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INVESTIGATION OF LONGITUDINAL POLARIZATION
AND OTHER PROPERTIES OF SOME BETA-TRANSI-
TIONS

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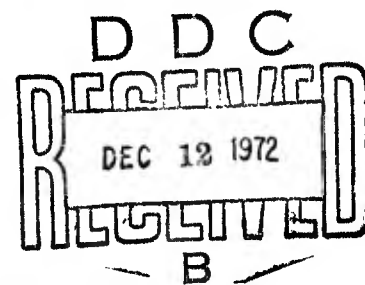
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FINAL REPORT

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13. ABSTRACT

Several hindered allowed β -transitions and forbidden decays are investigated through β -ray longitudinal polarization, β - γ correlation and β -shape factor studies. The results are presented and their significance is examined. No evidence is found, within experimental limits, for significant contributions of higher order effects in hindered allowed beta-decay with moderate energy release. Considerable success is achieved in understanding properties of several forbidden β -transitions in terms of meaningful nuclear models and expectations based on current theory of weak interactions. Studies of influence of multiple scattering of electrons on angular correlations are reported.

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1. On Higher Order Effects in Some Abnormal Allowed Beta-Transitions, K.S.R. Sastry, R.J. Ouellette, Y. Sharma and R. Strange, Phys. Letters 26B (1968) 207.
2. Beta-Gamma Directional Correlation in the Decay of ^{148}Pm , R.A. Amadori, N.K. Gupta and K.S.R. Sastry, Nucl. Phys. A118 (1968) 33.
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7. Matrix Elements for the $1^- \rightarrow 0^+$ Beta-Decay of ^{148}Pm , R.A. Amadori, J.R. Horgan, Jr. and K.S.R. Sastry, Book of Contributions, International Conference on Properties of Nuclear States, Montreal (1969) p. 225.
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3. Beta-Decay of La^{140} to the 2084 keV 4^+ Excited State of Ce^{140} , Bull. Am. Phys. Soc. 15 (1970) 643. (with J.R. Horgan, Jr.)

C. PAPERS IN PREPARATION AND COMPLETED WORK (Most of these will be submitted to Nuclear Physics Journal)

1. Beta-Ray Longitudinal Polarization in the Decay of ^{148}Pm , ^{115m}Cd and ^{32}P , R.A. Amadori, J.R. Horgan, Jr. and K.S.R. Sastry.
2. Studies on the Decay of ^{115}Cd and ^{140}La , J.R. Horgan, Jr. and K.S.R. Sastry.
3. Directional Correlation Studies on β -Transitions in the Lead Region, N.K. Gupta, D.V. Rao and K.S.R. Sastry.
4. Spin and Parity of the Ground State of ^{126}Sb , N.K. Gupta, R.A. Amadori, J.R. Horgan, Jr., and K.S.R. Sastry.
5. The Second Forbidden β -Decay of ^{94}Nb , N.K. Gupta and K.S.R. Sastry.
6. Some K-Shell Internal Conversion Coefficients, K.S.R. Sastry, R.E. Wood, J.M. Palms and P. Venugopala Rao.
7. Shape of the $1^- \rightarrow 0^+$ β -transition in the decay of ^{212}Bi , V. Bhale Rao, B. Sahai and K.S.R. Sastry.
8. Shapes of Beta-Spectra Using a 4π Si(Li) Spectrometer, K.S.R. Sastry.

9. Influence of Multiple Scattering of Electrons on β - γ and e^- - γ Correlations, N.K. Gupta, D.V. Rao and K.S.R. Sastry (to be communicated to Nucl. Instruments and Methods).

7. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS PERIOD:

a) Graduate Students:

- (1) R.A. Amadori, Ph.D. 1969. Thesis: Investigation of the Beta-Decay of the Ground State of Promethium-148 (University of Massachusetts, Amherst).
- (2) N.K. Gupta, Ph.D. 1969. Thesis: Nuclear Structure Studies Through Directional Correlations (University of Massachusetts, Amherst).
- (3) J.R. Horgan, Jr., Ph.D. 1970. Thesis: Investigation of the Beta-Decays of Cadmium-115m, Cadmium-115 and Lanthanum-140 (University of Massachusetts, Amherst).
- (4) Dandamudi V. Rao, Ph.D. 1972. Thesis: Nuclear Structure Studies on A=211 Isobars (University of Massachusetts, Amherst).
- (5) R.J. Ouellette, M.S. 1967. Thesis: Investigation of Higher Order Effects in Some Abnormal Allowed Beta-Decays (University of Massachusetts, Amherst).
- (6) R. Harding, M.S. 1970. Thesis: Inner Shell Electron Ionization by β -Particle Impact (University of Massachusetts, Amherst).

(7) Y. Sharma, M.S. 1971. Thesis: A Study of Beta-Gamma Angular Correlation in Some Abnormal Allowed Beta-Decays (University of Massachusetts, Amherst).

b) Undergraduate Students:

- (1) J.R. Mortarelli, B.S. 1967. Senior Honors Thesis: Design of a Short Magnetic Lens for β -Ray Polarization Studies (University of Massachusetts, Amherst).
- (2) John Preston, B.S. 1967.
- (3) Richard Strange, B.S. 1966.

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INVESTIGATION OF LONGITUDINAL POLARIZATION
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ABSTRACT

Several hindered allowed β -transitions and forbidden decays are investigated through β -ray longitudinal polarization, β - γ correlation and β -shape factor studies. The results are presented and their significance is examined. No evidence is found, within experimental limits, for significant contributions of higher order effects in hindered allowed beta-decay with moderate energy release. Considerable success is achieved in understanding properties of several forbidden β -transitions in terms of meaningful nuclear models and expectations based on current theory of weak interactions. Studies of influence of multiple scattering of electrons on angular correlations are reported.

I. INTRODUCTION AND STATEMENT OF THE PROBLEM

Early in 1965 an extensive series of experiments were planned to be carried out in this laboratory in order to measure properties of nuclear β -transitions such as β -ray longitudinal polarization, β -spectrum shapes and β - γ angular correlations. Such information was intended to be utilized to investigate

- (i) higher order effects in nuclear β -decay
- (ii) the β -decay matrix elements and their relation to specific nuclear models, and
- (iii) the validity of the relationships between matrix elements of the coordinate type and the relativistic type predicted by the current theories of weak interactions.

While facilities for β - γ angular correlation measurements and for β -spectrum shape studies were being developed through initial support provided by the University of Massachusetts, a proposal was submitted to the U.S. Army Research Office, Durham, N.C. for assistance to build the β -ray longitudinal polarization part of our program and for support of the β -decay studies planned to be carried out in this laboratory. With the materialization of grant support from the Army Research Office, Durham, effective October 1966 it became possible to carry out our experiments.

The Army grant ARO-D-31-124-G859 was made for the three year period (October 1966 to October 1969) and was extended to June 1970 since no additional funds were involved. A supplemental grant DAH-CO4-70-C-0064 was received for the period July 1970 - January 1971.

A summary of the nuclei investigated, the experimental methods used and the major interest in the work is given below:

NO.	NUCLEI	EXPERIMENTAL METHOD	INTEREST
1. a)	Pm ¹⁴⁸ , Cd ^{115m} , P ³²	β -ray polarization	β -decay matrix elements and models; higher order effects
2. a)	Na ²² , Co ⁵⁶ , Co ⁵⁸ , Co ⁶⁰ , Ag ^{110m} , Sb ¹²⁴ , Cs ¹³⁴ , Eu ¹⁵⁴ , Pm ¹⁴⁸	β - γ angular correlation	Higher order effects in allowed β -decay
b)	Cs ¹³⁴	Shape of β -spectrum	
3. a)	Sb ¹²⁶	β - γ angular correlation	Spin of Sb ¹²⁶
b)	Cd ¹¹⁵ , La ¹⁴⁰ , Pm ¹⁴⁸ , Tl ²⁰⁷ , Tl ²⁰⁸ , Pb ²¹¹ , Bi ²¹⁴	β - γ angular correlation	First forbidden β -decay matrix elements and models
c)	Nb ⁹⁴	β - γ angular correlation, β - γ (CP) correlation	Second forbidden β -decay matrix elements and models
d)	Nb ⁹⁴ , Cl ³⁶ , Cs ¹³⁷	Shape of β -spectrum	Second forbidden matrix elements
e)	Bi ²¹²	Shape of β -spectrum	First forbidden matrix elements and residual n-p interaction

Other completed studies include (1) effect of multiple scattering of electrons in the source on e^- - γ and β - γ correlations; (2) measurement of K-internal conversion coefficients, and (3) gamma-gamma directional correlation measurements using NaI-Ge(Li) detectors.

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II. THE EXPERIMENTAL METHODS - A BRIEF DISCUSSION

IIa) Beta-gamma Directional Correlation: Although for unpolarized nuclei the radiations (β, γ etc) are emitted isotropically, when one selects out the direction of emission of one of the radiations (say β -ray), the γ -radiation (if any) that follows the β -decay shows a definite angular distribution when observed in coincidence with the preceding radiation. The angular distribution function $N(\theta)$ is given by

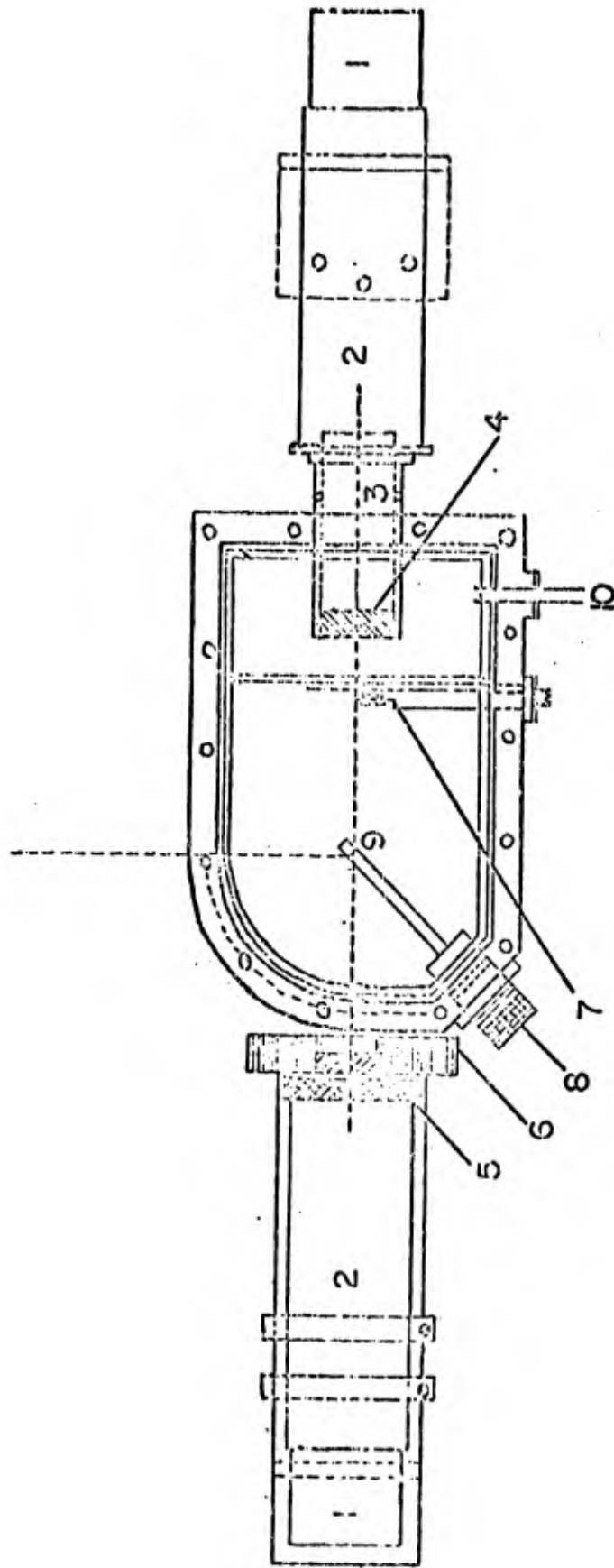
$$N(\theta) \propto 1 + A_2 P_2(\theta) + A_4 P_4(\theta) + \dots$$

where $P_n(\theta)$ are Legendre polynomials, and A_2, A_4 etc. are the angular correlation coefficients, and are functions of the nuclear matrix elements, the angular momenta of the nuclear states and the radiations involved and their energies. For allowed β -decay $N(\theta) =$ constant (i.e., isotropic β - γ correlation) unless significant contributions from higher order matrix elements occur. For first forbidden β -transitions

$$N(\theta) \propto 1 + A_2 P_2(\theta)$$

In the case of second forbidden β -transitions, the $P_4(\theta)$ term may also be present.

The experimental apparatus uses a NE102 plastic scintillator for β -rays and a 2"x2" NaI detector for γ -rays. A sketch of apparatus is shown in Fig. 1. Coincidence electronics of the slow-fast type are used with resolving times of about 30-40 nsecs. Provision exists for multichannel recording of the data and for simultaneous measurement of more than one β - γ cascade.



- 1 PRE-AMPLIFIER
- 2 PHOTOMULTIPLIER TUBE
- 3 LUCITE LIGHT PIPE
- 4 PLASTIC SCINTILLATOR
- 5 NaI(Tl) SCINTILLATOR

- 6 LEAD SHIELD
- 7 BETA DETECTOR GATE
- 8 SOURCE HOLDER
- 9 SOURCE
- 10 VACUUM OUTLET

FIGURE 1

The γ -detector is movable and the angle between β - and γ -detector axes can be varied from 90° to 180° . In another arrangement (not shown) a 3"x3" NaI detector is used and the angle between β - and γ -detector axes is variable from 90° to 270° . Special care is taken to minimize scattered γ -radiation from reaching the detectors. Contribution from γ - γ coincidence background is experimentally measured in each case by stopping the β -rays with an aluminum gate in front of the β -detector. For positron decays, the effect of annihilation quanta- β -coincidence background was evaluated in the manner described by Müller.¹ Other precautions and procedures employed are described by Gupta,² and by Amadori et al.³ In the case of β - γ correlation work involving hindered allowed β -transitions, about 2 to 3 million coincidences were collected at each angle, and in the evaluation of γ - γ coincidence background at least 5×10^5 to 10^6 coincidences were collected. This was necessary in view of very small β - γ anisotropies that were expected. The allowed β - $\gamma(\theta)$ measurements thus proved to be very time consuming.

IIb) Shapes of Beta-Spectra: The energy or momentum dependence of β -particles emitted in nuclear decay is predicted to follow the statistical distribution, $(W^2-1)(W_0-W)^2$, (W being β -ray energy and W_0 the end point), required by the sharing of the decay energy between the leptons and residual nucleus. Although the majority of β -transitions follow this phase space behaviour, several β -transitions display additional energy dependence of the β -spectrum. The energy dependence $C(W)$ which a β -transition displays over and above the statistical spectrum is known as the shape of the β -spectrum. It is a function of the β -decay matrix elements and β -ray energy and the end point.

Usually magnetic spectrometers of high resolution are employed in β -spectrum measurements and β -shape factor studies. This method is excellent for β -transitions without interference from other β -rays. Since nuclei often β -decay to excited states, one can have clean measurements only for the most energetic β -transition at energies above the end point of the inner β -group(s). Furthermore all inner group β -transitions suffer obscurity due to the outermost β -transition.

An apparatus for the study of β -spectra and their shapes has been developed in this laboratory utilizing two matched Si(Li) detectors. The principle is simple:

Although Si(Li) detectors with their very high resolution are excellent for accurate β -ray spectral studies, they suffer from the problem of backscattering of electrons in the detector. As a result β -spectra measured with a single detector are falsified even if the nucleus used emits only a single β -ray group. Backscattering corrections and spectrum unfolding methods may serve in some cases but, on the whole, the problem of backscattering essentially renders the Si(Li) detector quite useless for precision studies in spite of its high resolution.

An easy and effective way out is to use two Si(Li) detectors of identical characteristics with the source sandwiched between the detector faces. For electrons of any given energy, there will be then a full energy peak and a backscatter tail in either detector. However if one sums the output of the two detectors, the problem of backscattering is eliminated. The pulses from the two detectors can be summed externally by electronic means or internally. The external sum method is very tedious. The internal summation works very well

only if the detectors have identical response. In our case specially selected matched pairs of Si(Li) detectors have been used. The detector surfaces are insensitive and can be cleaned if desired. Two pairs of detectors are used: one with a 2 mm depletion depth, and the other with 5 mm depletion depth. The former is suitable for β -ray energies up to about 1.2 MeV while the latter is used for energetic β -rays up to about 2.5 MeV. The detectors, of course, are cooled by liquid nitrogen and low noise electronics are used. This way of operating the two detectors in parallel affects the resolution somewhat. Thus for detectors with a resolution of 5 keV FWHM at 0.600 MeV, the effective resolution is about 7 keV FWHM at the same energy when the internal summation is done.

The advantages of such a sandwich detector system are the following:

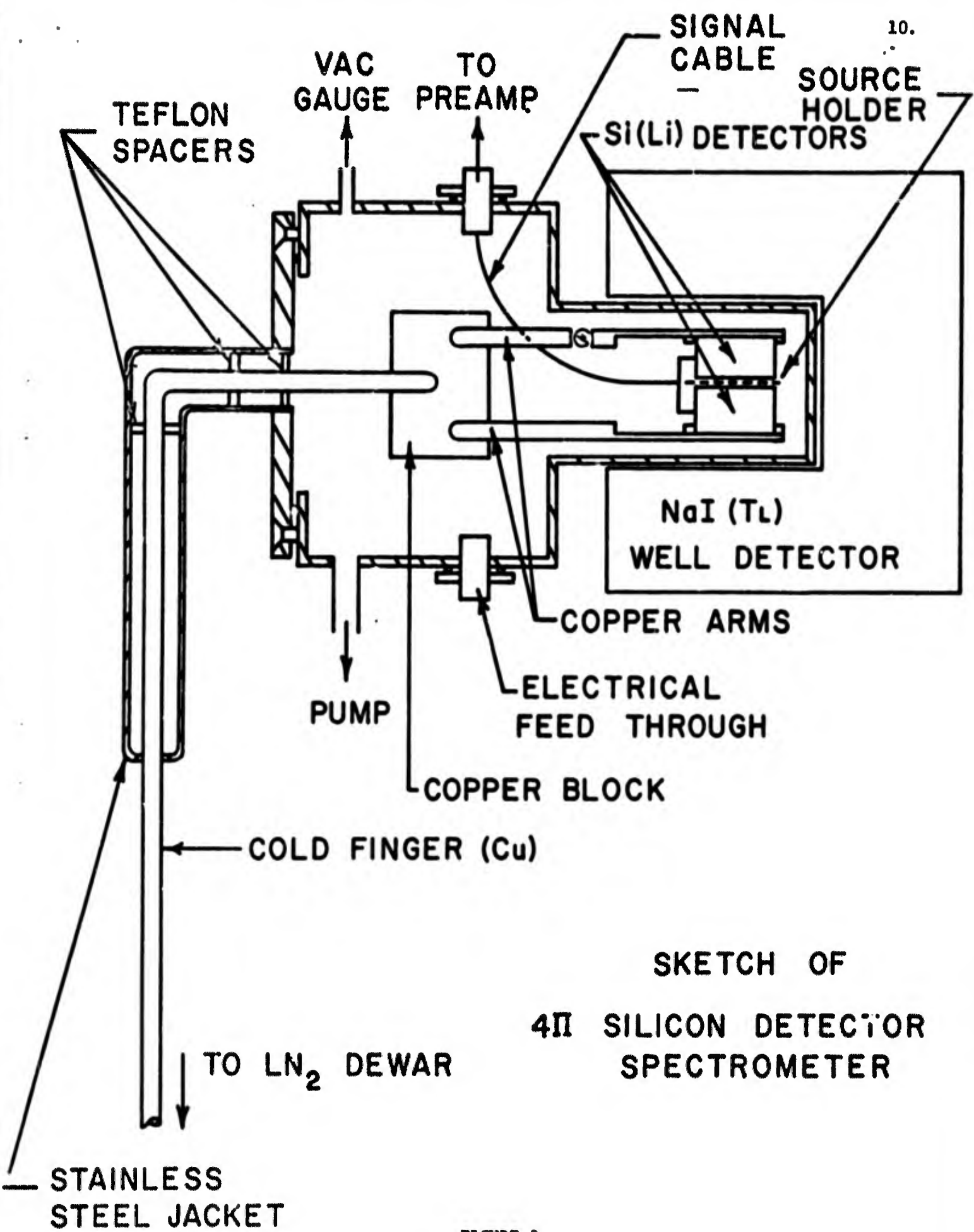
- (i) The geometry is essentially of the 4π type. Thus very weak sources are adequate. In fact the sources should be weak ($\sim 10^{3-4}$ dis/min) to prevent pile up effects.
- (ii) The measurements are fast, and the technique is suitable for nuclei of short halflives. Errors due to decay corrections inherent in point-by-point data collection in the case of magnetic spectrometers are avoided as all data are measured simultaneously.
- (iii) Long lived sources or sources of low specific activity can be studied with essentially no problems of energy degradation due to scattering in the source material since in this method only a very small amount of activity is needed for the experiment, and hence the mass of the source is very small.

(iv) Perhaps the greatest advantage offered by this method is its applicability for the study of inner β -transitions when observed in coincidence with the cascade gamma-ray. To facilitate such applications a 4"x3" NaI detector with a well of 2-1/4" dia x 2" depth is placed so as to envelop the Silicon detectors. This system also has the advantage that the true β -spectrum is obtained even if there is a large energy dependent β - γ correlation because of the 4π geometry.

A sketch of this 4π Silicon Detector Spectrometer is given in Figure 2. This instrument has been so far used to measure relatively simple situations so as to gain an understanding of systematic effects. The following β -spectra have been measured: (i) P^{32} (allowed) (ii) Tl^{204} (unique first forbidden) and (iii) Cl^{36} and Cs^{137} (second forbidden β -transitions). All of these are pure β -emitters, and their measured shapes (see Figure 3) are in good agreement with work utilizing magnetic spectrometers⁴ and other methods.⁵

To check the operation in the presence of cascade γ -rays, we measured so far β -spectrum of the allowed β -decay of Co^{60} in coincidence with the 1.17 and 1.33 MeV γ -rays in Ni^{60} . A statistical shape was obtained in spite of the large ft value ($\log ft = 7.5$) for an allowed β -decay.⁶ Encouraged by this result, we measured the shape of the $6^+ \rightarrow 4^+$ second forbidden β -decay of Nb^{94} in coincidence with the γ -rays in Mo^{94} . The experimental shape is in fine agreement with the magnetic spectrometer data of Hocquenghem and Berthier,⁷ and of Snyder and Beard.⁸

Measurement of the β -spectrum of the highly hindered allowed ($4^+ \rightarrow 4^+$) β -transition ($\log ft = 8.9$)⁶ in the decay of Cs^{134} has been



SKETCH OF
4π SILICON DETECTOR
SPECTROMETER

FIGURE 2

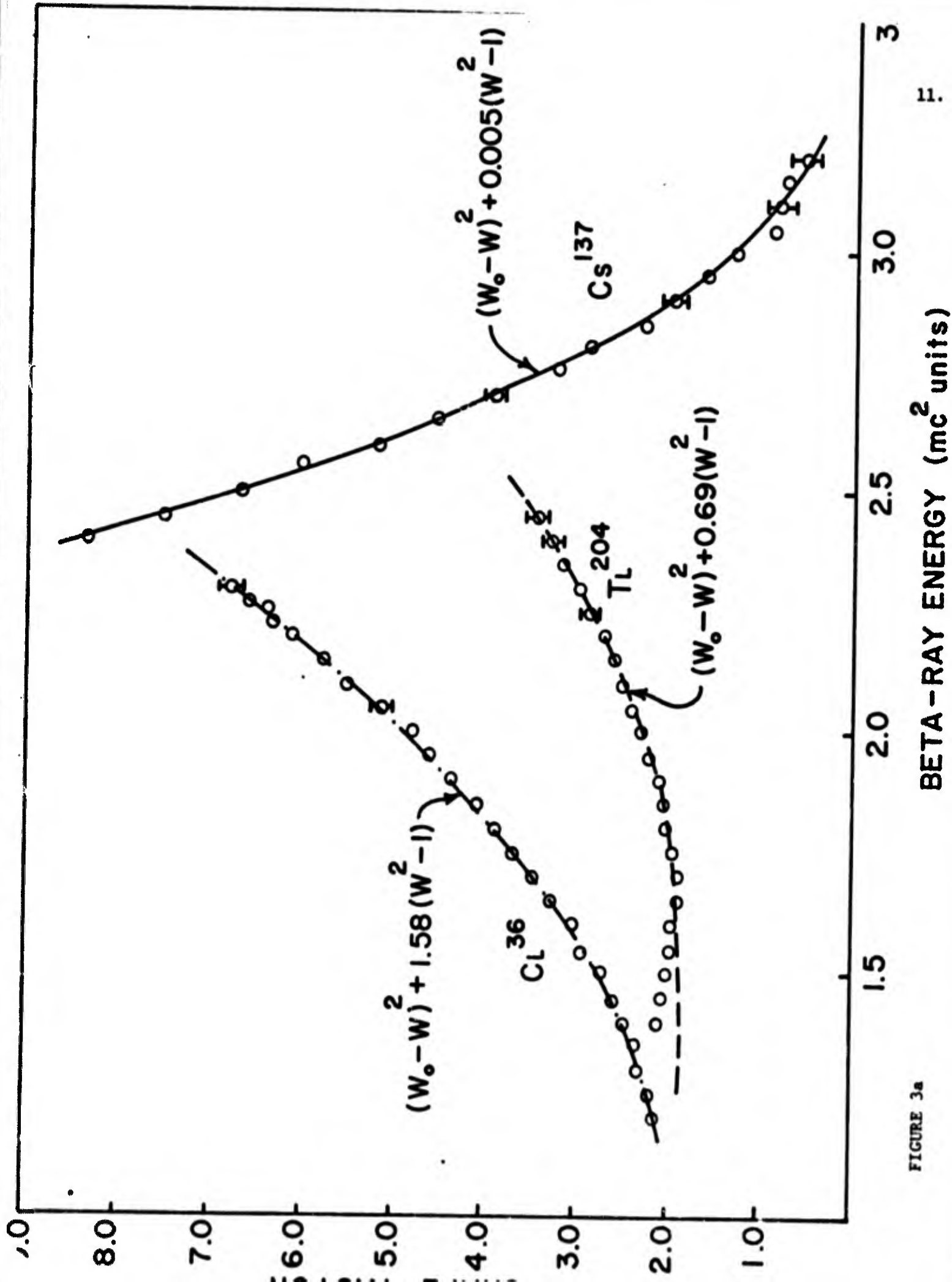


FIGURE 3a

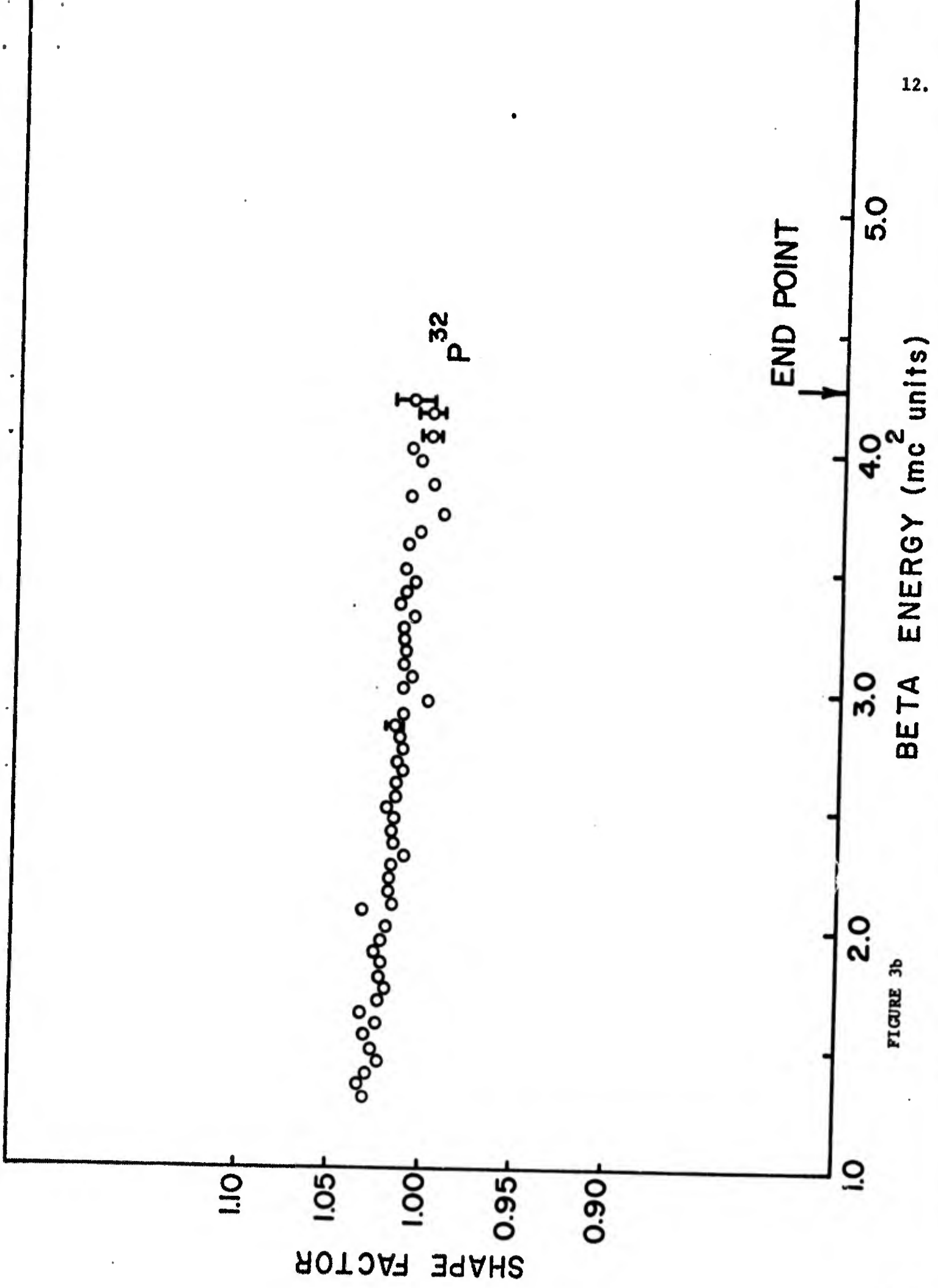


FIGURE 3b

made using β - γ coincidence method. Preliminary analysis does not indicate any significant deviation from the statistical shape, the implication being that the higher order contributions are negligible although the decay is strongly retarded.

In view of the above successes, we are in the process of undertaking an extensive series of measurements of shapes of β -spectra of inner- β -transitions and β -transitions in the decay of long lived and low specific activity sources.

A discussion of our results will be presented in Section III.

IIc) Beta-Ray Longitudinal Polarization

(i) Introduction: That nuclear β -rays are longitudinally polarized has been well established. Since β -ray longitudinal polarization (P_L) is a measure of the quantity $\langle \underline{\sigma} \cdot \hat{p} \rangle$, a pseudoscalar, observation of this quantity is evidence of parity non-conservation⁹ in the β -decay interaction. Frauenfelder et al.¹⁰ were the first to show experimentally that nuclear β^- rays are indeed longitudinally polarized to the extent of $-v/c$, (v being the speed of the β -particle and c the speed of light), the negative sign indicating a left-handed helicity for β^- particles.

Although the theory of weak interactions predicts $\pm v/c$ polarization for β^\pm -radiations, one expects that nuclear structure effects might alter this behavior in special cases. Such cases are interesting for an investigation of the β -decay matrix elements. The case of Bi^{210} with about 25-30% reduction from $-v/c$ polarization has been a classic example.¹¹

The β -ray longitudinal polarization measurements originally proposed sought to investigate the role of higher order contributions

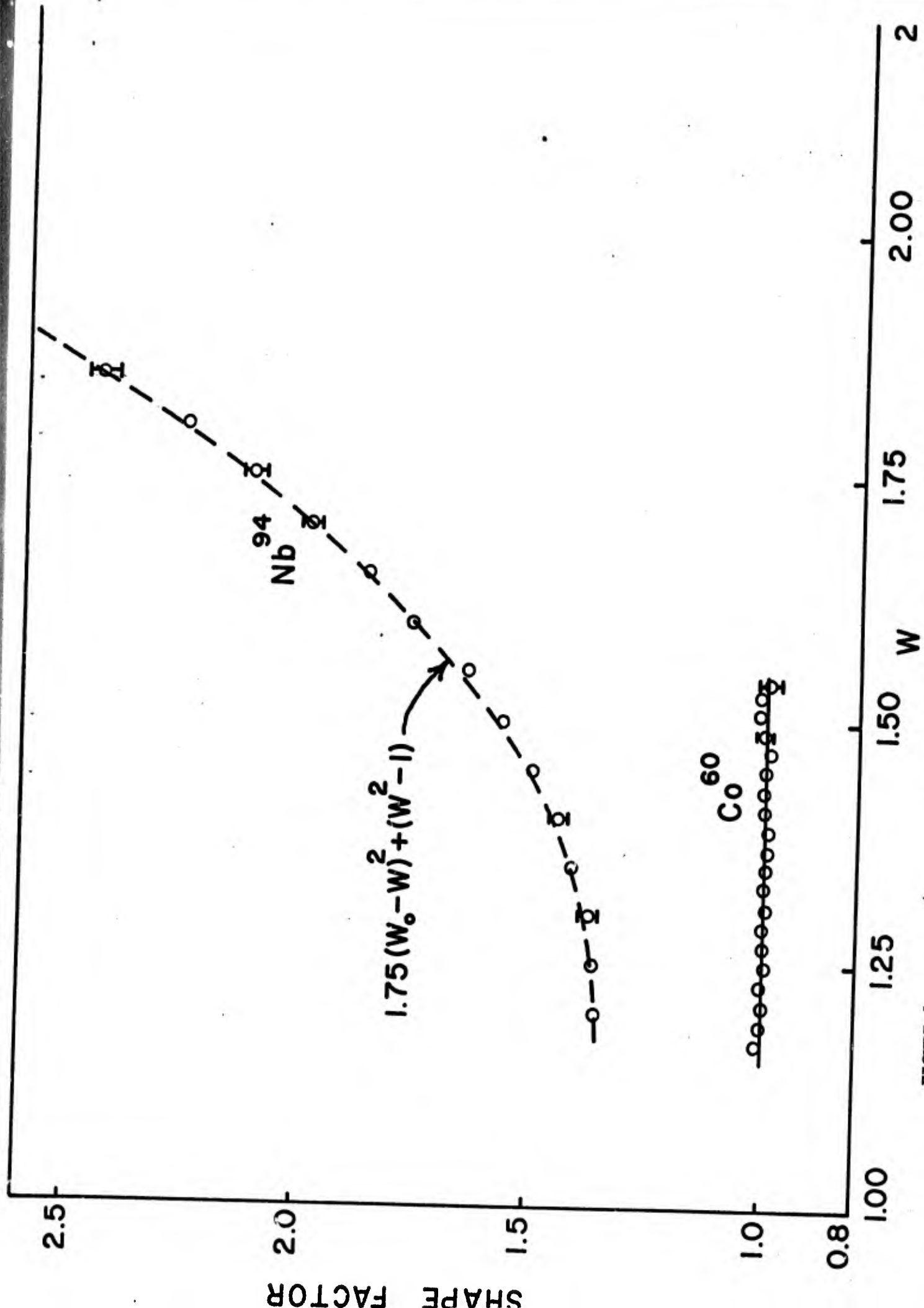


FIGURE 3c

BETA ENERGY (mc^2 units)

and other subtle effects in hindered allowed β -decay. Anticipating that such effects might be perceivable at low β -energies, we wanted to use the principle of Mott Scattering¹² in our measurements. By the time this grant became available, however, our experience with several allowed β -transitions in β - γ directional correlation studies¹³ and the experience of others^{14,15} indicated that the higher order effects are too small to be detectable in β -ray polarization measurements. On the other hand, measurements on first forbidden β -transitions seemed to be valuable in obtaining their β -decay matrix elements and thereby understanding the β -ray properties in terms of nuclear models. Another question of importance has been the relationship^{16,17} between the matrix elements $\langle \underline{r} \rangle$ and $\langle \underline{q} \rangle$ arising via the Vector interaction in first forbidden β -decay. For these reasons it was decided to concentrate on the first forbidden transitions. Instead of Mott Scattering, which is suitable mostly for low energy electrons, use has been made of e^-e^- scattering (Møller Scattering)¹⁸ suitable for energetic electrons ($E_\beta > 500$ keV).

(ii) Principle of Møller Scattering Method: The Møller Scattering method has been used earlier by Geiger et al.,¹⁹ Benczer-Koller et al.,²⁰ Ullman et al.,²¹ and Harmsen and Holm²² among others. Good discussions of the method, precautions and various corrections are discussed in the literature.^{23,24} In this report we shall briefly consider the principle and some special details of our apparatus. An extensive discussion has been given in the Ph.D. theses by Amadori²⁵ and by Horgan.²⁶ Details may also be found in a forthcoming paper by Amadori et al.²⁷

The basic principle of β -ray longitudinal polarization measurement is illustrated in Figure 4. Beta-particles of a well defined momentum are selected by means of a short magnetic lens and are incident on polarized electrons in a thin ferromagnetic foil located at the focus of the lens. After scattering, the "incident" and "target" electrons leaving the foil are observed in coincidence by means of suitably located detectors and appropriate electronics. The spin dependence of e^-e^- scattering is such that the scattering is more when the spins of the incident and target electrons are antiparallel. This is easily understood in terms of the Pauli principle for low electron energies. Let us denote by C_{\pm} the coincidence counting rates corresponding to the situation that the spin of the incoming electrons is parallel or anti-parallel relative to the direction of polarization of target electrons in the scattering foil. Then the scattering asymmetry $\delta = 2(C_+ - C_-)/(C_+ + C_-)$ is related to the polarizations of the incident and target electrons by the relation

$$\delta = 2(C_+ - C_-)/(C_+ + C_-) = 2P_L P_T R \quad (1)$$

where P_L = longitudinal polarization of the β -particle

P_T = polarization of target electron

$R = (1 - \sigma_p/\sigma_a)/(1 + \sigma_p/\sigma_a)$ and

$\sigma_{p(a)}$ = Moller Scattering cross sections for parallel (anti-parallel) spins.

The quantity P_T in the above expression for δ is given by the fraction f of polarized electrons in the foil. Since it is very difficult to polarize electrons in a thin foil along a direction

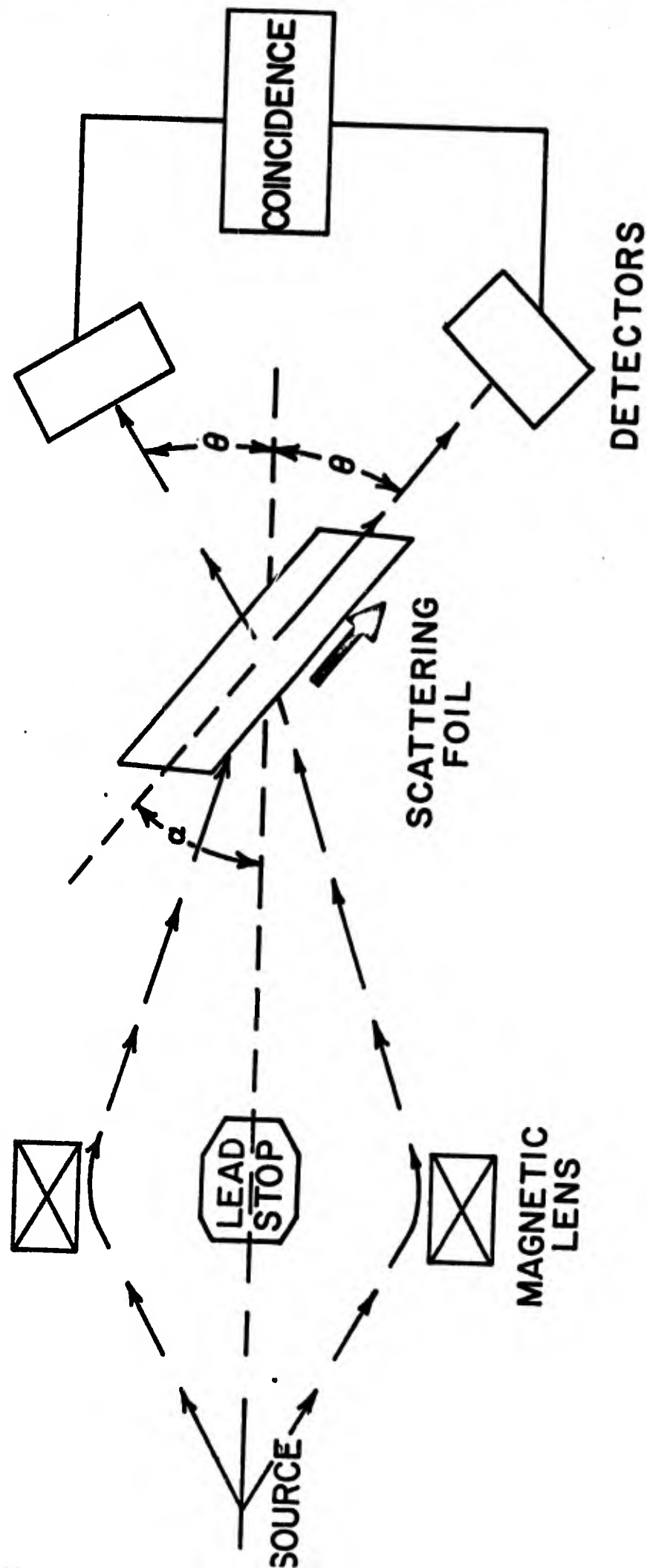


FIGURE 4

**SCHEMATIC ARRANGEMENT FOR BETA-RAY
LONGITUDINAL POLARIZATION MEASUREMENT (MØLLER SCATTER)**

normal to its surface, the ferromagnetic foil is oriented at angle α with respect to the horizontal axis of the spectrometer. The foil is located inside a pair of Helmholtz coils, and the electrons are polarized along the surface of the foil as shown by the heavy arrow in Figure 4. Then $P_T = f \cos \alpha$, and P_L is given by

$$P_L = \delta / (2R f \cos \alpha) \quad (2)$$

The cross section for Møller scattering from all the electrons of an atom is much smaller than the Mott cross section for scattering in the Coulomb field of the nucleus by a factor of about the atomic number Z of the scatterer. Therefore the events of interest must be detected from amongst a larger background of Mott scattered electrons. This is not a problem since there are characteristic differences between the two processes. The Mott scattered electrons carry essentially all their kinetic energy while Møller scattered electrons involve collisions between particles of equal mass. In such collisions, for 90° scattering in the center of mass system when the polarization effects are the strongest, each electron (incident and target) emerges with half the initial kinetic energy at an angle θ in the lab frame relative to the axis given by

$$\sin^2 \theta = 2mc^2 / (W + 3mc^2) \quad (3)$$

W being the total energy of the incident electron.

The detectors are therefore located at the appropriate angle θ given by equation (3), symmetrically with respect to the axis. By appropriate energy selection, only pulses in the detectors corresponding to half the incident electron energy are selected and a

coincidence is required between the two pulses to define a Møller scattering event.

It turns out that only about 2 electrons out of 26 in an iron atom in the scattering foil can be polarized. As a result the scattering asymmetry δ is only about 8-10%. However, the combination of the choice of the scattering angle, energy and coincidence relationships provides a "clean" measurement.

Equation (2) refers to the over simplified case of a single electron energy, scattering angle and the angle between the electron trajectory and the axis of the foil. In any experiment, a fairly wide range of all three quantities will be present. Thus it is necessary to appropriately average the quantities $\cos \alpha$ and R in equation (2). These procedures are discussed in great detail by Horgan.²⁶ In order to evaluate the absolute value of the polarization it is also necessary to determine the fraction f of polarized electrons in the foil, f being given by $M_s/N\mu$ where M_s = magnetic moment per unit volume in the ferromagnetic material (foil) due to electron spins, N = total number of electrons in the foil and μ = Bohr magneton.

The averaging processes mentioned above and the determination of f do introduce an error in the final result. These errors can be eliminated if one makes a measurement of δ for an unknown case and compares it with the δ measured at the same energy for a standard allowed β -transition for which the $-v/c$ polarization is very well established, keeping all other conditions constant. The $1^+ \rightarrow 0^+$ β -transition (with an end point of 1710 keV) of P^{32} has been chosen as our standard in view of the excellent experimental evidence^{21,28,29}

in support of a full - v/c polarization for this transition.

(iii) Experimental Arrangement: A sketch of the experimental arrangement used in this work is shown in Figure 5 and a reproduction of a photograph is shown in Figure 5a. The set up consists of two vacuum chambers separated by a 1 mil Mylar foil. The source is contained in the smaller chamber. It was arranged such that the source side of the system could be easily opened to air without disturbing the main system. The energy loss and depolarization effects in the Mylar foil separating the two systems are very small.

A lead stop prevents direct radiation from reaching the scattering foil and the detectors. The short magnetic lens was designed by Mortarelli,³⁰ and the electrons selected by the lens are focussed on the scattering foil, a Supermendur foil 0.2 mil thick. The focussing was verified by photographic means and by the use of counters. Baffle systems and stops were arranged such that stray scattering was minimized. The walls of the main chamber were lined with a 1/16" teflon sheet to minimize effect of scattering from the walls. Counter-to-counter scattering (which can simulate a Møller event) was prevented by appropriate shielding.

The detectors were surface passivated Si(Li) type supplied by SIMTEC Ltd., Canada, and had 2 mm depletion depth and 200 mm² area, and could stop electrons up to 1200 keV. These detectors were set up symmetrically with respect to the axis at the proper scattering angle for each chosen energy. The detectors were cooled to liquid nitrogen temperature. The resolution of the detectors was better than 20 keV for 1 MeV conversion electrons from Pb²⁰⁷.

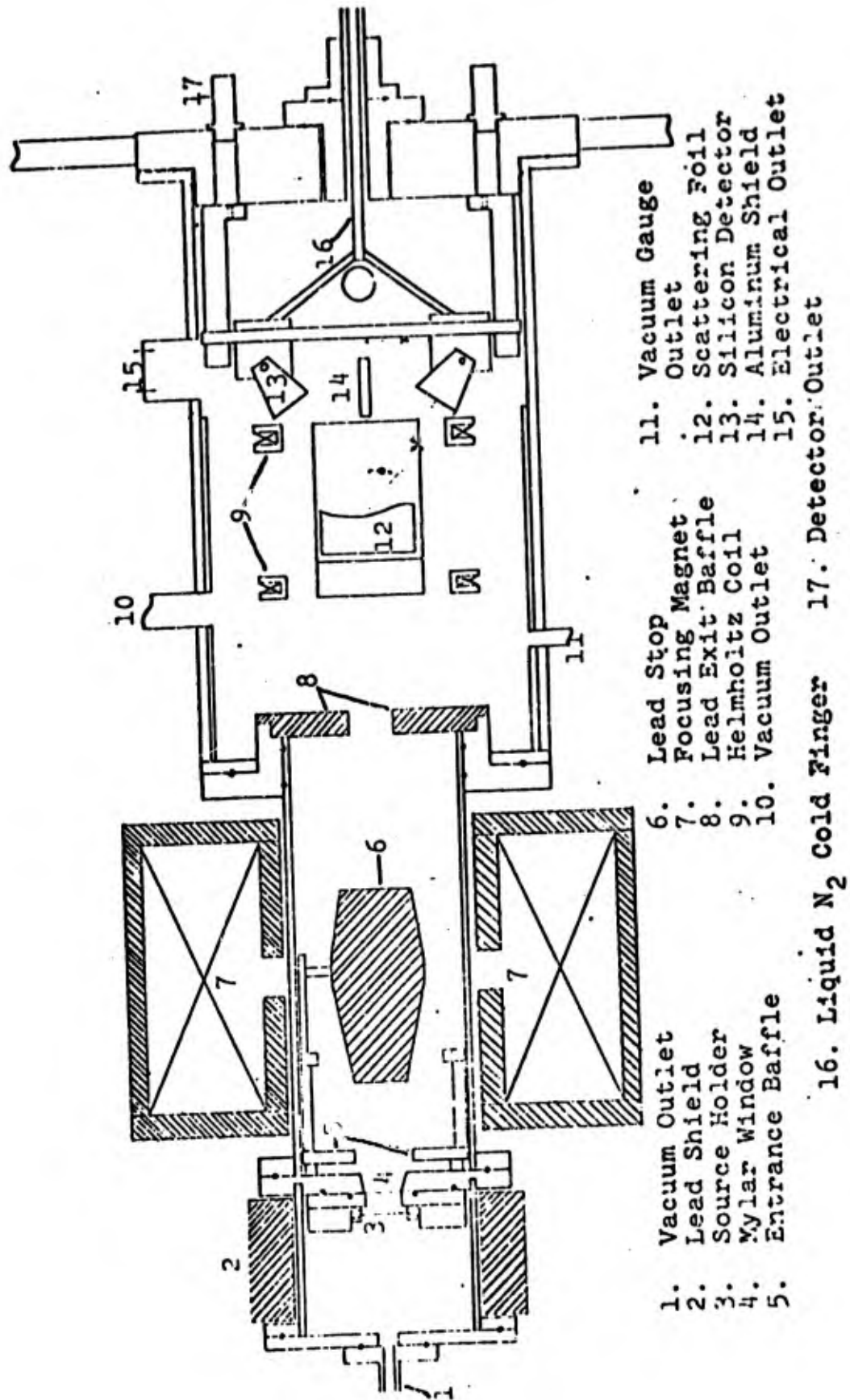
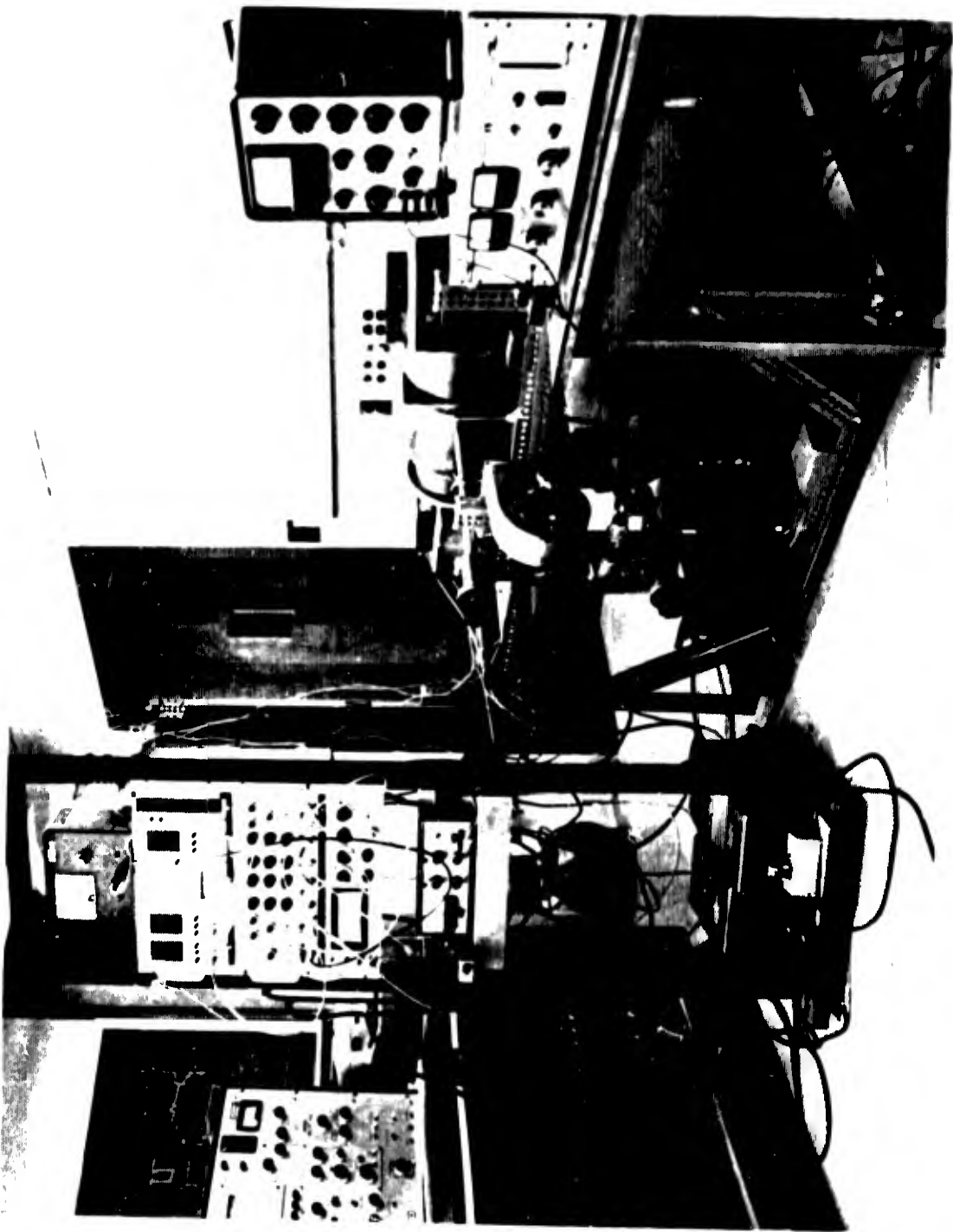


FIGURE 5



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The scattering foil was mounted on an aluminum frame and located at the center of the Helmholtz coils. The foil was at 30° relative to the horizontal.

The end plate of the main chamber has been arranged with a rotating seal so that the detector system can be turned in the vertical plane without affecting any other part of the system and without the need to break the vacuum. The chamber has, of course, the appropriate feed through for measurement of vacuum, and for signals and other electrical connections.

The slow-fast coincidence system of electrons used is shown in Figure 6. The data collection procedure was automated using Canberra Model 1473 Printing Scalers, Model 1489 Serial Scanner/Printer and Model 1490 Blind Timer. ORTEC Model 118A Fat Pre-amplifier, Model 410 Multimode Amplifier, Model 420 Timing Single Channel Analyzer and Model 414 Fast Coincidence Unit are used. The coincidence unit was operated at a resolving time of 30-35 nsecs.

(iv) Some Experimental Details and Procedures: The Pm^{148} (5.4 day) and $\text{Cd}^{115\text{m}}$ (43 day) sources as well as the P^{32} (14 day) were produced and supplied by The New England Nuclear Corporation. The sources were prepared by Dr. I. Gruverman of New England Nuclear Corporation on 0.05 mil. pore free nickel foils as well as 1/4 mil Mylar foils by evaporation method. The sources were spread over circular spots of diameter of about 8 mm. The uniformity of the sources was checked photographically, and their thicknesses were measured by weighing and by X-ray absorption methods. The P^{32} and

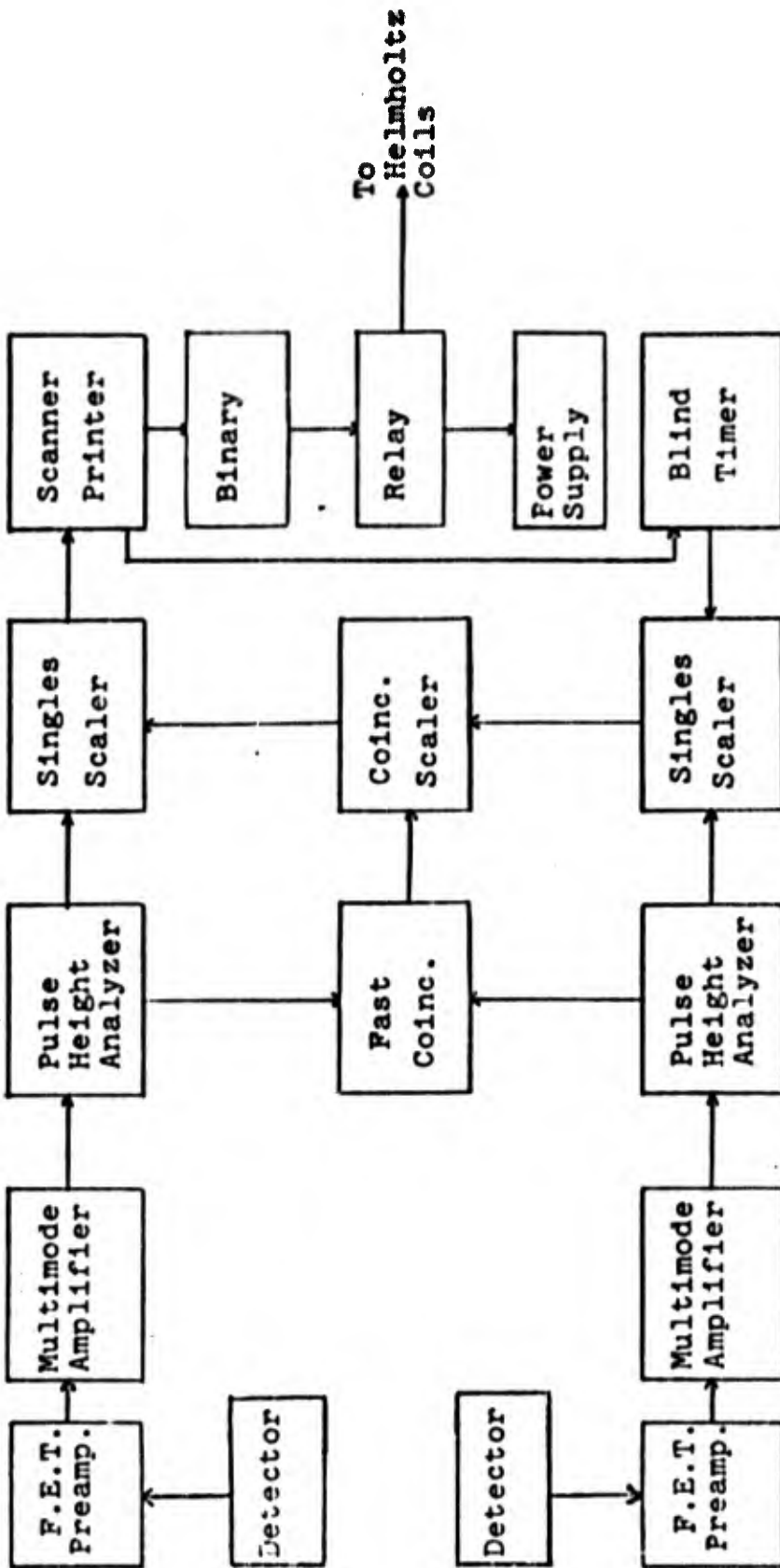


FIGURE 6

Pm^{148} sources used were less than 1 mg/cm^2 thick, and were about 25-50 millicuries at the start. The $\text{Cd}^{115\text{m}}$ sources were in the form of $\text{Cd}(\text{NO}_3)_2$ and had a thickness of 10 mg/cm^2 and the initial activity was 4.5 millicuries.

Magnet and detector calibrations were performed using conversion electrons from Bi^{207} and Cs^{137} sources. The first set of measurements were performed on 800 keV β -particles from Pm^{148} , P^{32} and $\text{Cd}^{115\text{m}}$. After gaining experience, Pm^{148} measurements were extended to 1000 keV and 1200 keV, while $\text{Cd}^{115\text{m}}$ measurements were extended to 600, 1000 and 1200 keV. The standard P^{32} measurements made at all these energies provided energy dependent polarization measurements for P^{32} in their own right. The coincidence counts varied from 60-120/min for P^{32} (true/chance $\sim 3-5$), $\sim 10-30$ /min for Pm^{148} (true/chance $\sim 2-4$) and 5-10/min for $\text{Cd}^{115\text{m}}$ (true/chance ~ 25). The low counting rates necessitated measurements over an extended period of time. Statistical accuracies of about 2% were obtained for δ measurements on P^{32} and about 5% on other measurements.

The Supermendur foils were kindly supplied by Mr. Gould of Bell Telephone Laboratories. The foil was magnetized initially to saturation at a field of about 30 oersteds and a holding field of 3 oersteds was used in the measurements. With the single channel analyzers set up to accept pulses corresponding to one half of the kinetic energy of the incident electrons in a narrow interval of 60 keV about the mean value, the coincidence counts, say, C_+ and the β -singles rates were determined for 20 minutes, the counts on the three scalars and counting time were printed out

on a tape, the scalers were reset, the field of Helmholtz coils (hence target polarization) was reversed and now C_- and β -singles were counted for the same length of time and recorded. This cycle of operations was repeated over and over automatically with better than 95% efficiency 24 hours a day. Regular checks for instrumental stability and reliability of operation were employed.

The data were corrected for accidentals and the measured δ 's of individual repetitions were tested statistically before the data were finalized and pooled together. It was found that correction for half-life of the decay had negligible effect since successive C_+ measurements were done in a time much less than the half-life of the source. The C_+ counts of course decayed with the well known half-lives.

(v) Systematic and Instrumental Effects: The instrumental asymmetry was measured using an aluminum foil of equivalent thickness and found to be small: $\delta_{Al} = +0.002 \pm 0.003$. For relative measurements it was only necessary to consider depolarization corrections for multiple and single scattering effects in the source. For P^{32} and Pm^{148} sources, these effects were less than 1%, but for Cd^{115m} the corrections ranged from 4% at 600 keV to 1.5% at 1200 keV. These corrections were calculated using the theory of Mühlischlegel and Koppe³¹ and Bienlein et al.³² Contributions due to β -Bremsstrahlung coincidence background and β - γ coincidence background were too small to be measurable. Multiple scattering effects in the scattering foil were considered for P^{32} in evaluating the absolute polarization.

(vi) Measurement of f: For P^{32} data we evaluated the absolute values of polarization at the experimental energies 600 keV, 800 keV, 1000 keV and 1200 keV. For this purpose a knowledge of f was necessary. This was obtained by measuring the magnetization using a calibrated flux meter. A hysteresis curve for 0.2 mil. Supermendur is shown in Figure 7. The measured magnetic moment M per unit volume contains not only M_s but a small contribution ($\sim 5\%$) due to orbital contributions. The desired quantity M_s is given by $M_s = 2(g'-1)M/g'$ where g' is the gyromagnetic ratio. Assuming that g' for Supermendur (49% Fe, 49% Co and 2% Va) is somewhere between the values for Fe^{33} and Co^{34} we used $g' = 1.89 \pm 0.04$. The value of f was found to be 0.0598 ± 0.0018 .

(vii) Some Remarks: The relative measurements performed here enabled more accurate determinations of polarization than one can obtain by measuring absolute values. The errors are essentially statistical (provided there is negligible depolarization in the source). The errors on results given in Section III can be improved but one has to weigh the returns of getting any new physics out by spending four times as much time and resources to reduce the error by a factor of two.

The use of silicon detectors contributed to minimize background due to β - γ coincidences. More important is the fact that the detectors were not affected by the field reversals in the Helmholtz coils. This has been a difficult problem with plastic scintillators and photomultipliers. Finally these silicon detectors in conjunction with magnetic momentum analysis helped define the energy accurately.

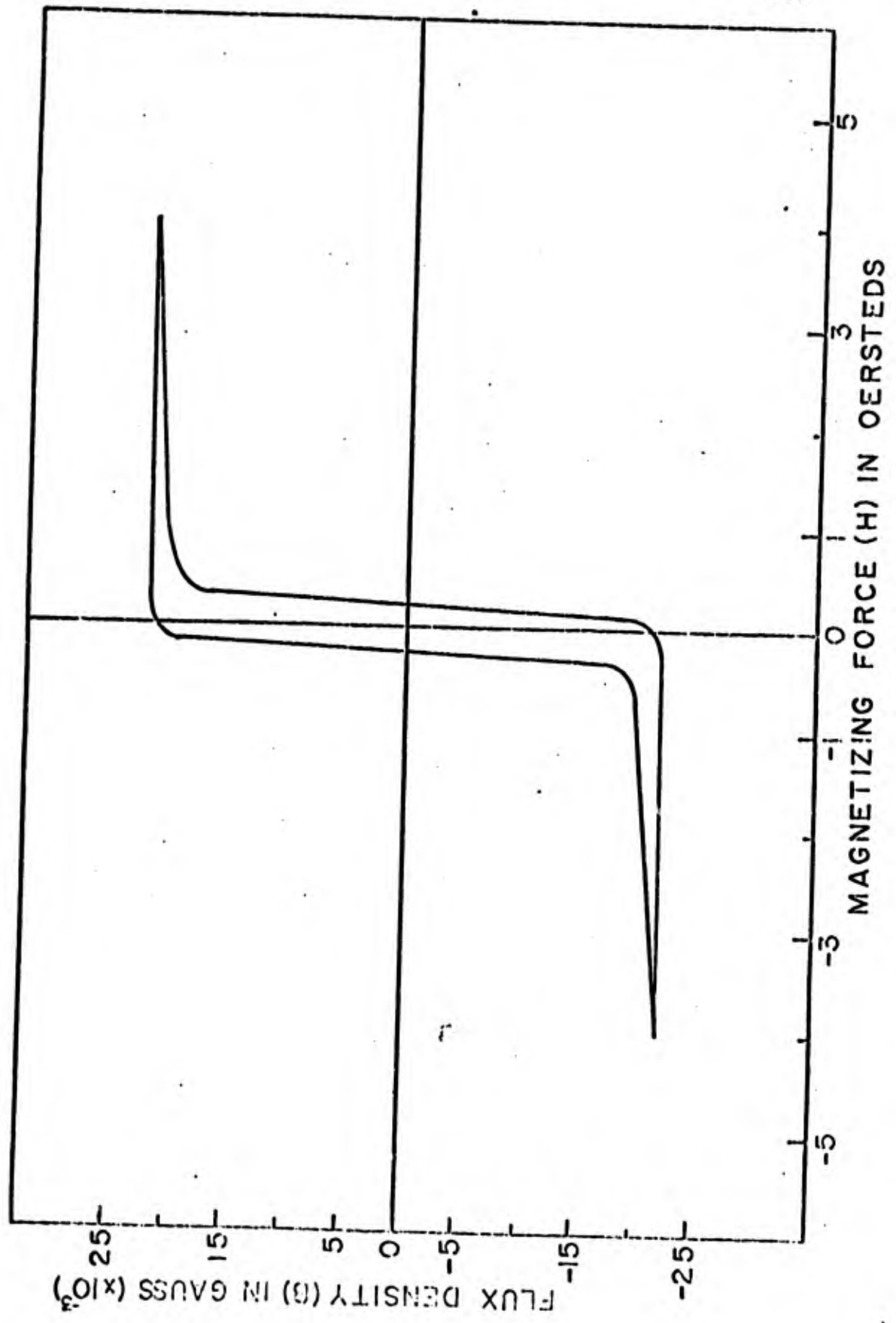


FIGURE 7

The present apparatus and method can be used up to about 2.5 MeV electrons if only we replace the present silicon detectors by those with a larger depletion depth. It is also suited for longitudinal polarization measurement of positrons utilizing the so-called Bhabha (e^+e^-) scattering. It is hoped that this facility can be used in the future with relatively limited funds to perform β -polarization measurements on more first forbidden β -transitions.

III. RESULTS AND DISCUSSION

In this section the results of various investigations using the methods of Section II are presented and discussed. To facilitate discussion we divide this into three sub-sections A, B and C involving allowed, first forbidden, and second and third forbidden transitions respectively. Sub-section D contains an account of other related work.

IIIa) Allowed Beta-transitions: Allowed β -transitions ($\Delta J=0, \pm 1, n$) are governed by the Fermi and Gamow-Teller matrix elements $\langle 1 \rangle$ and $\langle \underline{\sigma} \rangle$ respectively. In addition to these, contributions from other matrix elements $\langle \underline{\alpha} \cdot \underline{r} \rangle$, $\langle r^2 \rangle$, $\langle \underline{\sigma} r^2 \rangle$, $\langle (\underline{\sigma} \cdot \underline{r}) \underline{r} \rangle$, $\langle \gamma_5 \underline{r} \rangle$ and $\langle \underline{\alpha} \underline{x} \underline{r} \rangle$ occur when one considers interference effects between s and p and d wave leptons.³⁵ Detailed theoretical expressions for the β -spectrum shape factor, and β - γ and other directional correlations have been given by Morita³⁵ and by Behrens and Jänecke³⁶ based on Bühring's formalism.³⁷ Normally for allowed transitions with moderate energy release these latter contributions are small (indeed negligible) and these transitions are characterized by statistical spectra and isotropic directional correlations.

When large Q values are involved such as in the case of $B^{12} \rightarrow N^{12}$, $C^{12} \rightarrow N^{12}$ decays, the importance of these higher order contributions has been well established. Indeed the contribution of $\langle \alpha_{xr} \rangle$ is the central point in the weak magnetism effect³⁸ and Conserved Vector Current Theory,³⁹ amply verified by Wu and collaborators.⁴⁰ The small but significantly non-zero β - γ correlation observed by Boehm⁴¹ in F^{20} is understood in a similar way.

There is a large set of β -transitions for which the energy release is small or moderate but with comparative lifetimes (ft) orders of magnitude larger than for normal allowed transitions for which usually ft is in the range 10^3 - 10^5 sec. Do these hindered allowed transitions show any evidence of higher order contributions? In the early 1960's the answer to this question was controversial in the sense that there seemed to be conflicting evidence.⁴⁴ The answer to this question became important in view of subtle effects that were examined theoretically by Huffaker and Greuling⁴² and others.⁴³

In this laboratory a large number of hindered transitions of allowed character were investigated. These include $Na^{22}(3^+ \rightarrow 2^+$, log ft 7.3), $Co^{56}(4^+ \rightarrow 4^+$, log ft 8.7), $Co^{58}(2^+ \rightarrow 2^+$, log ft 6.6), $Co^{60}(5^+ \rightarrow 4^+$, log ft 7.5), $Sb^{124}(3^- \rightarrow 3^-$, log ft 7.7), $Bi^{134}(4^+ \rightarrow 4^+$, log ft 8.9), $Ag^{110m}(6^+ \rightarrow 6^+$, log ft 8.3) and $Eu^{154}(3^- \rightarrow 2^-$, log ft 10.0). The beta-gamma directional correlations in all these cases proved to be too small to be measurable, and within the limits of experimental error, the conclusion is that the correlations are isotropic in spite of the large ft values. These results have been published¹³ and some of their implications have been considered.⁴⁵ Since then two more β - γ cascades have been added to the above list of isotropic correla-

tions: $1/2^+(\beta^-)3/2^+(\gamma)1/2^-$ in Cd^{115} decay with $\log ft = 6.8$, and $1^-(\beta^-)1^-(\gamma)0^+$ cascade in the decay of Pm^{148} with $\log ft = 7.7$. The respective directional correlation coefficient A_2 is -0.001 ± 0.003 for $E_\beta > 350$ keV for Cd^{115} and -0.0008 ± 0.0030 for $E_\beta > 750$ keV for Pm^{148} .

The isotropic correlations measured in this laboratory have been in general agreement with other careful measurements published in recent years.^{1,14,15,16} It would seem reasonable to say that earlier results which implied "large" enough effects in allowed transitions are most probably instrumental in nature. Cipolla et al.¹⁵ claim that significant effects are seen in the decay of Tb^{160} . The extreme complexity of the decay scheme makes us wonder if this effect is real. All one can say is that β - γ directional correlations in the hindered allowed transitions are isotropic to within presently attainable accuracies. It would be desirable, though very difficult, to push the limits an order of magnitude down.

As pointed out by Sastry et al.¹³ either one of the following situations may exist: (a) the higher order matrix elements are also hindered in about the same way as $\langle \sigma \rangle$ resulting in essentially normal behavior for the β -transition except the large ft value, (b) the higher order matrix elements may be relatively enhanced but the observed isotropies might represent a cancellation effect. at least in some of the cases. It was shown that if the latter situation existed, one would expect to see small but measurable deviations from allowed statistical shapes in a way very similar to the $(1+b/W)$ type empirical shapes reported in the literature.⁴⁷ Should such a situation exist it was noted⁴⁵ that determination of $\langle 1 \rangle / \langle \sigma \rangle$ through β - γ circular polarization correlation results might be considerably affected.

We have developed our 4π Silicon Detector Spectrometer described in Section IIb) primarily to study the above implications. Our shape measurements on Co^{60} give a statistical shape (see Figure 3c). Beta-ray polarization measurements by Lazarus⁴⁸ down to $v/c = 0.4$ do not show any deviations from $-v/c$ longitudinal polarization. For the $4^+ \rightarrow 4^+$ transition in Cs^{134} ($\log ft = 8.9$) we find less than 3% variation over the energy range 100 keV to 600 keV. Measurements of shapes of other strongly hindered transitions are now contemplated.

In Figure 3b) is shown the shape for P^{32} measured in this laboratory. The deviation from constant shape over the energy range is about 3% and can be expressed in the empirical form $(1+0.04/W)$ or $(1-0.01W)$. These results do not support larger deviations reported earlier⁴⁹ and are in agreement with the work of Canty and Connor,⁵⁰ and of Fishbeck.⁵¹ The β -ray longitudinal polarization results from this laboratory for P^{32} shown in Figure 10 also agree with $-v/c$ polarization as do the results of Brosi et al.²⁸ and Wenninger et al.²⁹ As pointed out by Bühring,⁵² some small effects due to higher order contributions do seem to exist in this case. A detailed investigation based on nuclear models might be of value. The β -transition here involves the transformation of the 17th neutron to the 16th proton, $\nu d_{3/2} \rightarrow \pi s_{1/2}$, which is l -forbidden. For such cases, contribution of the matrix element $\langle (\underline{\sigma} \cdot \underline{r}) \underline{r} - \frac{1}{3} r^2 \rangle$ might be important since this operator is of the type T_{121} and the matrix element $\langle s_{1/2} || T_{121} || d_{3/2} \rangle$ is non-zero. A look at l -forbidden β -transitions in this way might prove to be interesting from the point of view of nuclear structure.

Although Wilkinson and collaborators⁵³ have drawn attention

recently to the possible existence of Second Class Currents in allowed β -decay, careful experiments^{54,55} by the same group seem to show that such effects may not be there after all!

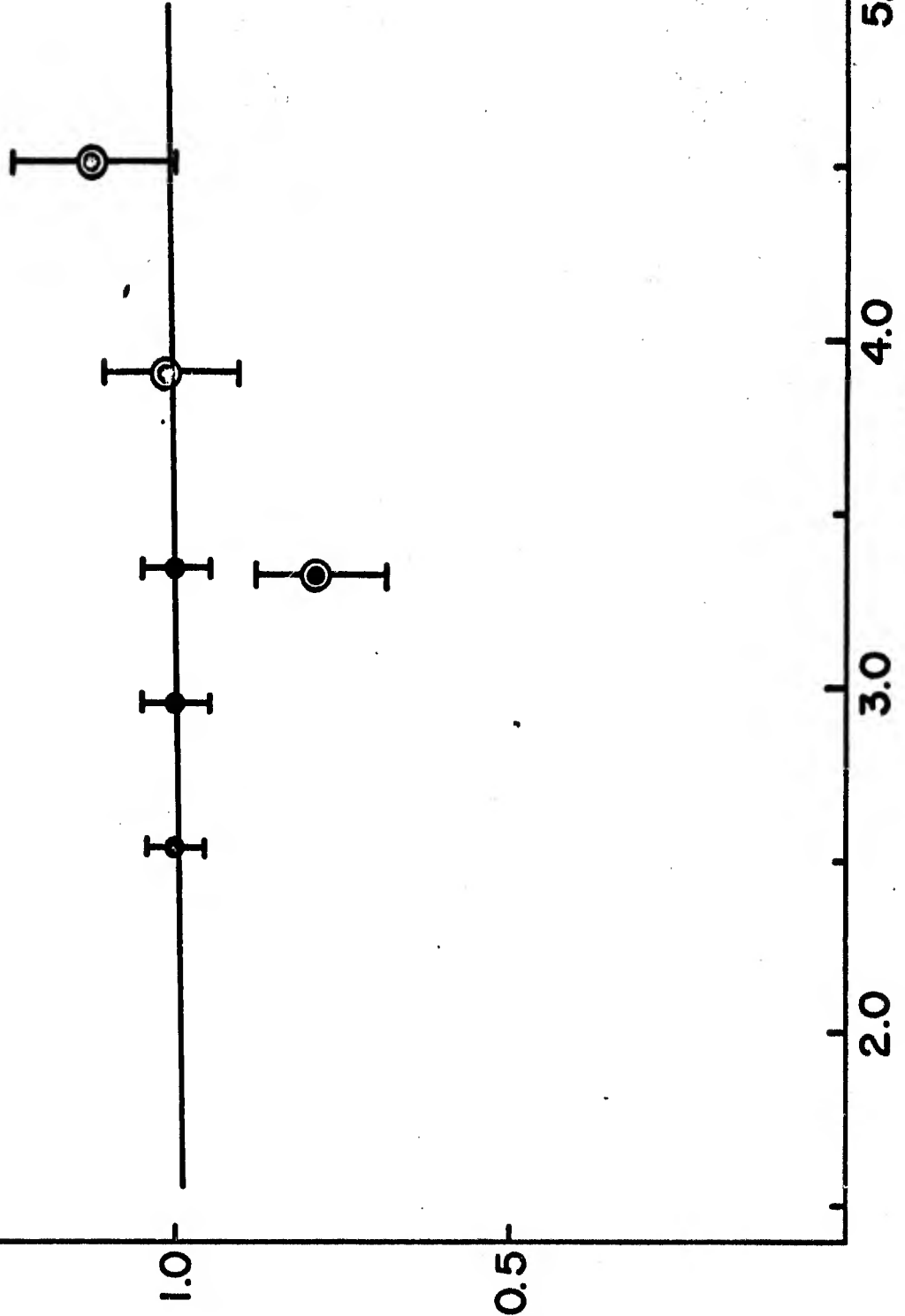
IIIb) First Forbidden Beta-transitions: First forbidden β -transitions ($\Delta J=0, \pm 1$, yes) of the non-unique type are governed in general by six matrix elements: $\langle \underline{\sigma} \cdot \underline{r} \rangle$, $\langle \gamma_5 \rangle$ of rank zero, $\langle \underline{r} \rangle$, $\langle \underline{\sigma} \underline{x} \underline{r} \rangle$ and $\langle \underline{\alpha} \rangle$ of rank one and $\langle B_{ij} \rangle$ of rank two. The aim of these studies is to determine these matrix elements, where possible, using observed properties of β -transitions and to compare them with model dependent expectations. When the experimental information available is not adequate to determine these parameters, meaningful nuclear models are used to calculate the matrix elements and the predicted behavior of β -transitions is compared with experimental results. It is found that in several cases β -transitions serve as a good probe of nuclear structure, especially the shell model aspects. We shall now present the results for various nuclei investigated and consider their implications briefly.

(i) ${}_{61}^{148}\text{Pm}_{87}$: The $1^- \rightarrow 0^+$ β -transition ($\log ft = 9.1$, $E_0 = 2.48$ MeV) is governed by only the three rank one matrix elements. A strongly energy dependent shape has been reported for this transition by Baba et al.⁵⁶ This suggested a possibility that the β -ray longitudinal polarization might show a deviation from $-v/c$. The work of van Klinken⁵⁷ using the double scattering method was quite indefinite (see Figure 8). Careful measurement of the β -ray polarization when combined with the ft value would permit a determination of the three matrix elements in this case.

The results of longitudinal polarization measurements are shown

P_M^{148}

$PL(W)/(1/c)$



○ VAN KLINKEN
● THIS WORK

W (mc^2)
FIGURE 8

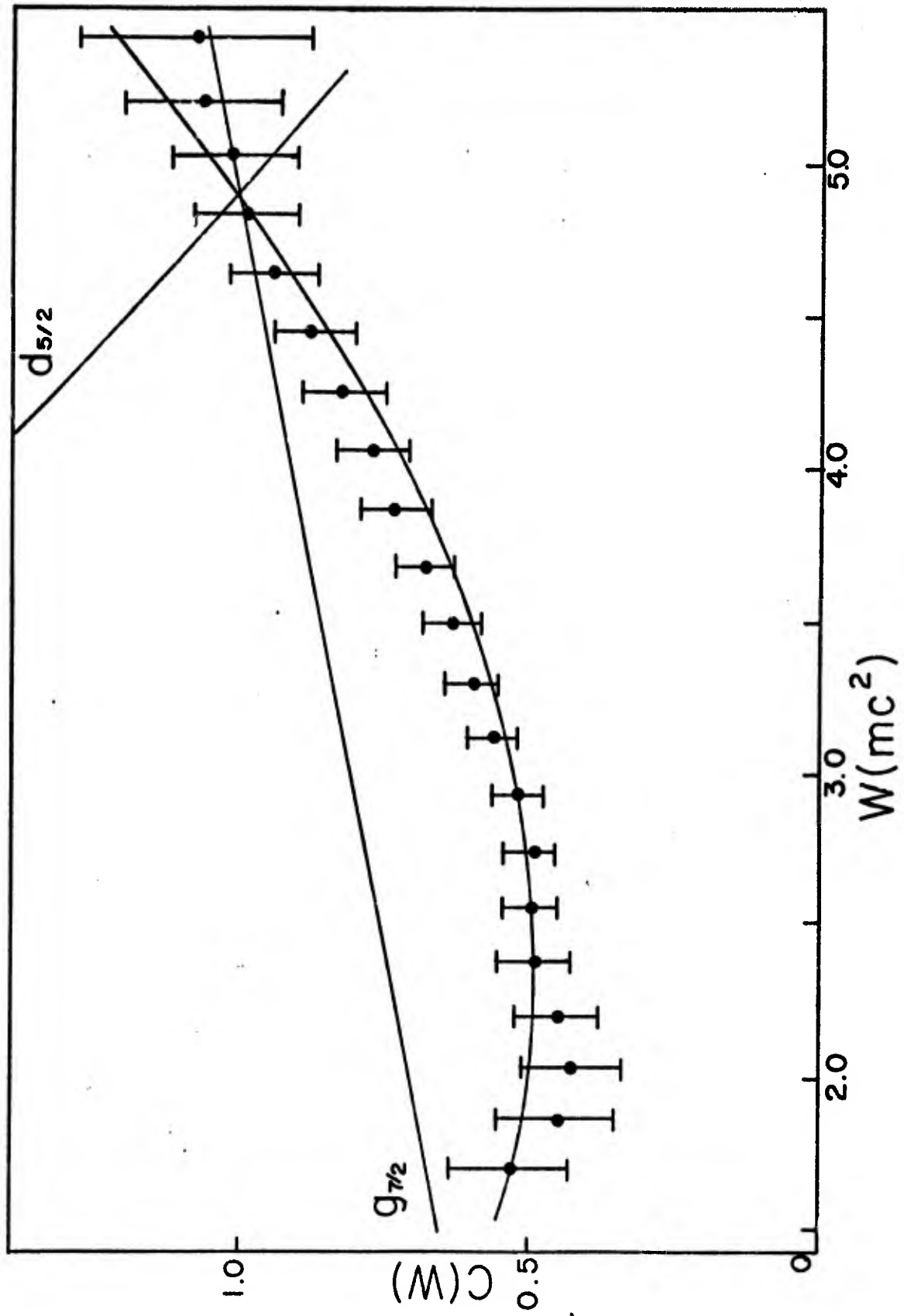


FIGURE 9

in Figure 8 along with those of van Klinken.⁵⁷ There is over all agreement that the polarization for β -rays above 800 keV is $-v/c$ or $P_L/(-v/c) = 1.0$. The low value of van Klinken at 1200 keV might be due to instrumental problems.

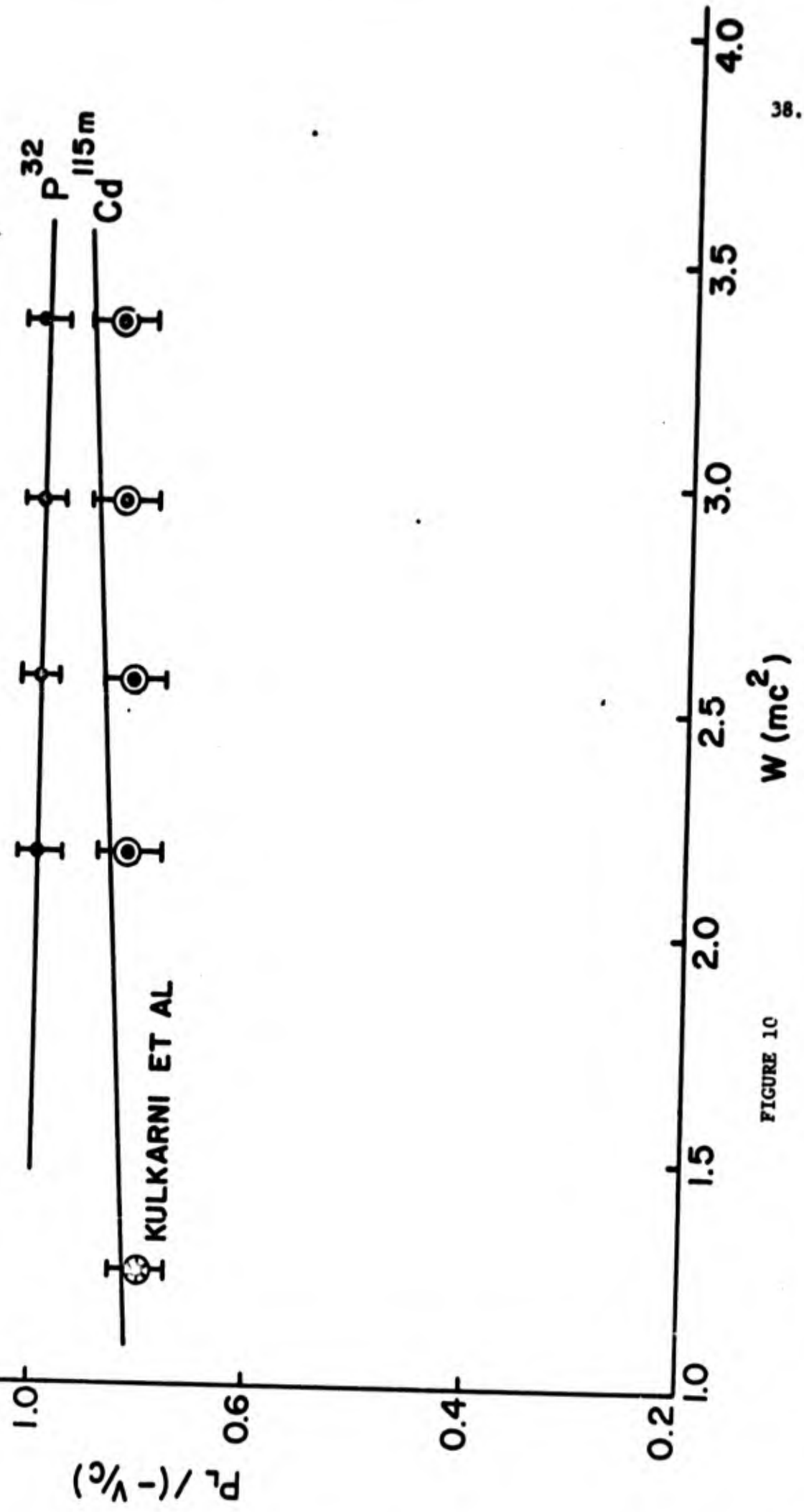
Analysis of the β -ray polarization data and the shape factor data (Figure 9) of Bata et al.⁵⁶ has been performed using the theoretical expressions of Morita and Morita⁵⁸ for shape and those of Lee-Whiting⁵⁹ for β -ray polarization. Exact electron radial wave functions tabulated by Bhalla and Rose⁶⁰ are used. The best fits to the data are given by the two ratios $x = -C_V\langle r \rangle / C_A\langle i\alpha r \rangle = +0.56 \pm 0.08$ and $y = -C_V\langle i\alpha \rangle / C_A\langle i\alpha r \rangle = 17.0 \pm 1.0$. The solid curves in Figures 8 and 9 represent the theoretical curves for the above values of x and y . These results for the matrix elements and interesting physical conclusions about the structure of Pm^{148} have been given in two preliminary communications.^{61,62} A detailed account will be included in the article by Amadori et al.²⁷ We shall state here the major conclusions: (i) The ratio $\langle i\alpha \rangle / \langle r \rangle = 31.0 \pm 6.0$ agrees with predictions^{16,17} based on Conserved Vector Current Theory. (ii) The shape of the β -transition and some retardation in decay rate are caused by a strong cancellation in the usually dominant combination $Y = -C_V\langle i\alpha \rangle - \xi(C_A\langle i\alpha r \rangle - C_V\langle r \rangle)$, ξ being the Coulomb energy factor. (iii) The β -transition proceeds primarily as a $\nu f_{7/2} \rightarrow \pi d_{5/2}$ transformation with a small admixture of the mode $\nu f_{7/2} \rightarrow \pi g_{7/2}$ (Baba et al.⁵⁶ draw the opposite conclusion due to a numerical error). (iv) The 1^- ground state should most predominantly have the structure $[(\pi g_{7/2}^{-3})_{7/2}(\nu f_{7/2}^{-3})_{5/2}]_{1^-}$ as required by its magnetic moment.⁶³ (v) It is found that this most

dominant structure of Pm^{148} cannot decay to the 0^+ ground state of Sm^{148} due to angular momentum coupling. (vi) The β -decay therefore proceeds only through small admixtures of the configurations $[\pi d_{5/2}^{-1}(\nu f_{7/2}^{-3})_{7/2}]_{1-}$ and $[(\pi g_{7/2}^{-3})_{7/2}(\nu f_{7/2}^{-3})_{7/2}]_{1-}$. This explains the strong hinderance of β -decay to the ground state of Sm^{148} .

The $1^- \rightarrow 2^+$ β -transition in the decay of Pm^{148} has been studied by means of β - γ correlations. The small directional correlations measured are understandable through several sets of the matrix element parameters. A measurement of the shape of this β -transition would be of interest. This work has already been published.³

(11) ${}_{48}\text{Cd}_{67}^{115m}$: The β -transition of interest here is the $11/2^- \rightarrow 9/2^+$ transition from the metastable state (43 day) of Cd^{115} to the ground state of ${}_{49}\text{In}_{66}^{115}$, with $\log ft = 8.7$ and $E_0 = 1.62$. A strongly energy dependent shape of the form $C(W)\alpha(1-0.78W - 17.2/W)$, where W is the β -ray total energy, has been reported by Sharma and Devare.⁶⁴ Kulkarni et al.⁶⁵ reported a β -ray longitudinal polarization of $P_L = - (0.80 \pm 0.05)v/c$ at 128 keV.

The purpose of our β -longitudinal polarization measurements was to determine this observable over a wide range of energies and to obtain β -matrix elements. Our results are given in Figure 10 along with our data for P^{32} which was used for relative measurements as a standard. A deviation of about 15% from a full - v/c polarization is confirmed. An attempt has been made to interpret the shape factor and polarization data in this case in terms of β -decay matrix elements. One expects that this transition may be described as a $\nu h_{11/2} \rightarrow \pi g_{9/2}$ transformation in the shell model. For this we have the ratios⁶⁶ $x = -C_V \langle \underline{r} \rangle / C_A \langle i \underline{\sigma} \underline{x} \rangle = 0.82$, $z = \langle B_{ij} \rangle / \langle i \underline{\sigma} \underline{x} \rangle = 2.1$.



KULKARNI ET AL

FIGURE 10

For values of Λ in the range 1.9 to 2.3, ($\langle i\alpha \rangle = \Lambda \xi \langle r \rangle$) (see references 16,17) the polarization data are explained. Variation of z did not affect the fit strongly. The shape factor however required about 35% larger value of z over the single particle value to obtain a satisfactory fit. It is desirable to perform a chi-square analysis of all data for the best parameters. Unfortunately no experimental errors on the shape factor are quoted. We are contemplating a shape factor measurement using our 4π silicon detector spectrometer. Although the precise matrix element ratios are not yet determined for the above reason, the physics of the situation is quite clear: the strong energy dependence of the shape factor and deviation of β -polarization from $-v/c$ are caused by an intense accidental cancellation of matrix elements in the combination $Y = -C_V \langle i\alpha \rangle - \xi (C_A \langle i\alpha r \rangle - C_V \langle r \rangle)$ as in the case of Pm^{148} . The values $x = 0.83$, $\Lambda = 2.25$, $z = 2.75$ seem to describe the situation here quite well. These numbers result in a very small value for Y ($\sim 0.04\xi$, $\xi = \frac{\alpha Z}{2R}$), which at least qualitatively explains the hindrance of the decay from the normal case of first forbidden transitions for which $Y \sim \xi$.⁶⁷ That the value of z is somewhat larger than for the single particle case might be due to the presence of a significant component in the wave function of ${}_{49}\text{In}^{115}$ with a $g_{9/2}$ proton hole coupled to a phonon.⁶⁸ This work along with the Pm^{148} work will be published soon.²⁷

(iii) Cd^{115} : The β - γ directional correlation involving the $1/2^+(\beta^-)3/2^-(\gamma)1/2^-$ cascade ($E_\beta = 850$ keV, $E_\gamma = 260$ keV) in the 2.3 day decay of ${}_{48}\text{Cd}_{67}^{115}$ has been studied in the β -ray energy range above 500 keV. The results are given below:

E_{β} (keV)	A_2
540	- 0.128 \pm 0.011
560	- 0.172 \pm 0.016
600	- 0.164 \pm 0.018
710	- 0.167 \pm 0.012
> 650	- 0.168 \pm 0.016

In view of severe interference effects due to the complexity of the radiations involved, it was not possible to obtain better experimental accuracies nor could we extend the data to lower energies. These results confirm the finding of Pandharipande et al.⁶⁹ that the 595 keV intermediate level in In^{115} involved in our cascade has $J^{\pi} = 3/2^{-}$. It is tempting to characterize the β -transition as transformation of an $s_{1/2}$ neutron to a $p_{3/2}$ hole state (49th proton). For such a transition we have $x = -0.83$ and $z = -3.16$ in the single particle shell model. Using these ratios a search for the best value of Λ in $Y = \Lambda \xi x$ yields $\Lambda \approx 0.2$ in strong disagreement with expectations based on CVC theory. On the other hand several other sets²⁶ may be found in agreement with CVC theory but the values of x and z differ then from the shell model picture. Since there is a general agreement that the 595 keV level may have other phonon coupled components,⁷⁰ our findings are not surprising. It would seem that the β -decay information can once again contribute to a better understanding of the nuclear structure in this case.

(iv) ${}_{51}^{\text{Sb}}{}_{75}^{126}$: Beta-gamma correlation measurement involving 6^{+} level in Te^{126} has been measured to be $A_2 = -0.045 \pm 0.013$ for

$E_\beta > 1300$ keV. This result does not support the 8^- assignment for spin-parity of Sb^{126} suggested by Orth et al.⁷¹ Our result and other available information are consistent with $J^\pi = 7^-$ assignment. A brief report of this work appeared in reference 72. A more detailed account will be published by Gupta et al.⁷³

(v) ${}_{57}^{140}\text{La}_{83}$: The structure of the 2084 keV level in Ce^{140} may be viewed as a $(\pi g_{7/2} \pi d_{5/2})_4^+$ two proton state⁷⁴ or as a more complex state in the quasi particle picture involving predominantly $(\pi g_{7/2})_4^+$ configuration⁷⁵ with smaller admixtures of $(\pi d_{5/2})_4^+$ and $(\pi g_{7/2} \pi d_{5/2})_4^+$ components. Both pictures explain the observed magnetic moment⁷⁶ of this level, $\mu \sim 4$ nuclear magnetons. Since La^{140} has essentially the structure $(\pi g_{7/2}^{-1} \nu f_{7/2})_3^-$, one may identify the β -decay of the 83rd neutron as predominantly a $\nu f_{7/2} \rightarrow \pi d_{5/2}$ transformation if the first picture is correct, and as a $\nu f_{7/2} \rightarrow \pi g_{7/2}$ transformation if the second picture is correct. The β - γ correlation involving the $3^-(\beta^-); 4^+(E2\gamma) 2^+$ cascade ($E_\beta = 1.68$ MeV, $E_\gamma = 487$ keV) has been measured by us and the results are shown in Figure 11 by the solid circles. Our data are in fair agreement with those of Fishbeck and Newsome⁷⁷ (shown by open circles). The data of Raghavan et al.⁷⁸ are considerably larger than ours, probably due to some over correction for interference from β - γ and γ - γ coincidence background. We have verified experimentally that the correlations are not smeared out due to extra nuclear field effects in spite of the large lifetime (~ 4 nsecs) of the 2084 keV intermediate level. This is presumably because the Cerium ion is in a Ce^{4+} electronic state which is diamagnetic.

A search for β -decay matrix element parameters shows that the data can be explained by a wide variety of sets, although a cancellation effect in the combination Y seems to be the cause of the large

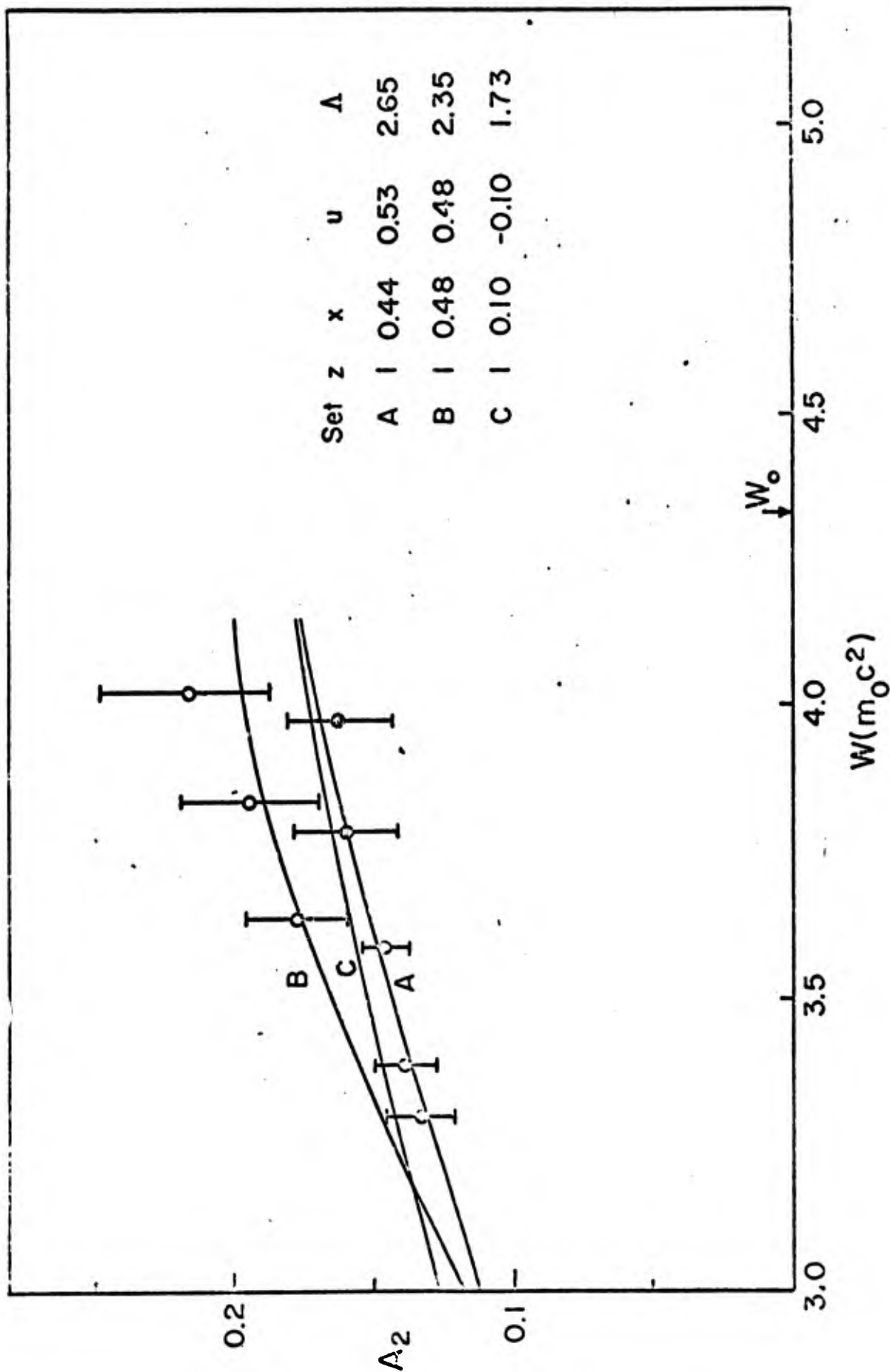


FIGURE 11

A_2 values. Sets A, B shown in Figure 11 agree with the simpler picture and with CVC theory. Kemper⁷⁹ finds that the more complex structure is also consistent with the directional correlation data. However the value of Λ in his case is about 5 and it would seem hard to understand such a large value in any theory relating $\langle i\alpha \rangle$ and $\langle r \rangle$. A measurement of the shape of the β -spectrum, though difficult in view of interference effects, might be of value in clarifying the situation. A preliminary report of this work has been presented.⁸⁰

(vi) First Forbidden Beta-Decays in the Lead Region: Apart from the strange¹¹ case of the β -decay of Bi^{210} , few systematic β -decay investigations have been reported until recently in the important lead region where shell model is expected to work well. Damgaard and collaborators⁸¹ have extensively investigated the rank zero and rank one combinations of the β -matrix elements using the ft values. In this laboratory the β - γ directional correlations have been investigated. It is found that in most cases the correlations and ft values are understandable within the framework of the shell model and CVC theory. Following is a summary of our findings.

a) ${}_{81}\text{Tl}_{126}^{207}$: The A_2 coefficient (≈ 0.03) for the $1/2^+$ (β^-) $3/2^-$ (γ) $1/2^-$ cascade in Tl^{207} can be understood by considering the β -transition as a $|\pi s_{1/2}^{-1}\rangle \rightarrow |\nu p_{3/2}^{-1}\rangle$ transformation.⁸²

b) ${}_{81}\text{Tl}_{127}^{208}$: The A_2 coefficients for the $5^+ \rightarrow 5_1^-$, $5^+ \rightarrow 4^-$ and $5^+ \rightarrow 5_2^-$ β -transitions in the decay of Tl^{208} to the excited states of the doubly magic ${}_{82}\text{Pb}_{126}^{208}$ are shown in Figure 12. Our results are consistent with the picture that the lowest 5^- and 4^- levels are most predominantly of the type $(\nu p_{1/2}^{-1}, \nu g_{9/2})_{5^-, 4^-}$ and the second 5^- level is complex. For the lower 5^- level, our

Fig. 1

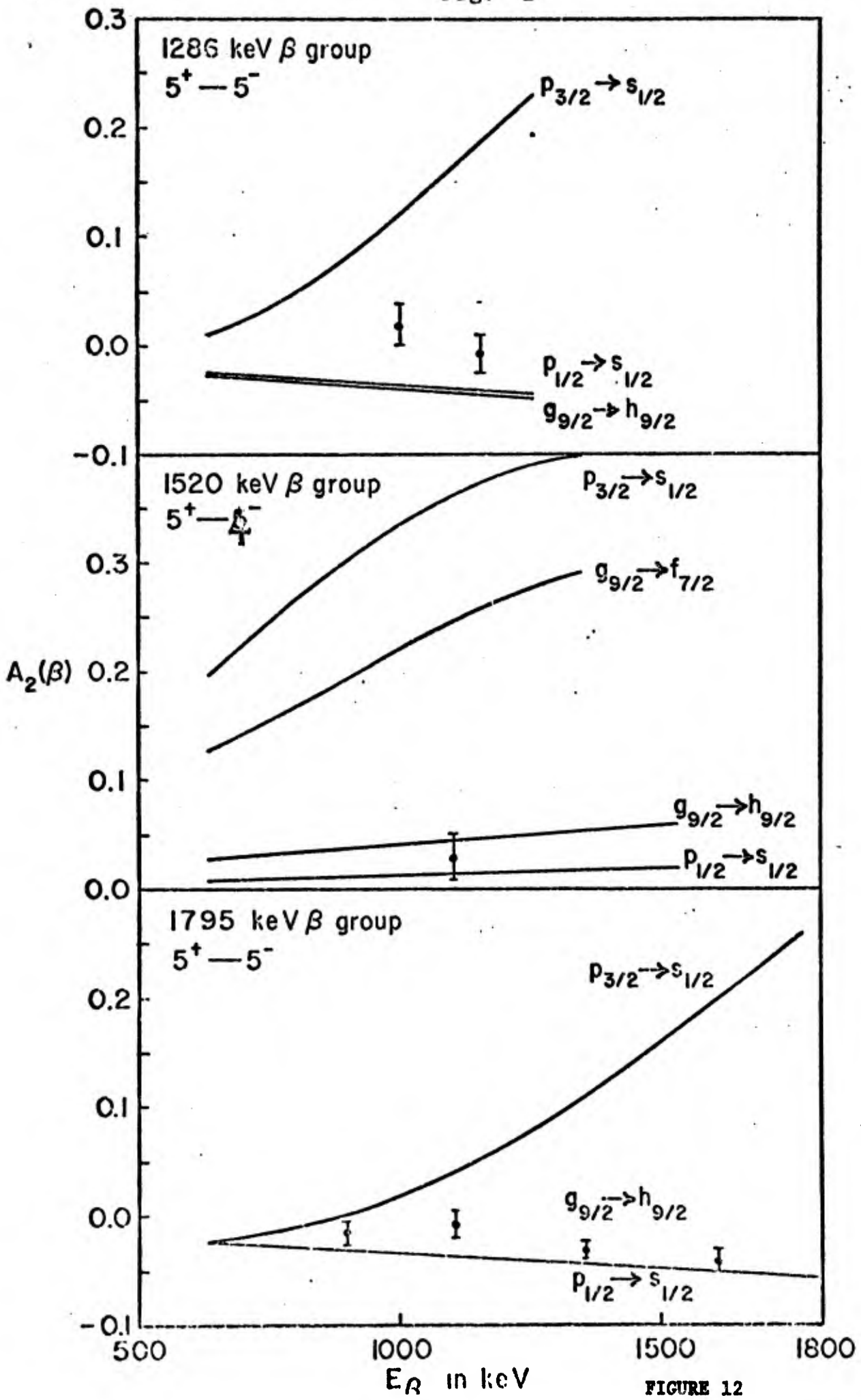


FIGURE 12

data and the g factor⁸⁴ for the level allow an estimate of the proton particle-hole component. Preliminary results have been reported⁸³ at the 1969 International Conference on Radioactivity in Nuclear Spectroscopy. It is interesting to note that the last odd $g_{9/2}$ neutron ($N = 127$) plays essentially no role in the decay to the 5_1^- and 4^- levels, while the transitions are made by breaking up the $N = 126$ closed shell. This is essentially due to energetic reasons.

c) $^{211}_{82}\text{Pb}_{129}$: The β -decay of $^{211}_{82}\text{Pb}_{129}$ to $^{211}_{83}\text{Bi}_{128}$ has been investigated in our laboratory and the work has been published.⁸⁵ This work also resulted in an extensive theoretical shell model study⁸⁶ of the levels, β -decays and electromagnetic transitions in $A=211$ isobars.

d) $^{214}_{83}\text{Bi}_{131}$: There is at present no clear evidence for the spin-parity assignment of this nucleus although it is presumed to be 1^- . Beta-gamma correlation studies by Gupta² yield small but significantly non-zero A_2 values for the $1.8 \text{ MeV}\beta - 769 \text{ keV}\gamma$ and $1.8 \text{ MeV}\beta - 1378 \text{ keV}\gamma$ correlations ($A_2 = -0.016 \pm 0.007$ and -0.018 ± 0.007 respectively). These results and other information available support $J^\pi = 1^-$ for Bi^{214} .

e) $^{212}_{83}\text{Bi}_{129}$: The shape of the $1^- \rightarrow 0^+$ β -transition here has been measured by Sastry and Sahai.⁸⁷ A small deviation from the statistical shape is found. Matrix element analysis suggests that the ratio $-C_V \langle \underline{r} \rangle / C_A \langle i \underline{\sigma} \underline{r} \rangle \sim +1.2$ and $\Lambda \sim 2.0$. These are quite similar to the familiar case¹¹ of Bi^{210} , the implication being that the residual interaction⁸⁸ present in Bi^{210} is also important here although a neutron pair is added. Similar situa-

tion seems to exist in Bi²¹⁴ with two neutron pairs on the basis of an analysis of the β -spectrum data² supplied kindly by Lührs and Mayer-Böricke.⁸⁹

IIIc) Second and Third Forbidden Beta-transitions

a) Ce³⁶ and Cs¹³⁷: The measured shapes of the $2^+ \rightarrow 0^+$ and $7/2^+ \rightarrow 3/2^+$ second forbidden β -transitions in Ce³⁶ and Cs¹³⁷ reported in Figure 3a are in fine agreement with earlier studies.

Matrix element analyses in these cases are in progress.

b) Nb⁹⁴: The $6^+(\beta^-)4^+(\gamma)2^+(\gamma)0^+$ cascade in the second forbidden β -decay of Nb⁹⁴ has been investigated by means of β - γ correlations. In view of finite source thickness and consequent washing out of the correlation, measurements have been made for source thicknesses in the range 1 mg/cm² to 8 mg/cm² and the results extrapolated to zero thickness agree very well with the measurements reported by Hocquenghem and Berthier.⁷ Our shape factor (Figure 3c) is in fine agreement with the work of Beard and Snyder⁸ and reference 7.

Analysis for the β -decay matrix elements (R_{ij} , T_{ij} , A_{ij} and S_{ijk}) shows however that the available information can be explained not only by the set reported by Hocquenghem and Berthier⁷ but by a band of sets some of which are in agreement with the value of Λ in the relation $\langle A_{ij} \rangle = -\Lambda \xi \langle R_{ij} \rangle$ predicted by Conserved Vector Current models.^{16,17}

A measurement of the β - γ circular polarization correlation has been carried out by this investigator along with Dr. S.K. Mitra of Tata Institute of Fundamental Research, Bombay, during the past year.

Preliminary analysis of data shows that the effect is about as large as for the well known case of Co⁶⁰ (same sign). The theoretical expressions for this quantity are now being developed. It is hoped that

this extra information would result in better definition of the experimental matrix elements and contribute to an understanding of the situation in terms of nuclear models.

c) ${}_{37}^{87}\text{Rb}_{50}$: The third forbidden β -decay matrix elements in this case have been investigated by analyzing the data of Egelkraut and Leutz⁹⁰ on the shape of the spectrum. It is found⁹¹ that the data are consistent with the picture that the decay is a $\nu g_{9/2} \rightarrow \pi p_{3/2}$ transformation. Furthermore the relation between the matrix elements of the Vector interaction predicted by the CVC model¹⁶ is consistent with the data.

IIIId) Other Studies

a) Extensive studies of the effect of multiple scattering of electrons on $e^{-}\gamma$ and $\beta\text{-}\gamma$ correlations have been made using the $e^{-}\gamma$ cascades in Bi^{207} decay and $\beta\text{-}\gamma$ cascade in Rb^{86} . Results of $e^{-}\gamma$ measurements⁹² have been presented to the International Conference on Angular Correlations in Nuclear Disintegrations, Delft, The Netherlands (1970) and are shown in Figure 13. These results agree with the theory of Frankel⁹³ based on multiple scattering theory of Goudsmit and Saunderson.⁹⁴ A complete paper including these results and those for other energies and elements obtained through $\beta\text{-}\gamma$ correlations will be shortly communicated to Nuclear Instruments and Methods.⁹⁵

b) Internal conversion coefficients in the K-shell for some low energy transitions have been measured using ultra high resolution Ge(Li) and Si(Li) detectors. Preliminary reports⁹⁶ of these works have appeared on various occasions. The purpose of these studies was to verify the new calculations of Hager and Seltzer,⁹⁷ to look for

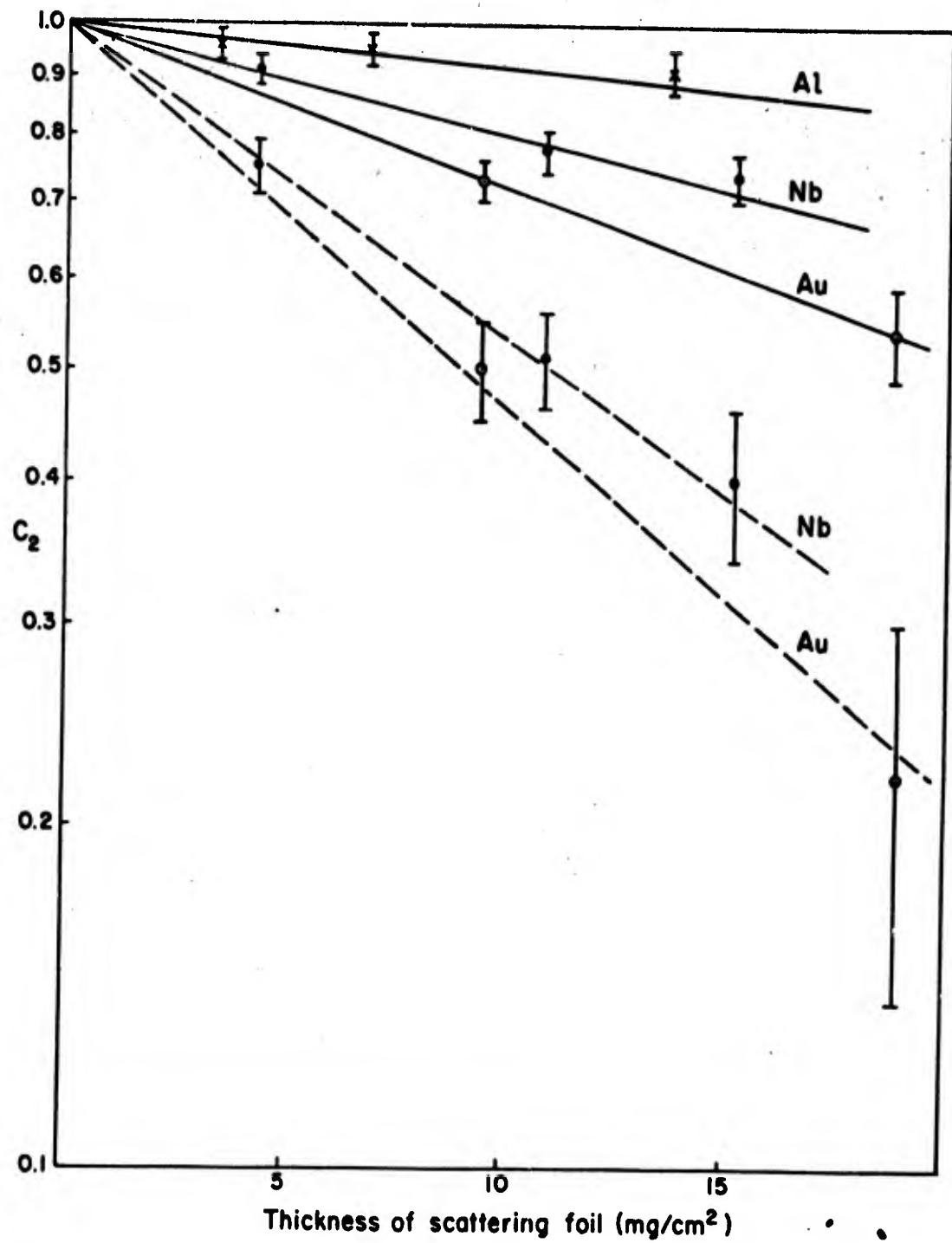


Figure 13

any penetration effects in hindered M1 transitions, and to examine if any threshold effects exist. A consolidated account of these studies will be submitted for publication in the near future. These studies have been done by this investigator in collaboration with the Emory group (J. Palms, R. Wood and P. Venugopala Rao).

IV. SUMMARY AND SUGGESTIONS

The major aspects of this work may be briefly summarized as follows: (i) Except perhaps in the shape of P^{32} no detectable effects due to higher order contributions are found even in the case of strongly hindered allowed β -transitions. It would seem that the higher order matrix elements are also suppressed by nuclear structure effects that hinder the leading Gamow-Teller matrix element. When the β -decay involves large energy as in some light elements or nuclei far off the β -stability line, one may expect to observe the effects of higher order matrix elements. Such studies may be valuable.

(ii) Beta-ray polarization and other studies on forbidden β -transitions have been worthwhile in that significant understanding of these in terms of their matrix elements and relevant nuclear models has been gained. Experimental studies of more observable quantities for many of these cases would be very useful. In particular, shapes of β -spectra in inner β -transitions, angular distributions of electrons from oriented nuclei, β -ray polarization in special cases such as Bi^{214} , Cs^{137} (second forbidden decay), gamma-decay of analog resonances and radioactivity studies through (γ, π) reactions near threshold are needed.

(iii) The present work supports Frankel's theory of the influence of multiple scattering of electrons in sources and absorbers on their angular correlations.

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