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Development of a NaI(Tl) spectrometer for use at intermediate energies and the analysis of the radiative proton capture reaction $^{15}\text{N}(p,\gamma)^{16}\text{O}$

Kalen, Joseph David, Ph.D.
The Ohio State University, 1987
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DEVELOPMENT OF A NaI(Tl) SPECTROMETER FOR USE AT INTERMEDIATE ENERGIES AND THE ANALYSIS OF THE RADIATIVE PROTON CAPTURE REACTION $^{15}\text{N}(p,\gamma)^{16}\text{O}$

DISSERTATION

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

By

Joseph David Kalen, B.S., M.S.

* * * * *

The Ohio State University

1987

Reading Committee:

Professor H. J. Hausman
Professor S. L. Blatt
Professor R. G. Seyler

Approved by

H. J. Hausman
Advisor
Department of Physics
To my Parents

whose love, guidance, and confidence

made everything possible.
ACKNOWLEDGEMENTS

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I also thank my friends at Hillel, whose friendship during my stay in Columbus made this a most pleasant time for me.

Finally, I would like to thank my family for all their support throughout my education.
VITA

April 9, 1956 ................ Born - New York, NY

May, 1978 ................... B.S., S.U.N.Y College at Brockport, NY

1978 - 1982 .................. Graduate Teaching Associate Department of Physics The Ohio State University Columbus, OH

June, 1982 ................... M.S., Physics The Ohio State University Columbus, OH

1982 - Present ............... Graduate Research Associate Department of Physics The Ohio State University Columbus, OH

PUBLICATIONS


FIELDS OF STUDY

Major Field: Physics
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I. INTRODUCTION

Radiative capture of light particles (≤ α's) is an important mechanism for studies in nuclear physics such as spectroscopy of shell-model states and decay of the Giant Dipole and Quadrupole Resonances. Development of large NaI(Tl) spectrometers designed for these studies, $E_\gamma \geq 10$ MeV, has historically proceeded along two lines: The "Argonne" type system [AlIa64] which used a large bare crystal with a slow set of phototubes, and slow anti-pileup electronics (double delay-line clip), and the "Stanford/Ohio State" system [Kohl63, Paul65, Blat68, Ling68 and Suff68] consisting of a central crystal surrounded by plastic scintillators.

The first of these systems [Kohl63 and Paul65] consisted of a central NaI(Tl) crystal surrounded by an annular plastic scintillator shield which is used in anticoincidence with the central crystal to reject cosmic-rays and events in which some of the shower escape from the crystal. The NaI(Tl) crystal and plastic scintillators are then surrounded by lead which is used as a shield for background radiation as well as a muon-converter for
efficient cosmic-ray rejection. Improvements on this system were performed by S.C. Ling et. al. [Ling68] with the addition of a front plastic scintillator anticoincidence shield for detection of any 0.511 MeV annihilation which may escape from the front face of the crystal, gain stabilization, and the use of Hi-Low anti-pileup techniques [Blat68]. A further improvement incorporated a linear pulse-shortening technique [Amse69] to reduce the number of pulses for which pileup could occur. This technique was first successfully utilized by E.M. Diener et. al. [Dien70]. All of these methods resulted in improved full-width-half-maximum (FWHM) resolution.

Since the early 1970's most gamma-ray spectrometers are comparable to the "Stanford/Ohio State" design, see the 1974 review by P. Paul [Paul74], where the performance of these NaI(Tl) spectrometers strongly depends on the design of the NaI(Tl) crystal, the plastic scintillator shield, signal processing electronics, and gain stabilization.

Improvements on the design of the NaI(Tl) crystal are attributed to growth of larger crystals and the ability to recompensate the crystal surface for improved uniformity and resolution at high γ-ray energies. Techniques for surface recompensation and growth of the NaI(Tl) crystal are described in appendix A. The plastic scintillator
shield consists of six optically isolated sections which enhances the collection efficiency of the anticoincidence shield. Chapter II describes the new Ohio State University Medium Energy Gamma Assembly (OMEGA II) NaI(Tl) spectrometer, which primary component is a 29.2 cm φ x 38.1 cm long central NaI(Tl) crystal. Signal processing electronics with refinements on gain stabilization techniques and tests of the NaI(Tl) spectrometer at various γ-ray energies is discussed in chapter III. These improvements in the NaI(Tl) spectrometer produces a resolution for OMEGA II of 2.4% full-width-half-maximum (FWHM) @ $E_γ = 22$ MeV and slightly better results of 2.25% FWHM @ $E_γ = 158$ MeV. Future considerations on designs of new NaI(Tl) spectrometers are discussed in chapter VI.

The improved NaI(Tl) spectrometer, OMEGA II, is used to study proton radiative capture reactions at intermediate energies at the Indiana University Cyclotron Facility (IUCF). The various mechanisms that describe radiative proton capture are discussed in chapter IV, which begins with a historical background leading to the present formalism of the direct-semidirect (DSD) phenomenological theory [Blat84]. The DSD theory is based on the shell model with a single particle-hole configuration and describes the processes in and about the giant dipole resonance (GDR), $E_p \approx 20$ MeV. At gamma-ray energies above
the GDR other mechanisms [Lond79, Gari81, Mcde86, and Lude87] are included such as meson exchange terms, the inclusion of a virtual $\Delta$ (1232 MeV), and use of the relativistic Dirac equation.

The models discussed in chapter IV are based on the shell model using a single particle-hole configuration, which simplifies for the doubly magic $^{16}$O nucleus. The experiment (performed with the OMEGA I spectrometer developed by M.A. Kovash [Kova78]) and results of the $^{15}$N(p,$\gamma$)$^{16}$O reaction is presented in chapter V with comparisons to the DSD phenomenological theory and that of McDermott et. al. [Mcde86] which considers a single particle mechanism along with meson exchange terms using the relativistic Dirac equation. A polarized proton beam experiment was also performed to determine the analyzing powers of the various excited states of interest in $^{16}$O.

The Brink-Axel hypothesis [Brin55 and Axel62] claims that all nuclear states have giant resonances built on them as first shown for the highly excited unresolved states composing $\gamma_{1,19}$ of $^{12}$C [Blat80]. Other confirmations were performed for final states of low excitation in the works in $^{12}$C [Angh83a] and in $^{28}$Si [Dowe83]. This hypothesis is also shown for the excited states of interest in $^{16}$O in chapter VI along with a discussion on the $^{15}$N(p,$\gamma$)$^{16}$O reaction.
II. NaI(Tl) SPECTROMETER

The radiative capture reaction experiments performed at the Indiana University Cyclotron Facility (IUCF), prior to 1987, has used the OMEGA I spectrometer, designed by M. Kovash [Kova78], which has as its main component a large 10"$\phi$ x 12" NaI(Tl) crystal. The central NaI(Tl) crystal is chosen due to its high efficiency at high gamma-ray energies above a few MeV and moderate energy resolution. Germanium is a poor choice due to its high resolution but low efficiency. Lead-glass and BGO (Bi$_4$Ge$_3$O$_{12}$) are also poor choices with their high efficiency but poorer energy resolution. The size, resolution, and uniformity of this central crystal allows radiative capture reaction experiments to be performed up to a gamma-ray energy of $E_\gamma = 100$ MeV, where the main mechanism of proton radiative capture reactions can be described by a phenomenological Direct-Semidirect (DSD) reaction theory [Haus87]. For gamma-ray energies above $E_\gamma = 100$ MeV, other mechanisms will contribute larger effects to the cross section than the Giant Dipole Resonance (GDR) combined with a direct reaction term, the DSD theory. These other theories [Gari81, Lond79, Mcde86, and Lude87], described in chapter IV, consider
contributions from charge exchange, the $\Delta(1232 \text{ MeV})$, and meson exchange terms.

To provide data to study these new theories, a new larger NaI(Tl) spectrometer had to be constructed. Bicron Co. [Bicr1] altered their original recompensation techniques and achieved improved uniformity and resolution of the NaI(Tl) crystal for use at the higher gamma-ray energy. This fact, along with their ability to grow larger NaI(Tl) crystals, prompted us at The Ohio State University to build a new larger NaI(Tl) spectrometer. Appendix A contains a discussion on growth and recompensation techniques for large NaI(Tl) crystals. This new NaI(Tl) spectrometer, OMEGA II, has as its main component a 11.5"$\phi$ x 15" long NaI(Tl) crystal capable of capturing gamma-rays in the energy region 20 MeV $\leq E_\gamma \leq$ 200 MeV. This section describes the major design elements of the NaI(Tl) spectrometer and the improvements in the spectrometer for increased efficiency in the energy region 100 MeV $\leq E_\gamma \leq$ 200 MeV.

1. NaI(Tl) Spectrometer Mechanical Design

The Ohio State University Medium Energy Gamma Assembly, OMEGA II, figures 2-(1,2,3, and 4), has as its main component a 11.5"$\phi$ x 15" long NaI(Tl) crystal manufactured at Bicron Co. [Bicr1]. The NaI(Tl) crystal is contained in an aluminum can of 0.125" thick walls and
0.062" thick front plate. The thickness of the aluminum is minimized in order to minimize interactions within the walls of the crystal housing. Magnesium Oxide (MgO), a white reflector powder, is packed between the crystal and aluminum housing of approx. 1/8" thick around the cylinder and 1/16" in the front. There is also a 1/8" thick pressure pad, on the front surface, containing 0.01" polyethylene and sponge rubber to allow the crystal to rest on its front face while being tested at Bicron Co. Seven 3" diameter RCA S83021EM1 phototubes with Mu-metal shields and transistorized bases, are arranged in a hexagonal distribution on the rear of the NaI(Tl) crystal, and view the scintillation process through 0.375" thick Pyrex windows. Pyrex (trademark for borosilicate glass) windows are used for matching the indices of refraction since the phototubes also use borosilicate glass. For gain stabilization there are six Siemens GL-56 green, gallium phosphide, Light Emitting Diodes, (LED's), located on the rear NaI(Tl) surface, and for future use seven DuPont CROFON fiber optics (0.04"φ x 24" length). The fiber optics is channeled into the Pyrex windows such that the incoming light from an exterior LED is channeled into the crystal. Surrounding the aluminum housing are three uniformly spaced 1" wide x 1" thick flanges to help distribute the weight of
the 207 lb. crystal which rests on the plastic scintillator annulus.

A $^6$Li thermal neutron ($E_n = 0.025$ eV) shield, manufactured at Oak Ridge National Laboratory, of 0.1" thickness surrounds the crystal, and a $13\phi \times 0.2$" thick sheet is located in front of the crystal. The 95% enriched $^6$Li metal is rolled and placed into a welded 0.031" thick wall aluminum housing. To prevent the $^6$Li from oxidizing the housing is coated with epoxy.

Surrounding the crystal and $^6$Li shield is an anti-coincidence shield containing BC-412 plastic scintillator, equivalent to NE-110. The plastic scintillator is made from polyvinyltoluene having 60% of the light output of Anthracene and a decay constant of 3.3 nsec. The 3" thick x 21" length plastic scintillator annulus surrounding the crystal is segmented into six optically isolated sections. Each section is viewed by two Amperex XP-2202B 2" diameter phototubes with transistorized bases and Mu-metal shields. The plastic scintillator is polished on all surfaces and wrapped with aluminum foil, except along the phototube surface. Placing dull black paper on the surface that contains the phototubes improves the fall time of the scintillation signal while only having a small effect on the rise time. The segmentation of the scintillator and studies of wrapping the scintillator is due to Sandorfi [Sand84].
Segmentation of the plastic annulus improves the overall collection efficiency of light at the backplane (phototube surface) of the shield. The plastic scintillator annulus is contained in a 0.062" thick wall aluminum housing. Each optically isolated section contains one GL-56 green LED and optical fiber for future use in gain stabilization. The front plastic scintillator shield is a truncated cone, 4" thick, containing three Amperex XP-2202B phototubes on 120° spacing. The phototubes are equally spaced to improve the collection efficiency of the shower. The front plastic shield is also wrapped in the same manner as the plastic annulus and contains three GL-56 green LED's and optical fibers for gain stabilization.

A 4" thick lead housing in a 1/4" outer stainless steel mold surrounds the detector for use as a shield for background radiation and as a muon-converter for efficient cosmic-ray rejection. The back plate contains apertures through which the phototubes on the plastic annulus extend. In addition, there are apertures through which high voltage, fiber optics, LED enable, and signal cables for the central NaI(Tl) crystal pass. Two small induction fans for cooling the transistorized bases and LED's are placed in a large aperture in the center of the back lead plate. The front plastic scintillator is cradled in a truncated lead cone which contains one of three different
removable lead collimators. The three collimators produce a 7" diameter beam spot on the rear of the NaI(Tl) crystal. With an increase in proton energy, the ability of the crystal and electronics to separate the fast neutrons and gammas from the target is improved by increasing the spectrometer to target distance. A minimum Time of Flight (TOF) of 3 nsec. is maintained over the entire proton energy region. The collimators produce a solid angle of 9.6 msr at a 1.0 m focus for proton energies $E_p \leq 100$ MeV, 5.6 msr @ 1.5 m focus for proton energies $100$ MeV $\leq E_p \leq 150$ MeV, and 3.6 msr @ 2.0 m for proton energies $E_p \leq 200$ MeV.

Surrounding the spectrometer is a thermal neutron shield, BORAL [Reac2], of 0.265" thickness. BORAL is a uniform dispersion of Boron-carbide ($B_4C$) in aluminum with aluminum clad on both sides. It is composed by weight of 25.2% Boron, 8.6% Carbon, 65.0% Aluminum, and 1.2% Iron and other elements. The front truncated cone is surrounded by borated polyester which is composed of 30% Boron-carbide and 70% polyester resin by weight in a 1/32" thick wall aluminum mold. The borated polyester is fabricated in this laboratory. The boron-carbide powder is loaded into a polyester resin (Stypol 40-5718) [Free3]. These ingredients are thoroughly mixed, then a catalyst Methyl Ethyl Ketone Peroxide is added as a hardening agent, and the mixture is poured into the aluminum mold. The
Figure 2-1: Profile of NaI(Tl) spectrometer
Figure 2-2

Front view of NaI(Tl) spectrometer
Figure 2-3

Rear view of NaI(Tl) spectrometer
Figure 2-4

Construction photographs of the spectrometer 
(clockwise from upper left)

11.5"\(\phi\) x 15" NaI(Tl) crystal with phototubes

11.5"\(\phi\) x 15" NaI(Tl) crystal with plastic scintillator anticoincidence shield

Assembled spectrometer in beam line #5 at IUCF
prime ingredient of the thermal neutron shield is boron. Natural Boron contains 20% $^{10}$B, which has a high thermal neutron cross section. The BORAL and borated polyester provide approximately a thermal neutron attenuation of $10^5$ and $10^6$ respectively. Due to the capture of thermal neutrons in $^{10}$B, an associated 0.48 MeV gamma-ray is emitted, and hence the boron-carbide must be placed external to the lead shield.

General properties of the NaI(Tl) crystal, plastic scintillator, and phototubes are located in appendix B.

2. NaI(Tl) crystal

R. Hofstader [Hofs48] in 1948 produced the first NaI(Tl) poly-crystalline sample approx. 3.2 cm$^3$, and proved its scintillation efficiency was greater than naphthalene, due to its density of 3.67 g/cm$^3$ versus 1 g/cm$^3$ for naphthalene. In 1949 R.Hofstader and J. McIntyre [Hofs49] using a 1 cm$^3$ NaI(Tl) crystal observed absorption lines of gamma rays as the first application as a spectrometer.

The major advances of NaI(Tl) crystals since 1948 are the uniformity of the thallium dopant, the ability to grow large single crystals, and compensation of the crystal after it has been grown.

2a. Monte-Carlo Calculations For Optimal Crystal Size

The size of the new OSU NaI(Tl) crystal was determined using a Monte-Carlo calculation based on the method by
Longo and Sestili [Long75], for photons of energy $E_\gamma \geq 100$ MeV. At this energy the primary interactions of photons are pair-production and bremsstrahlung. The Monte-Carlo calculation also incorporates an energy loss due to ionization and multiple scattering, to study the shower development within the NaI(Tl) crystal.

A packet ($N_0=10^4$) photons with an energy of $E_\gamma = 100$ MeV, is allowed to interact within the crystal at two different impinging angles with respect to the z-axis of the NaI(Tl) crystal. The number of interactions within the crystal depends upon the density and photon mass attenuation coefficient for NaI(Tl) [Agui84]. The length of the shower is contingent upon the energy of the photon and the radiation length of the NaI, while the radial development of the shower within the crystal has a maximum $5X_0$ (radiation length) outgrowth. Tracking along the path of the photons, the number of photon interactions is calculated along with the percentage of the shower captured by the crystal, that is generated due to the interactions of the photons within the NaI(Tl). Binning the captured energy in the crystal into 1 MeV bins, a plot of counts (i.e. the number of photons captured with a specific energy) vs. energy captured by the crystal is presented in figure 2-5. Curves (a) and (b) present the effect of resolution due to collimation angle. The larger the
collimator, the resolution degrades due to the percentage of the shower that can escape from the sides of the crystal. This has also been shown experimentally by Hasinoff [Hasi74] using different collimators on a 10"φ x 10" NaI(Tl) crystal. This effect can also be viewed as a comparison of different crystal radii, the smaller the radius the greater the percentage of shower that escapes. A comparison of curves (b) and (c), different lengths of NaI(Tl) with the same collimation, shows an improvement in the height of the low energy tail, (i.e. peak/tail ratio), where the shorter NaI(Tl) crystal has a greater percentage of shower escaping the rear of the crystal.

A $^3$H(p,γ)$^4$He experiment was performed with the new OSU 11.5"φ x 15" NaI(Tl) crystal at $E_γ = 20.9$ MeV. The program GAMMASPEC [Rack84] was used to obtain the best line shape parameters and response function, as discussed in appendix C. A comparison of peak/tail showed an improved peak/tail of 1.081 versus 0.643 for the 10"φ x 12" NaI(Tl) crystal.

Overall the Monte-Carlo calculation revealed that the loss of resolution is due to escapes of the shower from the sides of the crystal, and the height of the low energy tail, peak/tail ratio, is due to escapes of the shower from the rear.
Figure 2-5

Monte Carlo calculation for $E_\gamma = 100$ MeV
2b. Bare NaI(Tl) crystal tests

Two important parameters to test are the resolution and efficiency of the new crystal and their comparison to the values of the smaller 10"φ x 12" NaI(Tl) crystal.

The 11.5"φ x 15" NaI(Tl) crystal was set up on the 30°S beam line at the OSU Van de Graaff facility, and θdet=90°. The 5" thick lead collimator was set at 23" focus for a 2.07 msr solid angle, such that the beam produced a 7.85" dia. spot on the rear of the crystal. The gain of the (7) RCA S83021EM1 phototubes with accompanying transistorized bases was matched using 1.332 MeV γ-rays from a 60Co source and resulted in a total phototube current of 9 ma at an average high voltage of -1270 volts. The (7) 500 RG-58 cable signals from the phototubes were OR-ed in a 500 matcher and using RG/8 fast cable the signal was sent to the control room where another 50Ω matcher split the signal into linear and logic lines. The linear line was then sent into a LeCroy 2249SG charge sensitive Analog to Digital Converter (ADC), via an attenuator and an isolation transformer which reduced the 60 Hz pick-up noise on the signal. The logic line contained an Ortec AN101 linear amp, Phillips 711 discriminator, and an OSU ADC gate generator to gate the ADC with a double NIM level 600 ns pulse width. The START out of the gate generator supplied a NIM pulse to the OSU
EVENT TRIGGER, which outputed a BUSY signal and inhibited the ADC gate generator, while the signal was being analyzed by the ADC. A Jorway 217 Gated Clock at 10pps was used to attain a normalization of live time for room background subtraction. The Jorway 217 Gated Clock had a TTL pulse sent to a TTL/NIM LeCroy 688AL converter then to a LRS 2551 Scaler. The LRS 2551 Scaler was also inhibited by a signal from the EVENT TRIGGER to counter dead time of the system. The data acquisition was performed on a CAMAC based system that utilized the LeCroy 3500 system and the Data General S/130 minicomputer. The program UNICORN [Rinc85] performed the data manipulation on the Data General S/130 and controlled the LeCroy 3500 which in turn controlled the software and CAMAC hardware.

A variety of γ-ray sources were placed at the focus of the collimator, and the resolution and efficiency of the NaI(Tl) crystals were calculated using the program GAUFIT [Konz82]. The photopeak efficiency was determined by calculating the number of counts under the photopeak divided by the expected number of counts determined by the solid angle and activity of the γ-ray source. Figure 2-6 shows the improved resolution after background subtraction of the 11.5"φ x 15" versus the 10"φ x 12" NaI(Tl) crystals. Plotting ln Resolution vs. ln (E/(m₀c²)) as shown by Knoll [Kno179], the resolution is shown to depend on energy as
Figure 2-6

Resolution (FWHM) comparison of bare NaI(Tl) crystals (11.5" x 15" vs. 10" x 12")

\[ \ln R = \ln K - \frac{\ln E}{2} \]

\[ R = \frac{K}{\sqrt{E}} \]
Table 1

Comparison of Photopeak Efficiencies
(bare crystal)

Collimation: 2.07 msr

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>10&quot; $\phi \times 12&quot;$</th>
<th>11.5&quot; $\phi \times 15&quot;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.511 ($^{22}\text{Na}$)</td>
<td>59.2%</td>
<td>79.8%</td>
</tr>
<tr>
<td>1.173 ($^{60}\text{Co}$)</td>
<td>54.1%</td>
<td>73.0%</td>
</tr>
<tr>
<td>1.274 ($^{22}\text{Na}$)</td>
<td>62.5%</td>
<td>77.7%</td>
</tr>
<tr>
<td>1.332 ($^{60}\text{Co}$)</td>
<td>54.0%</td>
<td>85.4%</td>
</tr>
</tbody>
</table>
The improved efficiency of the larger crystal, shown in table 1, where the difference from 100% is due to escapes of the shower from the crystal.

The $^{11}$B(p,$\gamma$)$^{12}$C and $^3$H(p,$\gamma$)$^4$He reactions were used to determine the resolution at 12.47 MeV, 16.86 MeV, and 20.5 MeV from the $^{11}$B(p,$\gamma_1$), $^{11}$B(p,$\gamma_0$), and $^3$H(p,$\gamma$) reactions respectively. The proton beam energy of $E_p = 1$ MeV with a 1 $\mu$A beam current was used. The leading edge resolution attained for the 11.5" x 15" crystal is 2.7% @ 12.47 MeV, 2.2% @ 16.86 MeV, and 1.9%@ 20.5 MeV.

3. Plastic Anticoincidence Shield

The plastic anticoincidence shield incorporates two major functions, detecting background radiation, and detection of showers escaping the central NaI(Tl) crystal. The plastic shield covers 93% of 4$\pi$ of the NaI(Tl) crystal. The major improvement of OMEGA II from that of OMEGA I is the uniformity of the segmented shield. Moving a collimated $^{22}$Na source length-wise over one segment of the plastic annulus, the peak position of the 0.511 MeV line varied only $\pm$5% from the average position, and produced a uniformity of 5.7%, while OMEGA I has a 15% variance of peak position. Both spectrometers produced approximately 50% resolution in the plastic shield for a $^{60}$Co source placed near the position of the
middle of the NaI(Tl) crystal. The improvement in the uniformity is due to the improved light collection efficiency of the optically isolated sections of the plastic shield.

The signals from the 12 Amperex 2202B phototubes comprising the anticoincidence cylinder and 3 Amperex 2202B phototubes from the front plastic shield are OR-ed in a LeCroy LRS 428F Linear FAN-IN/FAN-OUT NIM module. The OR-ed signals are then split into logic and linear lines as will be discussed in chapter III. During a typical measurement, the count rate in the plastic anticoincidence shield is about 90 kHz above the plastic discriminator set at 220 keV, while the count rate in the NaI(Tl) is 24 kHz above the 'low' discriminator set at 0.5 MeV. A typical spectrum from a \( ^{11}B(p,\gamma)^{12}C \) reaction at a proton energy of \( E_p = 1.0 \) MeV is shown in figure 2-7. The 'rejected' spectrum in part (a) shows that the detected escaped radiation from primary events in the NaI reduces the low energy tail, which is composed of bremsstrahlung, Compton, and one and two electron escape events. Part (b) of figure 2-7 shows the 'accepted' spectrum, which is raw minus the rejected spectrum. This will be explained further in chapter III.

During a \( ^{11}B(p,\gamma)^{12}C \) reaction study at a proton energy of \( E_p = 1.0 \) MeV, the front plastic shield was
Counts

Figure 2-7
Spectra with various sorting conditions:
$^{11}\text{B}(p,\gamma)^{12}\text{C}$ @ $E_p = 1.0\text{ MeV}$
removed from the logic. The count rate of the plastic annulus was 1.02 kHz, while that of the total anti-coincidence shield was 1.3 kHz. Removing the front plastic shield, the resolution (FWHM), degraded from 2.5\% to 2.73\% @ 16.85 MeV. The percentage of rejected to raw spectrum was 50\% and 42\% when the front plastic shield was in and out of the logic respectively.

From these results we conclude that some of the 0.511 MeV photons are backscattered into the front plastic shield, and the segmentation of the anti-coincidence plastic shield improves the overall light collection efficiency, while also reducing the 'low energy tail'.

4. Background Radiation

Cosmic ray background is produced in the upper atmosphere from collisions between nuclei and high energy protons in the solar wind. These collisions produce a vertical flux of \( \pi \)-mesons of about 10 \( m^{-2}s^{-1}sr^{-1} \) at high altitudes [Hill72]. For incident proton energies \( \geq 1 \) GeV, the \( \pi^+, \pi^-, \) and \( \pi^0 \) are produced in equal abundance. The \( \pi^0 \) decays via two \( \gamma \)-rays \( (T_{1/2} = 10^{-6} \text{sec.}) \) at high altitudes and these high energy photons are attenuated by the atmosphere and not observed at sea level. The charged pions have longer lifetimes \( (T_{1/2} = 2.6 \times 10^{-8} \text{ sec. at rest}) \) and therefore travel
further before decaying into \( \mu \)-mesons. These muons 
\( (T_{1/2} = 2.2 \times 10^{-6} \text{sec.}) \) generate a large flux of electrons 
and positrons at sea level. These electrons and 
positrons compose the 'soft' component of the cosmic ray 
background, and are easily removed by 10 cm (= 4 in.) of 
lead shielding. The 'hard' component, which is composed 
of the high energy \( \mu \)-mesons, remains at sea level with a 
flux of \( 80 \text{ m}^{-2} \text{sec}^{-1} \text{sr}^{-1} \). This flux of \( \mu \)-mesons 
penetrates the lead shielding and is responsible for the 
high energy background observed in large NaI detectors. 
The 'hard' component of muons interact within the lead 
shield and produce a shower of low energy electrons, 
which is then detected in the anticoincidence shield. 
The lead and anticoincidence shields provide a cosmic ray 
rejection of 99.7%.

The neutron background is composed of fast neutrons 
produced in the target, collimator slits, and beam dump, 
and neutrons from these same sources that have been 
thermalized \( (E_n = 0.025 \text{ eV}) \) by the walls and shielding. 
The fast neutrons cause high count rates in the NaI(Tl) 
crystal at equivalent gamma-ray energies which can extend 
into the region of interest. Time-of-Flight (TOF) 
techniques which will be discussed in chapter III 
minimize the effects of fast neutrons. Another common 
method is to place paraffin between the target and
detector, which unfortunately degrades the resolution and efficiency of the spectrometer. Thermal neutrons also induce high count rates in the NaI crystal, although of lower energies. Thermal neutron capture on $^{23}\text{Na}$ produces $^{24}\text{Na}$ ($T_{1/2} = 15\text{ h}$) releasing a 6.93 MeV $\gamma$-ray, and on $^{127}\text{I}$ producing $^{128}\text{I}$ ($T_{1/2} = 25\text{ m}$) releasing a 6.83 MeV $\gamma$-ray. To shield for thermal neutrons, B$_4$C and $^6\text{Li}$ is installed in the spectrometer. The B$_4$C (BORAL and Borated Polyester) is located on the exterior and covers 97% of $4\pi$ of the spectrometer. $^{10}\text{B}$ has a high thermal neutron cross section, $\sigma_{^{10}\text{B}} = 3837$ barns, from the $^{10}\text{B}(n_{\text{th}},\alpha)^7\text{Li}$ reaction and a mass absorption coefficient of 231 cm$^2$/g. Combining boron and carbon to produce the compound B$_4$C, provides a net mass absorption coefficient $\mu_{\text{eff}} = 30$ cm$^2$/g. Upon capture of a thermal neutron on $^{10}\text{B}$, a 0.48 MeV $\gamma$-ray is produced. For this reason the $^{10}\text{B}$ shield is located exterior to the lead shield and reduces the thermal neutron flux approx. $10^5$. The $^6\text{Li}$ is located between the NaI(Tl) crystal and the anticoincidence shield since the lithium nuclei absorb thermalized neutrons via the nonradiative $^6\text{Li}(n_{\text{th}},\alpha)^3\text{H}$ reaction with a thermal neutron cross section, $\sigma_{^6\text{Li}} = 940$ barns [Igas 86]. The reduction of thermal neutrons from the lithium shield is $10^6$ and $10^{12}$ for the side and front shields respectively, which covers 77% of the crystal.
III. EXPERIMENTAL DESCRIPTION

The measurement of radiative capture cross sections and analyzing powers presents special requirements on the NaI(Tl) spectrometer. Due to the low cross section on the order of a few nb/sr at proton energies $100 \text{ MeV} \leq E_p \leq 200 \text{ MeV}$, and high count rates from neutrons associated with the target, the NaI(Tl) spectrometer incorporates gain stabilization and pile-up techniques. These techniques along with a description of signal processing, data acquisition, and the experimental facility at the Indiana University cyclotron is described in this chapter.

1. Gain Stabilization

To achieve optimum performance of the NaI(Tl) spectrometer during experiments, at proton energies in the region $100 \text{ MeV} \leq E_p \leq 200 \text{ MeV}$, the fluctuations of beam current (changes in count rate) must be countered. Several authors [Devi84, Gupt67] have treated the problem of count rate dependent gain shifts observed in photomultiplier tubes. The major and most obvious problem is due to high pulse currents causing voltage shifts in resistive voltage dividers. There also appears effects due to residual gas in the photomultiplier causing after pulses in high gain
first dynode phototubes [Yama84], and reversible effects on
the last few dynodes which cause the dissociation of the
surface molecules and the evaporation of cesium, affecting
the secondary emission ratio [Yama77].

To counter the voltage shifts in resistive voltage
dividers, the use of high β transistors (MOTOROLA MPS-U10)
are connected parallel to the resistor chain in the tube
base [Kova79, Kova78, Bicrl]. These transistors provide a
stable voltage between adjacent dynodes. Connected in an
emitter follower configuration, the transistors sense
variations in the voltage between the last four adjacent
dynodes as compared with the voltage on the parallel low
current divider connected between transistor bases.

To remove the effects of long- and short-term
variations in the gain of the phototubes on the NaI(Tl)
crystal, an active gain stabilization system is used
[Kova78, Kova79]. This method operates directly with the
fast anode signals produced by a Light Emitting Diode,
(LED), of fixed frequency of 1kHz and of fixed amplitude.
Due to the improved resolution of OMEGA II to that of
OMEGA I, the fast-gated-integrator stabilizer was improved.

The OSU designed and built fast-gated-integrator
stabilizer, fig.'s 3-(1,2), is controlled by a crystal-
controlled TTL oscillator operating at 1kHz which supplies
the trigger for three driver circuits 1) LED ENABLE, 2) NIM OUT, and 3) GATE DRIVER.

The LED ENABLE is a TTL pulse capable of driving a signal through a long 500 cable to turn on six independent LED DRIVER circuits, fig. 3-3, located near the NaI(Tl) phototubes. This TTL pulse supplies a signal to the VN10KM VMOS FET which serves as a switching device. C1 is the timing (RC discharge) capacitor. When Q1 is off, the capacitor is charged via the diode D1 and resistor R3, to the voltage setting \( V_D \) on the external precision voltage supply whose output determines the maximum amplitude of the LED light output. When Q1 is turned on, the capacitor discharges via Q1, R5, and the LED. R6 is used to bias the LED near its conduction level to offset the LED turn-on time. C1, R5, and the intrinsic resistance of the LED determines the RC time constant. This RC time constant, approx. 22 ns., is chosen such that a pulse from the Litronix GL-56 LED is shaped to have the same characteristics as a scintillation signal. Due to the wavelength of Thallium (\( \lambda = 410 \) nm) and the response of the photocathode of the phototube (\( \lambda = 400 \) nm), a blue emitting LED (\( \lambda = 480 \) nm) would be more efficient than the GL-56 green (\( \lambda = 565 \) nm) LED [Reit81]. A blue (Siemens SFH710) Silicon carbide, Aluminum Nitride (SiC:Al,N) LED was tested with our setup, but due to its intrinsic resistance,
the fall time of the signal could not be matched to a scintillation signal. The LED DRIVER circuit is connected to the LED via a short length of twinax (Belden 9271-500) 124Ω cable. The upgrade of the LED DRIVER had all capacitors changed to mica due to their improved temperature stability over that of ceramic capacitors. The VN10KM fast transistor has an internal resistance which varies with temperature. This variance allowed the VN10KM transistor to turn on the LED at different times with respect to the crystal-controlled oscillator in the gain stabilizer. This caused the Analog Converter QT100C (LeCroy hybrid Charge-to-time Converter), located in the gain stabilizer, fig. 3-1, to view different amounts of charge as the analog pulse shifted in time with respect to its gate. A OSU built Temperature Controlled Heater, fig. 3-4, is coupled via vacuum grease to the LED DRIVER to keep the VN10KM transistor at a constant temperature of (45±0.5)°C. This improved the shifting of the LED peak in the ADC over a 48 hr. run from ±0.42% to ±0.3%.

The GATE DRIVER circuit [Kova78, Kova79], fig. 3-2, supplies a NIM level signal to gate the LED produced signal from the phototubes at the QT100C charge-to-time converter.

NIM OUT circuit [Kova78, Kova79], fig. 3-2, supplies a NIM level signal to the signal processing electronics to
veto the LED produced signal from entering into the NaI(Tl) spectrum.

The prime component of the gain stabilizer is the direct-coupled charge-to-time converter, LRS QT100C, which is fully described by Kovash [Kova78]. Basically, the LED signal sets the QT100C hybrid to go 'low' for a time which is proportional to the collected charge. This time-averaged response to the LED signal is converted to a DC level and is then compared to a reference voltage. The difference is then inverted and amplified, and is then current-summed with the H.V. power supply's internal low voltage reference signal which changes the high voltage on the photomultiplier tubes (pmt's) so as to compensate for any gain shift detected. Changes in the gain stabilizer were made due to the improved resolution of OMEGA II to that of OMEGA I. The voltage reference, fig. 3-1, was changed from a LH0070-0 to a LM199H. The LM199H voltage reference has an improved output accuracy of ±0.05% versus ±0.1% for the LH0070-0. Other improvements are the output change/Temp. of ±0.005%/°C versus ±0.2%/°C and long-term stability of ±0.005%/year versus ±0.2%/year for the LM199H and the LH007-0 respectively. The gain stabilizer for OMEGA I had a 500kΩ carbon resistor located between the voltage reference and the comparator. This 500kΩ resistor was removed for the OMEGA II gain stabilizer due to its
temperature variance and also since the comparator views
only a DC level, the matching of impedance was not necessary.
The last change on the gain stabilizer is a 2.8 - 10 pF
variable capacitor in series with a 1kΩ metal film resistor,
added between the gate and analog input of the LRS QT100C.
This added circuit, a copy of all LeCroy charge sensitive
circuits, provides a pedestal adjustment by injecting charge
via the trimmer capacitor which is proportional to the
charge on the capacitor times the level of the gate. This
method assures the pedestal remains constant.

Tests of the gain stabilizer system was performed at
OSU using the Van de Graaff accelerator. The first test was
the change of the LED peak in the ADC for count rate
dependence. Figure 3-5 shows the resulting LED spectrum
when the count rate changes from 8kHz to 230kHz. With the
gain stabilizer disabled, a 2.34% change in the peak
position of the LED was attained, versus a 0.36% change
when the gain stabilizer is enabled. OMEGA I showed a 12%
and 0.7% change in the peak position of the LED when the
gain stabilizer was disabled and enabled respectively. The
initial 2.34% change of the LED spectrum peak position is
attributed to the improved gain stabilized phototubes on the
NaI(Tl) crystal. The final test of long-term stability of
the system was checked over a 12 hr. run, where the spectrum
of γ-rays from a $^9$Be($^3$He,γ)$^{12}$C reaction were recorded along
Figure 3-1

Schematic diagram of gain stabilizer: Analog board
Figure 3-2

Schematic diagram of gain stabilizer: Clock board
Notes:
1) All Resistors are metal film
2) All Resistances in ohm's.
3) All Capacitors in microfarads.

Figure 3-3
Schematic diagram of LED driver
Figure 3-4

Schematic diagram of Temperature Controlled Heater
Figure 3-5

Beam-off/beam-on LED spectra with gain stabilizer enabled, and disabled
with the position of the LED pulse. No deviations in excess of 0.58\% were observed versus 1\% for OMEGA I. This gave an average gain stability of 0.3\%.

2. Signal Processing and Histogram Definitions

The electronics used with the OMEGA II spectrometer is similar to those described in more detail in references [Blat68, Kova78, and Marc87]. A block diagram of the most recent experimental run is shown in fig.'s 3-\(6,7\). The seven anode signals from the phototubes on the NaI(Tl) crystal are passively summed (EG\&G ORTEC AN308N/L) and split into linear and logic lines. The linear signal is double delayed-line clipped to = 450 nsec., and split, to be analyzed by the gain stabilizer and the charge-sensitive ADC (LRS 2249SG). The logic lines are also split into 'Low' and 'Hi' lines. Due to the longer scintillation pulse from the larger NaI(Tl) crystal, the integrating clip on the 'Low' logic line was removed. In the 'Hi' logic line a Constant-fraction discriminator (ORTEC 934) replaced the Differential discriminator (ORTEC TD101) to remove the random time walks. This improved the FWHM of the Time-of Flight (TOF) spectrum, fig. 3-8, from =2.3 ns to =1.5 ns.

The Time-of Flight (TOF) method uses the pulsed cyclotron beam as a reference to separate the \(\gamma\)-rays of interest from the neutrons and other particles produced by various reactions from the target and background. The TDC
(LRS 2228A) starts its timing operation (Wilkinson rundown method) when a valid 'event' (i.e. Hi-LED) is detected in the NaI(Tl) crystal. The stop is a pulse from the next cyclotron beam burst. Software windows are placed on the gamma peak and on the high energy neutrons as shown in fig. 3-8. This allows the sorting algorithm of the data-acquisition system to select only gammas from all events being detected by the crystal. Figure 3-9 shows a spectrum for all events detected by the crystal ('RAW'), and the spectrum ('GAMMAS') which is generated by sorting only those events that are within the $\gamma$-ray window in the TOF spectrum. During the R286xx run at a proton energy $E_p = 151$ MeV, it was noticed that an extra neutron peak showed up in the TOF spectrum, figure 3-10A, showing that the beam exiting the cyclotron was hitting a magnet in beam line 5 upstream of the target chamber. This was detected by pulling the target and scintillation ladder out of the beam path. Retuning the cyclotron, reducing the $B$ field within the cyclotron, the extra neutron peak in the TOF spectrum was eliminated. Figure 3-10B, shows the TOF spectrum after the cyclotron was retuned, showing a time-independent background consisting of the mutual background and the $\beta$ and $\gamma$-rays due to the $^{127}\text{I}(n_{th},\gamma)^{128}\text{I}$ reaction in the NaI(Tl).

To achieve the required resolution for capture $\gamma$-ray studies, a method was needed to eliminate any events from
which energy escaped from the NaI(Tl) crystal into the plastic anticoincidence shield, but also necessary to account for these events in our cross-section calculation. These requirements were satisfied by requiring each time a valid event was detected in the NaI(Tl) crystal, the energy deposited in the plastic anticoincidence shield and the crystal was simultaneously recorded in the ADC. To obtain the required resolution, it was necessary to record only those valid events wherein the crystal captures the total energy of the $\gamma$-ray, the accepted spectrum. (A small amount of energy escapes from the rear of the crystal where there is no plastic shield, producing a small constant low energy tail on the observed $\gamma$-ray line shape.) This was performed by requiring that no events are detected in the plastic anticoincidence shield at the same time a 'GAMMA' event was detected in the NaI(Tl) crystal. In the OMEGA I spectrometer as described in references [Kova78 and Rack84a], if a valid 'GAMMA' event, (Hi$p$), not pile-up gamma, was in coincidence with a plastic event (hardware requirement), then a 'REJECTED' spectrum was recorded along with the plastic energy spectrum. A valid 'GAMMA' event recorded with no plastic event, (anticoincidence requirement), produces an 'ACCEPTED' spectrum.

Using a different logic for OMEGA II, its electronics splits the plastic anticoincidence shield into an Annulus
and Front plastic shields. The phototube anode signals from the Annulus and Front plastic shields were passively mixed (ORTEC AN308N/L) and split into logic and linear lines. The Annulus and Front linear lines were summed, 'FAN IN' (LRS 428F), to produce a plastic linear line to the ADC. The plastic logic lines consisted of an AMP (ORTEC AN101), constant-fraction discriminator (ORTEC 934), delay and an updating discriminator (LRS 821). The logic lines produced independent plastic Annulus and Front stops for the TDC. When a valid 'GAMMA' event starts the TDC, the stops from the plastic Front and Annulus produces a TOF spectra, fig. 3-(11A, 11B), where a software window was placed over those events in the plastic shields that were in coincidence with valid 'GAMMA' events. Those 'GAMMA' events that were in coincidence with events within the software window produce the 'REJECTED' spectrum, fig. 3-12, which are comprised of bremmstrahlung, Compton, and one and two electron escapes. A valid 'GAMMA' event recorded with no plastic event, (anti-coincidence requirement), produce an 'ACCEPTED' spectrum, figures 3-(9,12). The last requirement for the 'ACCEPTED' spectrum is a coincidence with the NIM INPUT REGISTER (JORWAY 65) BIT 3, Hi·P, a not pileup bit. To account for those events where some of the energy escapes into the plastic anticoincidence shield, for calculation of cross-sections, a two-parameter histogram was
Figure 3-6: Schematic diagram of experimental electronics, part I
Figure 3-7: Schematic diagram of experimental electronics, part II
Figure 3-8
Time-of-Flight spectrum
Figure 3-9

Spectra with various sorting conditions:
$^{11}\text{B}(p,\gamma)^{12}\text{C} @ E_p = 38 \text{ MeV}$
Figure 3-10

TOF spectra of background neutron peak before and after beam retune
Figure 3-11

Time-of-Flight spectra of NaI(Tl)-Plastic coincidence
Figure 3-12

$^{11}\text{B}(p,\gamma)^{12}\text{C}$ at $E_p = 38$ MeV spectra:
- GAMMAS
- ACCEPTED
- REJECTED

Counts

Channel

Figure 3-12

$^{11}\text{B}(p,\gamma)^{12}\text{C}$ @ $E_p = 38$ MeV spectra:
GAMMAS; ACCEPTED; REJECTED
Figure 3-13

2-D histogram of NaI(Tl) vs. Plastic coincidence; $^{11}\text{B}(p,\gamma)^{12}\text{C}$ @ $E_p = 38$ MeV

$^{11}\text{B}(p,\gamma)^{12}\text{C}$

$E_p = 38$ MeV

$\theta_{\text{lab}} = 60^\circ$

NaI(Tl) only

Plastic Energy

NaI(Tl) Energy
generated, fig. 3-13, where the X-axis corresponds to the energy detected by the NaI(Tl), and the Y-axis the energy in the plastic shield. A resum algorithm which uses this 2-D histogram to correct for events rejected by the software veto is described in reference [Jens84].

A histogram of LED pulses was also accumulated, as a check on the gain stabilization system, as described in section III-1. The LED events were recorded along with the NaI(Tl) and plastic events on the event tape, which provides a mechanism to account for drift in the electronics. The LED events are separated from other events by tagging it via the NIM INPUT REGISTER, Coincidence Register (C.R.) BIT 2, thus allowing the sorting algorithm to accumulate the LED pulses into a separate histogram.

3. Experimental Facilities

The experimental tests on the new NaI spectrometer, OMEGA II, were performed at The Ohio State University 7.0 MV positive Van de Graaff accelerator for γ-ray energies $E_γ \leq 28$ MeV, Run sequence no.'s TST2_x, and at the Indiana University Cyclotron Facility in Bloomington, Indiana, for γ-rays of $E_γ = 50$ and 158 MeV, runs R186xx and R286xx respectively.

The NaI spectrometer, OMEGA II, was set up on the 45°N beam line at The Ohio State University Van de Graaff Accelerator Laboratory. It was assembled as previously
described in chapter II, with the exception that the $^6$Li shield was not available for thermal neutron attenuation around the crystal. The electronics was set up similar to that described in section III-2, except the plastic anticoincidence shield not being split and the use of a hardware anticoincidence requirement as originally done with the OMEGA I spectrometer. Time-of Flight techniques were not used since the Van de Graaff accelerator is a continuous non-pulse machine. Other techniques for neutron rejection such as pulse-shape rejection could be used, but due to the large difference in the Q-value for $(p,\gamma)$ and $(p,n)$ reactions, no neutrons would enter the region of interest. Throughout the TST2 runs the target to detector collimator distance was fixed at $\approx 28''$ at a $\theta_{\text{lab}} = 90^\circ$. The collimator used illuminates a 7.85" diameter beam spot on the rear of the crystal.

The gain of the seven NaI(Tl) crystal phototubes were matched using 1.332 MeV $\gamma$-rays from a $^{60}$Co source with the main HV power supply set at -1400 volts and the individual pmt's in the range -1236 to -1354 volts, which resulted in an average voltage -1269 volts and a total pmt current of 9 ma. Then the gain of the 6 GL-56 green LED's, located on the rear of the NaI(Tl) crystal, were individually matched such that their total light output in the crystal would be greater than the highest $\gamma$-ray energy of interest. The gain
of the plastic anticoincidence shield was matched using a \(^{22}\)Na source with the main HV power supply at -1700 volts resulting in a total pmt current of 21.5 ma. The individual pmt's of the plastic shield were then mixed (LRS 428F) for a combined annulus and front linear signals. These 'mixed' signals of the front and annulus were then gain matched such that any first escape from the crystal would register the same energy in both shields. These two plastic signals were then mixed (LRS 428F) to produce a Plastic linear and logic lines.

The linear signal path was DC-coupled to prevent baseline drifts, due to high count rates, and low signal level, therefore any AC pickup must be eliminated. The NaI(Tl) spectrometer assembly was electrically isolated from the earth ground in the target room, and the power to the electronics was supplied by a power cord connected to the NIM bin power strip located in the control room. The ground of the spectrometer had the same ground as the NIM bin, supplied via the ground sheath of the 500 cables. Another problem was isolating all other grounds, signal cables from various beam lines in the target room from the common patch panel in the control room. This was accomplished by the exchange of the aluminum patch panel for a G-10 (phenolic) panel. The last step was the placement of small isolating-transformer boxes placed in the linear path.
before the ADC. Through these techniques, the effect of AC noise on the linear signals were minimized, although not completely eliminated.

The targets used for the TST2 runs, table 2, were manufactured at the Van de Graaff lab. The $^{11}$B target, manufactured by L. Rybarcyk, used elemental $^{11}$B powder with the electron gun evaporation technique onto a 0.01" thick 660µg Tantalum backing. The $^3$H (Tritium) targets were supplied by Dr. Donoghue, with a 10.5µg Cu backing, and the $^6$Be target was manufactured by J. McKamy [Mcka82]. The $^{11}$B and $^6$Be solid targets were 1.25" diameter, while the $^3$H target was 1" diameter and had a special holder that water cooled the target to prevent the $^3$H from evaporating due to heating from high beam currents.

The data acquisition system was performed on a CAMAC based system that utilized the LeCroy 3500 system and the Data General S/130 minicomputer. The program UNICORN [Rinc85] performed the data manipulation on the Data General S/130 and controlled the LeCroy 3500 which in turn controlled the software and CAMAC hardware.

The intermediate energy gamma-ray experimental tests, $E_\gamma = (50$ and 158) MeV, runs R186xx and R286xx respectively, were performed at the Indiana University Cyclotron Facility (IUCF). A schematic diagram of this facility is presented in fig. 3-14. The accelerator is of a separated sector
design and is capable of producing high resolution proton beams \((\Delta E/E = 1 \times 10^{-3})\) of continuously variable energy from 12 to 215 MeV with a maximum intensity of 6.0\(\mu\)A (400 nA for polarized proton beams). Other particles that can be accelerated are deuterons (24 Mev to 100 MeV), \(^3\text{H}\) (23 Mev to 270 MeV), \(^4\text{He}\) (30 Mev to 200 MeV), \(^6\text{Li}\) (46 Mev to 154 MeV), and \(^7\text{Li}\) (70 Mev to 101 MeV) [Iucf85]. The procedure to produce the particle beams is first the production of a high intensity continuous beam from an ion source held at approximately 500kV. The beam is then chopped and bunched at the frequency of the cyclotron, approximately 32 MHz. Then the ions are accelerated through the injector and main cyclotron which are of similar design. The time structure of the emitted beam is of sub-nanosecond duration, and can be pulse selected to 1 in \(N\) of the cyclotron frequency, where \(N\) ranges from 2 to 7. The pulse-selection is accomplished by the beam chopper. Pulse-selection was used for these experiments for the use of separating the gamma-rays from neutron induced events in the TOF spectrum.

The intermediate energy data was taken with the spectrometer assembled, as described in chapter II, except without the \(^6\text{Li}\) shield, in beam line 5 (old QDDM room), at 60° (run R186xx) and 40° (run R286xx), and in the horizontal plane of the incident beam, approximately 6.5' above floor level. Beam 'halo' is removed by two pairs of slits, slit
#3 and #7, located in beam line 3; the beam is then bent into beam line 5 and focussed onto the target position by dipole and quadruple magnets. As discussed in section III-2, the cyclotron was retuned due to the extra neutron peak produced in the TOF spectrum, upstream of the target, since the slits and 18" thick concrete wall shields were not capable of removing this background due to the high energy neutrons, $E_n = 150$ MeV.

The spectrometer used a lead collimator 9.6 msr at a 1m target to collimator distance and a 3.6 msr collimator at 2m target to collimator distance for the R186xx and R286xx runs respectively, both producing a 7" diameter beam spot on the rear of the NaI(Tl) crystal.

A Faraday cage was used to collect the amount of charge collected, which determined the beam charge on the target, since all targets used were relatively thin. Table 2 lists the targets used for these runs which were prepared by William Lozowski at IUCF. The target chamber was designed by D. Marchlenski [Marc87], constructed from a single aluminum pipe with 1/16" thick windows.

Before the start of a run, a scintillator at the bottom of the target ladder was positioned at the center of the beam pipe. The operator then positioned the beam through a 1/8" diameter hole in the scintillator by changing the beam optics so as to minimize the beam spot and room background,
and simultaneously maximize the total current collected in the Faraday cage. The target ladder was then repositioned (lowered) to allow the target to be positioned in the beam path.

The spectrometer was electrically isolated from earth ground in the target room by situating the spectrometer and its aluminum cradle on an insulating phenolic board. The power to the spectrometer was supplied through a 2-prong isolation transformer, which allowed the ground of the spectrometer to be attained via the ground sheaths of the 500 signal cables. The power to the electronics associated with the spectrometer was supplied through an isolation transformer located in the control room. We made use of our own cable, in order to prevent ground loop problems between the target and control rooms. The only problem area was that of a D.C. offset, \( \approx 15 \text{ mV} \), when the signal cable was connected to CAMAC, due to the differences in the computer and spectrometer grounds. As of now we are not sure if this D.C. offset has a time component. A small isolation transformer was put on the linear lines, run R186xx, to overcome any A.C. noise pickup, and during the R286xx run the isolation transformer was removed due to possible baseline shifts at high count rates.
Figure 3-14
Experimental area layout of IUCF
The electronics during the R186xx runs was set up as discussed above while the R286xx runs was set up as discussed in section III-2.

The data were taken using the data-acquisition program "XSYS/IUCF", a modified version of XSYS developed at TUNL, designed to run on IUCF's Digital Equipment Co. VAX 11/750 computer, 5 MB memory. The program "XSYS/IUCF" performs the data-acquisition I/O and event sorting, and controls the CAMAC operations and the direct-memory access (DMA) to the VAX through the Bi-Ra Micro-programmable Branch Driver (MBD) [Iucf85].

4. Spectrometer Performance

The analysis of the experimental tests, table 3, were performed on the Data General S/130 minicomputer for the TST2 runs, and on the μVAX II microcomputer for the intermediate energy experiments. Programs for both computers were of the same design except for the differences in the computer code for the respective computers. The data-acquisition program UNICORN [Rinc85] dumps the TST2 run spectra onto the disk in SPEC format [Rack84a]. The dump type spectra from "XSYS/IUCF" which are located on the VAX 11/750 disk is loaded onto a 1600 BPI tape for transfer to OSU. The "XSYS/IUCF" dump type spectra is then translated into SPEC format and loaded onto the μVAX II disk by the program 'XSPEC', designed by the author of this work,
is presented in appendix D. Another possibility is the replay of the XSYS/IUCF event tapes on the μVAX II microcomputer using the code "XSYS/IUCF".

For calculations required in the analysis of this data, the parameter $E_{\text{IN}}$ is calculated from $E_{\text{INC}}$ using the program LOSTENERGY [Marm73]. LOSTENERGY calculates the amount of energy lost, $\Delta E$, by the incident beam, $E_{\text{INC}}$, as it passes through the target material. The parameter $E_{\text{IN}}$, used for calculations, is the average value of $E_{\text{INC}}$ and $E_{\text{OUT}}$, or approximately the energy of the beam halfway through the target. The program KINMAT [Rinc81] is then used to determine the energy of the gamma-rays of interest and the highest energy neutrons that can enter the 'ACCEPT' spectrum according to the reaction, $E_{\text{IN}}$, $\theta_{\text{lab}}$, and the states of interest, shown in table 4.

Table 5 presents the count rate in the plastic anticoincidence shield and the NaI(Tl) crystal for various experimental runs. As the energy of the incident beam increases, the count rate in the plastic anticoincidence shield also increases, where the count rate is above the discriminator threshold (200keV for the TST2 runs, 450 keV run R186xx, and 1MeV for run R286xx). Run R286xx also shows that the front plastic shield has approximately 73% of the total plastic count rate due to the backscattered .511 MeV escapes and located in the path of the scattered $\gamma$-rays,
protons, and neutrons from the target. The lower crystal
'Low' count rate for the R286xx run was due to the higher
'Low' discriminator level than for past runs which resulted
in poorer pileup rejection.

As the incident energy increased, the percentage of the
total number of events detected only by the crystal
decreased. The %Accepts which is defined

\[
\text{Accept}
\]

\[
\% \text{Accept} = \frac{\text{Accept}}{\text{Accept} + \text{Rejected}} \times 100\% \quad (\text{III}-1)
\]

is shown in table 5. With the increase of γ-ray energies,
the developing shower within the crystal becomes larger and
has a greater chance of parts of the shower escaping into
the plastic anticoincidence shield (discussed in chapter II).
This feature was also exhibited with the BNL MK-III
spectrometer at an incident γ-ray, \( E_\gamma = 300 \) MeV, with 17%
Accepts [Dowe85], and also shown to depend upon the energy
threshold of the plastic shield.

The resolution of OMEGA II spectrometer was determined
by the computer program ERRFIT [Rinc86], which uses a
gaussian peak fitting routine to determine the full-width
at half maximum (FWHM) of the respective gamma-ray peaks of
interest (Accepted spectrum), shown in table 6, and also
takes into account beam broadening due to the target. The
80 nA run R286xx was replayed at OSU on the \( \mu \)VAX II micro-
computer with the data-acquisition program "XSYS/IUCF" to improve the accepted spectrum, changing the γ-ray window on the TOF, reducing the number of high energy neutrons from entering the accepted spectrum, run R28622_81. Figure 3-15 shows the final 'Accepted' spectrum with its resolution (FWHM). The large error on the resolution for run R28622_81, ±20%, is due to low statistics and the effect of a plastic proton plug placed inside the lead collimator during the 150 MeV $^{11}$B(p,γ)$^{12}$C run (R286xx) at IUCF. The proton plug, 5.88'' long, stops the 150 MeV protons from the $^{11}$B(p,p) reaction, tabulated in reference [Jann82], from impinging the crystal and front plastic shield and increasing their count rates.

The energy resolution (FWHM of the Accepted spectrum) of OMEGA II for the energy region 12 MeV to 158 MeV, plotted in fig. 3-16, reproduces a $\Delta E/E_\gamma = 0.0633(E_\gamma \text{ in MeV})^{-1/3}$ response. The BNL MK-III spectrometer produces an energy response $\Delta E/E_\gamma = 0.0592(E_\gamma \text{ in MeV})^{-0.31}$ [Sand84], while the SLAC CRYSTAL BALL, 40 cm long NaI(Tl) with 4π coverage produces a $\Delta E/E_\gamma = 0.1575(E_\gamma \text{ in MeV})^{-1/4}$ energy response [Kirk70]. If the NaI(Tl) detector was perfectly uniform, the amount of light reaching the phototubes photocathode would be proportional to the energy deposited by the γ-ray, and the resolution would only be determined by the statistical fluctuation on the number of photons emitted by
the Thallium. The resolution would thus have a response as $E_\gamma^{-1/2}$. The earlier spectrometers reproduced a resolution response $E_\gamma^{-1/4}$ [Heat79] which was attributed to the non-uniformity of the crystal, while the BNL MK-III and The Ohio State University OMEGA II crystals reproduce a resolution response $= E_\gamma^{-1/3}$ due to the recompensation techniques for improved uniformity introduced by Bicron Co. The $E_\gamma = 158$ MeV resolution does not follow the expected energy response of the crystal due to count rate problems associated with the signal processing electronics and not using an isolation transformer to eliminate the 60Hz pick-up noise on the NaI linear line to the ADC.

The count rate problem is demonstrated in figure 3-17, LED resolution vs. count rate in the plastic shield. The count rate in the plastic shield is used instead of the 'Low' count rate of the crystal since the plastic shield has a lower threshold on the discriminator reproducing a better representation of the count rate in the crystal. A flat distribution is expected if the resolution is independent of the count rate, but as shown at count rates above 100 kHz both spectrometers, OMEGA I&II, produce an increase of LED resolution. Techniques to improve the count-rate problem are under investigation along with improved pileup techniques.
The technique of double-subtraction [Sand84], formed by the removal of a fraction of the rejected spectrum from the accepted, is in order to make the region between the peaks go to zero in the accepted spectrum. This resubtracted fraction, on the order 30% to 40%, improved the resolution by subtracting more of the first escapes that lie within the low energy section of the photo-peak, shown in table 6. The double-subtraction technique was not performed on the R286xx run due to the low statistics of the accepted spectrum. A comparison of NaI(Tl) spectrometers at the gamma-ray energy $E_\gamma = 22$ Mev is shown in table 7. The BNL, Uppsala, and the OSU spectrometers have the improved resolution due to Bicron's ability to recompensate the surface of the crystal at the higher $\gamma$-ray energy, 6.13 MeV, while the larger OSU spectrometer diameter shows an improvement in the FWTM%.

The improvements of OMEGA II to past spectrometers has been achieved due to improvements by Bicron Co. at surface compensation techniques producing improved (FWHM) resolution at higher energies, and improved FWTM from a larger diameter NaI(Tl) crystal and segmentation of the plastic anticoincidence shield. These improvements along with an improved gain stabilizer has allowed us at OSU to embark on the study of the $\Delta$'s (1232 MeV) effect on radiative proton capture work on light nuclei at IUCF.
Table 2
Target Thickness and Energy Loss

<table>
<thead>
<tr>
<th>TARGET</th>
<th>EINC(MeV)(particle)</th>
<th>THICKNESS(mg/cm²)</th>
<th>ΔE(keV)</th>
<th>BEAM CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>²¹B</td>
<td>1.0 (proton)</td>
<td>0.084</td>
<td>18.74</td>
<td>1.5-3µA</td>
</tr>
<tr>
<td>³H</td>
<td>1.0 (proton)</td>
<td>2.081</td>
<td>639.5</td>
<td>2µA</td>
</tr>
<tr>
<td>³H</td>
<td>3.1 (proton)</td>
<td>2.081</td>
<td>198.63</td>
<td>0.3µA</td>
</tr>
<tr>
<td>⁹Be</td>
<td>3.4 (³He)</td>
<td>0.050</td>
<td>42.12</td>
<td>2µA</td>
</tr>
<tr>
<td>¹¹B</td>
<td>38.04 (proton)</td>
<td>30.6</td>
<td>391.84</td>
<td>20nA</td>
</tr>
<tr>
<td>¹¹B</td>
<td>151.07 (proton)</td>
<td>57.4</td>
<td>259.28</td>
<td>80nA</td>
</tr>
</tbody>
</table>

Table 3
Radiative Capture Reactions for test of NaI Spectrometer

<table>
<thead>
<tr>
<th>Run_ID</th>
<th>Reaction</th>
<th>EIN(MeV)</th>
<th>ø1ab(deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TST2_1</td>
<td>¹¹B(p,γ₁)¹²C</td>
<td>1.0</td>
<td>90</td>
</tr>
<tr>
<td>TST2_1</td>
<td>¹¹B(p,γ₀)¹²C</td>
<td>1.0</td>
<td>90</td>
</tr>
<tr>
<td>TST2_2</td>
<td>³H(p,γ)⁴He</td>
<td>0.85</td>
<td>90</td>
</tr>
<tr>
<td>TST2_4</td>
<td>³H(p,γ)⁴He</td>
<td>3.03</td>
<td>90</td>
</tr>
<tr>
<td>TST2_5</td>
<td>⁹Be(³He,γ₀)¹²C</td>
<td>3.38</td>
<td>90</td>
</tr>
<tr>
<td>R18609_1</td>
<td>¹¹B(p,γ₀)¹²C</td>
<td>37.84</td>
<td>60</td>
</tr>
<tr>
<td>R28622_81</td>
<td>¹¹B(p,γ₀)¹²C</td>
<td>150.94</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 4
Energy of γ-rays and highest neutrons

<table>
<thead>
<tr>
<th>RUNID</th>
<th>Eγ(MeV)</th>
<th>En₀(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TST2_1</td>
<td>12.417</td>
<td>---------</td>
</tr>
<tr>
<td>TST2-1</td>
<td>16.85</td>
<td>---------</td>
</tr>
<tr>
<td>TST2-2</td>
<td>20.395</td>
<td>---------</td>
</tr>
<tr>
<td>TST2-4</td>
<td>22.014</td>
<td>0.97</td>
</tr>
<tr>
<td>TST2-5</td>
<td>28.77</td>
<td>9.18</td>
</tr>
<tr>
<td>R18609_1</td>
<td>51.06</td>
<td>31.998</td>
</tr>
<tr>
<td>R28622_81</td>
<td>158.08</td>
<td>141.54</td>
</tr>
</tbody>
</table>
Table 5
%Accepts and Count Rate vs. $E_\gamma$

<table>
<thead>
<tr>
<th>Run ID</th>
<th>$E_\gamma$(MeV)</th>
<th>%Accepts</th>
<th>Plastic Count-Rate</th>
<th>X-Tal 'LOW' Count-Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>TST2_1</td>
<td>16.85</td>
<td>56.67</td>
<td>950Hz</td>
<td>1.1kHz</td>
</tr>
<tr>
<td>TST2_2</td>
<td>20.395</td>
<td>55.6</td>
<td>1.06kHz</td>
<td>1.1kHz</td>
</tr>
<tr>
<td>TST2_4</td>
<td>22.014</td>
<td>40.87</td>
<td>90.1kHz</td>
<td>24kHz</td>
</tr>
<tr>
<td>TST2_5</td>
<td>28.77</td>
<td>24.06</td>
<td>209.9kHz</td>
<td>60kHz</td>
</tr>
<tr>
<td>R18609_1</td>
<td>51.06</td>
<td>55.48</td>
<td>702.3kHz</td>
<td>171.3kHz</td>
</tr>
<tr>
<td>R28622_81</td>
<td>158.08</td>
<td>28.03</td>
<td>annul. 617.7kHz</td>
<td>29.6kHz</td>
</tr>
</tbody>
</table>

Table 6
Resolution vs. $E_\gamma$

<table>
<thead>
<tr>
<th>$E_\gamma$(MeV)</th>
<th>Double-Subtracted Resolution%</th>
<th>+Δ Resolution%</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.417</td>
<td>3.02</td>
<td>2.71</td>
</tr>
<tr>
<td>16.85</td>
<td>2.51</td>
<td>2.35</td>
</tr>
<tr>
<td>20.395</td>
<td>2.44</td>
<td>2.31</td>
</tr>
<tr>
<td>22.014</td>
<td>2.4</td>
<td>1.99</td>
</tr>
<tr>
<td>28.77</td>
<td>3.19</td>
<td>2.04</td>
</tr>
<tr>
<td>51.06</td>
<td>3.50</td>
<td>2.05</td>
</tr>
<tr>
<td>158.08</td>
<td>2.25</td>
<td>----</td>
</tr>
</tbody>
</table>

Table 7
Comparison of NaI(Tl) Spectrometers at $E_\gamma = 22$ MeV

<table>
<thead>
<tr>
<th>Spectrometer(size)</th>
<th>FWHM%</th>
<th>FWTM%</th>
<th>Double-subtracted FWHM%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stony Brook (10x12)</td>
<td>4.4</td>
<td>13</td>
<td>3.5</td>
</tr>
<tr>
<td>Seattle (10x12)</td>
<td>3.4</td>
<td>15</td>
<td>3.0</td>
</tr>
<tr>
<td>Osaka (10x12)</td>
<td>3.4</td>
<td>10</td>
<td>2.8</td>
</tr>
<tr>
<td>BNL MK-III (10x14)</td>
<td>2.2</td>
<td>6.4</td>
<td>2.1</td>
</tr>
<tr>
<td>OSU OMEGAI (11.5x15)</td>
<td>2.4</td>
<td>6.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Uppsala (9\text{\textfrac{3}{8}}x14)</td>
<td>1.5</td>
<td>7.2</td>
<td>----</td>
</tr>
</tbody>
</table>
Figure 3-15

Accepted spectrum: $^{11}\text{B}(p,\gamma)^{12}\text{C}$ @ $E_p = 151$ MeV
Figure 3-16
Resolution of NaI(Tl) spectrometer vs. \( E_\gamma \)

\[ R = 0.0633(E)^{-1/3} \]

- * double-subtracted
- • accepted (plastic disc. = 0.3 MeV)
- + accepted (plastic disc. = 1.3 MeV)
Figure 3-17
Count rate dependence on LED resolution
IV. RADIATIVE CAPTURE THEORY

1. Historical Background

The experimental results from \((p,\gamma)\) reactions on various nuclei in the energy region \(5 \text{ MeV} \leq E_p \leq 12 \text{ MeV}\), [Cohe55], showed that capture by the compound nucleus process (i.e. 'delayed' or '2-stage' process) failed to reproduce these experimental results. The compound nucleus process theory depends strongly on energy and mass number and decreases the cross-section sharply with an increase in either, while in the above data, no decreases in cross-section were found.

To explain the above experimental \((p,\gamma)\) cross-sections a phenomenological theory was developed by Lane and Lynn [Lane59], where "During the period of free motion in the mean nuclear potential field, the particle may radiate a photon and drop into a bound particle orbit." [Lane59], described 'Direct' or 'one-stage capture'. Wilkinson [Wilk56] showed the 'Direct' reaction to have a close relationship to the shell and optical models, where the initial state of the nucleus is described by the shell model. An incident nucleon \(\alpha'\), moving in the potential field of the target nucleus \(\beta'\) can make a direct transition to one of the unfilled particle states in the nucleus. Considering only E1 terms, since the photon wavelength is greater than the nucleon radius, along
with surface terms of the optical model potential, and electromagnetic transition probabilities, the cross-section for capture by a 'direct' transition is

\[
\sigma_{\alpha', \beta', \gamma} = \frac{8\pi \alpha^2 M}{3k' h^2} \sum (\frac{\epsilon}{\hbar c})^3 (\lambda + \lambda' + 1) |R^5/2I_{\lambda'} la'|^2 \quad (IV-1)
\]

where the various terms are fully described in reference [Lane59]. For rapid computation purposes a square well potential was used and the computation done in two regions \(r<R\) and \(r>R\) where \(R\) is the radius of the well. A problem in using a square well potential is that it can not reproduce the binding energy of individual particle orbits. The radiative proton capture experiments on \(^{142}\text{Ce}\) and \(^{209}\text{Bi}\) performed by Daly et. al. [Daly64], above a proton energy \(E_p=20\ \text{MeV}\), reported that the 'Direct' reaction process only predicts the magnitude of the cross-section if the 'Direct' reaction of [Lane59] also included a more realistic rounded potential [Daly64a].

In the region of the Giant Dipole Resonance (GDR), Brown and Clement et.al. [Brow64 and Clem65a], pointed out, that in addition to direct capture, a semi-direct capture will enhance the cross-section by a factor ~10. The process is called 'semi-direct' since the dipole state is itself an excitation made up of thousands of 'compound states', where this excitation arises from phase relations between these
compound states, which lasts long enough such that the protons are captured and the $\gamma$-ray emitted, in a time $\tau = \hbar / \Gamma_0$, before excitation can decay into compound states.

Lushnikov and Zaretsky [Lush65], using an infinite square-well potential, treated the giant resonance as a Fermi liquid in finite systems, for both non-interacting and interacting quasi-particles.

Clement et.al. [Clem65] treated the GDR as an excitation of collective vibrations. They view the GDR to consist of oscillations in the separation of the neutron and proton systems, such as oscillations of charge and mass density. During an oscillation of the density, the nuclear potential must also oscillate, producing a slightly deformed (non-spherical) potential with which the projectile particle interacts and can excite collective modes of the target.

Clement et.al. start with equation IV-1, obtained from [Lane59], and add a perturbed Hamiltonian, $H'$, in the initial state. Also, taking into account that the dipole state has a finite decay width, they obtain a cross-section with a Breit-Wigner form

$$\sigma = \sum_{L} \left( \frac{\pi \Gamma_{in} \Gamma_{\gamma}}{k^2 (\varepsilon_{L} - \varepsilon_{0})^2 + \Gamma^2 / 4} \right)$$

where the various terms are described in reference [Clem65].
Potokar [Poto73 and Poto73a] expanded on Clement et.al. by replacing the real nucleon-nucleus coupling interaction by a complex one having a real volume part and an imaginary surface peaked part. Potokar et.al. [Poto73a] states that "This Direct-semidirect theory (DSD) is formulated in detail only for those cases where the target nucleus has zero spin".

2. Present Formalism of the DSD Reaction

We denote the transition amplitude for the DSD reactions for radiative capture processes by

$$M = \langle \psi_f | H^\lambda | \psi_i \rangle$$  \hspace{1cm} (IV-3)$$

where $\psi_f$ and $\psi_i$ are the final and initial eigenstates of the nuclear hamiltonian $H$ with energies $E_f$ and $E_i$ respectively, and $H^\lambda$ is the electromagnetic interaction hamiltonian which acts as a transition operator for the creation of a photon with energy $E_\gamma = E_i - E_f$ and helicity $\lambda$. Employing the projection operator formalism [Poto80 and Blat84], let $P$ be a projection operator which projects, from the space of the nuclear hamiltonian, the part which corresponds to a nucleon coupled to the target ground state, and let $Q$ be the compliment of $P$. Equation IV-3 can be written as

$$M = \langle P\psi_f | H^\lambda | P\psi_i \rangle + \langle P\psi_f | H^\lambda | Q\psi_i \rangle + \langle Q\psi_f | H^\lambda | P\psi_i \rangle + \langle Q\psi_f | H^\lambda | Q\psi_i \rangle,$$  \hspace{1cm} (IV-4)
where the first term is the direct capture amplitude, the second and third terms comprise the initial and final semi-direct amplitudes, and the fourth is the nondirect or compound amplitude. $Q^\psi_i$ is approximated by a single state which represents a nucleon coupled to a coherent one-particle one-hole excitation of the target ground state (GDR). The third term of equation IV-4 is neglected since it is much smaller than the direct and initial semidirect operators [Brow64], along with the fourth term (nondirect), since the gamma-ray spectra of capture reactions are dominated by the $\gamma$-ray decays which populate single-particle or particle-hole states in light nuclei. This leads to the phenomenological direct-semidirect (DSD) model

$$M_{dsd} = \langle\psi_f|H^\lambda|\psi_i\rangle + \langle\psi_f|H^\lambda|Q^\psi_i\rangle. \quad (IV-5)$$

We define an effective transition operator $H^\lambda_{eff}$ [Blat84] which combines the direct and semi-direct terms into one, allowing equation IV-5 to be rewritten as

$$M_{dsd} = \langle\psi_f|H^\lambda_{eff}|\psi_i\rangle. \quad (IV-6)$$

This model is based on two assumptions: 1) the initial and final states in the capture process can be represented by states constructed from orthogonal one-nucleon configurations, and 2) the electromagnetic transition operator $H^\lambda$ can be represented as a sum of one-nucleon
operators, and this limitation should be considered since the transition operator $H^\lambda$ is known to contain two-body operators, due to the exchange of charged mesons between nucleons, which provide an important correction to the photoabsorption sum rule.

Potokar [Poto73 and Poto73a] reported that the cross-section for radiative capture of a fast nucleon from the initial state into the bound single-particle state of the final nucleus can be written as

$$\sigma_d \frac{dsd}{d\theta} = \sigma \left| F_{\text{eff}}(1'j';nlj) \right|^2 C^2 S$$  \hspace{1cm} (IV-7)

where $\sigma_d$ is the direct capture cross-section, $1'j'$ are the initial state quantum numbers, $nlj$ are the final state quantum numbers, $F_{\text{eff}}$ is an effective charge factor, and $C^2 S$ is the conventional spectroscopic factor.

The direct capture cross-section for nucleons capturing into bound states with quantum numbers $nlj$, for electric transitions of multipolarity $L$, is defined [Well82]

$$\sigma (\text{target spin } J_a) = \frac{2J_f+1}{2\pi E_f^2 (e^2/\hbar c) \ast} \left( \frac{2 \pi E_L \hbar (e^2/\hbar c) \ast}{(2J_a+1)(2J+1)} \right)^2$$

$$\frac{k_f}{E_a k_a} \left( \frac{(2J+1)B_L}{2J_a} \right)^2 |T|^2$$

where $L \geq J_a$.

where the terms are defined in reference [Well82].
Potokar gives the effective charge factor $F_{\text{eff}}$ by

$$F_{\text{eff}}(l'j';nlj) = 1 + \frac{1}{E - E_R + i\Gamma/2} \int_{u_{nlj}(r_0)}^{u_{nlj}(r_0)} h(r_0) u_{l'j'}(r_0) dr_0$$

where $u_{l'j'}(r_0)$ and $u_{nlj}(r_0)$ are the initial and final wave functions respectively of the nucleon being captured from a continuum state into a bound single-particle orbital, $h(r_0)$ is the form factor for the inelastic excitation of the collective state (GDR) by the incoming nucleon and $E_R$ and $\Gamma$ refer to the position and width of the resonance respectively. In the present work the form factor for E1 transitions was chosen as

$$h(r_0) \propto V_1 r f(r)$$

where $V_1$ is the real part of the symmetry term in the optical potential and $f(r)$ is the Wood-Saxon form factor.

Equation IV-7 can be parameterized [Blat84] in a Breit-Wigner form

$$\frac{d\sigma}{dE} = \left| 1 + \frac{\Delta E}{(E - E_R) + i\Gamma/2} \right|^2 C^2 S \sigma$$

where $E_R$ and $\Gamma$ are the energy and width of the GDR, $C^2 S$ is the spectroscopic factor attained from the literature, and $\Delta E$ is varied to fit the experimental cross-section.
Equation IV-7 was programmed in the computer code HIKARI written by Kitazawa [Kita80] and was used to perform the DSD-model calculations for polarized neutron capture on $^{13}$C [Wrig85], and for analysis of $(p,\gamma)$ reactions studied by our group [Haus87] and the $^{15}$N$(p,\gamma)^{16}$O reaction presented in chapter V. The position and width of the GDR along with the spectroscopic factor were obtained from the literature and used as input into the program HIKARI. The global optical model parameters (OMP) obtained from reference [Wats69] were used to calculate the radial wave functions of the captured particle as well as the continuum-state radial function for the incident proton.

3. Comparison of Models with Experiments: $E_\gamma < 100$ MeV

The DSD model was then critized by Fink et. al. [Fink72] by demonstrating the dependence of the integrated cross-sections upon the choice of the bound-state wave function. They fixed the final state to be the scattering state of their energy-dependent potential. Their best results of reproducing the experimental data were obtained using a square-well potential with non-orthogonal states. Calculations with orthogonal bound states lowered the cross-sections by a factor 3-5 at 40 MeV. Fink et. al. conclude that the cross-sections would change drastically if the scattering wave function is not chosen orthogonal to the bound state which should rule out plane-wave calculations.
Following up on the criticisms of Fink et. al. [Fink72], and the inability of the DSD theory to accurately reproduce the experimental data performed by Findlay et. al. [Find77] in the photon energy region $40 \text{ MeV} \leq E_\gamma \leq 100 \text{ MeV}$, Hebach et. al. [Heba76] decomposed the photonuclear transition matrix into different physical processes representing contributions from 1) the 'direct' shell-model transition with orthogonal wave functions, 2) the nucleon-nucleon correlations in the initial and final states, and 3) the gauge (or exchange) contributions where the electromagnetic field is coupled directly to the correlations between a proton and a neutron. They conclude that at energies above $E_\gamma = 80 \text{ MeV}$, the cross-section is dominated by the exchange contributions, and that $(\gamma,p)$ and $(\gamma,n)$ cross-sections are comparable in magnitude. To reproduce the $(\gamma,p)$ cross-sections they required an energy-independent local potential for the scattering state, while requiring orthogonality of the wave functions. Other problems were in considering a Wood-Saxon potential of the shell-model without a spin-orbit part, and in addition, the same shell-model was used for neutrons and protons while the Coulomb potential was neglected. A Yukawa potential was used for the exchange contributions in the cross-section calculations.
4. Model Comparisons with Experiments: $E_\gamma > 100$ MeV

The experimental cross-sections of $^{16}\text{O}(\gamma,p_0)$ reported by Mathews et al. [Math77], Leitch et al. [Leit85], and Turley et al. [Turl85] for $E_\gamma = 100 - 400$ MeV showed an unexpected energy dependence to the cross-section. In the energy region $E_\gamma = 40 - 100$ MeV, photonuclear (as well as proton capture) cross-sections decrease approximately exponentially with increasing energy. However, at $E_\gamma = 100$ MeV, the slope of the photonuclear cross-sections show a break (ie. change in slope).

Londergan and Nixon [Lond79] first proposed a direct quasi-free mechanism including virtual $\Delta(1232)$ excitations to describe the $(\gamma,p)$ reactions at medium energy. They use an approximate distorted-wave as a "modified plane wave", and do not include orthogonality corrections. In their paper they claim "although use of an energy-independent real central potential allows one to guarantee orthogonality of initial and final wave functions it provides an unrealistic description of the distortion of the outgoing proton." [Lond79]. They envision the $\Delta(1232)$ to be created by photon excitation of a nucleon in $(\gamma,p)$ reactions, where the intermediate state contains a virtual isobar and a one-hole state of the target nucleus. The isobar then decays into a $\pi + N$, and the $\pi$ is then absorbed by the residual nucleus to produce the observed final nuclear states. In the energy
region $E_p \approx 300$ MeV, the authors believe that the cross-section would be dominated by the isobar contribution. Comparison of their theory to $^{16}\text{O}(\gamma,p)$ data by Findlay et al. [Find77] provides good evidence for the effect of the $\Delta(1232)$ at the photon energies $E_\gamma \geq 100$ MeV, but also shows a deep minima in the energy distribution plots. This minima is produced by interference between the direct and isobar contributions [Mcde86].

Gari and Hebach [Gari81] decompose the transition matrix into three different contributions 1) shell model, 2) meson-exchange part, and 3) correlation (or nucleon-nucleon) part, where the correlation terms are dominated by the giant resonances of different multipoles that were first introduced by Brown [Brow64]. They use a Wood-Saxon type potential for the shell model without a spin-orbit part. The same potential is used for protons and neutrons and the Coulomb potential is neglected as with the procedure of Hebach et al. [Heba76]. Their results indicate that the correlation part of the transition matrix decreases with photon energies $\approx 1/E_\gamma$, indicating that at high energies the correlation terms are less significant than the meson exchange current. Problems with their work are that they consider electric multipoles up to order $L=4$ and neglect magnetic multipoles since they found their contributions to be only of a few percent. They criticize Londergan and Nixon
for not using orthogonal wave functions, which they use, but instead use a 'unrealistic deep' optical potential to describe the orthogonal states.

Theories proposed by Schoch [Scho78] using a quasi-deuteron model and Boffi et. al. [Boff82] using a non-relativistic distorted wave impulse approximation (DWIA) model in the description of knockout reactions induced by electromagnetic probes to discuss the problem of orthogonality have added to the number of microscopic processes that could be involved in these reactions.

The $^{16}\text{O}(\gamma, p_0)^{15}\text{N}$ experimental data performed by Turley et. al. [Tur185] at $E_\gamma = 196$ MeV with an angular distribution $22^\circ - 144^\circ$ and an energy distribution $E_\gamma = 100 - 400$ MeV by Leitch et. al. [Leit85], demonstrates that the above calculations of Gari and Hebach, Londergan and Nixon, Schoch, and Boffi et. al. either fail to reproduce the angular distribution or both the energy and angular distributions.

5. Recent Theoretical Models

Recent theories for intermediate energy photonucleon processes using different techniques have indicated improvements in reproducing the experimental data. Ludeking and Cotanch [Lude87] approached this problem using a coupled channel calculation based on a continuum shell model for photon energies in the region $E_\gamma = 50 - 400$ MeV. The authors diagonalize a 16-particle Hamiltonian in a model space.
spanned by products of continuum single-particle and bound states. Their model includes 1) antisymmetrization, 2) Pauli blocking, 3) all electric and magnetic transitions up to E11 and M9 (ie. to achieve convergence for the multipole expansion for the electromagnetic field), and 4) the complete effective two-body interaction for the description of the giant dipole resonance (ie. non-local, finite range interaction including spin, isospin, and tensor components). Further, the authors preserve the wave function orthogonality since "for photonuclear reactions nonorthogonal wave functions can generate sizeable differences between the density and current formulation for the electric transition operator." [Lude87]. The authors then include specific Δ degrees of freedom by treating the Δ⁺ and Δ⁰ equally with the nucleons (Δ-hole model). Their preliminary calculation with the introduction of the Δ isobar indicates approximately an order of magnitude increase in the cross-section in the region near the Δ threshold.

A collaboration of Van Orden and Picklesimer [Vano87] have formulated the (e,e'p) reaction using relativistic wave functions which can be modified to calculate (p,γ) analyzing powers since the virtual photon exchange in their theory could be used to calculate real photon emission.
A different approach performed by McDermott and Shepard [Mcde86] use the single particle quasi-free knockout mechanism (QFK), with various meson-exchange terms, and the use of the Dirac equation. The photocapture cross-section is given by

\[
\frac{d\sigma}{d\Omega} = \frac{2}{(4\pi)^2} m \frac{\varepsilon E_i + p^2 k}{\varepsilon_{\text{TOT}} p} \frac{|\langle \psi_f | r^0 J \cdot A | \psi_i \rangle|^2}{|S_{1j}|^2}, \quad \text{(IV-12)}
\]

which is rewritten as

\[
\frac{d\sigma}{d\Omega} = \frac{2}{(4\pi)^2} \frac{\varepsilon E_i + p^2 k \ 1}{\varepsilon_{\text{TOT}} p} \frac{S_{1j}}{2J_1+1} \sum_{lm} |J_{1jm}|^2, \quad \text{(IV-13)}
\]

where the current operator is defined

\[
J_{1jm} = \langle \phi_{1jm} | r^0 J \cdot A | \psi_{p,s} \rangle, \quad \text{(IV-14)}
\]

|S_{1j}|^2 is the spectroscopic factor, C^2 S, which appears as a multiplication factor for comparison of calculations to stripping reaction data, and the other terms are defined in reference [Mcde86]. To calculate the total cross-section, equation IV-13 must be summed over final helicities and averaged over initial spins. Evaluation of \( \psi_{p,s} \), the continuum wave function for direct capture, is a plane wave. The distorted wave impulse approximation (DWIA) is then used to calculate \( \psi_{p,s} \) due to distortions of the wave function by the strong nuclear forces of the target. The contributions
of the current operator are the direct capture, fig. 4-1a, and contributions involving pion exchange current, as shown in figure 4-1b.

Similarity of \((p,\gamma)\) and \((n,\gamma)\) cross-sections have posed problems for non-relativistic photocapture models, where the direct capture distorted wave calculation results in large differences between the two reactions because of the lack of electric charge on the neutron. The direct capture mechanism results in unequal cross-sections for these reactions in that it involves direct coupling to the electromagnetic field which breaks isospin symmetry. One method to solve this problem is to include the GDR where the photocapture process ejects a nucleon, either a proton or neutron with equal probability (ie. strong force is dominant), giving the neutron an "effective charge". Another method is the inclusion of pion exchange, where coupling through the pion field which is isovector, conserves isospin symmetry producing the same coupling strength for the neutron and proton.

Equation IV-13 was programmed in the computer code GAMMA written by J. McDermott [Mcde86] and was used to perform radiative capture analysis studied by our group [Haus87], and in chapter V.
Figure 4-1

Feynman diagrams for direct capture (a) and Pion exchange (b) for \((p,\gamma)\) reactions.
V. RADIATIVE PROTON CAPTURE REACTION $^{15}\text{N}(p,\gamma)^{16}\text{O}$

The Direct-Semidirect (DSD) phenomenological model [Blat84] along with other theoretical models [Gari81, Lond79, Lude87, and Mcde86] presented in chapter IV are all based on the shell model using a single particle, single hole configuration. These models greatly simplify for the doubly magic $^{16}\text{O}$ nucleus.

This chapter describes the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ radiative proton capture reaction experiment and analysis for comparison with the DSD model and the theoretical work performed by J. McDermott [Mcde86] using a single particle reaction along with meson exchange terms.

1. Experimental Description

The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ experiments were performed using the NaI spectrometer OMEGA I, described in references [Kova78, Rack84a, and Kim86], located in the gamma cave, (low intensity room), at the Indiana University Cyclotron Facility (IUCF), Bloomington, Indiana.

The OMEGA I spectrometer was constructed by M. Kovash [Kova78] and modified later [Rack84a] by the replacement of a single 10"$\phi$ x 12" long NaI(Tl) crystal while the older
crystal was composed of two cylindrical sections cemented together. When the crystals were exchanged, the lithium shield was removed since it had completely oxidized. The single NaI(Tl) crystal has seven RCA 8575 2" diameter (12 dynodes inline structure) phototubes located in a hexagonal array on one end. The phototube bases are transistorized voltage regulated. The crystal also has three green Light Emitting gallium phosphide Diodes (LED's) located on the rear surface, the same surface as the phototubes, for use in gain stabilization. The resolution of this spectrometer is about 2.2% @ $E_\gamma = 40$ MeV.

The NaI(Tl) crystal is covered by a 10 cm thick NE110 plastic scintillator and subtends a solid angle of 90% of $4\pi$ which serves as an anticoincidence shield. The annulus contains six Amperex 58DVP phototubes mounted on its rear face and the front shield contains three Amperex 56DVP phototubes mounted on its top surface.

The background and cosmic-ray shielding is composed of a wall of lead bricks, 5" thick in the front of the detector, 4" in the walls and roof, and 2" on the bottom. The thermal neutron shielding is composed of 3/8"-thick slabs of polyester resin mixed with boron carbide ($B_4C$), located external to the lead shielding, and provides an attenuation of approximately $10^9$ for thermal neutrons.
Gain stabilization techniques were used to remove the effects of long- and short-term variations in the gain of the crystal's phototubes. An active gain stabilization system was used as described fully in references [Kova78, Kova79], which held the gain constant within 0.7% during our extended runs (as long as 8 hours).

The electronics for signal processing and pileup rejection were similar to that described in chapter III, except the coincidence between the plastic scintillator shield and the NaI(Tl) crystal was performed by a hardware coincidence.

Since the linear signal path was DC-coupled to prevent baseline shifts under high count rates, any AC pickup in the signals must be eliminated. The detector assembly was electrically isolated from earth ground in the gamma cave, and power to the electronics associated with the detector was supplied via an isolation transformer, with the addition of a 3-prong-to-2-prong adapter, which left the ground of the detector floating. Use of our own signal cables, along with a heavy copper cable to act as a ground strap between the control room and the detector, allowed us to prevent any ground-loop problems. The signal processing electronics were powered through an isolation transformer located in the base of the computer data station in the control room. To further isolate our equipment from any
spurious grounds, we used the computer's remote CAMAC-crate system. This system had an optical link between the CAMAC crate and the computer to limit any AC pickup. Small-transformer boxes were placed on the linear signals at the input to the ADC as an added precaution.

Data was taken using the data-acquisition programs "DERIVE" and "RAQUEL", both designed to run on IUCF's Harris/Datacraft (192KB memory) minicomputers. The computer systems included CAMAC control and input/output capability, along with event-mode recording. The data was recorded on 9-track magnetic tape during the runs, and the resultant histograms were recorded onto a 7-track "dump" tape at the end of each series of runs. The details to get readable tapes into SPEC format required at our lab is given in reference [Rack84a].

1a. Gas Targets

The $^{15}$N gas target cell was constructed in a hollow brass cylinder, 0.95" long and 0.75" outside diameter, with a wall thickness of 0.032" as described in reference [Rack84a]. Havar foil is epoxied to the ends of the brass cylinder for windows. The gas cell was typically pressurized to 30psig (45psia).

The $^{15}$N gas used was purchased from Monsanto Research Corporation, Miamisburg, Ohio; the gas is rated at >99% pure.
After the gas cell was installed in the target chamber, a closed-circuit TV camera was set up to monitor the pressure gauge of the target gas cell from the control room, so that appropriate measures could be taken in the event of any slow leaks, or rupture of the foils.

For background runs, to account for any contribution due to the Havar foils and to properly account for any geometry-dependent effects, a mechanical pump was continuously connected to the cell.

1b. Polarization and Polarimeter

A polarized $^{15}\text{N}({\bar{p}},\gamma)^{16}\text{O}$ reaction was performed; the 385xx-series runs were taken using the cyclotron's polarized ion source operated in a fast spin-flip mode. The fast spin-flip mode periodically reverses between spin-up and spin-down, with data acquisition synchronized with the state of the spin; in our work, the time between spin-reversals was set at 60 seconds. Two copies of each histogram and scalers were defined by the program RAQUEL, with data accumulated into one set or the other depending on the spin state. At the end of a polarized run, the data were written to the dump tape as two separate files, spin-up with sequence number 1, then spin-down with sequence number 2.
The polarimeter was placed in beam line #2, between the injector and main cyclotron, and contained a $^4\text{He}$ gas cell which could be moved into and out of the proton beam under the command of the cyclotron control system. To measure the polarization, a pair of ORTEC solid-state detectors were mounted in a horizontal plane at an angle $112^\circ$ from the beam direction. The polarimeter chamber also included a set of collimation slits which allowed the operator to steer the beam through the center of the gas cell. The polarimeter was retracted from the beam path when $(p,\gamma)$ measurements were taken. The electronics used for polarization measurements is shown in figure 5-1. A pulser was included for measurements of dead-time in the two detectors.

The analyzing power for $^4\text{He}(p,p)^4\text{He}$ was calculated from phase shifts for an incident beam energy and lab angle of the detectors; the value used for this series of runs was $A_y, p = 0.948$. The beam polarizations were measured after every few runs to account for any variations of the polarization with time. From the pulse-height spectra accumulated by the left and right solid-state detectors of the polarimeter, figure 5-2, the areas of the proton elastic-scattering and pulser peaks above background were calculated, using the program GAUFIT [Konz82]. The polarization ($P$) of the beam is defined by
Figure 5-1: Schematic of polarimeter electronics
Figure 5-2
Polarimeter proton elastic-scattering spectrum
\[ \sigma_L = \text{Area}_{\text{elastic},L} \left( \frac{\text{Pulser scaler}}{\text{Area}_{\text{pulser},L}} \right) \]
\[ \sigma_R = \text{Area}_{\text{elastic},R} \left( \frac{\text{Pulser scaler}}{\text{Area}_{\text{pulser},R}} \right) \]

\[ p = \frac{1}{A_{\gamma,p}} \cdot \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \quad (V-1) \]

Noise on the right polarimeter spectrum remained, figure 5-2b, even after an interchange of electronics and replacement of the right detector. GAUFIT was used with background subtraction to fit the right proton elastic-scattering peak. A variance of 15% was calculated for \(|P^+|\) versus \(|P^−|\), while for a good polarization run this is approximately 5%. Due to the poor operation of the polarimeter, \(|P^+|\) is set equal to \(|P^−|\) for the 385xx runs. The beam polarization starts in spin-down and then switches to spin-up, suggesting that the spin-up polarization \(|P^+|\) should give a lower bound on spin-down \(|P^−|\) [Bach85].

2. Preparation of Spectra

The first step in analyzing the spectra is to transfer the data from the dump tape to the disk files on the Data General S/130 minicomputer. The data on the blocked dump tape was translated into a SPEC format by the program IUCFTAPE [Rack81], which records the spectra into a format usable within the analysis programs.

A table of the experimental runs which are used in the analysis is listed in Table 8. The runs are ordered by incident proton energy \(E_{\text{INC}}\), and the detector's lab...
angle. The run number, "Run ID", is given for each spectrum along with target thickness, target angle, and $E_p$, the average beam energy in the target. The average beam energy in the target ($E_p$) is calculated by the program LOSTENERGY as described in chapter III. Note that the calculation of $E_p$, the effect of the beam passing through one layer of the 0.25-mil Havar foil (composed of 17.9% Fe, 42.5% Co, 20.0% Cr, 13.0% Ni, 2.8% W, and trace amounts of Mn, Mo, C, and Be) be subtracted from $E_{\text{INC}}$ before computing $E_p$. Also note that each of two runs listed in Table 8 (710 + 711, C17 + C18A) was actually recorded as two separate but consecutive runs. For improved statistics these runs were added together before analysis, and for identification each pair of runs will be identified by the RUN ID of the first run of the pair.

The gamma-ray spectrum also included a background produced by the proton beam striking the Havar foil capping the gas cell. To account for this, for each beam energy and detector angle, a spectrum was taken with the $^{15}$N gas evacuated from the gas cell, producing a Havar only background spectrum. To remove the background contribution to the spectrum, the number of counts in the foil spectrum was normalized by the ratio of the integrated charge of the gas-plus-foils run to that of the foils-only run. The accepted normalized foils-only spectrum was then subtracted
### Table 8
Experimental Runs ($^{15}$N Target)

<table>
<thead>
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<th>Einc (MeV)</th>
<th>Run ID</th>
<th>Lab Angle</th>
<th>Thickness (mg/cm$^2$)</th>
<th>$E_p$ (MeV)</th>
<th>Target Angle</th>
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<tr>
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<td>38358</td>
<td>60°</td>
<td>8.9</td>
<td>89.34</td>
<td>0°</td>
</tr>
</tbody>
</table>

### Table 9
Gas Target and Associated Background Foil Runs

<table>
<thead>
<tr>
<th>Gas Run ID</th>
<th>Foil Run ID</th>
<th>Charge Normalization</th>
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<tr>
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<td>38546</td>
<td>38544</td>
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</tr>
<tr>
<td>710+711</td>
<td>718+719</td>
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<td>18322</td>
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<td>38528</td>
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</tr>
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<td>38518</td>
<td>38530</td>
<td>0.921</td>
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<tr>
<td>38504</td>
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<td>1.255</td>
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<td>3.747</td>
</tr>
<tr>
<td>38509</td>
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<td>38358</td>
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<td>1.606</td>
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from the accepted gas-plus-foils spectrum; this subtracted accepted spectrum was used in the fitting process. This process was performed using the program GAUFIT [Konz82]. Table 9 lists the Run ID's of the gas-plus-foils spectra with their associated foils-only spectra and the normalization factors used in the subtraction process. Figure 5-3 shows an accepted gamma-ray spectrum of \(^{15}\text{N}(p,\gamma)^{16}\text{O}\) plus foils along with its foils-only background accepted spectrum.

A polarized proton beam was used to acquire the spectra for the 385xx runs. The data files for each of the runs contain two complete sets of spectra and scalers, one for 'spin-up' polarization, and one for 'spin-down'. To calculate the total cross-section, 'spin-up' plus 'spin-down', the background subtracted accepted spectrum for the individual spin polarizations were added channel by channel using the program GAUFIT. The scalers were also summed and used for further calculations. Due to the moderate resolution of the NaI spectrometer, no horizontal shift was required in either spectrum to align the gamma peaks before summing the accepted polarized spectra.

3. Spectra Fitting

The NaI(Tl) spectrometer response function to monoenergetic gamma-rays is approximated by a gaussian peak matched to a decaying exponential tail on the low energy
Figure 5-3

$^{15}\text{N}(p,\gamma)^{16}\text{O}$ gamma-ray spectrum with foil-background spectrum (dash line)
side; this tail extrapolates with a flat background towards zero energy, with the details of the response function located in appendix B.

The parameter $S_2$, the resolution of the highest energy gamma-ray in the accepted spectrum, was determined using the program GAMMASPEC [Rack84]. Then a calibration of the spectrum, channel/Mev and offset, was calculated and determined as discussed in greater detail in reference [Kim86], obtaining a linear calibration formula $E_\gamma = (\text{offset} + \text{channel} \#)/(\text{channel}/\text{MeV})$.

The program KINMAT [Rinc81], a relativistic kinematics program, was then used to determine the gamma-ray energy in the lab reference frame from the proton beam energy and the final energy levels of the resultant reaction nucleus. When these gamma-ray energies for transitions to known energy states been calculated along with the linear energy/channel calibration, the peaks in the accepted spectrum can be fitted using the program GAMMASPEC [Rack84]. This program is used for fitting the various peaks of the spectrum with all parameters fixed allowing only the height of the peaks to vary. After an initial fit, the linear calibration is allowed to vary to find the best fit to all peaks of interest, from which the areas of the peaks are determined as discussed in appendix B and reference [Rack84a]. Table 10 lists for each RUN ID, $E_p$,
Table 10

Energy calibration and resolution results: $^{15}N(p,\gamma)^{16}O$

\[ S_3 = 0.28404 \quad S_4 = 0.13567 \quad S_5 = 0.97375 \]

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>Lab Angle</th>
<th>Run ID</th>
<th>Offset MeV</th>
<th>Channel Offset</th>
<th>$S_2$</th>
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<td>85.99</td>
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<tr>
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<td>53.738</td>
<td>7.957</td>
<td>172.290</td>
</tr>
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<td>3.094</td>
<td>83</td>
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<td>2.393</td>
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offset, channel/Mev, and lab angle along with the parameters $S_2, S_3, S_4, S_5$ used in the program GAMMASPEC.

4. Corrections to Fitted Peak Areas

The corrections to the fitted peak areas consists of four multiplicative corrections; 1) a resum correction to add back those events in which energy escaped from the NaI(Tl) crystal into the plastic scintillator anticoincidence shield, 2) a pileup correction in which piled-up events where rejected by the signal processing electronics, 3) a Time-of-Flight (TOF) correction for any gamma-rays which fall outside of the TOF window due to timing shifts, and 4) a correction for dead time in the electronics and data-acquisition system.

The resum correction factor is calculated with the program IURESUM; the procedure and details are given in references [Kova78, Jens84, and Kim86]. This correction factor ranges normally between 1.5 and 2.5 but increases up to 4.5 depending upon the proton energy and the plastic shield discriminator threshold. This resum correction factor is the most important and constitutes the largest correction and uncertainty in calculating the cross-section.

The pileup correction typically increased the peak area approximately 5%. Since the signal processing electronics rejects overlapping pulses to preserve the line
shape of the spectrum, those events that were piled up must be compensated in the cross-section calculation.

A TOF correction is calculated with the program GAUFIT, wherein some of the gamma-rays were rejected because they occurred outside the gamma-ray window. This correction is only of a few percent, and due to the improved timing of the cyclotron's RF, the latter runs did not require this correction.

Dead-time correction was used during some old runs when the scalers were constantly read. When an event trigger was placed in the electronics, a busy signal on the order of the dead time of the CAMAC electronics disabled the scalers during the read and process command of the CAMAC modules, thus not requiring this correction to be calculated. This correction is not necessary for the present electronics configuration as described in chapter III.

The correction factors for each run are shown in Table 11 and the details of the above corrections appears in references [Jens84 and Kim86].

5. Results of Fits

A typical background spectrum, using the empirical line shape, of the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction is shown in figure 5-4, Run ID R425, along with its fitted states. The states of interest are listed in Table 12. Gamma-rays from proton
### Table 11

Peak Area Correction Factors: $^{15}$N(p,γ)$^{16}$O

<table>
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<th></th>
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<th></th>
<th></th>
<th></th>
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<td>1.83</td>
<td>1</td>
<td>1.025</td>
<td>2.029</td>
</tr>
</tbody>
</table>
Figure 5-4
Gamma-ray spectrum with fitted states:
$^{15}\text{N}(p,\gamma)^{16}\text{O}$ @ $E_p = 21.8$ MeV
captures into the closed sub-shell nucleus $^{16}$O, labeled $\gamma'_{13}$, are a composite of three unresolved states ($E_X = 12.53$ MeV, $2^-; E_X = 12.9686$ MeV, $2^-; E_X = 13.254$ MeV, $3^-$) due to the insufficient resolution of the NaI spectrometer. The same situation is true for the cross-section calculations of $\gamma_{5,6}$ ($E_X = 8.872$ MeV, $2^-; E_X = 9.632$ MeV, $1^-$) states.

Table 12

<table>
<thead>
<tr>
<th>Gamma Name</th>
<th>$J^\pi, T$</th>
<th>$E_X$ (MeV)</th>
<th>$\Gamma$ (state width)</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>$3^-; 0$</td>
<td>6.1304</td>
<td>0</td>
</tr>
<tr>
<td>$\gamma_5$</td>
<td>$2^-; 0$</td>
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<td>0</td>
</tr>
<tr>
<td>$\gamma_6$</td>
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<td>510</td>
</tr>
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<td>0.8</td>
</tr>
<tr>
<td></td>
<td>$3^-; 1$</td>
<td>12.9686</td>
<td>1.9</td>
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<tr>
<td></td>
<td>$3^-; 1$</td>
<td>13.254</td>
<td>21</td>
</tr>
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</table>

After the determination of the peak areas and the correction factors, the differential cross-sections were calculated given by equation V-2,

$$\frac{d\sigma}{d\Omega} = \frac{\text{Peak Area} \cdot R}{N_p \cdot N_t \cdot d\Omega} \quad (V-2)$$

where $R$ is the correction factor of the peak area, $N_p$ is the number of the incident protons, $N_t$ is the number of target nuclei, and $d\Omega$ is the detector solid angle.
formula to calculate these terms are given in reference [Jens84]. For all runs the solid angle was $\Omega = 9.159$ msr, except for run ID 38358, $E_p = 89.3$ MeV, the detector was located 111.8 cm from collimator to target position (producing a solid angle $\Omega = 4.849$ msr) in order to sufficiently separate the neutrons from gamma-rays produced by the target in the time-of-flight spectrum.

The uncertainties in the cross-sections come primarily from two sources; 1) the uncertainty in the resum calculation, and 2) the uncertainty in the tail of the line shape used to fit the spectrum. Other uncertainties are associated with charge collection, solid angle, and thickness and uniformity of the target, and are considered to be small compared to the two major sources given above. A thorough analysis of the uncertainties is given in reference [Rack84a]. We set our cross-section uncertainty to $\pm 20\%$ of the calculated cross-section. The energy dependence and angular distribution cross-sections are listed in table 13 and 14 respectively.

For the polarized proton beam run, Run ID 385xx, analyzing powers were calculated for captures to the ground and excited states of interest in the product nucleus $^{16}O$. After the polarization $P_1$ and $P_\perp$ have been calculated, as discussed in section V-1b, the analyzing power for a gamma peak can be determined. Given a peak with areas $A_1$ and $A_\perp$
### Table 13

<table>
<thead>
<tr>
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<th>$(\gamma_0)$</th>
<th>$(\gamma_2)$</th>
<th>$(\gamma_{5,6})$</th>
<th>$(\gamma_{13,1})$</th>
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<td>$7.860\pm1.572$</td>
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### Table 14

<table>
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<th>$(\gamma_{5,6})$</th>
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<td>$0.188\pm0.037$</td>
<td>$0.582\pm0.116$</td>
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<td>$0.788\pm0.157$</td>
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<td>$0.374\pm0.074$</td>
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<td>$0.443\pm0.088$</td>
<td>$1.826\pm0.365$</td>
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<tr>
<td>60°</td>
<td>$0.341\pm0.068$</td>
<td>$1.220\pm0.244$</td>
<td>$0.473\pm0.095$</td>
<td>$2.247\pm0.449$</td>
</tr>
<tr>
<td>75°</td>
<td>$0.265\pm0.053$</td>
<td>$1.095\pm0.219$</td>
<td>$0.676\pm0.135$</td>
<td>$2.126\pm0.425$</td>
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<td>90°</td>
<td>$0.176\pm0.035$</td>
<td>$0.593\pm0.118$</td>
<td>$0.290\pm0.058$</td>
<td>$1.356\pm0.271$</td>
</tr>
<tr>
<td>120°</td>
<td>$0.031\pm0.006$</td>
<td>$0.149\pm0.029$</td>
<td>$0.187\pm0.037$</td>
<td>$0.442\pm0.088$</td>
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Table 15

$^{15}\text{N}(p,\gamma)^{16}\text{O}$

Analyzing powers vs. Lab Angle
($E_p = 49.69$ MeV)

<table>
<thead>
<tr>
<th>Lab Angle</th>
<th>$P_t^+$</th>
<th>$P_t^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>+0.718</td>
<td>-0.718</td>
</tr>
<tr>
<td>45°</td>
<td>+0.718</td>
<td>-0.718</td>
</tr>
<tr>
<td>60°</td>
<td>+0.743</td>
<td>-0.743</td>
</tr>
<tr>
<td>75°</td>
<td>+0.729</td>
<td>-0.729</td>
</tr>
<tr>
<td>90°</td>
<td>+0.729</td>
<td>-0.729</td>
</tr>
<tr>
<td>120°</td>
<td>+0.705</td>
<td>-0.705</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lab Angle</th>
<th>$A_Y(\gamma_0)$</th>
<th>$A_Y(\gamma_2)$</th>
<th>$A_Y(\gamma_{5,6})$</th>
<th>$A_Y(\gamma_{13})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>0.053±0.138</td>
<td>0.035±0.091</td>
<td>0.353±0.165</td>
<td>0.144±0.078</td>
</tr>
<tr>
<td>45°</td>
<td>0.473±0.126</td>
<td>-0.069±0.072</td>
<td>0.310±0.103</td>
<td>-0.202±0.055</td>
</tr>
<tr>
<td>60°</td>
<td>0.089±0.082</td>
<td>0.015±0.043</td>
<td>0.036±0.067</td>
<td>0.112±0.031</td>
</tr>
<tr>
<td>75°</td>
<td>-0.125±0.100</td>
<td>0.173±0.047</td>
<td>0.048±0.058</td>
<td>0.252±0.036</td>
</tr>
<tr>
<td>90°</td>
<td>-0.115±0.138</td>
<td>0.173±0.064</td>
<td>0.819±0.065</td>
<td>0.192±0.039</td>
</tr>
<tr>
<td>120°</td>
<td>0.751±0.292</td>
<td>-0.473±0.122</td>
<td>0.028±0.116</td>
<td>0.230±0.075</td>
</tr>
</tbody>
</table>
from the spin-up and spin-down beams, the analyzing power $A_y$ is calculated by

\[
A_y = \frac{A^+ - A^-}{(A^+|P^+| + A^-|P^-|)}
\]

and the uncertainty in the analyzing power is discussed in reference [Rack84a]. Table 15 lists the angular dependence of the analyzing powers of the interested states.

6. Analysis Programs (HIKARI and GAMMA)

The optical model parameters (omp) are input into HIKARI (DSD calculation) for calculating the continuum as well as the bound-state wave functions. To study the large energy range of the cross-sections, a global omp set from Watson et. al. [Wats69] was chosen to study the $^{15}N(p,\gamma)^{16}O$ reaction. This global omp of Watson et. al. were obtained from the optical model analysis of nucleon scattering from lp-shell nuclei in the proton energy region $E_p = 10 - 50$ MeV.

Along with the global omp set, other inputs into HIKARI are the position and width of the GDR and the spectroscopic factor, all obtained from the literature.

The program GAMMA, developed by J. McDermott [Mcde86] and discussed in section IV-5, considers a single particle reaction with meson exchange terms using the Dirac equation. Input into GAMMA comprises the shell model using
a 1p-1h configuration along with spectroscopic factors obtained from the literature.

The shell model parameters for the bound-state are determined from electron elastic scattering form factors which are obtained from fits of the experimental data acquired in the literature. States in the continuum use an impulse approximation with charge density distribution parameters obtained from reference [Adnt74] to generate the optical potential. From these calculations the bound-state as well as the continuum wave functions are determined, as completely explained in reference [Mcde86].

7. Results: $^{15}\text{N}(p,\gamma)^{16}\text{O}$

7a. $^{15}\text{N}(p,\gamma_0)^{16}\text{O}$

Energy dependence of the $^{15}\text{N}(p,\gamma_0)^{16}\text{O}$ differential cross-sections at a detector angle of 60° is shown in figure 5-5. Using detailed balance from the $^{16}\text{O}(\gamma,p_0)^{15}\text{N}$ reaction reported by Baglin et. al. [Bagl69], the data in the vicinity of the GDR centered at $E_p = 11.0$ MeV are also plotted as well as the cross-sections from the $^{16}\text{O}(\gamma,p_0)^{15}\text{N}$ reaction reported by Findlay et. al. [Find77] at $E_\gamma = 60, 80,$ and 100 MeV.

The programs HIKARI (dash) and GAMMA (solid), figure 5-5, use the single particle-hole configuration $(1p_{1/2}^+)(1p_{1/2}^-)$, where the ground state of $^{16}\text{O}$ is a hole in the $1p_{1/2}$ orbital. The particle-hole configurations for
the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reactions were obtained from $^{15}\text{N}(^{3}\text{He},d)^{16}\text{O}$ stripping reactions acquired from Fulbright et. al. [Fulb69]. The spectroscopic factor of 1.3 was obtained from the theoretical work of Zuker et. al. [Zuke68] for the HIKARI calculation and the program GAMMA used a spectroscopic factor of 1.85 acquired from [Fulb69]. The widths and positions of the various components of the giant resonance are E1 ($E_\gamma = 22.441$ MeV, $\Gamma_\gamma = 3.0$ MeV), E2 ($E_\gamma = 26.0$ MeV, $\Gamma_\gamma = 4.0$ MeV), and E3 ($E_\gamma = 48.0$ MeV, $\Gamma_\gamma = 10.0$ MeV) were obtained from references [Earl67, Hann74, and Gari81] respectively and are inputs into the program HIKARI along with a spin-orbit potential $V_{\text{SOPT}} = 5.5$ MeV. Also in figure 5-5 is a calculation of HIKARI with the optical model potential (omp) fixed (energy-independent omp) (dash-dot) at the position of the GDR, $E_p = 11.0$ MeV. Table 16 lists the percent contribution of each multipole to the total cross-sections for the two analysis programs HIKARI and GAMMA, with a comparison to the theory performed by Hebach et. al. [Heba76], which is discussed in section IV-3. Note the program GAMMA combines the E3 and E4 components.

The angular distribution of the differential cross-sections and the analyzing powers angular distribution at a proton energy $E_p = 49.69$ MeV is plotted in figures 5-6(a,b) respectively. Using detailed balance from $^{16}\text{O}(\gamma,p_0)^{15}\text{N}$ at
a gamma-ray energy $E_\gamma = 60$ MeV, reported by Findlay et. al. [Find77], their angular distribution is also plotted in fig. 5-6a. The gamma-ray energy from $^{15}$N(p,$\gamma_0$)$^{16}$O reaction at a proton energy $E_p = 49.69$ MeV produces gamma-rays in the energy region $59.5$ MeV $\leq E_\gamma \leq 57.9$ MeV for angles $30^\circ \leq \theta_{\text{lab}} \leq 120^\circ$. Due to the lower gamma-ray energy obtained from the (p,$\gamma$) reaction at $E_p = 49.69$ MeV, the angular differential cross-sections from (p,$\gamma$) shows a slightly higher cross-section than obtained from Findlay et.al. The $\theta_{\text{lab}} = 30^\circ$ data point for all $^{15}$N(p,$\gamma$)$^{16}$O angular distribution plots (plotted as an open circle) shows a lower cross-section than is calculated with the analysis programs. To obtain the $30^\circ$ data, the upstream target position was used as described in reference [Rack84a], and the proton beam refocused for the new target position, changing the amount of charge collected by the Faraday cup. The correct procedure is to position the proton beam such that it is centered in the upstream target position, and no refocus of the beam is performed. This method keeps the geometry of the beam, target, and Faraday cup constant throughout the experiment. HIKARI (dash) and GAMMA (solid) both reproduce the angular cross-sections, fig. 5-6a, in the mid angular range while for extreme forward and back angles the calculation by GAMMA gave an improved reproduction of the data.
Figure 5-5

Differential cross-sections for $^{15}\text{N}(p,\gamma)^{16}\text{O}$ as a function of energy at $\theta_{\text{lab}} = 60^\circ$. HIKARI DSD calculation omp energy-dependent (dash line), HIKARI DSD calculation omp energy independent (dash-dot), GAMMA calculation (solid).
Table 16

Contributions (in %) of different electric multipoles to the total cross-section for the $^{15}$N($p,\gamma$)$^{16}$O reaction.

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>Electric Multipole</th>
<th>Hebach et.al.</th>
<th>GAMMA</th>
<th>(omp fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.5</td>
<td>E1</td>
<td>89.5</td>
<td>82.1</td>
<td>86.7</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>10.0</td>
<td>15.8</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>0.5</td>
<td>2.2</td>
<td>0.3</td>
</tr>
<tr>
<td>61.9</td>
<td>E1</td>
<td>78.3</td>
<td>71.5</td>
<td>63.9</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>18.9</td>
<td>22.4</td>
<td>33.1</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>2.6</td>
<td>6.1</td>
<td>3.0</td>
</tr>
<tr>
<td>82.0</td>
<td>E1</td>
<td>65.2</td>
<td>67.1</td>
<td>43.1</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>26.2</td>
<td>23.0</td>
<td>46.5</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>7.6</td>
<td>9.8</td>
<td>10.5</td>
</tr>
<tr>
<td>100.0</td>
<td>E1</td>
<td>60.8</td>
<td>65.3</td>
<td>33.8</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>24.0</td>
<td>22.2</td>
<td>42.9</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>12.2</td>
<td>12.5</td>
<td>23.2</td>
</tr>
</tbody>
</table>
Figure 5-6

Angular distribution (a) and Analyzing power angular distribution (b) for \(^{15}\text{N}(p,\gamma)\,^{16}\text{O}\) @ \(E_p = 49.69\) MeV. HIKARI DSD calculation omp energy dependent (dash) and GAMMA calculation (solid).
The analyzing power angular distribution, fig. 5-6b, shows calculations from HIKARI (dash) and GAMMA (solid). The HIKARI (DSD) calculation shows a better agreement to the data than the GAMMA calculation. The E3 (octupole) component was not incorporated in HIKARI for the analyzing power calculations due to the large oscillations it produces at back angles. The data at $\theta_{\text{lab}} = 120^\circ$ for the analyzing power distribution was not plotted due to the very low statistics, approximately one count in the peak in the background subtracted accepted spectrum, producing a very large positive unreliable analyzing power.

7b. $^{15}\text{N}(p,\gamma)^{16}\text{O}$

The energy dependence of the differential cross-sections at $\theta_{\text{lab}} = 60^\circ$ is shown in figure 5-7. The data in the region of the GDR centered at $E_p = 16.0$ MeV is obtained from the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction reported by Chew et. al. [Chew77]. The $\gamma_1$ excited state ($E_x = 6.05$ MeV, $J^\pi = 0^+$) was not included in these fits since the $p + ^{15}\text{N}$ reaction channel only supplies 1p-1h states, whereas the $E_x = 6.05$ MeV(0+) state is predominately 4p-4h, so states that decay to it must be 3p-3h, 4p-4h or 5p-5h [Chew77].

The programs HIKARI (dash) and GAMMA (solid), fig. 5-7, use the single particle-hole configuration $(1d_{5/2}^+)(1p_{1/2}^-)$. HIKARI uses a spectroscopic factor of 0.32 and GAMMA employed a spectroscopic factor of 0.64 (2 x
GAMMA is a relativistic calculation and spectroscopic factors are calculated from a comparison of stripping reaction data and a non-relativistic calculation, suggesting that a spectroscopic factor for GAMMA would not be of equal value as that used in HIKARI. The positions and widths of the components of the giant resonance are $E_1 (E_\gamma = 20.998 \text{ MeV}, \Gamma_\gamma = 2.75 \text{ MeV})$ obtained from $^{15}\text{N}(p,\gamma_1)^{16}\text{O}$ reaction performed by Anghinolfi et. al. [Angh83] and the $E2$ component $(E_\gamma = 28.87 \text{ MeV}, \Gamma_\gamma = 1.50 \text{ MeV})$ from $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction performed by Sandorfi et. al. [Sand81]. The cross-sections from the data by Anghinolfi et. al. [Angh83], $^{15}\text{N}(p,\gamma_2)^{16}\text{O}$, were not plotted due to the different response function their group uses to ascertain peak areas. Their response function (line shape) does not include a low energy tail which extends to zero energy [Corv81 and Taiu83], as used by our group and shown in appendix B. Not including the low energy tail, lowers their cross-section relative to other calculations by 20 - 30%, which is approximately the area under the low energy tail. A spin-orbit potential $V_{\text{SOPT}} = 5.5 \text{ MeV}$ was input into HIKARI.

The angular distribution of the differential cross-sections and the analyzing power angular distribution at a proton energy $E_p = 49.69 \text{ MeV}$ is plotted in figures 5-8(a,b) respectively. HIKARI (dash) and GAMMA (solid) calculations
Figure 5-7

Differential cross-sections for $^{15}\text{N}(p,\gamma_2)^{16}\text{O}$ as a function of energy at $\theta_{\text{lab}} = 60^\circ$. HIKARI DSD calculation omp energy dependent (dash) and GAMMA calculation (solid).
Angular distribution (a) and Analyzing power angular distribution (b) for $^{15}\text{N}(p,\gamma)^{16}\text{O}$ @ $E_p = 49.69$ MeV. HIKARI DSD calculation omp energy dependent (dash) and GAMMA. calculation (solid).
are shown with GAMMA reproducing the angular distribution cross-sections better than HIKARI as also shown for the $^{15}$N(p,γ)${}^{16}$O data. The analyzing powers angular distribution plot, fig.5-8b, shows HIKARI (without an E3 component) reproducing the data more reliable than GAMMA. The data point at $\theta_{\text{lab}} = 120^\circ$ for the analyzing power measurement was not used due to its unreliable large negative analyzing power measurement.

7c. $^{15}$N(p,γ5,6)${}^{16}$O

Because the resolution of the NaI(Tl) spectrometer was insufficient and could not separate the two states $\gamma_5$ ($E_x = 8.872$ MeV, $J^\pi = 2^-$) and $\gamma_6$ ($E_x = 9.632$ MeV, $J^\pi = 1^-$), the calculations of the cross-sections, angular distribution, and analyzing powers grouped these two states.

An energy distribution of the differential cross-sections at $\theta_{\text{lab}} = 60^\circ$ is plotted in figure 5-9.

The single particle-hole configuration for $\gamma_5$ ($E_x = 8.872$ MeV) is $(1d_{5/2}^+\frac{1}{2})(1p_{1/2}^-\frac{1}{2})$, was acquired from reference [Fulb69]. The configuration for $\gamma_6$ ($E_x = 9.632$ MeV, $J^\pi = 1^-$) with a $1p_{1/2}$ hole has two possible proton orbital candidates, $2s_{1/2}$ and $1d_{3/2}$, producing $J^\pi = 1^-$ strength. Because a proton in the $2s_{1/2}$ orbital is more likely to couple to a $1p_{1/2}$ hole, the single particle-hole configuration was chosen $(2s_{1/2}^+\frac{1}{2})(1p_{1/2}^-\frac{1}{2})$. A
spectroscopic factor of 0.275 for the $E_x = 8.872$ MeV state was acquired from reference [Fulb69], and a spectroscopic factor of 1.0 was used for the $E_x = 9.632$ MeV state, since no reference of stripping reaction data was obtained. The position and width of the GDR (E1 component) acquired their approximate values from [Angh83] and later optimum values ($E_\gamma = 24.818$ MeV, $\Gamma_\gamma = 3.75$ MeV) were determined from optimization of the fits in figure 5-9.

HIKARI calculations use the above input parameters along with a spin-orbit potential $V_{S\text{OPT}} = 5.5$ MeV. The computation with the energy dependent omp (dash) and an energy independent omp (solid) fixed at the position of the GDR is shown in figure 5-9. HIKARI calculates the cross-sections for the individual states, then adding these differential cross-sections, the total $\gamma_{5,6}$ differential cross-section is computed.

The GAMMA calculations were not performed because the $(2s_{1/2}^{+1})(1p_{1/2}^{-1})$ coupling produced a larger cross-section than the coupling from the $(1d_{5/2}^{+1})(1p_{1/2}^{-1})$ particle-hole configuration. This is demonstrated to be incorrect as shown in figure 5-4, which shows the peak area due to $\gamma_5$ to be greater than the $\gamma_6$ peak area. The program GAMMA views the j-j coupling to play the dominant role in the determination of the differential cross-sections, which for excited states is not complete.
The angular distribution of the differential cross-sections and the analyzing power angular distribution is demonstrated in figures 5-10(a,b) respectively. The difference between an energy dependent omp (dash) and energy independent omp (solid) for the angular distribution is shown in figure 5-10a, where the energy independent omp (solid) provides better agreement to the data. A GAMMA (dash-dot) calculation was shown only with the \((1d_{5/2}^{+1})(1p_{3/2}^{-1})\) particle-hole configuration with a spectroscopic factor of 1.1 (4 x spectroscopic factor of the \(E_X = 8.872\) MeV state).

The analyzing power angular distribution is demonstrated in figure 5-10b, where the areas of the unresolved states \(\gamma_5\) and \(\gamma_6\) were summed and then used in equation V-3 to determine the experimental analyzing power measurement. The state \(\gamma_5\) (\(E_X = 8.872\) MeV) is the dominant state of this group as shown in figure 5-4. Hence, the theoretical calculation of the analyzing power was computed for the \(\gamma_5\) state using HIKARI with an energy dependent omp and a single particle-hole configuration \((1d_{5/2}^{+1})\) \((1p_{3/2}^{-1})\). HIKARI provides a good reproduction of the data in the mid angular range. The large errors for the forward angles are due to poor statistics in the data and the \(\theta_{lab} = 90^\circ\) data was not plotted due to a unreliable large positive analyzing power measurement.
Figure 5-9

Differential cross-sections for $^{15}$N($p,\gamma_{5,6}$)$^{16}$O as a function of energy at $\theta_{\text{lab}} = 60^\circ$. HIKARI DSD calculation om p energy dependent (dash) and omp energy independent (solid).
Angular distribution (a) and Analyzing power angular distribution (b) for $^{15}\text{N}(p,\gamma_{5,6})^{16}\text{O}$ @ $E_p = 49.69\text{ MeV}$. HIKARI DSD calculations omp energy dependent (dash) and omp energy independent (solid). GAMMA calculation (dash-dot).
7d. $^\text{15}N(p,\gamma){^\text{16}}O$

The three states that are grouped to comprise $^{113}_1\gamma'$, due to the insufficient resolution of the NaI(Tl) spectrometer are listed in Table 17, with their single particle-hole configuration and spectroscopic factors obtained from [Fulb69].

Table 17
$^{113}_1\gamma'$ States in $^{16}O$
references [Ajze77, Fulb69]
<table>
<thead>
<tr>
<th>$E_X$ (MeV)</th>
<th>configuration</th>
<th>$C^2S$ spectroscopic factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.53</td>
<td>$(1d_3/2^+)(1p_1/2^-)$</td>
<td>0.725</td>
</tr>
<tr>
<td>12.9686</td>
<td>$(1d_5/2^+)(1p_1/2^-)$</td>
<td>0.425</td>
</tr>
<tr>
<td>13.254</td>
<td>$(1d_5/2^+)(1p_1/2^-)$</td>
<td>0.480</td>
</tr>
</tbody>
</table>

The experimental data performed by Anghinolfi et. al. [Angh83] labels this region of $^\text{15}N(p,\gamma){^\text{16}}O$ as composed of two states, $E_X = 12.53$ MeV; $J^\pi = 2^-$ and $E_X = 13.129$ MeV; $J^\pi = 3^-$. Using these two states to fit the spectra obtained with the OMEGA I spectrometer, which has finer resolution than the spectrometer of Anghinolfi et. al. [Angh83], poor fits of the spectra were obtained. Determination of reliable fits is explained in reference [Jens84]. Testing various states within this region, the states listed in table 17 provided the choice fits. Both groups, Anghinolfi
et. at. and ours can not explicitly provide clear evidence which states compose the \( \gamma'_{13} \) region due to the insufficient resolution of the NaI spectrometers, but only suggest possible combinations.

An energy distribution of the differential cross-sections at \( \theta_{\text{lab}} = 60^\circ \) is demonstrated in figure 5-11. Calculations of HIKARI are shown with an energy dependent omp (dash) and an energy independent omp (solid), parameters fixed at the position of the GDR, along with a spin-orbit potential \( V_{\text{SOPT}} = 0.0 \text{ MeV} \). HIKARI can not compute an unbound state (excitation energy of the state of interest is greater than the Q-value of the reaction). Note the Q-value of \( ^{15}\text{N}(p,\gamma)^{16}\text{O} \) equals 12.128 MeV [Ajze86]. A binding energy of 5 keV is input into HIKARI for each individual state with the total differential cross-sections and angular distribution computed by adding the differential cross-section from each individual state composing the \( \gamma'_{13} \) region. The E1 (dipole) component position and width obtained their approximate values from [Angh83] and optimum values \( (E_{\gamma} = 20.69 \text{ MeV}, \Gamma_{\gamma} = 3.0 \text{ MeV}) \) were computed by optimizing the fits of the energy distribution of the differential cross-sections.

An angular distribution of the differential cross-sections and an analyzing power angular distribution at a proton energy \( E_p = 49.69 \text{ MeV} \) is shown in figures 5-12(a,b)
respectively. HIKARI calculations of the angular
distribution with an energy independent omp (dash) and an
energy dependent omp (solid) is demonstrated in figure 5-
12a, with the energy independent omp providing an improved
fit to the data.

The analyzing power of the angular distribution is
exhibited in figure 5-12b. Experimental analyzing power
measurements were computed by inputting the combined areas
of the individual states of $\gamma_{13}$ into equation V-3.
HIKARI calculated the theoretical analyzing powers of the
individual states using an energy dependent omp with their
respective particle-hole configuration as demonstrated in
figure 5-12b. The resultant analyzing power of the $\gamma_{13}$
group was computed using the equation

$$A_y = \frac{\sum_i (A\sigma)_i}{\sum_i (\sigma)_i} \quad (V-4)$$

where $A$ and $\sigma$ are the theoretical analyzing power and
differential cross-section respectively of the individual
states. This produced a null analyzing power for the $\gamma_{13}$
state.
Figure 5-11

Differential cross-sections for $^{15}\text{N}(p,\gamma'_{13})^{16}\text{O}$ as a function of energy at $\theta_{\text{lab}} = 60^\circ$. HIKARI DSD calculations with energy dependent (dash) and energy independent (solid).
Angular distribution (a) and Analyzing power angular distribution (b) for $^{15}\text{N}(p,\gamma_{13})^{16}\text{O}$ at $E_p = 49.69$ MeV. HIKARI DSD calculations with energy independent (dash) and energy dependent (solid).
VI. Discussion and Conclusion

This chapter is split into two separate sections concerning 1) conclusions and future trends of NaI(Tl) spectrometers and 2) conclusions of the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ analysis presented in chapter V comparing the DSD phenomenological theory [Blat84] and the theory by McDermott et. al. [Mcde86] with a single particle mechanism and meson exchange terms using the Dirac equation.

NaI(Tl) Spectrometer

a) Design considerations for future NaI(Tl) spectrometers

The NaI(Tl) crystal is surface recompensated with a 6.13 MeV $\gamma$-ray source to improve the uniformity and resolution of the crystal at high $\gamma$-ray energies. The average depth of penetration of the photons from a 6.13 MeV $\gamma$-ray source is only 8 cm, which reveals that only 21% and 55% of the total length and radius respectively of the OMEGA II NaI(Tl) crystal can be recompensated. Higher $\gamma$-ray sources or an electron beam should be used to penetrate the total volume of the crystal, which would improve the uniformity and resolution for use in the intermediate energy region where a 200 MeV $\gamma$-ray penetrates the entire
volume of the crystal.

A different approach is the construction of a smaller central crystal surrounded by an annulus of NaI(Tl), with each section resulting in improved recompensation due to their smaller dimensions. In the past, researchers didn't approve of this method because each section of the NaI(Tl) crystal was cemented to produce the larger crystal, and the interface destroyed any benefit provided by a larger segmented crystal. A recent spectrometer designed by J. Miller at Boston University and constructed at Bicron Co. [Mill86] incorporates a 10.5"φ x 22" long central NaI(Tl) crystal surrounded by four optically isolated NaI(Tl) quadrants which complete the 19.5"φ x 22" geometry. The central core consists of two cemented 10.5"φ x 11" long NaI(Tl) crystals. The resolution of this spectrometer is reported at ≤ 2.0% FWHM @ Eγ = 22 MeV.

Another future design consideration is the implementation of large-area photodiodes in place of photomultiplier tubes. The compact silicon photodiodes exhibit uniform sensitive areas, whereas the uniformity of the photocathode of the phototube can vary as much as 40%. Photodiodes are solid state devices which also display higher stability than the phototube. The only and major drawback is the photodiode has a poor quantum efficiency (50%) at the wavelength of the NaI(Tl) crystal (410nm).
Improvements in quantum efficiency of the photodiode at the wavelength of the NaI(Tl) crystal will then add another improvement to the energy resolution of the NaI(Tl) spectrometer.

b) NaI(Tl) spectrometer: conclusion

The full-width-half-maximum (FWHM) and full-width-tenth-maximum (FWTM) that have been achieved with the new OMEGA II spectrometer along with its refinement of gain stabilization, represent an improvement over past spectrometers operating in the intermediate energy region. Improvement in the FWTM is attributed to segmentation of the plastic scintillator shield in anticoincidence with a larger diameter NaI(Tl) crystal. The most important refinement is the new technique of surface recompensation by Bicron Co. for improved uniformity of the NaI(Tl) crystal producing an improved resolution (FWHM) of gamma-rays in the intermediate energy region.

Radiative Proton Capture: $^{15}\text{N}(p,\gamma)^{16}\text{O}$

The energy dependence of the 60° proton capture differential cross-sections in the 20-100 MeV energy range along with the angular distribution and the analyzing powers at a proton energy $E_p = 49.69$ MeV were presented in chapter V. A phenomenological DSD model with an energy dependent and independent optical model parameters were utilized to parameterize the experimental data. In both
cases, the DSD calculation reproduced the data in the region of the GDR up to a proton energy $E_p = 40$ MeV. At energies above the proton energy $E_p = 40$ MeV, the DSD calculation with an energy dependent omp overestimated the experimental differential cross-sections by factors as large as an order of magnitude. The omp used was obtained from the optical model analysis of proton elastic-scattering in the range 10 - 50 MeV [Wats69]. We tried, as discussed in chapter V, to obtain a global omp set to parameterize the data in the 20 - 100 MeV region, such that the omp [Wats69] was extended into the higher energies. This omp was not expected to optimize the fits at all energies. For example in some of the energy regions, a parameter exhibits an abrupt or discontinuous change. This is not appropriate since we believe that the omp should change smoothly and continuously over the entire energy range.

The phenomenological DSD calculation with an energy independent omp obtained a reasonable fit to the energy dependence of the differential cross-sections over the 20 - 100 MeV region. This omp was achieved by fixing the omp set at the GDR. In this formalism, the proton partial waves in the incident state are continuum wave functions [Well82], and are not orthogonal to the final wave function. Fink et. al. [Fink72] and Hebach et. al.
[Heba76] discuss the problems of using non-orthogonal wave functions in describing a single particle interaction. They show that use of a non-orthogonal wave function with an energy dependent Omp set could fit the experimental data, but no basic understanding of the physics of the interaction is attained. Although the energy independent Omp provided no insight into the physical processes, it does provide a method of reproducing the experimental data with a simple calculable model.

DSD calculations of the energy and angular distributions of the differential cross-sections were computed with contributions of the electric multipole up to $L = 3$. The energy and width of the various multipoles were obtained from the references. In view that the GDR is composed of many resonances and we are interested in a large energy global region, the width of the GDR was allowed to vary to optimize the fit within the region of the GDR. The number of electric multipoles shifted the peak of the angular distribution of the differential cross-section, i.e. $E_1$, $E_2$, and their interference terms the maximum cross-section occurs at $\theta = 60^\circ$ and with the addition of the $E_3$ component, the maximum occurs at $\theta = 50^\circ$.

The characteristics of the analyzing powers of the angular distribution was shown by Seyler and Weller
[Seyl84] that a proton captured into a 'stretched' 
\((j = 1 + \frac{3}{2})\) orbital, ie. \(d_{5/2}\) orbital as in the  
\(^{15}N(p,\gamma_z)^{16}O\) reaction, the analyzing power angular  
distributions are negative (positive) in the forward  
(backward) angles; whereas for a proton captured into a  
'jackknifed' \((j = 1 - \frac{1}{2})\) orbital, ie. \(p_{3/2}\) orbital as in  
the \(^{15}N(p,\gamma_0)^{16}O\) reaction, the analyzing powers are  
positive (negative) in the forward (backward) angles. The  
calculation for the states that comprise the \(\gamma_{1,3}\), group  
reproduced a null analyzing power as shown in chapter V,  
which is expected since \(\gamma_{1,3}\), is composed of stretched and  
jackknifed states. A fit to these states should also take  
into account that it is an unbound state with a mixture of  
\(T = 0\) and \(1\) states.

The theoretical calculations concerning a single  
particle mechanism with meson exchange terms using the  
Dirac equation was performed by GAMMA [Mcde86] and provides  
an improved reproduction of the experimental data above the  
GDR for the ground and 2\(^{nd}\) excited states. In the region  
of the GDR, \(E_p = 20\) MeV, GAMMA does not reproduce the  
experimental data because the distorted wave impulse  
approximation (DWIA) is a poor approximation in this energy  
region and the position and width of the GDR is not an  
input parameter. Hence, for these reasons it is not  
expected that GAMMA reproduce the experimental analyzing
powers at the proton energy $E_p = 49.69$ MeV. Even though the DWIA theory is a poor approximation at energies below 100 MeV, the calculations (GAMMA) of a single particle mechanism with meson exchange terms using the relativistic Dirac equation does provide an understanding of the physical processes in the energy region of interest 30 - 100 MeV.

The analysis of the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction considered a pure single particle-hole configuration for the GDR. This method was used to obtain the general fit of the reaction for a large energy region. O'Connell and Hanna [Ocon78] showed that the GDR of the ground state of $^{16}\text{O}$ is composed of many individual resonances with each resonance composed of various particle-hole configurations. Hence, it is not expected that the DSD and GAMMA calculations can attain an exact fit to the experimental data. This problem of a pure single particle-hole configuration assumption is also unrealistic for the excited states.

The results of this dissertation demonstrates that radiative proton capture reactions can be described over a large energy region with a shell-model using pure single particle-hole configurations. These conclusions are in agreement with the results of radiative proton capture on various light nuclei as reported by [Haus87]. This is demonstrated in figure 6-1 for the DSD calculation
with an energy dependent omp for all states of interest in $^{160}$ in the $\gamma$-ray energy region 10 - 60 MeV. GAMMA also gives reasonable results in the proton energy region 30 - 100 MeV for the ground and 2nd excited states as shown in chapter V. The position of the resonances for all interested states in $^{160}$, plotted as a function of $\gamma$-ray energy, figure 6-1, are within ± 2 MeV of the ground state. This clearly demonstrates the Brink-Axel hypothesis [Brin55 and Axel62] that all nuclear states have giant resonances built on them as also shown in the works in $^{12}$C [Angh83a] and in $^{28}$Si [Dowe83] for low excited states and in the highly excited unresolved states composing $\gamma_{191}$ in $^{12}$C [Blat80].

Improvements in the study of radiative proton capture can be made with refinements in the optical model parameters for the energy region of interest along with the determination of the particle-hole configurations in the GDR of the various states.
Energy distribution of the differential cross-sections for the states of interest in $^{16}O$ with a DSD calculation of an energy dependent omp.
Appendix A

Growth and Compensation of a NaI(Tl) Crystal

The NaI(Tl) solution containing 0.1 mole % of thallium is contained in a pointed platinum crucible at a temperature of 650°C. As the crucible is lowered into a container of decreasing incremental temperature, a seed is formed on the bottom of the crucible. As the crucible is lowered the seed enlarges. The growth of a large crystal takes approximately one month and an additional one month to anneal. The new OSU 11.5" φ x 15" crystal was grown and compensated by Bicron Corporation [Bicr1].

Dietrich et.al. [Diet73] showed that the scintillation process is associated with the transitions of the Tl⁺ impurity ions. Initially, the energy lost by the shower particles is deposited in the host lattice (NaI). Then by electron-hole diffusion and recombination the energy is transferred to the Tl⁺ sites. An electron after diffusion forms Tl⁰ at a Tl⁺ site and by recombination with a hole, energy is transferred by

\[ h + Tl^0 \rightarrow (Tl^+)^* \rightarrow Tl^+ + h\nu \]  \hspace{1cm} (A-1)

Alternately, a hole after diffusion interacts at a Tl⁺ site and forms Tl²⁺ and by recombination with an electron energy
is transferred via

\[ e + Tl^{++} \rightarrow (Tl^+)^* \rightarrow Tl^+ + h\nu. \]  \hspace{1cm} (A-2)

During the one month of growth the thallium tends to settle and decreases the uniformity of the scintillation. The settling of the thallium and the reflective properties of the crystal boundaries effect the uniformity of the crystal, which in turn affects the resolution.

To compensate for these effects the surface of the NaI(Tl) crystal can be changed to either enhance or degrade the reflectivity along the length of the crystal. This is done by mapping the crystal in 1" increments with a γ-ray source, with the requirement that the peak position of the γ-ray in the ADC from the 'summed' phototubes signal remains constant over the entire crystal. Traditionally, manufacturers compensated using a $^{137}$Cs (0.662 MeV) source. The problem is that the γ-rays from a collimated $^{137}$Cs source penetrate only 3.5 cm into the crystal, not allowing the central region of the crystal to be probed. Recently, the people at the Bicron Co. began using a $^{244}$Cm-$^{13}$C (6.13 MeV) γ-ray source [Dick70] which penetrates 8 cm into the crystal, and have a pair-production reaction half of the time so that the resulting shower penetrates further.

Bicron Co. with this method attained a pulse height resolution of 7.5% @ 0.662 MeV with a uniformity of ±1.0%
and a pulse height resolution of 2.9% at 6.13 MeV for the 11.5" x 15" NaI(Tl) crystal.

With this higher γ-ray compensation technique Sandorfi et al. [Sand84] showed, using the new BNL-MK III 10" x 14" NaI crystal, an optimal uniformity of ±0.6% was attained using a $^{137}$Cs source, and at $E_\gamma = 6.13$ MeV, attained a resolution of 4.2% with a uniformity of ±1.2%, without recompensation at 6.13 MeV. By recompensating at 6.13 MeV, the uniformity was reduced to ±0.4% and the resolution improved to 3.2%. The final result showed that gain matching the phototubes at 6.13 MeV, instead of 0.662 MeV, improved the BNL-MK III resolution at $E_\gamma = 20$ MeV approx. 0.3%, and rematching the phototubes gain at 20 MeV from a $^{11}$B(p,γ) reaction doesn't provide further improvement.
Appendix B

General Properties of NaI(Tl) crystal

wavelength of max. emission $\lambda_m$: 410 nm
decay constant: 0.23 $\mu$s
index of refraction: 1.83 @ $\lambda_m$
specific gravity: 3.67
radiation length: 2.59 cm
photon yield n/E: 40000 photons/MeV
dE/dx: 4.85 MeV/cm
rise time 11.5" @ 15" NaI(Tl): 70 ns 10-90%
fall time 11.5" @ 15" NaI(Tl): 660 ns 10-90%

General Properties of Plastic Scintillator BC-412

base: polyvinyltoluene
% light output of anthracene: 60%
decay constant: 3.3 ns
wavelength of max. emission $\lambda_m$: 434 nm
specific gravity: 1.032
index of refraction: 1.58 @ $\lambda_m$
H/C ratio: 1.104
radiation length: 43 cm
rise time of anticoincidence shield: 6.5 ns 10-90%
fall time of anticoincidence shield: 28 ns 10-90%

General Properties of Phototubes

<table>
<thead>
<tr>
<th>Property</th>
<th>RCA S83021EM1</th>
<th>Amperex XP-2202B</th>
</tr>
</thead>
<tbody>
<tr>
<td>photocathode dia.:</td>
<td>3&quot;</td>
<td>2&quot;</td>
</tr>
<tr>
<td>max. wavelength response:</td>
<td>400 nm</td>
<td>400 nm</td>
</tr>
<tr>
<td>no. of stages:</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>dynode structure:</td>
<td>teacup 1st.dynode box and grid</td>
<td>linear focused 1st.- 8th. dynode Cu-Be</td>
</tr>
<tr>
<td>dynode substrate:</td>
<td>Cu-Be 1st.- 8th. dynode proprietary last two</td>
<td></td>
</tr>
<tr>
<td>secondary-emitting</td>
<td>Alkali-antimonide 1st dynode BeO 2nd-8th dynode proprietary last two</td>
<td></td>
</tr>
<tr>
<td>dynode surface:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>photocathode material:</td>
<td>Sb-K-Cs (bialkali)</td>
<td>Sb-K-Cs</td>
</tr>
<tr>
<td>index of refraction:</td>
<td>1.52 @ 400 nm</td>
<td>1.52 @ 400 nm</td>
</tr>
<tr>
<td>anode rise time:</td>
<td>8.3 ns</td>
<td>3.5 ns</td>
</tr>
<tr>
<td>DC power supply:</td>
<td>-1400 volts</td>
<td>-1700 volts</td>
</tr>
<tr>
<td>average pmt. current:</td>
<td>1.28 ma</td>
<td>0.977 ma</td>
</tr>
</tbody>
</table>

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Appendix C

The response function of the NaI(Tl) spectrometer to monochromatic gamma-rays is approximated by a gaussian peak joined to a decaying exponential tail on the low energy side of the peak. The low energy tail extrapolates towards zero energy with a flat background. This line shape is defined in terms of seven parameters \(a_i\), \(i=1\) to 7) [Kova78];

\[
R(\xi, x) = \begin{cases} 
  a_6 + a_7 \exp(a_3(x-a_2)) & ; x < a_2 - a_5 \\
  a_1 \exp(-a_4(x-a_2)^2) & ; x \geq a_2 - a_5
\end{cases}
\]

(C-1)

where \(a_2\) is the position of the peak centroid, \(a_5\) is the number of channels between \(a_2\) and the transition from gaussian to exponential functions, and \(a_6\) is the height of the low energy tail. The parameters \(a_3\), \(a_4\), and \(a_5\) determine the shape of each peak.

For a typical gamma-ray spectrum each peak may have its own set of shape parameters \(\xi\). To retain the same line shape for the many peaks in the spectrum the values \(a_3\), \(a_4\), and \(a_5\) must be altered from peak to peak and be defined in terms of a single set of standard intrinsic shape parameters \(s_i\), \(i=1\) to 5), which is independent of peak height and spectrum offset. Considering a peak located at channel \(a_2\) above the offset \(\xi\), whose height is
a_1$, then parameters $a_3 - a_7$ can be defined in terms of the intrinsic shape parameters by:

$$\begin{align*}
\gamma &= s_2/(a_2 - \bar{a} + s_1) \\
a_3 &= s_3(\gamma) \\
a_4 &= s_4(\gamma)^2 \\
a_5 &= s_5/\gamma \\
a_6 &= a_1[1 - (2s_4s_5/s_3)]\exp(-s_4s_5^2) \\
a_7 &= a_1[2s_4s_5/s_3]\exp(s_5(s_3 - s_4s_5))
\end{align*}$$

(C-2)

The parameter $s_2$ is the 'resolution' parameter of the spectrum; if $s_2$ increases, the resolution improves.

The parameters for the 10"$\phi \times 12"$ NaI(Tl) spectrometer are:

$$s_3 = 0.284040 \quad s_4 = 0.13567 \quad s_5 = 0.97375$$

and those determined for the new 11.5"$\phi \times 15"$ NaI(Tl) spectrometer are:

$$s_3 = 0.311641 \quad s_4 = 0.124639 \quad s_5 = 1.21528.$$ 

These parameters are determined by isolating three gamma-ray peaks. Each peak was fit to a function of the form $C-1$, using the program GAMMASPEC written by T. Rackers, with the final value being the average. The program GAMMASPEC uses a $\chi^2$ minimization search of the parameter set written by J. Chandler at Indiana University.

Figure C1 shows a spectrum from $^3\text{H}(p,\gamma)^4\text{He}$ reaction at a proton energy of $E_p = 1$ MeV using the 11.5"$\phi \times 15"$ NaI(Tl) spectrometer. Part (b) shows a fit of a $\gamma$-ray
peak, $E_\gamma = 20.4$ MeV, using the $10'' \times 12''$ NaI(Tl) parameters. Notice that the low energy tail does not match the spectrum. Part (a) uses the new parameters attained for the $11.5'' \times 15''$ NaI(Tl) spectrometer. The $11.5'' \times 15''$ NaI(Tl) spectrometer shows an improvement in the peak/tail ratio, which is due to the increased length of the crystal, and the improved efficiency of the segmented anticoincidence shield. Using the new parameters attained from the OMEGA spectrometer and comparing the response function to OMEGA I spectrometer, a calculation of $a_5$ and $a_6$ for a high energy gamma-ray can be compared. From figure C1, $a_6$, the height of the low energy tail shows an improvement, and a calculation of $a_5$ shows that the gamma-ray peak in the spectrum is more of a gaussian shape for the $11.5'' \times 15''$ NaI(Tl) spectrometer, more channels in the gaussian before the exponential function, than for the $10'' \times 12''$ NaI(Tl) spectrometer.

From the shape parameters the area of a peak is defined by:

$$\text{AREA} = a_6 \left( a_2 - a_5 - 5 \right) + \left( a_7 / a_3 \right) \left( \exp(-a_3 a_5) - \exp((a_3(5-a_2)) \right)$$

$$+ \left( (\pi / a_4) (a_6 / 2) (1 + \text{erf}(\sqrt{(a_4 a_5})) \right) \quad (C-3)$$

from which the cross-section of the respective reaction can be calculated.
Figure C-1

Differences of line shapes for the OMEGA II and OMEGA I NaI(Tl) spectrometers.
Appendix D

Program to convert XSYS 'dump' type spectra into SPEC format

** XSYS Data Area Data-type Definitions **

** Any change in XSYS data area data types **

** should also be made in the VDA_TYPE **

** array at the end of this include file. **

---

Old type codes.

PARAMETER VMAX_TYPES=10  
PARAMETER V1D_TV=1         
PARAMETER V2D_JD=2         
PARAMETER V2D_AT=3         
PARAMETER V1D_R4=4         
PARAMETER V1D_R8=5         
PARAMETER VEVAL_DA=6        
PARAMETER V2D_DATE=7        
PARAMETER VPRDT_R4=8        
PARAMETER VPRDT_AT=9        
PARAMETER VSCAL_ID=10       
PARAMETER VMAX_TYYPE=8      
PARAMETER V1D_TV=1         
PARAMETER V2D_JD=2         
PARAMETER V2D_AT=3         
PARAMETER V1D_R4=4         
PARAMETER V1D_R8=5         
PARAMETER VEVAL_DA=6        
PARAMETER V2D_DATE=7        
PARAMETER VPRDT_R4=8        
PARAMETER VPRDT_AT=9        
PARAMETER VSCAL_ID=10       

New storage type, class codes.

PARAMETER VTYPE_K_MAX = 8  
PARAMETER VTYPE_GATE = 1   
PARAMETER VTYPE_II = 2     
PARAMETER VTYPE_II = 2     
PARAMETER VTYPE_II = 3     
PARAMETER VTYPE_II = 3     
PARAMETER VTYPE_II = 4     
PARAMETER VTYPE_II = 4     
PARAMETER VTYPE_II = 6     
PARAMETER VTYPE_II = 6     
PARAMETER VTYPE_II = 7     
PARAMETER VTYPE_II = 7     
PARAMETER VTYPE_II = 8     
PARAMETER VTYPE_II = 8     
PARAMETER VTYPE_II = 9     
PARAMETER VTYPE_II = 9     
PARAMETER VTYPE_II = 10    
PARAMETER VTYPE_II = 10    

---

STRUCTURE /XINFU/
INTEGER*4 AREA    
INTEGER*4 OLDTYPE  
BYTE TYPE, CLASS   
INTEGER*4 LLEN    
INTEGER*4 PLEN, RELP  
CHARACTER*8 AMAP     
INTEGER*4 XSIZ, YSIZ 
INTEGER*2 XOFFS, YOFFS 
INTEGER*2 XGAIN, YGAIN  
INTEGER*4 XFILL 
UNION MAP  
BYTE EVNUM, FLAGS, XSS, YSS  
PARAMETER VINFO&MAPPED = 1  
PARAMETER VINFO&TPROCESS = 4  
PARAMETER VINFO&USER = 16  
END MAP  
PARAMETER FLNAME = ' ' } Indicates calibration not TOF
character cfilename*(80)
character RUNID*(6)
INTEGER*4 LIST(1), NUM, X_RUN
real*8 X_SCLHED(124)
real*4 X_DIC(8)
logical*1 ANSI
record /INFO/ INFO1
character STUFF*4, C_TITLE*80, C_USER*12, C_PROGNAME*9
1 ,C_USERNAME*12, DUMMY*75
integer*4 X_DATA(65536)
INTEGER*2 ISIZE(2), IOFFSET(2), MOD(2), CHTYPE(10), IGAIN(2)
integer*4 ISEG, LENGTH

INTEGRER*4 I, IR, J, I1
integer*4 blksiz
character*84 cfilename1
integer*4 ios ! i/o status

INTEGRER*4 ZERO ! Null item used to pad the data record

C*****************************************************************************
C  Executable Code
C*****************************************************************************

C CONVERT XSYS TYPE # TO UNICORN TYPE #
CHTYPE(VID 1)=5 ! ID #4
CHTYPE(V2D-1)=6 ! 2D #4
CHTYPE(V2D-2)=2 ! 2D #2
CHTYPE(V2D-4)=3 ! ID #4
CHTYPE(V2D-8)=7 ! ID #8
CHTYPE(VSCAL-1)=0 ! EVAL ALLOCATED DATA AREA NOT USED
CHTYPE(VSD GATE)=0 ! 2D GATE BIT MAP NOT USED
CHTYPE(VPROT R4)=0 ! PROTECTED R4 AREA NOT USED
CHTYPE(VDISPLAY D)=0 ! DISPLAY ATTRIBUTE DATA AREA NOT USED
CHTYPE(VSCALE-1)=0 ! SCALER DATA BLOCK USED LATER

C TYPE *, ' THIS PROGRAM WILL TAKE A XSYS TYPE DUMP FROM DISC '
TYPE *, ' OR TAPE AND CONVERT IT TO A UNICORN SPECTRUM FORMAT '
TYPE *, ' *

C TYPE 709
FORMAT( ' WHAT FILE DO YOU WANT TO CONVERT TO SPECTRA FORMAT? ',$)
ACCEPT 977, CFilename

97
FORMAT(A)
ZERO = 0
IF (LENGTH(CFILENAME) .EQ. 0) CALL EXIT

C Open output file **
OPEN (UNIT=10, file=CFilename, STATUS='OLD', ACCESS='SEQUENTIAL', ORGANIZATION='SEQUENTIAL'
FORM='UNFORMATTED',RECORDTYPE='FIXED'
RECL=128, BLOCKSIZE=blksiz, ERR=80)

C Inquire to get file-spec with version number.
IF (quest(IUNIT=10) .EQ. 1) then
WRITE(5,79) CFilename1(index(CFILENAME), ')
79 FORMAT( 'File ', A, ' found.' )
C
300
NUM = 100
DO 100 IR = 1, NUM

C ** Write TUNL header **
READ(10,END=70) STUFF, X_RUN, INFO1
1 C TITLE(1:80), C_USERNAME(1:12), C_PROGNAME(1:9),
     (DUMMY),
     (X_SCLHED(1),I=1,24), (X_DIC(1),I=1,8),
     (ZERO, ZERO, ZERO, ZERO, ZERO, ZERO, ZERO)
C ** Dump X_DATA **
IF (IR.EQ.1) then
    ENCODE(6,701, RUNID), X_RUN
701 FORMAT( 'R', I5)
TYPE *, ' RUNID=', ' RUNID
TYPE 899
899 FORMAT( ' INPUT SEQUENCE NUMBER! ',$)
ACCEPT *, ISEQ
CALL NEWSPEC(27, RUNID, ISEQ, C_TITLE, ", IER)
CALL ERCHK('NEWSPEC', IER, *999)
ENDIF
DO 200 J = 1, INFO1.PLEN
   J1 = (J-1)*128
   READ(10) (X_DATA(J1+I), I=1, 128)
200 CONTINUE
IF(INFO1.OLDTYPE .EQ. VSCAL_14) GO TO 210
C CHANGE XSYS TYPE TO UNICORN TYPE
   ITYPE = CTYPE(INFO1.OLDTYPE)
   IF( ITYPE EQ. 0) GO TO 100
   IF( INFO1.CLASS .NE. VCLAS_SPEC) GO TO 100
C ** GET GAINS, SIZES AND OFFSETS **
   ISIZE(1) = INFO1.XSIZ
   ISIZE(2) = INFO1.YSIZ
   IGAIN(1) = INFO1.XGAIN
   IGAIN(2) = INFO1.YGAIN
   IOFFSET(1) = INFO1.XOFFSET
   IOFFSET(2) = INFO1.YOFFSET
C CREATE NEW SPECNUM
   CALL NEWARRAY(27, IR, ITYPE, ISIZE, INFO1.ANAM, IGAIN, IOFFSET,
         X_MODULES, X_DATA, IFR)
   CALL ERCHK('NEWARRAY', IER, *999)
210 CONTINUE
C CREATE SCALERS
   CALL WRSCLRS(27, X_DATA, 24, IER)
   CALL ERCHK('WRSCLRS', IER, *999)
100 CONTINUE
C***** Finish
90 CLOSE(UNIT=10)
81 IR=IR-1
WRIT(6,79) IR
78 FORMAT(' ',15, ' Data areas found'
90 TYPE 5, 'ERROR- NU FILE FOUND'
999 CALL EXIT
END
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purchased from Reactor Experiments, Inc., 963 Terminal Way, San Carlos, Cal. 94070


[Rinc81] KINMAT, program by T. Rinckel and P. Koncz, The Ohio State University

[Rinc85] UNICORN, program by T. Rinckel, The Ohio State University

[Rinc86] ERRFIT, program by T. Rinckel and L. Rybarcyk, The Ohio State University


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