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NUCLEAR SPECTROSCOPY OF SOME
LOW- LYING LEVELS IN $^{63}$Co

DISSE R TATION

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

By

Bernard Joseph Brunner, B.S., M.S.

* * * * *

The Ohio State University
1972

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CHAPTER I
INTRODUCTION

The study of Nuclear Physics originated with the discovery of naturally occurring alpha, beta and gamma radiation by Becquerel in 1896. The intervening years have been marked by relatively quiet periods of careful, detailed investigation of phenomenon followed by major breakthroughs in the theoretical treatment of the data and major advances in experimental equipment and techniques stimulating further investigations. Some of the highlights since the turn of the century include: the verification of the existence of the nucleus from the study of alpha particle scattering by Rutherford in 1911; the positive identification of the neutron in 1932 by Chadwick; the development of the powerful tool of Quantum Mechanics in the 1930's; and a major advance in the understanding of much qualitative and quantitative nuclear data through the development of the Shell Model Theory of nuclear structure by Mayer and Jensen in 1949. Major technological advances would include: the development of particle accelerators capable of producing intense beams of various projectiles with selectable
energies; the improvement in high resolution particle and gamma ray detectors; and the production of high quality electronic equipment for data taking and data analysis.

Each small step and each major development moves toward the ultimate goals of nuclear structure investigations: the comprehension of how nucleons are arranged in nuclei, how they move relative to each other, and what the nature of the force is that binds nucleons together into nuclei. The present work, as a small part of this overall picture, will take us into the $1f-2p$ shell region to study the nucleus, $^{68}$Co.

The basic shell model potential, a spherically symmetric, attractive, central potential well plus a spin-orbit potential, establishes an unevenly spaced sequence of energy levels characterized by quantum numbers $(n, \ell, j)$ where $n$ is the principal quantum number, $\ell$ is the orbital angular momentum and $j$ is the total angular momentum, $j = \ell + s$. The allowed energy levels for a particle moving in this potential are labelled in spectroscopic notation $(n\ell j)$ where $\ell$ is represented by the letters $s, p, d, f, g, \ldots$ for $\ell = 0, 1, 2, 3, 4, \ldots$. Thus $1f_{7/2}$ implies the first level with $j = 3$ and $j = 7/2$. In this scheme each level can contain $2j + 1$ identical particles with the nearly identical proton and neutron shells filling independently. The so-called magic numbers are the
numbers of protons or neutrons for which there are large energy spacings between two groups of closely spaced energy levels.

The most prominent feature associated with the $f_{7/2}$ shell is the fact that it is, to some extent, isolated. In considering the magic numbers 2, 8, 20, 28, 50, etc., there is only one shell between the two magic numbers 20 and 28, i.e. the $f_{7/2}$ shell. The isolation of the $f_{7/2}$ shell means that for many nuclei in this region, a good first approximation to their structure may be obtained by considering the particles in only one shell and ignoring the closed core below the shell. For this reason nuclei in this region have been the subject of many detailed theoretical and experimental investigations.

A. Previous Work

The odd-odd nucleus $^{58}_{27}$Co$_{31}$ has 27 protons and 31 neutrons. In a simple shell model picture, $^{60}$Co is described as having one proton hole in the $1f_{7/2}$ shell ($\pi f_{7/2}^{-1}$) and one neutron hole in the $2p_{3/2}$ shell ($\nu 2p_{3/2}^{-1}$). In studying this nucleus one would hope to gain a better understanding of the nature of the residual interaction (that which remains after all stronger interactions have been taken into account) between an unpaired proton and an unpaired neutron in the region near a closed shell. Furthermore, since ($\nu 2p_{3/2}^{-1}$)
below 2.6 MeV. The most complete gamma ray studies to date are the gamma-gamma and n-gamma coincidence works of (Ro 71) and Xenoulis and Sarantites (Xe 71), both using the $^{55}$Mn($\alpha$,n$\gamma$) reaction and studying levels below 2.0 MeV. The agreement between the latter two works is good below 1.5 MeV except for some disagreement in the placement of several weaker transitions with reported branchings of less than 15%. The level structure and decay scheme below 1.5 MeV as compiled from (Ro 71) and (Xe 71) is shown in Figure 1.

In the most recent works, done nearly simultaneously with the present work, Haas et al. (Ha 72) measured the mean lifetimes and other properties of the levels at 53.2 and 111.5 keV. Gehringer et al. (Ge 72) measured the lifetimes of 8 levels, by the Doppler Shift Attenuation Measurements (DSAM) using both the singles and coincidence methods following the $^{55}$Mn($\alpha$,n$\gamma$) reaction. Gehringer et al. also determined the spins of the levels at 365.6, 373.7 and 457.6 keV, and the multipole mixing ratios of the gamma radiation from these levels using an n-gamma coincidence experiment following the reaction $^{58}$Fe(p,n$\gamma$)

Two shell model calculations have been done on $^{66}$Co by Vervier (Ve 66a) and McGrory (Mc). These will be discussed in more detail in the next chapter.
is equivalent to 3 particles outside the closed shell at $N = 28$, one might expect to learn more about how two additional neutrons affect the structure resulting from the residual proton-neutron interaction.

In the past several years a large number of experimental studies have been done on $^{59}$Co. These fall into two main categories: 1) The study of level spins, parities and configurations by measuring the angular momentum transferred in various types of reactions; and 2) Level structure, decay schemes, branching ratios and spin assignments based on gamma ray studies.

Some of the more recent particle transfer studies include: single neutron pick-up, $(d,t)$ and $(^3$He,$\alpha)$ on $^{59}$Co by Robertson and Summers-Gill (Ro 71) and Schneider and Daehnick (Sc 72), respectively; proton stripping, $^{57}$Fe$(^3$He,d) by Trier et al. (Tr 69) and (Sc 72); deuteron pickup, $^{50}$Ni(d,$\alpha$) by Lynn et al. (Ly 72) and (Sc 72); deuteron stripping, $^{56}$Fe$(^3$He,p) (Ly 72); and $^{56}$Fe(p,n) by Tanaka et al. (Ta 70). Levels up to 4.1 MeV excitation have been identified in these works.

The earliest gamma ray work was done by Gorodetsky et al. (Go 65) and (Go 68) who studied levels up to approximately 1435 keV using $^{58}$Fe(p,n$\gamma$). Erlandson and Marcinkowski (Er 70) studied (p,$\gamma$) resonances up to 8.5 MeV excitation and the decay of levels
Figure 1  Gamma ray decay scheme for $^{68}$Co below 1.5 MeV as compiled from (Ro 71) and (Xe 71). Only the transitions observed in both works are included.
B. Purpose of the Present Study

The first quantities of importance in describing the structure of a nucleus are the energies, spins and parities of the levels. The values of these quantities are compared with the values computed using some model, and if the agreement is reasonable, one can describe the levels, to a first approximation, as having a specific configuration or mixture of configurations. The problem at this stage is that these quantities are not very sensitive to specific configurations and several models may reproduce these quantities equally well. More sensitive tests must be applied to the models, such as the computation of lifetimes and magnetic moments, to be able to select between the models.

The present work was undertaken to provide additional experimental information about the level structure of $^{58}$Co so that existing and future models of its structure may be more critically tested. The information obtained is in three categories: 1) additional evidence for spin assignments to six levels, 2) mean lifetimes of eight excited states, and 3) assignments of gamma ray multipole mixing ratios for five transitions.

Chapter II gives a brief discussion of nuclear structure primarily within the framework of the shell model. Chapter III
deals with the lifetime measurements using the Doppler Shift
Attenuation Method (DSAM). Chapter IV treats the spin and mixing
ratio assignments made using the assumptions of the compound
nucleus statistical model. The final chapter contains a discussion
of the experimental results in relation to the available theoretical
calculations and a comparison of $^{68}$Co with nuclei having
similar structure.
CHAPTER II
NUCLEAR STRUCTURE

In the absence of a comprehensive theory of nuclear structure, which hypothetically would be able to describe all the observable properties of nuclei, the nuclear physicist must rely on models which emphasize certain properties common to large numbers of nuclei. The models available may be categorized into two extremes: single particle models and collective models. In actual calculations however, the extremes are adequate only in very limited circumstances and a more realistic model often mixes elements from both extremes.

In single particle models the properties of nuclei are described in terms of one or more particles moving in a static potential well which results from the average effect of a spherical core of all the remaining nucleons. The single particle shell model makes reasonable predictions for many observed nuclear levels, but it fails to explain many others.

As more and more nucleons are added beyond a closed shell, the equilibrium shape of nuclei becomes ellipsoidal as illustrated
by the existence of large quadruple moments for nuclei far from closed shells. Ellipsoidal nuclei are found mainly in the mass regions $A \approx 25, 150 < A < 190, \text{ and } A > 220$. Some particle states in these nuclei are described by the Nilsson Model (Ni 55) in which the states are generated for nucleons moving under the influence of an ellipsoidal potential.

Collective motions of the nucleons are responsible for the vibrational and rotational character of excited states observed in many nuclei. The vibrations of the core about its equilibrium shape give rise to the evenly spaced, low-lying energy levels (neglecting interactions) observed particularly in even-even nuclei near closed shells. The rotation of an ellipsoidal core give low-lying energy levels proportional to $J (J + 1)$ (neglecting interactions). These are observed in strongly deformed nuclei.

Modifications of these two extreme types of models are often used to obtain a better agreement between model predictions and experimental observables. These modifications may include interactions among the different single particle configurations, as well as coupling between the motion of the particles outside the core and the collective motion of the core.

Since $^{68}\text{Co}$ lies in a region of small deformations near the closed shells at $N = Z = 28$, the first theoretical investigations
of its structure have been shell model calculations. Because these are the only calculations done thus far, the remaining discussion in this chapter will be limited to the shell model and its implications for $^{59}$Co.

A. Shell Model

In the shell model of the nucleus, the gross features of the system are described by a single particle-Hamiltonian operator of the form:

$$H_{sp} = \sum_{i=1}^{A} (T_i + V_i)$$

(1)

where $A$ is the total number of nucleons, $T_i$ is the kinetic energy of and $V_i$ is the two part potential seen by the $i^{th}$ nucleon. The first part of the potential is a spherically symmetric, attractive, central potential which describes the average effect of all the other nucleons on the $i^{th}$ nucleon. The second part is a spin-orbit potential of the form:

$$V_{so} = -V(r) \overrightarrow{l_i} \cdot \overrightarrow{s_i}$$

(2)

where $V(r)$ has sufficient magnitude for $H_{sp}$ to reproduce the magic numbers. The spin-orbit potential removes some of the degeneracy in the energy levels usually by lowering states with total angular momentum $j = \ell + 1/2$ below those with $j = \ell - 1/2$. 

The total Hamiltonian of the system is the single particle Hamiltonian plus the sum of all the two body interactions not included in the single particle Hamiltonian, i.e.

$$H = H_{sp} + \sum_{i < j} A V_{ij}. \quad (3)$$

This residual interaction is related to the actual potential and the single particle potential by:

$$\frac{A}{\tau} V_{ij} = \frac{A}{\tau} V^\text{actual}_{ij} - \sum_i A V_i \quad (4)$$

and is generally small in magnitude compared to the central and spin-orbit potentials. This two body interaction removes additional degeneracy in energy without drastically altering the single particle wave functions.

Structure information is obtained from the residual interaction in a three step process:

1) A complete set of orthonormal, antisymmetric wave functions $\Phi_i$ is chosen. These may be harmonic oscillator wave functions or some other approximations to the actual nuclear wave functions. These wave functions are specified by the quantum numbers $n$, $J$, $M$, $T$, $M_T$, $s$, $t$. The quantity $n$ is the principal quantum number, $J$ is the total angular momentum and $M_T$ is its
projection along the z axis. \( T \) is the isospin and \( M_T \) is its projection along the z axis. The seniority quantum number, \( s \), is defined as the number of particles remaining after removing all \( T = 1, J = 0 \) antisymmetric pairs. The reduced isospin, \( t \), is the isospin of the \( s \) remaining particles.

2) The wave functions, \( \Phi_i \), are used to obtain the interaction matrix elements \( \langle \Phi_a | \sum V_{ij} | \Phi_b \rangle \). Using coefficients of fractional parentage (c.f.p.'s) this matrix element may be written in terms of a sum over all possible two body matrix elements:

\[
\langle \Phi_a | \sum V_{ij} | \Phi_b \rangle = \frac{1}{2} k(k-1) \sum \sum \sum \Phi(k-2) \Phi(2) \Phi'(2)
\]

\[
\langle \Phi_a | \Phi(k-2), \Phi(2) \rangle^* \langle \Phi_b | \Phi(k-2), \Phi'(2) \rangle (5)
\]

\[
x \langle \Phi(2) | V_{k-1,k} | \Phi'(2) \rangle
\]

where \( k \) is the number of particles considered; \( \langle \Phi_i | \Phi(k-2), \Phi(2) \rangle \) is the coefficient of fractional parentage relating the wave function \( \Phi_i \) to the two particle wave function \( \Phi(2) \) and the \( k-2 \) particle wave function \( \Phi(k-2) \); and the summation is over all possible two body and \( k-2 \) body wave functions (Pr 62). The interaction matrix elements are diagonalized to obtain the eigenfunctions. There are
also c.f.p.'s for expressing the total wave function as a combination of single particle states and states of k-1 particles.

3) The eigenfunctions of the diagonalized matrix are used with the appropriate operators to compute the properties of nuclear states.

The above two body interaction matrix elements may be obtained in one of three ways:

1) An assumption is made about the form of the interaction potential and the matrix elements are computed using this potential and an appropriately selected set of single particle wave functions. In shell model calculations the residual interaction is frequently taken to be of very short range, usually some form of delta function potential. For odd-odd nuclei a common form of the p-n interaction is

\[ V_{pn} = - (V_0 + V_1 \vec{\sigma}_p \cdot \vec{\sigma}_n) \zeta (\vec{r}_p - \vec{r}_n) \]  

(6)

where the \( \sigma \)'s are the Pauli spin matrices (Ve 66b).

The parameters in the assumed potential are adjusted to fit experimental data from the nucleus of interest or from neighboring or similar nuclei.

2) The form of the potential is not assumed and the values of the matrix elements are obtained from experimental data on the
nucleus of interest or from neighboring nuclei. The assumption here is that the nuclear levels from which the experimental data is taken have certain structures.

3) The approach of Kuo and Brown (Ku 66 and Ku 68) uses effective residual interactions deduced from the free nucleon-nucleon potential. The nucleon-nucleon potential used is that of Hamada and Johnston (Ha 62) and is determined by scattering data below the meson threshold. The values of the constants in the potential are adjusted to give a best fit to observed structure.

A.1. *Ground State Spins*

For all but the simplest nuclei the calculations involving the complete Hamiltonian would be of unmanageable proportions, thus assumptions are made to introduce simplifications. In the extreme single particle shell model the neutron and proton shells fill independently and the nucleons have dynamically paired motion so that in the ground state, nuclear properties are determined by the last unpaired nucleon. This model correctly predicts the ground state spin of even-even nuclei to be $J^\pi = 0^+$, and that of odd-even nuclei to be $J = j_{odd}$, the angular momentum of the unpaired particle. The extreme single particle shell model only
predicts a range of values for ground state spins in odd-odd nuclei, 

\[ |j_p - j_n| \leq J_{gs} \leq j_p + j_n \]

and fails to adequately predict other ground state properties such as magnetic moment and quadrupole moment.

A less restrictive version of the shell model is the single particle shell model in which all nucleons in unfilled shells contribute to the ground state properties. The predictions for ground spins of even-even and odd-even nuclei remain the same. For odd-odd nuclei the ground state spin can be more accurately predicted using the single particle shell model and Nordheim's Rule (No 50) as modified by Brennan and Bernstein (Br 60). The Nordheim number is defined by:

\[ N = j_p - j_p + j_n - j_n \]

and spins are assigned according to:

- **Strong rule:** \( N = 0 \), \( J = |j_p - j_n| \)
- **Weak rule:** \( N = \pm 1 \), \( J = |j_p - j_n| \) or \( j_p + j_n \).

If there are \( k \) particles in the partially filled shell then \( j_a \) is replaced by \( J_a \), the resultant angular momentum of the \( k \) particles.

This rule is fairly well verified in the region \( 20 \leq A \leq 120 \).

Nordheim's strong rule illustrates that for the two body residual
interaction of Equation 4, the triplet state ($\vec{\sigma}_p$ and $\vec{\sigma}_n$ parallel) generally has lower energy than the singlet state and will be the ground state (Pr 62).

If an odd-odd nucleus has an isomeric state, it will frequently result from an angular momentum recoupling within the configuration which forms the ground state. Thus for odd-odd nuclei obeying Nordheim's weak rule, it is not uncommon to find the ground state with one of the two weak rule spin values and an isomeric state with the other. Although the triplet state of the $\vec{\sigma}_p, \vec{\sigma}_n$ interaction is usually favored for the ground state, the singlet state may be the ground state for nuclei obeying the weak rule. This may be accounted for by a small change in $V_1$ of the interaction potential of Equation 6 which causes a shift in relative energies as shown by de Shalit and Walecka (Sh 61).

Some examples of ground state and isomeric states in nuclei following the weak rule and having $J = |j_p - j_n|$ or $J = j_p + j_n$ are: $^{34}$Cl($0^+$), $^{34m}$Cl($3^+$) arising from the configuration ($\pi d_{3/2}$, $\nu d_{5/2}$) and $^{26}$Al($5^+$), $^{26m}$Al($0^+$) with the configuration ($\pi d_{5/2}^{-1}$, $\nu d_{5/2}^{-1}$).

Other examples are found in $^{38}$K, $^{60}$Sc, $^{54}$Co and $^{82}$Be (Br 60). $^{58}$Co also obeys the weak rule and has an isomeric state. The properties of its levels will be discussed in more detail in Chapter V.
A.2. **Excited States**

The spins and parities of excited states in odd-odd nuclei may arise from single particle states in several possible ways:

1) Raising of an unpaired nucleon to a higher energy state,

2) Recoupling of the angular momenta of the unpaired particles to another value in the range, \[ |j_p - j_n| \leq J < j_p + j_n, \]

3) Breaking of a pairing bond and raising one nucleon from either a core state or a partially filled state to a state of higher energy,

4) Collective motions such as rotations and vibrations.

Examples of three of these types of excited states are found in $^{68}$Co. As will be discussed in more detail in Chapter V, the levels at 0, 25, 366, and 457 keV seem to be predominantly due to angular momentum recoupling within the $(\pi f_{7/2}^{-1}, \nu 2p_{3/2}^{-1})$ configuration. The level at 53 keV will be seen to be largely of type 1 with the odd neutron being raised to the $f_{5/2}$ level. An example of breaking a pairing bond is also present in $^{68}$Co. There is evidence (Sc 72) for the existence of some component of $(\nu f_{7/2}^{-1})$ in the ground state. Here one pair within the closed $f_{7/2}$ shell is broken and the hole in the $2p_{3/2}$ shell is filled.

As yet no rotational or vibrational states have been identified in $^{68}$Co.
A. 3. Configuration Mixing

Although single particle states have been identified in many nuclei, these are usually not sufficient to account for the experimentally determined level schemes. The next approach is to consider configuration mixing between single particle states which are closely spaced in energy.

A good example of configuration mixing is given by Kurath (Ku 60) for the nucleus $^{208}$Pb. This nucleus has a closed proton shell at $Z = 28$ and two holes in the neutron shell $N = 126$. To describe the excited states of this nucleus various combinations for the distribution of the two holes in the $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, $1f_{13/2}$, and $2f_{7/2}$ are considered. All possible ways of distributing the holes in these states are considered and these produce a sequence of single particle energy levels and spins in the range $0^+$ to $4^+$ and $5^-$ to $7^-$. This sequence does not adequately reproduce the experimental spectrum so a mixture of the various configurations is considered. The states of $vp_{1/2}^{-2}$, $vf_{5/2}^{-2}$ and $vp_{3/2}^{-2}$ each produce levels with $J = 0^+$, and the ground state, as an example, is described by the wave function:

$$\psi_{g.s.} (J = 0^+) = 0.74 (p_{1/2})^{-2} + 0.11 (f_{5/2})^{-2} + 0.15 (p_{3/2})^{-2}$$
When other states are treated in a similar manner the agreement between the calculated and observed spectra is considerably improved.

Evidence has been presented (Sc 72) for some mixing of the \((\nu l_{7/2}^{-1})\) configuration into the ground state of \(^{60}\text{Co}\), and it is further suggested that this configuration may be important in higher excited states (see Chapter V).

B. Transition Probability

The quantities of interest in nuclear structure studies are the quantum mechanical wave functions which completely describe each level of the nucleus. By using different models which emphasize different aspects of our knowledge of nuclei, various forms of wave functions can be obtained. To test these diverse models one uses the wave functions with an appropriate quantum mechanical operator to calculate quantities readily measured in the laboratory. One such quantity is the mean lifetime of the nuclear excited states. The mean lifetime is the reciprocal of the transition probability which is given by:

\[
T(L; M) = \frac{8\pi (L+1)}{L([2L+1]!!)^2} \frac{1}{h} \left(\frac{\omega}{c}\right)^{2L+1} B(M, L)
\]

where \(L\) is the angular momentum carried away by a photon of energy \(\hbar \omega\), and \(B(M, L)\) is the reduced transition probability given by:
\[
B(\mathcal{M}, L; J_i - J_f) = \frac{1}{2J_i+1} \sum_{M_L M_i} |\langle J_f M_L | M_{LM} | J_i M_i \rangle|^2. \tag{8}
\]

where \(\mathcal{M}\) refers to magnetic multipole radiation (replaced by \(\mathcal{E}\) for electric multipole radiation), and \(M_{LM}\) is the magnetic multipole operator of order \(L\) and magnetic quantum number \(M\) (\(Q_{LM}\) for the electric multipole operator). Using the Wigner-Eckhart Theorem to remove the dependence on the magnetic quantum numbers, we obtain

\[
B(\mathcal{M}, L; J_i - J_f) = \frac{2J_f+1}{2J_i+1} |\langle J_f | M_L | J_i \rangle|^2. \tag{9}
\]

A good choice of nuclear wavefunctions is indicated by agreement between theoretical values of \(B(\mathcal{M}, L)\) and the values derived from experimental mean lifetimes (Ei 70).

The next chapter presents the results of the lifetime measurements for several excited states in \(^{68}\text{Co}\). With the existence of experimental lifetimes, the validity of existing and future theoretical descriptions of \(^{68}\text{Co}\) can be better tested.

C. \(^{68}\text{Co}\) Calculations

The nuclear structure calculations on \(^{68}\text{Co}\) have been done by Vervier (Ve 66a) and McGrory (Mc ). Vervier considered the
available orbits to be \( 1f_{7/2} \) for the proton hole and seniority 1 states for three neutrons in the \( 2p_{3/2}, 2p_{1/2}, \) and \( 1f_{5/2} \) states. The effective neutron-neutron interaction was taken from the work of Auerbach (Au 66) on the Ni isotopes. The effective proton-neutron interaction was taken from the work by Vervier (Ve 66b) and consisted of a zero range force (Equation 6) whose strength was determined from available data on nuclei between \(^{48}\text{Ca}\) and \(^{57}\text{Ni}\) with a single neutron in the \( 2p_{3/2} \) orbit.

The calculation by McGrory as taken from Ref. (Sc 72) was based on an inert \(^{48}\text{Ca}\) core and single particle energies in the \( f-p \) shell consistent with the spectrum of \(^{57}\text{Ni}\). Matrix elements used in the calculation were of the Kuo and Brown type (Ku 68).

The spins and energies predicted in these calculations will be compared with experimental values in Chapter V.
CHAPTER III
LIFETIME MEASUREMENTS

A. Introduction

The Doppler Shift Attenuation Method (DSAM) for measuring lifetimes of excited states in nuclei is based on the principle that the observed frequency, \( v \), of electromagnetic radiation, and hence its energy, \( h v \), is larger when a source of radiation moves toward a stationary observer and smaller when it moves away. For nuclei produced in a reaction and moving in some medium, the magnitude of the Doppler shift can be controlled by varying the time required to decelerate the ion. The maximum obtainable shift occurs for nuclei recoiling into vacuum. For nuclei recoiling into a solid or gaseous medium, the slowing of the ion and consequently the magnitude of the shift is dependent upon the mass and charge of the moving ion and the mass, charge and density of the stopping medium. A check on the results of lifetime measurements can be made by using different stopping materials (assuming that the stopping powers of the media are adequately known or represented by available theoretical descriptions).
B. Formalism

The measured energy of a gamma ray emitted by a recoiling nucleus moving at non-relativistic velocities is given by:

$$E_\gamma = E_0 \left[ 1 + \frac{v(t)}{c} \cos \theta \right]$$  \hspace{1cm} (10)

where $E_\gamma$ is the measured energy, $E_0$ is the energy of the gamma ray emitted from the nucleus when at rest, $v(t)$ is the velocity of the nucleus at the time of decay; and $\theta$ is the angle between the direction of motion of the decaying nucleus and the direction of emission of the $\gamma$ ray. In a DSAM experiment the decay of an ensemble of nuclei is observed and a time averaged energy is measured. To calculate an expression for this average energy, $E_\gamma$ is weighted by the fraction of nuclei which have not decayed after a time $t$, and the expression is then integrated over all time:

$$\langle E \rangle = \int_0^\infty e^{-t/\tau} E_0 \left[ 1 + \beta(t) \cos \theta \right] dt / \int_0^\infty e^{-t/\tau} dt$$  \hspace{1cm} (11)

where $c \beta(t) = v(t)$ and $\tau$ is the mean lifetime of the state of interest.

This can be rewritten as:

$$\langle E \rangle = E_0 \left[ 1 + \beta(0) F(\tau) \cos \theta \right]$$  \hspace{1cm} (12)

where

$$F(\tau) = \frac{1}{\beta(0) \tau} \int_0^\infty \beta(t) e^{-t/\tau} dt$$  \hspace{1cm} (13)
and $c\beta(o)$ is the initial recoil velocity of the nuclei. The quantity $F(\tau)$ is called the attenuation coefficient.

Consider the average energies $\langle E_1 \rangle$ and $\langle E_2 \rangle$ measured at angles $\theta_1$ and $\theta_2$, respectively:

$$\langle E_1 \rangle = E_0 \left[1 + \beta(o) F(\tau) \cos \theta_1 \right]$$

$$\langle E_2 \rangle = E_0 \left[1 + \beta(o) F(\tau) \cos \theta_2 \right].$$

These may be combined to obtain another expression for $F(\tau)$:

$$F(\tau) = \frac{\langle E_1 \rangle - \langle E_2 \rangle}{E_0 \beta(o) \left(\cos \theta_1 - \cos \theta_2\right)}.$$  
(15)

The numerator is the Doppler shift of the gamma ray energy for ions slowing down in some stopping medium. The denominator represents the Doppler shift for nuclei moving at the constant initial velocity $v(o)$, i.e. an unattenuated shift for ions recoiling into vacuum, $\Delta E_{\text{vac}}$. Thus $F(\tau)$ can be more clearly understood as the ratio of the attenuated to the unattenuated shifts:

$$F(\tau) = \frac{\Delta E_{\text{atten}}}{\Delta E_{\text{vac}}}.$$  
(16)

### B.1. Methods of Determining $\beta(o)$

A value of $\beta(o)$ is necessary in order to calculate $\Delta E_{\text{vac}}$ and the theoretical value of $F(\tau)$. The standard method is to detect the
outgoing light particle in coincidence with the gamma ray and then to
calculate ρ(o) from the kinematics. One problem with this method
is that counting rates are too low for states which are weakly
populated.

Two additional methods are available for determining ρ(o)
both of which entail the determination of an average component
of velocity along the z axis, the beam axis.

One can experimentally measure the average z component
of velocity by measuring the Doppler shift for a very thin target.
In this case most of the nuclei escape from the target with nearly
their initial recoil velocity. Since there is little attenuation of
the initial velocity, F(τ) ≈ 1. If the angles are measured with
respect to the beam direction one has:

$$
\langle \beta_z(o) \rangle = \frac{\Delta E_{\text{vac}}}{E (\cos \theta_1 - \cos \theta_2)}.
$$

(17)

The major difficulty with this approach is that the yield is low
for states with low cross sections. Thus it may be used only for
very strong transitions.

The second method involves computing the average z component
from a knowledge of the kinematics and the angular distribution
of outgoing light particles. From a measured or reasonably assumed
angular distribution of the outgoing light particle one can calculate
the angular distribution, \( \frac{d\sigma}{d\Omega}(\theta, \phi) \), of the recoiling ion. The average value of the z component of velocity is then found using the relationship:

\[
\langle \beta_z(0) \rangle = \frac{\int \frac{v(\theta)}{c} \cos \theta \frac{d\sigma}{d\Omega}(\theta, \phi) d\Omega}{\int \frac{d\sigma}{d\Omega}(\theta, \phi) d\Omega}
\]  

(18)

B.2. Slowing of the Recoiling Ions

The recoiling ion gives up its energy by two mechanisms:
1) electronic stopping, and 2) atomic or nuclear stopping. The former dominates at higher velocities \((v/c > 0.01)\) and is due to the recoil ion transferring energy by ionization or electronic excitation of the atoms in the stopping material. The electronic stopping power is proportional to the velocity of the ion:

\[
\frac{dE}{dx_e} = -kv
\]  

(19)

or in the formalism of Blaugrund (Bl 66)

\[
\frac{dE}{d\rho/e} = k\varepsilon^{1/2}
\]  

(20)

where \( \varepsilon \) and \( \rho \) are dimensionless variables related to energy and distance.
Nuclear stopping dominates at lower velocities \((v/c << 0.01)\) and is due to transfer of energy to the atoms of the stopping material by atomic or nuclear scattering of the ion through large angles. The nuclear stopping power is more complex than the electronic and is described in the theory of Lindhard, Scharff, and Schiott (LSS) \((\text{Li 63})\). The nuclear stopping power and an approximation to it are shown in Figure 2. The approximations to the curve are:

\[
\frac{d\varepsilon}{d\varepsilon_n} = \begin{cases} 
0.4 \varepsilon^{-1/3} & (1.2 < \varepsilon < 20) \\
0.4/1.2 & (0.1 < \varepsilon < 1.2) \\
0.4 \varepsilon^{1/3}/0.12 & (0.01 < \varepsilon < 0.1)
\end{cases}
\]

as taken from \((\text{Wo 69})\).

In order to account for change in direction of the recoiling ion in the calculation of \(F(\tau)\), the velocity must be multiplied by \(\cos \phi\):

\[
\beta(t) = \frac{v(t)}{c} \cos \phi
\]

where \(\phi\) is the angle between the initial direction of recoil and the direction of motion at time \(t\), and the bar indicates a time average. The expression for average energy then becomes:
Figure 2 LSS theoretical nuclear stopping power and approximation of Wosniak et al. (Wo 69).
Approximation to Theoretical Curve for Calculation

\[ \left( \frac{d\epsilon}{d\rho} \right)_n \]

\[ \epsilon^{1/2} \]
\[ \langle E \rangle = E_0 \left\{ 1 + \left[ \frac{1}{\tau} \int_0^\infty e^{-t/\tau} \frac{v(t)}{c} \cos \phi \, dt \right] \cos \theta \right\} \]  

(23)

and the attenuation coefficient:

\[ F(\tau) = \frac{1}{\beta(0)\tau} \int_0^\infty \beta(t)e^{-t/\tau} \cos \phi \, dt. \]  

(24)

The quantity \( F(\tau) \) is calculated using the code VCORR of Sprague (Sp 71).

**B.3. Target Thickness Corrections**

Any target used has a finite thickness. This means that reactions occurring near the back of the target can produce residual nuclei which recoil into the vacuum. If a significant number of excited nuclei recoil into vacuum and subsequently decay, the measured value of \( F(\tau) \) will be larger than it would be if no ions escaped. This effect must be considered when calculating the theoretical value of \( F(\tau) \).

A correction to \( F(\tau) \) has been shown by Robertson (Ro 70) to be:

\[ F(\tau)_\text{obs} = f F(\tau)_\text{calc} + (1-f) \frac{\bar{v}_e}{\bar{v}(0)} \]  

(25)

where \( F(\tau)_\text{calc} \) is the attenuation factor for an infinitely thick target, \( f \) is the fraction of the recoiling nuclei which de-excite
within the target, (1-f) is the fraction decaying in vacuum, $\bar{v}_e$ is the average velocity of the ions escaping into vacuum, and $v(o)$ is the initial recoil velocity. These quantities have been calculated in the formalism of Blaugrund (Bl 66) using the programs of Sprague (Sp 71).

For $^{58}$Co with initial recoil energy of 0.620 MeV the range is less than 0.2 mg/cm² in $^{55}$Mn, thus a target thickness of 3.5 mg/cm² corresponds to a thickness of more than 17 ranges. The effect of the finite target thickness on the $F(\tau)$ curve for this target is shown in Figure 3.

B.4. Cascade Correction

Another problem involved in lifetime measurements using the singles method is the possibility that the state of interest will be populated by cascades from higher states. Under this condition the recoiling nucleus would be slowed before the state of interest is populated. This would result in a smaller measured value of $F(\tau)$ and a larger value for the measured mean lifetime.

If the lifetimes of states feeding the level of interest are known and if the relative population of the state of interest from each cascade is known, the lifetime can be corrected for the
Figure 3  Effect of a finite target thickness on $F(\tau)$. The curves are for 0.620 MeV $^{68}$Co ions produced in a 3.5 mg/cm$^2$ $^{68}$Mn target.
EFFECT OF FINITE TARGET THICKNESS T

- T = 3500 $\mu g/cm^2$
- T = $\infty$

$F(\tau)$ vs. $\tau$

$\tau$ (sec)

$F(\tau)$

$10^{-14}$  $10^{-13}$  $10^{-12}$  $10^{-11}$
cascade effect. The observed value of the attenuation coefficient is given by Bell et al. (Be 69a):

\[ F(t_i) = \nu_i F_i(t_i) + \sum_{i=2}^{\infty} \frac{\tau_i F_i(t_i) - \tau_{i-1} F_i(t_i)}{\tau_i - \tau_{i-1}} \nu_i \frac{v_i(0)}{v_i(0)} \]  

(26)

where the subscript \( i \) refers to the level of interest, \( \nu_i \) is the relative population of this level from the \( i^{th} \) level, \( \nu_i \) is the relative amount of direct population, \( \tau_i \) and \( F_i(t_i) \) are the lifetime and attenuation coefficient for the \( i^{th} \) level and \( v_i(0) = v_i(t=0) \cos \phi \) accounts for the case with different values for the initial recoil velocity.

C. Experiment

C.1. Targets

A self-supporting Manganese target with thickness of approximately 3.4 mg/cm\(^2\) was used to measure the attenuated Doppler shift of gamma rays produced in the reaction \(^{55}\)Mn(\(\alpha, n \gamma\))\(^{58}\)Co.

The target was prepared by electrodepositing the Mn from a Mn SO\(_4\) solution onto an aluminum foil in the manner described by Bondar et al. (Bo 60). The aluminum was etched away with a solution containing Na OH, leaving a self-supporting Mn foil. Some Al and Na remained as contaminants in the target. The gamma ray
singles spectrum for 9.5 MeV alpha particles incident on this target is shown in Figure 4.

A second target for the DSAM experiment consisted of approximately 75 micrograms/cm² of Mn evaporated onto a carbon foil with a thickness of approximately 720 micrograms/cm². This target permitted a second set of lifetimes to be measured for $^{58}$Co ions recoiling into carbon.

Two additional thin targets of Mn with thickness of approximately 75 micrograms/cm² and 30 micrograms/cm² were produced by evaporating Mn onto carbon foils having a thickness of approximately 50 micrograms/cm². These were mounted in the chamber with the carbon side facing the beam and were used to obtain values for $\Delta E_{\text{vac}}$ as discussed in Section B.1. The Doppler shifts for several peaks using the 75 microgram/cm² target are shown in Figure 5.

C.2. Chamber

The target chamber consisted of a standard 1 inch section of Schedule 40 Aluminum pipe with the side walls milled to a .044 inch thickness. The beam was collimated to a diameter of approximately 0.1" with a series of three tantalum collimators located approximately 20", 14" and 10" in front of the target (Sp 71).
Figure 4  Gamma-ray singles spectrum from the reaction $^{55}\text{Mn}(\alpha, n \gamma)^{58}\text{Co}$ at $E_\alpha = 9.5$ MeV using electro-deposited target. The gamma-ray energies are given in keV.
Figure 5  Doppler shifts from 75 microgram/cm² Mn target. Note absence of shift for 511 keV peak.
COUNTS PER CHANNEL (X 100)

\[ \frac{\text{Counts}}{\text{Channel}} \times 100 \]

\[ \begin{array}{c}
\text{CHANNEL NUMBER} \\
\hline
700 & 800 & 900 & 1000 & 1100 & 1200 & 1550 & 1650 \\
\hline
\end{array} \]

\[ \text{\textit{\( \theta_\gamma = 150^\circ \)}} \]

\[ \text{\textit{\( \theta_\gamma = 30^\circ \)}} \]

\[ \begin{array}{c}
321 \text{ keV} \\
366 \\
432 \\
511 \\
583 \\
727 \\
774 \\
2.44 \pm 0.03 \text{ keV} \\
2.77 \pm 0.03 \text{ keV} \\
3.15 \pm 0.05 \text{ keV} \\
2.1 \pm 0.2 \text{ keV} \\
5.6 \pm 0.3 \text{ keV} \\
5.8 \pm 0.3 \text{ keV} \\
\end{array} \]
C.3. **Electronics**

Gamma ray spectra were taken using an Ortec true coaxial Ge(Li) detector with an active volume of 38.5 cc (39.1 mm dia. x 37.5 mm). The resolution of the detector-electronics system during the lifetime measurements was in the range between 5 and 6 keV (FWHM) as measured for the 1332 keV gamma ray peak from $^{60}$Co.

The detector was coupled to an Ortec Model 120 preamplifier and the output signal was amplified by an Ortec Model 440 A Selectable Active Filter amplifier. The amplifier output was analyzed in a Northern Scientific NS-625 Dual ADC which is interfaced with an IBM 1800 computer. The spectra were collected in 4096 channels (~0.5 keV/channel) and were subsequently stored on magnetic disk for later analysis.

C.4. **Doppler Shift Measurements**

The excited states in $^{60}$Co were produced in the reaction $^{55}$Mn($\alpha$, n $\gamma$)$^{60}$Co. This reaction was induced by a 9.5 MeV beam of doubly ionized $^4$He, produced by the Model CN Van de Graaff accelerator of The Ohio State University. Beam currents were $\sim$5 na for thick Mn targets, $\sim$70 na for the intermediate targets,
and \(~160\) na for the thinnest target. The beam was stopped in a Faraday cup located about 1.2 meters beyond the target and the beam current was integrated by a Brookhaven Model 1000 current integrator.

The detector was positioned 11.2 cm from the target center on a turntable which could be rotated about the target center. With this detector position and the above beam currents, the count rates ranged between 1000 and 3000 counts per second, depending on the target used. The count rates were kept nearly constant for the individual target.

Spectra were taken at 30° and 150° with respect to the beam direction in intervals of from 1 1/2 to 2 hours duration. After each interval, the angle was changed and the process repeated until adequate statistics (\(~10\%) were obtained for the weaker transitions. Total data collection time was 19 hours for the thick Mn target, 48 hours for the intermediate thickness target and 56 hours for the thick carbon-backed target.

One difficulty which may arise in DSAM experiments is that of the shifting of peak centroids due to electronic drift. This can be particularly serious when the runs are of long duration. To monitor this effect a \(^{60}\)Co source was placed on the rotation table in a fixed position relative to the detector. This source
along with the annihilation radiation peak provided gamma rays, unshifted by the Doppler effect, with energies of 511, 1173, and 1332 keV. Any significant shifting of these peaks would indicate the presence of electronic drift.

The monitor peaks were centroid analyzed in the individual spectra, then the spectra at each angle were summed. Spectra for which the centroids of these peaks showed too large a deviation from the average centroid were excluded from this sum. The monitor peaks in the summed spectra were then analyzed for centroid shifts. For the thick Mn target data the monitor peak shifts were well within the uncertainties in the measured energy shifts for the peaks in the same energy range (see Table 1). The shifts for the monitor peaks in the thick carbon spectra were considerably larger than in the thick Mn target spectra.

C. 5. Determination of $\bar{\varepsilon}_z(o)$

A value for $\bar{\varepsilon}_z(o)$ was obtained by making the assumption of isotropic distribution of the light particle in the center of mass system, then finding $\bar{\varepsilon}_z(o)$ as discussed in Section B.1. To check this assumption $\bar{\varepsilon}_z(o)$ was also calculated from the Doppler shift of gamma rays from a thin target as discussed in Section B.1. The quantity $\Delta E$ was measured using the two thin Mn targets.
<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$E_{30^\circ} - E_{150^\circ}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stopping Medium C Mn</td>
</tr>
<tr>
<td>321</td>
<td>0.43 ± 0.04 0.21 ± 0.03</td>
</tr>
<tr>
<td>366</td>
<td>0.76 ± 0.04 0.30 ± 0.03</td>
</tr>
<tr>
<td>432</td>
<td>0.65 ± 0.05</td>
</tr>
<tr>
<td>511$^a$</td>
<td>0.11 ± 0.02 -0.01 ± 0.01</td>
</tr>
<tr>
<td>727</td>
<td>3.98 ± 0.27 2.42 ± 0.15</td>
</tr>
<tr>
<td>774</td>
<td>4.09 ± 0.25 2.50 ± 0.18</td>
</tr>
<tr>
<td>988</td>
<td>2.4 ± 1.3</td>
</tr>
<tr>
<td>1173$^a$</td>
<td>0.21 ± 0.03 -0.09 ± 0.04</td>
</tr>
<tr>
<td>1332$^a$</td>
<td>0.12 ± 0.03 -0.08 ± 0.05</td>
</tr>
<tr>
<td>1378</td>
<td>9.37 ± 0.76 4.71 ± 0.60</td>
</tr>
<tr>
<td>1435</td>
<td>3.6 ± 2.2 1.55 ± 0.89</td>
</tr>
</tbody>
</table>

$^a$ Monitor peaks.
of approximately 30 and 75 μg/cm² thickness. These values of $\Delta E$ were plotted vs. target thickness and linearly extrapolated to find a zero thickness value $\Delta E_{\text{vac}}$ (Figure 6). Only two transitions (321 keV and 366 keV) were strong enough to have reasonably small uncertainty in $\Delta E_{\text{vac}}$. However, agreement within the error limits was obtained between $\bar{\beta}_z(0)$ determined from the isotropy assumption and its value for the five transitions (321, 366, 432, 727, and 774 keV) for which $\Delta E_{\text{vac}}$ could be determined.

An uncertainty of 4% was assumed for the chosen value of $\bar{\beta}_z(0) = 4.83 \times 10^{-3}$. This uncertainty resulted in 7.9% uncertainty in the adopted average recoil energy ($E_R = 0.620 \text{ MeV} \pm 0.050 \text{ MeV}$).

As is shown in Figure 7, the $F(\tau)$ curve is fairly insensitive to the value of $E_R$. The insensitivity of $F(\tau)$ to energies over the range of tens of kiloelectron volts plus the agreement between measured and assumed values of $\bar{\beta}_z(0)$ indicate that the chosen value of recoil energy $E_R = 0.620 \pm 0.050 \text{ MeV}$ is reasonable for this experiment.

D. Analysis

D.1. Centroid Analysis

Experimental values of the Doppler shifts were obtained from the centroid shifts of the gamma-ray peaks. To obtain the peak
Figure 6: Doppler shifts from two thin targets extrapolated to zero thickness to obtain estimate of $\beta_z(0)$. 
VACUUM RECOIL APPROXIMATION
THIN Mn TARGETS

ΔE (keV)

432 keV
ΔE_{VAC} = 3.74 ± 0.65

366 keV
ΔE_{VAC} = 3.17 ± 0.15

321 keV
ΔE_{VAC} = 2.57 ± 0.13

THICKNESS (μg/cm²)
Figure 7  Effect of different average initial recoil energies on $F(\tau)$. 
$F(\tau)$ vs. $\tau$  

STOPPING MEDIUM - MAGANESSE

$fe = 1.16$

$fn = 0.60$

$\langle E \rangle = 0.520 \text{ MeV}$

$\langle E \rangle = 0.620 \text{ MeV}$
centroid, an estimate of the background was made by fitting a quadratic function to six or more points on each side of the peak. The background for each peak channel was calculated and subtracted from the counts recorded in each channel. The centroid was then calculated using the relationship:

$$C = \sum_{K=i}^{f} \frac{K N_K}{N_K}$$

(27)

Where $C$ is the centroid, $N_K$ is the number of counts in the $K^{th}$ channel after the background has been subtracted, $i$ is the channel number of the lower end of the peak and $f$ is the channel number of the upper end of the peak.

The statistical uncertainty in the centroid was obtained from statistical uncertainty in the number of counts in each channel by the usual method of error propagation. The uncertainty is given by:

$$\Delta C = \frac{\sum K^2 \Delta N_K^2}{(\sum N_K)^2} + \frac{(\sum \Delta N_K^2)(\sum K N_K)^2}{(\sum N_K)^4}$$

(28)

where $\Delta N_K$ is the statistical uncertainty in the number of counts in the $K^{th}$ channel.

A typical result of the centroid analysis is shown in Figure 8. The vertical line marks the position of the centroid. The quadratic fit to the background is also shown.
Figure 8  Sample centroid analysis using 774 keV peak. The vertical line marks the centroid. The triangles mark the peak boundaries and the center of the background on each side of the peak. Also shown is the fit to the background.
D.2. **Lifetime Determination**

The measurement of the lifetime of an excited state in a nucleus requires a comparison between the lifetime and a known time interval. This known interval is the slowing-down time of an ion moving in some medium.

The attenuation factor, the ratio of the attenuated shift to the full shift, is a function of the slowing-down time and the lifetime. A theoretical value of the attenuation factor is calculated using the theory of Lindhard, Scharff and Schiott (LSS) (Li 63) as modified by Blaugrund (Bl 66) to include the effect of large angle scattering. The measured lifetime is obtained by comparing the measured attenuation factor with the theoretical attenuation factor, plotted as a function of lifetime (see Figure 10).

Blaugrund et al. (Bl 67) and Currie et al. (Cu 69) have found discrepancies between experimental stopping powers and the stopping powers calculated using the LSS theory as modified by Blaugrund (Bl 66). This discrepancy is corrected for by including the factors $f_e$ and $f_n$ as corrections to the specific energy loss in electronic and nuclear collisions respectively:

$$
\left( \frac{dc}{dp} \right)_{\text{total}} = f_e \left( \frac{dc}{dp} \right)_{\text{electronic}} + f_n \left( \frac{dc}{dp} \right)_{\text{nuclear}} \quad (29)
$$
where \( \varepsilon \) and \( \rho \) are the dimensionless energy and distance variable used in Section B.2. The values of \( f_e \) and \( f_n \) chosen for this experiment by comparison with the works of Blaugrund et al. and Currie et al. are:

\[
\begin{align*}
  f_e &= 1.16 \pm 0.16 \\
  f_n &= 0.80 \pm 0.20
\end{align*}
\]

for both the carbon and Mn stopping material. The calculated \( F(\tau) \) curve and the effect of the uncertainty in \( f_e \) and \( f_n \) are shown in Figure 9.

The uncertainties in the lifetimes arise from two sources:

1) the statistical uncertainties in the centroids of the peaks and
2) the uncertainty in the theoretical values of the stopping power.

The former uncertainty consists of two parts: 1) the standard deviation in the centroid as calculated using Equation 28 and 2) the variation of the centroid with differences in channels chosen during the analysis. This latter contribution is estimated by doubling the standard deviation.

The uncertainty in the theoretical values of the stopping power is not statistical in nature. This uncertainty arises from
Figure 9 $F(t)$ vs. $t$ including effects of uncertainties in stopping power.
$F(T) \text{ vs. } T$

Stopping Medium: Manganese

Average Initial Recoil Energy

$<E> = 0.620 \text{ MeV}$

$<\beta> = 0.48\%$

- $f_e = 1.32$, $f_n = 1.0$
- $f_e = 1.16$, $f_n = 0.8$
- $f_e = 1.00$, $f_n = 0.6$

$\tau$ (sec)
Figure 10  Method used for lifetime and error determination.
LIFETIME FOR 774 keV TRANSITION

\(<E> = 0.620 \text{ MeV}\)

\(F(\tau) = 0.39 \pm 0.03\)
\(\tau = 0.26^{+0.12}_{-0.08} \times 10^{-12}\)
the incompleteness of the data available on the stopping powers of recoiling ions moving in the stopping medium and is on the order of ± 20 per cent.

The method of determining the lifetime and errors is shown in Figure 10. This is a conservative estimate of the uncertainties but in turn gives a high degree of confidence that the results lie within the given range.

E. Results

The partial decay scheme of $^{58}$Co in Figure 11 shows the transitions studies in the Doppler shift experiment. The summed spectra for the forward and back angles were analyzed for centroid shifts and the results were checked. The two analyses agreed within statistics and the mean lifetimes obtained were averaged to give the mean lifetime of the levels. Values of the mean lifetimes were obtained using manganese and carbon as the stopping media for the recoiling ions. The lifetimes for both stopping media agreed within statistics and are listed in Table 2. The adopted experimental lifetimes are the values from the thick Mn target data. The results from the carbon backed target were not included, except for the 432 and 988 keV transitions because of the larger electronic drifts during the run (Table 1).
<table>
<thead>
<tr>
<th>Level</th>
<th>( E_\gamma )</th>
<th>( F(\tau) )</th>
<th>( \tau ) (10^{-12} \text{ sec})</th>
<th>( F(\tau) )</th>
<th>( \tau ) (10^{-12} \text{ sec})</th>
</tr>
</thead>
<tbody>
<tr>
<td>366</td>
<td>366</td>
<td>.10 ± .01^a</td>
<td>1.70^{1.00}_{-0.00}</td>
<td>.28 ± .02^a</td>
<td>0.92^{1.00}_{-0.00}</td>
</tr>
<tr>
<td>374</td>
<td>321</td>
<td>.08 ± .01</td>
<td>2.10^{1.00}_{-0.00}</td>
<td>.17 ± .02</td>
<td>1.73^{1.00}_{-0.00}</td>
</tr>
<tr>
<td>457</td>
<td>432</td>
<td>.22 ± .02^a</td>
<td>1.25^{1.00}_{-0.00}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>886</td>
<td>774</td>
<td>.39 ± .03</td>
<td>.25^{1.11}_{-0.07}</td>
<td>.63 ± .05</td>
<td>0.26^{1.00}_{-0.00}</td>
</tr>
<tr>
<td>1184</td>
<td>727</td>
<td>.40 ± .03</td>
<td>.24^{1.12}_{-0.07}</td>
<td>.66 ± .05</td>
<td>0.24^{1.00}_{-0.00}</td>
</tr>
<tr>
<td>1354</td>
<td>988</td>
<td></td>
<td>.29 ± .16</td>
<td></td>
<td>0.90^{1.00}_{-0.00}</td>
</tr>
<tr>
<td>1378</td>
<td>1378</td>
<td>.41 ± .06</td>
<td>.23^{1.13}_{-0.09}</td>
<td>.82 ± .08</td>
<td>0.15^{1.00}_{-0.00}</td>
</tr>
<tr>
<td>1435</td>
<td>1435</td>
<td>.17 ± .08</td>
<td>.87^{1.00}_{-0.00}</td>
<td>.27 ± .18</td>
<td>1.01^{1.00}_{-0.00}</td>
</tr>
</tbody>
</table>

^a^ Corrected for cascades from higher levels.
Figure 11 $^{58}$Co gamma-ray transitions studied by DSAM.
Table 3 summarizes the known information about the transitions studied. The energies, spins and branching ratios are from (Ro 71). The partial lifetimes were computed from the experimental lifetimes and the branching ratios by dividing the lifetime by the fraction of decays which proceed by the observed branch. The last two columns list the hinderances and enhancements (transition strengths) of the measured transition probabilities \((1/\tau)\) over the Weisskopf single particle estimates for pure M1 and pure E2 transitions. These factors are obtained by dividing the Weisskopf lifetime estimates by the experimental values of partial lifetime.

Figure 12 shows the systematics for the enhancement of E2 transitions in 1f-2p nuclei (Ar 71). By comparison it can be seen that the transitions studied (up to and including the 727 keV transition) are expected to be predominantly M1.

366 keV Level

Approximately 84.4 per cent of the population of the 366 keV level came directly from the reaction and 15.6 per cent from cascades from higher levels. The levels at 885 keV and 1040 keV contributed about 10 per cent of the population and the remaining 5.5 per cent came from 5 other levels. The relative contributions
<table>
<thead>
<tr>
<th>Level (keV)</th>
<th>( E_\gamma )</th>
<th>( J_i^m )</th>
<th>( J_f^m )</th>
<th>Branching (%)</th>
<th>Partial Lifetime ( (10^{-12} \text{ sec}) )</th>
<th>( ^1M^{12} )</th>
<th>( ^2E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>366</td>
<td>366</td>
<td>(3)+</td>
<td>2+</td>
<td>98.2</td>
<td></td>
<td>1.73_{-0.60}^{+1.80}</td>
<td>0.380</td>
</tr>
<tr>
<td>374</td>
<td>321</td>
<td>(5)+</td>
<td>(4)+</td>
<td>94</td>
<td></td>
<td>2.23_{-0.70}^{+1.30}</td>
<td>0.437</td>
</tr>
<tr>
<td>457</td>
<td>432</td>
<td>(4)+</td>
<td>5+</td>
<td>83.2</td>
<td></td>
<td>1.50_{-0.58}^{+0.45}</td>
<td>0.266</td>
</tr>
<tr>
<td>886</td>
<td>774</td>
<td>(4)+</td>
<td>(3)+</td>
<td>51</td>
<td></td>
<td>0.49_{-0.07}^{+0.11}</td>
<td>0.142</td>
</tr>
<tr>
<td>1184</td>
<td>727</td>
<td>(5, 4)+</td>
<td>(4)+</td>
<td>69</td>
<td></td>
<td>0.35_{-0.07}^{+0.12}</td>
<td>0.240</td>
</tr>
<tr>
<td>1354</td>
<td>988</td>
<td>(2, 1)+</td>
<td>3+</td>
<td>48</td>
<td></td>
<td>1.88_{-0.62}^{+0.82}</td>
<td>0.018</td>
</tr>
<tr>
<td>1378</td>
<td>1378</td>
<td>?</td>
<td>2+</td>
<td>100</td>
<td></td>
<td>0.23_{-0.08}^{+0.13}</td>
<td>0.053</td>
</tr>
<tr>
<td>1435</td>
<td>1435</td>
<td>(0, 1, 2)+</td>
<td>2+</td>
<td>100</td>
<td></td>
<td>0.87_{-0.88}^{+3.60}</td>
<td>0.013</td>
</tr>
</tbody>
</table>
Figure 12  Enhancement and hinderance of E2 gamma radiation in the 1f-2p shell region.
Enhancement and Hindrance of E2 Gammas in the $f_{7/2}$ Shell

- Even-even
- Odd-A
- Odd-odd

Weisskopf Estimate

$E_\gamma$ (MeV)
from each of the levels is shown in Table 4. The lifetime of this level was corrected for the effect of these cascades using the method of Bell et al. (Be 69a) described in Section B.4. The correction reduced the measured lifetime by approximately 15 per cent.

**374 keV Level**

This level was populated by approximately 20 per cent from decays of four higher levels. No correction was made since the lifetime of the 1075 keV level contributing about 16 per cent of the population was not measured. However, based on the corrections to the levels at 366 and 457 keV, the correction to this level would probably reduce the lifetime by the order of 15 to 20 per cent.

**467 keV Level**

The level at 457 keV was populated by approximately 13 per cent from the 1040 keV level and 14 per cent from the 1185 keV level. The correction to the measured lifetime reduced its value by 19 per cent.

**Higher Levels**

The higher levels were primarily populated by the reaction and no corrections were made to the measured lifetimes.
TABLE 4

POPULATION OF THE 366 keV LEVEL
FROM THE DECAY OF HIGHER EXCITED STATES

<table>
<thead>
<tr>
<th>Level</th>
<th>$E_\gamma$</th>
<th>Relative Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>457</td>
<td>432</td>
<td>1.3</td>
</tr>
<tr>
<td>885</td>
<td>520</td>
<td>4.5</td>
</tr>
<tr>
<td>1040</td>
<td>674</td>
<td>5.5</td>
</tr>
<tr>
<td>1050$^a$</td>
<td>684</td>
<td>0.8</td>
</tr>
<tr>
<td>1358</td>
<td>988</td>
<td>1.2</td>
</tr>
<tr>
<td>1514$^a$</td>
<td>1148</td>
<td>1.2</td>
</tr>
<tr>
<td>1522</td>
<td>1157</td>
<td>1.1</td>
</tr>
</tbody>
</table>

$^a$) Lifetime of level not measured.
Gehringer et al. (Ge .72) have measured the lifetimes of ten levels in $^{68}$Co, five of which correspond to levels studied in this work. The results of the present work as shown in Table 5 agree with their values within error limits.

In the present work a value for the lifetime of the 1040 keV level was obtained using the 583 and 674 keV transitions. The values were not included because there was evidence of contaminants with energies 583 and 677 keV. The first contaminant arose from the reaction $^{19}$F$(\alpha, n\gamma)^{22}$Na and the second from the reaction $^{27}$Al$(\alpha, n\gamma)^{30}$P. The $^{19}$F was probably present on the tantalum of the slits and target holder and possibly in the target itself. The aluminum was present in the thick target and also the chamber walls.
### Table 5

<table>
<thead>
<tr>
<th>Level</th>
<th>$E_\gamma$</th>
<th>Gehring et al.</th>
<th>Present Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>112</td>
<td>0.18 ± 0.03 ns</td>
<td>---</td>
</tr>
<tr>
<td>366</td>
<td>366</td>
<td>1.43$^{+1.32}_{-0.59}$</td>
<td>1.70$^{+1.08}_{-0.90}$</td>
</tr>
<tr>
<td>374</td>
<td>321</td>
<td>0.90$^{+0.73}_{-0.35}$</td>
<td>2.10$^{+1.30}_{-0.70}$</td>
</tr>
<tr>
<td>457</td>
<td>432</td>
<td>1.17$^{+0.90}_{-0.44}$</td>
<td>1.25$^{+0.45}_{-0.38}$</td>
</tr>
<tr>
<td>886</td>
<td>774</td>
<td>0.20$^{+0.08}_{-0.05}$</td>
<td>0.25$^{+0.11}_{-0.07}$</td>
</tr>
<tr>
<td>1040</td>
<td>583</td>
<td>0.20$^{+0.08}_{-0.05}$</td>
<td>---</td>
</tr>
<tr>
<td>1044</td>
<td>933</td>
<td>&gt; 1.7</td>
<td>---</td>
</tr>
<tr>
<td>1050</td>
<td>938</td>
<td>0.20$^{+0.08}_{-0.05}$</td>
<td>---</td>
</tr>
<tr>
<td>1184</td>
<td>727</td>
<td>0.20$^{+0.08}_{-0.05}$</td>
<td>0.24$^{+0.19}_{-0.07}$</td>
</tr>
<tr>
<td>1354</td>
<td>988</td>
<td>---</td>
<td>0.90$^{+2.09}_{-0.59}$ b</td>
</tr>
<tr>
<td>1378</td>
<td>1378</td>
<td>---</td>
<td>0.23$^{+0.13}_{-0.08}$</td>
</tr>
<tr>
<td>1435</td>
<td>1435</td>
<td>---</td>
<td>0.87$^{+3.00}_{-0.80}$</td>
</tr>
</tbody>
</table>

a) Corrected for cascades.

b) Lifetime from carbon stopping data.
CHAPTER IV

SPIN AND MIXING RATIO DETERMINATIONS USING THE
COMPOUND NUCLEUS STATISTICAL MODEL

A. Introduction

A.1. Previous Work with Compound Nucleus Statistical Model

The compound nucleus statistical model (CNS) is applicable to many types of reactions. Initially it was formulated for inelastic neutron scattering by Hauser and Feshbach (Ha 52) based on the work of Wolfenstein (Wo 51). The model was extended to include three radiations such as \((p, \gamma \gamma)\) or \((n, n'\gamma)\) by Satchler (Sa 54), and Sheldon (Sh 63) included the spin orbit interaction in the formalism. In a review article, Sheldon and Van Patter (Sh 66) suggest the possible extension to include other reactions involving spin \(1/2\) particles \([(n,p), (p,n), (^3\text{He},n), (^3\text{He},p), \text{and} (p,n\gamma)]\). Birstein (Bi 68) performed experiments using \((\alpha,n\gamma)\) and \((p,n\gamma)\) reactions and successfully analyzed the results on the basis of this model. Other experiments using the \((p,n\gamma)\) reaction have been
performed by Davidson et al. (Da 70a and Da 70b) and by Iyengar and Robertson (Iy 71a and Iy 71b). In the present work angular distributions of several gamma-ray transitions were measured following the reaction $^{56}\text{Fe}(p, n\gamma)^{58}\text{Co}$, and the results were analyzed using the assumptions of the compound nucleus statistical model (Hauser-Feshbach technique).

A.2. **Compound Nucleus Statistical Model**

If in a reaction of the type $A(a, b)B$ the energy of the incident particle is shared among all the nucleons until one or more nucleons gain enough energy to escape, it is said that the reaction proceeds via a compound nucleus mechanism. This may be written more descriptively as:

$$a + A \rightarrow C^* \rightarrow b + B$$

where $C^*$ represents the intermediate state or compound nucleus. The lifetime of a compound nucleus is greater than the time required for the light particle, $a$, to traverse the diameter of the target nucleus, $A$, i.e. $\tau_{\text{CN}} > 10^{-22} \text{ sec}$. Furthermore, a compound nucleus is ordinarily assumed to have no "memory" of how it was formed (except that energy, linear and angular momentum and parity are conserved). That is,
it makes no difference whether the intermediate state was formed
by \( a + A \), \( b + B \), or any other possible combination.

Experimentally, one would expect formation of a compound
nucleus if:

1. Either the incident or emerging particle or both
   have relatively low energy. For example, if an
   endothermic reaction \((Q < 0)\) is run just above
   threshold, conditions for formation of a compound
   nucleus are favorable.

2. The angular distribution of the emerging particle
   is symmetric about \(90^\circ\) with respect to the beam
   axis. This condition is a weak condition, however,
   and may not be used by itself. An asymmetry
   with respect to \(90^\circ\) may indicate the presence of a
   non-compound nucleus mechanism or it may in-
   dicate insufficient statistical averaging. Similarly
   this symmetry may sometimes result even if the
   reaction proceeds by a direct mechanism.

The statistical assumption means that a large number of
compound nucleus states with different values of \( J \) and \( \eta \) are
populated so that the strength function is much greater than unity
\((\Gamma/D >> 1)\), where \( \Gamma \) is the width of the state and \( D \) is the
average separation of the states. Under this condition, the
decay process is described by outgoing waves having random
phases which cancel. That is the outgoing waves add incoherently
and one would expect no one final state to be preferred over any
other.

Experimentally, one would expect the CNS model to be
applicable if:

1. The excitation energy of the intermediate state is
   such that \( \frac{T}{D} >> 1 \) \( (E_x \geq 12 \text{ MeV}) \).

2. The excitation function is smooth and featureless.
   This test may not be sufficient by itself since there
   may be some circumstances under which a transition
   having a structured excitation function could be
   analyzed by CNS (see Section E). However, if
   the statistical condition and the conditions for
   formation of a compound nucleus are satisfied and
   the excitation curve is structureless then the CNS
   method could provide an additional tool for deter-
   mining the spins and mixing ratios of excited states
   of nuclei (Ma 70).
B. Formalism

B.1. Cross Section

The general form of the differential cross section for outgoing radiation from a reaction is given by

\[ \frac{d\sigma}{d\Omega} = \sum a_{\nu} P_{\nu}(\cos \theta) \]  \hspace{1cm} (30)

where the summation extends over the angular momenta involved in the reactions and over the parameter \( \nu = 0, 2, 4, \ldots \) whose range is limited by vector momentum coupling conditions.

The angular dependence of the differential cross section is contained in the Legendre polynomials \( P_{\nu}(\cos \theta) \). The weighting factor, \( a_{\nu} \), includes the energy and angular momentum dependence. The value of \( a_{\nu} \) is determined by the nature and angular momentum of the incident and emerging particles and by the spins of the target and residual nuclei.

The conventions to be followed in the remainder of this discussion are shown in Figure 13. The upper case letters refer to the spins of the target ground state, compound nucleus state, initial and final states of the residual nucleus. The lower case letters refer to the spin, orbital and total angular momenta of the particles involved in the reaction. \( L_2 \) and \( L_2' \) are the multi-
Figure 13  Illustration of a compound nuclear reaction.
\[ \begin{align*} 
\text{TARGET} & \quad \rightarrow \quad J_0 \pi_0 \\
& \quad \uparrow \quad \text{j}_1 \ell_1 s_1 \\
\rightarrow \quad J_1 \pi_1 \\
& \quad \uparrow \quad \text{j}_2 \ell_2 s_2 \\
& \quad \downarrow \quad L_2 L'_2 \quad \rightarrow \quad J_2 \pi_2 \\
& \quad \downarrow \quad \rightarrow \quad J_3 \pi_3 
\end{align*} \]
polarities of the emitted gamma radiation. The symbol $J_1$ will be used for the quantity $\sqrt{2J_1 + 1}$.

For gamma radiation emitted in a reaction of the type $A(a, b \gamma)B$ the differential cross section is given by:

$$
\frac{d\sigma}{d\Omega} = \frac{1}{4} \chi^2 \int g \eta_\nu \langle j_1 j_1 J_o J_1 \rangle U_\nu \langle j_2 j_2 J_1 J_2 \rangle
\times A(LL' J_o J_3) \tau P_\nu (\cos \theta)
$$

(31)

where $0 \leq \nu \leq 2j_1$, $2J_1$, $2J_2$, $2L'$ that is, $\nu_{\text{max}}$ is less than or equal to the smallest of the right hand quantities. $\chi$ is the wavelength of the incident particle in the center-of-mass system.

For non-relativistic energies $\chi = \frac{\hbar^2}{2M E_1}$, where $M$ is the mass of the incident particle and $E_1$ is the energy of the incident particle in the center of mass frame.

The statistical spin factor $g = J_1^2 / (s_1 \cdot J_o)^2 (g = 1/2 \frac{J_1^2}{J_o^2}$ for spin 1/2 particles) accounts for the relative probabilities that the incident particle has the proper spin orientation to populate the state with spin $J_1$.

The remaining terms $\eta_\nu$, $U_\nu$, and $A_\nu$ are parameters respectively describing the formation and decay of the compound nucleus and the gamma decay of the excited state of the residual nucleus. These parameters contain the angular
momentum vector addition coefficients and consist of combinations of Clebsch-Gordon and Racah coefficients:

$$\eta_{\nu}(j_1 j_1 J_0 J_1) = (-1)^{J_1 - J_0 - 1/2} \frac{\hat{\alpha}}{\hat{\beta}} \langle \nu \sigma^{j_1 j_1} 1/2 - 1/2 \rangle$$

$$\times W(j_1 j_1 J_0 J_0; \nu J_1)$$  \hspace{1cm} (32)

where $$\langle \nu \sigma^{j_1 j_1} 1/2 - 1/2 \rangle$$ is a Clebsch-Gordon coefficient and $$W(j_1 j_1 J_0 J_0; \nu J_1)$$ is a Racah coefficient.

The parameter $$U_{\nu}$$ has a generalized form which can be used for unobserved radiation be it a particle or mixed multipolarity gamma radiation. For the present case the unobserved radiation is a particle and $$U$$ has the same form as $$\eta_{\nu}$$.

$$U_{\nu}(j_2 j_2 J_1 J_2) = \eta_{\nu}(j_2 j_2 J_1 J_2)$$

and finally

$$A_{\nu}(LL'J_3 J_2) = (1 + \hat{\alpha}^2)^{-1} \left[ F_{\nu}(LL J_3 J_2) + 2\hat{\alpha} F_{\nu}(LL'J_3 J_2) \right.$$  \hspace{1cm} (33)

$$+ \hat{\alpha}^2 F(LL' J_3 J_2) \right]$$

where

$$F_{\nu}(LL' J_f J_i) = (-1)^{J_f - J_i - 1} J_f L L' L_i$$

$$\times \langle \nu \sigma^{L L' 1 - 1} \rangle W(LL' J_i J_i; \nu J_f)$$  \hspace{1cm} (34)

and $$\hat{\alpha}$$, the gamma ray multipole mixing ratio is defined by
\[ \delta \equiv \frac{\langle J_f || L'|| J_i \rangle}{\langle J_f || L || J_i \rangle} \]  

\( \langle J_f || L'|| J_i \rangle \) are reduced matrix elements for the transition between the initial and final states.

\[ \tau \text{ is the Hauser-Feshbach penetrability term given by} \]

\[ \tau \equiv \frac{T_{\ell_1 j_1} (E_1) T_{\ell_2 j_2} (E_2)}{\sum_{j' E} T_{\ell j} (E)} \]  

where the \( T_{\ell j} \)'s are transmission coefficients dependent upon the orbital angular momentum (\( \ell_1 \)), total angular momentum (\( j_1 \)) and the center of mass energy (\( E_1 \)) of the incident and emerging particles.

The denominator consists of a summation over all possible channels (\( j, \ell, E \)) through which the compound nucleus may decay. \( \tau \) is the probability that the compound nucleus will be formed through channel (\( \ell_1 j_1 E_1 \)) and decay through channel (\( \ell_2 j_2 E_2 \)).

### B.2. Transmission Coefficients

The wave function for a reaction proceeding through a compound nucleus may be written as \( \psi_{\alpha \beta} = \chi_{\beta} \psi_{\alpha} + y_{\alpha} \psi_{\beta} \), where \( \chi_{\beta} \) is the amplitude of the incident wave function and \( y_{\alpha} \) is the amplitude of the outgoing wavefunction. A matrix element may be defined from this equation by \( U_{\alpha \beta} \equiv \frac{y_{\beta}}{\chi_{\beta}} \). The average of \( U_{\alpha \beta} \) over a small energy range is used in the definition of the transmission coefficients: \( T_{\beta} \equiv 1 - \sum_{\alpha} \left| U_{\alpha \beta} \right|^2 \). \( T_{\beta} \) then describes the loss of beam flux associated with the formation of the compound nucleus.
through channel 3. $g$ is used as a shorthand notation for the
parameters $(\ell, j, E_i)$ (Ma 70). The transmission coefficients are
calculated using the computer code ABACUS of Auerbach (Au 62).
The $T_a$ and $T_\beta$ are calculated by considering two separate
reactions: inelastic scattering of the actual incident particle
from the target and a fictitious problem of inelastic scattering
of the emerging light particle from the residual nucleus. Optical
model parameter inputs to ABACUS were taken from the
generalized optical model parameters of Bechetti and Greenlees
(Be 69b). These are shown in Table 6.

B.3. Statistical Averaging

A major question in doing experiments based on the assump-
tions of the compound nucleus statistical model is whether or not
there has been sufficient averaging over the states in the compound
nucleus. The adequacy of this statistical averaging may be
insured in one of two ways. One may measure the angular dis-
tributions at several successive energies with energy intervals
being approximately the energy spread of the beam in the target.
Alternatively one may use a thick target so that the energy
spread of the beam in the target allows the population of a sufficient
number of states in the compound nucleus.
TABLE 6
OPTICAL MODEL PARAMETERS USED IN CODE ABACUS

<table>
<thead>
<tr>
<th>Particle</th>
<th>( V_R ) (MeV)</th>
<th>( r_{R=so} ) (F)</th>
<th>( a_{R=so} ) (F)</th>
<th>( W^V ) (MeV)</th>
<th>( W_{SF} ) (MeV)</th>
<th>( r_I ) (F)</th>
<th>( a_I ) (F)</th>
<th>( V_{so} ) (MeV)</th>
<th>( r_C ) (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>59.17-0.32E</td>
<td>1.17</td>
<td>0.75</td>
<td>0</td>
<td>13.04-0.25E</td>
<td>1.32</td>
<td>0.90</td>
<td>6.2</td>
<td>1.3</td>
</tr>
<tr>
<td>n</td>
<td>54.64-0.32E</td>
<td>1.17</td>
<td>0.75</td>
<td>0</td>
<td>12.17-0.25E</td>
<td>1.32</td>
<td>0.90</td>
<td>6.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

\( V_R \) = Real part of the central potential.

\( W^V \) = Imaginary volume - absorptive part of the central potential.

\( W_{SF} \) = Imaginary surface - absorptive part of the central potential.

\( V_{so} \) = Spin orbit potential.

\( r \) = Radii of the various potentials.

\( a \) = Diffuseness parameter for the various potentials indicating breadth of potential's fall off region from 90 to 10 percent of maximum.

I = Imaginary.

C = Coulomb.

All r's vary with nuclear mass number according to \( r = r_k A^{n} \).
To obtain an estimate of the number of levels of a particular \( J \) and \( \pi \) populated in an experiment, one first calculates the energy level density at the excitation energy of interest in the compound nucleus. Integration of the density function over the energy spread of the beam in the target then yields the number of levels populated. The level density in \((\text{MeV})^{-1}\) for states of spin \( J \) at excitation energy \( U \) is given by (Gi 65):

\[
\rho(U, J) = \frac{\sqrt{\pi}}{12} \frac{\exp (2 \sqrt{aU}) (2J + 1) \exp [-((J+1/2)/2\sigma)^2]}{\sqrt{2\pi} a^{1/4} U^{5/4}} \tag{37}
\]

where \( U \) is the excitation energy corrected for pairing effects, \( a \) is the level density parameter, and \( \sigma \) is the spin cut-off parameter. Values of \( a \), \( \sigma \) and pairing effects corrections may be obtained from tables in Gilbert and Cameron (Gi 65).

C. Experiment

C.1. Target

The target used in this experiment had the following isotopic composition: 53.1\% \(^{56}\text{Fe} \), 41.9\% \(^{58}\text{Fe} \), 3.6\% \(^{57}\text{Fe} \) and 1.4\% \(^{64}\text{Fe} \). The thickness was 0.5 mg/cm\(^2\) with an effective thickness of 0.7 mg/cm\(^2\) when positioned at 45° with respect to the beam. The gamma ray singles spectrum taken at 90° while bombarding this target with 4.6 MeV protons is shown in Figure 14.
Figure 14  Gamma ray singles spectrum following the reaction $^{56}\text{Fe}(p, n \gamma)^{59}\text{Co}$ at 4.6 MeV.
C.2. Chamber

The target was mounted in a 1/16 inch thick stainless steel chamber having a geometry slightly larger than a quarter sphere with inside radius of 5 inches (Figure 15). At 0° the chamber has a 2 inch beam pipe opening. This permits the chamber to be used with a Faraday cup approximately 1.2 meters beyond the target or to be blanked off with a stainless steel plate having approximately the same thickness (see Appendix) and radii of curvature as the curved part of the chamber (Sm 72).

C.3. Electronics

The electronics for this experiment were similar to those used in the DSAM experiment. A Princeton Gamma Tech 80 cc (47.7 mm dia x 48.5 mm) modified coaxial Ge(Li) detector was used to detect the gamma radiation. The detector resolution ranged between 4.3 and 8.6 keV (FWHM) during the course of the experiment. The preamplifier was a Princeton Gamma Tech Model RG 10 and the amplifier was an Ortec Model 450 Research Amplifier. The remaining components were the same as described in Chapter III, Sections B.3 and B.4.
Figure 15  Scattering chamber.
C.4. Excitation Functions

An excitation function was measured in 20 keV steps for several prominent gamma transition de-exciting levels in $^{68}$Co between 112 keV and 1435 keV. The purpose of the excitation function was to find a region above and near threshold where the gamma-ray intensity was great enough to obtain adequate statistics in the angular distribution measurements. A second purpose was to search for any structure which might rule out analysis by means of the compound nucleus statistical model. The gamma-ray excitation functions are shown in Figure 16. The arrow on each curve shows the proton energies at which angular distributions were measured. The numbers outside the top margin indicate the energy levels in $^{58}$Fe whose isobaric analogs in $^{68}$Co are excited by protons incident on $^{58}$Fe with the energies indicated at the bottom margin. The curves for the 321 keV and 432 keV transition show pronounced structure and will be discussed in Section E.

A Q-value of $-3.091$ MeV made it possible to study the levels near threshold. Being near threshold enabled the transitions to be readily identified and eliminated any possible complications due to cascades from higher levels. Running with
Figure 16 Excitation functions for $^{58}\text{Fe}(p, n \gamma)^{58}\text{Co}$. 
proton energies on the order of 100 keV or 200 keV, above
threshold, insured that the emerging neutron would have energies
well below 1 MeV, thus satisfying one of the conditions favoring
formation of a compound nucleus.

C.5. Adequacy of Statistical Averaging

The density of states in the compound nucleus $^{69}$Co was
calculated using Equation 37 for an incident proton energy of
3.3 MeV. This corresponds to an excitation energy of 10.6 MeV
in $^{69}$Co. For the 0.5 mg/cm² target used in this experiment
the calculated number of CN levels of $J = 3/2$ was on the order of
200 and should provide adequate statistical averaging.

To check the adequacy of the statistical averaging, angular
distributions were measured for the 112 keV transition at 3.30,
3.33, 3.36 MeV. The angular distributions were fitted to a
three term even order Legendre polynomial series. The
coefficients of the individual angular distributions and the coeffi-
cients of the summed angular distributions all agreed within
statistics ($\leq 7\%$ for $A_2/A_0$) indicating that averaging over 600
or 200 levels of $J = 3/2$ gave the same results (Table 7). Thus
the effective target thickness of 0.7 mg/cm² provided adequate
statistical averaging for this experiment.
TABLE 7

LEAST SQUARES ANGULAR DISTRIBUTION COEFFICIENTS

vs. ENERGY -- 112 keV TRANSITION

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>$A_2/A_0$</th>
<th>$A_4/A_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.300</td>
<td>-0.251 (.014)</td>
<td>.001 (.014)</td>
</tr>
<tr>
<td>3.330</td>
<td>-0.248 (.018)</td>
<td>.022 (.018)</td>
</tr>
<tr>
<td>3.360</td>
<td>-0.258 (.012)</td>
<td>.018 (.012)</td>
</tr>
<tr>
<td>Sum of 3</td>
<td>-0.254 (.008)</td>
<td>.015 (.008)</td>
</tr>
</tbody>
</table>
G.6. Angular Distributions

Proton beams with energies between 3.33 and 4.73 MeV were used to populate levels in $^{60}\text{Co}$ using the $(p, n \gamma)$ reaction on $^{58}\text{Fe}$. The beam energies used to excite $^{60}\text{Co}$ levels just above threshold and the gamma transitions studied are shown in Figure 17. Beam currents ranged from 250 na at the lower energies to 60 na at the higher energies and count rates were in the range 2000 to 3000 counts per second.

The data taken at each angle was normalized to the total charge collected. The charge collected was 300 microcoulombs for the lower energy transitions, 800 microcoulombs for the 583 keV transition, and 200 microcoulombs for the 1435 keV transition.

The Ge(Li) detector was mounted on the rotation table 20.64 cm from the target center and gamma ray yields were measured at 0° and in 15° intervals between 30° and 90°. The target was placed at 45° with respect to the beam line and gold backings of 1 and 2 mil thickness were mounted behind the target to stop the proton beam. Corrections for absorption of gamma radiation in the backing material were made using tabulated values of gamma ray attenuation coefficients and
Figure 17  Gamma ray transitions studied using compound nucleus statistical model. The right hand column shows the proton beam energies and the approximate excitation in $^{58}$Co obtainable at these energies.
graphically extrapolating to the energies of the observed gamma rays (We 68). The estimated uncertainties in the backing corrections are on the order of 0.5% or less. The yields were also corrected for differential absorption in the 0° blank-off (see Appendix) and for analyzer dead time.

A bias of +300 V was applied to the target and backing to reduce the emission of electrons thus giving a more accurate measure of the total charge collected.

D. Analysis

The angular distributions were fitted to a three term even order Legendre polynomial series using a least squares fitting routine. The experimental points and the fits are shown in Figure 18. The cross section is in arbitrary units. The data were normalized to $A_0 = 1$ by dividing the data by the $A_0$ coefficient obtained in the above fit. This enabled the experimental angular distribution to be put into the form

$$W(\theta) = 1 + \frac{A_2}{A_0} P_2(\cos \theta) + \frac{A_4}{A_0} P_4(\cos \theta)$$

(38)

where $P_K$ are the Legendre polynomials and $\theta$ is the angle at which the gamma rays were detected in the lab system. This
Figure 18  Experimental angular distribution with least squares fit.
form facilitated comparison with the calculated angular distributions from the computer code MANDYF (Sh 71). The experimental and theoretical angular distributions were compared by plotting $\chi^2$ vs. $\arctan \delta$ (Figure 19). $\chi^2$ is defined by:

$$\chi^2 = \frac{1}{\nu} \sum \frac{1}{\sigma_i^2} \left[ W_i \exp - W_i \text{calc} (\delta, J_2) - 1 \right]^2$$

where $\sigma_i$ is the standard deviation in the yield divided by $A_0$, $\delta$ is the gamma-ray multipole mixing ratio, $J_2$ is the spin of the decaying level, and $\nu$ is the number of degrees of freedom.

The 0.1% limit is the value of $\chi^2$ for which there is only a 0.1% probability that this value will be exceeded for any given set of experimental points. Thus the most probable values of the mixing ratio are those for which $\chi^2$ has a minimum below this value. The values of the mixing ratios were obtained by fitting the region around the $\chi^2$ minima to a quadratic function and solving for $\delta$ analytically.

The uncertainties in $\delta$ are standard deviations and were obtained by the standard method of error propagation:

$$\sigma_k^2 = \sum_{k=2,4} \left( \frac{\delta}{A_k/A_0} \right)^2 \sigma_{A_k/A_0}^2$$

This quantity, $\delta(A_k/A_0)$, was obtained by fitting a function of the form
Figure 19 \( \chi^2 \) vs. \( \arctan \) \( \theta \) analysis of angular distributions.
\[ \frac{A_k}{A_0} = \frac{1}{1 + \delta^2} (a \delta^2 + b \delta + c) \]  \hspace{1cm} (41)

and solving for \( \delta (A_k/A_0) \) (Wa 63).

For M1(E2) transitions the percentage of E2 radiation, \( Q \), is related to \( \delta \) by:

\[ Q = \frac{\delta^2}{1 + \delta^2} \times 100\% \]  \hspace{1cm} (42)

E. Results

Angular distributions were measured for gamma rays of energy 112, 366, 321, 432, 583, and 1435 keV, respectively (see Figure 18). The spin assignments from previous works combined with the lifetime data indicate that the first five of these gamma rays must be predominately M1 transitions with a small admixture of E2, while the 1435 may be M1 (E2) or E2 (M3) (Table 3 and (Ge 72)). Thus in calculating the CNS angular distributions using MANDYF, the final state was assumed to have the spin previously assigned, and the spin of the decaying level was allowed to differ from the final state spin by 0 or \( \pm 1 \) unit of angular momentum for all transitions as well as \( \pm 2 \) units for the 1435 keV transition. The transitions are identified in the first
three columns of Table 8. The most probable values of $\delta$ found in the $\chi^2$ vs. $\arctan \delta$ analysis are given in column 4. Column 5 lists the $E2$ enhancements over the Weisskopf single particle estimates calculated using the probable values of $\delta$ and the lifetime data of this work and the lifetimes of the 112 and 1040 keV levels measured by Haas et al. (Ha 72) and Gehringer et al. (Ge 72), respectively. The last column lists the spin assignments consistent with the experimental work.

112 keV Level

The spin assignment of $3^+$ for the 112 keV level is unambiguous and is in agreement with previous works (Table 9). The mixing ratio is $\delta = 0.02 \pm 0.02$ and is in agreement with the value given by Haas et al. (Ha 72) $\delta = 0.04 - 0.02$. The difference in the sign of $\delta$ results from a difference in phase convention.

366 keV Level

The spin assignment of $3^+$ for this level is unambiguous and is in agreement with previous works (Table 9). The mixing ratio is $\delta = 0.00 \pm 0.01$ which agrees with the value $\delta = -0.018 \pm 0.023$ reported by Gehringer et al. (Ge 72).
TABLE 8

SPINS AND MIXING RATIOS FROM $\chi^2$ FIT CONSISTENT WITH E2 ENHANCEMENT SYSTEMATICS

| Transition (keV) | $J_i^\pi$ | $J_f^\pi$ | $\kappa$ | $|M|_E2^2$ | $J_f^\pi$ | Present Work |
|-----------------|-----------|-----------|----------|-------------|-----------|--------------|
| 112 $\rightarrow$ 0 | 3$^+$ | 2$^+$ | 0.02 $\pm$ 0.02 | 5.2$^a$ | 3$^+$ | 3$^+$ |
| | 2$^+$ | | -0.79 $\pm$ 0.19 | 5200.$^a$ | | |
| 366 $\rightarrow$ 0 | 3$^+$ | 2$^+$ | 0.00 $\pm$ 0.01 | | 3$^+$ | |
| | 2$^+$ | | -0.81 $\pm$ 0.12 | | 2100. | |
| 374 $\rightarrow$ 53 | 5$^+$ | 4$^+$ | 0.03 $\pm$ 0.02 | 9.5 | 5$^+$ | |
| | 4$^+$ | | -0.84 $\pm$ 0.26 | 3300. | | |
| | 3$^+$ | | 0.07 $\pm$ 0.07 | 38. | 3$^+$ | |
| 458 $\rightarrow$ 25 | 6$^+$ | 5$^+$ | 0.02 $\pm$ 0.01 | 1.1 | 6$^+$ | |
| | 4$^+$ | | 0.07 $\pm$ 0.02 | 0.84 | 4$^+$ | |
| 1040 $\rightarrow$ 457 | 5$^+$ | 4$^+$ | 0.05 $\pm$ 0.02 | 5.2$^b$ | 5$^+$ | |
| | 3$^+$ | | 0.02 $\pm$ 0.06 | 0.84$^b$ | 3$^+$ | |
| 1435 $\rightarrow$ 0 | 3$^+$ | 2$^+$ | 0.16 $\pm$ 0.01 | 0.35 | 3$^+$ | |
| | 2$^+$ | | -0.34 $\pm$ 0.12 | 0.75 | 2$^+$ | |
| | 1$^+$ | | 0.00 $\pm$ 0.08 | | 1$^+$ | |
| | 0$^+$ | | 11. | | 0$^+$ | |

$^a$ Lifetime data for 112 keV level is from (Ha 72).

$^b$ Lifetime data for 1040 keV level is from (Ge 72).
<table>
<thead>
<tr>
<th>Level (keV)</th>
<th>((p, \gamma))</th>
<th>(^{3}\text{He}, d)</th>
<th>(^{3}\text{He}, p)</th>
<th>((d, \alpha))</th>
<th>((d, t))</th>
<th>((\alpha, n \gamma))</th>
<th>((\alpha, n \gamma))</th>
<th>Present Work</th>
<th>Jπ Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>3(^{+})</td>
<td>3(^{+})(4(^{+}))</td>
<td>3(^{+})(4(^{+}))</td>
<td>(3(^{+}))</td>
<td>(3(^{+}))</td>
<td>(3(^{+}))</td>
<td>(3(^{+}))</td>
<td>3(^{+})</td>
<td>3(^{+})</td>
</tr>
<tr>
<td>366</td>
<td>3(^{+})</td>
<td></td>
<td></td>
<td>(3(^{+}))</td>
<td>3(^{+})(2(^{+}))</td>
<td>(3(^{+}))</td>
<td>(3(^{+}))</td>
<td>3(^{+})</td>
<td>3(^{+})</td>
</tr>
<tr>
<td>374</td>
<td></td>
<td></td>
<td></td>
<td>4(^{+})(3(^{+}))</td>
<td>5(^{+})</td>
<td>(4, 5(^{+}))</td>
<td>(5(^{+}))</td>
<td>5(^{+})</td>
<td>5(^{+}), 3(^{+})</td>
</tr>
<tr>
<td>458</td>
<td></td>
<td></td>
<td></td>
<td>4(^{+})(3(^{+}))</td>
<td>(4(^{+}))</td>
<td>(4(^{+}))</td>
<td>(4(^{+}))</td>
<td>4(^{+})</td>
<td>6(^{+}), 4(^{+})</td>
</tr>
<tr>
<td>1040</td>
<td></td>
<td></td>
<td></td>
<td>(3(^{+}))</td>
<td>(3, 4(^{+}))</td>
<td>3(^{+}), 2(^{+})</td>
<td>(3(^{+}))</td>
<td>5(^{+}), 3(^{+})</td>
<td>3(^{+})</td>
</tr>
<tr>
<td>1435</td>
<td>((0, 1, 2)^{+})</td>
<td></td>
<td></td>
<td></td>
<td>((0, 1, 2)^{+})</td>
<td>(1(^{+}))</td>
<td>((0, 1, 2, 3)^{+})</td>
<td>1(^{+})(0, 2, 3(^{+}))</td>
<td></td>
</tr>
</tbody>
</table>

a) Reference (Er 70)  

b) Reference (Tr 69)  

c) Reference (Ly 72)  

d) Reference (Ro 71)  

e) Reference (Xe 71)  

f) Reference (Sc 72)  

g) Reference (Ha 72) and (Ge 72).
1040 keV Level

Two spin assignments are possible for this level in the present experiment, 5+ and 3+. Table 9 summarizes the spin assignments of previous works. From this table we see that there is no additional evidence to support a 5+ assignment. Thus a 3+ assignment is made for the 1040 keV level. The mixing ratio is $\kappa = 0.02 \pm 0.06$.

1435 keV Level

An assignment of (1, 2, 3)* is made by Trier et al. (Tr 69) for a level at 1451 ± 15 keV. As assignment of 1+ is made by Schneider and Dashnick (Sc 72) for a level at 1432 ± 4 keV. Since no other levels lie within these error bars, both have probably observed the 1435 keV level of (Ro 71) and (Xe 71). Thus a tentative assignment of 1+ is made although there is not enough evidence to completely rule out a 0+, 2+, or 3+ assignment. For the 1435 keV gamma ray coming from a 1+ level at 1435 keV, the mixing ratio is $\delta = 0.00 \pm 0.08$, i.e. it is a pure M1 transition.
Strong resonances are present in the excitation function for the 321 keV transition (see Figure 16). The first resonance at 3.800 MeV incident proton energy, corresponds to the expected location of the isobaric analog to the 1.67 MeV $9/2^+$ state in $^{59}$Fe. The location of this resonance was calculated on the basis of investigations of elastic scattering from iron isotopes by Lindstrom et al. (Li 71). The level structure of $^{59}$Fe was taken from the work of Sperduto and Beuchner (Sp 64).

According to the theoretical work of Weidenmuller (We 67) the presence of an isobaric analog resonance at or near the incident beam energy may have the effect of enhancing the transmission coefficient for the entrance channel exciting the resonance. If indeed the resonance observed for the 321 keV transition is due to an isobaric analog resonance, then one could check the effect of this enhancement of a given transmission coefficient by altering the transmission coefficient input into MANDYF. Two extreme values for the $l = 4, j = 9/2$ transmission coefficient $T_{4,9/2} = 0.0$, $T_{4,9/2} = 1.0$ and the value from program ABACUS ($T_{4,9/2} = 0.00237$) were used as inputs to MANDYF. The effect on the calculated coefficients of the angular distribution ($A_2/A_0$ and $A_4/A_0$) are shown in Figure 20.
Figure 20  Theoretical angular distribution coefficients for the
321 keV transition as a function of the transmission
coefficient $T_{4\frac{3}{2}}$. 

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\[ W(\theta) = 1 + \frac{A_2}{A_0} P_2(\cos \theta) + \frac{A_4}{A_0} P_4(\cos \theta) \]

**Parameters:**
- \( E_p = 3.800 \text{ MeV} \)
- \( E_\gamma = 0.321 \text{ MeV} \)
- \( J = 5 \)
- \( T_{4.\frac{9}{2}} = 1.0 \)
- \( T_{4.\frac{9}{2}} = 0.0 \)
- \( \delta = -1.0 \)
- \( \delta = -0.1 \)
- \( \delta = 0.05 \)
- \( \delta = 0.1 \)
- \( \delta = 0.5 \)

**Nuclear Transition:**
- \( 374 \rightarrow 53 (4^+) \)
From the lifetime data, the E2 enhancement factor for the 321 keV transition considered as pure E2 is 7900 (Table 3), entirely too large as compared to known E2 enhancements in the 1f-2p region (Ar 71) (see Figure 12). To obtain more reasonable enhancements the value of the mixing ratio should be $|\delta| < 0.4$ corresponding to an E2 component of less than 14%. Figure 20 illustrates that for $|\delta| \leq 0.1$ there is little difference between the calculated mixing ratio for $T = 0.0$ or $T = 1.0$.

Analysis of the angular distribution by $\chi^2$ vs. arctan $\delta$

for $T = 0.00237$ yields spin values of $J = 5$ and $J = 3$ and mixing ratios of $\delta = 0.04 \pm 0.02$ and $\delta = 0.07 \pm 0.07$, respectively. The $\chi^2$ minimum for $J = 4$ gave a mixing ratio of $\delta = -0.84 \pm 0.26$, a percentage E2 mixture of $41 \pm 15\%$, and an E2 enhancement of $3200 \pm 1200$. The enhancement is not consistent with the systematics of 1f-2p nuclei (see Figure 12), and the $J = 4$ spin assignment is therefore rejected.

The $\chi^2$ vs. arctan $\delta$ analysis was also used to compare the data with the calculated angular distributions from MANDYF for $T_{4,9/2} = 0.0$ and $T_{4,9/2} = 1.0$. The results shown in Table 10 illustrate that the effect of drastically modified transmission coefficients changes the value of $\delta$ by only a small amount (although by a large percentage). The extreme values of $T$ change
**TABLE 10**

**MIXING RATIO FOR DIFFERENT VALUES OF**

$T_{4, 9/2} - 321$ keV TRANSITION

<table>
<thead>
<tr>
<th>$T_{4, 9/2}$</th>
<th>0.0</th>
<th>0.00237</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^\pi = 5^+$</td>
<td>$0.03 \pm 0.02$</td>
<td>$0.03 \pm 0.02$</td>
<td>$0.05 \pm 0.01$</td>
</tr>
<tr>
<td>$J^\pi = 3^+$</td>
<td>$0.07 \pm 0.07$</td>
<td>$0.07 \pm 0.07$</td>
<td>$0.07 \pm 0.09$</td>
</tr>
</tbody>
</table>
the measured percentage of the E2 component from $0.12 \pm 0.11\%$
to $0.27 \pm 0.14\%$ for $J = 5$ with no changes in $\delta$ on the percentage
of E2 for $J = 3$. Since a drastic change in transmission coefficient
still yields statistically consistent results we may conclude that, for
this particular case, analysis of the data in accordance with the
CNS model is valid.

There is no additional evidence to support an assignment
of $3^+$ to this level (Table 9), thus the spin and mixing ratio
assignments are $J^\pi = 5^+$, $\delta = 0.03 \pm 0.02$. This assignment is in
agreement with the value $J = 5^+$ and $\delta = -0.05 \pm 0.025$ measured
by Gehring et al. (Ge 72). The difference in the sign of $\delta$
results from a difference in phase conventions. This agreement
confirms the results of the check on the validity of using the
CNS model for analysis. However, the agreement is most likely
a result of this being a special case in which $\delta$ is small so that
enhancements of the transmission coefficients has little effect on
coefficients of the angular distribution. In general one could not
expect to be able to ignore the presence of resonance structure
and each case should be studied separately.

458 keV Level

The 432 keV gamma ray from the decay of the 458 keV level
also showed a strong resonance at 3.800 MeV incident proton energy. This resonance also corresponds to the expected location of the isobaric analog to the 1.67 MeV 9/2+ state in \(^{58}\text{Fe}\), thus analysis of the angular distribution of the 432 keV gamma ray was treated in the same manner as the 321 keV transition.

Analysis by \(\chi^2\) vs. \(\arctan \delta\) admits two spin assignments \(J = 6\) and \(J = 4\). The \(J = 6\) assignment has no additional evidence to support it, thus spin and mixing ratio assignments of \(J^\pi = 4^+\) and \(\delta = 0.07 \pm 0.02\) are made. The \(\delta\) values for \(T = 0.0\) and \(T_{4,9/2} = 1.0\) yield mixing ratios of \(\delta = 0.07 \pm 0.02\) and \(\delta = 0.03 \pm 0.01\) and E2 percentages of \(0.48 \pm 0.31\%\) and \(0.12 \pm 0.09\%\) respectively. Since the results for the two extreme transmission coefficients nearly agree within statistics (overlap in the third decimal place), we may again conclude that analysis with the CNS model assumptions is valid.

Gehringer et al. (Ge 72) measured values of \(J^\pi = 4^+\) and \(\delta = -0.109 \pm 0.045\) which are in agreement with the values determined in this experiment. The sign difference for \(\delta\) results from a difference in phase convention.
CHAPTER V
DISCUSSION OF RESULTS

A. Comparison of Theory and Experiment

A summary of the results of the experiments are shown in Figure 21 and Table 11. Figure 21 shows a modified decay scheme which includes only the transitions studied in the present work. The lifetimes, spins and mixing ratios shown are from the present experiments with the exception of the information about the ground state and the levels at 25 and 53 keV. Table 11 lists the partial lifetimes and the enhancement and hinderance factors over the Weisskopf single particle estimates for the transitions. The partial lifetimes are calculated by:

\[
\tau_{\text{partial}} = \frac{\tau_{\text{mean}} (1 + \alpha_T)}{Q \times b}
\]  

(43)

where \(\alpha_T\) is the internal conversion coefficient, \(Q\) is the quadrupole fraction, and \(b\) is the branching fraction.

The level energies and spins calculated by Vervier (Ve 66) and McGrory (Mc ) are compared with experimental values up to 1.5 MeV in Figure 22. The matchings of experimental
Figure 21  Summary of results.
\[ I(0, 2, 3)^+ \]

\[ \tau (\text{ps}) \]

- 0.87
- 0.23
- 0.90
- 0.24
- 0.26

\[ \delta = 0.02 \pm 0.06 \]

\[ \begin{array}{c}
58 \quad \text{Co} \\
27 \\
31
\end{array} \]
| $E_i$ (keV) | $E_f$ | $J_i^+$ | $J_f^+$ | Branching | Q | $t_{\text{partial}}$ (p s) | $|M|^2$ (W. u.) | $E_2$ | $t_{\text{partial}}$ (p s) | $|M|^2$ (W. u.) |
|-----------|------|--------|--------|-----------|---|---------------------|-----------------|-------|--------------|-----------------|
| 112$^a$   | 0    | 3+     | 2+     | 60        | .04+ .08 | 445±68  | 0.052±0.009 | 1.39±.25×10^6 | 2.45±.54  |
| 360       | 0    | 3+     | 2+     | 98.2      | 0.00±.01 | 1.73±1.60 | 0.380±0.139 | 1.39±.25×10^6 | 2.45±.54  |
| 374$^d$   | 53   | 5+     | 4+     | 94        | .09±.12 | 2.24±1.25 | 0.435±0.219 | 2.4±3.4×10^3 | 7.1±4.2   |
| 457       | 25   | 4+     | 5+     | 83.2      | .49±.28 | 1.51±.54 | 0.264±0.118 | 3.1±3.4×10^3 | 13.±7.5   |
| 1040$^b$  | 457  | 3+     | 4+     | 48        | .04±.24 | .42±.25  | 0.386±0.120 | 1.0±6.3×10^3 | .86±.74   |
| 1435      | 0    | (1+)   | 2+     | 100       | 0.00±.64 | .87±3.00 | 0.013±.016 | 1.39±.25×10^6 | 2.45±.54  |

a) Lifetime from Haas et al. (Ha 72).
b) Lifetime from Gehringer et al. (Ge 72).
c) Branching from Robertson and Summers-Gill (Ro 71).
d) Lifetime not corrected for cascades.
Figure 22  Comparison of theoretical and experimental level structures.
\[ \text{THEORY (McGRORY)} \]

\[ \text{EXPERIMENT} \]

\[ \text{THEORY (VERVIER)} \]
and theoretical levels were made by Robertson and Summers-Gill for Vervier's calculation and by Schneider and Daehnick for McGrory's. Since neither calculation includes transition probabilities, the discussion is necessarily limited to energy levels and spin assignments. Vervier's calculation adequately predicts the energies and spins of the first three levels. McGrory's calculation gives a better prediction for the relative energy separation of the levels at 366, 374, and 457 keV, however the energy values are approximately 200 keV too large. Vervier's calculation predicts the proper spins for the first seven levels and roughly the correct energy behavior, however, the separation of the three levels corresponding to the region from 366 to 457 keV is much too large. McGrory's calculation has the added advantage of predicting a larger number of levels up to approximately 1500 keV, however, even here there are not nearly enough levels predicted (Sc 72). As will be discussed later this paucity of levels is probably due to the lack of sufficient configuration mixing, including mixing from both the proton and neutron $f_{7/2}$ shells.

Both calculations fail to assign the proper ground state spin indicating a difference between the strength of the actual and assumed two-body residual interaction.
B. Structure of Individual Levels

Ground State

The spin and parity of the ground state have been determined as 2$^+$ by Dobrov and Jeffries (Do 57) using paramagnetic resonance and by Mann et al. (Ma 65) using $\beta$-\gamma circular polarization measurements. The 2$^+$ spin and parity of this level illustrates another case where Nordheim's weak rule (Chapter II, Section A.1) makes a valid prediction. In this case the ground state spin has the value $J = |j_p - j_n|$.

In the pure shell model this level is taken to have the configuration ($\pi f_{7/2}^{-1}$, $\nu 2p_{3/2}^{-1}$). The $^{60}$Co(d, t) work of Robertson and Summers-Gill (Ro 71) gives evidence for an admixture of approximately 25% ($\pi f_{7/2}^{-1}$, $\nu f_{5/2}^{-1}$). The $^{57}$Fe($^3$He, d) experiment of Schneider and Daehnick (Sc 72) shows an $\ell = 1$ angular distribution for this state indicating the presence of a ($\pi f_{7/2}^{-3}$, $\nu p_{3/2}$) ($\nu p_{3/2}^{-1}$) admixture. This $\ell = 1$ proton transfer was also observed earlier by Schwartz and Alford (Sc 68).

0.025 keV Level

This is an isomeric state with spin-parity 5$^+$ assigned by Strauch (St 50) and Hjorth (Hj 67). This level agrees with
Brennan and Bernstein's (Br 60) observation that many odd-odd nuclei with isomeric states have a ground state spin of

\[ J = |j_p - j_n| \]

and an isomeric state with \( J = j_p + j_n \) (or vice versa).

From their studies of the low lying levels Haas et al. (Ha 72) conclude that this level is predominantly \((\pi f_{7/2}^{-1}, \nu 2p_{3/2}^{-2})\). Based on the spectroscopic strengths of the \( ^{60}\text{Ni}(d,\alpha) \) reaction Schneider and Daehnick (Sc 72) postulate the presence of some \((\pi f_{7/2}^{-1}, \nu f_{7/2}^{-1})\) admixture in this state.

0.053 keV Level

On the basis of transfer reactions Schneider and Daehnick (Sc 72) assign a spin of \( 4^+ (3)^+ \). Robertson and Summers-Gill (Ro 71) assign a value of \( 4^+ \) as being in more reasonable agreement with the large retardation of the M1 transition to the 25 keV level. Haas et al. (Ha 72) make an assignment of \( 4^+ \) based on an n-\( \gamma \) correlation.

The long lifetime (10.2 \( \mu \)sec) (Br 64), (Ro 71), (Ha 72) and a strongly retarded M1 transition rate of \( 6 \times 10^{-9} \) w. u. (Ro 71) tend to indicate a major structural difference between the levels at 54 and 25 keV. The spectroscopic factors of Schneider and Daehnick indicate that this level is approximately 60%

\((\pi f_{7/2}^{-1}, \nu f_{5/2}^{-1}) 4^+ \)

and a transition of the type \((\pi f_{7/2}^{-1}, \nu f_{5/2}^{-1}) 4^+ \rightarrow \)

\((\pi f_{7/2}^{-1}, \nu 2p_{3/2}) 5^+ \) would be strongly retarded since it is
forbidden. From their measurement of the g factor Haas et al. (Ha 72) found this level to be consistent with a proton configuration of \( \pi f_{7/2}^{-1} \) and the three neutron configurations of \( \nu 2p_{3/2}^{-1} \), \( \nu 2p_{3/2} \) and \( \nu f_{5/2} \) with the first and third neutron configurations more favored.

112 keV Level

Using their measured value for the g factor, Haas et al. (Ha 72) conclude that this level is predominantly \( \pi f_{7/2}^{-1}, \nu f_{5/2} \) with an admixture of \( \pi f_{7/2}^{-1}, \nu f_{7/2}^{-1} \).

366 and 374 keV Levels

No structure has been clearly determined for these levels.

455 keV Level

On the basis of their \( ^{57}\text{Fe}(^{3}\text{He},d) \) work Trier et al. (Tr 69) suggest that this state has a large component of \( \pi f_{7/2}^{-1}, \nu p_{3/2} \), \( p_{1/2} \). Schneider and Daehnick (Sc 72) suggest a possible \( \pi f_{7/2}^{-1}, \nu f_{7/2}^{-1} \) component to explain the discrepancy in energy and spectroscopic strength between experiment and McGrory's calculation.
Higher Levels

These have not been identified with specific configurations as yet. They are undoubtedly subject to a great deal of configuration mixing as we have already seen for the lower states. Identification of the configurations is further complicated by the closeness in energy of the basic shell model configurations and the strong intermixing of levels of pure configuration.

C. Comparison with Other Nuclei

A comparison between $^{66}$Co and nuclei with similar structure can be useful in understanding both $^{68}$Co and the similarities and differences between it and other nuclei. In this section $^{68}$Co will be compared with $^{66}$Co and the result of the Pandya transformation applied to $^{66}$Co, and with the conjugate nucleus of $^{68}$Co, i.e. $^{66}$Sc.

C.1. Comparison with $^{68}$Co

$^{68}$Co and $^{66}$Co differ by two neutrons. In the simple shell model picture $^{68}$Co has a structure $(\pi f_{7/2}^{-1}, \nu 2p_{3/2})$ as compared to $(\pi f_{7/2}^{-1}, \nu 2p_{3/2}^{-1})$ for $^{66}$Co. From both of these configurations it is possible to form states with $J^\pi = 2^+, 3^+, 4^+, 5^+$. If we
allow the odd neutron in each nucleus to occupy the $2p_{1/2}$ and $1f_{5/2}$ states, it is also possible to form states with $J^\pi = 3^+, 4^+$ and $J^\pi = 1^+, 2^+, 3^+, 4^+, 5^+, 6^+$ respectively. If a neutron is raised from the $f_{7/2}$ shell, eight additional states with $J^\pi = 0^+$ to $7^+$ may be formed in a configuration $(\pi f_{7/2}^{-1}, \nu f_{7/2}^{-1})$. Finally, if we consider the odd neutron in $^{59}\text{Co}$ to occupy the $2p_{1/2}$ or $1f_{5/2}$ as before but permit the remaining two $p_{3/2}$ neutrons to couple to $j = 2^+$ instead of $0^+$, an additional 49 states with spins $0^+$ and $9^+$ could be produced. Thus it is clear that only a few simple configurations can give rise to a very complex level scheme.

The additional complexity of $^{58}\text{Co}$ as compared to $^{56}\text{Co}$ is clearly seen in the two works of Schneider and Daehnick (Sc 71) (Sc 72) in which they show 50 levels in $^{58}\text{Co}$ below 2.75 MeV as compared to 22 levels in $^{56}\text{Co}$. Thus one effect of the two additional neutrons is to produce more complexities in the level structure.

A detailed comparison between the two nuclei above 1.5 MeV would be extremely difficult. However, there may be merit in comparison at lower energies. The main feature that stands out is the energy gap between the first seven levels and the eighth level in both nuclei ($\approx 430$ keV for $^{58}\text{Co}$ and $\approx 340$ keV).

Below this gap the levels have the same spins though not necessarily in the same order. There is one $2^+$ level and two
each of $3^+$, $4^+$ and $5^+$. This similarity may indicate similarity in structure. However, one must be careful in making configuration assignments to realize that configuration mixing can drastically alter the energy sequence of the single particle configurations. As an example it looks as though the four lowest states $2^+$, $5^+$, $4^+$ and $3^+$ could all arise from a $(\pi f_{7/2}^{-1}, \nu 2p_{3/2}^{-1})$ configuration. However, the work of Schneider and Daehnick combined with Robertson and Summers-Gill on the 53 keV level indicated that it is 60% $(\pi f_{7/2}^{-1}, \nu f_{5/2}^{-1})$. Robertson and Summers-Gill's (d, t) work is consistent with the assumption that the levels below 1.1 MeV are predominantly $(\pi f_{7/2}^{-1}, \nu 2p_{3/2}^{-1})$ and $(\pi f_{7/2}^{-1}, \nu f_{5/2}^{-1})$.

Schneider and Daehnick and Robertson and Summers-Gill have used the Pandya transformation (Pa 56) to relate some single particle levels in $^{68}$Co and $^{68}$Co (Figure 23). The Pandya transformation relates the energy of a particle-hole spectrum to the corresponding particle-particle (hole-hole) spectrum by:

$$E_J[j^{-1} j'] = \sum_{J_0} (2J_0 + 1) W(j j' j'; J J_0) E_{J_0}[j j']$$

(44)

where $j$ is the angular momentum of the hole, $j'$ is the angular momentum of the particle and $J$ is the resultant angular momentum. Although the predictions of the Pandya transformation are not very
Figure 23  Level structures of $^{88}\text{Co}$, $^{66}\text{Co}$ and $^{50}\text{Sc}$. 
good, the levels at 0, 25, 366 and 455 are identified as coming
mainly from \( [\pi f_{7/2}^{-1}, \nu p_{3/2}^{-1}]_2^+, 3^+, 4^+, 5^+ \). At this time there is
not enough evidence to speculate as to whether the remaining
3\(^+\), 4\(^+\) and 5\(^+\) states in the low lying level schemes of \(^{68}\)Co
and \(^{66}\)Co have the same configurations.

C.2. Comparison with \(^{60}\)Sc

The conjugate of a nucleus is formed by replacing particles
in the unfilled shell with holes and holes with particles. Thus
the conjugate of \(^{68}\)Co (\(\pi f_{7/2}^{-1}, \nu p_{3/2}^{-1}\)) would be \(^{60}\)Sc (\(\pi f_{7/2}, \nu p_{3/2}\)).
The spectrum of \(^{60}\)Sc is also shown in Figure 23. Although the energy
spacing of the levels in \(^{60}\)Sc are much larger than in \(^{68}\)Co, there
are some qualitative similarities. The first four levels in each
nucleus have the same spins although in different order. The
first four levels in \(^{60}\)Sc are identified by Moazed et al. (Mo 69)
as being predominantly (\(\pi f_{7/2}, \nu p_{3/2}\)) just as four of the first
seven levels in \(^{68}\)Co are predominantly (\(\pi f_{7/2}^{-1}, \nu p_{3/2}^{-1}\))

Another similarity noted in Chapter II is that the first
excited state in both nuclei is an isomeric state. Just as in \(^{68}\)Co
the ground state and isomeric states have the two spin values
allowed by Nordheim's weak rule \( J = |j_p - j_n| \) and \( J = j_p + j_n \),
although the ground state and isomeric state spins for the two
nuclei are interchanged. This interchange is probably due to a
difference in the strength of the p-n interaction as noted by
de Shalit and Walecka (Sh 61). The apparent lack of intermingling
of levels with different configurations at low energies in $^{50}$Sc
indicates the importance of the two additional neutrons and six
additional protons in the ordering of the levels in $^{58}$Co.

The differences between $^{50}$Sc and $^{58}$Co probably are due to
the larger number of configurations available and the strong
configuration mixing in $^{58}$Co.

D. Summary and Conclusions

In the present work mean lifetimes were measured for the
first time for the levels at 1354, 1378 and 1435 keV. The lifetimes
measured for five other levels are in agreement with the values
reported by Gehringer et al. (Ge 72).

Unambiguous spin assignments of $J = 3^+$ were made for the
levels at 112 and 366 keV. These agreed with the results of the
n-γ correlation work (Ge 72) and (Ha 72). Additional evidence
was supplied for spin assignments of $5^+$ for the 374 keV level,
and $4^+$ for the 457 keV level. These are in agreement with the
n-γ correlation work of (Ge 72). The spin assignment of $3^+
for the level at 1040 keV agrees with previous works (Ro 71),
(Xe 71) and (Sc 72).
Additional evidence for a 1+ assignment to the level at 1435 keV was given to support this assignment in (Tr 69) and (Sc 72). However, other assignments of 0+, 2+ and 3+ could not be ruled out.

The mixing ratios for the 112, 321, 366, and 432 keV transitions agreed in magnitude within statistics with the values of (Ha 72) and (Ge 72). The mixing ratio for the 583 keV transition is reported in this work for the first time as $\delta = 0.02 \pm 0.06$. The 1435 keV transition is tentatively taken as a pure M1 transition.

Further experimental studies of the levels between 1 and 2 MeV and more detailed calculations, particularly of transition probabilities and gamma ray branching and mixing ratios are needed to arrive at a better understanding of $^{68}$Co.
APPENDIX

ISOTROPY CHECK ON 45° N SCATTERING CHAMBER

A new multipurpose scattering chamber was installed at the end of the 45° N beam line (Sm 72). Before using the chamber to measure angular distributions or correlations, a check had to be made to insure that no anisotropies were introduced by the chamber. Checks were made using a beam and also with a source.

The dynamic check was made by bombarding a 2 mg/cm² ⁴⁸Ti target with 5 MeV protons for approximately 8 hours to activate the target by the reaction ⁴⁸Ti(p, n)⁴⁸V. The subsequent β decay of ⁴⁸V produced gamma rays of 983 and 1311 keV. Spectra were taken at angles from -146° to +146° (+ angles were measured on the curved side of the chamber) for time intervals of 2000 sec to keep the statistical fluctuations below 1%. Since the gamma radiation should be isotropic, any anisotropy would be introduced by the chamber system.

The gamma ray yield between 0° and 120° is shown in Figure 24. The plot indicates that the chamber would have less
Figure 24  Result of chamber isotropy check.
CHAMBER ISOTROPY CHECK USING $\beta^-$ DECAY OF $^{48}$V

COUNTS ($\times 10^3$)

0  20  40  60  80  100  120

ANGLE (DEGREES)

○ 983 keV
● 1311 keV
than a 2 per cent effect on the anisotropy of measured angular distributions through this angular range.

The static check involved the use of an $^{131}$I source with gamma ray energies of 284, 364, and 637 keV and an 80 keV X-ray. This source was axially symmetric in the vertical direction and was mounted co-axially on the target support shaft. Spectra were taken on both the open (flat side cover removed) and closed sides of the chamber. The chamber was isotropic to these radiations to within approximately 2 per cent or better for the angles between $0^\circ$ and $120^\circ$.

A stainless steel blankoff was attached to the $0^\circ$ end (see Chapter IV, Section C.6) and the yield from the source was measured several times at this position also. This provided a check for any differential absorption between the blankoff and the curved side of the chamber. The percent corrections to yields at $0^\circ$ as a function of energy are shown in Figure 25.

The shape of the correction curve was checked by computing $\mu \chi$ from the data taken on the open side, the curved side, and at $0^\circ$. The experimental value of $\mu \chi$ was compared with known values of $\mu/\rho$ for iron taken from the CRC tables (We 68). The quantity $\mu$ is the gamma ray attenuation coefficient, $\chi$ is the
Figure 25  Percent correction to 0° yield as a function of gamma ray energy.
PERCENT CORRECTION TO 0° YIELD VS. ENERGY

CORRECTION (%) vs. ENERGY (MeV)
difference in thickness between 0° and the curved side of the chamber, and \( \sigma \) is the density of the absorbing material. The two curves \( \mu \gamma \) vs. \( E_{\gamma} \) and \( \phi \) vs. \( E_{\gamma} \) were parallel verifying the correctness of the shape of the curve \( \mu \gamma \) vs. \( E_{\gamma} \). From the experimental values of \( \mu \gamma \), the curve of % correction at 0° vs. energy was calculated.
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