+1*3*2)
  WDD=CORE(L+1*4*2)
  CPRE=FI(12,1)
  SPRE=FI(12,2)
  XTM13=(CPRE*(WAA*WCC-WBB*WDD)-SPRE*(WBB*WCC+WAA*WDD))*PLALL(L*K)+
  IXTM13
632 CONTINUE
SIG1(K+1)=(1.0E+27)*(ALAN**2)*0.25*(XTM13+XTM12+XTM23+COMSV(K+1*IH+1)+COMSV(K+2*IA)+COMSV(K+3*IX1))
703 CONTINUE
CALL PLOT
132 CONTINUE
131 CONTINUE
B00 RETURN
END
//LINKRUN EXEC PROCRUNFORT.PARM=LKD-XREF+TIME=LKD=1+TIME=GO=2500
//REGION GO=250K
//LKED=SYSLIN DD DSNAME=*.FMP,CMP=SYSLIN,DISP=OLD,DELETE*
//GO=FT07F001 DD SYOUT=8
//GO=SYSLIN DD *
ERRATA

Several changes have been made to the program, since the listing was made. These changes are noted below.

FORCS

8878 MULE = 1

IPAR = IPITY (MJE, JULIE)       ADDED

CALL LDETM

CALL SETOW

2635 JOHN = JULIE

ISTED = 1       ADDED

MIN = MJE

FUNK

The definition of the quantity $\chi^2$ has been changed to make the definition consistent with the standard definition. It has been assumed that the experimental uncertainty of the cross section is 5%. Also the program no longer searches on the ratio to Rutherford for angular distribution data. Thus the program no longer assumes the data is the ratio to Rutherford times one hundred as discussed for CARD N+7
to CARD M in Section 13 of Appendix D, part b.

NCAL = 0 and NOPT = 1.

54 CHHH = CHHH + ((SIG(I,K) = YEXP(I,K))**2)/
          ((0.05 * YEXP(I,K))**2)

57 CHHH = CHHH + ((SIG(I,K) - YEXP(I,K))**2)/
          ((0.05 * YEXP(I,K))**2)

6936 CHEVY = CHEVY + ((SIG(I,K) - YEXP(I,K))**2)/
              ((0.05 * YEXP(I,K))**2)
APPENDIX E

Programs Used in Reduction or Analysis
of $^9$Be($\alpha$, $\alpha$)$^9$Be Data

A description of the various programs used in the reduction and analysis of the data are presented. Listing and sample data cards are also included. The programs are discussed in the following sections:

1. SCALY (Data Reduction) page 291.
2. READY (Data Reduction) page 293.
3. DIXIE (Data Reduction) page 316.
4. CONVR (Experimental Cross Section) page 328.
5. HSPS (Coulomb Function) page 337.
6. CHECK (Checks output of HSPS) page 350.
7. NHPS (Neutron Penetrabilities) page 352.

Programs Associated with Data Reduction

1. SCALY

The data were reduced using several methods. Before the Van de Graaff Laboratory acquired an IBM 1800 Computer, all data reduction was done off-line. The data were collected in a
Nuclear Data 512 Channel analyzer which was read out onto paper punch tape. The tape was next converted to cards. A program called SCALY, using the cards as input data, then plotted the spectra on a line printer along with the counts in each channel and a running sum of the total counts. Using the SCALY output, data reduction was accomplished by hand. The $^9$Be peak was located in each spectrum and its limits determined by eye. The counts in all the channels in the peak were added and if there was background, it was estimated by averaging the background on either side of the peak and extrapolating under the peak using a straight line. The estimated background was then subtracted from the peak counts. Most of the data presented in the present work were reduced this way. Since the addition of the IBM 1800 Computer to the facilities of the laboratory, there is little need for SCALY outputs and for this reason, no listing or additional discussion of the program SCALY shall be given.
Two programs have been written for the "1800" which allow peak integration of spectra while data is being acquired. The first program which will be discussed is called READY and was written by F. L. Riffle, Dr. J. R. Duray, and the present author. In particle spectra the peak of interest is usually well separated and there is little need for an exotic peak fitting program. The purpose of READY is to integrate the peaks of interest and subtract background in much the same way one does by hand. After the program is told in what regions of the spectrum the peaks of interest are located, the program locates the peaks and performs the integration. If one is doing an angular distribution, or an excitation curve, the program need not be initialized for each run, but will follow the original peaks chosen.

**THEORY**

The criterion that is used in the program to locate the limits of integration for each peak is outlined here. The RMS deviation squared of a series of numbers \( N_i \) about their mean is defined as

\[
\Delta N^2 = \frac{1}{p} \sum_{i=1}^{p} N_i^2 - \left( \frac{1}{p} \sum_{i=1}^{p} N_i \right)^2 \tag{E2.1}
\]

where \( p \) is the number of \( N_i \). If the numbers \( N_i \) are described by
\[ N_i = m \text{ (where } m \text{ is a constant),} \quad \text{E2.2} \]

then the RMS deviation squared is zero.

Equation E2.2 is the equation for a horizontal straight line if we consider the ordinate of a graph to be the numbers \( N_i \).

Thus one might be able to use the criterion that the RMS deviation squared is zero, to determine flat backgrounds on either side of a peak in a spectrum, except for the statistics associated with the counting of nuclear events. Let us see how statistics will affect the result. Let us assume that we have a flat background with Gaussian statistics and define \( \zeta_i \) by

\[ N_i = m + \zeta_i \quad \text{where } \zeta_i = \pm \sqrt{m}, \text{ and } m \text{ is the mean} \quad \text{E2.3} \]

We substitute equation E2.3 into equation E2.1 and after a simplification we obtain

\[ \Delta N^2 = m - \left( \frac{\Sigma_i \zeta_i}{p} \right)^2 \quad \text{E2.4} \]

or

\[ \Delta N^2 \leq m \quad \text{E2.5} \]

Equation E2.5 is the criterion used in the program to determine the limits of a peak and is quite sensitive since the RMS
deviation squared is much greater than the mean when calculated on the side of a peak. If the background is not really flat but gently sloped, the criterion is relaxed somewhat in the program by allowing the RMS deviation squared be less than twice the mean.

GENERAL DESCRIPTION

The initial setting up of the program may be done in one of two ways. The run number which identifies the spectrum, the number of peaks to be integrated, and their channel numbers may be entered using the typewriter or this information may be entered by using the display scope. The program then locates each peak by looking for the channel with the largest number of counts in it, in a region of fifty channels centered about the channel which the user has specified as the peak channel, or which the program had last decided was the peak channel. The program then uses the criterion for a flat background (Eq. E2.5) and searches for the closest region on either side of the peak which satisfies the criterion. Because some peaks are very narrow and some very wide, the number of channels used in calculating the RMS deviation squared is determined from the number of channels at half-maximum of each peak. This is done to avoid an apparent satisfaction of the criterion on the top of a very wide peak.
The program tries to satisfy the criterion for flatness a total of four times, the first with the criterion for flatness calculated with the number of channels at half-maximum, then three more times with the number of channels in the calculation increased by one each time. This is done to give the user an idea of how much background is being subtracted and the consistency of the peak areas. For example, if a peak has a very long tail, part of this may be excluded during the first calculation but may be included on later calculations. After the four determinations of the peak area, the numbers are written out on the line printer and the program continues to the next peak unless it failed to satisfy the flatness criterion all four times. Then the peak is plotted on the display scope and the program awaits the user's response. The user may choose to continue without an area or may use an option which allows the background channels and peak limits be chosen using the display scope. If he chooses the latter option the area and background are then calculated using the chosen numbers and written out on the line printer. The program will then proceed to do the rest of the peaks chosen. If the user wishes, he may have the results of each "fit" displayed on the scope. The program will then await the user's response after each peak before continuing to do the next. The user then has the option to pick the peak limits
using the display scope if he finds none of the "fits" determined by
the program to be satisfactory.

If the next spectrum to be reduced has been stored on the
experimentalist's data disk with a sequential run number and the
user wishes the areas of the same peaks, though the peaks may have
shifted a few channels in the spectrum as they would in taking an
excitation curve or angular distribution, the program need not be
initialized again but will automatically proceed as before in
locating the peaks and determining the areas.

Because of the limited size of core of the "1800", the program
is written in many small programs. A flow chart showing the
relationships between all these programs is given on page 305.
The listings are given on pages 306 to 315. A short description
of each program is given next followed by explanations of all the
options and how to use the programs.

DESCRIPTION OF PROGRAMS IN READY

SKAT1: An interrupt program which queues PIKEM and
SASSY or READY on level 0614.

PIKEM: A program written by Professor S. L. Blatt which
is used in this instance to initialize program READY by allowing
one to pick on the display scope how many peaks are to be integrated
and their locations in the spectrum.
**SASSY:** A program which by-passes READY after PIKEM has been used and chains directly to FABIT.

**READY:** The initialization part of the program, where information is entered by keyboard. If initialization was done with PIKEM, this program is usually skipped unless one of the options in it are needed.

**FABIT:** Checks toggle switch 9 and data switch 1 and writes titles for the output. It chains to ABFIT.

**ABFIT:** Locates the peaks and performs the actual calculations and writes the output on the line printer. If the display scope is desired to show what the program has picked as a peak, then ABFIT calls special to FLICK.

**FLICK:** If data switch 0 is up, FLICK plots the peak which was chosen and the limits of integration on the display scope and chains to FLLIK. If data switch 0 is down, it returns to ABFIT unless no limits of integration were found in which case FLICK chains to FLLIK.

**FLLIK:** Identifies the peak with a channel number and run number which it writes on the display scope. FLLIK chains to FIXIL.

**FIXIL:** Checks the typewriter and the abort switch. If one is satisfied with the results of the program in finding the peak
and its integration limits, one hits "EOF" on the typewriter and
FIXIL calls back to ABFIT to do the next peak. If one does not
like the results, one puts up the abort switch and then hits "EOF"
on the typewriter. FIXIL then chains to FATTY.

**FATTY:** Sets up parameters for LTPEN and queues LTPEN
and LUCKY.

**LTPEN:** A program which was written by Professor S. L.
Blatt and is used in this instance to pick four channels, (using the
display scope), two on each side of the peak of interest. The four
channels determine where the background is to be averaged from
and the limits of integration of the peak.

**LUCKY:** Uses the parameters from LTPEN and determines
the background and peak area and chains to ABFIT.

**SUBROUTINES IN READY**

**GETIT:** Determines the parameters necessary to read data
from the experimentalist's data disk.

**ERMSG:** Writes out error messages in READY.

**SUB1:** Calculates the mean value of the counts in a given
region and the mean of the counts squared in the same region.
DISCUSSION OF OPTIONS

There are seven option switches and each is discussed in what follows.

A) DATSW 0  Up:  Plot of fit on scope.  For program to continue, one must push "EOF" on typewriter.  This must be done after last peak also.

Down:  No plot unless there is no fit, then it will plot anyway.  If there is a plot, one must push "EOF" on typewriter for program to continue.

B) DATSW 1  Up:  Allows SKAT1 to queue PIKEM if EXP (2) down.

Down:  SKAT1 will queue READY, then one must type in peak channels with typewriter.

In READY, if one used option 3, and if by chance EXP (2) down when DATSW1 down, then after READY, it will call VIAQ and stop.

C) EXP (1)  Up:  If EXP (2) down, DATSW1 up, then program steps up run number by one and proceeds automatically.
Down: If EXP (2) up, READY will then ask for four options.

1. Old parameters: Increases run number by one and program proceeds automatically (same function as EXP (1)).

2. New parameters: Feed in peak channels and NAVE. NAVE is the number of channels used to calculate the mean. In the present version of the program NAVE is calculated automatically so enter any number since this will be ignored.

3. Change run number only: Very convenient for redoing a run without having to go through PIKEM again.

4. Change NAVE only: Do Not Use, but if you do, program will continue and calculate its own NAVE, run number will be the same as last run done.

D) EXP (2) Up: Overrides DATSW1 and SKAT1 queues up READY which will ask you for four options.

Down: If EXP (1) up, program increases run number by one and continues. If EXP (1) down, SKAT1 brings in PIKEM.
E) ABORT SWITCH

Up: Use only after display of fit, if one doesn't like fit, put Abort Switch up and push "EOF". This will bring in LTPEN which will ask for how many parameters - **ALWAYS** choose four. Put Abort Switch down as soon as you see that LTPEN is being brought in, about one-half second or less. If you don't, LTPEN will stop and you won't be able to choose your background channels and peak limits. But the program **LUCKY** will think you have and continue. After choosing the correct 256 group and before choosing the last of the four background parameters, there are two switches "F" and "G" the position of which you must decide on, since **LUCKY** will read them.

**NOTE:** Always pick the four background parameters in increasing
order. One may choose the same parameter twice however. The second and third parameters chosen are the most important in that they determine the lower and upper limits of the peak integration.

F) CONTACT SWITCH ROW1, "2" Up: Background from upper side set to zero.
   Down: Background from upper side calculated.

G) CONTACT SWITCH ROW1 "3" Up: Background from lower side set to zero.
   Down: Background from lower side calculated.

NOTE: If both "F" and "G" up, then one just gets sum of peak counts, with no background subtracted.

USE OF PROGRAM

1) DICLE SKAT1 or SKAT2.

2) Flip up DATSW0 and DATSW1.

3) Flip down EXP (1) and EXP (2).

4) Push 0614 button.

5) Select number of peaks to be fit.
6) Position "Light-Pen" over peak and enter until all peak channels entered.

7) Look at fits, select one you like, push "EOF" if there is at least one satisfactory fit, or flip up Abort push "EOF" then flip down Abort. (See 8 if Abort used.)

8) Enter four parameters, in increasing order. Before entering last one determine how you wish to calculate background by positioning contact switches row 1, "2" and "3". Having done this, program will continue automatically until all peaks done.

9) After last fit, push "EOF", flip up EXP (1) and EXP (2).

10) If next run number has increased by one, just push 0614; program will follow the peak that you have initially selected.

11) If program loses peak, flip EXP (1) and EXP (2) down, push 0614, go to step 5.

12) If want to change run number only, leave EXP (2) up, flip down EXP (1), type in 3.
FLOW CHART OF READY

EXP(2) UP, EXP(1) DOWN

READY 1

FABIT 2

ABFIT 3

FLICK 4

FLLIK 6

FIXIL 8

ABORT (UP)

FATTY 7

LTPEN 8

LUCKY 9

ERMSG 2a

SUB 1 3a

PIKEM 11

SASSY 10

GETIT

SKAT 1 12

EXP(2) DOWN
EXTERNAL ABFIT

DIMENSION IBKG(4)
COMMON NAVF, XR, XSR, NSPEC(512), MCHAD, LEX, NZERX, MX
COMMON KL(9), KU(9), IAUF(4)
COMMON INSSEL, INSK(1), DUMV1(2), DUM(15), SCAL(15), ISYS(20), MCHAN(1)

EXTERNAL ABFIT
COMMON/1NSKEL/1NSK IIJ, DUMY1(2), DUMCIS, SCALCIS, I SYS(20)
COMMON JK, IIV, DY, KS(9)
COMMON XT, Y
COMMON IRJ
DEFINE FILE 3(4995, 64, INT3)
NUM=1

100 FORMAT(-INVALID PARAMETERS-)
    CALL VIAO
2 NUM=2
3 DO 4 J=1, NUM
       JP7+6+J
       NZERO=ISYS(5)
       NGRUP=(ISYS(JP)-NZERO)/64
       JPP=JP+3
       NGPF=(ISYS(JPP)-NZERO)/64
       IF(NGPF-NGRUP)1=6+6
6 IF(NGPF-NGRUP-317, 7, 1
7 IREC=ISYS(6)+NGRUP
       DO 5 K=1, 4
          KP=(K-1)*64+1
          KPP=KP+3
          READ(3-IREC)(NSPEC(K), I=KP, KPP)
5 IREC=IREC+1
     NCHAN=ISYS(JP)
     I=0
8 IF(NCHAN-641, 10, 14
9 I=I+1
     NCHAN=NCHAN-64
     GO TO 8
10 DO 11 K=1, 4
       KP=JP+K-1
11 IBKG(K)=ISYS(KP)-1*64
     IB=IBKG(2)-IBKG(1)+1
     B1=0
       DO 12 K=1, IB
          KK=IBKG(1)-1+K
12 B1=NSPEC(KK)+B1
       B1=B1/IB
       IB=IBKG(4)-IBKG(3)+1
       B2=0
       DO 13 K=1, IB
          KK=IBKG(3)-1+K
13 B2=NSPEF(KK)+B2
       B2=B2/IB
       CALL TOGSW(1, 92, ISSST)
       GO TO (777, 776).ISSST
777 B1=2*B1
    R2=0
776 CALL TOGSW(1, 93, ISSPE).
       GO TO (96, 778).ISSPE
86 B1=0
    R2=20*B2
778 IB=1BKG(3)-IBKG(2)+1
    BY)=(1-B1)*B2/B
EXTERNAL FIKIL
COMMON NAVE*XS*XS*NSPEC(512)*MCHAD*LEX*NZER*MX
COMMON KL(9)*KU(9)*IAVE(4)
COMMON/INSKEL/INSK(11)*DUMY(12)*IDUM(15)*SCAL(15)*ISYS(20)*MCHAN(1
82)*11*12*13*NE*NN*IL*1W(9)
COMMON JK*I*I+DY*KS(9)
COMMON XT*Y
COMMON IRJ
CALL PLOTS(1)
CALL ORGSC(1*0*1*0)
CALL FCHAR(0*0*0*0*0*0*0*0*0)
WRITE(1*205)11*12*13*MCHAN(JK)
FORMAT(13*---*13*---*13:*4*X:14*---*PEAK-)
XT*XT+IAVE(4)
CW*90*0/100*
CALL ORGSC(1*0*1*0)
IF (XT—8.9) 207*207*208
208 XT*8.5
207 CALL SCALF(CW*1.0*0.0*0.0)
Y=Y—4.0*DY
DO 6 JT=1*4
IF (KL(JT))7 .B 7
8 Y=Y*DY
GO TO 6
7 Y=Y+DY
CALL FCHAR(XT*Y*0.4*0.4*0.0)
WRITE(1*155)IAVE(JT)*KS(JT)
FORMAT(112*2*112)
6 CONTINUE
CALL SCOPE(0)
CALL CHAIN (FIKIL)
END

EXTERNAL FABIT
COMMON NAVE*XS*XS*NSPEC(512)*MCHAD*LEX*NZER*MX
COMMON IN*KL(9)*KU(9)*IAVE(4)
COMMON/INSKEL/INSK(11)*DUMY(12)*IDUM(15)*SCAL(15)*ISYS(20)*MCHAN(1
82)*11*12*13*NE*NN*IL*1W(9)
COMMON JK*I*I+DY*KS(9)
COMMON XT*Y
COMMON IRJ
IRJ = 1
CALL CHAIN (FABIT)
END

EXTERNAL FLLIK
COMMON NAVE*XS*XS*NSPEC(512)*MCHAD*LEX*NZER*MX
COMMON KL(9)*KU(9)*IAVE(4)
COMMON/INSKEL/INSK(11)*DUMY(12)*IDUM(15)*SCAL(15)*ISYS(20)*MCHAN(1
82)*11*12*13*NE*NN*IL*1W(9)
COMMON JK*I*I+DY*KS(9)
COMMON XT*Y
```
SUM=0.
DO 14 K=1,IB
  KK=ISYS(K)-1+K
14 SUM=NSPEC(KK)+SUM
SUM=SUM-BKG
KZ=(ISYS(1:2)+ISYS(3))/2
WRITE(*,15)ISYS(1),ISYS(2),ISYS(3),NZ,SUM,BKG
15 FORMAT(1X,'RUN=',13I7,1X,'PEAK=-14--CONTAINS=-1',
  1F9.0,' COUNTS=12=',F9.0)
4 CONTINUE
IRJ=IRJ+1
NN=IW(8)
JK=JK+1
IF(JK-NN)3033,3033,3034
3033 IW(9)=JK
  LEX=ISYS(4)
  NZERX=ISYS(5)
  MX=ISYS(6)
  CALL CHAIN(ABFIT)
3034 CALL VIAO
END
*STORECI M 1 LUCKY LUCKY COLDO
*FILE(3,EXPER+1)
*CCEND
// FOR FATTY
EXTERNAL LTPEN,LUCKY
COMMON NAVE,XB,XSBNSPEC(512),MCHAD,LEX,NZERX,MX
COMMON I,K(19),KU(9),IAVE(4)
COMMON/INSKEL/INSK(1),DUMY1(2),DUMY1(15),SCAL(15),ISYS(20),MCHAN(1)
  12I12,13,12,13,12,13,12,13,12,13,12,13,12,13
COMMON JK,III,IND(9)
COMMON XT,Y
COMMON IRJ
ISYS(1) = 11
ISYS(2) = 12
ISYS(3) = 13
ISYS(4) = LEX
ISYS(5) = NZERX
ISYS(6) = MX
CALL QUEUE(LTPEN,11+0)
CALL QUEUE(LUCKY,11+0)
CALL VIAO
END
*STORECI M 1 FATTY FATTY COLDO
*CCEND
// FOR FIKIL
*ONE WORD INTEGERS
*IOCS (KEYBOARD,TYPE*WRTER)
EXTERNAL FATTY
COMMON NAVE,XB,XSBNSPEC(512),MCHAD,LEX,NZERX,MX
COMMON I,K(19),KU(9),IAVE(4)
COMMON/INSKEL/INSK(1),DUMY1(2),DUMY1(15),SCAL(15),ISYS(20),MCHAN(1)
  12I12,13,12,13,12,13,12,13,12,13,12,13,12,13
COMMON JK,III,IND(9)
COMMON XT,Y
COMMON IRJ
100 FORMAT (-DONE--EOF-)
READ (8+101) KECN
101 FORMAT (A1)
CALL ABORT(ISTAT)
GO TO (10+11,1 STAT
10 IW(9)=JK
IW(8)=NN
CALL CHAIN(FATTY)
```
ISUM=0
DO 310 J=1,4
310 ISUM=ISUM+K(L(JTZ))
IF(ISUM>311)GO TO 201
311 CALL DATSW(0,JOCK)
GO TO (201+200),JOCK
200 CALL BACK
201 CALL PLOTS(1)
CALL ORG5C(1+0,1+0)
CALL ERASC
IKK=MCHAN(JK)-1
SPEC=NSPEC(IKK)
IF(SPEC<9.0)69,69,70
70 DO 50 J=11,10
SPEC=SPEC/10.0
AXP=J
IF(SPEC<2.0)51,51,40
40 IF(SPEC<5.0)7,7,60
60 IF(SPEC<10.0)82,82,50
50 CONTINUE
51 SF=5.0
GO TO 69
7 SF=2.0
GO TO 69
82 SF=1.0
69 IIC=MCHAN(JK)-30-1
IF(IIC)130,130,131
130 IIC=1
131 IFC=MCHAN(JK)+30-1
IF(IFC)812,132,132,133
133 IFC=512
132 XW=IFC-IIC
CW=9.0/XW
CALL SCALF(CW+1.0+0.0+0.0)
NCN=IIC
CALL SCOPE(1)
DO 81 J=IIC+1,FC
YCHAN(NSPEC(J)*)SF)*(10.0**AXP)
IF(YCHAN<9.0)99,99,83
83 YCHAN=9.0
9 X=J-NCN
CALL FFLOT(1,X,YCHAN)
CALL FFLOT(2,X,YCHAN)
CALL POINT(0)
81 CONTINUE
Y=0.333*NSPEC(IKK)*SF)*(10.0**AXP)
DY=0.5*Y
DO 143 IP=1,4
V=Y+DY
ISP=K(L(IP))
143 CONTINUE
Y=0.333*NSPEC(IKK)*SF)*(10.0**AXP)
DY=0.5*Y
DO 148 IP=1,4
Y=Y+DY
301 NSP=ISP-IAVE(IP)
IF(NSP)141,142,142
141 NSP=0
142 X=ISP-NCN
XT=NSP-NCN
IF(Y<9.0)145,145,144
144 Y=9.0
145 CALL FFLOT(1,X+Y)
CALL FFLOT(2,X+Y)
143 CONTINUE
Y=0.333*NSPEC(IKK)*SF)*(10.0**AXP)
DO 148 IP=1,4
Y=Y+DY
3P=KU(IPI)
IF(ISP)=030
303 NSP=ISP+1(AVE(IP))
IF(NSP=512)149,149,150
150 NSP=512
149 XS=ISP-NCN
XT=NSP-NCN
IF(Y-9.0)151,151,152
152 Y=9.0
151 CALL FPL(T(1,XS,Y))
CALL FPL(T(2,XT,Y))
148 CONTINUE
CALL CHAIN(FLLIX)
END
*STOREC 1 M 1 FLICK PIC COLDC
*END
// FOR
*ONE WORD INTEGERS
*ONE WORD INTEGERS
SUBROUTINE SUB1
COMMON NAVE,XB,XS,XSPEC(512),MCHAN(1),LEN,NZERO,MM
COMMON 1,KU,KL,AVE(4)
COMMON INSKEL/INSK(2),IDUMY(2),IDUM(15),SCAL(15),ISYS(20),MCHAN(1)
82)11,12,13,NEX,NE,IL,1W(9)
COMMON JK,INTDY,K5(9)
CAVE=NAVE
XB=0.0
DO 90 N=1,NAVE
NZ=M+MCHAN-1
XSPEC=NSPEC(NZ)
XB=XB+XSPEC
90 CONTINUE
XB=XB/CAVE
XS=0.0
DO 91 N=1,NAVE
NZ=M+MCHAN-1
XSPEC=NSPEC(NZ)
XS=XS+XSPEC
91 CONTINUE
XS=XS/CAVE
RETURN
END
*STORE 1 SUB1
// FOR ABFIT
*10CS1(1443 PRINTER+DISK)
EXTERNAL FLICK
DIMENSION DG(2),TAR(9),RAR(9),AREA(9)
COMMON NAVE,XB,XS,XSPEC(512),MCHAN,LEN,NZERO,MM
COMMON 1,KU,KL,AVE(4)
COMMON INSKEL/INSK(11),DUMY(2),IDUM(15),SCAL(15),ISYS(20),MCHAN(1)
82)11,12,13,NEX,NE,IL,1W(9)
COMMON JK,INTDY,K5(9)
COMMON XT,Y
COMMON IRJ
DEFINE FILE 34995,64,0,INT3)
IF(I(RJ)=1)2101,2101,2102
2102 JK=1(W(9))
GO TO 906
2101 JK=1
906 NCHEK=MCHAN(JK)
IF(NCHEK=512)101,101,102
101 I=1
GO TO 107
102 IF(NCHEK=124,17,107,104
103 I=513
    GO TO 107
104 IF (NCHK=1536) 105, 105, 106
105 I=1029
    GO TO 107
106 I=1537
107 M=M+((I~NZERO)/512)*8
    M=M+7
    DO 99 LL=M,M+1
       JMX=1+(LL-MIN)*64
       JFX=JMX+63
       READ(3,LL) (NSPEC,J,J=JMX,JFX)
99 CONTINUE
    NC=NC+1
    JJ=NC+2
    IF (JJ1) 108, 108, 109
108 JJ1=1
109 JJF=NCHEK+24
    ISPEC=0
    DO 81 J=J1, JF
       IF (ISPEC=NSPEC(J)) 2*2*81
    2 ISPEC =NSPEC(J)
       M=NC(JK)=J
81 CONTINUE
1010 V=V+ISPEC
    NECK=V/2.0+0.59
    DO 1902 JP=1, 24
       IZ=NC(JK)+JP
       IF (NECK=NSPEC(IY)) 1902, 1903, 1903
1000 IVAL=ARY
    GO TO 1904
1001 CONTINUE
1002 CONTINUE
1902 JP=1, 24
1003 IY=NY(JK)+J
    IF (NECK=NSPEC(IY)) 1905, 1907, 1907
1907 Y=ARY
    GO TO 1906
1005 CONTINUE
1905 IY=(IVAL+1)/2
    CALL TOG@SW(2*8, @FAT)
    GO TO (2*2*302) IFAT
2303 IF (JK=2*1*PY)
2302 IF (IY=1) 1910, 1910, 1911
1910 IY=2
1911 IZ=IY+3
    DO 1908 JP=1, 2*1*1Z
       NAVE = IP
1908 I=IP+1, IPZ
       I=IP+1, IPZ
       I=AVE(IZZ)+IP
1900 S=1
1600 DO 40 JJ=1, 2*1*5
       M=NC(JK)+JJ-1-(NAVE+1)
       CALL SUB1
       IF (XZ) 4, 41, 40
        4 CONTINUE
1000 MCHAR = MCHAR + 4
43 L=0
    K=0
    DO 92 JJ=1, 35
       MCHAR = MCHAR-(JJ-1)-(NAVE-1)
         J=J.

CALL SUB1
XG=XSR-2-XB*5
IF (K-1) 1102, 1101-1101
1101 L=L+1
1102 IF (XQ) 1100, 1100, 92
1100 K=K+1
IF (L-K+1) 1106, 1105-1106
1105 IF (K-3) 92, 1109, 1109
92 CONTINUE
IF (JL-35) 1109, 1106, 1106
1109 B1(1) = XA
(C=MCHAD + NAVE=1
DO 60 JJ=1,36+5
MCHAD=MCHAN(JK)+JJ-1
CALL SUB1
XG=XS8-XB**2-XB*5
IF (XQ) 65, 65, 60
60 CONTINUE
MCHAR=MCHAN(JK)
GO TO 66
65 MCHAR=MCHAD=4
66 L=0
K=0
DO 82 JJ=1,35
MCHAD=MCHAR+JJ=1
JL=JJ
CALL SUB1
XG=XS8-XB**2-XB*5
IF (K-1) 1202, 1201-1201
1201 L=L+1
1202 IF (XQ) 1200, 1200, 82
1200 K=K+1
IF (L-K+1) 1106, 1205-1106
1205 IF (K-3) 82, 1209, 1209
82 CONTINUE
IF (JL-35) 1209, 1106, 1106
1106 MMCC=MCHAN(JK)+1
NC=0
LC=0
BAR(JK)=0+
TAR(JK)=0+
AREA(JK)=0+
S=S+1=0
LMX=5+0+01
IF (LMX=1) 1506, 1505, 1505
1505 MCHAN(JK)=MCHAN(JK)+1
GO TO 1914
1209 B1(2) = XA
NC=MCHAD
TAR(JK)=0
DO 50 MJ=LC+NC
XSPEC=NSPEC(MJ)
TAR(JK)=TAR(JK)+XSPEC
50 CONTINUE
UC=NC
UP=LC
BAR(JK)=0+5+11(k+1)+BG(2)+UC=UP+1=0
AREA(JK)=TAR(JK)=PAR(JK)
MCHAN(JK)=MCHAN(JK)+1
1914 KLI(IZZ)=LC
KU(IZZ)=NC
KS(IZZ)=S+0+01
KLI=LC+I
WRITE (6,110) AREA(JK),BAR(JK),TAR(JK),MCHAN(JK),KLL,KUU,KS(IZZ),I
SAVE(I22)

110 FORMAT (1X,FB8.1,2X,F7.1,2X,F8.1,5X,I14,7X,B14,8X,I4,10X,I2:10X,I13)
MCHAN(JK),MCHAN(JK)+1

1900 CONTINUE
WRITE (6,1113)

1113 FORMAT (//)
MCHAN(JK),MCHAN(JK)+1
CALL SPECL (FLICK)
JK=JK+1
IF(JK=NN)906,906,1916

1916 CALL VIAO
END

#STOREC M 1 ABFIT ABFIT COLDO
#FILE (J3.EXPER)
#CCEND
// FOR ERMSG
#IOCS (TYPEWRITER)
#ONE WORD INTEGERS
COMMON NAVE*XB*XS*NSPEC(912),MCHAN*LEX*NZERO*NX
COMMON I4*KL(9),KU(9),IAVE(4)
COMMON/INSKEL/INSK(1),DUMY1(2),DUMY15),SCAL(15),ISYS(20),MCHAN(I)
COMMON JK,II+DY*KS(9)

113 FORMAT (12(I1X,11A1))
1206 FORMAT (-RUN =3(1X,11A3)=- NO FIT FOR PEAK AT =14=- FOR CAVG=-
8=-13=)
434 FORMAT (-SPECTRUM NOT FOUNO CALL VIAO=)
112 FORMAT (-CHECK ID NO=FLIP OPT=SW=DOWN=)
MMCC=MCHAN(JK)+1
GO TO (1,5,5+4,5)
1 WRITE (7*112)
2 WRITE (7*434)
3 WRITE (7*113) (MCHAN(JK),JK=1,NN)
GO TO 5

4 WRITE (7*1206) II+12+13+MMCC*NAVE
5 CALL BACK
END

#STOREC M 1 ERMSG ERMSG COLDO
#CCEND
// FOR FAB
#ONE WORD INTEGERS
#IOCS (1443 PRINTER)
EXTERNAL ERMSG
EXTERNAL ABFIT
COMMON NAVE*XB*XS*NSPEC(912),MCHAN*LEX*NZERO*NX
COMMON I4*KL(9),KU(9),IAVE(4)
COMMON/INSKEL/INSK(1),DUMY1(2),DUMY15),SCAL(15),ISYS(20),MCHAN(I)
COMMON JK,II+DY*KS(9)
COMMON XT*Y
COMMON IRJ
IRJ=1
CALL TOGSW(2,9,1STAT)
GO TO (1344+1343),1STAT

1343 CALL DATSFW(1,JOCK)
GO TO (1346+1347),1OCK

1347 CALL VIAO
1347 1=ISYS(1)
12=ISYS(2)
13=ISYS(3)
LEN=ISYS(4)
NZERO=ISYS(5)
1=1YR(1)
NN=ISYS(7)
NJPT=NN+10
DO 1345 JPT=11,NJPT
  JK=JPT-10
  MCHAN(JK)=ISYS(JPT)
1345 CONTINUE
WRITE(6,4112)(I+12,13)
4112 FORMAT (1H1,4X- THE RUN NUMBER IS =3(1X,13)/)
WRITE(6,4111)
WRITE(6,4110)
4111 FORMAT (4X- AREA = 5X-BKG = 5X-TOTAL = 6X-PEAK = 6X-STARTING = 5X-)
  FINAL=20X-CHANNEL-)
4110 FORMAT (27X-POSITION=1  +3X-SENSITIVITY=13X-AVERAG
  NE=//)
1344 IF (LEN) 433433,47
  CALL SPEC1(ERMSG1
  CALL VIA0
47 CALL CHA1N(ABFI)
  END
*STORECM M 1 FABIT FAB COL00
*CCEND
// FOR READY
*ONE WORD INTEGERS
*TDCS( 1443 PRINTER-TYPEWRITER-KEYBOARD-DISK)

EXTERNAL FARIT
DIMENSION INN(3)
COMMON NAVE*XS*XB*NSPEC(S12),MCHAN*LEN*NZERO*MM
COMMON I+K(9),KU(9),IAVE(4)
COMMON/INSKEL/INSK(1),DUMY(2),IDUM(15),SCAL(15),ISYS(20),MCHAN(1
  21)+1A+1B+NE-NN+IL
DEFINE FILE 1(3201+U*INT1)
DEFINE FILE 2(5601+U*INT2)
DEFINE FILE 3(4995+64*U*INT3)
DATA MSKE/Z0080/.
INN(2)=69
INN(3)=1
CALL CS(02001+INN(1),INN(3))
IL=IN0D(INN(1),MSKE)
IF(1L)995,13,996
995 CALL VIA0
996 IC+IC+1
GO TO 101
13 WRITE(7+208)
WRITE(7+813)
208 FORMAT (2X ENTER OPTS 1234 1-USE OLD PAR 2-ALL NEW PAR 3 1)
WRITE(7+801)
813 FORMAT (20X=3 CHANGE RUN NUMBER 4 CHANGE NAVE ONLY=)
READ(8+209)NE
209 FORMAT (111)
GO TO (996+200+806+1034)*NE
200 WRITE (7+201)
201 FORMAT (-X ENTER NUMBER OF PEAKS-)
READ (8+209)NN
806 WRITE(7+204)
204 FORMAT ((XXX-YYY-ZZZ=1X=ENTER THE RUN NUMBER OF THE DATA TO BE F
  IT-)
READ (8+205) 1A+1B+1C
205 FORMAT ([31X+131X+13]
  IFINE-3)+07266+266
807 WRITE(7+203)NN
203 FORMAT ((ENTER THE CHANNEL NUMBERS FOR THE =111= PEAKS TO BE FO
  LLOWED AND FIT=)
WRITE (7+311)
311 FORMAT ((XXX=)
DO 69 LLL=1,NN
READ (R*2041) MCHAN(LLL)

2041 FORMAT(1I4)
69 CONTINUE
101 WRITE (6,1112) IA,IB,IC
1112 FORMAT (1H1,4X='THE RUN NUMBER IS '-3(1X,I3)//)
WRITE(6,1111)
WRITE (6,991)
991 FORMAT (27X,*-AREA-*5X,*-RKG-*5X,*-TOTAL-*6X,*-PEAK-*6X,*-STARTING-*5X=
*FINAL-*20X,*-CHANNEL-*=)
CONTINUE
1034 WRITE (7,808)
808 FORMAT(-XX ENTER NUMBER OF CHANNELS OF AVERAGE STEP->
READ(I*219)NAVE
868 CONTINUE
219 FORMAT(1I2)
266 CALL GETIT(IA,IB,IC,LEX,NZERX,MX)
LEN=LEX
ZERO=NZERX
MX=MX
CALL CHAIN (FABIT)
END

STOREC1 M 1 READY READY COLDO
FILES (1*EXPER=1)*(2*EXPER=2)*(3*EXPER=1)

EXTEND
// FOR SKAT
EXTERNAL SUMCF,DSCAL
EXTERNAL READY
EXTERNAL PIKEM
EXTERNAL SASSY
DIMENSION IN(3)
DATA MSK1/Z0020/
DATA MSK2/Z0010/
DATA MSK3/Z0030/
IN(2)=69
IN(3)=3
CALL C5(02001,IN(1),IN(3))
L=LAND(IN(1),MSK1)
IF (L) 12+12,11
11 CALL QUEUE(SUMCF,11,0)
12 L=LAND(IN(1),MSK2)
IF (L) 14+14,13
13 CALL QUEUE(DSCAL,11,0)
14 L=LAND(IN(1),MSK3)
IF (L) 16+16,15
15 CALL DATSW(1,JOCK)
GO TO (18,17,16)
16 CALL QUEUE(PIKEM,11,0)
CALL QUEUE(SASSY,11,0)
GO TO 17
17 CALL QUEUE (READY=11,0)
17 CALL ENDS
CALL INTEX
END

STOREC1 M 1 SKATI SKATI COLDO 0614
EXTEND
// JOB XXXXX
// END
3. **DIXIE**

The use of READY as can be seen from the criterion for finding a peak is not suitable for spectra where there are several peaks within a few channels of each other. If the peak of interest is overlapped by another peak, then using READY will force the user to choose the option where the background channels are chosen by hand. Also for convenient use of READY, the data should be stored on the user's disk in sequential run numbers. Thus, if one wants to check data at various angles and energies but not necessarily the order in which the data were stored, one must initialize READY for each different case. DIXIE was written to handle the case where it is necessary to choose the background by hand, or when one wants to check data in such a fashion as would make the run numbers non-sequential.

**THEORY**

The program allows one to select four channels, two on each side of the peak to be summed. A background average is determined from the data in these four channels and the limits of the peak are determined by the second and third channels chosen. The area is determined by summing the counts from the second and third channels chosen and subtracting the average background extrapolated under the peak using a straight line.
GENERAL DESCRIPTION

The program has two modes of operation, one which is very similar to READY, and one which allows the user to check data conveniently. In the one mode, the run number of the spectrum desired and the channel number of the peak to be summed is punched onto a card. On starting the program, the card is read and two hundred and fifty-six channels of data centered within sixty-four channels of the peak channel are plotted on the display scope. The user then positions the "Light-Pen" over the desired channels and enters four selections in increasing order to choose background channels and the limits of the peak. The area and background are calculated and the output is written on the typewriter. Typewriter output is used since it is conveniently located near the display scope. Once the output is printed, the next card is read and the program awaits the selection of four more parameters. This will continue until the last card is read.

In the other mode, after entering the run number of the desired spectrum by keyboard, the number of peaks and their channel positions are entered using the display scope. The operation of the program is then identical to that of the first mode except that no data cards are read. If the next spectrum has been stored with a sequential run number and the same peaks are desired, the
program will skip the initialization step and bring in the spectrum
and await the selection of the four channels.

In both modes, one may determine the average background
with two switches which can set the background from either side
of the peak to zero. This is especially useful if two peaks are
overlapped and one wants to determine average background from one
side of the peak only.

As in READY, the program is broken up into many smaller
programs. A flow chart showing their relationship is given on
page 323. The listings of the programs are given on pages 324
to 327.

DESCRIPTION OF PROGRAMS IN DIXIE

PSKAT: An interrupt program which queues programs PIKEM
and PETER, or FANNY on level 0613.

PIKEM: The user chooses the number of peaks and their
positions in the spectrum using the display scope. (See page 297).

PETER: This program sets up more parameters for and
chains to DIXIE.

FANNY: If DIXIE has been initialized and the data have been
stored in sequential run numbers, FANNY sets up parameters for
DIXIE, thus skipping PIKEM and PETER and chaining to DIXIE.
**DIXIE**: In this program various option switches are checked to determine if initialization has been done by PIKEM or whether it is to get the information from cards read from the card reader. DIXIE calls special to LTPIN and then calls chain to PKSIM.

**LTPIN**: The spectrum is displayed on the storage scope and the user selects four channels, two on either side of the peak. LTPIN calls back to DIXIE.

**PKSIM**: The area and the background are calculated and the output written on the typewriter. PKSIM then chains back to DIXIE until all the peaks are done and then exits.

**SUBROUTINES IN DIXIE**

**CHECK**: This subroutine finds the scale for plotting the data on the display scope.

**GETIT**: Subroutine which brings back the disk location of a desired spectrum.

**DISCUSSION OF OPTIONS**

There are five option switches and each is discussed below.

A) **DATSW 2**

**Up**: No cards read from the card reader. Assumes initialization has already taken place.
Down: Cards read from card reader to initialize program.

B) EXP (3)
Up: Allows PSKAT to queue PIKEM and PETER.
Down: If EXP (1) down, program stops.
If EXP (1) up, PSKAT queues FANNY.

C) EXP (1)
Up: (a) If program DIXIE is queued, and DATSW 2 is down, card read from card reader.
(b) Allows PSKAT to queue FANNY if EXP (3) down.
Down: If DATSW 2 is down, writes out the following message: "READY CARD READER, PUT TOGSW 8 UP, AND START". NOTE: TOGSW 8 is EXP (1).
If DATSW 2 is up and EXP (3) down, program stops.

D) CONTACT SWITCH ROW1 "2": Same as "F", on page 303.

E) CONTACT SWITCH ROW1 "3": Same as "G" on page 303.
USE OF PROGRAM

Part 1: To check data with non-sequential run numbers.

1. Put DATSW 2, EXP (1), and EXP (3) on down positions.
2. Queue DIXIE.
3. Place cards in card hopper with the run number and peak channel on each card.
4. Push "START" on computer console. Flip EXP (1) up.
5. Select four channels in increasing order by positioning "Light-Pen" over the desired channel and entering. Before selecting last parameter, check CONTACT SWITCHES ROW1, "2" and "3" to decide background averaging. See Section 2, Appendix E.
6. Program will continue until EXP (1) put in down position.
   Do this before last spectrum to be done.

Part 2: To reduce data with sequential run numbers.

1. Dicke PSKAT on level 0613.
2. Put DATSW 2 and EXP (3) up and push 0613 button.
3. Using the display scope, enter the number of peaks, and their channel numbers.
4. Using the "Light-Pen" select four channels as in step 5 of Part 1.
5. After last peak done, flip EXP (3) down and EXP (1) up.

The program will then proceed automatically to step 4
the next time button 0613 is pushed.

6. To change number of peaks or positions, put EXP (3)
up, push 0613 and do step 3.
FLOW CHART OF DIXIE

PSKAT

EXP(3) UP

PIKEM

EXP(3) DOWN

PETER

STOP

FANNY

QUEUE

DIXIE

GETIT

CHECK

DATSW 2

UP

DOWN

EXP(1)

READY CARD READER

READ CARD

LTPIN

EXP(1) UP

DATSW 2 DOWN

PKSIM

EXP(1) DOWN, DATSW 2 DOWN

STOP

<0

VK-NN

DATSW 2 UP

>0

EXP(1) UP
EXTERNAL DIXE
DIMENSION NSPEC(256), IBKG(4)
COMMON/INSLK/ISK(1), D(2), ISCAL(15), SCAL(15), SYS(20), "CHAN(09),

DEFINE FILE (4995, 64, U, INT3)
CALL DATSY(2, JCK)
GO TO (71, 70, JCK)

71 NCHEK="CHAN(JK)
   IF(NCHEK=512172, 72, 73)
   IT=1
   GO TO 95
73 IF(NCHEK=1024) 74, 74, 75
74 IT=112
   GO TO 95
75 IF(NCHEK=1536) 76, 76, 77
76 IT=1025
   GO TO 95
77 IT=1537
85 NCHEK=NCHEK-IT+1
   JJ=NCHEK-24
   JJF=NCHEK+24
70 JP=11
   NZERO=SYS(5)
   NGRUP=SYS(JP)-NZERO)/64
   JPP=JP-3
   NGPF=SYS(JPP)-NZERO)/64
   IF(NGPF=NGRUP) 1, 64+6
6 IF(NGPF=NGRUP=3) 7, 7+1
1 WRITE(7, 100)
100 FORMAT(' INVALID PARAMETERS')
   CALL VIA3
7 IREC=SYS(6)-GRUP
   DO 5 K=1, 64
      KP=K-1*64+1
      KPP=KP-63
      READ3(3, IREC) (NSPEC(I), I=KP, KPP)
5 IREC=REC+1
   IF(JOCK=1191, 91, 92)
91 ISPFC=0
   DO 81 J=JI, JCF
      IF(ISPEC="SPEC(JJ)"12, 2, 81)
2 ISPEC="SPEC(JJ)
   XCHAN(JK)=J
81 CONTINUE
   MCHAN(JK)="CHAN(JK)+IT
92 NCHAN=SYS(JP)
   I=0
8 IF(NCHAN=64) 10, 10, 9
9 I=I+1
   NCHAN=NCHAN+64
   GO TO 8
10 DO 11 K=1, 64
      KP=JP+K-1
11 IBKG(I)=SYS(KP)-I*64
   IB=IKKG(I)-IKKG(I)+1
   B1=0
   DO 12 I=1, 10
      KK=IKKG(I)+1*K
12 B1=NSPEC(KK)+1
  91=91/10
13 B2 = NSPEC( KK ) + 2
CALL TOGSH ( 1 , 0 , 2 , ISSET )
GO TO ( 777 , 776 ) , ISSET
777 B1 = 2 * B1
B2 = 0.
776 CALL TOGSH ( 1 , 0 , 3 , ISPE )
GO TO ( 86 , 778 ) , ISPE
86 B1 = 0.
B2 = 2 * B2
778 IB = IAKG ( 3 ) - IAKG ( 2 ) + 1
BKG = ( IB2 + 91 ) / 2 * 19
SUM = 0.
DO 14 K = 1 : 19
KK = IAKG ( 2 ) + K
SUM = SUM + BKG
14 WRITE ( 7 * 15 ) , ISYS ( 1 ) , ISYS ( 2 ) , ISYS ( 3 ) , 2 * SUM , BKG
FORMAT ( ' RUN ' , 13 * ' S ' , 13 * ' S ' , 13 * ' S ' , PEAK ' , 14 * ' CONTAINS ' ,
1 F9.0 , COUNTS , 2 * ' BKG IS ' , F9.0 )
IF ( JOCK = 1 ) B7 , 87 , 88
87 JK = JK + 1
IF ( JK < 1102 ) B102 , 101
88 CALL TOGSW ( 2 , 9 , ISTUD )
GO TO ( 102 , 101 ) , ISTUD
102 CALL CHAIN ( DIXIE )
101 CALL VIEW
END

// FOR PETER
*LIST ALL
EXTERNAL DIXIE
COMMON / INSKEL / INSK ( 10 , D ( 2 ) ) , ISCAL ( 15 ) , SCAL ( 15 ) , ISYS ( 20 ) , MCHAN ( 09 ) ,
INJ , JK
MN = ISYS ( 7 )
NJPT = NN + 10
DO 1130 JPT = 11 , NJPT
JK = JPT - 10
1130 MCHAN ( JK ) = ISYS ( JPT )
JK = 1
CALL CHAIN ( DIXIE )
END

// FOR PSKAT
*LIST ALL
EXTERNAL PIKF , PETER , FANNY
CALL TOGSH ( 2 , 15 , ISTUD )
GO TO ( 102 , 101 ) , ISTUD
101 CALL TOGSH ( 2 , 17 , IITTUD )
GO TO ( 102 , 17 ) , IITTUD
100 CALL QUEUE ( PIKF , 11 , 01 )
CALL QUEUE ( PETER , 11 , 01 )
GO TO 17
102 CALL QUEUE ( FANNY , 11 , 01 )
17 CALL ENTS
CALL INTEX
END
EXTERNAL LTPIN\PKSIM
COMMON/INSKEL/INSK(1)+D(2)*ISCAL(15)+SCAL(15)+ISYS(20)+CHAN(109)+
1N4-JK
COMMON NSPEC(256),ICHECK,NZ,IREC,IREC,ISCAL,NGLEN,NZO,J0
DEFINE FILE1(320+1+U+INT1)
DEFINE FILE2(560+4+U+INT2)
DEFINE FILE3(4995+64+U+INT3)
CALL DATS(7+JOCK)
GO TO (95+96)+JCCK
96 CALL TOGSX(2+9+ISTUD)
GO TO(102+101)+ISTUD
101 WRITE(7+103)
103 FORMAT('READY CARD READER, PUT T0SW 8 UP, AND START')
PAUSE
102 CONTINUE
READ(52)11+12+13+NZ
1 FORMAT(13(I3+I1)+I1+I4)
CALL GETIT (I1+12+13+LENT+NZERO+MM)
IF(LENT)10+10+12
10 WRITE(7+5)
6 FORMAT('SPECTRUM NOT FOUND')
CALL VIA3
12 ISYS(1)=11
ISYS(2)=12
ISYS(3)=13
ISYS(4)=LENT4
ISYS(5)=NZERO
ISYS(6)=MV
IFIJOCK=1195,95,97
95 NZ=NCACH(JK)
97 ISYS(7)=4
ISYS(8)=4
ICHECK=3
ISCAL=1
NGLEN=256
NZ=NZ-128
NZ=NZ/64*64+1
CALL CHECK (REC)
CALL SPECL (LTPIN)
CALL CHAIN (PKSIM)
END
EXTERNAL DIXIE
COMMON/INSKEL/INSK(11),D12,ISCAL(15),SCAL(15),ISYS(20),"CHAN(09)
14%JC
DEFINE FILE1(320+1,UINT1)
DEFINE FILE2(56C+4,UINT2)
DEFINE FILE3(4995+64,UINT3)
ISYS(3)=ISYS(3)+1
JK=1
I1=ISYS(1)
I2=ISYS(2)
I3=ISYS(3)
CALL SETIT(I1,I2,I3,LEN,NZERO,NM)
ISYS(4)=LEN
ISYS(5)=NZERO
ISYS(6)=""
CALL MAIN(DIXIE)
END
4. CONVR

Normalization of experimental yields to laboratory cross section is accomplished by use of equation

\[ \frac{d\sigma}{d\Omega} \text{LAB} = \frac{Yq'}{Q_T} \Delta\Omega T, \]

where \( Y \) is the experimental yield

\( q' \) is the effective charge per particle striking the target,

\( Q_T \) is the total charge collected,

\( \Delta\Omega \) is the solid angle subtended by the detector,

and \( T \) is the number of target nuclei per cm\(^2\).

In this experiment, the conversion of experimental yields is made tedious for several reasons. The \(^9\)Be data were taken with four detectors simultaneously, each of which has a different solid angle of acceptance. The data were taken with several different targets and for different amounts of total charge. Also the effective charge per particle striking the target changes with bombarding energy. In addition, it is desirable to convert the laboratory cross section to center of mass cross section for easy comparison with theory.

The program CONVR, using the experimental yields as input data, calculates the laboratory cross section, the center of mass
cross section, the center of mass scattering angle, Rutherford cross section in both the laboratory system and center of mass system, the ratio of the experimental cross section to Rutherford cross section, and prints the output on the line printer.

EQUATIONS USED IN THE CONVR

For elastic scattering, the laboratory scattering angle \( \psi \) is related to the center of mass scattering angle \( \theta \) by equation E4.2.

\[
\tan \psi = \frac{\sin \theta}{\frac{m_1}{m_2} + \cos \theta}
\]

where \( m_1 \) is the mass of the projectile,

and \( m_2 \) is the mass of the target.

We see from equation E4.2 that for elastic scattering, the center of mass scattering angle is independent of the bombarding energy and depends only on the masses and laboratory scattering angle. Solving for \( \theta \) in terms of \( \psi \) we get,

\[
\theta = \psi + \sin^{-1} \left( \frac{m_1}{m_2} \sin \psi \right)
\]

Equation E4.3 is quite useful since the data were measured at laboratory angles. Once \( \theta \) is known, one can easily calculate the conversion from laboratory cross section to center of mass cross section by equation E4.4.

\[
\frac{d\sigma}{d\Omega} \text{ c.m.} = \frac{d\sigma}{d\Omega} \text{ LAB} \frac{\sin^2 \psi}{\sin^2 \theta} \cos (\theta - \psi)
\]
Also once $\theta$ is known, the calculation of Rutherford cross section is trivial and is given by

$$\frac{d\sigma}{d\Omega} = 1.296 \frac{Z_1 Z_2 (m_1 m_2)^2}{E m_a} \frac{1}{\sin 4 \theta/2} \text{(mb)}$$

where $Z_1$ and $Z_2$ are the atomic numbers of particles 1 and 2 respectively.

$E$ is the bombarding energy in MeV.

The $^9\text{Be}$ targets were bombarded with singly ionized helium-four ions. As the helium ions pass through the target, they capture or lose orbital electrons until an equilibrium charge distribution is attained. "Several measurements of the equilibrium charge distributions for helium ions in matter have shown that the distributions are essentially independent of the material used."(25) The effective charge per helium ion striking the target was determined using the graph of "Charge Exchange of Helium Ions" page 27 of Nuclear Data Tables (1960). To facilitate computation, the present author has used a mathematical expression to approximate the data for He$^+$ ions from 1.7 to 5.2 MeV. The mathematical expression for the fraction of He$^+$ ions at a given energy as determined by the present author is

$$f^+ = \frac{.24}{E^{1.86}}$$

Where $E$ is the laboratory bombarding energy in MeV and .12 and 1.86 are empirical constants.
Above 1 MeV, the beam of helium ions after passing through the target is almost all single and double plus so that the effective charge $q'$ is

$$q' = 2q f^{++} + q f^+$$  \hspace{1cm} \text{E4.7}$$

where $f^{++}$ is the fraction of double plus ions.

Since the fraction of neutral helium is less than .01 above 1 MeV, we know that $f^{++} + f^+ \approx 1$ so that $q' = q (2 - f^+)$. 

Using equation E4.6, the effective charge $q'$ is given by the expression

$$q' = 1.6021 \times 10^{-19} \left(2 - \frac{24}{E^{1.02}}\right) \text{Coul.}$$  \hspace{1cm} \text{E4.8}$$

As an order of magnitude, for an energy of 3 MeV, the beam being collected in the Farady cage is about 97% double plus and at 5.0 MeV the beam is about 99% double plus.

**USE OF PROGRAM CONVR**

The solid angles and five different target thicknesses are stored in the program. The user specifies these and other information by an ID card which precedes the experimental yields which are also punched on cards. To change the target thicknesses, one must change the appropriate cards in the program. See listing on page 334. A description of the data cards is given below.
DATA CARDS

Card 1  MM:  A number from 1 to 99 which tells program how many sets of data are to be normalized.

Card 2  NN:  This variable can have two values only and it precedes each set of data and tells the program whether the data is an excitation curve or an angular distribution.

01:  An excitation curve.

00:  An angular distribution.

Card 3  ID Card: If NN is 01, the following information is punched on the card.

EMIN:  The starting energy of the excitation curve in the laboratory system in MeV.

EMAX:  The final energy of the excitation curve. Note that the program assumes that the energy steps are 50 keV. This can be changed by changing card DE in program.

PST:  The laboratory scattering angle in degrees.

Q:  The total charge collected in μcoul.

T:  A number from 1 to 5 which specifies which target was used.
If NN is 00, then the ID card contains this information.

**PSII:** The starting angle of the angular distribution.

**PSIF:** The final angle of the angular distribution. Note that the program assumes five degree steps but can be changed by changing card DISI in the program.

**ELABB:** The laboratory energy (in MeV) at which angular distribution taken.
// JOB XXXX
// FOR CONVR
#NONPROCESS PROGRAM
#ONE WORD INTEGERS
#IOCS (CARD=1434PRINTER)
DIMENSION Y(50),OMEGA(4),TAR(6),SIGEL(50),SIGEC(50),RATIO(50),
THETA(50),ELAR(50),SRCM(50),GEE(50),SIG(100)
303 FORMAT(8(2X*1E12.4))
302 FORMAT(7X,*THETA*,6X,*GEE*,4X,*SRCM*,10X,*ELAB*,11X,*YIELD*,7X,
1,*SIGEL*),7X,*SIGEC*(6X,*RTORU*=/)
400 FORMAT(112)
305 FORMAT(2(2X*1E12.4))
304 FORMAT(6X,*TARGET*,6X,*OMEGA*=/)
200 FORMAT(1H1)
299 FORMAT(5F10.3)
301 FORMAT(2X,10F7.0)
TM=9.01219
N=1
L=0
PM=0.0026
READ(5,299)MM
NN=1
Z1=2.0
Z2=4.0
DE=0.05
PS1=9.0
15 IF(NN).EQ.1.2
2 READ(5,400)LMAX
READ(5,299)JJJ
READ(5,300)EMIN,EMAX,PST,O1,T
N=(EMAX-EMIN)/DE+1.0
ELA=EMIN
READ(5,301)Y(1),I=1,LMAX
GO TO 3
1 READ(5,300)PS1,PS1F,ELABB,O1,T
N=(PS1F-PS1)/PS1+1.0
ELA=ELABB
READ(5,301)Y(1),I=1,N
PS5=PS1
3 OMEGA(1)=2.5845E-04
OMEGA(2)=2.62E-04
OMEGA(3)=5.56E-06
OMEGA(4)=9.1BE-05
TAR(1)=.0E+18
TAR(2)=.0E+18
TAR(3)=.0E+18
TAR(4)=.0E+18
TAR(5)=2.06E+18
TAR(6)=1.79E+18
K=0
DO 4 KK=1,LMAX
4 LKY=Y(KK)
IF(LKY.LT.120.4)20
20 K=K+1
ELAB(K)=ELA
IF(NN).EQ.5.6
6 65=PS5
GO TO 7
9 ELAB(K)=ELABB
7 PS1=PS5/57.29578
X=(PMK*IN(PST))/TM
YYYY=(MIX/(1.-X))
THET=PSI+ATAN(VV)

THETA(K)=57.29578*THET

W=THET-PSI

GEE(K)=((SIN(PSI)/SIN(THET))**2)*COS(W)

SRCM(K)=1.296*(Z1*Z2*(PM+TM)/(ELAB(K)*TM)**2)/(SIN(THET/2))**4

RSL=SRCM(K)/GEE(K)

K=PS5/55+0.01

JK=PS5/55+0.01

MX=PS5/130.0+0.01

IF(K) 8=8.9

8 LL=3

GO TO 14

9 IF(JK) 10=10+11

10 LL=4

GO TO 14

11 IF(MK) 12=12+13

12 LL=2

GO TO 14

13 LL=1

14 YYY=ELAB(K)

QI=1.6021E-19*(2.0-0.24/(YYY**1.86))

JJ=+4.01

Y(KK)=Y(KK)/10.0

SIGEL(K)=Y(KK)*QI**1.0+27/(O+0.06+OMEGA(LL)*TAR(JJ))

RATIO(K)=SIGEL(K)/RSL

SIGEC(K)=GEE(K)*SIGEL(K)

ELA=ELAB(K)+DE

PS5=PS5+DE

LMX=K

4 CONTINUE

WRITE(6,304)

WRITE(6,305)*TAR(JJ)+OMEGA(LL)

WRITE(6,306)

WRITE(6,307)*THETA(K)+GEE(K)+SRCM(K)+ELAB(K)+Y(K)+SIGEL(K)

15 SIGEC(K)+RATIO(K)+K=1+LMX

WRITE(6,200)

DO 18 K=1+LMX

LM=1+LM

SIG(LM)=SIGEC(K)+100*0

18 CONTINUE

IF(JJ) 19=19+21

21 READ(S,402)*XZYT

402 FORMAT(1F12.0)

WRITE(S,301)*SIG(K)+LM+LM

WRITE(S,402)*XZYT

LM=0

19 IF(N=M-M1) 16=17+17

16 N=M+1

GO TO 15

17 CALL EXIT

END

// XEQ CONVR

// CCEND

// JOB XXXX

// END
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5. HSPS

In the expression for the elastic scattering cross section, there appear certain quantities which must be evaluated using regular and irregular Coulomb wave functions. These functions up to order six are generated in HSPS and used to calculate hard sphere phases, penetrabilities, modified Coulomb phases and certain other associated quantities necessary to evaluate the elastic scattering cross section formula.

THEORY

In the paper of Blatt and Biedenharn[7], hard sphere phases are defined by the following expression.

$$\exp(2i \phi_\ell) = \frac{G_\ell(R) - F_\ell(R)}{G_\ell(R) + F_\ell(R)}$$ \hspace{1cm} E5.1

where $G_\ell$ and $F_\ell$ are irregular and regular Coulomb wave functions of order 1.

This equation is easily solved for $\phi_\ell$ and one obtains

$$\phi_\ell = -\tan^{-1} \frac{F_\ell}{G_\ell}$$ \hspace{1cm} E5.2

Another quantity depending on Coulomb wave functions is the penetrability $P_\ell$ defined as

$$P_\ell = \frac{1}{F_\ell^2 + G_\ell^2}$$ \hspace{1cm} E5.3
Thus to evaluate either one of these quantities requires accurate values of $F_L$ and $G_L$. The Coulomb wave functions are functions of two variables $\rho$ and $\eta$. One can find tabulated values for the Coulomb wave functions of order zero and one for given values of $\rho$ and $\eta$ in many texts, but usually has to interpolate between tabulated values to his values of $\rho$ and $\eta$. Also it is very difficult to find complete tables which go up to order six. For these reasons the present author has written a program to calculate Coulomb wave functions.

The approach is to calculate $F_0$, $F_1$, and $G_0$ using power series expansions, and then to generate the other $F_L$'s using downward recurrence, and the $G_L$'s by upward recurrence. Though $F_0$ and $G_0$ can be accurately calculated using power series for ranges of $\rho$ and $\eta$ between one and ten, $F_1$ is not accurately calculated with the power series because of computer truncation errors. Since using the recurrence relationships requires $F_1$, the value calculated with the power series is used only as a starting value and redetermined through downward recurrence.

The power series expansions for $F_L(\rho, \eta)$ and $G_0(\rho, \eta)$ are given by:

$$F_L(\rho, \eta) = C_L(\eta)\rho^{L+1}$$
$$\Phi_L(\eta, \rho)$$
where one determines $C_L$ by the relationship

$$C_L(\eta) = \frac{(L^2+\eta^2)^{1/2}}{L(2L+1)}$$

and $C_{L-1}(\eta)$, $C_0 = 2\pi\eta/(e^{2\pi\eta}-1)$

and

$$\mathcal{F}(\rho, \eta) = \sum_{k=L+1}^{\infty} A^L_k(\eta) \rho^{k-L-1}$$

where one determines the $A^L_k$ by

$$(k+L)(k-L-1)A^L_k = 2\eta A^L_{k-1} - A^L_{k-2} \quad (k>L+2)$$

and

$$A^L_{L+1} = 1 \quad A^L_{L+2} = \frac{\eta}{L+1}.$$

$$G_0(\rho, \eta) = \frac{(e^{2\pi\eta}-1)}{\pi} F_0(\rho, \eta) \left[ 1n2\rho - 0.42278434 + \eta^2 \sum_{S=1}^{\infty} \frac{1}{S(S^2+\eta^2)} \right] + \left( \frac{e^{2\pi\eta}-1}{2\pi\eta} \right)^{1/2} \left[ 1 + \sum_{k=2}^{\infty} B_k \rho^k \right], \quad \text{E5.5}$$

where $B_0 = 1$, $B_1 = 0$ and for $k>2$

$$k(k-1)B_k - 2\eta B_{k-1} - B_{k-2} - (2k-1)2\eta A^0_k.$$

Using equation E5.4 to determine $F_0$ and $F_1$ and equation E5.5 for $G_0$, one could use the following relationships to determine the remaining Coulomb wave functions.
\[ F_{L-1} G_L - F_L G_{L-1} = L(L^2 + \eta^2)^{-1/2} \quad \text{E5.6} \]

\[ L\left[(L+1)^2 + \eta^2\right]^{1/2} U_{L+1} = (2L + 1) \left[\eta + \frac{L(L+1)}{\rho}\right] U_L - (L+1)\left[L^2 + \eta^2\right]^{1/2} U_{L-1}, \quad \text{E5.7} \]

where \( U_L \) can either be \( F_L \) or \( G_L \).

On first inspection, it would appear equation E5.7 could be used to generate \( F_L \)'s by upward recurrence. However, the \( F_L \)'s decrease in magnitude very rapidly with \( L \) and all accuracy is soon lost. Nevertheless, the \( G_L \)'s, can be calculated with equation E5.7 without loss of accuracy because \( G_L \) in an increasing function of \( L \). Equation E5.6 is used together with \( F_0, F_1, \) and \( G_0 \) to find \( G_1 \) and then using equation E5.7 one can obtain the other \( G_L \)'s he desires.

Since \( F_1 \) by the power series is not accurate and since one cannot generate the other \( F_L \)'s by upward recurrence, a different approach is used. Equation E5.7 is rewritten to give a downward recurrence.

\[ F_{L-1} = (2L+1) \left[\eta + \frac{L(L+1)}{S}\right] F_L - L \left[(L+1)^2 + \eta^2\right]^{1/2} F_{L+1} / (L+1)\left[L^2 + \eta^2\right]^{1/2} \quad \text{E5.8} \]
If one defines $\mathcal{F}_L$ by equation E5.9 and substitutes into equation E5.8, one obtains the same equation as E5.8 except that $F_L$ is replaced by $\mathcal{F}_L$. The constant $\alpha$ is evaluated by use of equation E5.6 and is given by,

$$\alpha = (1+\eta)\frac{1}{2} (F_0G_1 - F_1G_0).$$

To use downward recurrence, the approach is to arbitrarily assign two starting values such as in equation E5.11 and generate the lower $\mathcal{F}_L$'s by use of equation of E5.8.

$$\mathcal{F}_{L_{\text{MAX}}+1} = 0.1,$$

$$\mathcal{F}_{L_{\text{MAX}}} = 0.0,$$

where $L_{\text{MAX}}$ is ten larger than the largest value of $L$ desired.

One goes through the downward recurrence again with $L_{\text{MAX}}$ fifteen larger than the largest $L$ desired. On determining the two normalizing constants $\alpha$ and $\alpha'$ for the two series of $\mathcal{F}_L$'s just generated, one converts the $\mathcal{F}_L$'s to $F_L$'s and compares them. If they are the same
within the desired precision up to the maximum $L$ desired, one can stop. If they are not, one increases $\text{LMAX}$ by five more and generates another series of $\tilde{F}_L$'s until two consecutive normalized sets do agree. Note however, that the normalizing constant $\alpha$ depends on $G_1$ which was found using the power series value of $F_1$. Thus in the program, $G_1$ is recalculated with the new value of $F_1$ and the constant $\alpha$ is re-evaluated. With the new value of $\alpha$, $F_1$ is recalculated and compared with the $F_1$ just found. If they are the same within one part in a thousand the program is satisfied it has good values of $F_1$ and $G_1$.

Using the new value of $G_1$ the remaining $G_L$'s are calculated using upward recurrence. If the two $F_1$'s do not satisfy the criterion, the program again goes through the downward recurrence but evaluating the constant $\alpha$ with the new value of $G_1$. This continues until the normalizing constant $\alpha$ does not change within desired precision when reevaluated. The program is allowed a total of ten times through the downward recurrence and if the criteria above are not satisfied, the program stops.

Once the regular and irregular Coulomb wave functions have been calculated, hard sphere phases and penetrabilities are evaluated using equations E5.2 and E5.3 respectively.

As mentioned the Coulomb wave functions are functions of the variables $q$ and $\eta$. In the present work these variables are defined as

$$p = k R$$

E5.12
where \( k \) is the wave number, \( R \) is nuclear radius,

\[
\eta = Z_1 Z_2 e^2/\hbar v, \tag{E5.13}
\]

where \( Z_1 \) and \( Z_2 \) are the atomic numbers of the projectile and target respectively,

\( e \) is the electronic charge,

\( \hbar \) is Planck's constant divided by \( 2\pi \),

and \( v \) is the relative velocity.

In the program the quantities which appear in equations E5.12 and E5.13 are evaluated as follows:

\[
R = 1.2 \times 10^{-13}(A_1^{1/3} + A_2^{1/3}) \tag{E5.14}
\]

where \( A_1 \) and \( A_2 \) are the mass number of the projectile and the target respectively.

\[
k = \frac{1}{\hbar} \frac{2E}{\mu} \tag{E5.15}
\]

where \( E \) is the center of mass energy and \( \mu \) is the reduced mass.

\[
v = \frac{2E}{\mu} \tag{E5.16}
\]

where \( E \) is the center of mass energy, \( \mu \) is the reduced mass.
\[ \eta = \frac{Z_1 Z_2 C}{137.037 \nu} \]

where \( C \) is the velocity of light, and 137.037 is the fine structure constant.

Another quantity calculated in the program which is a function of \( \eta \) is the modified Coulomb phase \( \psi_{L} \). In Blatt and Biedenharn\(^3\), \( \psi_{L} \) is defined as

\[
\psi_{L} = \sigma_{L} - \sigma_{0} \text{ or } e^{i \psi_{L}} \frac{(\ell + i \eta)(\ell - 1 + i \eta) \cdots (1 + i \eta)}{(\ell - i \eta)(\ell - 1 - i \eta) \cdots (1 - i \eta)}, \quad E5. 18
\]

where \( \sigma_{L} \) are the Coulomb phases.

Solving equation E5. 18 for \( \psi_{L} \) one obtains

\[
\psi_{L} = \sum_{S=1}^{\ell} \tan^{-1} \frac{\eta}{S} \quad \ell \geq 1 \quad \psi_{0} = 0, \quad E5. 19
\]

which is thus trivially evaluated.

**GENERAL DISCUSSION**

Since \( p \) and \( \eta \) depend on energy, the calculations are performed for a set of energies which correspond to the energies at which the experimental data were taken. It is assumed in the program that the data were taken in 50 keV steps, but this can be changed by changing card: EP=EP+0.05. Note that in the program a maximum of only forty-one energies are allowed. The various quantities are punched
on cards which are used as input data for the program which calculates elastic scattering, (EORCS). A listing of HSPS is given on page 346.

The equations for \( p \) and \( \eta \) above were for elastically scattered charged particles. To calculate reaction cross sections for charged particles, one still needs the various quantities defined above, but the definitions for \( p \) and \( \eta \) are modified as follows:

\[
R' = 1.2 \times 10^{-13} (A_3^{1/2} + A_4^{1/3}), \quad \text{E5.20}
\]

where \( A_3 \) and \( A_4 \) are the mass numbers of the outgoing projectile and the residual nucleus respectively.

\[
p' = \frac{R'}{h} 2\mu'(E+Q)^{1/2}, \quad \text{E5.21}
\]

where \( \mu' \) is the reduced mass of particle 3 and 4 and \( Q \) is the "Q-value" of the reaction.

\[
\eta' = \frac{Z_3Z_4e^2}{h} \frac{\mu'}{2(E+Q)}^{1/2}, \quad \text{E5.22}
\]

where \( Z_3 \) and \( Z_4 \) are the atomic numbers of particles 3 and 4.

The user chooses whether he is doing reactions or elastic scattering by setting the variable NREAT in the program to one or zero respectively. The "Q-value" is entered by changing the card QQ in the program.
// JOB
// FOR HPS
*NONPROCESS PROGRAM
*LIST ALL
*EXTENDED PRECISION
*ICOS(CARD,153.3 PRINTER)

DIMENSION F(4),G(4),PHI(B),DELTA(B),P(B),LVA(8),KMXX(2),
1PL(9*25),COUPH(8)

106 FORMAT(4(1E16+6F+2X)+11I)
113 FORMAT(' F(L) ',G(L),' DELTA(L) ')
112 FORMAT(1X,'RHO= '1E16+6F+4X,'ETA='1E16+6F+4X,'X=
106 FORMAT(1X,'RHO= '1E16+6F+4X,'ETA='1E16+6F+4X','= '1E16+6F+4X)
115 FORMAT(1X,'S12,2(2X,1E16.9,2X)')

LMAX=6
HB=1.054430E-27
NREAT=0
TW=9.01219
PV=0.00086
ZT=4.0
ZP=2.0
QQ=1.275
O%=12.000
OPV=1.000982
OZT=6.0
OZP=0.0
QQ=QQ+1.602060E-06
RM=(P+T)*(1.65970E-24)/(P+T)
EP=0.0
DB=3.0
JE=1.0
R=12.0E-13*(TW**0.333+E**0.333)
E=(TW/(R+T))**EP+1.602060E-06
VEL=FSQR(T*E/2)
FK=FSQR(T*E/2)/R
RHO=FK*R
ETA=ZP*ZT/9979300E+10/(137.037000*VEL)
J=0
M=LMAX
L=0

IF(NREAT=1)=816,817,817
817 RHP=(OT**EPV+1.65970E-24)/(OT+OPV)
RP=1.25E-13*(OT**0.333+E**0.333)
RHOP=RP*(FSQR(RP*(E+QU)+2.0))/HB
ETAP=(OZT*OZP+2.9279300E+10/137.0371)*ESQR(RHP/(2.0*(E+QU)))
WRITE(6,'(151900*ETA+RHP*ETAP)
ETA=ETAP
RHO=RHOP
ETA=ETA+0.9999999999
IF(ETA>131.4431)=818,818,818
831 HO=1.0
GO TO 30
816 HO= FSQR(6.283185307*ETA/(EXP(6.283185307*ETA)-1.0))
830 SUMR=0.0EOO
80 CBK1=1.0EOO
CRK=0.0EOO
CALK=1.0EOO
DL=L
CAK=ETA/(DL+1.0EOO)
AK=CAK
PHIK=1.0EOO+ETA+RHO/(DL+1.0EOO)
K=IN=L+3
LJ=0
DO 91 K=K+4,99
K=K
83 CALL EXIT
79 BK=0.0E0
GO TO 84
82 K=K+1
DK=K
BK=(2.0E0-CX*ETA-CBK1-(2.0E0*DX-1.0E0)*ETA*AK+2.0E0)/(DK*DK*DK)
SUM=SUM+ BK*(RHO**K)
CBK1=CBK
CBK=AK
K=K+1
84 DK=K
AK=(2.0E0*ETA+CAK-CAK1)/(DK+DL)*(DK-1.0E0)
PHIK=PHIK+AK*(RHO**(K-L-1))
IF(K-99)=97-87
89 DO EAVL(AK*(RHO**(K-1))=1.0E-15
QQ=EAVL(AK*(RHO**(K-2))=1.0E-10
IF(Q)=48+74-73
74 L=J=1
IF(L=3)=98-89
73 IF(U)=87-99
88 C=CAK=CAK1
CONTINUE
87 J=J+1
KMAX(J+)=K
PHI(L+)=PHIK
F(I)=1.0E0*ETA/W0+F(I)
IF(1-L)=94-95
99 SUMS=0.0E0
DO 96 IS=1+1+1
S=IS
SUM=SUM+1.0E0/(S+S+ETA*ETA+S)
96 CONTINUE
SUM=SUM+0.12437190E-0*ETA*ETA
XT=2.0E0=ETA/W0+F(I)
YT=ALOG(2.0E0*RHO)-0.2278434*SUMS
ZLT=1.0E0+SUMS
G(I)=XT*YT+ZLT/W0
L=L=1
GO TO 90
94 L=1
F(2)=F(2)*(ESQ+1.0E0+ETA**2)/3.0E0
DL=1.0E0
G(L)=1.0E0*(DL/(ESQ+DL**2+ETA**2))+F(I+1)*G(I)/F(I)
WRITE(6,411)=1.0E0*G(I)+G(I)
411 FORMAT(1X,3(1F12.8,2X))
M=M+1
DO 120 L=1+1
L=L+1
120 CONTINUE
1=2
906 J=1+1
LLMAX=LLMAX+I
LLL=LLMAX+I
EL=0.0E0
FLP=0.0E0
DL=LLMAX
DO 901 LL=1+LLMAX
=LLMAX=LL+1
CONST=(DL*1.0E0)*(ESQ*(DL**2+ETA**2))
FLL=1.0E0*DL+1.0E0)*ETA*EL/CONST*(1.0E0*DL+1.0E0)*(DL**2+DL)
501 CONTINUE
IF(J-1904*594*505)
904 I=3
GO TO 506
905 LLL=LWAX+1
DO 502 K=1+LLL4
K=J-1
ALPHA=(FL(1J)+G(1J)-FL(2J)+G(1J))\(+ESOR(1*OE0+ETA**2)\)
Beta=(FL(1J)+G(1J)-FL(2J)+G(1J))\(+ESOR(1*OE0+ETA**2)\)
DIFF=EAVL(FL(4J)/ALPHA-FL(NK)/BETA)-1*OE-02
IF(DIF)=502*592*507
507 I=I+1
IF(J-101506*506*508
508 WRITE(6+509)DIF
509 FORMAT(1E16.9)
CALL EXIT
502 CONTINUE
ALPHA=ALPHA
FL(2J)=FL(2J)/ALPHA
FL(2J)=FL(1J)*G(2J)+G(1J)*ESOR(1*OE0+ETA**2)
FL(2J)=FL(1J)*G(2J)+G(1J)*ESOR(1*OE0+ETA**2)
XT=EAUL(FL(2J)/ALPHA-FL(2J)/BETA)=1*OE-03
WRITE(6+509)IX IF
IF(XIF)=529+523+533
533 I=I+1
GO TO 506
523 DO 105 LLL=1+LLL4
FL(LLL+1)=FL(LLL+1,4J)/ALPHA
LL=LLL-1
LVAL(LLL)=LL
DELTA(LLL)=EATM\(+ESOR(1*OE0+ETA**2)\)/G(LLL)
G(LLL)=1*OE0+F(LLL)+G(LLL)+G(LLL)+2*OE0*RHO
105 CONTINUE
DO 310 N=2,LLL4
LNN=1
DL=L
GIL(2J)=FL(1J)*G(1J)+G(1J)*ESOR(1*OE0+ETA**2)+G(L+1)(DL+1,OE0)*G(1J)(DL+1,OE0)*G(IL)\(+DL*1*ESOR(1*OE0+ETA**2)\)
310 CONTINUE
9013 JMAX=LWAX+1
COUPH(L1)=OE0
SUM=OE0
DO 401 L=2,MAX
AL+L
SUM=SUM+ATAN(ETA/(AL-1*OE0))
COUPH(L)=SUM
401 CONTINUE
E=EP
FAMRO=1*OE0/FK
READ(5*432)TT
402 FORMAT(1F12.2)
400 FORMAT(1E12.4)
IF(TREAT-1987*807*907
907 DO 39 J=1,JMAX
DELTA(J)+DELTA(J)+COUPH(J)
39 CONTINUE
WRITE(5*400)PJ,J=1,JMAX
WRITE(5*400)DELTA(J),J=1,JMAX
GO TO 913
913 WRITE(5*400)PJ,J=1,JMAX

WRITE (5, 420) (DELTA(J), J=1, JMAX) EFA 'HD
WRITE (5, 420) (CORDER(J), J=1, JMAX) ETA
810 EP=EP+0.05000
300 CONTINUE
CALL EXIT
END
6. CHECK

In HSPS, the power series values of $F_0$, $F_1$, and $G_0$ along with the criterion that the new $F_1$'s found are the same to one part in a thousand are the only information printed on the line printer. This information is used only to check that the program is not having difficulty in calculating the Coulomb wave functions. The program CHECK has a dual purpose. One to give the user a printed output of the quantities calculated in HSPS; the second, to check the cards punched.
// JOM
// FOR CHKCK
*NON-PROCESS PROGRAM
*LIST ALL
*ONE Word INTERF
*IOCS(CARD=1443 PRFTER)
DIMENSION P(41,8), DELTA(41,8), COUPH(41,8)
402 FORMAT(1H1)
403 FORMAT(1X,E12.4)
400 FORMAT(1X,E12.4)
IMAX=41
DO 1 I=1,IMAX
READ(5,400) (P(I,L),L=1,8)
READ(5,400) (DELTA(I,L),L=1,8)
READ(5,400) (COUPH(I,L),L=1,8)
1 CONTINUE
DO 2 II=1,IMAX
WRITE(4,403) (P(II,L),L=1,8)
2 CONTINUE
WRITE(6,402)
DO 3 II=1,IMAX
WRITE(6,403) (DELTA(II,L),L=1,8)
3 CONTINUE
WRITE(6,402)
DO 4 II=1,IMAX
WRITE(6,403) (COUPH(II,L),L=1,8)
4 CONTINUE
CALL EXIT
END
7. NPHS

For neutral particles, one still needs the penetrability function but only needs one phase $\xi_l$. $\xi_l$ is defined the same as $\psi_l$ (page 337 eq. E5.2) except that for neutral particles $\eta$ is zero. For $\eta$ zero, the Coulomb functions reduce to spherical Bessel functions and one has

$$F_L(\rho, 0) = \rho j_L(\rho), \quad \text{E7.1}$$

where $j_L$ is the regular spherical Bessel function,

and

$$G_L(\rho, 0) = \rho \eta_L(\rho)$$

where $\eta_L$ is the irregular spherical Bessel function.

Thus one has that $\xi_l$ and $P_l$ are

$$\xi_l = -\tan^{-1} \frac{j_l}{\eta_l} \quad \text{E7.2}$$

$$P_l = \frac{2/\xi}{j_l^2 + \eta_l^2} \quad \text{E7.3}$$

It would seem that HSPS with $\eta$ equal to zero could be used to evaluate equations E7.2 and E7.3 but it turns out that for $\eta$ equal to zero the approach used in HSPS will not work. However, it is quite trivial to evaluate spherical Bessel functions. In the program the
Bessel functions are evaluated as follows:

\[ j_\ell = \frac{R_\ell \sin \rho}{\rho} + \frac{S_\ell \cos \rho}{\rho} \]  
\[ \eta_\ell = \frac{R_\ell \cos \rho}{\rho} + \frac{S_\ell \sin \rho}{\rho} \]

where \( R_\ell \) and \( S_\ell \) are determined from

\[ R_\ell + iS_\ell = \sum_{S=0}^{\ell} \frac{i^{S-\ell}}{2^S S!} \frac{(\ell+S)!}{(\ell-S)!} \rho^{-S} \]

Using \( R_\ell \) and \( S_\ell \) equations 2 and 3 become

\[ \ell = -\tan^{-1} \left( \frac{R_\ell \sin \sigma + S_\ell \cos \sigma}{R_\ell \cos \rho - S_\ell \sin \rho} \right) \]  
\[ P_\ell = \frac{2\rho}{R_\ell^2 + S_\ell^2} \]

As in HSPS for reaction cross sections, one gives the program the "Q-value" and \( \rho \) is determined by equation E5.21.

The program makes the calculations for a set of energies as in HSPS and punches the results on cards. To give the user a written output, a program very similar to CHECK is used. This program also has the name CHECK but can easily be distinguished because there are only the two quantities \( P_\ell \) and \( \ell \) which are written on the line printer.

The listings of NHPS and this CHECK are given on pages 354 and 355.
// JOB
// FOR CHECK
ONE WORD INTEGERS
NONPROCESS PROGRAM
LIST ALL

1003(1443 PRINTER,CARD)
DIMENSION PENTR(41,7),ZELTA(41,7)
400 FORMAT(4E12.4)
401 FORMAT(1X,7(E12.4,2X))
402 FORMAT(1H1)
IIYAX=41
DO 9003 I=1,IIYAX
READ(5,400)(PENTR(I,L),L=1,7)
READ(5,400)(ZELTA(I,L),L=1,7)
8003 CONTINUE
DO 9004 I=1,IIYAX
WRITE(6,402)(PENTR(I,L),L=1,7)
8004 CONTINUE
WRITE(6,402)
DO 9005 I=1,IIYAX
WRITE(6,401)(ZELTA(I,L),L=1,7)
8005 CONTINUE
CALL EXIT
END
APPENDIX F

Application of EORCS to Other Reactions

The program EORCS, written by the present author to calculate elastic scattering and reaction cross section, was discussed in Appendix D. In this section the application of the program to various reactions and the reliability of program EORCS are briefly discussed.

To check the reliability of program EORCS, a calculation was performed on the reaction $^{12}\text{C}(^3\text{He}, ^3\text{He})^{12}\text{C}$ which could be compared to the results of Kuan et al. $^{28}$. Because the spin and parity of the ground state of $^{12}\text{C}$ is $0^+$ and that of the $^3\text{He}$ projectile is $1/2^+$, the cross section formula for the elastic scattering of charged particles in the "single-level" approximation may be simplified considerably and rewritten in a much more concise form than presented in Chapter III. The analysis of Kuan et al. used this concise form. Using the level parameters given by Kuan et al., a calculation was performed with program EORCS (with the modifications mentioned in Section 12, Appendix D). The results of the calculation are not presented here since exact comparison with the results of Kuan are difficult. However, the agreement in the shape of the cal-
culations is excellent and where it is possible to compare magnitudes, there is also excellent agreement.

The reliability of the program was further checked by comparing isolated resonance shapes for $^{12}\text{C}(d,d)^{12}\text{C}$, calculated with EORCS and an independent program written by H. Schieck which is in the form of scattering amplitudes. Agreement was excellent.

In the analysis of elastic scattering data, it is generally possible to tell the dominant $\ell$-value of a particular state. However, without additional information it is usually very difficult to determine the spin of the state unambiguously. To supplement the elastic scattering data, the $^{9}\text{Be}(\alpha,n)^{12}\text{C}$ data of Weil et al. was studied. It should be mentioned here that it is not the purpose of the present author to fit all the data of Weil. The purpose is to see if the level parameters, found from the elastic scattering analysis are consistent with this data.

The $^{9}\text{Be}(\alpha,n_0)^{12}\text{C}$, and the $^{9}\text{Be}(\alpha,n_2)^{12}\text{C}^*$ angular distribution data were fit with Legendre polynomials and the coefficients plotted as a ratio to $A_0$ (see Figures 13 and 14). No detailed error analysis of these ratios was done; for it was the purpose of this analysis to obtain only a qualitative ideal of the various $\ell$-values involved. The arrows indicate resonances seen in the $^{9}\text{Be}(\alpha,n)^{12}\text{C}$ data.

In the $^{9}\text{Be}(\alpha,n_0)^{12}\text{C}$ fit (Fig. 13) one will notice a large negative $A_0$ contribution which peaks at 5.0 MeV. The contributions of odd
\( \xi \)-values to the cross section are possible only if states of opposite parity interfere. In addition, by observing at which energies the interference contributions have a maximum value (either positive or negative), it may be possible to gain some information about the relative widths of the states involved and their resonances energies. As has been mentioned earlier, from the analysis of the ground state polarization data,\(^ {3,4} \) there are \( \frac{5}{2}^+ (1) \) and \( \frac{3}{2}^+ (3) \) states at 4.2 and 4.5 MeV respectively. There was also found to be a significant contribution from a \( \frac{5}{2}^- (4) \) state around 5 MeV. From the selection rules for non-vanishing \( \xi \) coefficients, of these three states only the \( \frac{5}{2}^+ (1) \) state and the \( \frac{5}{2}^- (4) \) state may interfere to give an \( A_8 \) contribution. Since one may argue that the \( A_8 \) contribution should be larger at the narrower of the two states, it would appear that the \( \frac{5}{2}^- (4) \) state should be positioned at 5.0 MeV. However, the \( \frac{A_8}{A_0} \) contribution is almost symmetric about 5 MeV indicating that there is at least another positive parity state with a spin \( \geq \frac{5}{2} \) above 5 MeV. From the analysis of the elastic scattering data an assignment of either a \( \frac{3}{2}^+ (1) \), or \( \frac{5}{2}^+ (1) \) state has been given to the state at 5.4 MeV. However, as mentioned before, only the \( \frac{5}{2}^+ (1) \) state may give \( A_8 \) contributions. Work is in progress for further analysis of the \( ^9\text{Be}(\alpha, n_0)^{12}\text{C} \) and \( ^9\text{Be}(\alpha, n_3)^{12}\text{C} \) data.
Figure 13. Coefficients of Legendre Polynomial Fit of $^9\text{Be}(\alpha, n_0)^{12}\text{C}$ Angular Distributions. The coefficients are plotted as a ratio to $A_0$. The arrows indicate the position of known resonances.
Figure 14. Coefficients of Legendre Polynomial Fit of $^{9}$Be$(\alpha, n_2)^{12}$C Angular Distributions. The coefficients are plotted as a ratio to $A_0$. The arrows indicate the position of known resonances.
To check the sensitivity of the calculations to channel radius, and also the relative importance of the correction terms due to finite nuclear size, isolated resonance shapes for $^6$Be($\alpha$, $\alpha$)$^6$Be were calculated and are presented in Figure 15. These shapes were calculated using a width of 90 keV in the center of mass, with the partial reduced widths equal and the partial width for elastic scattering equalling the total width. In the first half of the figure, the resonance shape for a 7/2$^+$ isolated level is shown. The channel radius was calculated using $R = R_0(A_1^{1/3} + A_3^{1/3})$, where $R_0$ is in fermis. The most striking variation in the isolated resonance shape occurs when the correction terms due to finite nuclear size are included. It is thus necessary that these terms be included in the calculations. The other half of the figure shows isolated resonance shapes for different spins and parities, where all the correction terms have been included. The shapes are calculated at angles for which $P_{\xi odd} = 0$, $P_2 = 0$, $P_3 = 0$, $P_4 = 0$. Because of the small variation in the isolated resonance shapes with channel radius, a value of $R_0$ equal to 1.2 fermis has been used in all subsequent calculations.

As a final check of the program EORCS, calculations were performed on the $^{24}$Mg($p$, $p$)$^{24}$Mg data of H. J. Hausman et al. As the data is shown in Fig. 16. The solid lines are calculations obtained with the inclusion of 1/2$^+$ and 3/2$^+$ states at known resonance
Figure 15. Isolated Resonance Shapes for $^9$Be($\alpha$, $\alpha$)$^9$Be. The first half of the figure shows the variation of an isolated $7/2^+$ level with: hard sphere phases ($r_0$), the relative signs of the incoming $g'$s, and the inclusion of correction terms due to finite nuclear size (size). The other half of the figure shows the variation of the resonance shapes for different spins and parities. (All terms have been included.) The shapes are calculated at the zeros of the Legendre polynomials $P_{l_{\text{odd}}}$, $P_2$, $P_3$, and $P_4$. 
Figure 16. Calculations of $^{24}$Mg(p, p)$^{24}$Mg Cross Section. The data was taken by Hausman et al. The solid lines are the preliminary results of compound nucleus calculations discussed in the text.
energies. These results are preliminary only, but are included here to show that the program may be used to study reactions other than $^9\text{Be}(\alpha, \alpha)^9\text{Be}$. 
APPENDIX G

Tabulation of the Experimental Elastic Scattering Cross Section Data

For the convenience of the reader, the experimental elastic scattering cross section data is presented in tabular form. The data is tabulated according to the target used in the measurement. The target thickness of each target is presented in Table 6 of Appendix B and the experimental uncertainty of the cross section is presented in Table 7 of Appendix B. An asterisk appearing beside data is to indicate that the value is interpolated. A dagger indicates that the data were taken with a target different than the one under which the data is being listed.
<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>Target E SIG (lab) (mb/sr)</th>
<th>SIG (c. m.) (mb/sr)</th>
<th>E (MeV)</th>
<th>Target D SIG (lab) (mb/sr)</th>
<th>SIG (c. m.) (mb/sr)</th>
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</thead>
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<td>129.3</td>
<td>94.2</td>
<td>3.80</td>
<td>29.3</td>
<td>21.3</td>
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<td>63.0</td>
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<td>45.4</td>
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<td>4.70</td>
<td>59.6</td>
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</tr>
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### 5.85 MeV Angular Distribution

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REFERENCES


12. F. Ajzenberg-Selove, private communication.


