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BETA - GAMMA DIRECTIONAL CORRELATIONS
IN Mn^{56} AND Pm^{148}

by
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The theory of beta - decay predicts the correlation between the emission directions of a beta particle and a subsequent gamma-ray in the form of series in which nuclear matrix elements of the beta interaction Hamiltonian are unknown parameters. An experimental determination of the correlation for a specific isotope is important for the evaluation of these matrix elements which, in turn, provides a check on the accuracy of nuclear wave functions.

For a 1^+ allowed beta - decay, only the first term of the series is usually considered to be finite. This predicts a correlation coefficient, A_2 , of zero. However, the allowed 2.86 MeV beta transition in Mn^{56} has an unusually large log ft value (7.2) indicating that the first term in the series is reduced by some nuclear effect. If the higher order terms of the series are not also reduced by the same effect, their contributions will be enhanced and there will be a finite correlation. Measurements were made on this isotope giving a coefficient $A_2 = -0.0030 \pm 0.0011$. This shows that higher order terms do have an observable effect

in this case and must be included in the theoretical description of this isotope. A check for systematic errors was made by comparing the result of the measurement on Mn^{56} to that for a similar measurement on I^{131} which gave $|A_2| < 0.0005$.

For a first - forbidden beta transition, the first terms in the series for the correlation function are identically zero. The terms remaining predict a non-zero correlation coefficient which is a function of the beta-ray energy. If this functional dependence of the correlation coefficient is not dominated by the effects of the nuclear Coulomb field (the ξ -approximation), the measured correlation can provide information about the relative magnitudes of the contributing matrix elements.

Directional correlation measurements were made on the first - forbidden 1.90 MeV beta transition in the decay of Pm^{148} as a function of the beta energy from 1.0 MeV to 1.7 MeV. The correlation coefficient varied from 0.041 ± 0.002 to 0.004 ± 0.017 in this range. The results of the measurement show that the energy dependence of the correlation does not follow the ξ -approximation. This can be the result of mutual cancellation of matrix elements or of their reduction by nuclear selection rules.

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CHAPTER I

INTRODUCTION

The Problem

The directional distribution of radiation from an assemblage of a large number of unoriented nuclei is isotropic, as expected from physical symmetry. However, consider a two step radiation cascade as shown in Figure 1, where the level from which a gamma transition originates is populated by beta emission. If the directional distribution of the gamma radiation is observed relative to a fixed direction of the preceding beta emission, the gamma distribution may not be isotropic. That

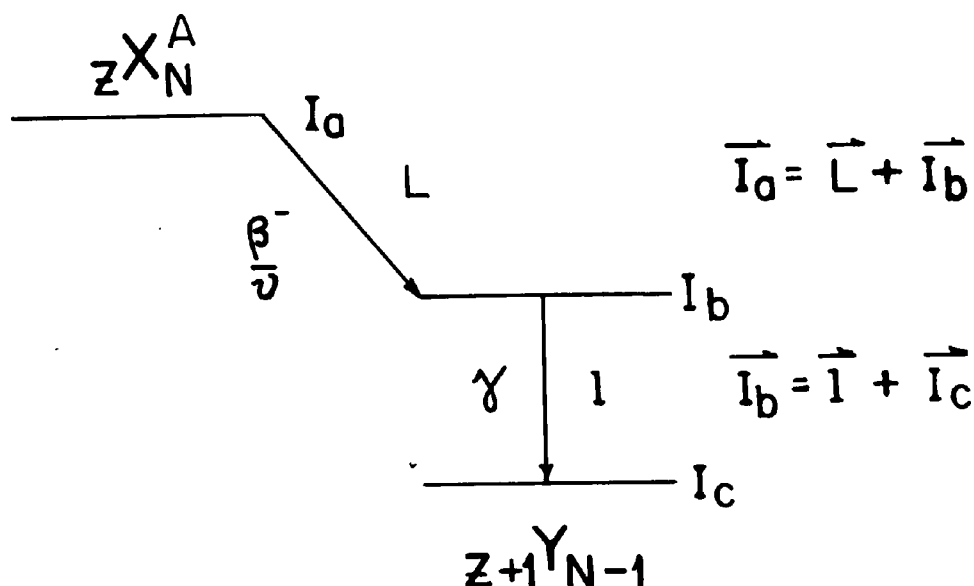


Fig. 1 -- General decay scheme for the beta emitters of interest. The spins of the nuclear levels are denoted by I ; the total angular momentum of the leptons, by L ; and the angular momentum of the gamma-ray, by l .

is, there may be an anisotropic correlation between the directions of particles emitted in cascade.

The theoretical form of the correlation function depends only on the angular momenta of the particles involved and on the nuclear matrix elements of the interaction Hamiltonians. In particular, the correlation is predicted to be isotropic unless a finite fraction of the leptons are emitted with a non-zero orbital angular momentum. Moreover, the correlation can be written, in general, as a function of a product of two terms, each of which depends on the properties of only one transition in the cascade.

Since the numerical value of the contribution to the correlation from the gamma transition can be predicted by theory, a measurement of the beta - gamma directional correlation determines the value of the beta contribution. This information is useful in the evaluation of the nuclear matrix elements of the beta transition since these matrix elements appear as unknown parameters in the beta term of the correlation function.

In most cases where the energy of the beta transition is small compared to the Coulomb energy (ξ) of the electron at the nuclear surface, the variation of the correlation with the beta energy observed is predicted by theory (the ξ -approximation), and is insensitive to the values of the individual matrix elements. However, when the characteristics of the beta transition are such that this approximation is not applicable, the energy dependence of the correlation reflects the relative magnitudes of the several matrix elements contributing to the transition.

A beta transition with a log ft value larger than usual for the

class (given by selection rules) to which the transition belongs, has a reduced contribution from the matrix elements which are usually the largest. Since dominance of these matrix elements is important for the applicability of the ξ -approximation, a reduced contribution from these matrix elements suggests a deviation from the ξ -approximation. The first - forbidden 1.90 MeV beta transition in Pm^{148} investigated in this work indicated, by its large $\log ft$ value (9.2), that a determination of the correlation as a function of the beta energy would be fruitful.

Similarly, the large $\log ft$ value (7.2) of the allowed 2.86 MeV beta transition in Mn^{56} indicated that the single matrix element usually dominating decays of this type (the Gamow - Teller matrix element), is reduced. In an allowed decay, a reduction in the principal matrix element implies an enhancement of the effects of the matrix elements of a higher degree of forbiddenness. Since the directional correlation of a decay whose beta transition is generated by an allowed matrix element is isotropic, any observed anisotropy in the correlation results from contributions from higher order matrix elements.

The results of other experiments on beta transitions are related to the nuclear properties through the same matrix elements which determine the directional correlation. Therefore, the present investigation of the correlation has a connection with these other experiments. Specifically, shape factor measurements on the beta transition of interest in Mn^{56} (1) had an ambiguous interpretation regarding the presence of contributions from higher order matrix elements. While a consideration of the results of the present work is not able to resolve the ambiguity, it does allow a statement about the expected magnitude of contributions from higher order matrix elements to the shape factor.

For the case of the first - forbidden decay of Pm^{148} , no other experiments have been performed. If data from other types of experiments becomes available, it should be possible to determine the values of the several matrix elements involved by a suitable computer analysis (2).

Directional Correlation Experiment

The source - detector geometry for the correlation experiment is shown in Figure 2. The detector for the beta radiation is held fixed in space while the gamma detector is moved in the plane formed by the axes of the two detectors. In essence, the data from the experiment consists

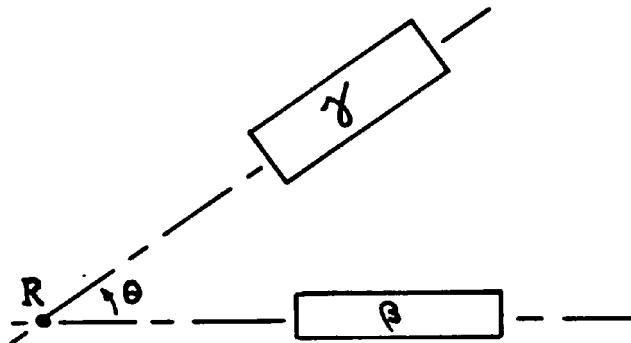


Fig. 2 -- Source - detector geometry. R = radioisotope; β = beta detector; γ = gamma detector.

of the number of coincidence events (i.e., an event occurring in each detector within a short time interval, say $3 \cdot 10^{-8}$ sec.) for each of several angles, θ . The detection of two events in coincidence is most probable if both particles originate in the decay of the same nucleus.

The observed correlation is not necessarily isotropic in spite of the random orientations of the many nuclei in the source (3, p. 165). Consider the emission of a particle from an isolated nucleus: the probability that this particle is emitted in a direction, θ , relative to the

spin axis of the nucleus is a function of θ . Conversely, if a beta particle is observed in a given direction, there is an anisotropic probability for the orientation of the nucleus relative to that direction. Thus, radiations will be detected more often from nuclei in some orientations than from those in others. The anisotropic distribution, relative to the nuclear axis, of the subsequent gamma radiation then becomes observable as an anisotropy of the coincidence rate relative to the angle between the detectors.

The Correlation Function

For any radiation process, the quantities of interest (electron momentum, photon direction, etc.) will appear as variables in the matrix elements of the interaction Hamiltonian between the initial and final states of the system (including nuclear and lepton or photon fields):

$$\langle \Psi_f | H_{\text{int}} | \Psi_i \rangle \quad (1.1)$$

The correlation function, $W(\theta)$, for randomly oriented nuclei undergoing a two step decay process is given by (4, p. 1017)

$$W(\theta) = S \sum_{\Psi_i} \sum_{\Psi} \sum_{\Psi'} \sum_{\Psi_f} \langle \Psi | H_{\text{int}}(\beta) | \Psi_i \rangle \langle \Psi' | H_{\text{int}}(\beta) | \Psi_i \rangle^* \cdot \langle \Psi_f | H_{\text{int}}(\gamma) | \Psi \rangle \langle \Psi_f | H_{\text{int}}(\gamma) | \Psi' \rangle^* \quad (1.2)$$

where $H_{\text{int}}(\beta)$ and $H_{\text{int}}(\gamma)$ are the interaction Hamiltonians for the beta and gamma transitions, respectively. Intermediate states are represented by Ψ and Ψ' ; S indicates summation and averaging over all unobserved quantities, which includes nuclear orientations. The results of the correlation experiment permit only a determination of the dependence of W on θ , not the magnitude of W . Therefore, any angle independent

factors in an expression for $W(\theta)$ can be normalized.

It can be shown that the angular dependence of the type of correlation considered here can be expressed as (4, p. 1068)

$$W(\theta) = \sum_{k=0, 2} A_k(\beta) A_k(\gamma) P_2(\cos\theta) \quad (1.3)$$

where the A_k 's are angle - independent coefficients containing the reduced matrix elements of the respective interaction Hamiltonians.

For the gamma transition, the A_k 's are known and are numerically tabulated in a normalized form as functions of the quantities $F_k(l, l', I_f, I)$ with $F_0 = 1$, where l, l' are the gamma-ray multipolarities, and I, I_f , the nuclear spins (5). Consideration of the beta portion of the correlation coefficient, $A_k(\beta)$, is left to the next chapter.

CHAPTER II

THE BETA INTERACTION

Introduction

This chapter briefly covers the formalism leading from the interaction Hamiltonian for beta emission to the observable quantities of the emitted particles. It will be seen that the role of the nucleus is expressed in terms of quantities which are independent of the lepton properties. These quantities are the matrix elements which were mentioned in the preceding chapter.

Since all of the formalism in this chapter is covered thoroughly in the literature, no attempt has been made to make it complete or self-contained. Its purpose is to present the salient features of the connection between the experiment and the information about the nucleus which the experiment provides. For the same reason, nothing is said about the historical development of the present form of the interaction.

Particle Currents (6)

Considering beta emission as a result of the interaction of two four - vector currents, J_{α}^A and J_{α} , of the nucleon and lepton fields, the Hamiltonian density is

$$h_{\beta} \propto g \sum_{A=1}^4 \sum_{\alpha=1}^4 J_{\alpha}^A(pn) \cdot J_{\alpha}(e\nu) \cdot \delta(\hat{R}^A - \hat{r}), \quad (2.1)$$

(the term for positron emission is omitted). Here, g represents the

strength of the interaction, a refers to the a -th nucleon, and the delta function formally imposes a point interaction at the position of this nucleon, $\vec{R}^a$. The nucleon current is

$$J_{\alpha}^a(pn) = \Psi_f^{\dagger} \frac{1}{2}(C_V - C_A \gamma_5) \beta^a \gamma_{\alpha}^a \tau_+^a \Psi_i, \quad (2.2)$$

where τ_+^a is the isospin operator which formally changes a neutron into a proton, and the Ψ 's are nuclear wave functions. The combination of Dirac matrices, $\beta \gamma_{\alpha}$, forms a four - vector, while $\gamma_5 \beta \gamma_{\alpha}$ forms an axial four - vector; the C 's represent the relative strengths of the two contributions, with $C_A/C_V \approx -1.2$. This form for the nucleon current is supported by observations of free neutron decay as well as by other experiments.

Similarly, experiments (e.g., electron polarization) suggest that the lepton current be written as

$$J_{\alpha}(e\nu) = \psi_e^{\dagger} \frac{1}{2}(1 + \gamma_5) \beta \gamma_{\alpha} \psi_{\nu}^c, \quad (2.3)$$

where ψ_{ν}^c is the charge conjugate of the neutrino wave function. The emission of the antineutrino is treated here as an absorption of a neutrino of energy $-cq$ (q is the neutrino momentum). The factor $\frac{1}{2}(1 + \gamma_5)$ formally requires that the lepton interaction be proportional to the left - hand components of the leptons. With the Hamiltonian written with this choice of currents, it is a combination of scalar and pseudo-scalar terms which makes the Hamiltonian non-invariant under the parity operation.

Matrix Elements (7)

The matrix element $\langle \Psi | H_{\text{int}}(\beta) | \Psi_i \rangle$ of equation 1.2 is now

proportional to

$$\begin{aligned} & \sum_a \sum_{\alpha} \iint d\vec{r} d\vec{R} \delta(\vec{R}^a - \vec{r}) \\ & \times [\Psi^\dagger (c_V - c_A \gamma_5) \beta^a \gamma_\alpha^a \tau_+^a \Psi_1] \\ & \times [\psi_e^\dagger (1 + \gamma_5) \beta \gamma_\alpha \psi_\nu^c]. \end{aligned} \quad (2.4)$$

The delta function reduces the above to an integral over the nuclear coordinates, $\vec{R}$, with the electron and neutrino wave functions as functions of $\vec{R}$. These lepton wave functions can be calculated from the Dirac equation; however, the nuclear wave functions cannot be calculated, so the integral cannot be evaluated. By suitable approximations, this integral can be expanded in a series, each term of which is a product of a combination of lepton wave function components and of an integral containing only nuclear wave functions and operators.

The first step is the expansion of the expression for the lepton current (eq. 2.3) in terms of spherical tensors. This gives a series whose terms involve successively higher values of lepton angular momentum. Because of the lesser probability of creating particles with larger values of orbital angular momentum (because of the smaller values of the lepton wave functions at the nucleus), this expansion yields a convergent series for the integral 2.4.

Introducing the non-covariant notation, $\gamma_\alpha(-i\beta\vec{\alpha}, \beta)$, the integrand of 2.4 becomes

$$\Psi^\dagger \left\{ (c_V - c_A \gamma_5) J_4(e\nu) + i(c_V \gamma_5 - c_A) \vec{\sigma}^a \cdot \vec{J}(e\nu) \right\} \tau_+^a \Psi_1, \quad (2.5)$$

where $\vec{\sigma} = -\gamma_5 \vec{\alpha}$. The expansion of the lepton current in spherical tensors is (7)

$$J_4 = \sum_{L m} C_{Lm}(R^a) (i^L Y_{Lm})^* \quad (2.6)$$

and

$$\vec{\sigma}^a \cdot \vec{J} = \sum_{J L m} C_{JLm}(R^a) (i^L \vec{\sigma}^a \cdot \vec{T}_{Jm}^L)^\dagger, \quad (2.7)$$

where

$$\vec{T}_{Jm}^L = \sum_{\mu = 0, \pm 1} \langle L (m-\mu) 1 (\mu) | J (m) \rangle Y_{L, m-\mu} \hat{e}_\mu. \quad (2.8)$$

The coefficients C_{Lm} and C_{JLm} are combinations of radial lepton wave functions components containing the dependence on lepton energies. This expansion also contains the information about the directions of the emitted leptons in such a form that equation 1.3 can be written as it is.

The matrix element 2.4 is now

$$\begin{aligned} & \sum_a \int d\vec{R} \Psi^\dagger \left\{ (C_V - C_A \gamma_5^a) \sum_{L m} C_{Lm} (i^L Y_{Lm})^* \right. \\ & \left. + i (C_V \gamma_5^a - C_A) \sum_{J L m} C_{JLm} (i^L \vec{\sigma}^a \cdot \vec{T}_{Jm}^L)^\dagger \right\} \tau_+^a \Psi_i. \end{aligned} \quad (2.9)$$

At this point the approximation is made that the lepton wave functions, and therefore the C's, are constant over the nuclear volume and they are evaluated at the nuclear radius, R. This leaves only the nuclear wave functions and the spherical tensor operators in the integral.

The dependence of the several terms in the remaining integral on the nuclear orientation can be separated by the Wigner - Eckart theorem; e.g.,

$$\begin{aligned} & \int d\vec{R} \Psi^\dagger \sum_a \left\{ \gamma_5^a (i^L \vec{\sigma}^a \cdot \vec{T}_{Jm}^L)^\dagger \tau_+^a \right\} \Psi_i \\ & = \langle I (M) J (m) | I_1 (M_1) \rangle \langle \gamma_5 \vec{\sigma} \cdot \vec{T}_J^L \rangle. \end{aligned} \quad (2.10)$$

Where, the first factor on the right of the equality is a Clebsch - Gordan coefficient and the second factor is a reduced nuclear matrix element.

Observables

By using the results of the preceding development in the equation for the correlation function (eq. 1.2), the desired relation between the nuclear matrix elements and the observable correlation is obtained. This relation is then regrouped to exhibit the form of equation 1.3.

A convenient formulation of the observable phenomena for beta transitions is given by Morita and Morita (8). The correlation function is given by them as

$$W(\theta) = \sum_{k=0, 2} \left\{ \sum_{L \leq L'} w(I I L L'; k I_1) b_{L L'}^{(k)} \right\} \quad (2.11)$$

$$\times F_k(1, 1, I_f, I) P_k(\cos\theta),$$

where the gamma transition is assumed to be a pure multipole, and w is a Racah coefficient. The lepton radial wave functions and the nuclear matrix elements, whose tensor ranks are denoted by L, L' , are grouped in in the b 's which are called the beta particle parameters. The shape factor for the beta spectrum is given by the term in brackets in equation 2.11 with $k = 0$.

The particle parameters presented in reference 8 are those for a first - forbidden transition. Formulae for these parameters for an allowed decay including contributions from higher order matrix elements, are given by M. Morita (9).

CHAPTER III

EXPERIMENTAL METHODS

The Apparatus

Directional correlation measurements were made with an automated beta - gamma scintillation spectrometer. The radiation detection and angle - measuring portion of the apparatus is diagramed in Figure 3.

A magnetically shielded Harshaw Integral Line 3" X 3" NaI(Tl) scintillator mounted on a support which is pivoted about an axis through the center of the source forms the gamma detection system. This system provides a directional selection and, with the associated electronics, an energy selection of gamma-rays. The energy resolution of the gamma spectrometer is about 7% at 660 keV. A 3/4" lead shield around the crystal side reduces gamma-ray scattering. The wall of the vacuum chamber and a lucite disk, which is placed on the face of the detector, prevent beta particles from entering the gamma scintillator. The angular position of the gamma detector is changed automatically by a motor which is controlled by the timing circuitry.

To avoid scattering and attenuation of the beta radiation by the air, the source is mounted in the center of a cylindrical (5" diameter by 7" high) vacuum chamber. The aluminum wall of the chamber is thin enough (1/16 ") to avoid appreciable absorption of the gamma radiation. An inner lining of lucite minimizes scattering of beta particles from the wall of the chamber.

The beta scintillation detector is mounted in the wall of the

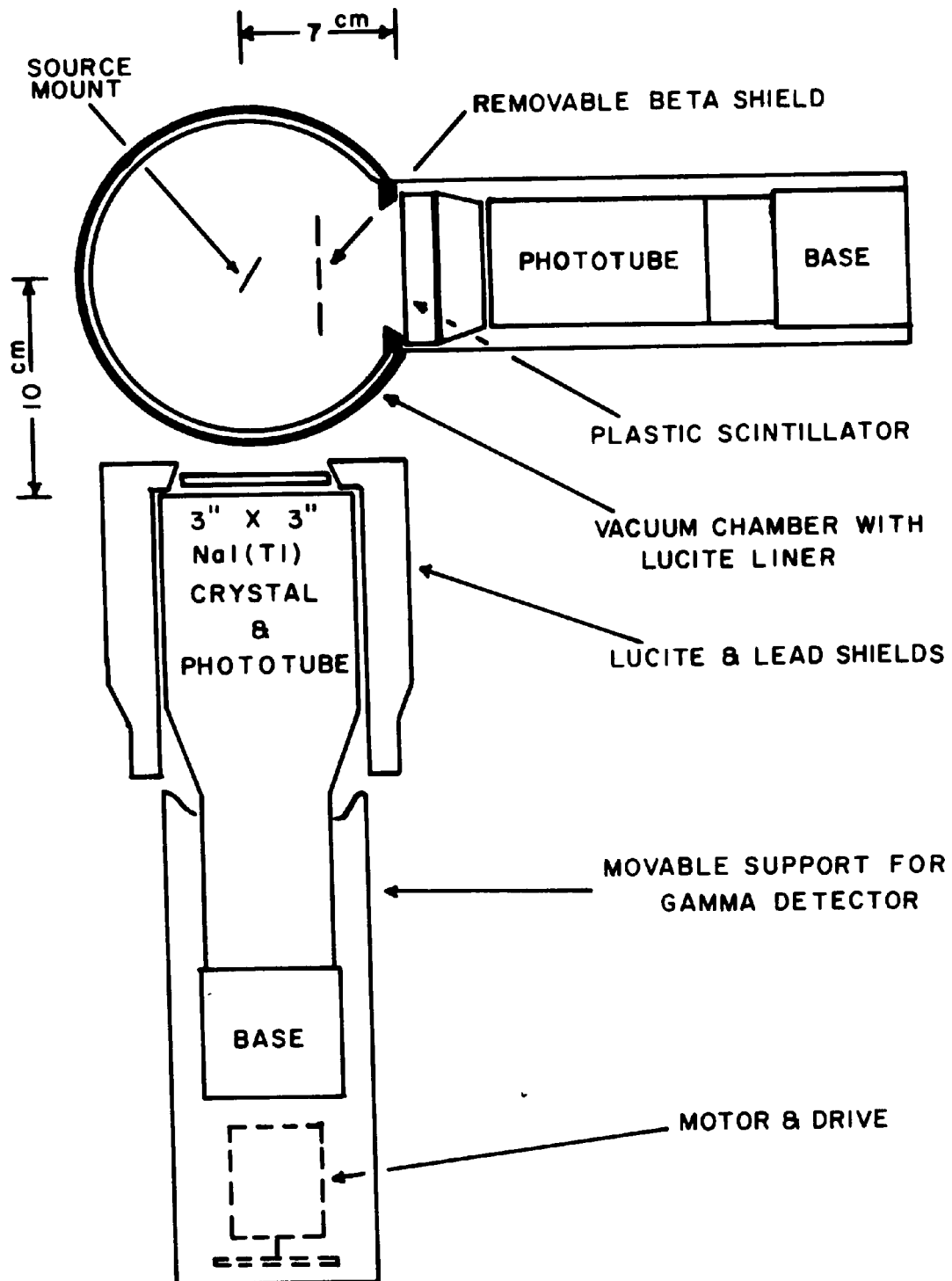


Fig. 3 -- Schematic diagram of the correlation apparatus (not to scale).

vacuum chamber and consists of a plastic scintillator of sufficient thickness to stop the most energetic beta particles from a given source (0.63" for Mn^{56} , and 0.40" for Pm^{148}). A tapered lucite light pipe couples the scintillator to a photomultiplier tube. At 632 keV, this arrangement has an energy resolution of about 18%. An aluminum mask is mounted on the front surface of the scintillator to prevent edge effects. This makes the effective detector aperture 4.6 cm in diameter.

Although the thickness and low Z of the plastic scintillator results in a very low gamma detection efficiency for the beta detector, there is a small gamma - gamma coincidence background which must be considered. The asymmetry and extent of this background is measured with the beta detector shielded from the beta radiation by an aluminum shield and the beta - gamma asymmetry is corrected accordingly.

Some of the Pm^{148} sources had an intense low-energy beta radiation (< 0.23 MeV) from the Pm^{147} target isotope (see section on sources). To prevent this radiation from reaching and overloading the beta detector system, a 5 mil aluminum absorber was placed on the face of the beta scintillator. The effects of this absorber are negligible for the radiation in the energy range of interest (> 0.90 MeV), as can be seen by comparing the conversion electron line in Bi^{207} with and without the absorber in place (see Fig. 4). The slight increase in gain with the absorber in place is the result of an increased light collection efficiency because of the reflectivity of the absorber.

Pulses are fed from the phototube bases through preamplifiers into a Hamner transistorized modular fast coincidence system.* This system consists of double - delay - line amplifiers, single - channel

* Hamner Electronics Co., Inc., Princeton, New Jersey.

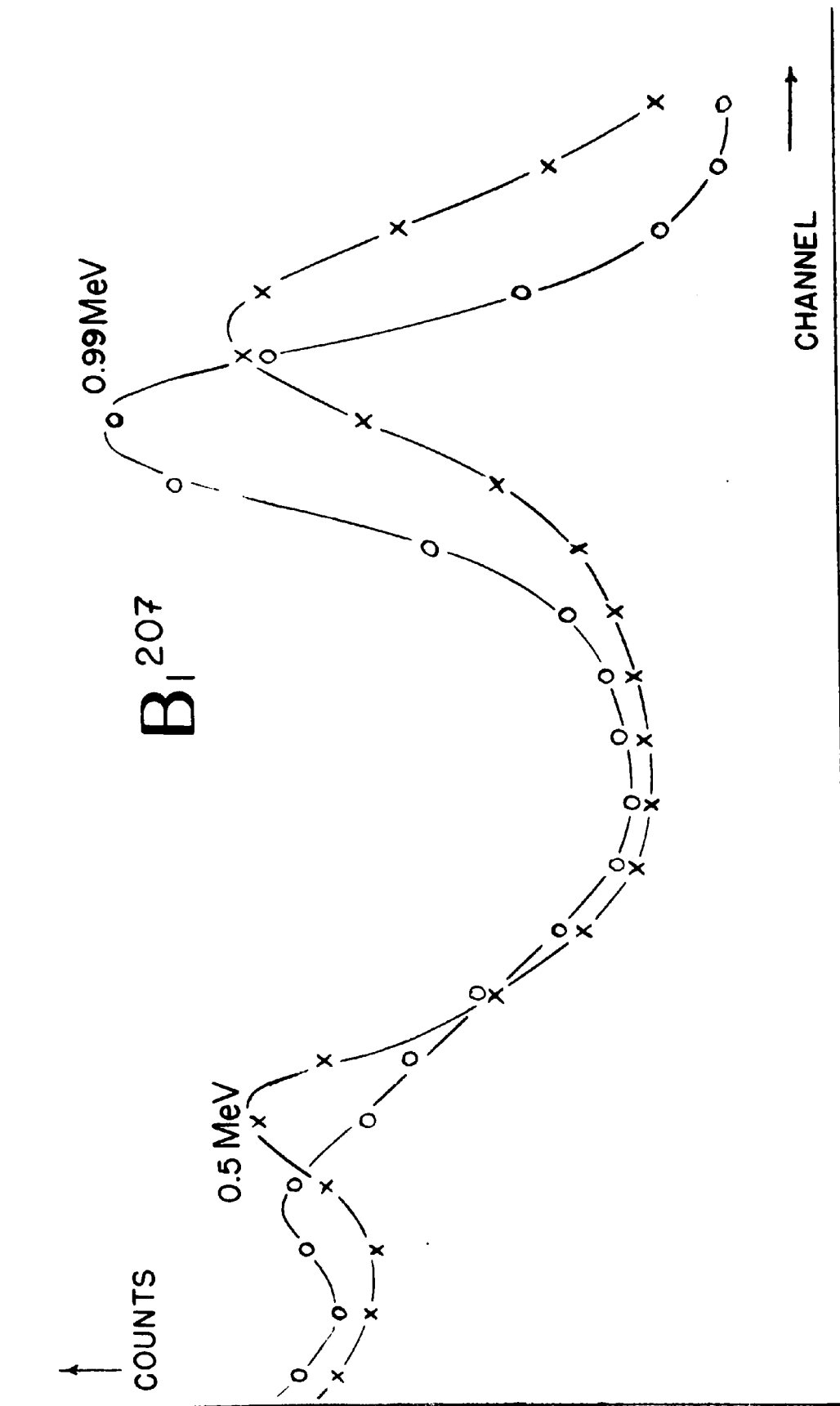


Fig. 4 -- Multichannel spectrum of Bi^{207} showing the spectrum with (x) and without (o) the 5 ml aluminum shield on the face of the beta scintillator.

pulse height analyzers, and fast coincidence units. The pulse height analyzers serve the dual purpose of energy selection and production of timing signals from the cross-over point of the doubly - differentiated amplifier pulses. Resolving times of 20 nsec. can be obtained with this system without appreciable loss of coincidence efficiency.

Pulses from the phototube base of the beta detector are also branched into the low - level input of a multichannel analyzer. The analyzer is operated in a coincidence gated mode with gating pulses provided by the Hamner coincidence system for a broad region of beta energies. This broad energy region is selected by one of the single - channel pulse height analyzers. Use of the multichannel in this manner permits a simultaneous measurement of the coincidence rate at several beta energies. A second pulse height analyzer in the beta channel is used to measure the coincidence rate at a beta energy window which is varied from run to run. This provides a supplementary measurement to that from the multichannel analyzer. (A block diagram of the electronic module interconnections is shown in Figure 5.)

Source Preparation

The samples of Mn^{56} were prepared by irradiation of natural metallic manganese (100% Mn^{55}) with thermal neutrons in the Ford Nuclear Reactor at The University of Michigan. Irradiation times varied from 5 to 10 minutes at a thermal neutron flux of about $2 \cdot 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$. Half life measurements and gamma spectra established the radiochemical purity of the samples. The NaI(Tl) gamma spectra gave gamma-ray energies which agreed with those quoted in Nuclear Data Sheets (10).

Promethium - 148 was prepared by two methods: 1) proton

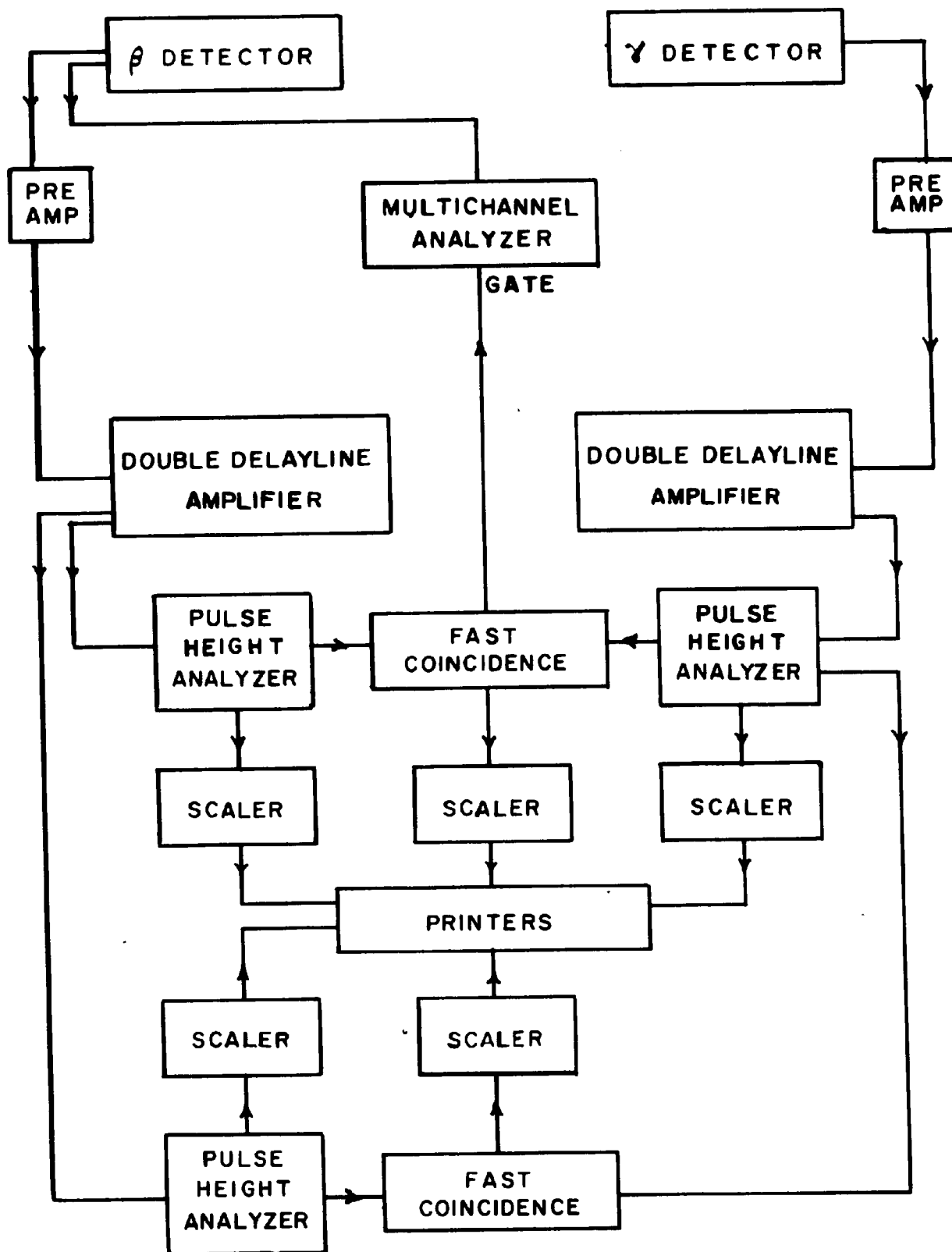


Fig. 5 -- Block diagram of electronic system.

bombardment of Nd^{148} ; and 2) thermal neutron irradiation of Pm^{147} . The Nd^{148} (p, n) Pm^{148} production was done at the Oak Ridge Cyclotron Laboratory. Separation of the Pm^{148} from the target Nd^{148} was carried out at The University of Michigan by cation - exchange resin - column methods.

Carrier - free Pm^{147} ($T_{1/2} = 2.5$ y.) was obtained commercially and irradiated with thermal neutrons in batches of 5 mCi in the Ford Nuclear Reactor for periods of 6 days. Each irradiation yielded about 0.5 mCi of Pm^{148} . No observable amount of Pm^{149} was produced by double neutron capture. The NaI(Tl) gamma spectra of Pm^{148} were in essential agreement with those given by Baba, Ewan, and Suarez (11).

The ratio of the 5.4 day to the 41 day (isomeric) activity was approximately 2 : 1. However, as can be seen from the decay scheme (see Fig. 9), no interference with the measurement on the cascade of interest in the ground state decay is expected from the isomeric decay.

Working samples of all radioactive materials were deposited on 1/4 mil mylar films which were supported by a one inch diameter aluminum ring. Manganese sources were deposited by vacuum evaporation of the metal or by drying manganese chloride solution on the films. All other isotopes were deposited by the drying method and covered with a Zapon or second mylar film.

For the I^{131} sources, it was necessary to form silver iodide - 131 on the mylar film to prevent sublimation of the iodine in the vacuum chamber. This was done by adding silver nitrate to the sodium iodide - 131 on the mylar film.

The source densities were not critical because of the high energy (> 0.5 MeV) of the beta particles investigated. The sources were, however, reasonably thin with estimated densities of $0.2 \text{ mg} / \text{cm}^2$.

Source diameters were about 1 cm.

Data Collection and Processing

Data was taken with the gamma detector stopped at angular positions of 90° , 180° , and 270° with respect to the direction of beta detection. After each counting interval (5 to 30 minutes), the data was automatically printed out and the gamma detector was moved to another angle. The data consisted of beta and gamma singles counts, from the single - channel pulse height analyzers; coincidence counts, from the coincidence units; and the beta coincidence spectrum, as recorded in the multichannel analyzer. All data was transcribed onto punch-cards for processing by electronic computer.

The recorded coincidence count for each data point was corrected by subtracting chance coincidences, as computed by

$$N(\text{chance}) = (2\tau / T) N(\beta) N(\gamma), \quad (3.1)$$

where, 2τ is the resolving time of the coincidence unit; T is the counting time for the data point; $N(\beta)$ and $N(\gamma)$ are the recorded number of beta and gamma singles for the time T , respectively.

After the chance coincidences were subtracted, the resulting true coincidence counts were normalized by dividing each by the corresponding gamma singles count. This normalization corrected for any spatial asymmetries in the source and for the decay of the source. The spatial source asymmetry, which was computed separately from the gamma singles counts, averaged to less than 0.1% for any series of measurements.

The beta - gamma coincidence asymmetry was computed from

$$A_{\beta\gamma} = \frac{n_{\beta\gamma}(180^\circ)}{n_{\beta\gamma}(90^\circ \text{ or } 270^\circ)} - 1, \quad (3.2)$$

where $n_{\beta\gamma}(\theta)$ is the true, normalized coincidence count at the angle θ . This asymmetry was computed for each pair of data points, averaged, and the standard deviation computed. For the coincidence data from the multichannel analyzer, where the count per data point was small, the true, normalized coincidence counts were also summed for each energy (channel) and angle for the entire run. The asymmetry was then computed from these sums and compared to the asymmetry as computed by the first method. For the lowest energy points (which have the highest number of counts), the asymmetries computed by the two methods were in substantial agreement.

Measurements of the gamma - gamma coincidence background asymmetry were made by the same procedure followed for the beta - gamma asymmetry, but with the beta shield in place. In order to determine the extent to which this gamma - gamma background contributed to the measured beta - gamma asymmetry, the coincidence rate was measured several times with the beta shield alternately in place and removed, other experimental conditions remaining the same. The measurement of these coincidence rates was repeated for different positions of the gamma counter and at the beginning of each beta - gamma correlation run.

The ratio

$$s = R_{\gamma\gamma} / R_{\beta\gamma} \quad (3.3)$$

was computed from these coincidence rates; where, $R_{\gamma\gamma}$ is the rate with the beta shield in place, and $R_{\beta\gamma}$ with the beta shield removed. The

beta - gamma asymmetry was then corrected for the background gamma - gamma asymmetry by

$$A_{\beta\gamma}(\text{true}) = \frac{1}{1-s} \left[A_{\beta\gamma}(\text{measured}) - s A_{\gamma\gamma}(\text{measured}) \right], \quad (3.4)$$

where $A_{\gamma\gamma}$ was computed by the same formula (eq. 3.2) as $A_{\beta\gamma}$.

With equation 1.3 written in a normalized form as

$$W(\theta) = 1 + A_2(\beta) A_2(\gamma) P_2(\cos\theta), \quad (3.5)$$

the beta - gamma correlation coefficient is given in terms of the asymmetry as

$$A_2(\beta-\gamma) \equiv A_2(\beta) A_2(\gamma) = \frac{2 A_{\beta\gamma}}{3 + A_{\beta\gamma}}. \quad (3.6)$$

The finite solid angle of the particle detectors results in a measured correlation which is attenuated from that which would be measured with point detectors. It can be shown (12) that this solid angle effect gives an observed correlation of

$$W(\theta) = 1 + Q_2(\beta) A_2(\beta) Q_2(\gamma) A_2(\gamma) P_2(\cos\theta), \quad (3.7)$$

where the Q_2 's are attenuation factors (≤ 1) for each detector. Consequently, the true correlation coefficient is given by

$$A_2(\beta-\gamma) = \frac{1}{Q_2(\beta) Q_2(\gamma)} \frac{2 A_{\beta\gamma}}{3 + A_{\beta\gamma}}. \quad (3.8)$$

Attenuation coefficients for the gamma detector were obtained from the work of B. Herskind and Y. Yoshizawa (13). For the beta detector, the attenuation coefficient was calculated from the solid angle subtended by the detector assuming 100% detection efficiency which

is justified by the thickness of the scintillator and by the shielding against edge effects. The attenuation coefficient is given by (4, p. 1193)

$$Q_2(\beta) = \frac{1}{2} \cos\theta (1 + \cos\theta), \quad (3.9)$$

where θ is the half-angle subtended at the source by the detector.

Previous considerations (14) have shown that the errors introduced by assuming a point source are negligible for this particular experimental arrangement.

For both the Mn^{56} and the Pm^{148} measurements, the plastic scintillator apertures were 4.60 cm in diameter and at a distance of 7.0 cm from the source. This gave a solid angle correction factor for the beta detector of $Q_2(\beta) = 0.926 \pm 0.010$.

The gamma scintillator was 10.0 cm from the sources, with $Q_2(\gamma) = 0.936 \pm 0.005$ for Mn^{56} ; and $Q_2(\gamma) = 0.931 \pm 0.005$ for Pm^{148} . The total attenuation factors were then 0.867 for Mn^{56} , and 0.931 for Pm^{148} .

CHAPTER IV
MANGANESE 56

Introduction

The expansion of the matrix element of the beta interaction (eq. 2.4) in a series in terms of increasing lepton angular momentum (eq. 2.9) contains terms which allow for any change of nuclear angular momentum and parity. Ordinarily, only the non-vanishing terms with the lowest lepton orbital angular momentum are retained. However, if there is some selection rule operative that reduces the magnitudes of these lowest order terms, then it is necessary to consider higher order terms in the expansion.

For an allowed beta transition, the terms that are retained in the expansion (2.9) are those generating no nuclear parity change and no lepton orbital angular momentum. The reason for the last condition is one of magnitudes and must be dropped to allow retention of terms of non-zero orbital angular momentum in special cases. These additional terms, then, represent higher order contributions to allowed transitions. Second - forbidden transitions also permit no nuclear parity change, but do require orbital angular momentum for the leptons. In this spirit, higher order contributions to the allowed transitions are called contributions from second - forbidden decay, although the matrix elements governing true second - forbidden transitions are not retained because of their lesser magnitudes.

Reduction of the magnitudes of the lowest order terms governing

a transition should be manifested by a $\log ft$ value which is larger than usual for the class to which the transition belongs. This is the case for the allowed 2.86 MeV beta transition in Mn^{56} (see Fig. 6) which has a $\log ft$ value of 7.2, whereas allowed decays usually have $\log ft$ values in the range 3 - 6. This might be understood by assuming that the matrix element usually governing an allowed decay of this type ($\langle \hat{\sigma} \cdot \hat{T}_1^0 \rangle = \int \hat{\sigma}$) is reduced because of a change in the l - value of the transforming neutron: $p_{3/2} \rightarrow f_{7/2}$ (l - forbiddenness) (15). If the higher order terms are not also reduced by the same selection rule, their contribution may be observable.

With contributions from higher order terms and, therefore with leptons of non-zero orbital angular momentum, there will be a finite $A_2(\beta)$ term in the beta - gamma directional correlation function. A measurement of this correlation will then show a small deviation from isotropy. Similarly, contributions from higher order terms will make the shape factor (C) dependent on electron energy. The energy spectrum of the beta particles should then show a deviation from statistical shape. For both the beta - gamma angular correlation function and the beta energy spectrum, the largest terms of the new contributions from the higher order matrix elements will be in the form of interference products between the allowed and second - forbidden - type matrix elements.

Previous Work

The beta spectrum shape factor can be expressed in a general form as

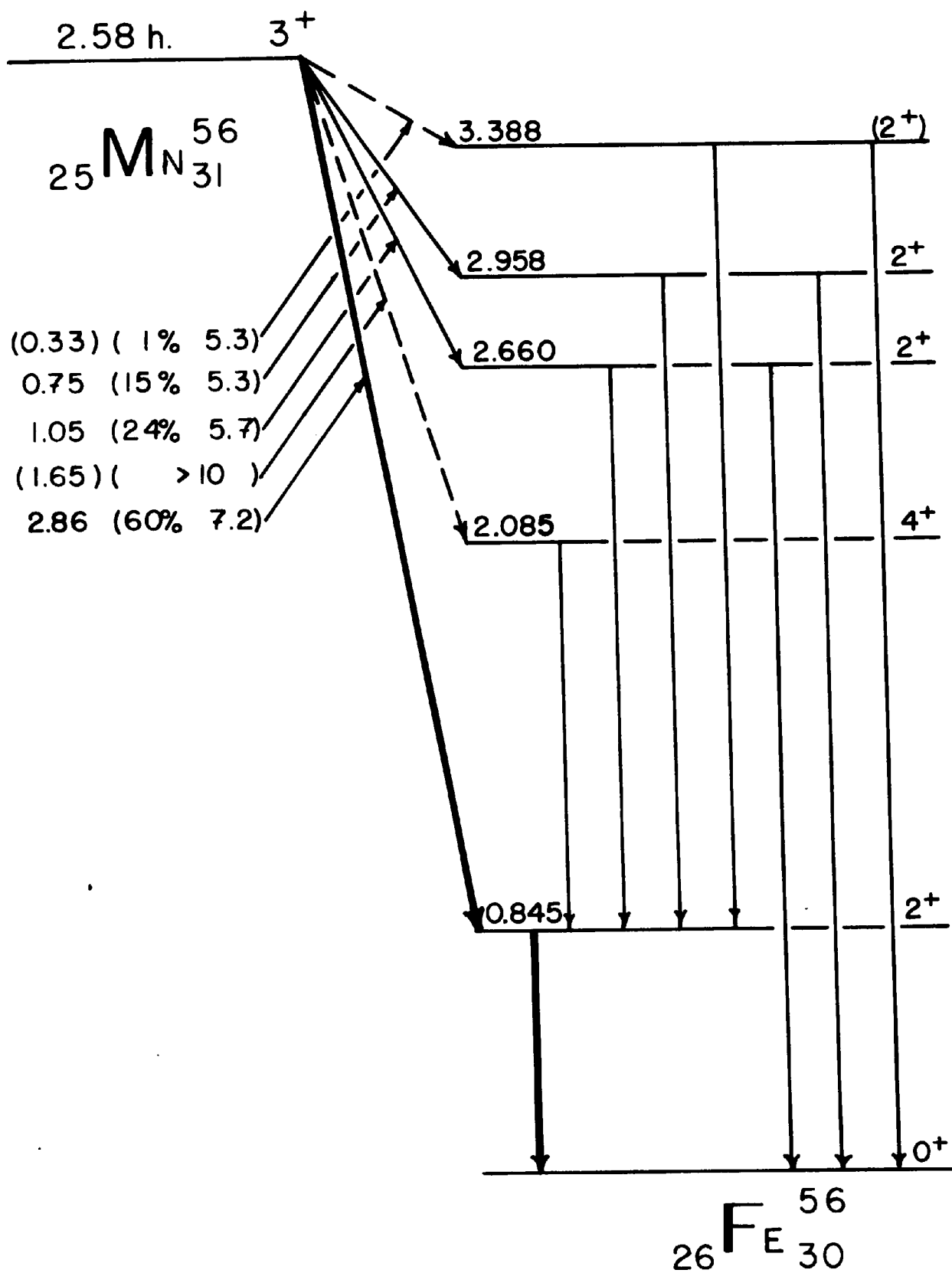


Fig. 6 -- Decay of Mn^{56} .

$$C(W) = 1 + a W + b / W + c W^2, \quad (4.1)$$

where W is the electron energy (in units of the electron rest mass energy, $m_0 c^2$) and a , b , and c are energy - independent coefficients whose magnitudes are small compared to unity. Because of the small magnitudes of these coefficients, most allowed and several first - forbidden beta spectra can be fitted with an energy - independent shape factor, $C(W) = 1$.

Deviations from statistical shape (i.e., an energy - dependent shape factor) have been observed in several accurate measurements on various isotopes (16). A definite deviation from allowed shape has been observed in the high - energy beta decays ($W_0 \approx 33 m_0 c^2$) of B^{12} and N^{12} (17, 18). For these isotopes, the effect can be understood on the basis of the conserved - vector - current (CVC) theory (19). However, deviations of beta spectra from statistical shape have also been observed for allowed transitions with low - energy endpoints ($W_0 \approx 2 - 5 m_0 c^2$). In general, the coefficient a is small and ranges from 0.004 to 0.04. A striking shape factor anomaly has been observed by the Indiana group (1), who find that most of their well - measured beta spectra can be fitted by an empirical shape factor of the form $C(W) = 1 + b / W$. The coefficient b is positive for both negatron and positron transitions, and of the order of $0.2 \leq b \leq 0.4$.*

Several attempts have been made to measure asymmetries in beta - gamma directional correlations involving allowed beta transitions. In most cases, the experimental accuracy was such that only an upper limit

* For a summary of shape factor measurements, see for instance Table I in ref. 16 and p. 1388 in ref. 20.

of 0.1% could be put on the anisotropy. In Na^{22} , Co^{56} , Mn^{56} , and Tb^{160} , anisotropies up to a few percent have been reported (21 - 23).

Contrary to an earlier measurement of Mn^{56} , where an isotropic correlation was reported (24), a relatively large asymmetry of 2.2 % was observed by Lobashov and Nazarenko (22). But when Howe, Langer, Spejewski, and Wortman (1) performed a very accurate measurement of the beta spectrum of the transition of interest in this isotope, they found the distribution to be essentially statistical with no positive evidence for a contribution from higher order terms. Nevertheless, their data was such that those authors could fit the spectrum with a shape factor, $C(W) = 1 + 0.3 / W$. If there is such a deviation from statistical shape which is caused by higher order terms, the directional correlation should show a small anisotropy. But the magnitude of the anisotropy reported in reference 22 is rather surprising. Because of this inconsistency, a careful investigation of the beta - gamma directional correlation in Mn^{56} was undertaken.

Measurements and Results

The beta - gamma directional correlation of the 2.86 MeV β^- -- 0.845 MeV γ cascade in Mn^{56} (see Fig. 6) was measured at average beta energies of 1.3 MeV and 2.3 MeV with energy ranges of 0.3 MeV and 0.7 MeV, respectively. Altogether, 80 runs were made with about 28 data points per run. A total of 10^6 true coincidences were accumulated for each gamma detector position and for each energy range.

The lower energy range was chosen to have a gamma - gamma background which was large enough to allow a good measurement of its asymmetry and of its contribution to the measured beta - gamma

correlation. In the lower energy range ($1.10 \leq E_\beta \leq 1.40$ MeV), this gamma - gamma background was 5% of the total coincidence rate and had an asymmetry of $A_{\gamma\gamma} = +0.329 \pm 0.008$. In the higher beta energy range ($2.16 \leq E_\beta \leq 2.86$ MeV), where only the weak 2.52 MeV gamma transition contributes, the gamma - gamma background was only 0.3% of the total coincidence counting rate and had an asymmetry of $A_{\gamma\gamma} \approx +0.1$. The accuracies of the measured gamma - gamma background were limited by the low counting rates, particularly in the higher energy range.

The measured beta - gamma asymmetry was positive in the lower energy range, which was expected since the large positive gamma - gamma background asymmetry contributed strongly in this range. However, the measured beta - gamma asymmetry was negative in the higher energy range in spite of the positive, albeit weak, contribution from the gamma - gamma background (see Table I, column 2). This negative beta - gamma asymmetry could not have come from the gamma - gamma background since any contribution to a measured asymmetry from a positive asymmetry background tends to make the measured asymmetry positive. From the correction formula for the gamma - gamma background (eq. 3.4) with $A_{\gamma\gamma}(\bar{E} = 2.3 \text{ MeV}) \approx +0.1$ and $s \approx 0.003$, the measured beta - gamma asymmetry would appear positive ($\approx +0.3 \cdot 10^{-3}$) if the actual beta - gamma asymmetry were zero.

The correction for the gamma - gamma background in the higher beta energy range amounts to $s A_{\gamma\gamma} \approx +0.3 \cdot 10^{-3}$, and is neglected since it is within the experimental error of the measured beta - gamma asymmetry in this range. The value given for the true beta - gamma asymmetry in the lower energy range has been corrected for the gamma - gamma background. But this beta - gamma asymmetry serves mainly as a

TABLE I

Directional Correlation Results Mn^{56}, I^{131}

Energy range	Asymmetry ^A	Gamma-gamma asymmetry ^A	$\frac{N_{\gamma\gamma}}{N_{\beta\gamma}}$	Correlation coefficient ^B
E(MeV)	$A_{\beta\gamma} \times 10^2$	$A_{\gamma\gamma}$	S	$A_2 \times 10^2$
Mn^{56}				
1.10 - 1.40	$+1.64 \pm 0.13$	$+0.329 \pm 0.006$	0.0551 ± 0.0012	-0.10 ± 0.15^C
2.16 - 2.86	-0.33 ± 0.18	$+0.1$	0.0033	-0.30 ± 0.11
2.16 - 2.86	-0.45 ± 0.10			
I^{131}				
0.400-0.500	$+0.01 \pm 0.03$			< 0.05
0.500-0.606	$+0.02 \pm 0.07$			

^AWithout corrections.^BCorrected for solid angle.^CCorrected for gamma-gamma background.

check of consistency since the beta - gamma asymmetry is completely masked by the gamma - gamma asymmetry in the actual measurement. Nevertheless, it is reassuring that the value obtained for the true beta - gamma asymmetry in the lower beta energy range is not in disagreement with the value obtained in the higher energy range.

In order to be certain that the asymmetries measured were not due to systematic errors, a check measurement on the allowed 0.606 MeV β -- 0.364 MeV γ cascade in I^{131} (see Fig. 7) was made after 40 runs had been completed on the measurements of Mn^{56} . Again, two beta energy ranges were selected: $0.40 \leq E_{\beta} \leq 0.50$ MeV and $0.50 \leq E_{\beta} \leq 0.60$ MeV. All other experimental conditions were the same as for the beta - gamma correlation measurements on Mn^{56} . The change of nuclear spins and parities in the decay of I^{131} are in agreement with the requirements for its classification as an allowed decay, so the beta - gamma directional correlation for this cascade is expected to be isotropic.

A total of 10^7 true coincidences were accumulated in the measurement of the correlation of the cascade in I^{131} . The measurements gave the vanishingly small asymmetries of 0.0001 ± 0.0003 and 0.0002 ± 0.0007 for the two respective energy ranges, confirming the proper alignment of the experimental apparatus.

After the check measurements on I^{131} had been completed, the measurements on Mn^{56} were continued in the upper energy range. The results of this second set of measurements are in agreement with those of the first set of 40 runs (see Table I).

Conclusions

From the beta - gamma directional correlation measured in this

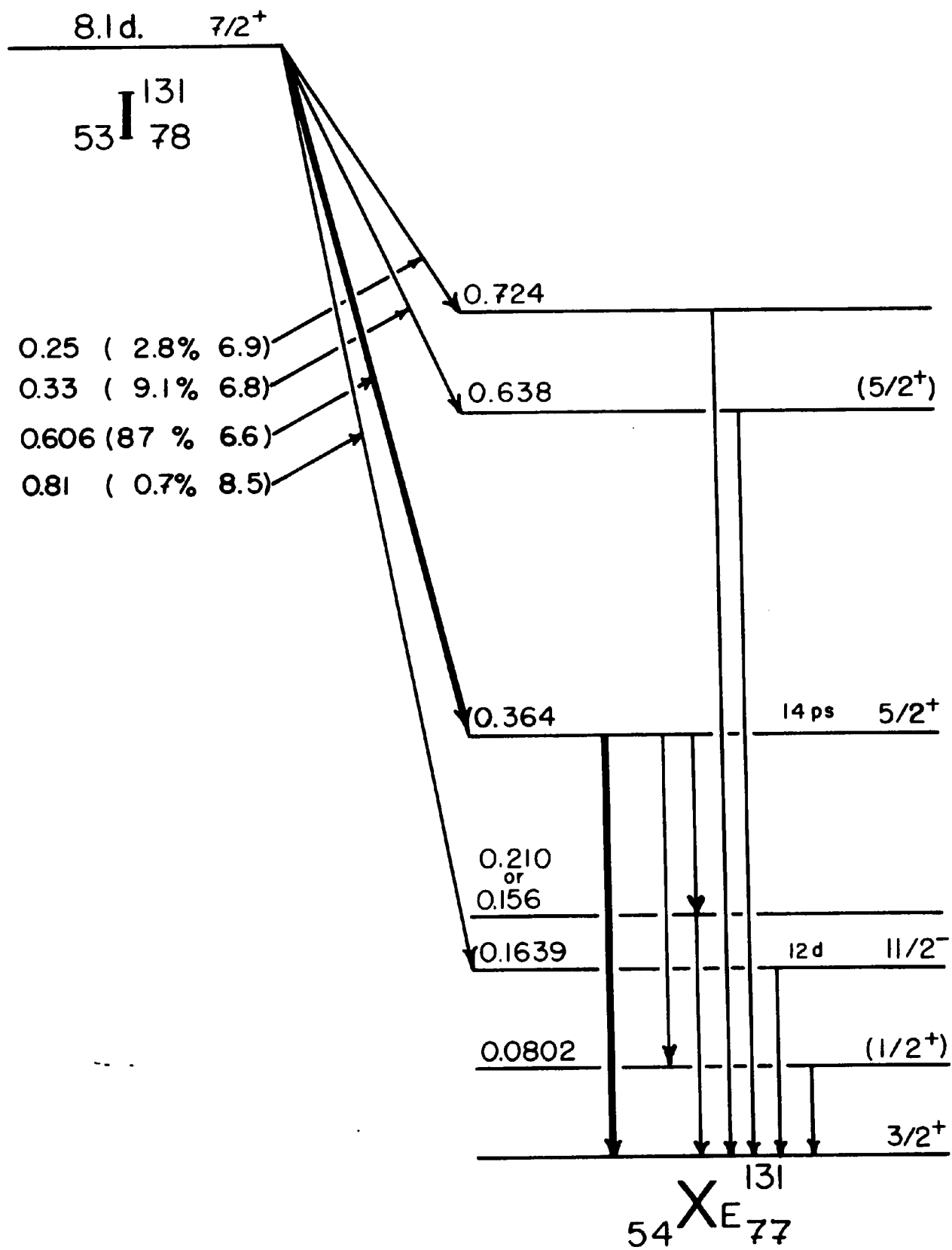


Fig. 7 -- Decay of I^{131} .

work, it is possible to estimate the effects of the second - forbidden - type matrix elements on the shape factor for the beta spectrum. A relation between the beta - gamma directional correlation and the shape factor can be obtained by using the formulations of Morita (9) for these quantities.

The directional correlation coefficient $A_2(\beta\gamma) = A_2(\beta) A_2(\gamma)$ of equation 3.5 is given by

$$A_2(\beta\gamma) = \sqrt{\frac{1}{6}} b_{11}^{(2)} / (7 C) \quad (4.2)$$

for a $3^+ (\beta) 2^+ (\gamma) 0^+$ transition. The spectrum shape factor is

$$C(W) = -\sqrt{\frac{1}{3}} b_{11}^{(0)}. \quad (4.3)$$

Particle parameters (see Chapter II) are denoted by the b's. By dividing the expression for the particle parameters by the square of the Gamow - Teller matrix element, $(\int \vec{\sigma})^2$, these parameters can be expressed in terms of the ratios of interfering second - forbidden - type matrix elements to the Gamow - Teller matrix element:

$$\begin{aligned} \frac{-\sqrt{\frac{1}{3}} b_{11}^{(0)}}{(\int \vec{\sigma})^2} &= 2 C_A^2 \left\{ L_0 \left[1 - \frac{2}{3} q \left(\frac{1}{2} q v + x - u \right) \right] \right. \\ &\quad \left. + N_0 \left[\frac{2}{3} q (2 y - v) + 2 (x + u) \right] \right\}, \end{aligned} \quad (4.4)$$

and

$$\frac{\sqrt{\frac{1}{6}} b_{11}^{(2)}}{(\int \vec{\sigma})^2} = 2 C_A^2 \left\{ L_{12} \left[\frac{1}{3} q (v + y) + 2 x - u \right] \right\} \quad (4.5)$$

$$+ N_{21} (3 y - v) \} , \quad (4.5)$$

where

$$\begin{aligned} x &= i \int \vec{\sigma}_5 \cdot \vec{r} / \int \vec{\sigma} & u &= \frac{C_V}{C_A} \int \vec{\sigma} \times \vec{r} / \int \vec{\sigma} \\ y &= \int (\vec{\sigma} \cdot \vec{r}) r / \int \vec{\sigma} & v &= \int \vec{\sigma} r^2 / \int \vec{\sigma}. \end{aligned} \quad (4.6)$$

The terms L_0 , N_0 , L_{12} , and N_{21} are combinations of lepton radial wave function components; q is the neutrino momentum. Terms involving the second rank tensors of true second - forbidden transitions have been neglected.

As they stand, there are four unknown parameters, x , y , u , and v , in equations 4.4 and 4.5. However, certain relationships between the matrix elements reduce the number of parameters to one. By assuming uniform nuclear matter (9),

$$v \approx \frac{3}{5} R^2 \quad y \approx \frac{3}{5} R^2 \eta , \quad (4.7)$$

where R is the nuclear radius ($3.1 \cdot 10^{-3} A^{1/3} (\frac{\pi}{m_0 c})$) and η is a model - dependent parameter. The CVC theory (19) gives the relations

$$x \approx \frac{1}{2M} - \frac{3}{20} \Lambda \alpha Z R \eta \quad u \approx \frac{C_V}{C_A} \frac{4.7}{M} , \quad (4.8)$$

where, M is the bare nucleon mass, 1836; $C_V / C_A = -1.19$. The quantity Λ is given by $\Lambda \approx 1 + (W_0 - 2.5) A^{1/3} / Z = 1.62$.

The expression for A_2 is dependent on the electron energy through the neutrino momentum, $q = W_0 - W$, and through the terms L_0 , N_0 , L_{12} , and N_{21} which contain electron wave function components. If

electron radial wave functions computed for a finite nuclear charge distribution were used to evaluate the latter expressions, it would be impossible to exhibit the energy dependence of A_2 in an explicit manner. Therefore, the approximations given by Morita (9), including terms up to $(\alpha Z)^2$, have been used. The usual Konopinski - Uhlenbeck approximation cannot be used here since it gives results which differ by several percent from those given by the more nearly exact expressions which include finite de Broglie wavelength effects (25).

The equations for A_2 can now be solved for the nuclear parameter, η . This parameter is displayed as a function of A_2 in Figure 8 for a beta energy of $5.5 (m_0 c^2)$ which is the average beta energy for the upper energy range of the correlation measurement on Mn^{56} . The value of the measured correlation coefficient is shown with error bars, indicating a range for the possible values of η which would be in agreement with the measured correlation.

Since the shape factor also depends on η , the range of values of η which are compatible with the measured correlation limits the possible forms of the energy dependence of the shape factor. The coefficients a , b , and c of the shape factor (eq. 4.1) are given as functions of η by grouping the terms of equation 4.4 on the basis of their dependence on the electron energy. These coefficients are presented in Figure 8 as functions of A_2 and, therefore, as functions of η also. As can be seen from this figure, a positive coefficient, $b \approx +0.3$ cannot be reconciled with the very small negative correlation observed in the present experiment. But the order of magnitude of the a coefficient which has been observed in low - energy allowed transitions is in agreement with a small negative asymmetry.

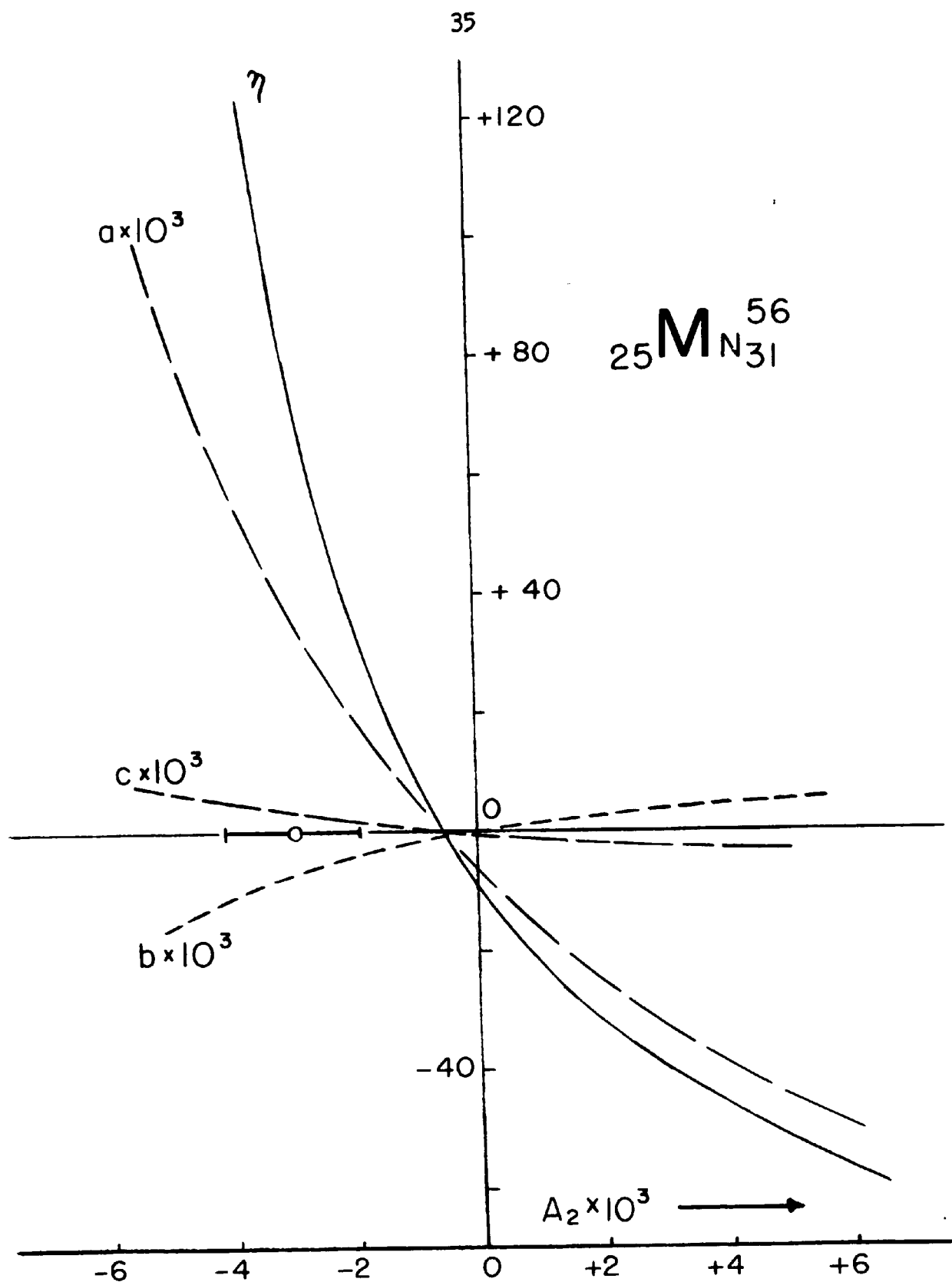


Fig. 8 -- Plot of the nuclear parameter η and the spectrum shape factor coefficients a , b , and c as functions of the directional correlation coefficient, A_2 .

As can be seen from Figure 8, a shape factor which would be consistent with the beta - gamma directional correlation measured in this experiment should be of the form

$$C(W) = 1 + 0.04 W - 0.01 / W. \quad (4.9)$$

The energy dependence of a shape factor of the above form may be too small to be experimentally observed in the limited energy range available for an accurate beta spectrum measurement on the transition of interest in Mn^{56} .

CHAPTER V
PROMETHIUM 148

Introduction

In contrast to allowed decays, where any observable beta - gamma directional correlation arises from the contribution of interference products of allowed and second - forbidden - type nuclear matrix elements, the correlation in a first - forbidden decay is governed by the squares and cross products of the predominant matrix elements themselves. Thus one finds that the correlation involving first - forbidden transitions is larger than any correlation involving an allowed transition, and can be of the order of 10^{-2} to 10^{-1} . Furthermore, the correlation is usually large enough to be measured as a function of the beta particle energy.

If the endpoint energy of the beta transition is large compared to the Coulomb energy, the correlation, measured as a function of beta particle energy, can provide information about the relative values of the possible six matrix elements which can contribute to the transition. If the endpoint energy is not large compared to the Coulomb energy, the correlation will vary with the beta particle energy as p^2 / W (the ξ -approximation), where p is the electron momentum and W is the electron energy. In this case, the data for the correlation can be used to determine the values of linear combinations of matrix elements rather than the values of the matrix elements themselves. However, in the latter case, a reduction of the values of some of the matrix elements

or a near mutual cancellation of some of the matrix elements can lead to a reduction of the coefficient for the p^2 / W term in the function for the correlation coefficient. This can give rise to an energy dependence of the correlation which, again, can be useful for the determination of the values of individual matrix elements.

The 1.90 MeV beta transition from the ground state of Pm^{148} (see Fig. 9) would be expected to exhibit the typical features of a transition which is described by the ξ -approximation since $\xi > W_0$, with $\xi = 13.4$ and $W_0 = 4.7$. However, the $\log ft$ value (9.2) is somewhat higher than usual for a non-unique first - forbidden transition. This suggests that the usually predominating matrix elements for a 1^- decay, $\langle if \rangle$ and $\langle \hat{\sigma} \times \hat{f} \rangle$, might either be reduced by a nuclear selection rule or by cancellation. In either case, the directional correlation should show a deviation from the p^2 / W dependence of the ξ -approximation (26).

It is interesting to note that when Baba, Ewan, and Suarez (27) studied the spectrum shape factor of the outer 2.45 MeV beta transition in Pm^{148} , they concluded that both cancellation and selection rules were operative. They ascribed the rather large $\log ft$ value (9.2) to a reduction in the size of the nuclear matrix elements and the large shape factor to a cancellation effect.

The same authors (28) performed a beta - gamma directional correlation experiment on the 1.90 MeV β -- 0.550 MeV γ cascade in Pm^{148} . They report an anisotropy of less than 6% for an integral measurement over a beta energy range of 1.5 MeV to 1.8 MeV. From this they conclude that the 1.90 MeV beta transition is not unique since a unique transition would produce a larger anisotropy. This confirmed the

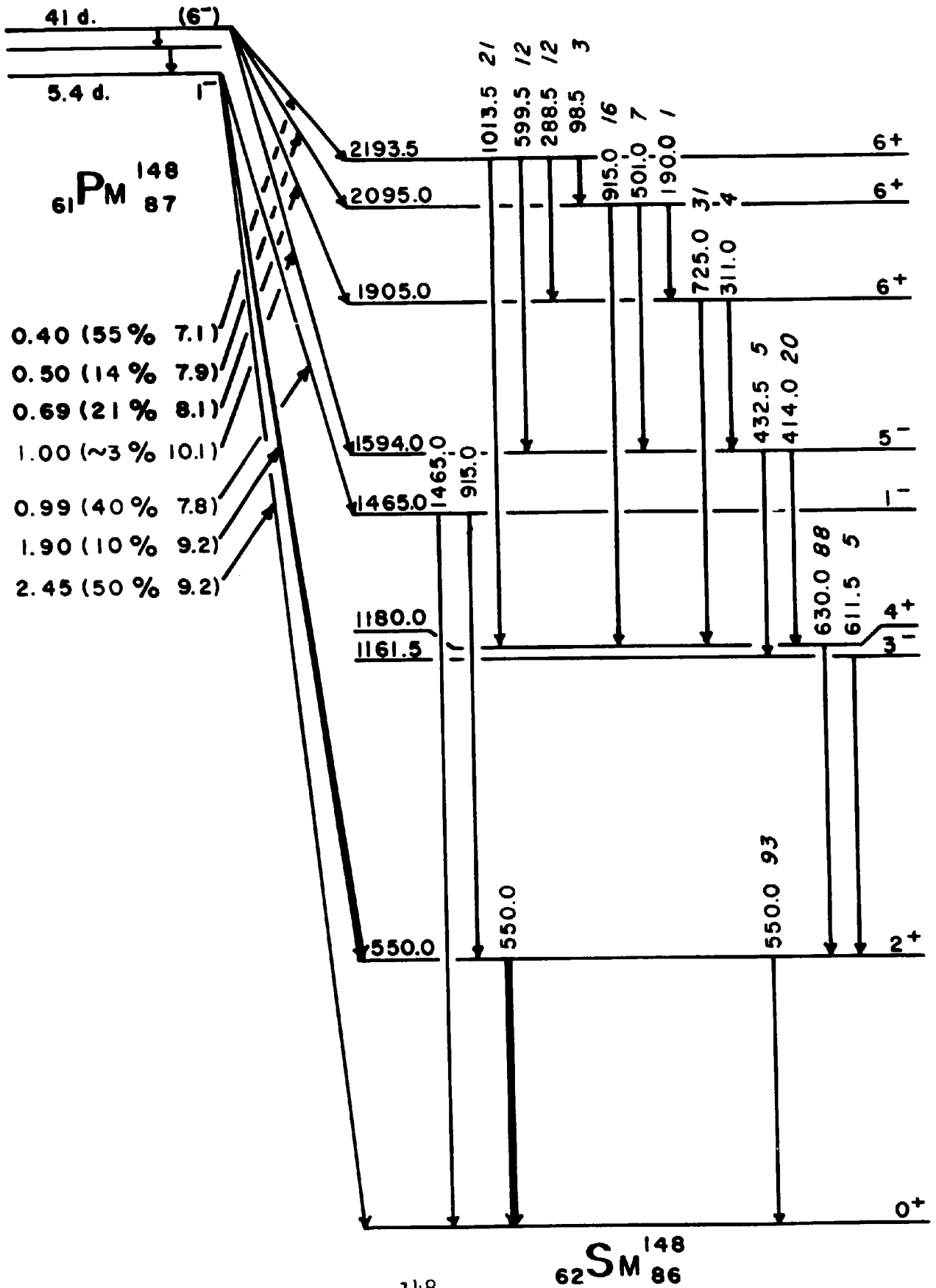


Fig. 9 -- Decay scheme for ^{148}Pm .

assignment of a spin of 1 to the ground state of Pm^{148} .

Thus it appeared that the determination of the beta - gamma directional correlation as a function of the beta energy for this cascade would be useful for the eventual determination of the nuclear matrix elements of the beta transition.

Decay Scheme

Extensive investigations of the decay of Pm^{148} (28 - 31) have established the decay scheme shown in Figure 9. The gamma-ray energies and intensities shown in this figure are those determined during the course of the present investigation. The energy and intensity measurements on the gamma-ray transitions were made with a $4 \text{ cm}^2 \times 0.5 \text{ cm}$ Ge(Li) spectrometer with Y^{88} (898.0, 1836.1 keV) and Na^{22} (1274.5 keV) used as calibration sources (32). Corrections were made for nonlinearities in the spectrometer system and for detector efficiency (33). The energies given in Figure 9 are to within $\pm 1 \text{ keV}$ and the intensities are to within $\pm 15\%$. These results are in substantial agreement with those given by Baba, et al. (28). The electron conversion coefficients and the strength of the isomeric transition (7%) as given by those authors were used to supplement the information obtained from the Ge(Li) spectrum.

The spectrum of Pm^{148} taken with the sources used for the measurements on the beta - gamma directional correlation is shown in Figure 10. The peak at 122 keV is from the gamma transition in the Pm^{147} target material. The peak at approximately 76 keV is from the isomeric transition in Pm^{148} ; the 68 keV gamma peak from the same isomeric transition was obscured in the Compton background.

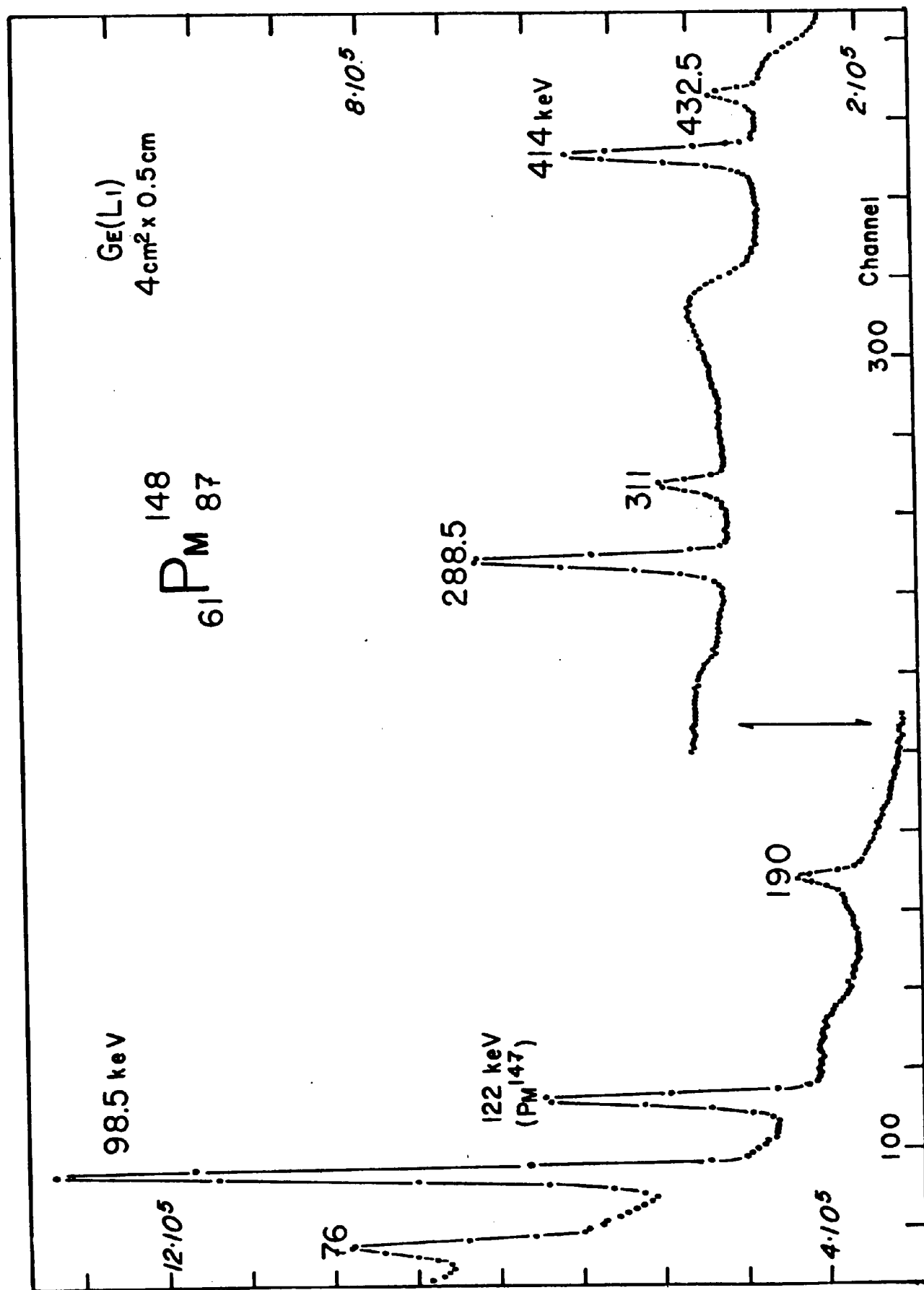


Fig. 10 -- Ge(Li) gamma-ray spectrum of ¹⁴⁸Pm.

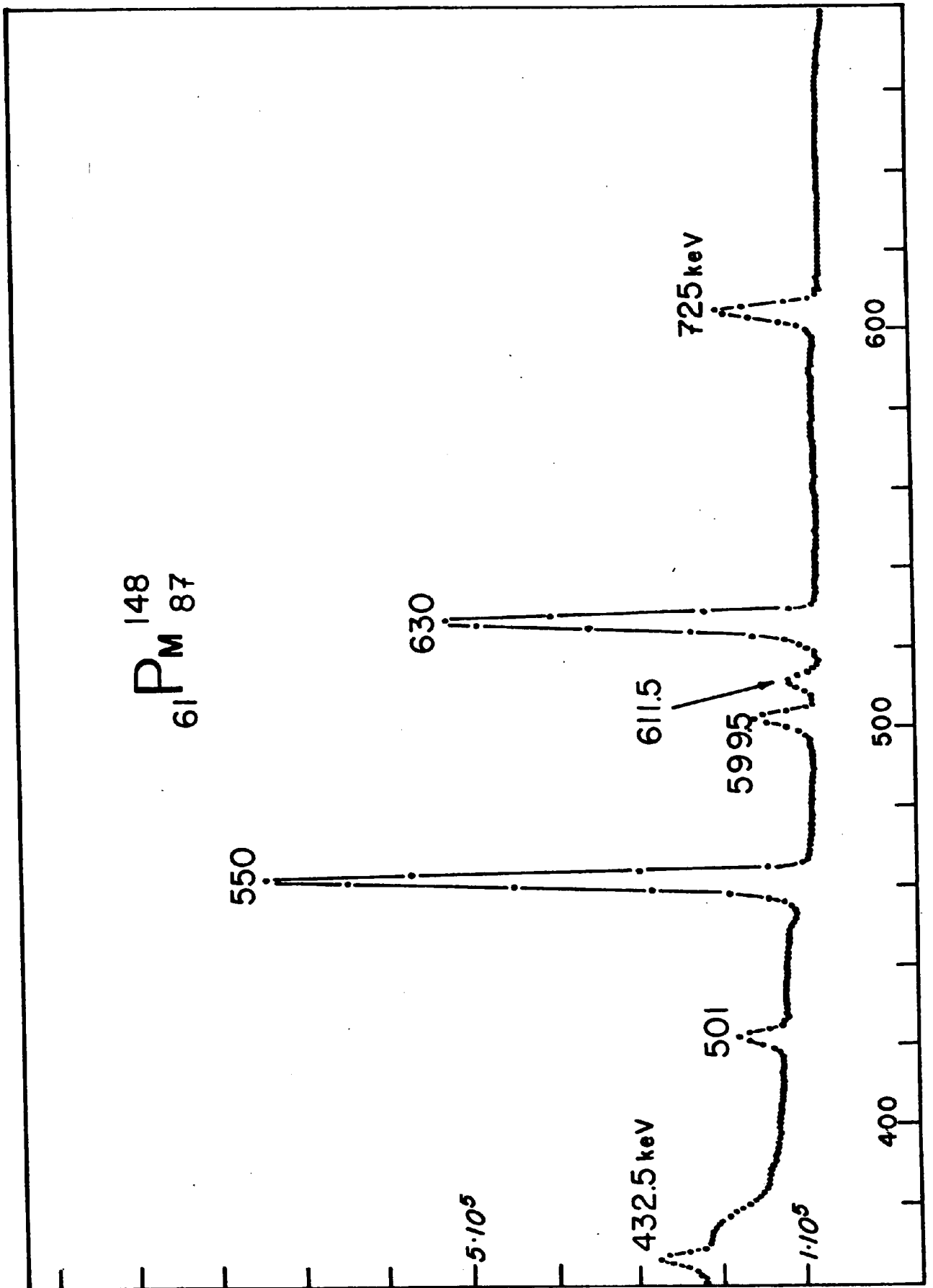


Fig. 10 -- cont.

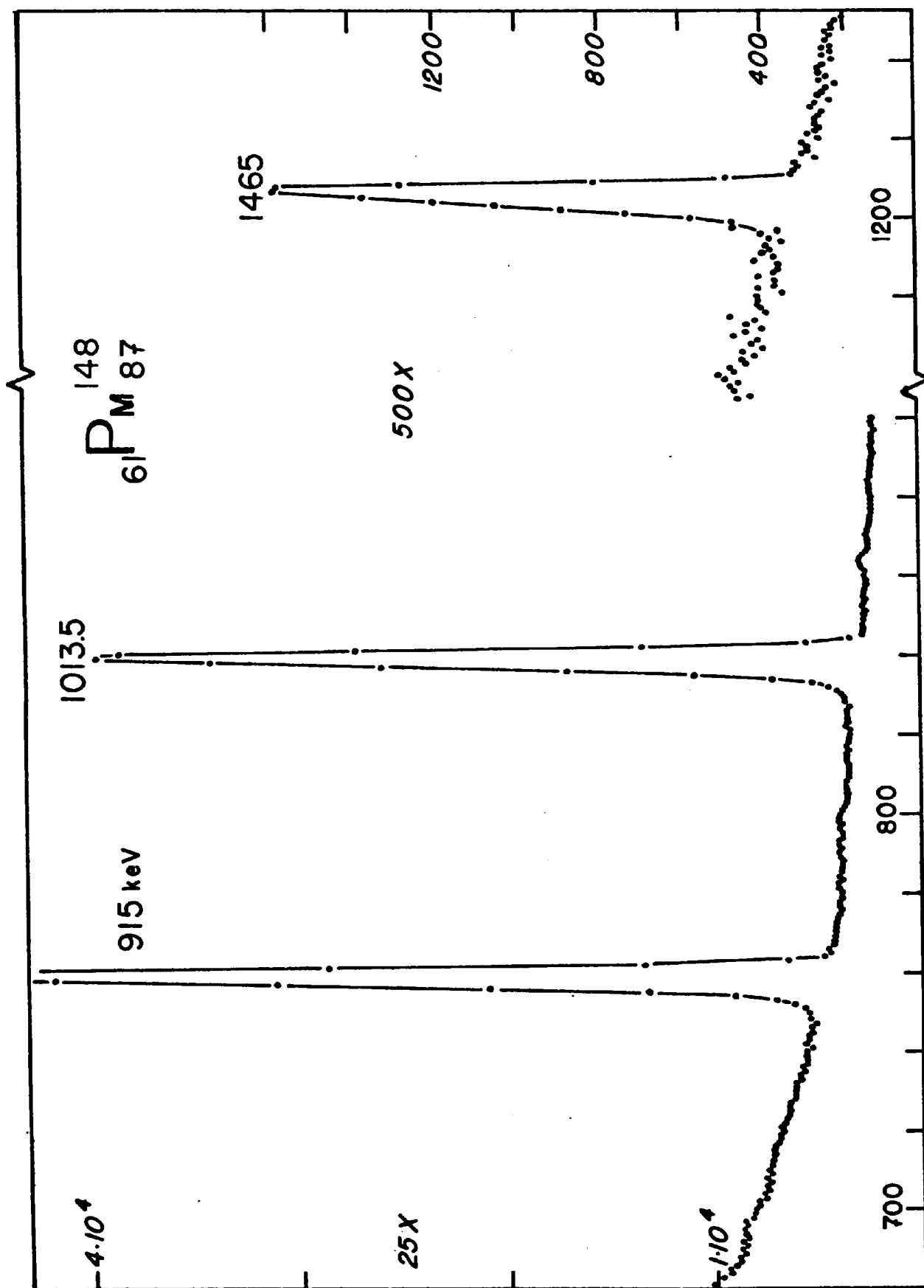


Fig. 10 -- cont.

Directional Correlation Measurements

The beta - gamma directional correlation of the 1.90 MeV β^- - 0.550 MeV γ cascade was measured as a function of the beta energy in the range 0.82 MeV to 1.69 MeV. Inspection of the decay scheme (Fig. 9) shows that there should be no interference from either a gamma - gamma coincidence background or from another beta - gamma cascade if the beta energy in the cascade of interest is selected above 1.0 MeV. This absence of interference is confirmed by the linearity of the Fermi plot (Fig. 11) and by the lack of any measurable gamma - gamma coincidence background with the beta detector shielded from the beta radiation.

Simultaneous measurement of the correlation for 9 beta energies in the range indicated was made by use of a multichannel analyzer operated in the mode discussed in Chapter III. At the same time, an additional single - channel analyzer -- coincidence unit combination was used to measure the correlation for a beta energy window of 0.2 MeV with different average energies for each run. This provided a cross check on the performance of the gating circuits of the analyzer and a confirmation of the energy variation of the correlation as calculated from the multichannel analyzer data.

A total of 24 measurements were made on three different Pm^{148} sources. The total true coincidences ranged from $120 \cdot 10^3$ to $12 \cdot 10^3$ per angle per energy point over the energy range investigated. The ratio of true - to - chance counts varied from 2 to 24 depending on the initial strength of the sources.

The results of the measurements are summarized in Figure 12 and

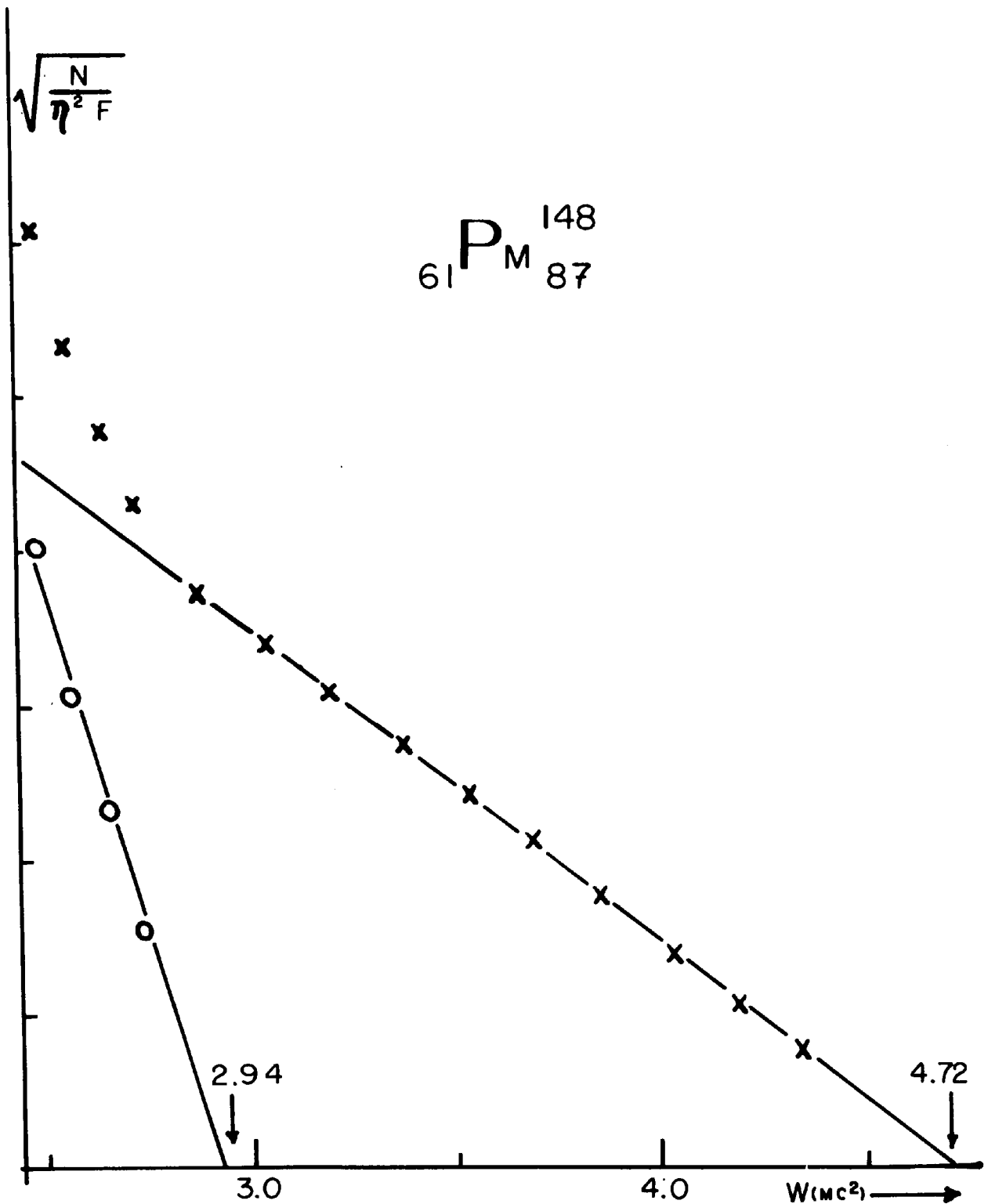


Fig. 11 -- Fermi plot of the multichannel analyzer beta spectrum of Pm^{148} (5.4 d.) in coincidence with the 550 keV gamma transition with chance coincidences subtracted (X). The 0.99 MeV beta transition (O) appears after subtraction of the 1.90 MeV beta component.

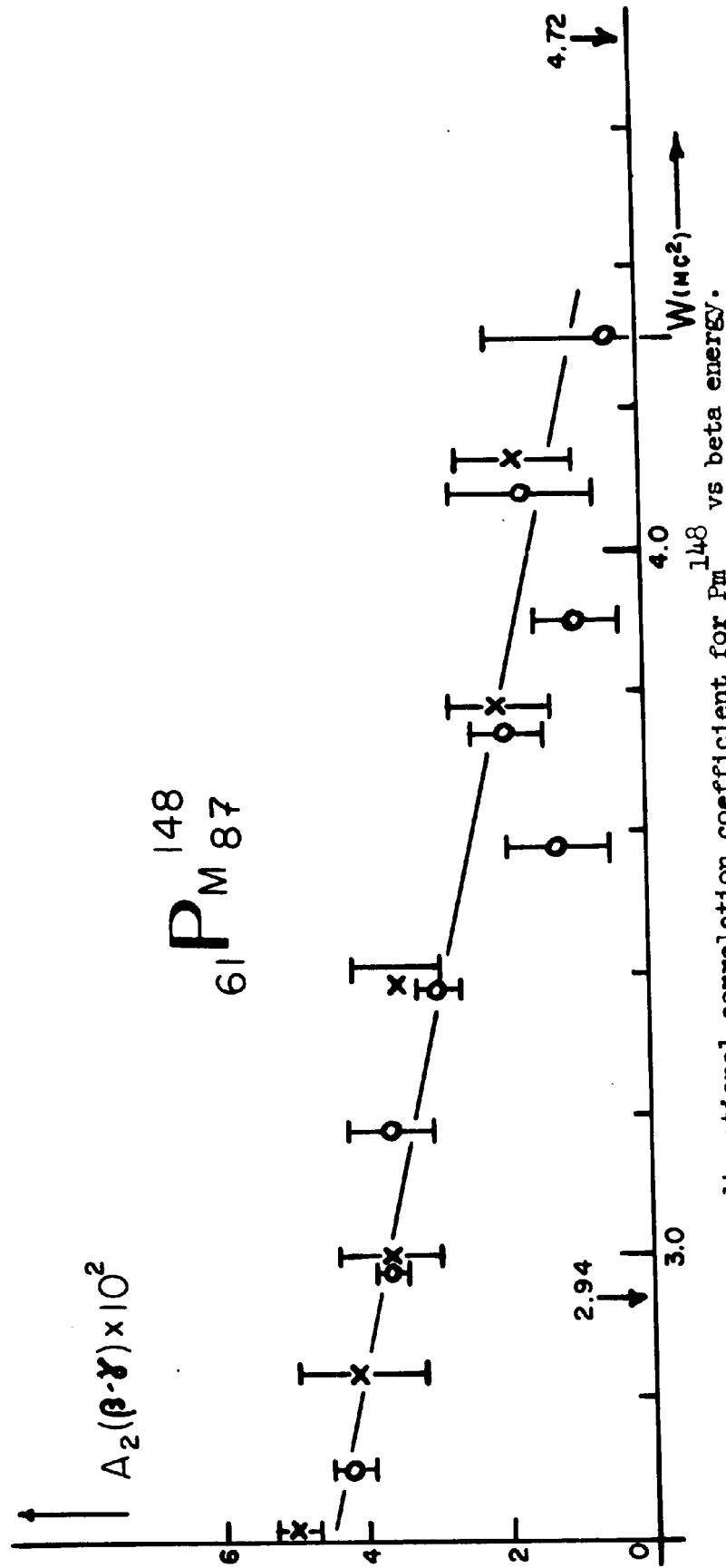


Fig. 12 -- Beta - gamma directional correlation coefficient for $^{148}_{61}\text{Pm}$ vs beta energy.

in Table II where the coefficient $A_2(\beta-\gamma)$ has been computed from the measured asymmetry and corrected for solid angle effects. The results of the measurements from both the multichannel and single - channel analyzers are presented with the average energy for each point. The coefficient $A_2(\beta-\gamma)$ is that appearing in the equation for the correlation function

$$W(\theta) = 1 + A_2(\beta-\gamma) P_2(\cos\theta) \quad (5.1)$$

and is equal to the product of the correlation coefficients for the beta and gamma radiations:

$$A_2(\beta-\gamma) = A_2(\beta) A_2(\gamma). \quad (5.2)$$

The $2^+ (\gamma) 0^+$ radiation observed in the cascade of interest is a pure electric quadrupole with $A_2(\gamma) = -0.5976$, as given by theory. The coefficient $A_2(\beta)$ has been computed from the above relation and is also presented in Table II. Since the gamma - gamma interference was at most 5% of the counting rate for even the lower beta energy points, no corrections were made for this background which is within the experimental error for these points.

Conclusions

It is evident from the results of the measurement that the ξ - approximation does not describe the energy dependence of the correlation coefficient, $A_2(\beta)$. This can be seen even more clearly by considering the reduced correlation coefficient, which is calculated from

$$\epsilon_0(\beta) = A_2(\beta) W / (\lambda_2 p^2). \quad (5.3)$$

TABLE II
Correlation Coefficients for Pm 148

$\bar{E}$ (MeV)	$\bar{W}$ (MC ²)	$A_2(\beta - \gamma)$		$A_2(\beta)$	$\epsilon_0(\beta)$
		Multichannel	Single-channel		
0.82	2.60	-----	+0.050 $\pm$ 0.003	-0.084 $\pm$ 0.005	-0.047 $\pm$ 0.003
0.91	2.77	+0.042 $\pm$ 0.003	-----	-0.070 $\pm$ 0.005	-0.036 $\pm$ 0.003
0.94	2.84	-----	+0.041 $\pm$ 0.009	-0.069 $\pm$ 0.015	-0.034 $\pm$ 0.007
1.01	2.98	+0.036 $\pm$ 0.002	-----	-0.060 $\pm$ 0.003	-0.028 $\pm$ 0.001
1.02	3.00	-----	+0.036 $\pm$ 0.009	-0.060 $\pm$ 0.015	-0.028 $\pm$ 0.007
1.11	3.18	+0.036 $\pm$ 0.006	-----	-0.060 $\pm$ 0.010	-0.026 $\pm$ 0.004
1.21	3.38	+0.029 $\pm$ 0.003	-----	-0.049 $\pm$ 0.005	-0.019 $\pm$ 0.002
1.22	3.39	-----	+0.035 $\pm$ 0.006	-0.059 $\pm$ 0.010	-0.023 $\pm$ 0.004
1.32	3.58	+0.012 $\pm$ 0.007	-----	-0.020 $\pm$ 0.012	-0.007 $\pm$ 0.004
1.40	3.74	+0.019 $\pm$ 0.005	-----	-0.032 $\pm$ 0.008	-0.011 $\pm$ 0.003
1.42	3.78	-----	+0.020 $\pm$ 0.007	-0.033 $\pm$ 0.012	-0.011 $\pm$ 0.004
1.48	3.90	+0.009 $\pm$ 0.006	-----	-0.015 $\pm$ 0.010	-0.005 $\pm$ 0.003
1.58	4.08	+0.016 $\pm$ 0.010	+0.017 $\pm$ 0.008	-0.028 $\pm$ 0.015	-0.009 $\pm$ 0.005
1.69	4.30	+0.004 $\pm$ 0.017	-----	-0.007 $\pm$ 0.028	-0.002 $\pm$ 0.008

This reduced coefficient is presented in Table II and displayed in Figure 13. If the correlation had followed the p^2 / W dependence of the ξ -approximation, $\epsilon_0(\beta)$ would have been a constant. The function $\lambda_2(W)$ is a Coulomb correction factor and is tabulated by Kotani and Ross (34) along with another Coulomb correction factor, $\lambda_1(W)$.

If the electron radial wave functions are simplified by the use of the Konopinski - Uhlenbeck approximation (26), the reduced correlation coefficient can be written as (4, p. 1094)

$$\epsilon_0(\beta) = \frac{R_3 + (\lambda_1 / \lambda_2) e W}{C(W)} \quad (5.4)$$

where, R_3 and e are energy - independent combinations of nuclear matrix elements; $C(W)$ is the beta spectrum shape factor; and λ_1 / λ_2 is a nearly constant ratio of Coulomb correction factors, $\lambda_1 / \lambda_2 \approx 1$.

The shape factor may be considered to be constant to allow for a rough evaluation of the results of the measurement. This assumption is supported by the linearity of the Fermi plot of the beta transition (Fig. 11) investigated. With this simplification, the expression for the reduced correlation coefficient becomes a linear function of the beta energy. The line in Figure 13 is a least squares fit to the data points of the expression

$$\epsilon_0(\beta) = (R_3 / C) + (\lambda_1 / \lambda_2) (e / C) W, \quad (5.5)$$

with $(R_3 / C) = -0.103 \pm 0.007$ and $(\lambda_1 / \lambda_2) (e / C) = +0.024 \pm 0.002$.

In the modified B_{ij} -approximation (4, p. 1100), the second rank tensor matrix element is assumed to be relatively large and the

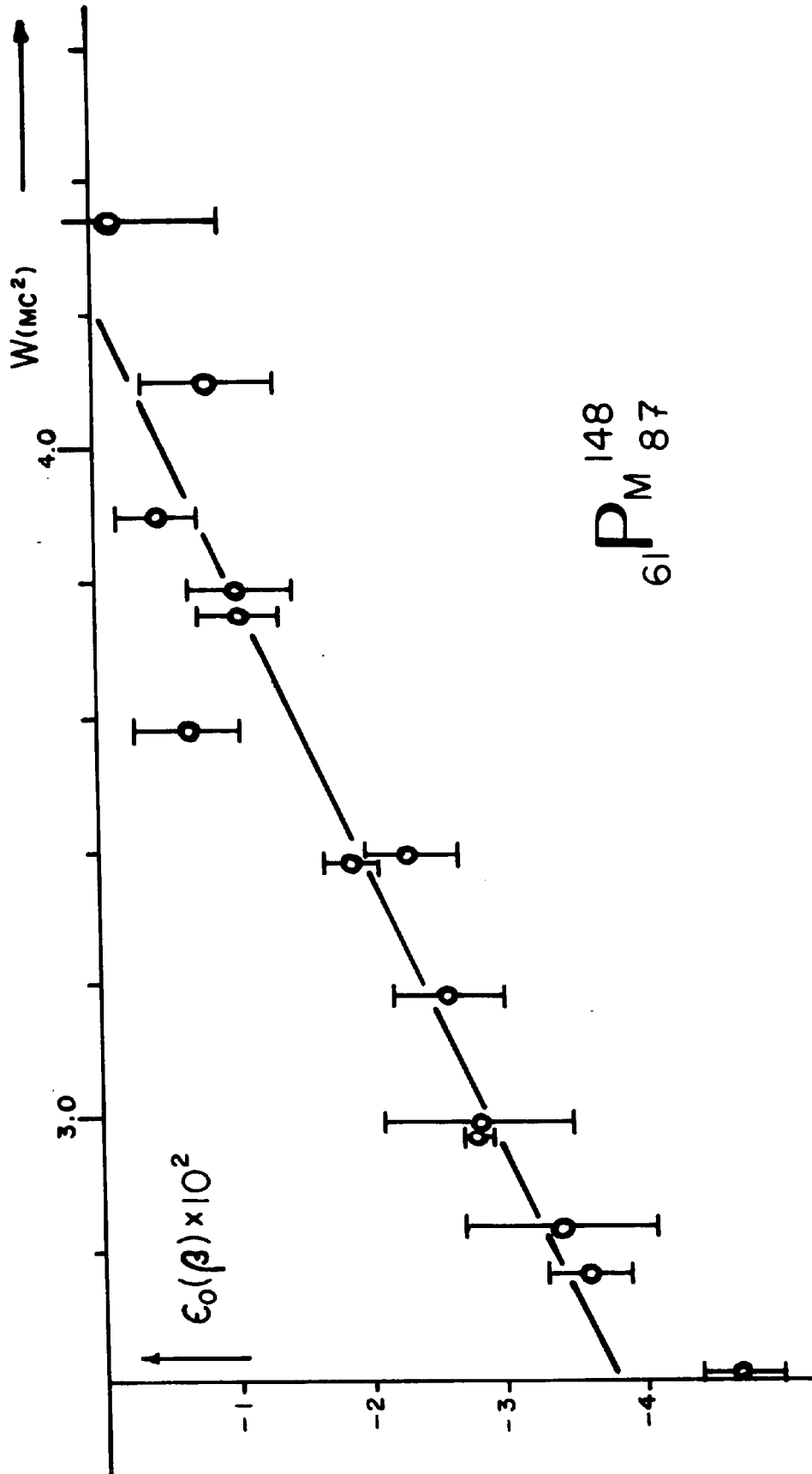


Fig. 13 -- Reduced beta correlation coefficient for Pm^{148} vs β energy.

expressions for R_3 and e become

$$R_3 = -0.342 z_2 Y_1 \quad \text{and} \quad e = -0.0348 (z_2)^2 \quad (5.6)$$

where the matrix elements are denoted by the parameters

$$z_2 = C_A \langle iB_{ij} \rangle \quad (5.7)$$

and

$$Y_1 = + \frac{1}{R} C_V \langle \hat{\alpha} \rangle + \xi (C_V \langle i\hat{f} \rangle + C_A \langle \hat{\sigma} \times \hat{r} \rangle)$$

with R , the nuclear radius.

The disagreement in the signs of the experimental and theoretical values for the energy coefficient, (e / C) , can be taken to mean that the modified B_{ij} -approximation does not describe this beta transition. That is, the matrix elements $\langle \hat{\alpha} \rangle$, $\langle i\hat{f} \rangle$, and $\langle \hat{\sigma} \times \hat{r} \rangle$ are small, but not zero for this transition. Here again, it appears that both the cancellation of matrix elements and selection rule effects are operative.

Thus the correlation measured in this investigation will be useful for the determination of the values of the individual matrix elements. Unfortunately, the directional correlation data alone is not sufficient to allow a determination of these matrix elements. Measurements on the shape factor and on the beta - gamma circular polarization, for example, would be necessary to provide data for a computer search for possible values of matrix elements.

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