A MEASUREMENT OF THE TOTAL ISOVECTOR
M1 RADIATIVE WIDTH OF THE 16.6-16.9 MeV DOUBLET IN 8Be

JEFFREY M. LONG

1978
A MEASUREMENT OF THE TOTAL ISOVECTOR
M1 RADIATIVE WIDTH OF THE 16.6-16.9 MeV DOUBLET IN $^8$Be

A Dissertation
Presented to the Faculty of the Graduate School
of
Yale University
in Candidacy for the Degree of
Doctor of Philosophy

by
Jeffrey MacKay Long

December 1978
The isovector M1 radiative widths of the two strongly isospin mixed $2^+$ levels at 16.6 and 16.9 MeV excitation in $^8$Be for a transition to the 2.94 MeV $2^+$, T=0, first excited state of $^8$Be have been measured through the radiative capture reaction $^4$He ($^4$He,γ) $^8$Be*. This experiment was undertaken as part of a search for evidence of second-class weak interaction currents in the mass 8 system.

A $^4$He beam from the Wright Nuclear Structure Laboratory MP tandem accelerator passed through a 100 keV thick $^4$He gas target. The resulting gamma-rays were detected by an anti-coincidence shielded lead-collimated 30 cm. x 30 cm. NaI(Tl) spectrometer, placed at a backward angle of 125°. A p-γ coincidence measurement using the reaction $^{10}$B($^3$He,p)$^{12}$C*(15.11) (γ)$^{12}$C provided a photopeak efficiency curve for the spectrometer.

An excitation function over the range of 16.4-17.1 MeV in $^8$Be was measured at 125°. This was an almost direct measurement of the total M1 width, which was determined by fitting the excitation function to a curve generated from 2-level R-matrix theory. The isovector M1 width $\Gamma_{M1}^{\Delta T=1}$ was found to be 6.91 ± 0.85 eV; there was no evidence for a direct interaction contribution. An angular distribution at 16.9 MeV gave a rough value for the E2/M1 mixing ratio.

When the resulting weak magnetism form factor, which is proportional to the square root of $\Gamma_{M1}^{\Delta T=1}$, was compared with the results of a recent β-α angular correlation measurement on the beta decays of $^8$Li and $^8$B to the same final state, no evidence was found for the existence of second-class currents in the mass 8 system.
ACKNOWLEDGEMENTS

The author is indebted to many of the faculty and staff of the Wright Nuclear Structure Laboratory for assistance in many aspects of this research. Special thanks goes to Dr. G.T. Garvey of Argonne National Laboratory for his suggestion of this experiment.

I am grateful to my advisor, Dr. D. Allan Bromley, for help and advice and for his reading of the manuscript; to the accelerator staff and especially to Mr. Kenzo Sato for many long and difficult hours maintaining accelerator operation; to Messrs. George Saportin and Joseph Cimino and the machine shop staff for precision workmanship; to Dr. Peter D. Parker for advice and encouragement; to Mrs. Sandy Sicignano for her patient and expert drawing of the figures; and to Laurie Liptak for her expert typing of this dissertation.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
</tbody>
</table>

Chapter 1: INTRODUCTION AND MOTIVATION FOR THE EXPERIMENT

1.1 Brief Historical Background                                           1
1.2 The Conserved Vector Current Theory                                    4
1.3 Mirror Beta Decays                                                      7
1.4 Correlation Experiments                                                8
1.5 Mass 20 Measurements                                                    9
1.6 Mass 19 Measurements                                                    13
1.7 Mass 12 Measurements                                                    14
1.8 Mass 8 Measurements                                                     16
1.9 Comments                                                               18
Chapter 1 References                                                       22

Chapter 2: THE CONSERVED VECTOR CURRENT THEORY APPLIED TO THE MASS 8 SYSTEM

2.1 The Mass 8 System                                                       24
2.2 The $\beta^+ - \alpha$ Angular Correlation                              27
2.3 Comparison with Experiment                                              32
Chapter 2 References                                                       35
APPENDICES

I-A: DATA ACQUISITION PROGRAM FOR SINGLES EXPERIMENTS  161
I-B: DATA ACQUISITION PROGRAM FOR COINCIDENCE EXPERIMENTS  175
II-A: UPPER LIMITS FOR $\Delta T=2$ GAMMA-RAY TRANSITIONS IN Be$^8$  187
II-B: HEAVY ION RADIATIVE CAPTURE STUDIES  192
II-C: Hg$^{204}(\alpha,\gamma)$Pb$^{208}$  214
LIST OF TABLES

1-1 Second Class Currents in Nuclear Systems 19
4-1 Error Analysis for Efficiency Determination 96
5-1 Error Analysis in the Determination of $\Gamma_{\Delta T=1}^{M1}$ 148
6-1 Isovector M1 Radiative Widths of the 16.6-16.9 MeV Doublet in Be$^8$ 151
# LIST OF FIGURES

1-1 Angular Correlations in Beta Decay 11
2-1 Energy Levels in the Mass 8 System 26
3-1 Beam Line for Radiative Capture Experiments 41
3-2 A Schematic Illustration of the NaI(Tl) Spectrometer 48
3-3 Radiative Capture Experiment Electronics 52
3-4 Signal Processing 55
3-5 A Sample Gamma-Ray Spectrum 59
4-1 Annular Detector Assembly 66
4-2 Signal Processing and TAC Circuit 70
4-3 The Hard-Wired TAC Circuit 72
4-4 The Computer Interface 74
4-5 The Proton Singles Spectrum 80
4-6 The TAC Spectrum 82
4-7 The Gamma-Ray Spectrum 84
4-8a Gated Proton Spectrum 86
4-8b Gated Proton Spectrum 86
4-9a Gated TAC Spectrum 88
4-9b Gated TAC Spectrum 88
4-10 Gated Gamma-Ray Spectrum 90
4-11 NaI Response Function 99
4-12 Gamma-Ray Spectrum with Detector Response Removed 103
4-13 Predicted Gamma-Ray Peak Shapes 105
5-1 Background Subtraction Test 112
5-2 A Background Subtracted Gamma-Ray Spectrum 114
5-3 The Measured Excitation Function and Fit 118
5-4 The Angular Distribution 122
5-5 A Set of Excitation Functions with Variable $\Gamma_{M1}^{\Delta T=1}$ 132
5-6 Direct Interaction and Interference Effects 134
5-7 A Comparison of Mixing Parameters 136
5-8 Contours of Constant $\chi^2_\nu$ 142
5-9 Contours of Constant $\chi^2_\nu$ 144
5-10 Four $\chi^2_\nu$ Plots 146
6-1 Weak Magnetism and Gamow-Teller Form Factors 154
6-2 Measured and Predicted Asymmetries 156
II-A-1 Selected Energy Levels of Be$^8$ 190
II-B-1 Energy Level Diagram for F$^{19}$ 196
II-B-2 Excitation Function for the Li$^7$(C$^{12},Y_0,1,2$)F$^{19}$ Radiative Capture Reaction 198
II-B-3 Energy Level Diagram for Ne$^{21}$ 200
II-B-4 Excitation Function for the Be$^9$(C$^{12},Y_0,1$)Ne$^{21}$ Radiative Capture Reaction 202
II-B-5 Energy Level Diagram for Mg$^{25}$ 204
II-B-6 Excitation Function for the Be$^9$(0$^{16},Y_0,1,2$)Mg$^{25}$ Radiative Capture Reaction 206
II-B-7 Excitation Function for the C$^{13}$(C$^{12},Y_0,1,2$)Mg$^{25}$ Radiative Capture Reaction 208
II-B-8 Energy Level Diagram for Mg$^{24}$ 210
II-B-9 Excitation Function for the C$^{12}$(C$^{12},Y_0$)Mg$^{24}$ Radiative Capture Reaction 212
II-C-1  Energy Level Diagram for Pb$^{208}$  

II-C-2  Excitation Function for the Hg$^{204}$(α,γ)  Pb$^{208}$ Radiative Capture Reaction
INTRODUCTION AND MOTIVATION FOR THE EXPERIMENT

1.1 BRIEF HISTORICAL BACKGROUND

Of the many subfields of nuclear physics, beta decay is unique as both a great patriarch and a great innovator in twentieth century physics. Beta radioactivity had been observed at the beginning of the field of nuclear physics in the late nineteenth century; today nuclear beta decay measurements are providing data crucial to the understanding of the fundamental nature of weak interactions.

The early experiments in beta decay had determined that beta rays were electrons and that they were not emitted with a single discrete energy like α and γ rays but were emitted with a large energy spread. Rather than abandon the principle of energy conservation, Pauli in 1930 postulated the existence of a third particle among the beta decay products: a particle of no rest mass, no charge, no magnetic moment, and incapable of electromagnetic or strong interactions. The idea of the neutrino (anti-neutrino) led a few years later to the first successful theory of beta decay, formulated by Fermi in 1933/4.¹

To describe the weak interaction, Fermi developed his
theory in direct analogy with the electromagnetic interaction. He proposed the weak interaction Hamiltonian density

\[ H = \frac{-G}{\sqrt{2}} J_{\mu} L_{\mu} \]  

(1-1)

where \( \frac{G}{\sqrt{2}} \) is the weak interaction coupling constant giving the strength of the interaction, \( J_{\mu} \) is the weak nucleonic current density, and \( L_{\mu} \) is the lepton field. \( J_{\mu} \) and \( L_{\mu} \) were constructed from Dirac vector bilinear covariants:

\[ J_{\mu} = \bar{\psi} p_{\gamma} \mu \psi n \]  

(1-2)

\[ L_{\mu} = \bar{\psi} e_{\gamma} \mu \nu \psi \]  

(1-3)

where \( \psi \) and \( \bar{\psi} \) were proton, neutron, electron, and anti-neutrino Dirac spinors. Drawing from the perturbation theory which described electromagnetic transitions, Fermi arrived at the transition probability per unit time for a nuclear system to change from an initial state \( i \) to a final state \( f \) by means of the weak interaction:

\[ W_{fi} = \frac{2\pi}{\hbar} \rho(E)|H_{fi}'|^2 \]  

(1-4)

where \( H_{fi}' \) is the volume integral of the product of the Hamiltonian density for the specific \( i+f \) transition and the electron-neutrino wave functions, and \( \rho(E) \) is the statistical factor (density of possible final states in electron-neutrino phase space). The above formalism thus describes the decay
Fermi's theory was subsequently extended by Bethe and Bacher\(^2\) to include couplings corresponding to all the Dirac bilinear covariants. With the weak interaction operator now written as \(0\), the generalized Hamiltonian density for \(\beta^+\) decay became

\[
H = g \sum C_i (\bar{\psi} \gamma^5 \psi \bar{\psi} \gamma^5 \psi) + \text{h.c.} \quad (1-5)
\]

where h.c. is the Hermitian conjugate. The types of interaction are determined by relativistic wave mechanics for spin — \(\frac{1}{2}\) particles and there are only five, each with its own coupling constant \(gC_i\) (where \(\sum |C_i|^2 = 1\) and all \(C_i\) are real): scalar, vector, tensor, axial vector, and pseudoscalar. The summation extends over all the \textit{a priori} equally acceptable classes. By 1956 the nonconservation of parity in weak interactions had been established and this required the addition to equation (1-5) of five odd coupling forms, where \(\gamma_5\) appears in the lepton bracket.

Many experiments done over decades were devoted to the study of these various couplings. The agreement among experiments in nuclear beta decay, beta asymmetry measurements, electron-neutrino angular correlations, and neutrino helicity measurements provided conclusive evidence that of all the possible couplings, there are only vector and axial vector. This is consistent with the breakdown of parity and charge conjugation. Neutron beta decay asymmetry measurements and
$\beta$-$\gamma$ angular correlation studies then firmly established the relative sign between $C_V$ and $C_A$; the interaction is $V$ minus $A$.

1.2 THE CONSERVED VECTOR CURRENT THEORY

Before and during the time that the V-A nature of the weak interaction was being established a search was in progress for a Universal Fermi Interaction that would describe the processes of beta decay, muon decay, muon capture, and strange particle decay by the same set of coupling constants. A successful form of such an interaction was proposed by Feynman and Gell-Mann$^3$ and others in 1958; this has since become known as the Conserved Vector Current (CVC) theory.

The CVC theory was not the only theory capable of deducing the V-A interaction. A new principle of chirality invariance$^4$ had been proposed which led directly to the V-A four-fermion combination. It simply required that the four-fermion interaction not depend on the choice of $\psi$ or $\gamma_5\psi$ for each particle in the interaction.

However, the approach of Feynman and Gell-Mann was to represent massive relativistic spin-$\frac{1}{2}$ particles by two-component Pauli spinors satisfying a second-order Klein-Gordon equation. These wave functions were then used to construct a weak interaction Hamiltonian density without gradient couplings and this led to an interaction with equal
amounts of vector and axial vector strength. From this point
the CVC hypothesis was proposed based on the observation of
nearly equal decay constants in muon, pion, and neutron beta
decay and from an analogy with the universal coupling strength
de the electromagnetic interaction.

The electromagnetic current is conserved and satisfies
the continuity equation

$$\nabla \mu J_{\mu}^{\text{EM}} = 0$$ (1-6)

If noninteracting nucleons satisfied the free Dirac equa-
tion, the electromagnetic current could be written as

$$J_{\mu}^{\text{EM}} = \frac{1}{2} \bar{\psi}_N (1 + \tau_3) \gamma_{\mu} \psi_N$$ (1-7)

where the $\frac{1}{2} (1 + \tau_3)$ isospin operator projects out protons.
This current is conserved. But nucleons are strongly inter-
acting particles and satisfy a Dirac equation with source
terms from meson-nucleon couplings, so the Dirac equation
becomes

$$(\not{\Phi} - m) \psi_N(x) = g_{\pi N} \gamma_5 (\tau \cdot \phi(x)) \psi_N(x)$$ (1-8)

where $\phi$ is the pion field and $g_{\pi N}$ is the pion-nucleon coupling
strength. If equation (1-6) still holds then additional pion
currents need to be added to equation (1-7). The electro-
magnetic current then becomes

$$J_{\mu}^{\text{EM}} = \frac{1}{2} \bar{\psi}_N (1 + \tau_3) \gamma_{\mu} \psi_N + i[\phi^* \tau_3 \nabla \mu \phi - (\nabla \mu \phi)^* \tau_3 \phi] + \ldots$$ (1-9)
Noting the similarities between weak and electromagnetic interactions, Feynman and Gell-Mann then proposed that a more general vector current is conserved. If the three-component of isospin is identified with the isovector electromagnetic current and the \((l+\bar{l})\) isospin components represent the weak vector current, the total vector current is written as

\[ J_\mu = \frac{1}{2} \bar{\Psi}_N (l+\bar{l}) \gamma_\mu \Psi_N + i [\phi^* \nabla_\mu \phi - (\nabla_\mu \phi)^* \phi] + \ldots \]  

(1-10)

The CVC hypothesis states that this current is conserved.

This leads to two important results which make the theory highly useful. First, the electromagnetic and weak vector currents are related to each other by a rotation in isospace and are separately conserved. Strong interactions are assumed to be isospin-invariant and isospin is taken to be a good quantum number. Second, the theory allows a fairly direct calculation of weak form factors, especially the induced terms that are first order in recoil. Most important is the resultant relationship between electromagnetic and weak vector form factors that is independent of the details of any model-dependent calculation.

The various types of form factors can be divided into two classes, depending on their transformation properties under G parity, as first carried out by Weinberg. First-class vector and axial vector currents are respectively odd.
and even under G parity while the opposite holds for the second-class currents.

The CVC theory then poses a challenge to experimentalists: on the one hand, to test the correctness of the hypothesis, and on the other hand, to determine whether or not the second-class currents exist.

1.3 MIRROR BETA DECAYS

Aside from the early 1960's work devoted to investigations of the CVC weak magnetism predictions, the first intense experimental activity devoted to a testing of the CVC hypothesis was the early 1970's work of Wilkinson on mirror beta decays. In measurements on a number of nuclear systems he noted asymmetries in the intrinsic rates of mirror beta decays and a correlation of the asymmetry with the total energy released. It appeared that the asymmetries were due to the effects of second-class axial vector currents but it is now apparent that they were due to electromagnetic distortions of the nuclear states. The asymmetry must be written

\[
\frac{f_t^+}{f_t^-} - 1 = \delta^{\text{SCC}} + \delta^{\text{nucl}}
\]  

where the second-class current (SCC) contribution is generally masked by uncertainties in the calculated and very model-dependent nuclear structure contribution, \(\delta^{\text{nucl}}\). Since \(f_t^+\) asymmetry measurements were eventually found inadequate in
determining the existence of second-class currents, other methods had to be found.

1.4 CORRELATION EXPERIMENTS

Facing the problem of finding a model-independent basis for investigating second-class currents, Holstein and Treiman turned to correlation experiments and, treating the nucleus as an elementary particle, worked out a detailed formalism examining correlation effects through second order in recoil.

They identified two basic classes of experiments for effectively searching for second-class currents: either a lepton-particle (lepton-gamma-ray) directional correlation measurement or a measurement of the energy dependence of the asymmetry parameter in the angular distribution of leptons emitted in the decay of a polarized nucleus. The latter class involves measuring the direction in which decay leptons are emitted relative to the direction of nuclear polarization. The former class of experiments is illustrated schematically in Figure 1-1. In this case the experiment involves leptons produced by beta decay in a transition to a nuclear excited state and particles or gamma-rays which are the subsequent decay products of that excited state. The direction of particle or gamma-ray emission is measured relative to the direction of lepton emission to produce an angular correlation.
Both classes of experiments are looking for effects at the 1% level and both yield results as a linear combination of the weak magnetism and second-class induced-tensor form factors. However, if CVC is assumed, the model-independent relationship between the weak magnetism form factor and the measured isovector M1 width for the associated gamma decay ($\gamma$(M1) in Figure 1-1) allows the separation of second-class current effects. The second type of experiment has the disadvantage that Coulomb effects must also be separated.

During the past few years, a number of experiments have been done using these methods to search for second-class currents. The following sections briefly summarize some of the recent ones. The notation necessarily used here is explained in greater detail in Chapter 2.

1.5 MASS 20 MEASUREMENTS

Recently R.D. Cousins et al. have performed a $8^+\alpha$ angular correlation measurement in the decay of Na$^{20}$ to the 7.42 MeV state of Ne$^{20}$. The correlation is of the form

$$w(\theta) = 1 + a(E) \cos \theta + p(E) \cos^2 \theta \quad (1-12)$$

where $p(E)$ contains weak magnetism, Gamow-Teller, and induced tensor form factors. The weak magnetism form factor can be calculated from the analogous M1 decay width, and the Gamow-Teller form factor can be calculated from the $ft$ value. Using their value for the energy averaged coefficient $\bar{p}$ and assuming
Figure 1-1: Angular Correlations in Beta Decay.
Shown schematically are two possible angular correlation experiments. In one case an angular correlation measurement is made between a lepton in a $\beta^+ \!$ decay to a nuclear excited state and a gamma-ray from the subsequent decay of that excited state. In the second case the angular correlation measurement is made between the lepton and a particle from the decay of the excited state.
ISOSPIN TRIPLET

ANGULAR CORRELATION EXPERIMENTS
CVC, they concluded that they have observed no effects of second-class currents.

Tribble and May\textsuperscript{12} have measured the $\beta^-$-$\gamma$ angular correlation for the decay of $\mathrm{F}^{20}$ to the 1.63 MeV state of $\mathrm{Ne}^{20}$ which then $\gamma$-decays to the ground state. Coincidence data were measured at $\theta_{\beta^-\gamma} = 90^\circ$ and $180^\circ$ and the asymmetry was determined as a function of the $\beta$ energy. The correlation resembles equation (1-12) except $a(E)$ is zero, and the $p$ coefficients for $\beta^+$ decay are

$$p_+ = \frac{E}{4m_nA_c} \left( + b \frac{d_{II}}{A_c} - d_1 \right) \quad (1-13)$$

where $E$ is the beta energy, $m_n$ the nucleon mass, $A$ the mass number, $b$ the weak magnetism form factor, $c$ the Gamow-Teller form factor, $d_1$ the first class induced tensor form factor, and $d_{II}$ the second class induced tensor form factor. A least squares fit to the asymmetry data gave a value for the energy slope in equation (1-13) which, when compared to a recent $\mathrm{Na}^{20} \beta^+$-$\gamma$ correlation measurement, gave a value for $\frac{b}{A_c} - \frac{d_{II}}{A_c}$. When $b$ and $c$ were calculated as above, it was found that $\frac{d_{II}}{A_c}$ was zero within statistics. Similar measurements involving $\mathrm{F}^{20}$ and $\mathrm{Na}^{20}$ were carried out by Rolin et al.\textsuperscript{13} with similar results: no second-class currents.

Another experiment of a different type involving the $\beta^-$-decay of $\mathrm{F}^{20}$ was carried out by Genz et al.\textsuperscript{14} in order to test the CVC hypothesis. For the decay of $\mathrm{F}^{20}$ to the first excited state of $\mathrm{Ne}^{20}$ they measured the half-life and endpoint
energy and extracted a shape factor. From the energy dependence of the shape factor and the value of the $f_t$ asymmetry (equation (1-11)), they concluded that the CVC theory was upheld and that no second-class currents were observed.

1.6 MASS 19 MEASUREMENTS

F.P. Calaprice et al. have measured the energy dependence of the $B$ asymmetry parameter in the $B^+$ decay of polarized Ne$^{19}$ to F$^{19}$ by measuring the angular correlation between the initial nuclear spin of Ne$^{19}$ and the direction of positron emission. The correlation is given by

$$w(\theta) = F_1(E) + F_4(E)P \frac{p}{E} \cos\theta \quad (1-14)$$

where $P$ is the nuclear polarization, $p$ and $E$ are the momentum and energy of the positron, and $\theta$ is the angle between positron emission and polarization direction. Because this is a transition between members of a $\frac{1}{2}^+$ isospin doublet, the factors $F_1$ and $F_4$ above contain, to first order in recoil, only four nuclear form factors: $a, b, c$, and $d_{II}$, where $a$ is the allowed vector form factor. For $T = \frac{1}{2}$ states, $a = 1.00$ to within 1%. The weak magnetism form factor $b$ is given by

$$b = \sqrt{3} A (\mu_{Ne^{19}} - \mu_{F^{19}}) \quad (1-15)$$

where $\mu$ is the magnetic moment of the nucleus in nuclear magnetons. The magnitude of $c$ is determined from the decay rate and the negative sign of $c$ is determined from the strongly
destructive interference effect it has on the energy independent part of the $\beta$ asymmetry parameter $A(E) = F_4(E)/F_1(E)$. This leaves the energy dependent part of $A(E)$ as a sizeable fraction of the total and is a real experimental advantage.

From a plot of the percentage asymmetry versus $\beta^+$ energy a best value was obtained for the slope $\frac{dA(E)}{dE}$, and using the formulas for $F_1$ and $F_4$ given by Calaprice et al., this led immediately to a value for $d_{\gamma}$: $d_{\gamma}/A_c = -8.0 \pm 3$. Therefore a large second-class form factor is needed to explain the observed energy dependence of the $\beta$ asymmetry. Furthermore this form factor is nearly the same magnitude as the weak magnetism form factor and is of opposite sign. The calculations were straightforward and unencumbered by large model dependent nuclear corrections except that small finite-nuclear-size Coulomb corrections needed to be applied to $F_1$ and $F_4$.

Unfortunately, according to a recent communication from Calaprice, the above published data are in error because of experimental problems. It appears that when corrections are made there will be no strong evidence supporting the existence of second-class currents. At the present time the outcome of this experiment is not firmly established.

1.7 MASS 12 MEASUREMENTS

A similar $\beta$-decay asymmetry experiment was performed using polarized $B^{12}$ and $N^{12}$ by K. Sugimoto et al. The measured asymmetry was
for $\beta^+ \rightarrow c^{12}$, where the quantities are defined as for equation (1-14). The nuclear polarization was measured and the alignment was found to be very small. In terms of form factors the asymmetry $A^+$ can therefore be written

\begin{equation}
A^+ = P \frac{P}{E} \left[ \frac{3}{2} \left( \frac{1}{A} - \frac{d_I}{A_c} \right) + \frac{E}{3m_n} \left( \frac{d_{II} - b}{A_c} \right) \right]
\end{equation}

(1-17)

using quantities as defined for equation (1-13). One possible experimental difficulty is evident here: the energy dependent part of $A^+$ is much smaller than the energy independent part.

From plots of the percentage asymmetry versus $\beta$ energy the energy slopes $\alpha_-$ and $\alpha_+$ were extracted. Since

\begin{equation}
\frac{dA^-}{dE} + \frac{dA^+}{dE} = P \frac{P}{E} (\alpha_+ - \alpha_-) = P \frac{P}{E} \left[ \frac{2}{3m_n} \left( \frac{d_{II} - b}{A_c} \right) \right]
\end{equation}

(1-18)

a value for $\frac{d_{II} - b}{A_c}$ can readily be found. $c$ can be found from the average $f^t$ value of the two decays and $b$ can be calculated from the isovector $M_1$ radiative width of the $T_z = 0$ member (15.11 MeV state in $C^{12}$) of the $B^{12}_c - C^{12}_c - N^{12}$ isospin triplet. As for the published mass 19 data, this yields a value for the second-class form factor $d_{II}$ as large as the weak magnetism term but opposite in sign.

Another experiment in the mass 12 system, not involving angular correlations, was carried out by Calaprice and
and Holstein who measured the shapes of the beta spectra for Gamow-Teller decays and reanalyzed the N and B data of Lee et al. They found no support for the weak magnetism prediction of the CVC theory. This conclusion was rebutted by Wu et al. who reanalyzed the N and B data using new Fermi functions and end point values and found agreement with the theoretical shape factors predicted from the weak magnetism of the CVC theory.

1.8 MASS 8 MEASUREMENTS

In 1973 Tribble and Garvey performed a 8-α angular correlation measurement in the mass 8 system. They measured the number of 8 particles from the 8 decays of Li and B to the first excited state of Be in coincidence with the breakup α's from that state.

The sources were first produced by the reactions Li(d,p) Li and Li(He ,n)B and were then rotated into the center of a detector matrix consisting of four silicon surface-barrier detectors for detecting α particles and two plastic scintillators for detecting 8 particles. The detectors were arranged to give coincidence measurements at angles of θ 8-α = 0, 90, 180, and 270 degrees. The expected angular correlation is given by

\[ w(θ_{8-α}) = 1 + a^\pm \cos θ_{8-α} + p^\pm \cos^2 θ_{8-α} \]  

(1-19)

where θ_{8-α} is the angle between the 8 particles and the
breakup α's. The coefficients were determined for each β detector separately by integrating over the full spectrum of breakup α's. Corrections were applied for finite source and detector sizes and the final values were calculated by averaging the 90° and 270° data for each β detector. Experimental values were obtained at β energies of 5 to 13 MeV.

The physics of the decay lies essentially in the p± coefficients. Calculations for these coefficients have been carried out to second order in momentum transfer using the impulse approximation. The difference of the p± coefficients is given by

\[ \delta^- = p^- - p^+ = \frac{E_B}{m_n} \left[ \frac{b}{A_c} - \frac{d_{II}}{A_c} - \frac{(E_0 - E_B)}{m_n} \sqrt{\frac{3}{28}} \frac{g}{A_c^2} - \frac{3}{\sqrt{14}} \frac{f}{A_c} \right] \] (1-20)

where \( E_B \) is the total β energy, \( E_0 \) is the β endpoint energy, \( f \) and \( g \) are second-forbidden vector form factors, and the rest of the terms are defined as for equation (1-13). A least-squares fit to all the data points for \( \delta^- m_n/E_B \) indicated a negligible energy slope and therefore a very small contribution from the second-forbidden vector terms. It also determined that \( \frac{b}{A_c} - \frac{d_{II}}{A_c} = 6.8 \pm 0.4 \). Aside from estimating the form factors from nuclear wave functions, this was as far as the calculations went. What was needed to pin down the size of the second-class current contributions was a measurement of the isovector M1 radiative width of the \( T_z = 0 \) member.
of the $\text{Li}^8$-$\text{Be}^9$-$\text{B}^8$ triplet, which is related in a model independent way to the weak magnetism form factor $b$.

This value was provided by Nathan et al.\textsuperscript{23} in a 1974 measurement. The quoted value for the radiative width,

$$\Gamma_{\text{M}_1}^{\Delta T=1} = 4.8 \pm 0.7 \text{ eV},$$

was the weighted mean of the results of two experiments, one at Brookhaven and one at Princeton. When the $\Gamma_{\text{M}_1}^{\Delta T=1}$ and $\beta^\pm -\alpha$ correlation measurements were combined and the $\text{Be}^8$ final state distribution was taken into account, it was determined that no second-class currents had been observed in the mass 8 system.

1.9 COMMENTS

Table 1-1 gives a summary of the preceding sections; the column on the right indicates whether the experiments have found evidence for the existence of second-class currents. Only the two $\beta$ decay asymmetry experiments in the mass 12 and 19 regions show positive evidence, and one is questionable.

The mass 8 results, however, require further experimental research. When the isovector M1 radiative width $\Gamma_{\text{M}_1}^{\Delta T=1}$ for the 16.6 - 16.9 MeV doublet in $\text{Be}^8$ was measured by Nathan et al., two different values were found that were nearly three standard deviations apart. One experiment at Brookhaven yielded a value $\Gamma_{\text{M}_1}^{\Delta T=1} = 6.20 \pm 0.74 \text{ eV}$ while the other at Princeton yielded $\Gamma_{\text{M}_1}^{\Delta T=1} = 4.46 \pm 0.47 \text{ eV.}$\textsuperscript{24} The discrepancy was unaccounted for, and the possibility of making an independent measurement of
TABLE 1-1

SECOND CLASS CURRENTS IN NUCLEAR SYSTEMS

<table>
<thead>
<tr>
<th>Mass System</th>
<th>Recent Experiments</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>$\beta^+ - \alpha$ angular correlations(^{21,22})</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>(1975)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>$\beta^+$ decay asymmetry from polarized nuclei(^{17})</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>(1975)</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>$\beta^+$ decay asymmetry from polarized nuclei(^{15})</td>
<td>Yes?</td>
</tr>
<tr>
<td></td>
<td>(1975)</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>$\beta^+ - \alpha$ angular correlation(^{11})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1977)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta^+ - \gamma$ angular correlations(^{12,13})</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>(1977)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$ft$ asymmetry of mirror Gamow-Teller decays(^{14})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1976)</td>
<td></td>
</tr>
<tr>
<td>8,12,18,20,24,28,30</td>
<td>$ft$ asymmetries of mirror Gamow-Teller decays(^{6,7,8})</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>(1970-74)</td>
<td></td>
</tr>
</tbody>
</table>
with an accuracy of $\pm 10\%$ was the principal motivation for the experiment reported in this thesis. An accurate measurement of $\Gamma_{M1}^{\Delta T=1}$ would allow an unambiguous calculation of the weak magnetism form factor which in turn would allow the mass 8 $\beta^+ - \alpha$ correlation data to be examined for effects of second-class currents with all model-dependent calculations completely removed. It was therefore of prime importance to the question of the existence of second-class currents in the mass 8 system that a new and accurate value of $\Gamma_{M1}^{\Delta T=1}$ be measured.

In summary, an examination of the mass 8 system was chosen to provide a new and accurate value of $\Gamma_{M1}^{\Delta T=1}$ which could then be applied to accurate and recently measured mass 8 $\beta^+ - \alpha$ angular correlation data to extract an unambiguous value for the magnitude of second-class currents in the mass 8 system. To measure $\Gamma_{M1}^{\Delta T=1}$ for the 16.6 - 16.9 MeV doublet in Be$^8$, the radiative capture reaction $^4\text{He}(\alpha,\gamma)^7\text{Be}$ was chosen. A $^4\text{He}$ beam from the Wright Nuclear Structure Laboratory MP tandem Van de Graaff accelerator was directed through a 100 keV thick $^4\text{He}$ gas target and the resulting gamma-rays were detected by an anticoincidence shielded lead-collimated 30 cm. x 30 cm. NaI(Tl) spectrometer placed at an angle of 125° to the alpha beam. The spectrometer was calibrated in a p-$\gamma$ coincidence measurement using the reaction $^{10}\text{Be}(\alpha,\gamma)^{12}\text{C}$ (15.11)($\gamma$)$^{12}\text{C}$. An excitation function over the range of 16.4 to 17.1 MeV in Be$^8$ was measured and fitted with a theoretical excitation function generated from 2-level R-matrix theory. The isovector M1 radiative width
Gamma extracted from this fit was \( 6.91 \pm 0.85 \text{ eV} \). This result combined with the \( \beta^+ - \alpha \) angular correlation measurements described in Section 1.8 led to the conclusion that there is no evidence for second-class currents in the mass 8 system.

After the He\(^4\)(\(\alpha,\gamma\))Be\(^8\) experiment described herein was completed, we learned of two similar He\(^4\)(\(\alpha,\gamma\))Be\(^8\) experiments that had been performed parallel to ours. One by Bowles and Garvey\(^{25}\) at Princeton yielded a value for \( \Gamma_{M1}^{\Delta T=1} \) equal to \( 6.10 \pm 0.53 \text{ eV} \); the other by Paul et al.\(^{26}\) at Strasbourg found \( \Gamma_{M1}^{\Delta T=1} = 7.37 \pm 1.0 \text{ eV} \). Both experiments support the absence of second-class currents. In fact most of the evidence presented in this chapter supports the predictions of the conserved vector current theory and leads to the conclusion that second-class currents do not exist.

The next chapter will discuss the conserved vector current theory and present a formalism pertinent to the examination of weak interaction currents in nuclear systems. Succeeding chapters will describe the He\(^4\)(\(\alpha,\gamma\))Be\(^8\) experiment (Chapter 3) and the calibration of the large NaI spectrometer used in this experiment (Chapter 4) and finally the analysis of the data that leads to a value for \( \Gamma_{M1}^{\Delta T=1} \) (Chapter 5) and a value for the magnitude of second-class induced-tensor currents in the mass 8 system (Chapter 6).
CHAPTER 1 REFERENCES

2.1 THE MASS 8 SYSTEM

The essential elements of the mass 8 system are shown in the level diagram of Figure 2-1. The $2^+$ states shown by heavy lines are members of the isospin triplet that is of principal interest. Tribble and Garvey have measured the $\beta^+-\alpha$ angular correlations for the beta decays of the outer members of this triplet to the broad first excited state of Be$^8$ which subsequently breaks up into two alpha particles. The experiment reported here has measured the analogous gamma decay strength of the $T_z=0$ member of the isospin triplet to the same final state. As the diagram shows the measurement is complicated by the fact that the $2^+, T=1$ state of interest is strongly isospin mixed with a nearby $2^+$ state. This is one of the most well known and well-studied cases of isospin mixing between nuclear levels, where the amount of isospin mixing has been accurately determined in a variety of experiments by J.B. Marion, F.C. Barker, and others. Because of this isospin mixing a simple measurement of the transition rate cannot be made; instead it is necessary to measure an excitation function.
Figure 2-1: Energy Levels in the Mass 8 System. Members of the $\text{Li}^8-\text{Be}^8-\text{B}^8$ isospin triplet are shown by heavy lines. The central member is strongly isospin mixed with a nearby $T=0 \ 2^+$ state. Both $T=0$ and $T=1$ states have gamma decay widths for gamma-ray transitions to the first excited state of $\text{Be}^8$. 
LEVEL DIAGRAM FOR $A = 8$
extending through both levels using the reaction $^4\text{He}(^4\text{He},\gamma_1)^8\text{Be}^{8\ast}$ and then extract the isovector part of the M1 radiative width.

To make a decision on the strength of the second-class currents in this mass system it is necessary to first develop an angular correlation for the $\beta^+-\alpha$ experiment, then to relate the measured isovector M1 radiative width $\Gamma_{M1}^{\Delta T=1}$ to the weak magnetism form factor $b$, and finally to incorporate $b$ into the $\beta^+-\alpha$ angular correlation measurements. The following section summarizes the calculation of the theoretical $\beta^+-\alpha$ angular correlation as carried out by Holstein$^5$ and by Tribble.$^2,^6$

2.2 THE $\beta^+-\alpha$ ANGULAR CORRELATION

The theory of Holstein uses the elementary particle approach to examine allowed beta decay to second order in momentum transfer and assumes the vector-axial vector form of the weak interaction. The transition probability is

$$dW = \frac{F(Z,E)}{(2\pi)^5} |T|^2 \delta^4 (p_1-p_2-p-k) d^3p_1 d^3p_2 d^3p d^3k \quad (2-1)$$

where $p_1$, $p_2$, $p$, and $k$ are the four-momenta of the parent, daughter, electron, and antineutrino, respectively. $F(Z,E)$ is the Fermi function which corrects for dominant Coulomb effects. The four-dimensional delta function expresses conservation of momentum and energy.

The $T$ matrix in equation (2-1) is written as

$$T = \frac{G_v}{\sqrt{2}} \cos\theta_c \langle f|V_\mu(x) + A_\mu(x)|1>L^\mu \quad (2-2)$$
where $V_{\nu}(x)$ and $A_{\nu}(x)$ are the nuclear vector and axial vector currents, $G_{\nu}$ is the weak coupling constant, $\theta_{c}$ is the Cabibbo angle ($\theta_{c} \approx 15^\circ$), and $L^{\mu}$ is the lepton current which can be written as

$$L^{\mu} = \bar{u}(p)\gamma^{\mu}(1 + \gamma_{5})\nu(k)$$  \hspace{1cm} (2-3)

where $\bar{u}(p)$ and $\nu(k)$ are Dirac spinors for the electron and antineutrino, respectively. Implicit in $T$ is an average over initial spins and sum over final spins. The vector and axial vector parts of $T$ have been calculated by Holstein in terms of ten invariant form factors to order $q^{2}R^{2}$:

$$L^{\mu} < f|V_{\mu}|i> =$$

$$[a(q^{2}) \frac{\bar{p} \cdot L}{2M} + e(q^{2}) \frac{\bar{g} \cdot L}{2M}] \delta_{jj}, \delta_{mm},$$

$$+ i \frac{b(q^{2})}{2M} \frac{c^{m'km}}{j'1j} (\bar{q} \times L),$$

$$+ \frac{c^{m'km}}{j',2j} \left[f(q^{2}) \frac{d^{(2M)}}{112} L_{n} q_{n'} + \frac{e(q^{2})}{(2M)^{2}} \frac{\bar{p} \cdot L}{2M} \frac{4\pi}{5} \frac{1}{2} Y_{2} k(q)q^{2} \right] + ...$$  \hspace{1cm} (2-4)

$$L^{\mu} < f|A_{\mu}|i> =$$

$$C^{m'km}_{j',lj} \frac{\epsilon_{ijk}}{4M} \frac{\epsilon_{i'j'k'}}{4M} \left[ (c(q^{2})L_{n}q^{5} - a(q^{2})L_{n}q^{5} + \frac{b(q^{2})}{(2M)^{2}} q^{5} \frac{4\pi}{5} \frac{1}{2} j_{2}(q^{2}) \right]$$

$$+ \frac{c^{m'km}}{j',3j} \frac{c^{nn'k}}{123} \frac{d^{(2M)}}{112} L_{n} \frac{4\pi}{5} \frac{1}{2} Y_{2} n'(q) \frac{q^{2}}{(2M)^{2}} j_{3}(q^{2}) + ...$$  \hspace{1cm} (2-5)
In these equations \( M = \frac{1}{2} (M_1 + M_2) \) where \( M_1 \) and \( M_2 \) are the parent and daughter masses; \( \vec{p} = \vec{p}_1 + \vec{p}_2 \); \( \vec{q} = \vec{p}_1 - \vec{p}_2 = \vec{p} + \vec{k} \); the \( C_{1}^{m_{1},m_{2}}^{m_{3}} \) factors are vector-addition coefficients expressing conservation of angular momentum, where the parent (daughter) nucleus has spin \( J(J') \) and spin component \( m(m') \) along some axis of quantization. Repeated Latin indices are summed from 1 to 3 and repeated Greek indices are summed from 1 to 4.

As zero momentum transfer, the form factors above have these identifications: \( a(0) \) - Fermi, \( c(0) \) - Garnow-Teller; in recoil order, \( b(0) \) - weak magnetism, \( d(0) \) - induced tensor, \( e(0) \) - induced scalar, \( h(0) \) - pseudoscalar; to order \( q^2 R^2 \), \( f \) and \( g \) - second forbidden vector, \( j_2 \) and \( j_3 \) - second forbidden axial vector.

The expressions in equations (2-1), (2-2), (2-4), and (2-5) are combined in a long and complicated calculation. The phase space factor is first calculated including the recoil of the daughter nucleus to first order in \( E/M \) where \( E \) is the beta energy. The \( T \) matrix is manipulated thru a series of angular momentum decompositions from the parent nucleus thru intermediate states to the final nuclear states including the break-up alpha particles. A transformation to the laboratory frame is performed and an integration over neutrino angles is done to give finally this transition probability for \( \beta \) decay:

\[
\frac{dW}{F_{\nu}(Z,E)} = \frac{2(\cos \theta_C)^2}{(2\pi)^5 (E_0 - E)^2} p E dEd\Omega_e d\Omega_k \\
\times \left\{ f(E) + g(E) \frac{\vec{k} \cdot \vec{p}}{E} + h(E) \left[ \frac{(\vec{k} \cdot \vec{p})^2}{E^2} - \frac{1}{3} \frac{p^2}{E^2} \right] \right\} 
\]  

(2-6)
where $\vec{p}$ is the beta momentum, $\hat{k}$ is a unit vector in the direction of the alpha particle, and $E_0$ is the beta endpoint energy. $\hat{k} \cdot \vec{p}$ is therefore proportional to $\cos \theta$. The spectral functions $f(E)$, $g(E)$, and $h(E)$ are given for $\beta^+ \to \alpha$ decay by

$$f(E) = c^2 - \frac{2}{3} \frac{E_0}{M} (c^2 \pm cb + cd) + \frac{2}{3} \frac{E}{M} (5c^2 \pm 2cb) - \frac{1}{3} \frac{(m_e)^2}{ME} (2c^2 \pm 2cb + cd) \quad (2-7)$$

$$g(E) = \frac{-2c^2E}{MV^*} \quad (2-8)$$

$$h(E) = \frac{E}{M} \left\{ \frac{1}{2} (c^2 \pm cb - cd) - \frac{1}{\sqrt{14}} \left[ \mp \sqrt{\frac{3}{2}} cg \frac{(E_0 - E)}{2M} \pm \frac{3}{2} cf - 3cJ_2 \frac{(E_0 - 2E)}{4M} \right] - \frac{3}{2\sqrt{35}} cj \frac{E}{M} \frac{(E + 2E_0) c^2}{2M(v^*)^2} \right\} \quad (2-9)$$

where $v^*$ is the center-of-mass alpha particle velocity. Since the Fermi admixture is negligible in this $\beta$ decay, the form factor $a$ has been set equal to zero as has been $e$, which is proportional to $a$. $h$ is multiplied by $(\frac{m_e}{8m_p})^2$ and is ignored. Furthermore only axial vector currents are allowed to be second-class so that $c = c_I \pm c_{II}$ and $d = d_I \pm d_{II}$, but $c_{II}$ is assumed to be zero.

From equation (2-6) the angular correlation between $\beta^+$ and $\alpha$ particles is seen to be of the form
\[ W(\theta_{\beta^+ - \alpha}) = 1 + a^+ \cos \theta_{\beta^+ - \alpha} + p^+ \cos^2 \theta_{\beta^+ - \alpha} \quad (2-10) \]

where
\[ a^+ = \frac{g(E)}{c^2} = -\frac{2E}{M\gamma^*} \quad (2-11) \]

and
\[ p^+ \frac{h(E)}{c^2} = \frac{E}{2m_n} \left\{ \frac{1}{A} + \frac{b}{A^2 c} - \frac{d}{A^2 c} \pm \sqrt{\frac{3}{28}} \frac{g}{A^2 c} \frac{(E_0 - E)}{m_n} \right\} \quad (2-12) \]

where \( m_n \) is the nucleon mass and \( A \) is the mass number. Comparing the \( \beta^- - \alpha \) and \( \beta^+ - \alpha \) correlations we take the difference of the \( p \) coefficients and find
\[ \delta^- = p^- - p^+ = \frac{E}{m_n} \left\{ \frac{b}{A^2 c} - \frac{d_{II}}{A^2 c} - \sqrt{\frac{3}{28}} \frac{g}{A^2 c} \frac{(E_0 - E)}{m_n} - \frac{3}{\sqrt{14}} \frac{f}{A^2 c} \right\} \quad (2-13) \]

From the measured values of \( \delta^- \) and this expression we would like to determine the magnitude of \( d_{II} \). It is fortunate (and guaranteed by the CVC theory) that each of the remaining form factors is related to its electromagnetic counterpart; furthermore \( f \) is proportional to \( g \). We have as model-independent relationships
\[ b^2 = \frac{6M^2}{\alpha E_Y} \Gamma_{\Delta T=1} \] 
\[ f^2 = \frac{20M^2}{\alpha E_Y^3} \Gamma_{\Delta T=1} \] 
\[ g = -\sqrt{\frac{2}{3}} \left( \frac{2M}{\Delta} \right) f \] 
\[ (2-14) \]
\[ (2-15) \]
\[ (2-16) \]

where \( \alpha \) is the fine structure constant, \( \Delta = M_1 - M_2 \), and \( \Gamma_{\Delta T=1}^{M1} \) and \( \Gamma_{\Delta T=1}^{E2} \) are the analogous isovector radiative widths. Applied specifically to the mass 8 system we have

\[ b = 213.68 \left[ \frac{\Gamma_{\Delta T=1}^{M1}}{E_Y} \right]^{1/2} \]
\[ (2-17) \]

where \( \Gamma_{\Delta T=1}^{M1} \) is in eV and \( E_Y \) is in MeV. If

\[ \delta_1 = \sqrt{\frac{\Gamma_{\Delta T=1}^{E2}}{\Gamma_{\Delta T=1}^{M1}}} \]

equation (2-13) reduces to

\[ \delta^- = \frac{E}{m_n} \left\{ \frac{b}{Ac} \left[ 1 - \sqrt{\frac{5}{21}} \left( 1 + 2 \frac{E}{E_0} \delta_1 \right) \right] - \frac{d_{II}}{Ac} \right\} \]
\[ (2-18) \]

since \( E_0 \sim \Delta \). Therefore if \( \Gamma_{\Delta T=1}^{M1} \) and \( \delta_1 \) are measured, the right-hand side of equation (2-18) can be compared to the experimental values of \( \delta^- \) to see if there are any contributions from second-class currents.

2.3 COMPARISON WITH EXPERIMENT

The expression in equation (2-18) is, however, an appro-
appropriate one to use only for a sharp final state. As mentioned in section 1.8 the experimental values of \( \delta^- \) were derived from an integration over all endpoint energies \( E_0 \) and equation (2-18) should be rewritten to reflect this:

\[
\frac{\delta^- m_n}{E} = \sum_{E_0} \left\{ b(E_0) \left[ 1 - \sqrt{\frac{5}{21}} \left( 1 + 2 \frac{E}{E_0} \delta_1(E_0) \right) \right] - d_{II}(E_0) \right\} c(E_0) f(E_0,E) \]

\[ A \sum_{E_0} c^2(E_0) f(E_0,E) \]  

(2-19)

where \( f(E_0,E) = (\epsilon_0 - \epsilon)^2 \epsilon (\epsilon^2 - 1)^{1/2} \) with \( \epsilon = E/m_e c^2 \) is the phase space factor for beta decay. Equation (2-19) will not reduce to equation (2-18) because, as pointed out by Nathan et al., the radiative and beta decays populate the spectrum of final states differently and \( b(E_0)/c(E_0) \) is not a constant.

Again because the final state is not sharp \( b^2 \) must be rewritten as

\[
b^2(E_\gamma) = \frac{6M^2}{3 \alpha E_\gamma} \Gamma_{M1} \Delta T = 1 \sum_{E_\gamma} \frac{N(E_\gamma)}{\Sigma N(E_\gamma)} \]  

(2-20)

where \( N(E_\gamma)/\Sigma N(E_\gamma) \) is the fractional gamma transition strength centered around \( E_\gamma \) and is obtained by unfolding the NaI detector response from the measured gamma ray spectrum. Similarly the distribution for \( c^2 \) is obtained from measurements of the half-lives of \( B^8 \) and \( Li^8 \) and from the spectra of alphas following the beta decays. \( c^2 \) is calculated from

\[
c^2(E_0) = \frac{6165}{f(E_0)^{1/2}} \sum_{E_0} \frac{N(E_0)}{\Sigma N(E_0)} \]  

(2-21)
where $N(E_0) / \Sigma N(E_0)$ is the fractional decay strength gotten from the alpha spectra.

Distributions for $c^2$ and $b^2$ have been calculated by Bowles. What remains to be done is a measurement of $\Gamma_{M1}^{\Delta T=1}$ using the $^4\text{He}^4(\alpha,\gamma)\text{Be}^{8*}$ reaction. This experiment is described in the next chapter.
CHAPTER 2 REFERENCES

3.1 THE EXPERIMENTAL CHALLENGE

The measurement of the total isovector M1 radiative width of the 16.6 - 16.9 MeV doublet in Be\(^8\) posed many formidable problems. In the first place the width of each member of the doublet is almost entirely an alpha particle width and the gamma-ray width (to the first excited state of Be\(^8\)), by early experiments,\(^1\) is known to be a very small fraction of the total. This precludes any kind of coincidence experiment and suggests the radiative capture experiment He\(^4\)(\(\alpha,\gamma\))Be\(^8^\ast\) as the only reasonable means to measure the radiative width \(\Gamma_{M1}^{\Delta T=1}\).

In general radiative capture cross sections are small, on the order of 10 \(\mu\)b/sr or less, and great care must be taken to minimize background radiations so they do not overwhelm the gamma radiation of interest. In this case the background problem is compounded because a gas target must be constructed to hold the He\(^4\) and the gas target windows can be expected to contribute much of the background radiation of neutrons and both high energy and low energy cascade gamma-rays. Further background radiation can come from parts of the beam line.
struck by the beam, the shielded beam dump (Faraday cup) itself, and collimating slits. No competing background is expected from the He\(^{4}\) gas, however, since the \((\alpha,n)\) and \((\alpha,d)\) Q-values are too high compared with the alpha particle energies needed for the experiment.

If a NaI(Tl) gamma-ray spectrometer is constructed to detect gamma-rays from the He\(^{4}\)(\(\alpha,\gamma\)) Be\(^{8}\)\(^*\) reaction with reasonable efficiency, it will be enormously sensitive to all these background radiations. The resulting accidental summing of many low energy pulses will produce a pile-up that can overwhelm the photopeak in the gamma-ray spectrum unless the electronics used for signal processing are specifically designed to deal with this problem. Furthermore, the spectrometer and electronics must be designed to identify and sort the cosmic radiation (mostly muons) that any large volume NaI(Tl) crystal is sensitive to.

Facing a large background the experiment can achieve good counting statistics only by accumulating a large amount of beam charge, and since beam current is limited primarily by what the gas target windows can accept without destruction, this implies a long running time. During this time the experimenter must be prepared to identify gain or zero shifts and correct for them since any such shifts would reduce the energy resolution in the accumulated gamma-ray spectrum.

To meet these challenges we have used a low background beam line, a gas target with Kapton windows, a cosmic ray anti-
coincidence-shielded total absorption NaI(Tl) gamma-ray spectrometer, a DC coupled fast counting electronics network that greatly reduces pile-up, a gain stabilization system that corrects for shifts in electronics, and an IBM 360/44 data acquisition system for sorting and processing gamma-ray spectra.

3.2 ACCELERATOR AND BEAM LINE

The beam of alpha particles was first produced in a Duoplasmatron ion source as He$^+$ ions and then accelerated through an electron exchange canal filled with lithium vapor. The emerging He$^-$ ions were preaccelerated into the low energy terminal of the Wright Nuclear Structure Laboratory MP tandem Van de Graaff accelerator and were then attracted to the positively charged central terminal. In the central terminal carbon foils stripped the He$^-$ ions of all electrons and the emerging He$^{++}$ ions were accelerated away from the terminal and out of the accelerator. When the central terminal was charged to 11 MV, a beam of 33 MeV He$^{++}$ ions was produced.

The beam was then focussed and steered through two sets of 30 mil wide slits that formed the object and image of a 90° precision NMR controlled analyzing magnet that allowed the beam energy to be determined to one part in $10^4$. Then the beam was steered through a switching magnet into the beam line shown schematically in Figure 3-1.

After the switching magnet the beam was directed through
a set of four adjustable tantalum slits that defined the beam as the object for the downstream focusing quadrupole lens; its image lay at the upstream window of the gas target. The target area was shielded from these slits by a one meter thick concrete wall. A second set of current-monitored tantalum slits 6 inches upstream from the gas target served to direct the beam through the target during focusing (at 130 mils x 170 mils) but were opened wide (250 mils x 250 mils) during the course of the experiment. For a beam current of 300 na, only about 0.02 na struck the slits giving a negligible background.

The beam then passed thru the gas target in the center of a 10" diameter cylindrical aluminum target chamber lined with 5 mil tantalum. It then entered a Faraday cup lined with lead and tantalum and struck a tantalum beam stop buried deep in the middle of a beam dump heavily shielded by blocks of iron, lead, and borated paraffin. The entire beam line from the Faraday cup to switching magnet was very carefully optically aligned when the beam line was not evacuated, to insure that the beam passed down the center of the beam line and thru the center of the gas target and scattering chamber. Essentially the beam struck nothing in the target room but the gas target and the beam stop, creating a nearly background-free beam line. Further details of the beam line construction can be found in Shay\(^2\) and Brassard.\(^3\)
Figure 3-1: Beam Line for Radiative Capture Experiments.

A schematic representation depicting the important elements of the beam line used in the \( \text{He}^4(\alpha,\gamma_1) \text{Be}^{8*} \) experiment.
3.3 GAS TARGET AND GAS HANDLING SYSTEM

Many boundary conditions were necessarily considered in the design of the gas target. First it was essential that the NaI spectrometer be calibrated and that it not be moved or changed in any way between the calibration experiment and the \( \text{He}^4(\alpha,\gamma)\text{Be}^8 \) experiment. (This eliminated possible sources of error.) The calibration experiment that was selected dictated a detector angle of 55° or 125° and since the background was much less at backward angles, 125° was chosen. This also had the great advantage that the radiative width \( \Gamma_{\text{M}1}^{\Delta T=1} \) would be measured directly, to first order in mixing, without contributions from competing E2 radiation, because the detector was placed at a zero of \( P_2(\cos\theta) \) in the angular distribution of gamma-rays. At this angle it was difficult to shield the NaI spectrometer from the gas target windows, so it was decided to construct a short gas target in full view of the spectrometer and then have the effective target thickness precisely known without further calculations or calibrations. The effective solid angle was determined by integrating over the length of the gas target.

The energy thickness of the gas target was derived from considerations of how much of the excitation function should be integrated at each data point, and 100 keV was found to be a good compromise between a small integration and a large yield. Including the allowed size of the gas target window and the gas pressure it can hold, these considerations lead to a gas target 2 inches long, holding \( \text{He}^4 \) gas at a pressure of 40 cm Hg.
at an average laboratory temperature of 21.1°C and therefore having $\rho t \approx 0.443 \text{ mg/cm}^2$.

Considerable time was spent selecting the gas target windows. Commercial foils tested included 0.1 mil Havar, 0.04 mil nickel, 0.3 mil Kapton and 0.08 mil Parylene. Not surprisingly the parylene, $(C_8H_8)_n$, produced the least background, even 20% better than a comparable thickness of Kapton, $(C_{22}H_{10}N_2O_4)_n$; however the parylene was fairly permeable to helium and tended to degrade rapidly when heated by an alpha beam. Finally 0.3 mil Kapton (1.08 mg/cm$^2$) was chosen; it gave the next least background, was not permeable to helium, and held up without rupture under beam currents of 300 nA or more focussed to a 100 mil square area and under 1 atm. gas pressures.

The gas cell was made of brass and lined with tantalum, was 2 inches long and had 0.5 inch diameter entrance and exit Kapton windows. The entire assembly was tested with a 34 MeV $\alpha$ beam to see if the background produced by the windows was tolerable. It was found that at $125^\circ$ the background amounted to ~100 counts per MeV per microcoulomb in the region of the expected photopeak from the $^4\text{He}(\alpha,\gamma)^7\text{Be}$ reaction. It was considered that this would make it possible to do the experiment with good statistics if an amount of charge on the order of 1000 microcoulombs were collected.

Helium gas at a purity of 99.997% was supplied to the gas target through a specially designed gas handling system that regulated the gas pressure, measured the pressure by using a mercury manometer, and passed the gas through a liquid nitrogen
trap or its way to the gas target. The manometer was continuously monitored by a TV camera, as a precaution against impending foil failure. Local heating of the gas by the alpha beam was considered negligible since over the duration of the experiment the gas reached equilibrium with the large volume of gas in the gas handling system and was surrounded by efficient heat sinks, including the gas cell, the target chamber, and the pipes of the gas handling system. It was observed that the gas pressure dropped steadily during the course of the experiment so that at the end it was about 4% below its starting value. Considering this change in pressure, the uncertainty in cell thickness, the uncertainty in gas temperature and pressure (1 mm out of 40 cm Hg) and the uncertainty in gas impurities, the overall error in gas target thickness and composition is estimated to be 4%.

3.4 CHARGE MEASUREMENT

Special precautions were taken in setting up the beam line and the Faraday cup to insure an accurate measurement of the total charge accumulated. The Faraday cup was checked with a precision ohmmeter and found to be - for our purposes - perfectly insulated as was the target chamber. The target chamber was then connected by wire to the Faraday cup so that all beam current that entered the target chamber was registered in the Faraday cup. This completely bypassed the problem of electrons spraying from the gas target windows into the Faraday cup and the problem of the alpha particles picking up electrons in
passing through the gas target windows.

An error in charge measurement could arise if not all the beam current passing into the target chamber went through the gas target. However, tight collimation and precise alignment as well as continual measurement of the beam current on the upstream collimating slits assured that no beam entering the target chamber went anywhere except thru the center of the gas target. Beam deflection and Rutherford scattering in the gas target windows were negligible. Electrons sprayed downstream from the gas target windows were of no consequence but electrons backscattered upstream could escape the target chamber; however, it is highly improbable that electrons would backscatter 6 inches up a 2 inch diameter target chamber entrance port. Therefore all charge passing thru the gas target was registered in the Faraday cup with minimal error.

The Faraday cup was connected to a low impedance beam current integrator, which provided a read-out of the total charge accumulated. This current integrator was precisely calibrated by a specially built high impedance calibrator containing a bank of high precision resistors. It is estimated that the overall error in charge measurement for alpha particles is 2%.

3.5 THE NaI(Tl) SPECTROMETER

The gamma rays from the \( \text{He}^4(\alpha,\gamma_1)\text{Be}^{8*} \) reaction were detected in a 29.2 cm. by 30.5 cm. NaI(Tl) total absorption
spectrometer with three salient features that made it ideal for detecting low yield high energy gamma rays: its large volume, its cosmic ray anticoincidence shield, and its light-emitting diode gain stabilization system. The spectrometer is shown schematically in Figure 3-2.

The NaI(Tl) crystal, which is close to 100% efficient for 20 MeV gamma rays, was surrounded by a 5 inch thick lead shield and a thin cadmium sheet designed to reduce the flux of gamma rays and thermal neutrons into the crystal. The lead collimator was tapered to fit the solid angle and had an angular acceptance of 8.35°. The solid angle of 66 msr was determined to better than 1%. The entire assembly could be rotated about an axis through the target and perpendicular to the beam line through laboratory angles from 30° to 130°.

At the rear of the NaI(Tl) crystal was a bank of six XP1031 photomultiplier tubes coupled to the crystal via a lucite light pipe. The tubes represented a compromise between good resolution and high speed and their gains and rise times were carefully matched. The signal at the output of the six anodes, tied together in a 50 Ω back-terminated network, had a rise time of 50 nsec and a decay time of 250 nsec. The FWHM of the photopeak produced by this combination was approximately 6% for 20 MeV gamma rays.

Surrounding the crystal was a set of six 1/8 inch thick plastic scintillator sheets that formed the cosmic ray anticoincidence shield. Each scintillator was coupled via low loss adiabatic light pipes to fast (τ_p < 2nsec), DC coupled, high
Figure 3-2: A Schematic Illustration of the NaI(Tl) Spectrometer. A horizontal cross section shows the NaI(Tl) crystal surrounded by a lead shield and four of the six plastic scintillator sheets that make up the cosmic ray anticoincidence shield.
SCHEMATIC ILLUSTRATION OF EXPERIMENTAL APPARATUS

- Target
- Helium beam
- Collimator
- Lead shielding
- \( \theta_{\text{lab}} \)
- NaI(Tl) Crystal (29x30 cm)
- Lucite light pipe
- 1 of 6 photomultiplier tubes
- 1 of 3 light emitting diodes
- Plastic scintillator sheets
A cosmic-ray muon passing through the crystal must pass through two of the plastic scintillators and generate signals in two phototubes. A fast coincidence (15-30 nsec) between any two plastic scintillators was required to generate a veto signal that caused the coincident event in the NaI crystal to be tagged as a cosmic ray event. In this way 95% of the NaI crystal events caused by cosmic rays could be rejected. Our method of using thin anticoincidence shields is in contrast to other groups that have used shields of much larger volume and greater efficiency. In typical radiative capture experiments at high energy, however, the number of background neutrons is very high, and they would be registered with a high counting rate in any large volume plastic scintillator. They would therefore cause a high rate of random coincidences with NaI crystal events and an unknown and fluctuating fraction of real gamma ray events would be rejected. The thin plastic scintillators avoid this problem and accept lesser efficiency for cosmic ray detection.

Coupled to the NaI crystal was a set of three gallium phosphide light emitting diodes (LED's), driven at a rate proportional to the beam current and by a pulse shaped so that their light output resembled a gamma-ray scintillation. The LED pulses were routed to our computer and used to monitor gain shifts. If the centroid of a set of LED pulses shifted relative to a reference set a feedback gain stabilization
loop changed the voltage supplied to the XP1031 phototubes and changed the gain to compensate for the gain shift. This system gave a gain stabilization of better than 1%. Furthermore the LED pulses provided a convenient indication of electronic pile-up since pile-up was readily visible as an accumulation of counts in the high energy tail above the narrow LED reference peak. The counting rate was kept low enough so that no more than 5% of the total counts appeared in the high energy tail.

3.6 ELECTRONICS AND SIGNAL PROCESSING

The electronics apparatus which processed signals from the NaI(Tl) spectrometer was designed principally to avoid pile-up, correct for gain shifts, and reject cosmic rays from the gamma-ray spectrum. A block diagram of the electronics is shown in Figure 3-3.

The signals from the six XP1031 photomultiplier tubes were added in a 50 Ω back-terminated network and sent to the fast-counting system, shown by the dashed box in Figure 3-3, where they were amplified, clipped, and integrated before being sent to an analog to digital converter (ADC) at the computer interface. The coincidence logic module received signals from the cosmic ray anticoincidence shield voter coincidence unit (A signal was generated whenever two or more of the six plastic scintillator signals were in coincidence.), from the LED magnetic pick-up coil which generated a signal
Figure 3-3: Radiative Capture Experiment Electronics. For simplicity, only one of the six plastic scintillators is shown. The boxes labeled "fast counting system" and "coin. logic" are shown in more detail in Figure 3-4.
RADIATIVE CAPTURE EXPERIMENT ELECTRONICS

56 DVP PHOTOmultiplier

PLASTIC SCINTILLATOR
PILOT "M", 1/8" THICK

SIX XP1031 PHOTOmultipliers (ANODE OUTPUTS ADDED)
SIX PLASTIC SCINTILLATORS

SIX FAST DISCR.
FAST VOTER COIN. (2 OUT OF 6)

FAST COUNTING SYSTEM

FAST DC AMP.
FAN-OUT
FAST DC AMP.
FAST DC DISCR.

HIGH VOLTAGE SUPPLY
PHOTOMULTIPLIER CONTROL UNIT
GAIN STABILIZATION FEED-BACK SIGNAL

COIN. LOGIC
ROUTING SIGNALS:
\( \gamma \) RAY
COSMIC RAY
LIGHT PULSE

FAST DC AMP.
CLIP LINE
TERMINATION \( \Omega = 13 \Omega \)
DELAY LINE
OPEN
INTEGRATING LINEAR GATE
LINEAR SIGNAL

COMPUTER INTERFACE
(ADC'S, SCALERS, AND DIGITAL OUTPUT)

IBM 360/44 CPU

DISPLAY
PRINTER
MAG. TAPE
TYPEWRITER AND KEYBOARD

52
every time a NaI(Tl) pulse passed a preset discriminator threshold. It generated a set of logic signals sent to the computer interface to enable the on-line IBM 360/44 computer to sort the ADC spectrum into spectra corresponding to real gamma rays, cosmic rays, and LED (light pulser) events.

The lower part of Figure 3-3 depicts the method of gain stabilization. During data accumulation, the computer monitored the position of the LED spectrum centroid and generated a digital signal to compensate for any change. This was converted to an analog signal on a 0-10 volt scale, amplified by the photomultiplier control unit to a 0-100 volt scale, and added to the high voltage level supplying the XP1031 phototubes. This feedback loop kept the gains of the phototubes stable even under shifting loads due to varying beam current.

The DC-coupled fast counting system and coincidence logic network are shown in greater detail in Figure 3-4. The signal from the XP1031 phototubes which had an exponential tail with a 250 nsec fall time was first amplified and then clipped by a properly terminated 50 Ω line to form a signal approximately 250 nsec wide. If the pulse height passed a preset discriminator threshold a fast DC-coupled linear gate opened for a 250 nsec duration, integrated the pulse, and sent a pulse whose height was proportional to the total charge accumulated in the phototube signal to an ADC at the computer interface. Because the gate opening time was only 250 nsec, the probability that two different pulses would be integrated together was substantially reduced. In this way pile-up was
The details of the fast counting system and coincidence logic network which shape and process signals from the NaI(Tl) spectrometer in the target room and send them to the computer interface.
very largely avoided; there was no additional network designed to reject pile-up pulses. This method of clipping pulses does not greatly affect the energy resolution, as one might expect it to. In fact very short gate opening times can be used without greatly degrading the energy resolution beyond the intrinsic resolution of the NaI(Tl) crystal, as discussed by Brassard. The entire system was DC-coupled and this eliminated the problem of baseline shifts associated with AC-coupled systems.

In the lower part of Figure 3-4 is the coincidence network designed to sort the gamma ray, cosmic ray, and LED pulses. First a fast (110 nsec) coincidence is established between a 500 nsec wide square pulse from the discriminator of the fast counting system and a 500 nsec wide square pulse from the cosmic ray anticoincidence shield network. This produces a cosmic ray logic signal. Second, to generate a light pulser (LED) logic signal a slow (2 µsec) coincidence is established between the fast counting discriminator pulse and a stretched (4 µsec) signal from the light pulser magnetic pick-up coil. Finally the logic signal corresponding to real gamma rays is generated in a slow (2 µsec) coincidence unit that accepts the fast counting discriminator pulse only if it is not blanked by either the stretched light pulser pulse or the stretched cosmic ray signal. The three logic signals are then sent to the computer interface where they are used to sort the signals from the integrating linear gate into spectra
containing real gamma rays, cosmic rays, and LED pulses. The IBM 360/44 data acquisition program which accomplishes this sorting as well as corrections for gain shifts is listed in Appendix I-A. Further details of the fast counting system, the coincidence network, the gain stabilization system, and the LED's can be found in Shay² and Brassard.³

3.7 SUMMARY

The NaI(Tl) spectrometer assembly and its associated electronics described above meets all the experimental challenges listed in section 3.1 principally through the reduction and sorting of background radiations, the achievement of fast counting with minimal pile-up and good resolution, and the use of LED's in a gain stabilization system. A sample spectrum of real gamma-rays produced by this system is shown in Figure 3-5. The spectrum was taken with 40 cm Hg of He gas in the gas target at a laboratory angle of 125° with an alpha beam energy of 34.24 MeV at the principal resonance of the He⁴(α,γ₁)Be⁸* reaction at 16.90 MeV excitation energy. The broad photopeak from this reaction lies around channel 600 (at an energy of 13.38 MeV) above a steep exponential background. This background is due almost entirely to the Kapton windows of the gas target as was proven experimentally by collecting a spectrum under conditions where the alpha beam passed thru the gas target without windows. Hardly any counts resulted. The cutoff around channel 480 is electronic and is due to the fast counting discriminator in Figure 3-4.
Figure 3-5: A Sample Gamma-Ray Spectrum.

The gamma-ray of interest from the He$^+$($\alpha$,\gamma_1$)Be$^8*$ reaction at $E_x = 16.90$ MeV is the broad photopeak centered around channel 600. The huge background is due almost entirely to the gas target Kapton windows.
Gamma-ray spectrum
Gas in
$E_{\text{lab}}^{\text{lab}} = 34.24 \text{ MeV}$
$\theta_{\text{lab}} = 125^\circ$
700 $\mu$C

Counts vs. channel number:

- Counts range from 1000 to 10,000.
- Channel number range from 0 to 1040.

E$_y$ (MeV) scale:
- Channels 12, 13, and 14 are highlighted.
Another peak appears in the spectrum around channel 670, but it appears with equal strength in the background spectrum accumulated when the He gas was evacuated from the gas target. This photopeak is due to Doppler shifted 15.11 MeV gamma-rays from the $1^+, T=1$, state of $^{12}C$, excited through the inelastic scattering of alpha particles in an isospin forbidden reaction on elements in the gas target windows.

The energy calibration of the spectrum, as for all the gamma-ray spectra, was obtained from the stable LED source which had been previously calibrated using the $^{11}B(p,\gamma_0)^{12}C$ and $^{12}C(a,\gamma_0)^{16}O$ reactions.

It was utterly impossible to extract, with good statistics, a photopeak directly from the spectrum shown in Figure 3-5. The technique was to accumulate one spectrum with the gas target full of He gas and then another at the same beam energy and with the same accumulated charge with the gas target evacuated (connected by an open pipe to the evacuated target chamber).

Except for the photopeak at channel 600 the background spectrum looked exactly the same as the gas-in spectrum in Figure 3-5. Subtracting the background spectrum from the gas-in spectrum produced a photopeak that could be fitted to extract the differential cross section for the $^{4}He(a,\gamma_1)^{8}\text{Be}$ reaction. But before this could be done a calibration experiment was needed to determine the photopeak efficiency and the shape of the NaI(Tl) response function to high energy gamma rays. This calibration experiment is discussed in the next chapter.
CHAPTER 3 REFERENCES

5. C. Brassard, Nucl. Instr. and Meth. 94 (1971) 301.
4.1 THE $^7\text{B}(\text{He}^3,p)^{12}\gamma^{(15.1)}(\gamma)^{12}$ REACTION

The extraction of differential cross sections from the $\text{He}^4(\alpha,\gamma^8)^{\text{Be}}$ spectra could not be accomplished with any degree of accuracy without a prior calibration of the NaI(Tl) spectrometer. Previous analyses\(^1\) of gamma ray peak shapes generated by this spectrometer have assumed a NaI response function in the form of a Gaussian photopeak with a flat low energy tail, which fits the spectra well. But the procedure used to extract differential cross sections neglected the counts in the low energy tail and was therefore open to some question. It was recognized that a calibration reaction which gives a sharp photopeak and a measure of the photopeak efficiency would eliminate most of these uncertainties in the analyses of our gamma-ray spectra.

After an exhaustive search of gamma-ray calibration reactions, where we considered both precision and gamma-ray energy, we found that the $^7\text{B}(\text{He}^3,p)^{12}\gamma^{(15.1)}(\gamma)^{12}$ reaction offered the best opportunity to calibrate the
NaI(Tl) spectrometer at gamma-ray energies comparable to those in the $\text{He}^4(\alpha,\gamma)\text{Be}^8$ experiment. The $\text{B}^{10}(\text{He}^3,p)\text{C}^{12}$ reaction populates the $1^+, T=1$ state at 15.11 MeV in $\text{C}^{12}$, which has a large and precisely measured $\gamma$-decay branch to the ground state of $\text{C}^{12}$. The relative gamma-ray branching ratio for this state has been measured by Alburger and Wilkinson to be $\Gamma_{\gamma}/\Gamma = 0.92 \pm 0.02$. Combining this result with the alpha decay branching ratio of the same state, which has been measured to be $\Gamma_{\alpha}/\Gamma = 0.041 \pm 0.009$, we obtain the gamma-ray branching ratio $\Gamma_{\gamma}/\Gamma = 0.882 \pm 0.021$ for the 15.11 MeV state in $\text{C}^{12}$, assuming that it has only an alpha and a gamma width. We can therefore obtain a large and accurately known (to 2.4%) yield of 15.11 MeV gamma rays. Unfortunately we cannot obtain as accurate a yield of gamma-rays at lower energies; otherwise we could have two calibrations spanning the $\text{He}^4(\alpha,\gamma)\text{Be}^8$ gamma-ray energies. For example, the $1^+, T=0$ state at 12.71 MeV in $\text{C}^{12}$ has a gamma-ray branching ratio $\Gamma_{\gamma}/\Gamma = 0.025 \pm 0.004$, with an accuracy of only 15%, and therefore not desirable to use in a calibration experiment.

In the $\text{B}^{10}(\text{He}^3,p)\text{C}^{12}(15.11)\gamma\text{C}^{12}$ experiment protons populating the 15.11 MeV state were detected at an angle of 180° to the $\text{He}^3$ beam in coincidences with de-excitation gamma-rays to the ground state. For this particular $1^+$ to $0^+$ transition the proton-gamma-ray angular correlation has, at most, the form $f(\theta) = a_0 P_0(\cos\theta) + a_2 P_2(\cos\theta)$, where $\theta$ is the angle between the protons and the 15.11 MeV gamma-rays. While the proton angular distribution is not relevant, it is
expected to be nearly isotropic. Since only the isotropic component of the correlation is known with a 2.4% accuracy, the NaI(Tl) spectrometer was placed at an angle of 125° to the He³ beam, causing \( P_2(\cos \theta) \) to vanish when integrated over the finite solid angle. The efficiency of the spectrometer can then be determined from the ratio of p-γ coincidence counts to total proton singles counts:

\[
\frac{\epsilon d\Omega}{4\pi} = \frac{C}{S \cdot B}
\]  

(4-1)

where \( \epsilon d\Omega \) is the product of detector efficiency and effective solid angle, \( C \) is the number of p-γ coincidences at 125°, \( S \) is the number of singles counts for protons feeding the 15.11 MeV state, and \( B \) is the branching ratio given above for the 15.11 MeV to ground state transition. To eliminate most sources of systematic error, this calibration experiment was performed with the NaI(Tl) spectrometer and its associated electronics set up exactly as described in Chapter 3. Nothing, including the position of the detector, was changed between this experiment and the He⁴(α,γ₁)Be⁸* experiment.

4.2 THE SOLID STATE DETECTOR ASSEMBLY

Protons from the B¹⁰(He³,p)C¹²* reaction were detected at 180° to the He³ beam by the apparatus shown in Figure 4-1. The diagram is drawn so that upstream to the He³ beam is on the left and downstream is on the right. A 200 na He³ beam
Figure 4-1: Annular Detector Assembly.
The $^3\text{He}$ beam passes thru the tantalum-lined annulus of the 1000μ silicon surface-barrier annular detector on the left and strikes the $^\text{B}^{10}$ target on the right. Emerging protons travel upstream through a small solid angle and pass through a thin polyethylene absorber before striking the active area of the annular detector. All dimensions are given in inches. Dotted portions of the figure indicate tantalum, except for the active area of the solid state detector. Portions with slanted lines indicate teflon spacers and unmarked areas indicate aluminum. Further details of the assembly are given in the text.
at an energy of 6.0 MeV was first collimated by a pair of tantalum slits forming an 80 mil square and then directed through a thick tantalum funnel and tantalum canal through the silicon surface barrier detector annulus before striking the ~150 µg/cm² self-supporting target of enriched B¹⁰.

Protons recoiling from the target passed upstream through a small solid angle and through a 6.9 mg/cm² polyethylene, \((\text{CH}_2)_n\), absorber before striking the active area of the annular detector. The stack of bar magnets preceding the absorber, in an aluminum tunnel lined with the tantalum, produced a magnetic field of approximately 500 gauss perpendicular to the beam axis was designed to prevent electrons from reaching the detector in the event an absorber was not used. The absorber was chosen to pass protons feeding the 15.11 MeV state in C¹² and those of somewhat lower energies but to stop more massive particles. 6.7 MeV protons feeding the 15.11 MeV state lost approximately 500 keV in the absorber while \(^3\text{He}\) and heavier particles were stopped entirely. The detector was a 1000 µ silicon surface barrier annular detector with an active area of 150 mm², chosen to fully stop protons up to an energy of approximately 11 MeV, corresponding to protons feeding the 9.64 MeV state in C¹². The solid angle was well defined by a pair of tantalum sheets with circular apertures so that no particles struck the detector except in its active area. The set solid angle was 9.75 msr and reflected a compromise between getting too small a solid angle and having protons detected too far away from 180° to the \(^3\text{He}\) beam. To
avoid ground loops the detector was insulated by teflon and grounded only through its output at its preamp.

4.3 ELECTRONICS AND SIGNAL PROCESSING

Figure 4-2 shows the circuits used to process signals from the annular detector (the "particle leg") and from the gamma-ray fast counting system (the "gamma leg"). Each leg produced timing pulses for the time to analog converter (TAC), which produced an output having a pulse height proportional to the time delay between the TAC start and stop signals. The blocks in the diagram represent for the most part standard Ortec Nuclear Instrument Modules.

In the particle leg the pulse generator was used continuously to check for gain shifts. The amplified signals from the annular detector were sent thru a biased amp which accepted signals from greater than 4.0 MeV protons and were then sent to the computer interface and an off-line pulse height analyzer. The Ortec amplifier following the preamp generated a bipolar pulse with a well-defined stable crossover point that the timing single channel analyzer used for generating sharp (20 nsec) timing pulses for the TAC. In the gamma leg the timing single channel analyzer gate was set to accept pulses above approximately 9.0 MeV. An off-line pulse height analyzer recorded the gamma-ray spectrum accepted by this TSCA.
Figure 4-2: Signal Processing and TAC Circuit.

The upper portion of the figure, the particle leg, shows the processing of signals from the solid state detector in Figure 4-1. The lower portion, the gamma leg, processes the gamma-ray pulses from the fast counting system in Figure 3-3. Both legs produce sharp pulses for the time to analog converter (TAC), which sends its output to the computer interface. The circuit was constructed of Ortec Nuclear Instrument Modules.
\[ B^{10}(He^3, p)C^{12 \ast}(\gamma)C^{12} \]

**PARTICLE LEG**

- 300 V Bias
- Pulse Generator
  - Preamp
    - Biased Amp
      - Pulse Shaper
- Annular Detector
  - To Hard-Wired TAC Circuit
  - To Lin Part ADC

**GAMMA LEG**

- Fast DC AMP
  - AMP
    - TSCA
      - Delay
      - Gated Biased Amp
        - Pulse Shaper
        - PHA
- Fast DC Disc
  - From Fast Counting System
  - From TAC true Start
  - To Lin TAC ADC
  - To Computer Interface

**SIGNAL PROCESSING AND TAC CIRCUIT**
Figure 4-3: The Hard-Wired TAC Circuit.

This circuit was designed as a cross check for the computer processed TAC signals of Figure 4-2. It connects to the terminals marked "P" and "γ" in Figure 4-2.
HARD-WIRED TAC CIRCUIT
Figure 4-4: The Computer Interface.

This circuit accepted the output signals of the circuits in Figures 3-4 and 4-2 and fed a bank of Analog to Digital Converters and Scalers at the computer interface. The event signals on the right instructed the computer in sampling the ADC's and Scalers.
The TAC produced a square 2 μsec bipolar pulse with pulse height proportional to the time delay between the start (gamma) pulse and stop (particle) pulse. A TAC True Start pulse, used for triggering at the computer interface, was produced for every start pulse. The gamma-ray pulses were fewer in number than the particle pulses and therefore were chosen to start the TAC. A delay in the particle leg TSCA assured that coincident pulses would be placed in the center of the TAC spectrum. The TAC was adjusted so that maximum output corresponded to a 1.0 μsec delay between start and stop pulses. The TAC output was sent to the computer interface and also routed via a gated amp to an off-line pulse height analyzer, used only to provide a continuous monitor of the TAC performance.

To provide a cross check on the computer interface and its associated software, signals from the gamma and particle legs were also sent to the hard-wired TAC circuit shown in Figure 4-3. This circuit accomplished the gating and counting of the computer interface but in a less flexible manner. One gate was set by a TSCA on the 15.11 MeV peak in the proton spectrum; the other was set to pass gamma-ray pulses above 80% of the photopeak energy. A gate was set on the TAC output and a scaler recorded the number of counts in the TAC peak. When connections for random coincidences and background counts were applied the results recorded here agreed with the more sophisticated analysis involving the computer interface.
Figure 4-4 shows how the computer interface was setup. It was basically a bank of analog to digital converters (ADC's) and scalers whose periodic sampling was controlled through the software by the "event" pulses listed on the right hand side of the figure. The major advantage over a hard-wired system was that all the event pulses and ADC and scaler counts were stored on magnetic tape during the experiment and replayed later for thorough analysis. The software was made flexible enough so that analyzers and gates could be created by the programming and changed as often as needed during the off-line analysis.\(^6\)

The top two lines in the figure are part of the LED gain stabilization system described in Chapter 3. The next line is a row of scalers that recorded pulses from the beam current integrator (BCI). Those labeled "DT" were turned on only when their associated ADC's were dead, giving deadtime as a fraction of total BCI pulses. The "P.M. Stop" signal stopped data collection whenever the NaI(Tl) spectrometer photomultipliers registered too high a current and were shut off.

The next part of the diagram is divided into ADC's that generated the gamma-ray, particle and TAC singles spectra (\(\gamma\)ADC, PART ADC, and TAC ADC) and those that generated the gated spectra (\(\gamma\)ADC(2) and PART ADC(2)). The \(\gamma\)ADC and TAC ADC were triggered by external signals (labeled \(\gamma\)ADC TRIG and TAC TRUE START respectively) to provide a well defined gate opening time, and through the event signals, a precise sampling time. The PART ADC triggered from its well-timed
square analog signal. Two of the ADC's were independent while the other three, the TAC ADC, $\gamma$ADC(2), and PART ADC(2), had the same trigger. The latter two members of this triad were blanked by the deadtime signal of the TAC ADC, the last member to be triggered, so that they would accept no further counts until the TAC ADC was ready to be triggered again. This assured a one-to-one correspondence of all counts collected by ADC's on this string. This was essential since the data acquisition computer program (listed in Appendix I-B) created coincidence spectra from one of the ADC's in this string by setting gates on the spectra of the other two. For example, a coincidence gamma-ray spectrum would be obtained from $\gamma$ADC(2) by setting one gate on the 15.11 MeV peak of the particle spectrum of PART ADC(2) and another gate on the TAC peak in the spectrum of TAC ADC. The gains of $\gamma$ADC(2) and PART ADC(2) were matched to $\gamma$ADC and PART ADC to generate the same spectra, but the spectra contained fewer counts since data were collected only when pulses feeding the TAC of Figure 4-2 fell within its coincidence time range of 1 usec.

The rest of the figure contains scalers for the various event pulses and delays used for coordinating gate opening and sampling times with the analog signals for the five ADC's. The event pulses generated the sampling of ADC's and scalers and the sorting of ADC counts according to the coding of the data acquisition program. For example, if a gamma-ray (EV1) or cosmic ray (EV3) or LED (EV6) event pulse was
received at the computer interface γADC would be amplified and its count placed in the computer's soft-wired analyzer for either gamma-rays or cosmic rays or LED events. If a TAC (EV4) event was received, the TAC ADC count would be put in the TAC spectrum and counts from γADC(2) and PART ADC(2) would be used to generate a γ-p coincidence spectrum. The flexibility of this system is its major advantage, since it uses soft-wired analyzers generated by the computer programming which can be easily changed during off-line analysis.

4.4. DATA ANALYSIS AND SAMPLE SPECTRA

Some of the spectra that were generated in the computer's soft-wired analyzers during the B₁⁰(He³,p)C₁²*(γ)C₁² experiment are shown in the next six figures. Two of the figures show singles spectra while the rest show coincidence spectra. Each coincidence spectrum was generated from the full spectrum of one of the group of three ADC's in Figure 4-4, the TAC ADC, the γADC(2), and the PART ADC(2), by accepting only those counts that were in coincidence with counts falling within two gates set on each of the other two ADC's of the group.

Figure 4-5 shows the proton singles spectrum, where each proton group is marked with its corresponding excitation energy (in MeV) in C₁². The 15.11 MeV peak near channel 450 was identified after a calibration was determined from the more prominent proton peaks. The annular detector was not thick
Figure 4-5: The Proton Singles Spectrum.
The proton groups from the $^{10}\text{B}(\text{He}^3,p)^{12}\text{C}^*$ reaction which fed the various excited states of $^{12}\text{C}$ are identified by arrows and numbers indicating the excitation energies (in MeV) of those states. The cutoff near channel 960 corresponds to the maximum energy protons that the annular detector could stop. The 9.64 MeV group has a proton energy near 10.9 MeV while the 16.11 MeV group has an energy near 5.3 MeV.
$^{10}\text{B}(\text{He}^3, p) ^{12}\text{C}^*(\gamma) ^{12}\text{C}$

PROTON SINGLES SPECTRUM

COUNTS $\times 10^3$

CHANNEL NUMBER
Figure 4-6: The TAC Spectrum.
The abscissa represents the time delay between the gamma-ray and particles signals received by the TAC in Figure 4-2. Full scale is 1.0 μsec. The base width of the coincidence peak near channel 400 is approximately 20 nsec.
$^{10}\text{B}(\text{He}^3, p)^{12}\text{C} (\gamma) ^{12}\text{Cl}$

TAC SPECTRUM
UNGATED
This is a spectrum of gamma rays obtained in coincidence with all particle and TAC counts. Gates were set over the whole range of proton energies shown in Figure 4-5 and the whole range of delays shown in Figure 4-6. The prominent photopeak is due to Doppler-shifted 15.11 MeV gamma-rays while the lesser photopeak is due to 12.71 MeV gamma-rays. The cutoff near channel 440 is electronic and is due to the TSCA of the gamma leg in Figure 4-2.
$^{10}\text{B}(\text{He}^3, p)^{12}\text{C} * (\gamma)^{12}\text{C}$

GAMMA SPECTRUM
PROTON AND TAC GATES
WIDE OPEN
A proton spectrum obtained in coincidence with counts falling in the TAC peak of Figure 4-6 and with gamma-rays above 90% of the 15.11 MeV photopeak energy (Figure 4-7). The 15.11 MeV proton group is prominent.

Figure 4-8b: Gated Proton Spectrum.
A proton spectrum obtained in coincidence with counts falling in the TAC peak of Figure 4-6 and within a gate set around the 12.71 MeV photopeak of Figure 4-7. The 12.71 MeV proton group appears near channel 640, corroborating the energy calibration of Figure 4-5. The 15.11 MeV group still appears in this spectrum since part of the 15.11 MeV gamma-ray peak was included in the gamma-ray gate.
$^7\text{Li}(^3\text{He}, p)^{12}\text{C}^* (\gamma) ^{12}\text{C}$

GATED PROTON SPECTRUM
GATES: TAC PEAK
$E_{\gamma} \geq 90\% \gamma$ PEAK

$^{10}\text{B}(^{3}\text{He}, \gamma)^{12}\text{C}^*$

GATED PROTON SPECTRUM
GATES: TAC PEAK
12.71 MeV $\gamma$ PEAK
Figure 4-9a: Gated TAC Spectrum.
TAC counts obtained in coincidence with proton counts falling within a gate set on the 15.11 MeV peak of Figure 4-5 and with gamma-ray counts falling above 90% of the 15.11 MeV photopeak energy (Figure 4-7).

Figure 4-9b: Gated TAC Spectrum.
TAC counts obtained in coincidence with proton counts falling within a gate set on the 15.11 MeV peak of Figure 4-5 and with gamma-ray counts falling above 80% of the 15.11 MeV photopeak energy (Figure 4-7). These two spectra give a direct comparison of the 80% and 90% photopeak efficiencies.
$^{10}\text{B}^{(3}\text{He},\text{p})^{12}\text{C}^* (\gamma)^{12}\text{C}$

GATED TAC SPECTRUM
GATES: 15.11 MeV PROTON PEAK
$E_\gamma \geq 90\% \gamma$ PEAK

COUNTS

CHANNEL NUMBER

0 80 160 240 320 400 480 560 640 720 800 880 960 1040 1120

32 28 24 20 16 12 8 4 0
Figure 4-10: Gated Gamma-Ray Spectrum.

A gamma-ray spectrum obtained in coincidence with counts falling in the TAC peak of Figure 4-6 and with proton counts falling within a gate set on the 15.11 MeV peak of Figure 4-5. With fair statistics this spectrum depicts the NaI(Tl) spectrometer response function for 15.11 MeV gamma-rays down to the electronic cutoff point near channel 440.
$^{10}\text{B (He, }^3\text{p}) \text{Cl}^2 \text{(y) Cl}^2$

GATED GAMMA SPECTRUM
GATES: TAC PEAK
15.11 MeV PROTON PEAK
enough to stop protons feeding the ground state and 4.44 MeV state of C\(^{12}\) but these groups show up nevertheless around channel 340 and channel 560, respectively, since the proton energies were partially absorbed. Other small peaks are due to target contaminants. Great care was taken to avoid C\(^{12}\) contaminants since protons from the reaction C\(^{12}\)(He\(^3\),p)N\(^{14}\) would have obliterated the 15.11 MeV peak.

Of prime interest is the total number of counts in the 15.11 MeV peak, less background, since this is the singles counts (S) needed for equation (4-1). Using three Gaussians and an exponential background a fit was performed for the 15.11 MeV peak and the two adjacent peaks at lower energies. The net number of counts under the 15.11 MeV peak was 19146 with a total error of 4%. (It was necessary to collect 8500 microcoulombs of charge to achieve this accuracy. However, cross sections should not be calculated from the peaks in Figure 4-5 since the B\(^{10}\) target, whose thickness has no bearing on this experiment, was partially torn.) The PART ADC of Figure 4-4 which collected this spectrum had a large dead-time of 74\% as determined with negligible error (0.2\%) by the counts accumulated in the PART ADC DT Scalar. The corrected 15.11 MeV peak counts is therefore 73525.

Figure 4-6 shows the TAC spectrum (ungated) where the abscissa is the time delay between gamma-ray and particle signals and full scale is 1.0 \(\mu\)sec. The narrow (20 nsec) coincidence peak near channel 400 rises above a background of random coincidences of about 31 counts per channel. The
counts in the peak are true coincidences between protons feeding the 15.11 MeV state in $^{12}\text{C}$ and the deexcitation gamma-rays from this state that register in the NaI(Tl) spectrometer.

Figure 4-7 shows a gamma-ray spectrum from $\gamma$ADC(2) in Figure 4-4 obtained in coincidence with counts passing through gates set to accept all the proton counts of Figure 4-5 and all the TAC counts of Figure 4-6. The spectrum contains two photopeaks: the larger one due to 15.11 MeV gamma-rays and the smaller one due to 12.71 MeV gamma rays. The peak near channel 440 was produced by electronic cut-off. This spectrum clearly depicts the essential features of the NaI(Tl) response function in the region of the photopeak, without the obstruction of a large background found in the singles gamma-ray spectrum (not shown here). The counts under the principal photopeak are not important but the shape of the photopeak is crucial to the development of the calculated response function to be discussed in Section 4.5.

Figures 4-8a and 4-8b show gated proton spectra where one of the gates was set on the TAC peak of Figure 4-6. In the upper figure the second gate was set to admit gamma-rays (of Figure 4-7) above 90% of the 15.11 MeV photopeak energy, producing a prominent 15.11 MeV proton group with 192 counts between channels 427 and 467. This is the uncorrected coincidence count needed for equation (4-1). In the lower figure the second gate was set on the 12.71 MeV photopeak of Figure 4-7. The appearance of both the 15.11 MeV and 12.71
MeV proton groups confirmed both the identification of the small photopeak in Figure 4-7 and the energy calibration of the spectrum of Figure 4-5.

Gated TAC spectra are shown in Figures 4-9a and 4-9b. For each coincidence spectrum one gate was set on the 15.11 MeV proton group of Figure 4-5. For the upper spectrum the second gate was set to accept gamma-rays above 90% of the photopeak while for the lower spectrum it was 80% of the photopeak. The counts in the upper TAC peak total 176 while those in the lower peak total 198. The 90% count differs from that of Figure 4-8a because the proton gate set for this coincidence count was narrower than the full peak shown in Figure 4-8a. The TAC peak gate set for Figure 4-8a is shown by these figures to be neither too narrow or too wide; therefore the coincidence count from Figure 4-8a is the correct one to use in equation (4-1). Figures 4-9a and 4-9b are used to give the ratio of 90% counts to 80% counts.

The last coincidence spectrum, shown in Figure 4-10, is a gated gamma-ray spectrum where gates have been set on the TAC peak of Figure 4-6 and the 15.11 MeV proton group of Figure 4-5. The statistics are not sufficient to give a clear response function to 15.11 MeV gamma-rays but the efficiencies for 80% and 90% of the photopeak can be readily calculated. The counts are 198 and 177, respectively, the same as obtained from the gated TAC spectra.

All of the coincidence counts obtained above must be corrected for a random coincidence component. Many random
coincidence spectra were generated by putting a gate either off the TAC peak and in the random coincidence background of Figure 4-6 or on the 14.08 MeV proton group of Figure 4-5, which has no associated gamma decay strength. None of these spectra are shown here since they all contained fewer than 20 counts spread over 1020 channels and resembled the random background of Figure 4-9a. As an example, the random component corresponding to the number of counts obtained by summing the counts in Figure 4-10 from 80% and 90% of the photopeak to channel 1020 is two in each case. This was determined by using the same gates used to obtain Figure 4-10 but shifting the TAC gate to the random part of the spectrum. Of most importance to the calculation of true gamma-proton coincidences is the random count underlying the proton peak in Figure 4-8a. The counts are two in number as determined by putting the TAC gate, having the same width, in the random part of the spectrum. Therefore the true gamma-proton coincidences for the 90% efficiency measurement are 190 in number. From the ratio of counts in the TAC peaks of Figure 4-9a and 4-9b the corresponding 80% efficiency count is 214. These counts must be corrected for the small absorption of the gamma-rays in the target chamber wall and for the common dead time of the TAC ADC, \( \gamma \text{ADC}(2) \), and PART ADC(2) of Figure 4-4, which is 6.9%. Therefore the true 90% count is 204, and the true 80% count is 230. Equation (4-1) can now be used to determine the photopeak efficiencies at 90% and 80% of the peak channel number.
The solid angle is 66 msr.

\[ \varepsilon(90\%) = \frac{204}{73525 \cdot 0.882} \cdot \frac{4\pi}{0.066} = 0.599 \quad (4-2) \]

\[ \varepsilon(80\%) = \frac{230}{204} \cdot \varepsilon(90\%) = 0.675 \quad (4-3) \]

The total error in this determination is 8.3%. The different components of the error are given in Table 4-1, where they have been added in quadrature to give a minimum estimate of the total error. The chosen NaI(Tl) response function must therefore reproduce the above efficiencies within the quoted accuracy.

4.5 THE NaI(Tl) RESPONSE FUNCTION

The chosen mathematical form of the NaI(Tl) response function must fulfill two criteria: it must precisely fit the photopeak shown in Figure 4-7 and it must reproduce the 80% and 90% efficiencies given in equations (4-2) and (4-3). It should further match the generally known characteristics of NaI response functions; namely, it should have a Gaussian photopeak with an exponential tail and a constant or slightly sloping low energy tail.

Several functional forms were tried before the final form shown in Figure 4-11 was selected. The response function was broken up into three regions, the first being a gently sloping low energy tail of the form
### TABLE 4-1

**ERROR ANALYSIS FOR EFFICIENCY DETERMINATION**

\[
\frac{\epsilon d\Omega}{4\pi} = \frac{C}{S \cdot B}
\]

<table>
<thead>
<tr>
<th>Item</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-γ coincidence counts (C)</td>
<td>6.8%</td>
</tr>
<tr>
<td>singles proton counts (S)</td>
<td>4.0%</td>
</tr>
<tr>
<td>branching ratio (B)</td>
<td>2.4%</td>
</tr>
<tr>
<td>Dead time</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total in quadrature</td>
<td>8.3%</td>
</tr>
</tbody>
</table>
I: \[ f(x) = \frac{F}{(C-x)^{\alpha}}, \quad 0 < x \leq B \] (4-4)

where \( x \) represents channel number.

The second region was an exponential:

II: \[ f(x) = Ge^{-\omega^2/\lambda} e^{(2\omega/\lambda) \cdot (x-A)}, \quad B \leq x \leq A \] (4-5)

and the third region was a Gaussian:

III: \[ f(x) = Ge^{-(x-x_0)^2/\lambda}, \quad x > A \] (4-6)

The junction points are given by \( A = x_0 - \omega \) and \( B = A - y \), where \( \omega \) and \( y \) are adjustable parameters. In region I, \( \alpha \) is a third adjustable parameter but \( F \) and \( C \) are determined by requiring a smooth joint at \( x=B \):

\[ C = B + \frac{\alpha}{r} \] (4-7)

and

\[ F = \left( \frac{\alpha}{r} \right)^\alpha Ge^{-\omega^2/\lambda} e^{(2\omega/\lambda) \cdot (B-A)} \] (4-8)

where \( r = \frac{2\omega}{\lambda} \). \( G \) is the peak height, \( x_0 \) is the peak position and \( \lambda \) is related to the Gaussian full width at half maximum.

A fit was performed to the spectrum of Figure 4-7, including the 12.71 MeV peak and the exponential background, to determine \( \lambda, \omega, \) and \( y \). The final fit was excellent; in fact, the fitted function was only slightly distinguishable from the measured spectrum and was well represented by Figure 4-7. The least \( \chi^2 \)
Figure 4-11: NaI Response Function.

A calculated NaI response function to 15.11 MeV gamma-rays Doppler shifted to 14.88 MeV. This function was used to fit the photopeak in Figure 4-7. The portion of the function used to calculate the 80% efficiency found in Section 4.5 is shown by diagonal lines. The inset gives the calculated photopeak efficiency as a function of the lower cutoff point, such as the 80% mark given by a vertical line near channel 566.
NaI RESPONSE FUNCTION:
MONOCHROMATIC PEAK SHAPE
\[ E_\gamma = 14.88 \text{ MeV} \]
value was found with $\lambda = 643.4$, $\omega = 13$, and $y = 44$ (and $x_0 = 708$ and $G = 24800$). These values are reflected in Figure 4-11 but are not applicable to other photopeak energies and positions unless properly scaled. The scaling

$$\lambda = \frac{R \cdot x_0^2}{PE}$$  \hspace{1cm} (4-9)

$$\omega = \frac{S \cdot \sqrt{\lambda}}{PE}$$  \hspace{1cm} (4-10)

$$y = \frac{T \cdot \sqrt{\lambda}}{PE}$$  \hspace{1cm} (4-11)

assures that these essential parameters can be used for response functions to different energy gamma-rays. In this case $PE = 14.882$ MeV, the average value of the Doppler shifted 15.11 MeV gamma-ray. Doppler broadening over the range of the solid angle had a negligible effect on the width $\lambda$.

The parameter $\alpha$ could not be determined from Figure 4-7 because the low energy tail was obscured by the exponential background, as is normally the case. However, various values of $\alpha$ were tried until good agreement was obtained between calculated 80% and 90% efficiencies and those found in Section 4.4. The height of the low energy tail at channel zero and its slope are sensitive to the parameter $\alpha$, and therefore the efficiencies calculated are likewise sensitive. With a final choice of $\alpha = 0.24$, the following efficiencies were found:
They represent the best mean values when compared to the measured values of equations (4-2) and (4-3) and differ by only 1%, well within statistics. This value of $\alpha$ gives a tail height at channel zero which is a reasonable 4% of peak height.

All the parameters of the response function have then been determined, and the response function to 14.88 MeV gamma-rays is expected to scale through the gamma-ray energies of the $^4\text{He}(\alpha,\gamma^1)\text{Be}^{8*}$ experiment which range from 12.95 MeV to 13.53 MeV. This scaling as well as the general shape of the NaI response function is well supported by previous measurements such as by Bramblett et al. who used an annihilation-photon coincidence technique to directly measure response functions. The negligible contribution of first and second escape peaks has been well established by previous measurements using our NaI(Tl) spectrometer.

4.6 THE SHAPE OF THE $^4\text{He}(\alpha,\gamma^1)\text{Be}^{8*}$ PHOTONEAK.

The NaI(Tl) response function as shown in Figure 4-11 cannot be used to fit gamma-ray spectra from the $^4\text{He}(\alpha,\gamma^1)\text{Be}^{8*}$ reaction without further modification because the final state in this reaction is not sharp but about 1.56 MeV broad in the center of mass. The final peak shape is a result of a convo-
As determined by Bowles et al., this graph depicts the distribution $N(E_\gamma)$ of gamma-rays from the 16.91 MeV $2^+$ state in Be$^8$ to the set of levels comprising the broad first excited state of Be$^8$. It is plotted as yield of gamma-rays relative to peak versus center-of-mass gamma-ray energy, where the cut-off point at 10 MeV, corresponding to an excitation energy of 6.9 MeV, represents the experimental limit in unfolding this spectrum with good statistics from the measured gamma-ray spectrum.
EXPERIMENT of T. BOWLES et al.
GAMMA SPECTRUM WITH DETECTOR RESPONSE REMOVED

16.91 MeV EXCITATION in Be$^8$
Figure 4-13: Predicted Gamma-Ray Peak Shapes.

Given here is a comparison of three kinds of line shapes for gamma-rays of 13.38 MeV, the Doppler-shifted value for gamma decays from the 16.91 MeV state to the first excited state of Be$^8$. Curve A shows the monochromatic NaI(Tl) response function, scaled to this energy from Figure 4-11. Curve C shows Curve A folded with the asymmetrical gamma-ray distribution of Figure 4-12. For comparison Curve B shows Curve A folded with a simple Gaussian of 1.56 MeV full width at half maximum. The bump on Curve near channel 520 is the result of the cut-off in integration at 10 MeV in Figure 4-12. The inset shows the calculated photopeak efficiency for Curve C versus the lower cutoff point as a fraction of peak channel number.
PREDICTED GAMMA PEAK SHAPES

A. MONOCHROMATIC FOR $E_\gamma = 13.38$ MeV
MONOCHROMATIC RESPONSE FUNCTION FOLDED WITH
B. GAUSSIAN OF FWHM (C.M.) = 1.56 MeV
C. NON-GAUSSIAN OF FWHM (C.M.) = 1.55 MeV
FROM EXPERIMENT OF T. BOWLES et al.
olution of the NaI(Tl) response function with the gamma-ray distribution of the final state. If the response function to gamma-rays of energy $E_\gamma$ is written $R(x,E_\gamma)$, where $x$ is channel number, and the number of gamma-rays having energy $E_\gamma$ is written $N(E_\gamma)$, the final peak shape is

$$F(x) = \int_{E_\gamma} N(E_\gamma) R(x,E_\gamma) dE_\gamma \quad (4-14)$$

Our experiments did not have sufficient statistics to allow us to determine $N(E_\gamma)$ from our He$^4(\alpha,\gamma)_1$Be$^{8*}$ spectra, therefore we relied upon a previous measurement of T. Bowles et al.\(^9\) who determined the energy distribution of gamma-rays making a transition to the first excited state of Be$^8$ from the 16.91 MeV level by unfolding the NaI response function from the measured 16.91 MeV gamma-ray spectrum. Their result for $N(E_\gamma)$ is shown in Figure 4-12.

Figure 4-13 shows the gamma-ray spectrum (Curve C) derived from folding the distribution $N(E_\gamma)$ of Figure 4-12 with the response of the NaI(Tl) spectrometer to monochromatic gamma-rays (Curve A). This convolution was accomplished by numerical integration. The resulting theoretical form of the gamma-ray photopeak was used to fit all the gamma-ray spectra at various excitation energies from the He$^4(\alpha,\gamma)_1$Be$^{8*}$ reaction. No more than the photopeak was ever needed so that the unphysical bump in Curve C near channel 520, resulting from
an abrupt cut-off in numerical integration, never entered into the fit. For comparison with Curve C Curve B shows the convolution of a simple Gaussian with the NaI(Tl) response function. In Curve C a greater number of counts lies in the region on the low energy side of the photopeak, producing a marked asymmetry. The total area under each of the three curves in the same.

To serve as a fitting function for all the $^{4}He(α,γ_{1})^{8}_{Be}$ spectra Curve C was scaled in energy from 13.38 MeV through the range of 12.95 MeV to 13.53 MeV. A major assumption is that the distribution $N(E_{γ})$ of Figure 4-12 remains the same for gamma-rays of different energies such as those from the 16.63 MeV level. This assumption is supported by measurements of T. Bowles et al. which show that the distribution $N(E_{γ})$ from the level at 16.63 MeV is substantially the same as Figure 4-12. Therefore Curve C is expected to scale simply according to the scaling of the NaI(Tl) response function, without much change in shape over the 580 KeV range of gamma-ray energies. The fitting of Curve C to the $^{4}He(α,γ_{1})^{8}_{Be}$ spectra is discussed in the next chapter. We feel that with this method of generating theoretical response functions with known photopeak efficiencies that little room is left for systematic errors in the analyses of our gamma-ray spectra.
5.1 BACKGROUND SUBTRACTION

There were two major steps in the analysis of data from the \( ^4\text{He}(\alpha,\gamma_1)^8\text{Be} \) experiment. The first step was to subtract the background gamma-ray spectrum accumulated with the gas cell evacuated from the spectrum accumulated 40 cm Hg of \( ^4\text{He} \) gas in the cell. The second step was to fit the photopeak appearing in the residual spectrum with the peak shape derived in Chapter 4 and then to extract a cross section.

The background subtraction performed was a direct channel by channel subtraction of the two spectra with two small corrections. The first adjustment corrected for gain shifts in the NaI(Tl) spectrometer photomultiplier tubes between the two experiments. Using the positions of the stable LED pulser peaks as a guide one spectrum was compressed until it matched the other in gain. This was necessary particularly since the exponential background was not entirely smooth and the irregularities had to match to cancel properly. The second adjustment corrected for the different dead times of the ADC generating the gamma-ray spectra. The gas-out spectrum was multiplied by a normalization factor, always near unity, before it was subtracted from the gas-in spectrum.

As a test of the background subtraction procedure two gas-out spectra were subtracted from one another. Both were
accumulated for 800 microcoulombs of beam charge at a laboratory angle of 125° and an alpha beam energy of 33.58 MeV. The gain shift correction factor was 0.974 and the normalization factor 0.997, both typical figures. The residual gamma-ray spectrum is shown in Figure 5-1 and has the expected oscillatory behavior around an average count which is zero (in fact a total of 19 from channel 700 to 1020) within statistics. This result supports the general subtraction procedure used to obtain He$^4(\alpha,\gamma) Be^{8*}$ photopeaks from the gas-in spectra. In fact Figure 5-1 resembles closely an off-resonance residual gamma-ray spectrum.

The background subtracted spectra were stored on magnetic tape for later analysis by the peak fitting program. Also stored were spectra containing tallies of the channel by channel statistics of subtraction used for determining the errors in the final fits.

5.2 THE CALCULATION OF CROSS SECTIONS

Figure 5-2 is representative of the kind of spectrum obtained after the background subtraction is performed. Both gas-in and gas-out spectra were accumulated at an alpha beam energy of 34.24 MeV (leading to the 16.9 MeV resonance of the He$^4(\alpha,\gamma) Be^{8*}$ reaction), at an angle of 125° for the NaI spectrometer, for the same amount of beam charge (700 μc), and for the same amount of time (61 minutes). After small corrections were made as described above the gas-out spectrum was subtracted from the gas-in spectrum (shown in Figure 3-5)
Figure 5-1: Background Subtraction Test.

Two gamma-ray spectra were accumulated for 800 μc at an alpha beam energy of 33.58 MeV with the gas target evacuated. One spectrum was subtracted from the other and the result is shown here. The large oscillations in the region of 12 to 14 MeV are predictable from the poor statistics of subtraction due to the large background produced by the gas target kapton windows in this energy region. The subtraction was stopped at channel 520 since no further part of the spectrum was needed.
GAMMA-RAY SPECTRUM
BACKGROUND SUBTRACTION TEST

$E_{\text{lab}}^i = 33.58$ MeV
$\theta_{\text{lab}} = 125^\circ$
800 $\mu$C
Figure 5-2: A Background Subtracted Gamma-Ray Spectrum.
Two spectra were accumulated for 700 µc at a spectrometer laboratory angle of $125^\circ$ and an alpha beam energy of $34.2^4$ MeV, one spectrum with 40 cm Hg He$^4$ gas in the gas target and the other with an evacuated target. The residual gamma-ray spectrum shown here is the result of the subtraction of the gas-out spectrum from the gas-in spectrum. The typical statistics in the region of the photopeak ($100 \pm 50$ counts) is to be expected when the original spectra each have 1500 counts per channel in this region. The solid curve gives the best fit to the photopeak, using the peak shape developed in Chapter 4.
He\(^4\) (α, γ) Be\(^8\)\(^*\)

GAMMA-RAY SPECTRUM
BACKGROUND SUBTRACTED

\(E_{\alpha}^{\text{LAB}} = 34.24\) MeV

\(\theta_{\text{LAB}} = 125^\circ\)

700 \(\mu\)c
leading to the residual gamma-ray spectrum shown here. A photopeak is evident around channel 620, showing the typical statistics of background subtraction to be expected when both gas-in and gas-out spectra have nearly 1500 counts per channel in this energy region. The subtraction was terminated at channel 520 since lower gamma-ray energy regions had poor statistics and nothing but rapid oscillations as in Figure 5-1.

The solid curve in Figure 5-2 shows the fit to the photopeak producing the least Chi-squared value, using the peak shape developed in Chapter 4. The computer program used to generate this fit has been described in much detail and listed completely by Brassard. Our modified version contained new coding to produce the peak shapes appropriate for this experiment.

Briefly, the fitting program performed two corrections to the spectrum and then used the gradient search method to find the peak shape giving the least $\chi^2$ value. First a first order correction for pile-up was applied to the spectrum using the LED pulse shape to determine the amount of pile-up. The correction was a small one since the number of counts in the high energy pile-up tail of the Gaussian LED peak was never more than 5% of the total. Provisions were made to perform a cosmic-ray background subtraction based on the number of cosmic ray counts in the extreme high-energy part of the spectrum. This correction was never applied, however, since the gas-in and gas-out spectra were accumulated for the same
amount of time and therefore had equal cosmic ray background counts. The total count in the high energy region of the residual spectrum, for example channels 720 to 1020 in Figure 5-2, was zero within statistics.

The only function needed to fit the photopeak in Figure 5-2 was the peak shape derived in Chapter 4 (Curve C of Figure 4-13). In the search for the best fit giving the minimum $\chi^2$ value only two parameters were varied: the peak position (channel number) with the associated scaling of the peak shape and the height of the photopeak at maximum. The peak energy was precisely known from kinematical calculations and verified by the energy calibration provided by the LED spectrum.

After the best values for peak height and peak position were calculated and the best fit peak shape therefore determined, an integration was performed under the entire peak shape from zero energy to give a total number of counts proportional to the differential cross section for the $^{4}\text{He}(\alpha,\gamma_{1})^{8}\text{Be}^*_{\gamma}$ reaction. The statistical error was determined by error matrix techniques standard to non-linear least squares fitting procedures. The cross section was then calculated from the total yield, collected beam charge (for Figure 5-2, 700 µc), target thickness ($0.443 \text{ mg/cm}^2$ of $^{4}\text{He}$), and solid angle (66 msr). Corrections were applied to take account of the dead time of the ADC generating the spectrum (in this case 2.60%, a typical figure) and the absorption of gamma-rays passing through the gas target and target chamber walls. 13.38 MeV gamma-rays underwent an
Figure 5-3: The Measured Excitation Function and Fit.

Sixteen measured values of the 125° differential cross section for the $^4\text{He} (\alpha,\gamma^*)^8\text{Be}$ reaction spanning the regions of the 16.63 MeV and 16.91 MeV resonances are shown plotted against the excitation energy in $^8\text{Be}$. The vertical lines at each data point give the total error while the horizontal lines give the target thickness in the center-of-mass system. The legend in the figure refers to the parameters of the best fit excitation function shown by the solid curve through the data points.
$\theta_{\text{LAB}}=125^\circ$ DIFFERENTIAL CROSS SECTIONS
INTEGRATED OVER TARGET THICKNESS $\Delta E_{\text{LAB}}=93.6$ keV
WITH STRAGGLING = 40.0 keV

$\Gamma^{\Delta T=1}_{\text{MI}} = 6.91 \pm 0.85$ eV

NO DIRECT INTERACTION
BUT WITH $Y_{\text{OFF}} = 26$ nb/sr
average absorption of 9.03% in passing through the 5 mil tantalum lining of the gas target, the 60 mil walls of the brass (60% copper, 40% zinc) gas target, the 5 mil tantalum lining of the target chamber, and the 3/16 inch aluminum target chamber walls. The cross section was then converted to its center-of-mass value by dividing by the Jacobian, which in this case was 0.923, a mean value for 13.38 MeV gamma-rays Doppler shifted over the range of the solid angle. The final center-of-mass differential cross section derived from the peak in Figure 5-2 was 1895 ± 243 nb/sr.

The sixteen measured values of the differential cross section spanning the region of the two resonances at 16.63 and 16.91 MeV are shown in Figure 5-3 together with their total errors and associated target thicknesses. The cross sections on the low and high energy tails represent estimates of the minimum cross sections that could have been detected after background subtraction. The best fit to the excitation function (shown by the continuous curve) is discussed in Section 5.5.

5.3 THE ANGULAR DISTRIBUTION

Before the excitation function can be fitted the amount of mixing of E2 radiation with M1 radiation must be determined in order to calculate the theoretical excitation function accurately. From Figure 2-1 the gamma-ray transition in the He⁴(α,γ₁)Be⁸* reaction is seen to be between two 2⁺ levels;
therefore the radiation can have M1, E2, M3, and E4 components, where the latter two components are negligible. To determine the amount of E2 to M1 mixing it is necessary to measure the angular distribution of gamma-rays from the He$^4(\alpha,\gamma)$Be$^8*$ reaction. Results of such a measurement at the principal resonance (16.9 MeV) in the excitation function are shown in Figure 5-4. Six cross sections are plotted as a function of center-of-mass angle and are fitted with a theoretical angular distribution.

This angular distribution can be derived by using either Z coefficients (which do not specify the E2-M1 relative phase) or the formulas of Rose and Brink. The theoretical angular distribution is

$$W(\theta) = A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta) \quad (5-1)$$

where

$$A_0 = 1 + \delta^2 \quad (5-2)$$
$$A_2 = 0.5 - 1.464 \delta - 0.153 \delta^2 \quad (5-3)$$
$$A_4 = -0.490 \delta^2 \quad (5-4)$$
$$\delta = \left(\frac{\Gamma_{E2}}{\Gamma_{M1}}\right)^{1/2} \quad (5-5)$$

The measured angular distribution was fitted with the function given in equation (5-1) and best values were derived for $A_2^{\text{exp}}$ and $A_4^{\text{exp}}$. However, the lowest reduced Chi-squared value ($\chi^2 = 0.18$) was obtained by using only $P_0$ and $P_2$ in
Figure 5-4: The Angular Distribution.

The angular distribution of gamma-rays from the He$^4 (\alpha, \gamma) \text{Be}^{8*}$ reaction at the 16.9 MeV resonance was measured at six angles. The cross sections are shown with their total errors as a function of center-of-mass angle. The distribution was fitted with an expansion in even order Legendre polynomials up to fourth order.
\( \text{He}^4(\alpha, \gamma) \text{Be}^8 \)

**ANGULAR DISTRIBUTION**

Fitted with

\[
\frac{d\sigma}{d\Omega} = \sum_{n=0,2,4} A_n P_n (\cos \theta_{\text{cm}})
\]

16.90 MeV EXCITATION in \( \text{Be}^8 \)

\( E_{\text{lab}} = 34.24 \text{ MeV} \)
the fitting function, giving $A_2^{\text{exp.}}/A_0^{\text{exp.}} = 0.08 \pm 0.38$. The computer program that generated the least-squares fit is described fully and listed in Shay. Because the solid angle is finite, geometrical correction coefficients $Q_K$ had to be applied to relate measured $A_K^{\text{exp.}}$ coefficients to theoretical $A_K^{\text{theor.}}$ coefficients: $A_K^{\text{theor.}} = A_K^{\text{exp.}}/Q_K$, where $Q_2 = 0.984$ and $Q_4 = 0.948$ for our solid angle, which has an angular spread of $16.7^\circ$. Therefore

$$\frac{A_2^{\text{theor.}}}{A_0^{\text{theor.}}} = \frac{0.5-1.4646-0.1536^2}{1+5^2} = 0.08 \pm 0.38 \quad (5-6)$$

Solving this equation for $\delta$ gives

$$\delta_{16.9} = 0.27 \pm 0.25 \quad (5-7)$$

a value with a nearly 100% error. A more accurate value could not be obtained because the angular distribution measurement was hampered by a large neutron and gamma-ray background that rose rapidly as the detector was moved to forward angles. In the analysis of our excitation function we therefore elected to use the more accurate E2-M1 mixing ratios of Bowles, who performed angular distribution measurements at both the 16.6 and 16.9 MeV resonances and found

$$\delta_{16.9} = 0.388 \pm 0.045 \quad (5-8)$$

and

$$\delta_{16.6} = -0.062 \pm 0.046 \quad (5-9)$$
5.4 THE THEORETICAL EXCITATION FUNCTION

The theoretical excitation function was derived from 2-level R-matrix theory. Using the form appropriate for two levels as developed by Barker, we have an expression for the total cross section in the region of the 16.6 and 16.9 MeV resonances:

\[
\sigma_T = \pi \omega \chi^2 \left[ \sum_{\lambda=a}^{b} \frac{\Gamma_{i\lambda} \Gamma_{f\lambda}}{\Gamma_{f\lambda}} \left( \frac{E_\lambda - E}{E} \right)^2 \right]^{1/2} \left( 1 - \frac{1}{2} \sum_{\lambda=a}^{b} \frac{\Gamma_{\lambda}}{\Gamma_{f\lambda}} \left( \frac{E_\lambda - E}{E} \right) \right)^{1/2}
\]

(5-10)

The sum ranges over the two 16.6(a) and 16.9(b) levels; \( \Gamma_{i\lambda} \) is the entrance channel width for the state \( \lambda \); \( \Gamma_{f\lambda} \) is the exit channel width for the state \( \lambda \); \( \Gamma_{\lambda} \) is the total width for the state \( \lambda \); \( E_\lambda \) is the resonant energy for the state \( \lambda \); and \( E \) is a variable excitation energy. \( \omega \) is the angular momentum statistical factor given by

\[
\omega = \frac{2J+1}{(2S_p+1)(2S_t+1)} = 5
\]

(5-11)

where \( J \) is the final state spin (2), \( S_p \) is the projectile spin (0), and \( S_t \) is the target spin (0). \( \chi^2 \) is calculated from the laboratory energy of the projectile (\( E_L \) in MeV):

\[
\chi^2 = \frac{0.209}{m_1 E_L} \left( \frac{m_1 + m_2}{m_2} \right)^2
\]

(5-12)
where $\kappa^2$ is in barns, $m_1$ is the projectile mass in amu, and $m_2$ is the target mass in amu. Except for direct interaction terms there are no further coherent or incoherent additions to equation (5-10) because, as seen from Figure 2-1, there is only one possible channel spin ($S=0$) and one possible entrance channel angular momentum ($l=2$) leading to the two $2^+$ states. Nathan$^7$ has shown conclusively that equation (5-10) properly accounts for the interference effects between the two resonances and that neither an incoherent sum of two Breit-Wigner resonances nor a simple addition of two isolated Breit-Wigner resonant amplitudes will lead to the correct excitation function.

The resonant energies and entrance channel widths are the means of many experimental values.$^8$ Recognizing that both $2^+$ levels are strongly isospin mixed we write

$$\psi_a = \psi_{16.6} = \alpha |T = 1> + \beta |T = 0>$$

$$\psi_b = \psi_{16.9} = \beta |T = 1> - \alpha |T = 0>$$

so that the entrance channel alpha-particle widths $\Gamma_{\lambda\lambda}$ are given by

$$\Gamma_{\lambda\alpha}^{1/2} = \Gamma_{\alpha\lambda}^{1/2} = \beta \Gamma_{\alpha}^{1/2}$$

$$\Gamma_{\lambda\beta}^{1/2} = \Gamma_{\beta\lambda}^{1/2} = -\alpha \Gamma_{\alpha}^{1/2}$$

where $\alpha^2 + \beta^2 = 1$ and
\[ \Gamma_{aa} = 107 \text{ keV} \quad (5-17) \]
\[ \Gamma_{ab} = 77 \text{ keV} \quad (5-18) \]
\[ E_a = 16.627 \text{ MeV} \quad (5-19) \]
\[ E_b = 16.911 \text{ MeV} \quad (5-20) \]

Then
\[ \Gamma_a = \Gamma_{aa} + \Gamma_{ab} = 184 \text{ keV} \quad (5-21) \]

and
\[ \alpha = 0.647 \quad (5-22) \]
\[ \beta = -0.763 \quad (5-23) \]

The relative sign of \( \alpha \) and \( \beta \) is derived from the destructive interference observed between the two levels in the \( ^{10}\text{Be}(d,\alpha)\) \( \text{Be}^{8*} \) reaction. The exit channel gamma-ray widths (for a transition to the first excited 2\(^+\) state of \( \text{Be}^8 \) only) are unknowns to be measured in our experiment:

\[ \Gamma_{fa}^{1/2} = \Gamma_{\gamma a}^{1/2} \quad (5-24) \]
\[ \Gamma_{fb}^{1/2} = \Gamma_{\gamma b}^{1/2} \quad (5-25) \]

Equation (5-10) therefore becomes

\[
\sigma_T = \pi \omega^2 \left( \frac{\beta \Gamma_a^{1/2} \Gamma_{\gamma a}^{1/2}}{E_a - E} + \frac{-\alpha \Gamma_a^{1/2} \Gamma_{\gamma b}^{1/2}}{E_b - E} \right)^2 \left( 1 - \frac{1}{2} \left[ \frac{\Gamma_{aa}}{E_a - E} + \frac{\Gamma_{ab}}{E_b - E} \right] \right) \quad (5-26)
\]
where the widths of the two 16.6 and 16.9 MeV states are almost entirely alpha particle widths so that \( \Gamma_a \approx \Gamma_{\alpha a} \) and \( \Gamma_b \approx \Gamma_{\alpha b} \). Equation (5-26) reduces to

\[
\sigma_T = \pi \omega k^2 \cdot \frac{\Gamma_a \left[ \frac{1}{2}(E_b - E) - \alpha \gamma_b \frac{1}{2}(E_a - E) \right]^2}{(E_a - E)^2(E_b - E)^2 + \frac{\Gamma_a^2}{4}(E_m - E)^2}
\]  

(5-27)

where \( E_m = \alpha^2 E_a + \beta^2 E_b = 16.805 \) MeV.

If direct interactions are included the basic form of equation (5-10) must be changed to include the possible addition of a coherent direct interaction background given by \( \alpha e^{i\phi} \) and an incoherent background given by \( Y_{\text{OFF}} \). Furthermore a differential cross section is needed for comparison with the experimental data; this can be developed by the addition of the appropriate angular distribution amplitudes \( f_{a \frac{1}{2}}(\theta) \) and \( f_{b \frac{1}{2}}(\theta) \). Equation (5-26) then becomes

\[
\left. \frac{d\sigma}{d\Omega} \right|_{\text{CM}} = \pi \omega k^2 \cdot \frac{\beta \Gamma_a \gamma_b \frac{1}{2} f_{a \frac{1}{2}}(\theta) - \alpha \Gamma_a \gamma_b \frac{1}{2} f_{b \frac{1}{2}}(\theta)}{E_a - E - \frac{\Gamma_a^2}{4}(E_m - E)^2} + \frac{\Gamma_{\alpha a} \frac{1}{2}}{E_a - E} + \frac{\Gamma_{\alpha b} \frac{1}{2}}{E_b - E} + \alpha e^{i\phi} + Y_{\text{OFF}}
\]  

(5-28)

Since the excitation function was measured at a laboratory angle of 125° where \( P_2(\cos \theta) \) is zero, the addition of the angular distribution factors given by equations (5-1) through (5-5) for the values of \( \delta \) given by equations (5-8) and (5-9)
amounts to only a 3\% correction. The angular distributions \( f_a \) and \( f_b \) are evaluated at the center-of-mass angles with the appropriate values for \( \delta_a \) and \( \delta_b \) and with geometrical corrections to account for the integrations over the solid angle.

The extraction of the gamma-ray isovector M1 radiative width \( \Gamma_{M1}^{\Delta T=1} \) from the excitation function is complicated by the presence of three additional gamma-ray transition amplitudes. If \( A_{M1}^1 \) is the isovector M1 amplitude, \( A_{M1}^0 \) is the isoscalar M1 amplitude, \( A_{E2}^1 \) is the isovector E2 amplitude, and \( A_{E2}^0 \) is the isoscalar E2 amplitude such that

\[
\epsilon = \frac{A_{M1}^0}{A_{M1}^1} \quad (5-29)
\]

\[
\delta_1 = \frac{A_{E2}^1}{A_{M1}^1} \quad (5-30)
\]

\[
\delta_0 = \frac{A_{E2}^0}{A_{M1}^1} \quad (5-31)
\]

then the gamma-ray width for level a is given by

\[
\Gamma_{\gamma a} = |\alpha A_{M1}^1 + \beta A_{M1}^0|^2 + |\alpha A_{E2}^1 + \beta A_{E2}^0|^2 \quad (5-32)
\]

so that

\[
\Gamma_{\gamma a}^{1/2} = |\alpha|^{1/2}[(1 + \frac{\delta_1}{\alpha} \epsilon^2 + (\delta_1 + \frac{\delta_0}{\alpha} \delta_0)^2]^{1/2} \quad (5-33)
\]
and the gamma-ray width for level b is given by

\[ \Gamma_{\gamma b} = |\beta A_{M1}^1 - \alpha A_{M1}^0|^2 + |\beta A_{E2}^1 - \alpha A_{E2}^0|^2 \]  

(5-34)

so that

\[ \Gamma_{\gamma b}^{1/2} = \beta \Gamma^{1/2}[(1 - \frac{\alpha}{\beta} \varepsilon)^2 + (\delta_1 - \frac{\alpha}{\beta} \delta_0)^2]^{1/2} \]  

(5-35)

where \( \Gamma = \Gamma_{M1}^{A=1} |A_{M1}^1|^2 \). The relative sign of \( \Gamma_{\gamma a}^{1/2} \) and \( \Gamma_{\gamma b}^{1/2} \) in equations (5-33) and (5-35) was chosen to reproduce the observed destructive interference in the tails of the resonances and the observed constructive interference between the two resonances.

The values for \( \varepsilon, \delta_1, \) and \( \delta_0 \) can be found from the angular distributions at the two resonances and from the shape of the excitation function. The relationships are given by

\[ \delta_{16.6} = \delta_a = (\frac{\Gamma_{aE2}}{\Gamma_{aM1}})^{1/2} = \frac{|\alpha A_{E2}^1 + \beta A_{E2}^0| \delta_1 + \frac{\alpha}{\beta} \delta_0}{|\alpha A_{M1}^1 + \beta A_{M1}^0|} = \frac{1}{1 + \frac{\beta}{\alpha} \varepsilon} \]  

(5-36)

\[ \delta_{16.9} = \delta_b = (\frac{\Gamma_{bE2}}{\Gamma_{bM1}})^{1/2} = \frac{|\beta A_{E2}^1 - \alpha A_{E2}^0| \delta_1 - \frac{\alpha}{\beta} \delta_0}{|\beta A_{M1}^1 - \alpha A_{M1}^0|} = \frac{1}{1 - \frac{\alpha}{\beta} \varepsilon} \]  

(5-37)

With \( \varepsilon \) determined by Bowles from the shape of his excitation function, \( \delta_1 \) and \( \delta_0 \) can be calculated from the values given in equations (5-8) and (5-9):
\[ \varepsilon = -0.038 \pm 0.021 \]  \hspace{1cm} (5-38)

\[ \delta_1 = 0.190 \pm 0.033 \]  \hspace{1cm} (5-39)

\[ \delta_0 = 0.218 \pm 0.032 \]  \hspace{1cm} (5-40)

All the essential parameters have then been determined for equation (5-28) to be used as a theoretical excitation function to fit the measured excitation function. \( E \) is a variable excitation energy and \( \Gamma, A, \phi, \) and \( Y_{\text{OFF}} \) are parameters to be determined by the best fit.

Some excitation functions, all derived from equation (5-28) using the fixed parameters given above, are shown in the next three figures. Figure 5-5 graphically depicts the behavior of equation (5-28) as a function of excitation energy \( E \) for no direct interaction contributions. This is essentially equation (5-27) with small corrections for the angular distribution amplitudes included. Each excitation function is shown for one value of \( \Delta T=1 \) which simply determines the overall scale of the function.

Figure 5-6 shows the prominent effect of a coherent direct interaction contribution as small as \( |A|^2 \alpha \sigma_{\text{DI}} = 15 \text{ nb/sr} \). The heavy line shows the best fit obtained with a zero direct interaction amplitude while the curves consisting of dashed lines show the effect of the phase of the direct amplitude on its interference with the resonant amplitude. As a function of relative phase \( (\phi) \), even for a small direct amplitude, the peak energies shift and the peak to peak and peak to valley
Figure 5-5: A Set of Excitation Functions with Variable $\Gamma_{\Delta T=1}^M$. Shown here are a set of five excitation functions calculated directly from equation (5-28) using parameters given in the text. The direct interaction terms have been set equal to zero. Each curve was generated by varying only the M1 radiative width $\Gamma_{\Delta T=1}^{\Delta T=1}$, which behaves simply as a scale factor. The values of $\Gamma_{\Delta T=1}^{\Delta T=1}$ are listed in the inset next to the reduced Chi-squared values for the corresponding fits to the data shown in Figure 5-3. The heavy central line shows the excitation function closest to the best fit.
\( \text{He}^4 (\alpha, \gamma) \text{Be}^{8*} \)

\( \theta_{\text{LAB}} = 125^\circ \) DIFFERENTIAL CROSS SECTIONS

NO DIRECT INTERACTION

\[ \Gamma_{\text{MI}}^{\Delta T=1} \text{ (eV) } \times \chi^2 \nu \]

- 8.00 \quad 0.750
- 7.50 \quad 0.335
- 7.00 \quad 0.166
- 6.50 \quad 0.243
- 6.00 \quad 0.567

BEST FIT: \( \Gamma_{\text{MI}}^{\Delta T=1} = 6.91 \pm 0.85 \text{ eV} \)

EXCITATION ENERGY (MeV)
Figure 5-6: Direct Interaction and Interference Effects. A set of five excitation functions calculated directly from equation (5-28) using parameters given in the text show the strong effect of a non-zero coherent direct interaction background. The legend in the figure lists the different values for $Ae^{-i\phi}$ used in equation (5-28) along with the reduced Chi-squared values for the corresponding fits to the data. The excitation function generating the best fit is shown by the heavy line.
$\theta_{\text{LAB}} = 125^\circ$ DIFFERENTIAL CROSS SECTIONS

DIRECT INTERACTION AND INTERFERENCE EFFECTS

<table>
<thead>
<tr>
<th>LINE</th>
<th>$\sigma_{\text{DI}}$ (nb/sr)</th>
<th>$\phi$</th>
<th>$x^2_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0°</td>
<td>0.162</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0°</td>
<td>0.820</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>90°</td>
<td>0.770</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>180°</td>
<td>0.724</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>270°</td>
<td>0.706</td>
</tr>
</tbody>
</table>

$\Gamma^{\Delta T=1}_{\text{MI}} = 6.91$ eV
Figure 5-7: A Comparison of Mixing Parameters.

Shown here are two excitation functions calculated from equation (5-28), one with a set of mixing parameters (See equations (5-29) to (5-31).) given by Bowles^5 (Set A) and one with a set of mixing parameters given by Nathan^7 (Set B). The two sets lead to quite different predictions of peak to peak and peak to valley ratios for the two resonances. Our data favor set A.
$^{4}\text{He} (\alpha, \gamma) ^8\text{Be}^*$

$\theta_{\text{LAB}} = 125^\circ$ THEORETICAL EXCITATION FUNCTIONS

$\Gamma_{\text{MI}} = 6.91 \pm 0.85$ eV

NO DIRECT INTERACTION

PARAMETER SET A

$\epsilon = -0.038$

$\delta_0 = 0.218 \quad \chi^2_\nu = 0.162$

$\delta_1 = 0.190$

PARAMETER SET B

$\epsilon = 0.097$

$\delta_0 = 0.048 \quad \chi^2_\nu = 0.595$

$\delta_1 = 0.045$

$\frac{d\sigma}{d\Omega}$ (nb/sr) vs. EXCITATION ENERGY (MeV)
ratios are noticeably changed. Because of this an upper limit can be effectively set on the coherent direct interaction contribution, which is essentially zero.

Figure 5-7 presents two contrasting excitation functions, one developed with Bowles's set of mixing parameters (Set A) and the other with Nathan's set (Set B). The principal differences lie in the peak to peak and peak to valley ratios for the two resonances. Our best fit was obtained using Bowles's parameters which were held fixed while a search for the best value of $\Gamma_{M1}^{\Delta T=1}$ was performed.

5.5 THE FIT TO THE EXCITATION FUNCTION.

Before the excitation function calculated from equation (5-28) could be compared to the measured data two further calculations had to be performed. At each excitation energy for each measured data point shown in Figure 5-3, the excitation function in the region of the data point was first folded with a straggling distribution function and then integrated over the energy thickness of the gas target.

Straggling is discussed in detail by Rossi. It was assumed here that the gas target and the entrance kapton window were thick enough so that the probability density function $g(E',E_L)$ that the incident alpha beam of initial laboratory energy $E_L$ had an energy $E'$ was a Gaussian:

$$g(E',E_L) = \frac{1}{\sqrt{2\pi}\Delta^2} e^{-\frac{(E'-E_L)^2}{2\Delta^2}}$$  (5-41)
\( \Delta \) is a straggling parameter proportional to the half-width half-maximum of the Gaussian distribution and is to be determined from the best fit to the excitation function. At every laboratory energy \( E_L \) the excitation function was convoluted with the straggling distribution to give an averaged cross section \( S(E_L) \):

\[
S(E_L) = \frac{1}{0.9546} \int_{E_L-2\Delta}^{E_L+2\Delta} g(E',E_L) \frac{\partial \sigma}{\partial \Omega} \Big|_{\text{cm}} (E') \, dE'
\]

(5-42)

\( E' \) is the laboratory energy and is related to the excitation energy \( E \) by \( E = E'/2 - 0.092 \). The factor 0.9546 was applied to the normalized Gaussian \( g(E',E_L) \) to compensate for the limited integration of only \( 2\Delta \) on either side of \( E_L \). The integration was accomplished numerically.

This averaged cross section \( S(E_L) \) was then numerically integrated over the full energy range of the target giving \( T(E_{LC}) \) as the final averaged cross section to be compared with the measured data of Figure 5-3. We have

\[
T(E_{LC}) = \frac{1}{2\varepsilon'} \int_{E_{LC}-\varepsilon'}^{E_{LC}+\varepsilon'} S(E_L) \, dE_L
\]

(5-43)

where \( E_{LC} \) is the energy at the center of the target corresponding to the excitation energies shown by dots in Figure 5-3, and \( \varepsilon' \) is one-half the energy thickness of the gas.
target in the laboratory frame.

Figure 5-3 shows the averaged excitation function $T(E_{LO})$ plotted as a function of excitation energy in Be. At each point an integration was performed with a straggling parameter $\Delta = 40.0$ keV (the best fit value) and with a target thickness $2\varepsilon' = 93.6$ keV. The smoothing effect of these integrations is readily seen in comparing Figures 5-3 and 5-5.

In summary, the combination of equations (5-28), (5-42), and (5-43) produced an energy averaged excitation function appropriate to compare to the experimental data. In the search for the best fit to the data shown in Figure 5-3 this procedure generated trial excitation functions, where the parameters $T_{\Delta T=1}^{M_1}$, $A$, $\phi$, $Y_{OFF}$, $\Delta$, and baseline shift were varied. The baseline shift parameter EBS was added to the excitation energy to account for shifts in the peak energies due to incorrectly calculated energy losses in the kapton windows and helium gas. After many trials the best fit was obtained with a reduced Chi-squared value $\chi^2_v = 0.16$ for

$$T_{\Delta T=1}^{M_1} = 6.91 \text{ eV}$$  \hspace{1cm} (5-44)

$$A = 0$$  \hspace{1cm} (5-45)

$$\phi = 0$$  \hspace{1cm} (5-46)

$$Y_{OFF} = 26 \text{ nb/sr}$$  \hspace{1cm} (5-47)

$$\Delta = 40.0 \text{ keV}$$  \hspace{1cm} (5-48)

$$\text{EBS} = 0$$  \hspace{1cm} (5-49)
where the rest of the parameters in the fit were unchanged from their values given in Section 5.4. The error for \( \Gamma_{M1}^{AT=1} \) determined solely from the statistics of the fit was 0.42 eV or 6.1%. The best value for \( Y_{OFF} \) is not statistically significant since errors for the cross sections on the tails of the resonances are all over 100 nb/sr. The value for the straggling parameter \( \Delta \) was higher than the expected maximum of 20 keV, including incident beam resolution, and this could reflect the presence of a straggling distribution that is not entirely Gaussian. It is estimated that this could cause an error of 5% in the final determination of \( \Gamma_{M1}^{AT=1} \). The baseline shift parameter EBS was essentially zero meaning only that beam energies and energy losses were correctly calculated.

The next two figures show Chi-squared plots obtained by holding all but two parameters fixed at their best fit values and varying only the two remaining parameters. Figure 5-8 shows contours of constant \( \chi^2_\nu \) as a function of \( \Gamma_{M1}^{AT=1} \) and EBS with a well-defined minimum at the best values. Figure 5-9 gives \( \chi^2_\nu \) polar contour plots as a function of \( A(\sigma_{DI}) \) and \( \phi \), showing a lowest \( \chi^2_\nu \) value at \( A=0 \). Figure 5-10 shows the variation of \( \chi^2_\nu \) with one specific parameter with all others held at their best values. At a minimum \( \chi^2_\nu \) value of 0.16 the values for these parameters are \( \varepsilon = -0.04 \), \( \alpha = 0.6 \), \( Y_{OFF} = 26 \) nb/sr, and \( \Delta = 40.0 \) keV. In the extraction of the best value for \( \Gamma_{M1}^{AT=1} \), however, we have elected to use values for \( \varepsilon \) and \( \alpha \) determined by more accurate experiments: \( \varepsilon = -0.038 \) and \( \alpha = 0.647 \). Our values for \( \varepsilon \) and \( \alpha \) giving a minimum \( \chi^2_\nu \) did not differ substantially from these values.
Figure 5-8: Contours of Constant $\chi^2_\nu$.

$\chi^2_\nu$ contours are plotted as a function of $\Gamma_{M1}^{\Delta T=1}$ and baseline shift EBS with all other parameters at their best fit values. A clear minimum is at $\Gamma_{M1}^{\Delta T=1} = 6.9 \text{ eV}$ and EBS = 0.
CONTOURS OF CONSTANT $X^2_\nu$
AS FUNCTION OF $\Gamma_{MI}^{\Delta T=1}$
AND BASELINE SHIFT WITH
$\sigma_{Di}=0$ AND $\phi=0$
STRAGGLING = 40.0 KeV
Figure 5-9: Contours of Constant $\chi^2_v$.

$\chi^2_v$ contours are plotted using the polar coordinates of $A (\sigma_{\text{DI}})$ and $\phi$ with all other parameters at their best fit values. A clear minimum is at $A=0$. 
CONTOURS OF CONSTANT $X^2_{\nu}$ AS FUNCTION OF $\sigma_{DI}$ AND $\phi$
WITH $\Gamma_{mi}^{AT} = 6.91$ eV AND
ZERO BASELINE SHIFT
STRAGGLING = 40.0 KeV

$X^2_{\nu} = 2.0$
$X^2_{\nu} = 1.0$
$X^2_{\nu} = 0.5$
Figure 5-10: Four $\chi^2_v$ Plots.

For each plot one parameter is varied while all the others are held at their best values. The first plot shows $\chi^2_v$ as a function of the radiative width mixing parameter $\epsilon$ with $\epsilon = -0.04$ at the minimum. The second plot shows $\chi^2_v$ as a function of the isospin mixing parameter $\alpha$ with $\alpha = 0.6$ at the minimum. The third plot shows $\chi^2_v$ as a function of the incoherent direct background $Y_{0FF}$ with $Y_{0FF} \sim 26$ nb/sr at the minimum of a shallow curve. The fourth plot shows $\chi^2_v$ as a function of the straggling parameter $\Delta$ with $\Delta \sim 40$ keV at the minimum. The minimum $\chi^2_v$ value is 0.16.
A best value for $\Gamma_{M1}^{\Delta T=1}$ has been determined to be $\Gamma_{M1}^{\Delta T=1} = 6.91$ eV. The statistical error was determined by the fit to the measured excitation function given in Figure 5-3. The other components of the error are given in Table 5-1. All are added in quadrature to produce a total error in the value of $\Gamma_{M1}^{\Delta T=1}$ of 12.3% so that

$$\Gamma_{M1}^{\Delta T=1} = 6.91 \pm 0.85 \text{ eV}$$ \hspace{1cm} (5-50)

The best values of all the other parameters needed to produce the fit yielding the best value of $\Gamma_{M1}^{\Delta T=1}$ are also summarized in Table 5-1. Any errors in the measurements of these values have not been incorporated into the error of $\Gamma_{M1}^{\Delta T=1}$ since they were treated as fixed parameters. The total error quoted above represents a minimum possible error.
TABLE 5-1

ERROR ANALYSIS IN THE DETERMINATION OF $\Gamma_{M1}^{\Delta T=1}$

<table>
<thead>
<tr>
<th>Item</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics from Fitting Routines</td>
<td>6.1%</td>
</tr>
<tr>
<td>Charge Collected</td>
<td>2.0%</td>
</tr>
<tr>
<td>Target Thickness</td>
<td>4.0%</td>
</tr>
<tr>
<td>Efficiency (and solid angle)</td>
<td>8.3%</td>
</tr>
<tr>
<td>Straggling</td>
<td>5.0%</td>
</tr>
<tr>
<td><strong>Total in quadrature</strong></td>
<td><strong>12.3%</strong></td>
</tr>
</tbody>
</table>

$\Gamma_{M1}^{\Delta T=1} = 6.91 \pm 0.85$ eV

Parameters of the Best Fit

- $\Gamma_a = 184$ keV
- $E_a = 16.627$ MeV
- $E_b = 16.911$ MeV
- $\alpha = 0.647$
- $\beta = -0.763$
- $\epsilon = -0.038$
- $\delta_1 = 0.190$
- $\delta_0 = 0.218$
- EBS = 0
- $A = 0$
- $\phi = 0$
- $Y_{OFF} = 26$ nb/sr
- $\Delta = 40.0$ keV
CHAPTER 5 REFERENCES

THE RESULT
AND ITS IMPLICATIONS

By measuring an excitation function for the $\text{He}^4(\alpha,\gamma_1)$ $\text{Be}^8$ reaction spanning the 16.6-16.9 MeV doublet in $\text{Be}^8$ we have found that the isovector M1 radiative width for these two states in a transition to the first excited state of $\text{Be}^8$ is

$$\Gamma_{\text{M1}}^{\Delta T=1} = 6.91 \pm 0.85 \text{ eV} \quad (6-1)$$

This represents the total isovector M1 width since the differential cross section for a transition to the ground state of $\text{Be}^8$ is only 40 nb/sr at peak and the radiation is entirely E2. A summary of recently measured values for $\Gamma_{\text{M1}}^{\Delta T=1}$ is given in Table 6-1. It should be emphasized that when this work was initiated only the first two entrees were available and were clearly in disagreement.

To relate our measured value of $\Gamma_{\text{M1}}^{\Delta T=1}$ to the $\beta^+ - \alpha$ angular correlation measurements of the $\text{Li}^8$ and $\text{B}^8$ beta decay experiment described in Section 1.8 it is first necessary to determine the weak magnetism form factor via equation (2-20) and then determine predicted values for $\delta^- m_n/E_B$ via equation (2-19). When the predicted values of $\delta^- m_n/E_B$ are compared with the experimental values the magnitude of $d_{II}$ in equation (2-19)
TABLE 6-1

ISOVECTOR M₁ RADIATIVE WIDTHS OF THE
16.6-16.9 MeV DOUBLET IN Be⁸

<table>
<thead>
<tr>
<th>Group</th>
<th>$\Delta T = 1$ M₁ Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nathan et al. (Brookhaven)²</td>
<td>6.20 ± 0.74 eV</td>
</tr>
<tr>
<td>Nathan et al. (Princeton)²</td>
<td>4.46 ± 0.47 eV</td>
</tr>
<tr>
<td>Bowles et al.³</td>
<td>6.10 ± 0.53 eV</td>
</tr>
<tr>
<td>P. Paul et al.⁴</td>
<td>7.37 ± 1.0 eV</td>
</tr>
<tr>
<td>Present work</td>
<td>6.91 ± 0.85 eV</td>
</tr>
</tbody>
</table>
will be determined and this will decide whether or not second-
class currents have been observed in the mass 8 system.

The weak magnetism form factor \( b(E_Y) \) and its dependence
on excitation energy are determined from

\[
b^2(E_Y) = \frac{6M^2}{\kappa_{E_Y}} \left[ \Delta T = 1 \right] \frac{ML}{N(E_Y)}
\]

(See Section 2.3.) and the unfolded gamma-ray spectrum of
Figure 4-12. The result\(^5\) is shown in Figure 6-1 and is compared
with the Gamow-Teller form factor \( c \) which has a markedly different
energy dependence. For our value of \( \Delta T = 1 \) the peak value
of \( b^2 \) is 52.2. The peak value of \( c^2 \) is \( 6.9 \times 10^{-3} \) as deter-
dined by Bowles\(^5\) after analysis of the alpha particle spectra
following the beta decays of \( B^8 \) and \( Li^8 \).

With the \( b^2 \) and \( c^2 \) form factors determined as in Figure
6-1 up to 6.9 MeV excitation energy, equation (2-19) can then
be used to calculate the values for \( \frac{\delta_{mn}}{E_\beta} \) to provide a compari-
son with the measured data shown in Figure 6-2. Changing the
summations in equation (2-19) to integrals, changing the
variable of integration to excitation energy \( E_X \), where
\( E_0 = \epsilon - E_X \) and \( \epsilon \) is the average mass difference (16.993 MeV),
and dropping for the moment the \( d_{\Pi} \) term, we have

\[
\frac{\delta_{mn}}{E_\beta} = \int_0^{E_\beta} e^{-E_\beta b(E_X)c(E_X)[1- \frac{\sqrt{5}}{2} (1+2 \epsilon/E_X) \delta_1(E_X)](\epsilon - E_X - E_\beta)^2 e^{E_X} dE_X
\]

(6-3)
Figure 6-1: Weak Magnetism and Gamow-Teller Form Factors. The energy dependence of the weak magnetism form factor $b^2$ was determined by Bowles\textsuperscript{5} from Figure 4-12. The magnitude relative to peak is plotted versus center-of-mass gamma-ray energy. Using our value of $\Gamma_{M_1}^{\Delta T=1}$ the peak value of $b^2$ is 52.2. The Gamow-Teller form factor $c^2$ was determined by Bowles\textsuperscript{5} by analyzing the spectra of alpha particles following the beta decays of B\textsuperscript{8} and Li\textsuperscript{8}. Its peak value is $6.9 \times 10^{-3}$. Note that $b^2$ and $c^2$ do not have the same energy dependence. The error bars shown on the curve for $b^2$ represent statistical errors relative to the error for the peak value.
DATA of T. BOWLES et al.

- $b^2$
- $c^2$

MAGNITUDE RELATIVE TO PEAK

C.M. GAMMA-RAY ENERGY (MeV)
Figure 6-2: Measured and Predicted Asymmetries.

The data points shown are the experimentally measured values of $\delta m_n/E_\beta$ from the experiment described in Section 1.8. The solid curve does not represent a fit but is the prediction of equation (6-3) using the form factors presented in Figure 6-1 and no second-class currents. The shaded area represents the range of $\delta m_n/E_\beta$ values corresponding to a range of one standard deviation in both $\Gamma_{M1}^{\Delta T=1}$ and $\delta_1$. 
PREDICTED VALUES COMPARED WITH MEASURED VALUES
For each value of $E_B$ given in Figure 6-2 the integration extends over all possible end-point energies. In accomplishing the integration numerically we have assumed that $b$ and $c$ drop abruptly to zero at 6.9 MeV excitation energy. This is an ad hoc assumption but necessary in the absence of measured data on the behavior of $b$ and $c$ above 6.9 MeV excitation energy. We have also assumed, for reasons of lack of evidence to the contrary, that $\delta_1 = 0.190$ is a constant independent of excitation energy; this is the same as assuming that the isovector $E2$ and $M1$ matrix elements have the same energy dependence. Using these assumptions and the measured values of $b$ and $c$ given in Figure 6-1, we have generated the solid curve of predicted values of $\delta^-m_n/E_B$ shown in Figure 6-2.

To include the effect of a second-class induced tensor form factor we subtracted $\frac{d_{T\Pi}}{A_C}$ from the right-hand side of equation (6-3) and then performed a linear least squares fit to the data of Figure 6-2 using $\frac{d_{T\Pi}}{A_C}$ as the only variable parameter. We found

$$\frac{d_{T\Pi}}{A_C} = 1.27 \pm 1.8$$ (6-4)

where the error includes only the statistical errors of the $\delta^-m_n/E_B$ data points and the errors of $\frac{\Gamma^{\Delta T=1}_{M1}}{M1}$ and $\delta_1$ and does not include any errors involving assumptions used to calculate equation (6-3). Our results are therefore consistent with the absence
of second-class induced tensor currents in the mass 8 system.

In summary we conclude that our results have provided a model-independent confirmation of the conserved vector current theory and have given evidence that second-class currents do not exist in the mass 8 system. We emphasize that in parallel with but entirely independent of the work reported here new measurements have been carried out by Bowles et al.\textsuperscript{3} and by P. Paul et al.\textsuperscript{4} as shown in Table 6-1. The results of all three of these studies are entirely consistent, agreeing with the first rather than the second of Nathan's\textsuperscript{2} measurements, and as the above arguments show do not support the existence of second class currents in the mass 8 system. Indeed the agreement among these difficult measurements, excluding the second of Nathan's at Princeton, is gratifyingly good.

Referring to Table 1-1 and noting that the mass 12 and 19 measurements may well be in error (See Chapter 1.) we see that overwhelming evidence supports the conclusion that second-class (G parity nonconserving) weak interaction currents do not exist. In the future this should lead to simplifications in the theory of weak interactions and has already led to the development of gauge theories of the strong interaction which do not admit second-class currents. All of the correlation experiments described in Chapter 1 are difficult and should be repeated but when this is done it is highly probable that they will support our conclusion that second-class currents do not exist.
CHAPTER 6 REFERENCES


APPENDICES
APPENDIX I-A

DATA ACQUISITION PROGRAM FOR SINGLES EXPERIMENTS

This appendix lists the computer program used by our on-line IBM 360/44 computer to process data collected by our computer interface during the He\(^4\)(\(\alpha\),\(\gamma\))Be\(^8\) experiment. Its basic function was to cause periodic sampling of the bank of ADC's and scalers, sort the gamma-ray spectra into real gamma-ray, cosmic ray, and LED components and generate signals for the gain stabilization feedback loop. This was accomplished by a set of logic signals, called "events", received by the computer interface and generated by the network described in Section 3.6. Details of the computer interface and its associated programming are found in Reference 6 of Chapter 4.

The first section of the listing gives the job control deck with a list of the modules for the various phases. In four subroutines belonging to the root phase, block data is set up; the routine RDSCLR reads scalers at the computer interface; the routine CALPOS calculates the position of the centroid of the LED pulses and estimates pile-up; and the routine SUM performs a summing operation for CALPOS. In the first phase INIT creates analyzers and scalers. In the second phase START allows the operator to type in various initialization data. The principal phase is RUN which provides for the collection and processing of data received by the computer interface according to the arrival of "event" signals. The
coding is broken into "event" blocks with brief descriptions at each heading. The gain stabilization feedback is accomplished in the coding for event 6, which causes a recently collected LED spectrum to be examined for a shift in its centroid relative to a reference spectrum and makes the appropriate correction in the voltage applied to the photomultiplier tubes. In the fourth phase STOP provides the services of printing, plotting, and taping the final spectra and data with the aid of the subroutines PRNT, PTTP, and CPLOT.
/* 
 //DATAJOB DUMP
 //SYS000 ALLOC INT,QUEU=
 //SYS001 ALLOC LNK,QUEU=
 //SYS021 ALLOC JPC,191='MPWRK' 250,50,FMT
 //LAB 720
 //SYS03 ALLOC DIRJPC,191='MPWRK',0,14,FMT
 //LAB 360
 //SYS004 ACCESS TAPE,181=
 //SYS015 ALLOC OFLO,0,0,0
 //LAB 720
 //SYS021 ACCESS D3,1827DEV='OFEC01'
 //SYS023 ACCESS D4,1827DEV='OFRO2'
 //SYS003 ALLOC DESCRIP,191='MPWRK',50
 //LAB 360
 //SYS002 ACCESS SDSIP
 //EXEC COPIER(SIZE360,BLOK5,END'ZZZ)

 YSPSLR JC=CA CACA 1 YSPSL JC DA=CA 00000001
 CACA H YSPSLT JC DA=CA CACA 4 YSPRG00000002

 CACA JC DA=CA CACA - YSPRT JT DA=CA 00000003
 CACA IA YSPRCE JT DA=CA 00000004

 CACA YSPCAL1 LD D C YSPCALB LD D A 00000005
 SINFO LD D YSPCAL SCALB SCALC 00000006

 CACA 00000007

 CACA 00000008
 CACA 00000009
 CACA 00000010

 YSPCAL1 LD D A

 CACA /*

 //SYS019 ACCESS DESCRIP
 //EXEC

 MODULE BLKDAT
 MODULE RDSCLR
 MODULE CALPOS
 MODULE SUM
 MODULE INIT
 MODULE START
 MODULE RUN
 MODULE STOP
 MODULE PRNT
 MODULE PTTP
 MODULE CPLOT

 PHASE MAIN,ROOT
 INCLUDE SDAMAIN1 R
 INCLUDE BLKDAT L
 INCLUDE RDSCLR L
 INCLUDE CALPOS L
 INCLUDE SUM L

 PHASE EVINITY.
 INCLUDE INIT L
 PHASE EVSTRT, EVINIT
 INCLUDE START L
 PHASE EVRUN, EVINIT
 INCLUDE RUN L
 PHASE EVSTOP, EVINIT
 INCLUDE STOP L
 INCLUDE PRNT L
 INCLUDE PTTPL L
 INCLUDE CPLOT L

 /*
 //UNLOAD SYS004
 /*
 //DELDACO JOB
 //ACCESS JPC,191='MPWRK'
 //DELETE JPC
 //ACCESS DIRJPC,191='MPWRK'
 //DELETE DIRJPC
 //ACCESS DESCRIP,191='MPWRK'
 //DELETE DESCRIP
 */
//BLKDAT EXEC FORTRAN (MAP)

BLOCK DATA

COMMON/BLK1/VOLTA,CT,DA
REAL VOLTA/2048.0/
INTEGER CT/0/,DA(5)/5*0/
COMMON/BLK2/CEN,IPILE
COMMON/BLK3/XI,ORRR,TYPER,RUN,MAXC,FAC,FOC,FR,IR,KEY,CODE, 
1EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
REAL XI/4.0/,ORRR/5000.0/
INTEGER TYPER/O/,RUN,FAC/100/,FOC/10/,FR/200/,IR/O/,KEY/O/
INTEGER=2 CODE,EP,ANGLE,BEAM,FRSTCH/100/,LASTCH/800/,PMHV,SW/1/
COMMON/BLK4/DATV,DATTV
INTEGER DATV(5)/5*0/,DATTV(5)/5*0/
COMMON/BLK5/DAT,DATT
INTEGER DAT(5)/5*0/,DATT(5)/5*0/
END

//RDSCLR EXEC FORTRAN (MAP)

SUBROUTINE RDSCLR(N)
READS THE FIVE SCALERS AND STORES OR ERASES THE DATA

COMMON/BLK1/VOLTA,CT,DA
COMMON/BLK4/DATV,DATT
INTEGER CT,DA(5)
INTEGER DATV(5),DATTV(5)
INTEGER_DAT(5),DATT(5)
GO TO (1,2,3,4),N
1 DO 11 I=1,5
11 DA(I)=IDADV0(I)
RETURN

2 DO 22 I=1,5
22 DATT(I)=DATT(I)+DATV(I)
RETURN

3 DO 33 I=1,5
33 DATV(I)=0
RETURN

4 DO 44 I=1,5
44 DATT(I)=0
RETURN

END

//CALPOS EXEC FORTRAN (MAP)

SUBROUTINE CALPOS(A)
CALCULATES CENTROID AND PILE-UP FOR FIRST CHANNEL AT I = 10
ANALYZER A MUST HAVE AT LEAST 10 BINS
COMMON/BLK2/CEN,IPILE
INTEGER A
NPTS=IDARNG(A)
ISW=1
TOTAL = SUM(1020., A) - SUM(9., A)

5 S = 0.
HTOT = TOTAL/2.
DOB I = 10., NPTS
CEN = 1 - 1
S = S + IDAGET(A, I)
IF (S.GE.HTOT) GO TO 20
10 CONTINUE

20 CEN = CEN + (HTOT + IDAGET(A, I) - S)/IDAGET(A, I)
IF (ISW.EQ.2) GO TO 60
TTOT = TOTAL/10.
S = 0.
DOB 30 I = 10., NPTS
TENTH = 1 - 1
S = S + IDAGET(A, I)
IF (S.GE.TTOT) GO TO 40
30 CONTINUE

40 TENTH = TENTH + (TTOT + IDAGET(A, I) - S)/IDAGET(A, I)
REFL = 2*CEN - TENTH
PILE = 0.
DO 20, S = TOTAL - SUM(REFL, A) + SUM(9., A)
IF (PILE.LE.0.1) GO TO 60
IF (SUM(1020. + 98*CEN, A).GE.(.7*TOTAL)) GO TO 50
WRITE(10, 11)
11 FORMAT('THE REGION WITHIN 2% OF THE LP CENTROID DOES NOT CONTAIN 7
10% OF THE COUNTS.'
GO TO 60
50 TOTAL = TOTAL - PILE
ISW = 2
GO TO 5
60 IPILE = PILE
RETURN
END

//SUM EXEC FORTRAN(MAP)
REAL FUNCTION SUM(X, A)
INTEGER A
NPTSS = IDARNG(A) - 1
IF (X.LT.1.) X = 1.
IF (X.GT.(NPTSS + 1)) X = NPTSS + 1
SUM = 0.
DOB 10 I = 1, NPTSS
J = (I +)
SUM = SUM + IDAGET(A, I)
IF (X.LE.J) GO TO 20
10 CONTINUE
20 SUM = SUM + IDAGET(A, J) * (X - I)
RETURN
END

//INIT EXEC FORTRAN(MAP)
SUBROUTINE INIT
COMMON SPSLR, SPSL, SPSLT, SPRG, SPRGT, SPRCP, SPRCT
INTEGER SPSLR, SPSL, SPSLT, SPRG, SPRGT, SPRCP, SPRCT
COMMON SCAL, SCALB, SCALC
INTEGER SCAL, SCALB, SCALC
REAL A(7), SPSLR, SPRG, SPRGT
CREATE SPSLR, SPSL, SPSLT, SPRG, SPRGT, SPRCP, SPRCT
CREATE SCAL, SCALB, SCALC, SINFO
IERR = 0.
CALL SDAIDP(A(I),I,IERR,E2)

CONTINUE
RETURN
END

SUBROUTINE START
COMMON/BLK1/VOLT,A,CT,DA
COMMON/BLK3/XI,ORR,TYPER,Run,MaxC,FAC,FOC,FR,IR,KEY,CODE,
EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
INTEGER CT,DA(5)
INTEGER TYPER,Run,FAC,FOC,FR
INTEGER IERR/0/
INTEGER*2 CODE,EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
INTEGER*2 IDAT

FORMAT(11)
100 FORMAT(F6.1)
101 FORMAT(A2,A4)
105 FORMAT(F6.2)
106 FORMAT(F6.1)
107 FORMAT(F10.1)
IF(SW.EQ.2) GO TO 122
108 WRITE(TYPER,109)
109 FORMAT('TO INITIALIZE PARAMETERS TYPE 1, 2, OR 3. OTHERWISE TYPE 14.(
')
READ(TYPER,100,ERR=108) IYF
IF(IYF.EQ.4) GO TO 122
IF(IYF.NE.1) GO TO 117
201 WRITE(TYPER,110)
110 FORMAT('TYPE IN ALLOWED CHANNEL SHIFT OF LP CENTROID F5.2.
')
READ(TYPER,105,ERR=201) XI
202 WRITE(TYPER,111)
111 FORMAT('TYPE IN NUMBER OF COUNTS REQUIRED FOR LP SOURCE 14.(
')
READ(TYPER,102,ERR=202) FR
203 WRITE(TYPER,112)
112 FORMAT('TO GET A LINEAR PLOT OF THE GAMMA RAY SPECTRUM TYPE 9111
AND TYPE IN THE FULL SCALE NUMBER OF COUNTS(F6.1) 'TO GET A LOG
2PLOT TYPE 012.... UP TO 8 DEPENDING UPON THE THRESHOLD REQUIRED(I
31).
')
READ(TYPER,101,ERR=203) IR,ORR
204 WRITE(TYPER,113)
113 FORMAT('TO REWIND THE TAPE TYPE 1 OTHERWISE TYPE 0.(
')
READ(TYPER,100,ERR=204) KUU
IF(KUU.NE.1) GO TO 115
REWIND 4
WRITE(TYPER,114)
114 FORMAT('TAPE REWOUND')
115 WRITE(TYPER,116)
116 FORMAT('FOR PMHV CONTROL TYPE 1 OTHERWISE TYPE 0.')
READ(TYPER,100,ERR=115) KEY
117 IF(IYF.NE.2) GO TO 119
205 WRITE(TYPER,118)
118 FORMAT('CODE(A2),RUN(A4) EP(F6.1) ANGLE(F6.1) MAXC(F10.1)')
READ(TYPER,103,ERR=205) CODE,RUN
READ(TYPER,106,ERR=205) REP
EP=HFIX(REP)
READ(TYPER,106,ERR=205) RANGL
ANGLE=HFIX(RANGE)
READ(TYPER,107,ERR=205) RMAXC
MAXC=IFIX(RMAXC)
119 IF(IYF.NE.3) GO TO 108
206 WRITE(TYPER,120)
120 FORMAT('TYPE BEAM (F6.1) FRSTCH (F6.1) LASTCH (F6.1) PMHV (F6.1)')
      READ(TYPER,106,ERR=206) RBEAM
      BEAM=HFIX(RBEAM)
      READ(TYPER,106,ERR=206) RRSTCH
      FRSTCH=HFIX(RRSTCH)
      READ(TYPER,106,ERR=206) RASTCH
      LASTCH=HFIX(RASTCH)
      READ(TYPER,106,ERR=206) RPMHV
      PMHV=HFIX(RPMHV)

207 WRITE(TYPER,121)
121 FORMAT('TYPE BC I PER MICROCOULOMB F6.1 AND NUMBER OF PULSES PER S
SECOND TO CLOCK SCALER F6.1')
      READ(TYPER,106,ERR=207) RFAC
      FAC=IFIX(RFAC)
      READ(TYPER,106,ERR=207) RFDC
      FOC=IFIX(RFOC)
      GO TO 108

122 WRITE(TYPER,123)
123 FORMAT('TO START PUSH EVENT 11')
      SW=1
      ENTER EVENT MODE
      EVENT 11 START COUNTING
      IF(CT.EQ.0) VOLTA=2048.
      IDAT=HFIX(VOLTA)
      CALL SCLWR(1,IDAT,IERR)
      CALL ROSCLR(1)
      RETURN
      END

//RUN EXEC FORTRAN(Map)
SUBROUTINE RUN
COMMON SPSLR,SPSL,SPSLT,SPRG,SPRGT,SPCRP,SPCRT
INTEGER SPSLR,SPSL,SPSLT,SPRG,SPRGT,SPCRP,SPCRT
COMMON SCAL,SCALB,SCALC
INTEGER SCAL,SCALB,SCALC
COMMON /BLK1/VOLTA,CT,DA
COMMON /BLK2/CEN,IPILE
COMMON /BLK3/XI,ORRR,TYPER,RUN,MAXC,FAC,FOC,FR,IR,KEY,CODE,
EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
COMMON /BLK4/DATV,DATT
COMMON /BLK5/DAT,DATT
COMMON REFGEN
COMMON SW1
INTEGER CT,DA(5)
INTEGER TYPER,RUN,FAC,FOC,FR
INTEGER DATV(5),DATT(5)
INTEGER DAT(5),DATT(5)
INTEGER IERR/0/
INTEGER*2 CODE,EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
INTEGER*2 IDAT,SW1
LOGICAL STOP,.FALSE./
LOGICAL STOP1/.FALSE./
ILP=0
SW1=1
ENTER EVENT MODE

EVENT 13 STOP COUNTING
SW1=2
STOP=.TRUE.
GO TO 227

230 EVENT END
EVENT 14 CONTROL OF EVENT 6 PRINTOUT
ILP=ILP+1
ILP=MOD(ILP,2)
EVENT END

EVENT 16 STOP IF BEAM CURRENT TOO LOW
STOP1=.TRUE.
WRITE(TYPER,231)
231 FORMAT('DATA COLLECTION STOPPED BECAUSE OF LOW BEAM CURRENT.')
EVENT END

EVENT 15 START DUE TO BEAM RECOVERY
WRITE(TYPER,232)
232 FORMAT('BEAM CURRENT RECOVERED AND DATA COLLECTION RESUMED.')
CALL RDSCLR(1)
STOP1=.FALSE.
EVENT END

EVENT 12 INTERRUPT BY PH CONTROL UNIT
STOP=.TRUE.
WRITE(TYPER,200)
200 FORMAT('PHOTOMULTIPLEXER CURRENT EXCEEDS MAXIMUM VALUE ALLOWED.'
1'TO KEEP CURRENT DATA AND PROCEED TYPE 1 TO DELETE CURRENT DATA A
2ND PROCEED TYPE 2.')
READ(TYPER,201) IA
201 FORMAT(11)
IF(IA.EQ.1) GO TO 203
WRITE(TYPER,202)
202 FORMAT('CURRENT DATA DELETED AND COMPUTER PROCEEDS.')
CALL RDSCLR(1)
STOP=.FALSE.
GO TO 227
203 WRITE(TYPER,204)
204 FORMAT('NOTHING ERASED AND COMPUTER PROCEEDS.')
CALL RDSCLR(1)
STOP=.FALSE.
EVENT END

EVENT 3 COSMIC RAY EVENTS
IF(STOP) GO TO 205
IF(STOP1) GO TO 205
DATV(1)=DATV(1)+1
PHA SPCR(1)
205 EVENT END

EVENT 5 BCI EVENT
IF(STOP) GO TO 206
IF(STOP1) GO TO 206
DATV(2)=DATV(2)+1
DAT(1)=DAT(1)+10ADWD(1)
DAT(2)=DAT(2)+10ADWD(2)
DAT(3)=DAT(3)+10ADWD(3)
SCALE SCAL(1-3)
IF((DATV(2)+0.1DATV(2)) .GE. 000) GO TO 224
206 EVENT END

EVENT 1 GAMMA RAY EVENT
IF(STOP) GO TO 207
IF(STOP1) GO TO 207
DATV(4)=DATV(4)+1
DAT(5)=DAT(5)+10ADWD(1)
PHA SPRO(2)
SCALE SCAL(1)
207 EVENT END

EVENT 6 LIGHT PULSER EVENT
IF(STOP) GO TO 228
IF(STOP) GO TO 228
IF(COUNT .GE. FR) GO TO 228

CT=CT+1
DAT(4)=DAT(4)+IDADWD(1)
PHA SPSLR(2)
SCALE SCALC(1)
IF(COUNT .LT.FR) GO TO 228

DAT(4)=DAT(4)+DAT(4)
DAT(4)=0

ESTIMATION OF THE CENTROID OF THE REFERENCE SPECTRUM

CALL CALPOS(SPSLR)
REFCEN=GEN
WRITE(TYPER,210) REFCEN

210 FORMAT('REFERENCE PEAK IS CENTERED AT CHANNEL F7.2')

IF(PILE-UP LT.0) GO TO 212
WRITE(TYPER,211) PILE

211 FORMAT('PILE-UP='I3', COUNTS:')

GO TO 214

212 WRITE(TYPER,213) PILE

213 FORMAT('WARNING...PILE-UP='I4', COUNTS:')

214 DO 215 I=0,1020

215 CALL SDAPUT(1, ID, GET(I,1), GET(I,2), SPSLT, I, SPSLT, I)
GO TO 228

216 DAT(3)=DAT(3)+1
DAT(4)=DAT(4)+IDADWD(1)
PHA SPSLR(2)
SCALE SCALC(1)
IF(DAT(3).LT.FR) GO TO 228

STABILITY TEST

CALL CALPOS(SPSLR)
DCEN=REFCEN-GEN
IOU=MAXC(DATV(2)-DATV(2))

IF(ABS(DCEN).GT.XI) GO TO 219

IF(PILE.EQ.0) WRITE(TYPER,218) PILE, IOU

218 FORMAT('TEST GOOD PEAK AT CH F7.2', PILE-UP='I4', COUNTS 'I8'

1 LEFT:')
GO TO 225

219 IF(KEY.EQ.0) GO TO 221
WRITE(TYPER,220) PILE, IOU

220 FORMAT('OUTSIDE LIMIT PEAK AT CH F7.2', PILE-UP='I4', COUNTS 'I8'

1 BCI LEFT')
GO TO 225

HV CORRECTION IF ANY

221 IF(PILE.EQ.0) WRITE(TYPER,222) REFCEN, GEN

222 FORMAT('REFERENCE LP CENTROID AT CH F10.2', CURRENT LP CENTROID

1 AT CH F10.2)

DVOLT=198.9*(DCEN/REFCEN)

VOLTA=VOLTA+40.95*DVOLT

IF(VOLTA.GE.4095.) VOLTA=4095.

IF(VOLTA.LE.0.) VOLTA=0.

IDAT=HFIX(VOLTA)
 CALL SCLWR(1, IDAT, IERR)
 IF(PILE.EQ.0) WRITE(TYPER,223) VOLTA

223 FORMAT('THE VOLTAGE HAS BEEN ADJUSTED, DAC CHANNEL F7.2')
GO TO 227
DATA IS STORED OR ERASED

224 STOP=.TRUE.
225 DO 226 I=1,1020
226 CALL SDAPUT(IDAGET(SPSL,1)+IDAGET(SPSLT,1),SPSL,1)
227 CLEAR SPSL SPRG SPCR
228 CALL RDSCLR(3)
229 RETURN END

STOP EXEC FORTRAN(MAP)

SUBROUTINE STOP
COMMON SPSLR,SPSL,SPSLT,SPR,SPRGT,SPCRP,SPCRT
INTEGER SPSLR,SPSL,SPSLT,SPR,SPRGT,SPCRP,SPCRT
COMMON SCAL,SCALB,SCALC
INTEGER SCAL,SCALB,SCALC
COMMON BLK1/VOLTA,CT,DA
COMMON/BLK2/CEN,IPILE
COMMON/BLK3/XI,ORRR,TYPER,REN,MAXC,FAC,FOC,FR,IR,KEY,CODE,
EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
COMMON/BLK4/DATV,DATT
COMMON/BLK5/DAT,DATT
COMMON REF
COMMON SW1
INTEGER CT,DA(5)
INTEGER TYPER,REN,FAC,FOC,FR
INTEGER DATV(5),DATT(5)
INTEGER DAT(5),DATT(5)
INTEGER ERR/0/
INTEGER#2 CODE,EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
INTEGER#2 SW1
INTEGER#2 CHARGE,DT,ICC,TANT
INTEGER#2 LPE/0/,LPFC/0/

300 FORMAT(I1)
301 FORMAT('CURRENT DATA NOT SUBJECT TO LP TEST HAS BEEN DELETED.')
302 WRITE(TYPER,303)

303 FORMAT('CURRENT DATA NOT SUBJECT TO LP TEST HAS BEEN DELETED.')

PRINT AND PLOT THE SPECTRA

400 FORMAT(I1)
401 FORMAT('BLOGM='IR,
402 CHARGE=DATT(2)/FAC
403 REP=EP/100.
404 RANGLE=ANGLE/10.
405 WRITE(6,401) CODE,REPREP,RANGLE,CHARGE,BEAM,LPE,LPFC,FRSTCH,
406 LASTCH,PMHV
11/4 CHARGE(MC8)='16' BEAM(INA)= '14' LP(E(MEV)= '12'  
1' LPFC= '12' FIRST CHANNEL='14' LAST CHANNEL='14' 
WRITE(6,402) 
402 FORMAT('O LIGHT PULSER REFERENCE SPECTRUM/ '  '18/' SCALED BCI REJECTED= '16/' LP EVEN' 
******) 
403 FORMAT('TO PLOT RESULTS TYPE 0=NO 1=GR 2=GR+LP  3=GR+LP+RLP,*') 
READ(TYPER,400) KEY2 
IF (KEY2.NE.3) GO TO 404 
CALL CALPOS(SPSLR) 
MINCHN=CEN-50 
MAXCHN=CEN+50 
MIN=MINCHN 
CALL C PLOT(SPSLR,BLG MN,C T SFS,M INCHN,MAXCHN,M IN) 
404 CALL CALPOS(SPSLT) 
LPCTS=SUM(CEN+50.,SPSLT)-SUM(CEN-50.,SPSLT) 
TANT=DATT(2)/FOC 
ITONT=TANT/60. 
TUNT=TANT-ITONT*60. 
D T=FLOAT((DATT(1)-(DATT(3)-DATTV(2)))*100)/FLOAT(DATTV(2)) 
DTT=HTFIXDABS(DT*100.) 
DATT(3)=DATTV(3)+CT 
WRITE(6,405) DATT(2),DATT(3),DATT(4),LPCTS,DT,DATT(3),DATT(4),1 
1PILE,ITONT,TUNT 
405 FORMAT('OBC) EVENTS= '18/' SCALED BCI REJECTED= '16/' LP EVEN' 
1TS= '18/' COUNTS IN LP PEAK='18/' DEAD TIME[S]= 'F5.'  
22/' SCALED BCI= '18/' SCALED LP= '18/' TOTAL PILE-UP(  
3CNTS)= '15/' ORunning TIME= '13.' MINUTES, 'F4.1' SECONDS) 
WRITE(6,406) 
406 FORMAT('O LIGHT PULSER TOTAL SPECTRUM/ '  '18/') 
CALL PRNT(SPSLT) 
IF((KEY2.NE.3).AND.(KEY2.NE.2)) GO TO 407 
MINCHN=CEN-50 
MAXCHN=CEN+50 
MIN=MINCHN 
CALL C PLOT(SPSLT,BLG MN,C T SFS,M INCHN,MAXCHN,M IN) 
407 WRITE(6,408) DATT(4),DATT(5) 
408 FORMAT('ONE NUMBER OF GAMMA RAY EVENTS= '18/ SCALED NUMBER OF GAMMA  
1RAYS= '18/') 
WRITE(6,409) 
409 FORMAT('O GAMMA RAYS TOTAL SPECTRUM/ '  '18/') 
CALL PRNT(SPRGT) 
IF((KEY2.EQ.0).AND.(KEY2.EQ.2)) GO TO 410 
CT SFS=ORRR 
MINCHN=FRSTCH 
MAXCHN=LASTCH 
MIN=MINCHN 
CALL C PLOT(SPRGT,BLG MN,C T SFS,M INCHN,MAXCHN,M IN) 
410 WRITE(6,411) DATT(1) 
411 FORMAT('ONE NUMBER OF COSMIC RAY EVENTS= '18) 
WRITE(6,412) 
412 FORMAT('OCOSMIC RAYS TOTAL SPECTRUM/ '  '18/') 
CALL PRNT(S P CRT) 
WRITE(T YPER,413) 
413 FORMAT('TO PUT RESULTS ON TAPE TYPE 1 OTHERWISE TYPE 2,*') 
READ(TYPER,400) KO 
IF(KO.NE.1) GO TO 415 
TANT=DATT(2) 
ICC=DATTV(3) 
WRITE(4,414) CODE,RUN,EP,ANGLE,CHARGE,DT,BEAM,TANT,ICC,LPE,LPFC,  
FRSTCH,LASTCH,PMHV 
414 FORMAT(2,A4,12A2)
CALL PTTP(SPSLT)
CALL PTTP(SPRGT)
END FILE 4

BACKSPACE 4

CALL FTUNLD(6)

C
***************
C
WRITE(TYPER,304)
C
304 FORMAT('TYPE 1 TO CLEAR ANALYZERS TYPE 2 TO KEEP DATA FOR CONTINUATION RUN.')
READ(TYPER,300) IK
IF(IK.EQ.2) GO TO 307
C
CLEAR SPSL SPSLT SPRGT SPRGRT
CLEAR SCAL SCALB SCALC
CALL SCLWR(1,2048,1ERR)
CALL RDSCLR(4)
C
WRITE(TYPER,306)
C
306 FORMAT('EVERYTHING ERASED.1')
307 IF(IJ.EQ.3) SW=2
RETURN
END

C
 PRNT EXEC FORTRAN(MAP)
 SUBROUTINE PRNT(ANZ)
    INTEGER ANZ
    INTEGER A(200)
    NPTS=IDARGN(ANZ)
    DO 2 I=1,NPTS,200
      IJ=I+199
      IF(IJ.GT.NPTS) IJ=NPTS
    2   A(IJ)=IDAGET(ANZ,IK)
      IL=IJ-I+1
      WRITE(6,3) (A(IM),IM=1,IL)
    3  FORMAT(1H0,20I6/(1X,20I6))
RETURN
END

C
 PTTP EXEC FORTRAN(MAP)
 SUBROUTINE PTTP(ANZ)
    INTEGER ANZ
    INTEGER A(180)
    NPTS=IDARGN(ANZ)
    DO 2 I=1,NPTS,180
      IJ=I+179
      IF(IJ.GT.NPTS) IJ=NPTS
    2   A(IJ)=IDAGET(ANZ,IK)
      I=I+1
      DO 3 IK=1,IJ
      3   A(IK)=IDAGET(ANZ,IK)
      WRITE(4,3) (A(IK),IK=1,180)
    3  FORMAT(180A2)
RETURN
END

C
 CPLT EXEC FORTRAN(MAP)
 SUBROUTINE CPLT(ANAL,RLOGMN,CSTSFS,MINCHN,MAXCHN,MN)

C BLOGMN=9 FOR LINEAR SCALE
C BLOGMN=MINIMUM ON LOG SCALE (10*BLOGMN)
C CTSFS=NUMBER OF COUNTS FULL SCALE ON LINEAR SCALE
C MCHN=MINIMUM CHANNEL TO BE PLOTTED
C MAXCHN=MAXIMUM CHANNEL TO BE PLOTTED
C MIN=MINIMUM CHANNEL TO START DETERMINING COUNTS FULL SCALE

INTEGER ANAL
   INTEGER=2 J(7)/'1', '2', '3', '4', '5', '6', '7', 'A'/, 'IC'/*1/
   INTEGER=2 R/111/, 'S', 'T'/*1/, 'D(10)'/*100*/H,'111', DSAV
   NPTS=IDARMNG(ANAL)
   IF(MAXCHN.GE.NPTS) MAXCHN=NPTS
   LOGMN=| FIX(BLOGMN+.0001)
   IF(MINCHN.LE.1)MINCHN=2
   IF(MAXCHN,MCHN)MAXCHN=MINCHN
   IF(LOGMN,GE.9)GO TO 1015
   NMAX=IDAGET(ANAL,MCHN)
   NMIN=IDAGET(ANAL,MCHN)
   DO 1 I=MCHN,MAXCHN
   NC=IDAGET(ANAL,11)
   IF(NMAX,LT,NC)NMAX=NC
   IF(NMIN,GT,NC)NMIN=NC
   1 CONTINUE
   IF(NMAX,LT,1)NMAX=1
   XMAX=ALOG10(FLOAT(NMAX))
   CYCLE=XMAX-FLOAT(IFIX(XMAX))
   NCYCLE=1(IFIX(XMAX)-LOGMN
   IF(CYCLE,GT,0)NCYCLE=NCYCLE+1
   IF(NCYCLE,LE,0)NCYCLE=1
   CYCLE=NCYCLE
   NSPACE=100/CYCLE
   DO 45 I=1,NCYCLE
   K=I*NSPACE
   II=I+LOGMN
   45 D(K)=J(II)
   WRITE(6,101)(D(K),K=1,100)
   101 FORMAT(1HO,8X,1I,100A1)
   DO 50 K=1,100
   50 D(K)=A
   DO 55 I=1,NCYCLE
   K=I*NSPACE
   D(K)=S
   55 D(K-1)=R
   WRITE(6,103)(D(K),K=1,100)
   103 FORMAT(7X,2H10,100A1)
   DO 60 K=1,100
   60 D(K)=A
   DO 65 I=1,NCYCLE
   K=I*NSPACE
   D(K)=T
   65 D(K-1)=R
   WRITE(6,104)(D(K),K=1,100)
   104 FORMAT(9H COUNTS 1,100A1,' TOTAL CH #1')
   GO TO 1030
   1015 CYCLE=1.0
   IF(CTSFS,GT,1.)GO TO 1025
   CTS=1.
   IF(MIN,LT,MCHN)MIN=MCHN
   DO 1016 I=MCHN,MAXCHN
   CT=IDAGET(ANAL,1)
   IF(CTS,LT,CT)CTS=CT
   1016 CONTINUE
   GO TO 1017
   1025 CTS=CTSFS
   1017 WRITE(6,1203)CTS
   1203 FORMAT(21H COUNTS FULL SCALE = ,F6.1)
   1030 NMAX=0
   DO 8 I=MCHN,MAXCHN
NC=IDAGET(ANAL,1)
CT=NC
NMAX=NMAX+NC
D(1)=T
DO 140 K=2,100
   140 D(K)=A
   IF(LOGMN,GE,9)GO TO 200
   XPLOT=0.
   IF(NC,LE,1)GO TO 320
   XPLOT=ALOG10(CT)-BLOGMN
   GO TO 300
   200 XPLOT=1.
   IF(CT,GE,CTS)GO TO 320
   XPLOT=CT/CTS
   300 IF(XPLOT,LT,0,XPLOT=0.*
   320 NPL0T=100.*XPLOT/CYCLE+1.5
   DSAV=D(NPL0T)
   D(NPL0T)=IC
   NMIN=1
   WRITE(6,102)NC,NMIN,(D(K),K=1,101),NMAX
   102 FORMAT(1H ,16,15,IX,101A1,17)
   D(NPL0T)=DSAV
   RETURN
   END
APPENDIX I-B

DATA ACQUISITION PROGRAM FOR COINCIDENCE EXPERIMENTS

This appendix lists the computer program used to direct the on-line data collection and processing for the calibration experiment described in Chapter 4. It is based on the singles program listed in Appendix I-A and has essentially the same function. Coincidence analyzers have been added as well as new coding to process TAC events received at the computer interface, which is set up as described in Section 4.3. Not listed here are the job control deck and the subroutines CALPOS, SUM, and CPLET, which are the same as those listed in Appendix I-A.
OPTION DEVICE. DECK. NOSPEC

ANALYZER*2D SPSL(1019) SPSL(1019) SPSLT(1019) SPRG(1019)
1SPRG(1019) SPCR(1019) SPCR(1019) SPCR(1019) SPART(1019)
1STACP(1019) STACP(1019) SDEP(10-1019/#,1019)
1SDEP(10-1019/#,1019) SGPR(10-1019/#,1019) SGPR(10-1019/#,1019)
ANALYZER*2N CNCP1(1019/#,1019/#,1019) CNCR1(1019/#,1019/#,1019)
1CNCP1(1019/#,1019/#,1019) CNCR2(1019/#,1019/#,1019)
1CNCP3(1019/#,1019/#,1019) CNCR3(1019/#,1019/#,1019)
1CNCP5(1019/#,1019/#,1019) CNCR5(1019/#,1019/#,1019)
1CNCP7(1019/#,1019/#,1019) CNCR7(1019/#,1019/#,1019)
1CNCP6(1019/#,1019/#,1019) CNCR6(1019/#,1019/#,1019)
1CNCT(1019/#,1019/#,1019) CNCT(1019/#,1019/#,1019)
SCLER SCALA(3) SCALB(1) SCALC(1)
STRUCTURE COINC=(CNCP1,CNCR1,CNCT1,CNCP2,CNCR2,CNCT2,CNCP3,CNCR3,
1CNCT3)
STRUCTURE COINC2=(CNCP4,CNCR4,CNCT4,CNCP5,CNCR5,CNCT5,CNCP6,CNCR6,
1CNCT6)
STRUCTURE $INFO=(SCALA,SCALB,SCALC)

//BLKDAT EXEC FORTRAN(MAP)
BLOCK DATA
COMMON/BLK1/VOLTA,CT,DA
REAL VOLTA/2048/.
INTEGER CT/0/,DA(9)/9*0/
COMMON/BLK2/CEN,IPILE
COMMON/BLK3/XI1,ORDR,TYPER,RUN,MAXC,FAC,FDC,FR,IR,KEY,CODE,
1EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW,
REAL X1/4./,ORDR/5000/.
INTEGER TYPER/O/,RUN/FAC/100/,FDC/10/,FR/200/,IR/O/,KEY/O,
1INTEGER*2 CODE,EP,ANGLE,BEAM,FRSTCH/100/,LASTCH/800/,PMHV,SW/1/
COMMON/BLK4/DATV,DATT
INTEGER DATV(9)/9*0/,DATT(9)/9*0/
COMMON/BLK5/DATV,DATT
INTEGER DAT(9)/9*0/,DATT(9)/9*0/
END

//ROSCLR EXEC FORTRAN(MAP)
SUBROUTINE ROSCLR(N)
C READS THE NINE SCALERS AND STORES OR ERASES THE DATA
COMMON/BLK1/VOLTA,CT,DA
COMMON/BLK4/DATV,DATT
COMMON/BLK5/DATV,DATT
INTEGER CT,DA(9)
INTEGER DATV(9),DATT(9)
INTEGER DAT(9),DATT(9)
go to (1,2,3,4,1),N
1 DO 11 I=1,9
11 DA(I)=ITADVW(I)
1 DO 22 I=1,9
2 RETURN
INTEGER IERR/0/
INTEGER CODE,EP,ANGLE,BEAM,FRSTCH,LASTCH,PMHV,SW
INTEGER IDAT

100 FORMAT(11)
101 FORMAT(11,F6.1)
102 FORMAT(4)
103 FORMAT(A2,A4)
105 FORMAT(F5.2)
106 FORMAT(F6.1)
107 FORMAT(F10.1)
IF(SW.EQ.2) GO TO 122
108 WRITE(TYPER,109)

109 FORMAT('TO INITIALIZE PARAMETERS TYPE 1, 2, OR 3, OTHERWISE TYPE 14,'))
READ(TYPER,100,ERR=108) IYF
IF(IYF.EQ.4) GO TO 122
IF(IYF.NE.1) GO TO 117
201 WRITE(TYPER,110)

110 FORMAT('TYPE IN ALLOWED CHANNEL SHIFT OF LP CENTROID F5.2,'))
READ(TYPER,105,ERR=201) XI
202 WRITE(TYPER,111)

111 FORMAT('TYPE IN NUMBER OF COUNTS REQUIRED FOR LP SOURCE F5.1,'))
READ(TYPER,102,ERR=202) FR
203 WRITE(TYPER,112)

112 FORMAT('TO GET A LINEAR PLOT OF THE GAMMA RAY SPECTRUM TYPE 9(11)
1 AND TYPE IN THE FULL SCALE NUMBER OF COUNTS(F6.1) '/TO GET A LOG
2PLOT TYPE 0,1,2,... UP TO 8 DEPENDING UPON THE THRESHOLD REQUIRED(1
31),'))
READ(TYPER,101,ERR=203) IR,ORR
204 WRITE(TYPER,113)

113 FORMAT('TO REWIND THE TAPE TYPE 1 OTHERWISE TYPE 0,'))
READ(TYPER,100,ERR=204) KUU
IF(KUU.NE.1) GO TO 115
REWIND 4
204 WRITE(TYPER,113)

114 FORMAT('TAPEREWIND')
115 WRITE(TYPER,116)

116 FORMAT('FOR PMHV CONTROL TYPE 1 OTHERWISE TYPE 0,'))
READ(TYPER,100,ERR=115) KEY
117 IF(IYF.NE.2) GO TO 119
205 WRITE(TYPER,118)

118 FORMAT('CODE(A2),RUN(A4) EP(F6.1) ANGLE(F6.1) MAXC(F10.1)')
READ(TYPER,103,ERR=205) CODE,RUN
READ(TYPER,106,ERR=205) REP
EP=HFIX(REP)
READ(TYPER,106,ERR=205) RANG
ANGLE=HFIX(RANGLE)
READ(TYPER,107,ERR=205) RMAXC
MAXC=IFIX(RMAXC)
119 IF(IYF.NE.3) GO TO 108
206 WRITE(TYPER,120)

120 FORMAT('BEAM(F6.1) FRSTCH(F6.1) LASTCH(F6.1) PMHV(F6.1)')
READ(TYPER,106,ERR=206) RBEAM
BEAM=HFIX(REQ)
READ(TYPER,106,ERR=206) RFRSTCH
FRSTCH=HFIX(RFRSTCH)
READ(TYPER,106,ERR=206) RRSTCH
RSTCH=HFIX(RRSTCH)
READ(TYPER,106,ERR=206) RLASTCH
LASTCH=HFIX(RLASTCH)
READ(TYPER,106,ERR=206) RPMHV
PMHV=HFIX(RPMHV)
207 WRITE(TYPER,121)

121 FORMAT('TYPE BC1 PER MICROCOULOMB F6.1 AND NUMBER OF PULSES PER S
1 SECON TO CLOCK SCALER F6.1')
READ(TYPER,106,ERR=207) RFAC
FAC=IFIX(RFAC)
READ(TYPER,106,ERR=207) RFAC
FOC = IFIX(RFOC)
GO TO 108
122 WRITE(TYPER,123)
123 FORMAT(* TO START PUSH EVENT 11 *)
SW=1
ENTER_EVENT_MODE
EVENT 11 START COUNTING
IF(CT.EQ.0) VOLTA=2048.
IDAT=IFIX(VOLTA)
CALL SCLWR(1, IDAT, IERR)
CALL RDSCLR(1)
RETURN
END

//RUN EXEC FORTRAN(MAP)
SUBROUTINE
COMMON/GLOBAL/CNCP1,CNCR1,CNCT1,CNCP2,CNCR2,CNCT2,CNCP3,CNCR3,
CNCT3,CNCP4,CNCR4,CNCT4,CNCP5,CNCR5,CNCT5,CNCP6,CNCR6,CNCT6
INTEGER CNCP1,CNCR1,CNCT1,CNCP2,CNCR2,CNCT2,CNCP3,CNCR3,
CNCT3,CNCP4,CNCR4,CNCT4,CNCP5,CNCR5,CNCT5,CNCP6,CNCR6,CNCT6
COMMON SPSLR,SPSL,SPSLT,SPRG,SPRGT,SPCRP,SPCRT
INTEGER SPSLR,SPSL,SPSLT,SPRG,SPRGT,SPCRP,SPCRT
COMMON SPARP,SPART,STACP,STACT
INTEGER SPARP,SPART,STACP,STACT
COMMON SEDEP,SEDET,SGPRP,SGPRT
INTEGER SEDEP,SEDET,SGPRP,SGPRT
COMMON SCALC,SCALB,SCAL
INTEGER SCALC,SCALB,SCALC
COMMON/BLK1/VOLTA,CT,DA
COMMON/BLK2/CEN,IPILE
COMMON/BLK3/X1,ORR,TYPEP,RUN,MAXC,FAC,FOC,FR,IR,KEY,CODE,
EP,ANGLE,BEAM,FSTCH,LASTCH,PMHV,SW
COMMON/BLK4/DATV,DATT
COMMON/BLK5/DAT,DATT
COMMON REFSEN
COMMON SM1
INTEGER CT,DA(9)
INTEGER TYPEP,RUN,FAC,FOC,FR
INTEGER DATV(9),DATT(9)
INTEGER IERR,0/
INTEGER CODE,EP,ANGLE,BEAM,FSTCH,LASTCH,PMHV,SW
INTEGER IDAT,SWI
LOGICAL STOP,FALSE,
ILP=0
SWI=1
ENTER_EVENT_MODE
EVENT 13 STOP COUNTING
SWI=2
STOP=TRUE.
GO TO 227
230 EVENT END
EVENT 14 CONTROL OF EVENT 6 PRINTOUT
ILP=ILP+1
ILP=MOD(ILP,2)
EVENT END
EVENT 15 STOP IF BEAM CURRENT TOO LOW
STOP1=TRUE.
WRITE(TYPER,231)
EVENT 15 START DUE TO BEAM RECOVERY
WRITE(TYPER,232)
EVENT END

EVENT 12 INTERRUPT BY PM CONTROL UNIT
STOP=.TRUE.
WRITE(TYPER,200)
EVENT END

EVENT 3 COSMIC RAY EVENTS
IF(STOP) GO TO 205
IF(STOPI) GO TO 205
DATV(1)=DATV(1)+1
PHASPRG(1)
EVENT END

EVENT 5 BCI EVENT
IF(STOP) GO TO 206
IF(STOPI) GO TO 206
DATV(2)=DATV(2)+1
DAT(1)=DAT(1)+10ADW(11)
DAT(2)=DAT(2)+10ADW(12)
DAT(3)=DAT(3)+10ADW(33)
DAT(7)=DAT(7)+10ADW(4)
DAT(8)=DAT(8)+10ADW(5)
SCALE SCALB(1-3)
IF((DATV(2)+DATV(2)).GE.MAXC) GO TO 224
EVENT END

EVENT 1 GAMMA RAY EVENT
IF(STOP) GO TO 207
IF(STOPI) GO TO 207
DAT(5)=DAT(5)+10ADW(11)
PHASPRG(2)
SCALE SCALB(11)
EVENT END

EVENT 2 PARTICLE EVENT
IF(STOP) GO TO 300
IF(STOPI) GO TO 300
DAT(5)=DAT(5)+1
DAT(6)=DAT(6)+10ADW(11)
PHASPRG(2)
EVENT END

200 FORMAT('PHOTOMULTIPLIER CURRENT EXCEEDS MAXIMUM VALUE ALLOWED.
1' TO KEEP CURRENT DATA AND PROCEED TYPE 2 TO DELETE CURRENT DATA A
2ND PROCEED TYPE 2.)
READ(TYPER,201) IA
201 FORMAT(11)
IF(IA.EQ.1) GO TO 203
WRITE(TYPER,202)
EVENT END

204 FORMAT('NOTHING ERASED AND COMPUTER PROCEEDS.
')
CALL RDSCLR(1)
STOP=.FALSE.
GOTO 207
EVENT END

300 EVENT END
EVENT 4 TAC EVENT
IF(STOP) GO TO 301
IF(STOP1) GO TO 301
DATV(6)=DATV(6)+1
DAT(9)=DAT(9)+1DADVW(1)
PHA SEDEP(4,2)
PHA SGRPP(4,3)
PHA STACP(4)
PHA CNCP1(4,3,2)
PHA CNCT1(4,3,2)
PHA CNCR2(4,3,2)
PHA CNCP3(4,3,2)
PHA CNCT3(3,2,4)
PHA CNCR4(3,2,4)
PHA CNCP5(2,4,3)
PHA CNCT5(2,4,3)
PHA CNCR6(2,4,3)
301 EVENT END

EVENT 6 LIGHT PULSER EVENT
IF(STOP) GO TO 228
IF(STOP1) GO TO 228
IF(CT.GE.FR) GO TO 216
CT=CT+1
DAT(4)=DAT(4)+1DADVW(1)
PHA SPSLR(2)
SCALE SCALC(1)
IF(CTLT.FR) GO TO 228
DATT(4)=DAT(4)+DAT(4)
DAT(4)=0

ESTIMATION OF THE CENTROID OF THE REFERENCE SPECTRUM

CALL CALPOS(SPSLR)

REFCEN=CENT
WRITE(TYPER,210) REFCEN
210 FORMAT('REFERENCE PEAK IS CENTERED AT CHANNEL,'F7.2)
IF(IPILE.LT.0) GO TO 212
WRITE(TYPER,211) IPILE
211 FORMAT('PILE-UP='I3* COUNTS.*)
GO TO 214
212 WRITE(TYPER,213) IPILE
213 FORMAT('WARNING...PILE-UP='I4* COUNTS. ')
214 DO 215 I=1,1020
215 CALL SDAPUT(IDAGET(SPSLR,1)+IDAGET(SPSLT,1),SPSLT,1)
GO TO 228
216 DATV(3)=DATV(3)+1
DAT(4)=DAT(4)+1DADVW(1)
PHA SPSL(2)
SCALE SCALC(1)
IF(DATV(3).LT.FR) GO TO 228

STABILITY TEST

CALL CALPOS(SPSLR)
OCEN=REFCEN=CENT
IOU=MAXC-DATV(2)-DATV(2)
IF(ABS(IOU).GT.GT.XI) GO TO 219
IF(IPILE.EQ.0) WRITE(TYPER,218) CEN,IPILE,IOU
218 FORMAT('TEST GOOD PEAK AT CH,,'F7.2' PILE-UP='I4* COUNTS 'I.B CBI
1 LEFT.')
GO TO 225
219 IF(KEY.EQ.1) GO TO 221
WRITE(TYPER,220) CEN,IPILE,IOU
220 FORMAT('OUTSIDE LIMIT PEAK AT CH. F7.2' PILE-UP=14' COUNTS=10'
1 BCI LEFT')
GO TO 225
C
C HV_CORRECTION IF ANY
C
C********************
221 IF(ILP.EQ.0) WRITE(TYPER,222) REFERENCE CEN
C
222 FORMAT('REFERENCE LP CENTROID AT CH. F10.2' CURRENT LP CENTROID
1 AT CH. F10.2)
DVOLT=198.9*(IDCEN/REFERENCE)
VOLTA=VOLTA+40.95*DVOLT
IF(VOLTA.GE.4095.) VOLTA=4095.
IF(VOLTA.LE.0.) VOLTA=0.
IDAT=FIX(VOLTA)
CALL SCLRIL,1,IDAT,1ERR)
IF(ILP.EQ.0) WRITE(TYPER,223) VOLTA
223 FORMAT('THE VOLTAGE HAS BEEN ADJUSTED. DAC CHANNEL = F7.2')
GO TO 227
C
C DATA IS STORED OR ERASED
C
C********************
224 STOP=.TRUE.
225 DO 226 1=1,1020
CALL SDAPUT(IDGGET(SPSLT,1)+1DAGET(SPSLT,1),SPSLT,1)
CALL SDAPUT(IDGGET(SPRG,1)+1DAGET(SPRG,1),SPGRT,1)
CALL SDAPUT(IDAGET(SPARP,1)+1DAGET(SPARP,1),SPART,1)
CALL SDAPUT(IDAGET(SEDEP,1,1)+1DAGET(SEDEP,1,1),SEDEP,1,1)
CALL SDAPUT(IDAGET(SGPRP,1,1)+1DAGET(SGPRP,1,1),SPRGT,1,1)
CALL SDAPUT(IDAGET(STACP,1,1)+1DAGET(STACP,1,1),STACT,1,1)
CALL SDAPUT(IDAGET(CNCP1,1,1,1)+1DAGET(CNCP1,1,1,1),CNCT1,1,1,1)
CALL SDAPUT(IDAGET(CNCP2,1,1,1)+1DAGET(CNCP2,1,1,1),CNCT2,1,1,1)
CALL SDAPUT(IDAGET(CNCP3,1,1,1)+1DAGET(CNCP3,1,1,1),CNCT3,1,1,1)
CALL SDAPUT(IDAGET(CNCP4,1,1,1)+1DAGET(CNCP4,1,1,1),CNCT4,1,1,1)
CALL SDAPUT(IDAGET(CNCP5,1,1,1)+1DAGET(CNCP5,1,1,1),CNCT5,1,1,1)
CALL SDAPUT(IDAGET(CNCP6,1,1,1)+1DAGET(CNCP6,1,1,1),CNCT6,1,1,1)
226 CALL ROCSCLR(2)
227 CLEAR SPSL SPRG SPCR
CLEAR SPAR SPST
CLEAR SEDEP SGPR
CLEAR CNCP1 CNCT1 CNCR2 CNCR3 CNCR4 CNCR5 CNCT5 CNCR6
CALL RDSCLR(3)
IF(DATTV(2).GE.MAX1 GO TO 229
IF(ISW1.EQ.2) GO TO 229
228 EVENT END
229 RETURN
END

//STOP EXEC FORTRAN(MAP)
SUBROUTINE STOP
COMMON/GLUL/5NC1,5NCR1,CNCT1,5NC2,5NCR2,CNCT2,5NC3,5NCR3,
1NCN3,CNCP4,5NCN4,5NCN5,5NCN6,5NCN6
5NC6,5NCN7
INTEGER CNCP1,5NCR1,CNCT1,5NC2,5NCR2,CNCT2,5NC3,5NCR3,
1NCN4,CNCP4,5NCN4,5NCN5,5NCN5,5NCN6,5NCN6,5NCN6
COMMON SPSLT,SPSL,SPSLT,SPRGT,SPGRT,SPRGT,SPRGT
INTEGER SPSL,SPSLT,SPSLL,SPRGT,SPRA,SPRGT,SPCPR,SPCR
COMMON SPAR,SPSP,STACP,STACT
INTEGER SPARP, SPART, STACP, STACT
COMMON SEDEP, SEDET, SGPRP, SGPRPT
INTEGER SEDEP, SEDET, SGPRP, SGPRPT
COMMON SCALA, SCALB, SCALC
INTEGER SCALA, SCALB, SCALC
COMMON BLK1/VOLTA, CT, DA
COMMON/BLK2/CEN, IPLLE
COMMON/BLK3/X1, ERR, TYPERP, RUN, MAXC, FAC, FOC, FR, IR, KEY, CODE,
1EP, ANGLE, BEAM, FRSTCH, LASTCH, PMHV, SW
COMMON/BLK4/DATV, DATT
COMMON/BLK5/DAT, DATT
COMMON REFCEN
COMMON SWI
INTEGER CT, DA(9)
INTEGER TYPERP, RUN, FAC, FOC, FR
INTEGER DATV(9), DATT(9)
INTEGER ERR/O/
INTEGER*2 CODE, EP, ANGLE, BEAM, FRSTCH, LASTCH, PMHV, SW
INTEGER*2 SWI
INTEGER*2 CHARGE, DT, ICC, TANTT
INTEGER*2 LPE/O/, LPFC/0/
FORMAT(1)
IF(SWI.EQ.1) GO TO 302
WRITE(TYPERP,301)
FORMAT('CURRENT DATA NOT SUBJECT TO LP TEST HAS BEEN DELETED.

301 WRITE(TYPERP,303)
302 WRITE(TYPERP,303)
303 FORMAT('TYPE 1 TO PRINT OUT TYPE 2 TO ERASE EVERYTHING
1"TYPE 3 TO STAY ON STOP BUT WITHOUT PRINTING OUT TYPE 4 TO STOP A
2ND REINITIALIZE.
READ(TYPERP,300) IJ
IF(IJ.GE.3) GO TO 307
IF(IJ.EQ.2) GO TO 305
PRINT AND PLOT THE SPECTRA

400 FORMAT(II)
BLOGHN=IR
CTSF=0.
CHARGE=DATT(2)/FAC
REP=EP/100.
RANGLE=ANGLE/10.
WRITE(6,401) CODE, RUN, REP, RANGLE, Charge, BEAM, LPE, LPFC, FRSTCH,
LASTCH, PMHV
11/' CHARGE(MCB)= '16/' BEAM(NA)= '14/' LPE(MEV)= '12/
1/' LPFC= '12/' FIRST CHANNEL= '14/' LAST CHANNEL= '14/
2/' PMHV(VOLTS)= '14
WRITE(6,402)
402 FORMAT('LIGHT PULSER REFERENCE SPECTRUM!/***************
1**********
CALL PRINT(SPSLR,1)
WRITE(TYPERP,403)
403 FORMAT(1TO PLOT RESULTS TYPE O=NO 1=GR 2=GR+LP 3=GR+LP+RLP.
1)
READ(TYPERP,400) KEY2
IF(KEY2.NE.3) GO TO 404
CALL CALPOS(SPSLR)
MINCHN=CEN-50
MAXCHN=CEN+50
MIN=MINCHN
CALL CPlot(SPSLR, BLOGHN, CTSFS, MINCHN, MAXCHN, MIN)
404 CALL CALPOS(SPSLT)
LPCT=SUM(CEN-50., SPSLT)-SUM(CEN-50., SPSLT)
TANT=DATT(2)/FOC
ITONT=TANT/60.
TUNT=TANT-ITONT#60
DTT = FLOAT(DATT(1) - DATT(3) - DATT(2)) * 100 / FLOAT(DATT(2))

DTT = FIX(ABS(DTT * 100.1))

DATT(3) = DATT(3) * CT

WRITE(6,405) DATT(2), DATT(1), DATT(3), LPCTS, DTY, DATT(3), DATT(4), TNP, TONT, TUNT

405 FORMAT('BCI EVENTS= '18/', SCALED BCI REJECTED='16/', LP EVENT

1TS= '18/', COUNTS IN LP PEAK='18/', DEAD TIME('%)= 'F5.,

229' SCALED BY = '18/', SCALED LP= '18/', TOTAL PILE-UP (3CMS)= '15/', ORunning Time= '13' MINUTES, 'F4.1 SECONDS')

WRITE(6,406)

406 FORMAT('LIGHT PULSER TOTAL SPECTRUM')

CALL PRNT(SPSLT,1)

WRITE(6,408) DATT(4), DATT(5)

408 FORMAT('NUMBER OF GAMMA RAY EVENTS= '18/')

WRITE(6,409)

409 FORMAT('GAMMA RAYS TOTAL SPECTRUM')

CALL PRNT(SPRGT,1)

WRITE(6,410)

410 FORMAT('NUMBER OF COSMIC RAY EVENTS= '18/')

CALL PRNT(SPRG1,1)

WRITE(6,411)

411 FORMAT('COSMIC RAYS TOTAL SPECTRUM')

CALL PRNT(SPSLT,1)

WRITE(6,412)

412 FORMAT('NUMBER OF PARTICLE EVENTS= '18/')

WRITE(6,413)

413 FORMAT('PARTICLE TOTAL SPECTRUM')

CALL PRNT(SPRGT,2)

WRITE(6,414)

414 FORMAT('GATED PARTICLE SPECTRUM')

CALL PRNT(SPRG1,2)

WRITE(6,415)

415 FORMAT('GATED GAMMA SPECTRUM')

CALL PRNT(SPSLT,2)

WRITE(6,416)

416 FORMAT('GATED TAC SPECTRUM')

CALL PRNT(SPSLT,3)

WRITE(6,417)

417 FORMAT('TOTAL SPECTRUM')

CALL PRNT(CNCR1,3)

WRITE(6,418)

418 FORMAT('TYPE 1 TO PRINT PARTICLE AND TAC SPECTRA OTHERWISE TYPE 2')

READ(TYPER,400) KO

400 FORMAT('')

WRITE(6,500) DATT(5), DATT(6), DATT(7)

500 FORMAT('NUMBER OF PARTICLE EVENTS= '18/', SCALED NUMBER OF PARTICLE EVENTS= '18/', PARTICLE ADC DT COUNTS= '18')

WRITE(6,501)

501 FORMAT('TOTAL PARTICLE SPECTRUM')

CALL PRNT(SPART,1)

WRITE(6,510)

510 FORMAT('GATED PARTICLE SPECTRUM')

CALL PRNT(SGRT,1)

WRITE(6,511)

511 FORMAT('GATED GAMMA SPECTRUM')

CALL PRNT(SGRT2,1)

WRITE(6,512)

512 FORMAT('GATED TAC SPECTRUM')

CALL PRNT(SGRT,2)

WRITE(6,520)

520 FORMAT('NUMBER OF TAC EVENTS= '18/', SCALED NUMBER OF TAC EVENTS= '18/', TAC ADC DT COUNTS= '18')

WRITE(6,521)

521 FORMAT('TOTAL TAC SPECTRUM')

CALL PRNT(STACT,1)

WRITE(6,505)

505 FORMAT('NUMBER OF COINCIDENCE EVENTS TO BE PRINTED OR TYPE 1 TO SKIP')

READ(TYPER,506) IDA

506 FORMAT('')

WRITE(6,522)

522 FORMAT('')

READ(TYPER,523) KO

523 FORMAT('')

WRITE(6,524)

524 FORMAT('')

READ(TYPER,525) KO

525 FORMAT('')

WRITE(6,526)

526 FORMAT('')
IF(IDA.EQ.19) CALL PRNT(CNCP2,3)
IF(IDA.EQ.21) CALL PRNT(CNCP2,3)
IF(IDA.EQ.23) CALL PRNT(CNCP3,3)
IF(IDA.EQ.25) CALL PRNT(CNCP4,3)
IF(IDA.EQ.27) CALL PRNT(CNCP4,3)
IF(IDA.EQ.29) CALL PRNT(CNCP5,3)
IF(IDA.EQ.31) CALL PRNT(CNCP6,3)
IF(IDA.EQ.33) CALL PRNT(CNCP6,3)
GO TO 504

507 WRITE(TYPER,413)
413 FORMAT('TYPE 1 TO PUT GAMMA RAY SPECTRUM ON TAPE OTHERWISE TYPE 2
1.*)
READ(TYPER,400) KO
IF(KO.NE.1) GO TO 508
TANTT=DATV(2)
ICC=DATV(3)
WRITE(4,414) CODE, RUN, EP, ANGLE, CHARGE, DT, BEAM, TANTT, ICC, LPE, LPFC,
1FRSCH, LASTCH, PMHV
414 FORMAT(A2, A4, 12A2)
CALL PTTP(SPSLT,1)
CALL PTTP(SPRGT,1)
END FILE 4
BACKSPACE 4

508 WRITE(TYPER,509)
509 FORMAT('TYPE 10 (12) OF ANY SPECTRUM TO BE PUT ON TAPE IF NONE TYPE
1PE 99.*)
READ(TYPER,506) IDA
IF(IDA.EQ.99) GO TO 415
IF(IDA.EQ.9) CALL PTTP(SPART,1)
IF(IDA.EQ.11) CALL PTTP(STACT,1)
IF(IDA.EQ.13) CALL PTTP(SEDET,2)
IF(IDA.EQ.15) CALL PTTP(SGPRTR,2)
IF(IDA.EQ.17) CALL PTTP(CNCR1,3)
IF(IDA.EQ.19) CALL PTTP(CNCP2,3)
IF(IDA.EQ.21) CALL PTTP(CNCT2,3)
IF(IDA.EQ.23) CALL PTTP(CNCR3,3)
IF(IDA.EQ.25) CALL PTTP(CNCP4,3)
IF(IDA.EQ.27) CALL PTTP(CNCT4,3)
IF(IDA.EQ.29) CALL PTTP(CNCR5,3)
IF(IDA.EQ.31) CALL PTTP(CNCP6,3)
IF(IDA.EQ.33) CALL PTTP(CNCT6,3)
END FILE 4
BACKSPACE 4
GO TO 508
415 CALL FTUNLD(6)

WRITE(TYPER,304)
304 FORMAT('TYPE 1 TO CLEAR ANALYZERS TYPE 2 TO KEEP DATA FOR CONTINU
ATION RUN.*)
READ(TYPER,300) IK
IF(IK.EQ.2) GO TO 307
305 CLEAR SPSLR SPSLT SPRGTR SPCRT
CLEAR SPART STACT
CLEAR SEDET SGPRTR
CLEAR CNCR1 CNCP2 CNCT2 CNCR3 CNCP4 CNCT4 CNCR5 CNCP6 CNCT6
CLEAR SCALA SCALB SCALC
CALL SCLWR(0,2048,1,EERR)
CALL RDSCLR(4)
CT=0
WRITE(TYPER,306)
306 FORMAT('EVERYTHING ERASED.*)
307 IF(IJ.EQ.3) SW=2
RETURN
END
**/PRNT EXEC FORTRAN(MAP)**

```fortran
SUBROUTINE PRNT(ANZ,ID)
  INTEGER ANZ
  INTEGER A(700)
  NPTS=IDARNG(ANZ,1)
  DO 2 I=1,NPTS,200
    J=1+199
    IF(J.GT.NPTS) J=NPTS
    DO 1 I=1,J,200
      IF(ID.EQ.1) A(I+1)=IOAGET(ANZ,I)
      IF(ID.EQ.2) A(I+1)=IOAGET(ANZ,1,I)
      IF(ID.EQ.3) A(I+1)=IOAGET(ANZ,1,1,I)
    1 WRITE(6,3)(A(I),I=1,1)
      3 FORMAT(7H0,20I6/<IX,2016))
  2 RETURN
END

**/PTTP EXEC FORTRAN(MAP)**

```fortran
SUBROUTINE PTTP(ANZ,ID)
  INTEGER ANZ
  INTEGER A(180)
  NPTS=IDARNG(ANZ,1)
  DO 2 I=1,NPTS,180
    J=1+179
    IF(J.GT.NPTS) J=NPTS
    DO 1 I=1,J,180
      IF(ID.EQ.1) A(I+1)=IOAGET(ANZ,I)
      IF(ID.EQ.2) A(I+1)=IOAGET(ANZ,1,I)
      IF(ID.EQ.3) A(I+1)=IOAGET(ANZ,1,1,I)
    1 WRITE(4,3)(A(I),I=1,1)
      3 FORMAT(180H0,1X,20I6/<IX,1X,20I6))
  2 RETURN
END
```
APPENDIX II-A

UPPER LIMITS FOR $\Delta T=2$ GAMMA-RAY TRANSITIONS IN $\text{Be}^8$

The discovery in the past decade of $T=2$ levels in $T_z=0$ nuclei has provided an opportunity to test the $|\Delta T| \leq 1$ isospin selection rule for electromagnetic decays. This rule follows directly from the assumption that the electromagnetic current transforms as a sum of isoscalar and isovector components, an assumption that needs to be tested experimentally.

If an additional isotensor component exists, it might be observed in a $\gamma$-ray transition for which $\Delta T=2$. Such an isospin-forbidden transition is possible in $\text{Be}^8$ (Figure II-A-1) from the $0^+, T=2$ state at 27.483 MeV$^1$ to the $2^+, T=0$ first excited state. Although this E2 transition competes with parallel isospin-favored M1 decays, particularly through the state at 17.64 MeV, it is favored by the large transition energy and the absence of a transition to the ground state. It has the greatest chance of being observed if the $T=2$ state is populated through the $^6\text{Li} + d$ channel, since this entrance channel width is approximately 80% of the total width.$^2$

Using an anticoincidence-shielded, lead-collimated 30 cm x 30 cm NaI(Tl) spectrometer placed at a backward angle of 115° and its associated electronics set up as described in Chapter 3, we searched for $\gamma$-rays from the $\text{Li}^6(d,\gamma_1)\text{Be}^{8*}$ reaction at excitation energies in the neighborhood of the 27.483 MeV state. Deuterons ranging in energy from 6.910 to 6.990 MeV in 10 keV steps bombarded a 15 keV thick target
of Li$_2$O (isotopically pure Li$^6$) evaporated onto a 50 $\mu$g/cm$^2$ carbon backing. At each point 1500 $\mu$C of charge were collected.

No $\gamma$-ray transitions to the first excited state of Be$^8$ were observed. An estimate of the number of counts that could have been detected above background yielded an upper limit for the center-of-mass differential cross-section of 4.5 nb/sr. If an isolated Breit-Wigner resonance is assumed, the cross-section at resonance is $\sigma_0 = \chi^2 \omega d_0 / \Gamma \Delta T = \frac{2}{\pi} \Delta T / \Gamma$. (The E2 radiation is isotropic.) The statistical factor $\omega = 1/9$, and $d_0 / \Gamma$ is assumed from shell model calculations to be 0.78. Therefore $\Gamma_{\Delta T = 2} / \Gamma < 2 \times 10^{-6}$ and since $\Gamma = 10$ keV, $\Gamma_{\Delta T = 2} < 0.02$ eV. Since the Weisskopf estimate for this E2 transition is 7.0 eV, $\Gamma_{\Delta T = 2}$ is less than 0.3% of a Weisskopf unit.

This result can be viewed as either a limit on isospin impurities in the T=2 state or a limit on the magnitude of the isotensor current. We note that at the present time no experiment performed in a nuclear system has yielded evidence for an isotensor current.
Figure II-A-1: Selected Energy Levels of Be$^8$. Of principal interest is the possible $\Delta T=2$ E2 gamma-ray transition from the $T=2$ state at 27.5 MeV to the first excited state of Be$^8$. 
APPENDIX II-A REFERENCES

Following the discovery\(^1\) of a resonance in the Li\(^7\) \((0^{16}, y_0, 1)\)Na\(^{23}\) reaction, we undertook an examination of the systematic behavior of heavy ion radiative capture in the same mass region of the periodic table. Energy level diagrams and measured excitation functions for the five reactions we studied are given in the following nine figures.

The Yale MP tandem Van de Graaff accelerator supplied the heavy ion beams over the range of energies indicated in the figures. Throughout the five experiments, high energy gamma-ray spectra were measured at 90° by our anti-coincidence-shielded lead-collimated 30 cm. x 30 cm. NaI(Tl) spectrometer, which was set up with its associated electronics as described in Chapter 3. The targets, one commercial and others made by electron gun evaporation, were 200-300 \(\mu\)g/cm\(^2\) thick on the average. The Li\(^7\) target was made by evaporating Li\(^7\) onto a 1/4 mil Cu backing screwed to a rotating target frame and was transferred under vacuum to the target chamber. The target thickness was continuously monitored by using a GeLi detector to measure the yield of the low-energy gamma-rays from Li\(^7\). Within statistics no loss of Li\(^7\) was observed.

We were able to verify Feldman's observation of the Li\(^7\) \((0^{16}, y_0, 1)\)Na\(^{23}\) resonance with a peak cross section of \(~100\) nb/sr at \(\theta_{\text{LAB}} = 90°\); however, no gamma-ray transitions...
to low-lying states were observed for the other five reactions we studied. The cross sections are shown in the figures. The vertical bars represent the statistical upper limits to the center-of-mass cross sections; the horizontal bars, the target thicknesses; the heavy vertical lines on the abscissas, estimates of the Coulomb barriers.

The upper limit on each cross section shown in the figures was estimated by summing gamma-ray background counts over a region that a photopeak would have extended given the target thickness and detector response. It was then assumed that two standard deviations \( (2\sqrt{N}) \) above this background count \( (N) \) would have been observed and this was taken as a probable upper limit on the 90° cross section. The upper limits are statistical and to these estimates, which are good to within a factor of two, the target thickness error of 15% (30% for the Li\(^7\)), the solid angle error of 5%, and the charge accumulation error of 5% should be added. The fluctuations in the upper limits are due to variations in the amount of charge collected and to background counts changing with beam energy.

Our measurements did not indicate the presence of any appreciable cross section or any resonance for the reactions we studied. An extension of a previous \(^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}\) measurement\(^1\) was carried out following the observation of a state at \( E_x \sim 31 \text{ MeV} \) in \(^{24}\text{Mg}\) and the observation that the \(^{12}\text{C}\) yield from the electrofission of \(^{24}\text{Mg}\) increases in this region.\(^2\)

The experiments were all conducted in the region of the
Coulomb barrier since at lower center-of-mass energies the barrier would impede the fusion of the ions and at higher energies the greater number of open channels would compete with the radiative capture. Furthermore, radiative capture is not likely to be observed for ions much heavier than the ones we examined due to neutron evaporation. In the mass 50 region,\(^3\) for example, the ratio of total capture (including cascades) to total reaction cross section is on the order of \(10^{-5}\).

We conclude on the basis of our several experiments that radiative capture has in general a very small chance of being the outcome of any heavy ion collision. The Li\(^7\) \((0^{16},\gamma_{0,1})\)Na\(^{23}\) resonance remains an intriguing anomaly.
Figure II-B-1: Energy Level Diagram for $^{19}\text{F}$. The excitation region investigated was 20-26 MeV and upper limits were put on the $\gamma_0$, $\gamma_1$, and $\gamma_2$ transitions.
Figure II-B-2: Excitation Function for the Li\(^7\)(C\(^{12}\),\(\gamma_0,1,2\)) F\(^{19}\) Radiative Capture Reaction.

The vertical error bars represent upper limits on the cross sections.
$\text{Li}^7(\text{C}^{12},\gamma_0,1,2)\text{F}^{19}$

$\theta_{\text{LAB}} = 90^\circ$

$\frac{d\sigma}{d\Omega} (\text{nb/sr})$

EXCITATION ENERGY IN F$^{19}$ (MeV)
Figure II-B-3: Energy Level Diagram for Ne$^{21}$. The excitation region investigated was 23-25 MeV and upper limits were put on the $\gamma_0$ and $\gamma_1$ transitions.
$\gamma_0 \quad \gamma_1 \quad \gamma_2$

$17.080$

$\text{Be}^9 + \text{C}^{12}$

$23-25 \text{ MeV}$

$\text{Ne}^{21}$

$0.00 \quad \frac{3}{2}^+$

$0.35 \quad \frac{5}{2}^+$

$1.75 \quad \frac{7}{2}^+$
Figure II-B-4: Excitation Function for the $\text{Be}^9(\text{C}^{12},\gamma_{0,1})\text{Ne}^{21}$ Radiative Capture Reaction.

The vertical error bars represent upper limits on the cross sections.
A graph showing the excitation energy in Ne$^{2+}$ (MeV) as a function of $d\sigma/d\Omega$ (nb/sr). The graph includes the reaction $\text{Be}^9(C^{12},\gamma_{0,1})\text{Ne}^{2+}$ with $\theta_{\text{LAB}} = 90^\circ$. The excitation energy values are marked at 0, 2, 4, 6, 8, 10, 12, 14, and 16 MeV.
The excitation region investigated was 23-32 MeV for the Be\(^9\) (0\(^{16}\),\(\gamma_0,1,2\))Mg\(^{25}\) reaction and 24-29 MeV for the C\(^{13}\)(C\(^{12}\),\(\gamma_0,1,2\))Mg\(^{25}\) reaction. Upper limits were put on the \(\gamma_0,\gamma_1\), and \(\gamma_2\) transitions.
The diagram illustrates a nuclear transition with energy levels. The reaction \( \text{Be}^9 + \text{O}^{16} \rightarrow \text{C}^{13} + \text{C}^{12} \) is shown, with energies of 23-32 MeV and 24-29 MeV. The levels of Mg\(^{25}\) are marked with quantum numbers: \( \frac{3}{2}^+ \), \( \frac{1}{2}^+ \), and \( 0^+ \), with probabilities of 0.97, 0.59, and 0.00, respectively. The level of C\(^{13}\) is marked with a quantum number of \( \frac{3}{2}^+ \) and 16.315 MeV.
Figure II-B-6: Excitation Function for the Be$^9(0^{16},\gamma_{0,1,2})$ Mg$^{25}$ Radiative Capture Reaction.

The vertical error bars represent upper limits on the cross sections.
Be$^9$(O,$\gamma_{0,1,2}$)Mg$^{25}$

$\theta_{LAB} = 90^\circ$

EXCITATION ENERGY IN Mg$^{25}$ (MeV)
Figure II-B-7: Excitation Function for the $^{13}_c^1$(C$^{12}_c,\gamma_0,1,2$) 
Mg$^{25}$ Radiative Capture Reaction.

The vertical error bars represent upper limits on the 
cross sections.
$d\sigma/d\Omega (\text{nb/sr})$

EXCITATION ENERGY IN Mg$^{25}$ (MeV)

$C^{13}(C^{12},\gamma_{0,1,2})Mg^{25}$

$\theta_{\text{LAB}} = 90^\circ$
Figure II-B-8: Energy Level Diagram for Mg$^{24}$. The excitation region investigated was 24-31 MeV and upper limits were put on the $\gamma_0$ transition.
Figure II-B-9: Excitation Function for the $^{12}\text{C}(^{12}\text{C},\gamma_0)^{24}\text{Mg}$ Radiative Capture Reaction.

The vertical error bars represent upper limits on the cross sections.
$^{12}_C(C, ^{12}_C \gamma_0) ^{24}_{Mg}$

$\theta_{LAB}=90^\circ$
APPENDIX II-B REFERENCES

APPENDIX II-C

\[ \text{Hg}^{204}(\alpha,\gamma)\text{Pb}^{208} \]

We studied the reaction \( \text{Hg}^{204}(\alpha,\gamma)\text{Pb}^{208} \) in the region of the Coulomb barrier to see if it would be feasible to use this reaction to elucidate the nature of giant quadrupole resonances in \( \text{Pb}^{208} \). At 14 MeV the isoscalar GQR lies below the Coulomb barrier and at 30 MeV the isovector GQR lies above it.

An alpha beam produced by the Yale MP tandem Van de Graaff accelerator bombarded a 2 mg/cm\(^2\) \( \text{Hg}^{204} \) target, an amalgam of mercury and bismuth on a 2 mg/cm\(^2\) gold backing. High energy gamma-rays were detected at 90\(^\circ\) by our anticoincidence-shielded lead-collimated 30 cm. x 30 cm. NaI(Tl) spectrometer, which was set up with its associated electronics as described in Chapter 3. Figure II-C-1 presents a \( \text{Pb}^{208} \) level diagram and Figure II-C-2 gives upper limits to the three radiative capture cross sections we measured. The upper limits were determined as described in Appendix II-B; we assumed that two standard deviations above the background count would have been observed. We observed no ground state transitions.

On the basis of our feasibility study, we feel that the giant quadrupole resonances in \( \text{Pb}^{208} \) are better examined through inelastic scattering experiments rather than through the radiative capture of alpha particles. For the \( \text{Hg}^{204}(\alpha,\gamma)\text{Pb}^{208} \) reaction below the Coulomb barrier, penetrability considerations preclude any observation of the isoscalar GQR. Above the Coulomb barrier the greater number of open channels competes with radiative capture and this precludes any observation of the isovector GQR through the \( \text{Hg}^{204}(\alpha,\gamma)\text{Pb}^{208} \) reaction.
The excitation region investigated in the Hg$^{204}$($\alpha$,γ)Pb$^{208}$ reaction was 16-23 MeV. Upper limits were set on the γ₀ transition.
Figure II-C-2: Excitation Function for the $\text{Hg}^{204}(\alpha,\gamma)\text{Pb}^{208}$ Radiative Capture Reaction.

The vertical error bars on the three measured cross sections represent upper limits. The horizontal error bars represent target thicknesses in the center-of-mass system. All cross sections were measured below the Coulomb barrier, indicated by a heavy bar on the abscissa around 25 MeV.
$\text{Hg}^{204}(\alpha, \gamma_0)\text{Pb}^{208}$

$\theta_{\text{LAB}} = 90^\circ$

$\frac{d\sigma}{d\Omega}$ (nb/sr)

EXCITATION ENERGY IN $\text{Pb}^{208}$ (MeV)