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Part A: Studies in K-Capture Positron Branching Ratios

Part B: Search for a Low-Lying 0^+ State in Gallium-68

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STUDIES IN K-CAPTURE POSITRON BRANCHING RATIOS

ABSTRACT

K-capture to positron branching ratios have been measured in the decay of Na^{22}, Co^{58} and Ga^{68} -- all pure Gamow-Teller emitters, using coincidence scintillation spectrometer techniques. The measured values are 0.105 ± 0.004 for Na^{22}, 5.08 ± 0.17 for Co^{58}, and 1.28 ± 0.12 and 0.10 ± 0.02 for Ga^{68}. From these the Fierz interference term is computed to be $b = -0.004 \pm 0.012$, -0.004 ± 0.14, -0.03 ± 0.02 and $+0.03 \pm 0.01$ respectively. These results indicate that the Fierz interference in Gamow-Teller interaction is very small.

The decay of 270 day Ge^{68} was investigated in equilibrium with Ga^{68} to look for a possible low-lying O^+ level in Ga^{68} using X-ray X-ray and X-ray γ-ray coincidences. The result was negative. Besides the 9 kev K X-ray, the 1.07 Mev gamma ray in the decay of Ga^{68} and annihilation radiation, no other gamma rays were detected (< 8 o/o of 1.07 Mev gamma ray). The number of positrons per 1.07 Mev γ-quantum was determined as 19.47 ± 2.10. The ratio of positrons to the 1.07 Mev level and ground state of Zn^{68} was found to be $(1.76 \pm 0.22) \times 10^{-2}$.

Studies with a Ge^{68} source chemically separated from Ga^{68} showed no gamma rays (< 1 o/o of total Ge^{68} decays). By following the growth of annihilation radiation, an upper limit of 0.4 o/o per decay could be set on the amount of positron emission by Ge^{68}.

A search for an electric monopole (EO) transition from the 2.3 Mev level to the O^+ ground state of Zn^{68} was made using plastic scintillators and an anti-coincidence arrangement. An upper limit of $(5 \pm 25) \times 10^{-9}$ conversion electrons per decay of Ga^{68} could be set. This is interpreted as evidence against a possible O^+ spin assignment for the 2.3 Mev level, but the interpretation is not conclusive.

A brief review is presented regarding the status of Fierz interference in beta-decay as revealed by present studies and other experiments.

General Introduction

a) The Interaction in Beta-Decay:

The central problem in the theory of beta-decay has been the determination of the nature of the interaction responsible for this decay. In general the interaction can be a linear combination of five types, namely scalar (S), vector (V), tensor (T), axial vector (A), and pseudoscalar (P), all satisfying the requirement of relativistic invariance. Beta-decay can be classified as allowed or forbidden depending on the change in angular momenta and parities of the nuclear states involved. The selection rules permit a further distinction between transitions as Fermi or Gamow-Teller. The selection rules are:

Allowed $\Delta J = 0$ Fermi

No

$\Delta J = 0, \pm 1$ Gamow-Teller

No $0 \rightarrow 0$

First forbidden $\Delta J = 0, \pm 1, \pm 2$ Gamow-Teller

Yes

$0, \pm 1$ Fermi

and so on.

The Fermi transitions involve only the interactions S and V, and the interactions A and T characterize Gamow-Teller transitions. A transition allowed by both types of selection rules should therefore involve S, V, A, T and perhaps P. There is strong evidence that the P interaction is unimportant. The fact that transitions obeying both kinds of selection rules are observed indicates that the beta-interaction is an admixture of both Fermi and Gamow-Teller types. It remains to determine the ratio of these interaction strengths. A study of the angular correlation between the electron and the neutrino in an allowed pure transition can be used to distinguish which of the interactions S or V, or A or T is predominant. It is now established from such experiments[1] that the Fermi interaction is mostly V and the Gamow-Teller interaction mostly A. The neutron decay (mixed transition) combined with the O^{14} decay (pure Fermi transition) leads to the determination of the relative strengths of Fermi and Gamow-Teller interactions. The recent Russian measurement of 11.7 ± 0.4 min. for the half life of the neutron leads to $(C_{GT}/C_F)^2 = 1.42 \pm 0.08$.

Considering only pure transitions, Fermi or Gamow-Teller, one can expect interference between the two types S and V, or A and T. The possible existence of such terms was first pointed out by Fierz[2] and hence these terms are called Fierz interference terms. It is the principal objective of the present work to make an estimate of this effect in Gamow-Teller transitions. Such interference is possible in the electron-neutrino angular correlation expression, but because of the difficulties involved in such experiments these terms are often neglected. Interference between A and V in a mixed transition can also occur, but we will not concern ourselves with this here, nor will we treat forbidden transitions.

b) Fierz Interference

The general expression for the energy distribution of electrons (positrons) in an allowed transition can be written as[3]

$$N(W)dW = [2\pi^3]^{-1} pW(W_0 - W)^2 F(Z,W)\,\xi\,(1 \pm 2b/W)\,dW$$

where
$$\xi = |\textstyle\int 1|^2 \left[k^{-2}\left(|C_S|^2 + |C_S'|^2\right) + \left(|C_V|^2 + |C_V'|^2\right)\right] + |\textstyle\int \sigma|^2 \left(|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2\right)$$

and
$$\xi b = \pm\gamma \left[|\textstyle\int 1|^2 \,\mathrm{Re}\left\{k^{-1}\left(C_S C_V^* + C_S' C_V'^*\right)\right\} + |\textstyle\int \sigma|^2 \,\mathrm{Re}\left\{C_A C_T^* + C_A' C_T'^*\right\}\right]$$

Here the + sign refers to electron and - to positron emission. The other symbols are explained as follows:

$pW(W_0 - W)^2$ is the statistical weight factor which determines, in the absence of the coulomb field, the sharing of energy between the electron and the neutrino.

$F(Z, W)$ is the coulomb field factor which represents the effect of nuclear charge on the emitted electron.

p is the momentum of the electron.

W is the energy of the electron in relativistic units.

W_o is the maximum energy of the electron or positron

$k = \int 1 / \int \beta$

where $\int 1$ = the scalar matrix element

$\int \beta$ = the vector matrix element

k = 1 only if the motion of the nucleons is non-relativistic, since in this case $\beta = \gamma_4 = 1$.

Putting k = 1, we get

$$b = \pm \gamma \left[\frac{Re\,(C_S C_V^* + C_S' C_V'^*) |\int 1|^2 + Re\,(C_A C_T^* + C_A' C_T'^*) |\int \sigma|^2}{(|C_S|^2 + |C_S'|^2 + |C_V|^2 + |C_V'|^2) |\int 1|^2 + (|C_A|^2 + |C_T|^2 + |C_A'|^2 + |C_T'|^2) |\int \sigma|^2} \right]$$

is called the Fierz interference term. Here $\gamma = \sqrt{1 - (\alpha Z)^2} \simeq 1$ represents the screening effect due to the atomic electrons.

C_i = S, V, A, T = is the coupling constant for parity conserving interaction

C'_i = S, V, A, T = is the coupling constant for parity non-conserving interaction.

The complex conjugation on the coupling constants represents the possibility of time reversal invariance in the beta-decay process.

An immediate consequence of $b \neq 0$ is that the spectral shape of an allowed transition will deviate from the statistical shape because of the inverse dependence on W through b. One way of seeing this deviation experimentally is to plot the form factor $N(W) / [F(z, W) pW (W_o - W)^2]$ as a function of W. From this kind of analysis the limits set on b_{GT} are $-0.09 \leq b_{GT} \leq 0.20$. Because of the weak dependence on W such deviations are rather hard to detect. Further the analysis has so far been generally restricted to Gamow-Teller transitions only. Recently, Daniel[4] has applied this method to estimate the Fierz term in the decay of N^{13} $(1/2^- - 1/2^-)$. He obtained b_F = 0.14 using the O^{14} ft value to evaluate the Fermi part of the matrix element.

Integrating expression (1) over the allowed spectrum, we obtain

$$2\pi^3 (ft)^{-1} \ln 2 = \xi + \xi b \langle W^{-1} \rangle \qquad (2)$$

where $f = \int_1^{W_0} F(Z,W)(W_0-W)^2 pW\,dW$ is the so-called Fermi function, and $\langle W^{-1}\rangle = f^{-1}\int_1^{W_0} F(Z,W)\,p(W_0-W)^2\,dW$ is the expectation value of W^{-1} over the allowed spectrum.

Thus a consequence of $b \neq 0$ is that the ft values will depend on W^{-1}. From a plot of $2\pi^3\left[ft\,|\int 1|^2\right]^{-1}\ln 2$ vs. $2\gamma|\int 1|^2\langle W^{-1}\rangle$ which should give a straight line provided k = 1 and the matrix elements remain the same, Gerhart[3] finds from an analysis of data for 0 0, No (Fermi) transitions -- O^{14}, Al^{26} and Cl^{34}, that

$$b_F = \gamma \frac{Re\,(C_S C_V^* + C_S' C_V'^*)}{(|C_S|^2 + |C_S'|^2 + |C_V|^2 + |C_V'|^2} = 0.00 \pm 0.12$$

the chief uncertainty being due to the assumption regarding k. (Recently Altman and MacDonald[5] have considered the effect of coulomb and relativistic corrections to the evaluation of the Fierz term and conclude that the corrections are within experimental uncertainties.) The matrix elements were evaluated b y Gerhart on the basis of charge independence of nuclear forces.

Another fruitful approach for the evaluation of b has been the method of K-capture to positron branching ratios first exploited by Sherr and Miller[6]. In the following section we will describe the information that can be derived from a study of K/β^+ ratios and in particular about the Fierz term.

c) K-Capture Positron Branching Ratios

The study of the shapes of beta-spectra together with the ft values and the shell model (to determine parities) has been very useful in classifying transitions as to the order of forbiddenness. When, however, between two nuclear states enough energy is available for both K-capture and positron emission, a useful quantity that can be measured is the K-capture positron branching ratio. In fact it was one of the early triumphs of the Fermi theory of beta-decay that the K-capture mode of decay was observed as predicted. A measurement of K/β^+ ratio can be used to find the energy difference between two nuclear states if it is known otherwise that the transition is allowed. However, it is observed[7] that all allowed shape transitions (most first-forbidden transitions) have allowed branching ratios also. Thus it is not possible to determine whether an allowed shape transition is indeed allowed, without a knowledge of the parity change. However, the K/β^+ ratio does show a detectable change for unique first forbidden and higher transitions intensified with increasing order of forbiddenness[8]. These latter transitions can probably be much more easily identified on the basis of the shape of the positron spectrum and life-time. In such cases K/β^+ ratios can only serve as an additional check on the assignment. However, the chief virtue of measurement of the K/β^+ ratio for supposedly pure transitions is that it lends itself to the estimation of small-order effects in beta-decay such as the Fierz term. Consider a pure transition, say a Gamow-Teller transition. Then for this transition the probability for positron emission is

$$P_+ = \frac{1}{2\pi^3}\int_1^{W_0} F(Z,W)\, pW(W_0-W)^2\, dW \;\xi(1-2b/W)$$

where the various quantities have already been defined (see page 2). (Note that the terms involving C_S and C_V are set equal to zero.)

The probability for K-capture to the same state can be written as

$$P_K = \frac{1}{4\pi^2}(W_0+W_K)^2\, g_K^2(R)\, \xi(1+2b)$$

where $g_K^2(R) = \frac{1+\gamma}{2\Gamma(2\gamma+1)} R^{2\gamma-2}(2\alpha Z_{eff})^{2\gamma+1}$ is the Dirac radial function.

W_o = total energy available for the transition in m_oc^2 units,

$W_K = \gamma \simeq \sqrt{1-\alpha^2 Z^2}$

So that the ratio of K-capture to positron emission becomes

$$P_K/P_+ = \frac{(1/4\pi^2)(W_0+W_K)^2\, g_K^2(R)\, \xi(1+2b)}{(1/2\pi^3)\int_1^{W_0} F(Z,W)\, pW(W_0-W)^2\, dW\, \xi(1-2b/W)} = R$$

If the Fierz interference term were zero, then putting b = 0, we get

$$(P_K/P_+)_{b=0} = \frac{(1/4\pi^2)(W_0+W_K)^2\, g_K^2(R)}{(1/2\pi^3)\int_1^{W_0} F(Z,W)\, pW(W_0-W)^2\, dW} = R_0$$

Dividing (2) by (1), we obtain

$$R/R_o = \frac{1+2b}{\left[1-2b\langle W^{-1}\rangle\right]}$$

where W^{-1} has already been defined.

$$\therefore\; b = \frac{R/R_0 - 1}{2\left[1 + R/R_0\langle W^{-1}\rangle\right]}$$

Thus a measurement of R can be used to evaluate b. It should be noted that the matrix elements cancel out in the ratio.

Before comparing the theoretical K/β^+ ratio with the observed value, correction for the finite size of the nucleus and screening of the positron and the bound K-electron have to be made. Further, if the measured quantity is the total electron-capture, then correction for capture from higher shells has to be made to obtain the K-capture alone.

For allowed transitions the finite size correction has been shown to be negligible[7]. The screening correction, on the other hand, is not insignificant. Recently Perlman, Welker and Wolfsberg[9] have evaluated the effect of screening on the positron wave function and have given in graphical form the ratio of screened to unscreened values. For most Z values of interest the screening on the K-electron is taken into account by putting $Z_{effective} = Z_K - 0.3$. Zweifel[7] has evaluated the deviation of the actual Z_{eff} from this Slater screening. Regarding correction for capture from higher shells, only L-capture is important for most cases of interest. (At high Z, M capture also becomes important.) Correction for L_{II}-capture is obtained by using L/K ratios given in graphical form by Rose and Jackson[10].

We have applied the K/β^+ ratio technique for the decays of Ga^{68}, Co^{58} and Na^{22}, all pure Gamow-Teller emitters, to obtain the Fierz interference term. Part A of this report contains a description of experiments on each of these nuclei, followed by a summary of available data on Fierz interference in beta-decay as obtained by various methods. Part B of the report deals with some incidental studies on a search for a low-lying O^+ state in Ga^{68} and a search for electric monopole transition from the 2.3 MeV level in Zn^{68}.

PART A

1. K-Capture Positron Branching Ratios in the Decay of Ga^{68}

a. Introduction

The decay of 68 min Ga-68 has been studied by Mukerji and Preiswerk[11] and recently by Crasemann et al.[12]. The decay was found to consist of two modes, the predominant mode ($\sim$87 o/o) being decay to the ground state of Zn-68 by positron emission and electron capture, and the other branch leading to the first excited state at 1.07 Mev by positron emission and electron capture followed by a gamma-ray of about 1.1 Mev. The energies of the positron groups leading to the ground state and the first excited state were measured by means of a magnetic spectrometer to be 1.88 Mev $\pm$ 0., and 0.77 Mev respectively by Mukerji and Preiswerk[11] and found to be 1.94 $\pm$ 0.05 and 0.92 Mev by Crasemann[12]. More recently Daniel[13] has measured the end-point of the high energy positron group to be 1.88 $\pm$ 0.02 Mev. The ratio of the intensities of the low-energy positron group to the high energy group was found by Creasemann to be $(4.1 \pm 1.4) \times 10^{-2}$. No other gamma-rays were observed, and conversion electrons were absent.

The log ft values for the positron decays are 5.3 (to the ground state) and 5.2 (to the 1.07 Mev level). The spin of the ground state of even-even Zn-68 is 0^+ and that of the first excited state 2^+ from systematics of even-even nuclei[14]. These spins together with the allowed log ft values make 1^+ a most likely assignment for the Ga-68 ground state. This assignment has been confirmed by a recent direct measurement of spin by Hubbs et al.[15]. It follows then that the positron decays are pure Gamow-Teller transitions ($\Delta J = 1$, No). Hence it was thought worthwhile to measure the K/β^+ ratios to obtain an estimate of the Fierz term. Incidental to these measurements, other quantities of interest were also obtained.

b. Source Preparation

Since the decay of 270-day Ge-68 leads to the 68 minute Ga-68, a source of Ge-68 was produced as follows. Zinc was electroplated onto a copper backing and was bombarded for 96 microampere-hours with 30 Mev alpha-particles at the cyclotron of the Department of Terrestrial Magnetism, Washington, D. C. (through the courtesy of Drs. Heydenburg and Temmer). 23 weeks after the bombardment the zinc layer on the copper backing was dissolved in a few cc of conc. HCl containing Ge carrier. $GeCl_4$ was distilled onto a receiver. GeS_2 was precipitated by saturating with H_2S, then washed and dissolved in NH_4OH. Sources were prepared by evaporating drops of this solution onto a formvar backing. Measurements were made on Ga-68 in equilibrium with Ge-68.

c. K/β^+ Ratios

Description of the method: The decay scheme as given by Crasemann et al[12] is shown schematically in Fig. 1. Since our measurements were made on Ga-68 in equilibrium with Ge-68, the numbers of these two nuclei decaying per unit time are equal. If $f_{\beta+}^1$ and f_ϵ^1 denote the fraction of positrons and electron-captures to the first excited state at 1.07 Mev and $f_{\beta+}^0$ and f_ϵ^0 denote corresponding quantities to the 0^+ ground state, then we have

$$f_{\beta+}^1 + f_\epsilon^1 + f_{\beta+}^0 + f_\epsilon^0 = 1$$

Now consider the arrangement shown schematically in Fig. 2. As is indicated in the figure, counters I and II detect annihilation radiation, counter III 1.07 Mev gamma-ray, and counter IV, K X-ray.

For the singles counting rate we have

$$N_{0.5}^{I} = 2N_0 E^{I} \left(f_{\beta+}^1 + f_{\beta+}^0\right) = a$$

$$N_{1.07}^{III} = N_0 E^{III} \left(f_{\beta+}^1 + f_\epsilon^1\right) = b$$

$$N_x^{IV} = N_0 f_y E^{IV} \left(f_\epsilon^1 + f_\epsilon^0 + 1\right)/(1 + L/K) = c$$

where the superscripts denote the counters and the subscripts denote the radiations being measured,

E = efficiency of the counter

N_0 = the source strength

f_y = the K fluorescence yield

and L/K the ratio of L to K captures.

For the coincidences, we have

$$N_{0.5,0.5}^{I,II} = 2N_0 E^{a} \left(f_{\beta+}^1 + f_{\beta+}^0\right) = \alpha$$

$$N_{0.5,1.07}^{I,III} = 2N_0 E^{I} E^{III} f_{\beta+}^1 = 2N_0 E^{V} f_{\beta+}^1 = \beta$$

$$N_{x,1.07}^{IV,III} = N_0 E^{IV} E^{III'} f_\epsilon^1/(1 + L/K) = \gamma$$

where E is the combined efficiency of counters I, II for annihilation radiation

$E^{III'}$ = efficiency of the 1.07 counter without absorber (used to annihilate positrons).

The preceding analysis is based on the following assumptions:

a) Conversion of the 1.07 MeV gamma-ray is negligible

b) Contribution to X-rays due to pure electron-capturing 12-day Ge-71 is negligible

c) No positrons are emitted by Ge-68

d) The contribution to annihilation radiation due to pairs from 1.07 MeV gamma ray is negligible

e) Compton background of 1.07 gamma-ray has been subtracted from the 0.511 photo-peak

f) The decay scheme is essentially correct.

With these assumptions and with the help of the preceding relations, we obtain

$$f_\epsilon^1/f_{\beta^+}^1 = \frac{ab}{\alpha\beta}\frac{E^{a}}{E^{I}}\frac{E^{V}}{E^{III}} - 1 = \left[\frac{ab}{\alpha\beta}\right]_{Ga^{68}}\left[\frac{\alpha\beta}{ab}\right]_{Na^{22}} 1.11 - 1$$

$$f_{\beta^+}^1/f_{\beta^+}^0 = \frac{a}{b}\left[1 + f_\epsilon^1/f_{\beta^+}^1\right]\Big/\left(\frac{2E^{I}}{E^{III}}\right) - 1$$

and

$$f_k^0/f_{\beta^+}^0 = R\left[\frac{E^{III'}C}{\gamma} - \frac{N_0 f_y E^{IV} E^{III'}}{\gamma} - 1\right]$$

where $R = (f_k^1/f_{\beta^+}^1)(f_{\beta^+}^1/f_{\beta^+}^0)$ and $f_y E^{IV} = (\gamma/b)\frac{E^{III}}{E^{III'}}\left(1 + 1/(f_k^1/f_{\beta^+}^1)\right)$

In these equations the unknowns to be found are the various efficiencies and N_o, the source strength. We can assume with negligible error that $E^{III} = E^{III'}$. To find the various efficiencies, we replace Ga^{68} by Na^{22} which has similar and known decay scheme. However, in using Na^{22}, two corrections are necessary. First is the difference in range of Lucite of Na^{22} positrons ($\sim$0.540 MeV) and Ga^{68} positrons ($\sim$1.9 MeV). This will affect the solid angle of the counters for annihilation radiation. Secondly, the efficiency of $1\frac{1}{2}$" x 1" NaI(Tl) crystal for detecting the 1.28 MeV gamma ray of Na^{22} is slightly lower than that for detecting the 1.07 MeV gamma ray of Ga^{68}. N_o can in principle be determined by making a chemical separation of Ga from Ge and studying the K X-rays as a function of time. The extrapolation to zero time would then give N_o, if the fluorescence yield and the L/K capture ratio are assumed. This procedure is, however, subject to two uncertainties: (a) absorption in the source itself due to softness of the X-rays, and (b) reckoning zero time. An approximate value of N_o is given by $N_o \simeq 1.15\ a/2E^I$, if it be assumed that the positrons account for 87 o/o of the transitions.

d. Experimental

The source was placed in a lucite well of 6 mm thickness all round. This ensured the complete stopping of the positrons. The source plus absorber assembly was mounted on a lucite pillar which could be rotated about an axis. Fig. 2 shows the experimental set-up, which has already been described. Counters 1 and 2 employ 2" x 2" x 2" NaI(Tl) and counter 3 a $1\frac{1}{2}$" x 1" NaI(Tl) crystal mounted on DuMont6292 photomultiplier tubes. Counter 4, which detected the K X-ray, consisted of a thin freshly cleaved (~1 mm thick and 1 cm square) NaI crystal mounted directly by means of silicone on another DuMont 6292 phototube and sealed with an 0.0005" aluminum foil which served as a light reflector. Counters 1 and 2 had resolution (full width at half maximum) of 12 and 16 o/o respectively for the 0.661 MeV gamma ray of Cs-137. The X-ray counter had resolution of 40 to 60 o/o, depending on the nature of the crystal, for the 9 KeV K X-ray. The use of 2" cube NaI(Tl) crystals facilitated the evaluation of the Compton contribution of the 1.07 MeV gamma ray of Ga-68 or 1.28 MeV gamma ray of Na-22 to the 0.511 MeV photopeak. The use of very thin crystals for the K X-ray helped to discriminate considerably against higher energy gamma rays.

The outputs from the phototubes were fed to Atomic Model 205B preamplifiers, and after amplification by Model N-301 non-overloading Hamner amplifiers were analyzed by means of Model 510 single channel analyzers of the Atomic Instrument Company. The outputs from the pulse height analyzers could be fed to a scaler. For the coincidence measurements the outputs from the pulse height analyzers (whose delays were matched) were fed to a coincidence circuit whose resolving time 2τ was determined by two independent source methods to be 3.2 microseconds. The experiments which initially were done with single channel analyzers were subsequently repeated with Model 520-M 20 channel analyzer of the Atomic Instrument Company. In this case the variable gate in the multi-channel analyzer replaced the coincidence circuit.

The experimental procedure was to measure the singles and coincidences first with Ga-68 and then with Na-22 under identical geometry. In order to eliminate the effects of scattering from the surrounding shield, no shielding was used. Source to detector distances of 1" to $1\frac{1}{2}$" were used. Whereas the procedure for estimating the counting rates for the annihilation radiation and 1.07 MeV gamma ray were straightforward, the analysis of the K X-ray presented a problem. It was found that despite the use of very thin crystals, the K X-ray peak was superposed on a rather high background, apparently due to the higher energy gamma rays. In order to obtain the intensity of the observed X-ray, the spectrum was repeated with an 0.01" aluminum foil which would attenuate the X-ray but not the high energy gamma rays. By normalizing this spectrum with the spectrum without the absorber beyond the K X-ray region and subtracting the background, the intensity of the K X-rays could be estimated. It must be mentioned in this connection that the use of non-overloading amplifiers in observing the K X-ray was very essential.

e. Results

Table I summarizes the results of a typical run. Background corrections have been made. With the weak source used ($\sim$ 1/10 microcurie) and a resolving time of 3 microseconds, the accidental rate was negligible. The corrections mentioned earlier for Na-22 were made as follows: To determine the 0.511 MeV solid angle correction, the counting rate in the annihilation radiation peak was measured as a function of distance between source and detector. From this the correction corresponding to the actual distance used in the experiment was obtained. This amounted to (10 $\pm$ 0.5) o/o. The correction for difference in the efficiency of $1\frac{1}{2}$" x 1" NaI crystal for detecting 1.07 MeV gamma ray of Ga-68 and 1.28 MeV gamma ray of Na-22 was computed from the curves of Bell to be 8 o/o. It must be pointed out here that the corrections just cancel out for

The singles gamma spectrum of Ga-68 taken with the 2" cube crystal is shown in Fig. 3. Besides the annihilation radiation and the gamma ray around 1 MeV, no other gamma ray was observed ($<$ 8 o/o of 1.07 Mev gamma ray). The energy of this gamma ray was found to be 1.067 $\pm$ 0.035 MeV. Na-22 (0.511 and 1.28 MeV, Cs-137 (0.661 MeV) and Co-60 (1.17 and 1.33 MeV) served as calibration sources. The number of positrons

Table I. Summary of Data on Ga^{68} (For symbols, see text)

	Ge^{68}	Na^{22}
a	93.7 ± 3.1 cps	154.0 ± 3.0 cps
b	0.78 ± 0.3 cps	32.0 ± 0.7 cps
c	86.5 ± 2.2 cps	
α	14.73 ± 0.50 cps	25.17 ± 0.70 cps
β	$(6.8 \pm 0.4) \times 10^{-3}$	(0.56 ± 0.02)
γ	$(7.5 \pm 0.4) \times 10^{-3}$	

$$E^{III} = (\beta/a)_{Na} \; 1.08 \times 1.11 = (4.78 \pm 0.18) \times 10^{-3}$$

$$\frac{E^{III}}{2E^{I}} = 0.85\,(b/a)N_a = 0.22 \pm 0.01$$

$$N_o \simeq (4520 \pm 200) \text{ cps}$$

$$f_y E^{IV} = (17.0 \pm 0.9)\,10^{-3}$$

$$f_k^{1}/f_{\beta+}^{1} = 1.28 \pm 0.12 \qquad f_{\beta+}^{1}/f_{\beta+}^{0} = (1.76 \pm 0.23) \times 10^{-2}$$

$$f_k^{0}/f_{\beta+}^{0} = 0.10 \pm 0.02$$

No. of positrons per 1.07γ: Detector 2" cube NaI
Source at 1"

$$\left.\begin{array}{l} N_{1.07} = 2.08 \text{ cps} \\ N_{0.5} = 186.4 \text{ cps} \end{array}\right\} Ga^{68} \qquad \left.\begin{array}{l} N_{1.28} = 74.0 \text{ cps} \\ N_{0.5} = 305.1 \text{ cps} \end{array}\right\} Na^{22}$$

$$N_{\beta+}/N_{1.07} = \left(N_{0.5}/N_{1.07}\right)_{Ga} \left(\frac{\epsilon_{1.28}}{\epsilon_{0.5}}\right) \frac{1}{2} \qquad \text{uncorrected}$$

Corrections: $\frac{\epsilon_{1.28}}{\epsilon_{1.07}} =$ 0.90: solid angle for 0.511 = 10 o/o

$$N_{\beta+}/N_{1.07} = (19.47 \pm 2.10)$$

per 1.07 MeV gamma ray was found to be 19.47 ± 2.10 by comparison with Na-22. An efficiency ratio of 0.90 ± 0.04 was assumed for the 1.28 and 1.07 MeV gamma rays. This value is to be compared with 14.4 ± 1.7 of Crasemann et al. and 27.3 ± 3 of Horen[18]. However, a value of 22 ± 3 was also obtained by Horen from coincidence measurements. The value for $f_{\beta^+}^{0}/f_{\beta^+}^{1}$ is in agreement with the work of Horen. This quantity is an interesting byproduct, since the ratio of the positron branches is determined without measuring the beta spectrum as such.

f. <u>Discussion</u>

Before comparing the experimental results with theory, it is necessary to examine some of the assumptions made early in the analysis. The assumption that the conversion of 1.07 MeV gamma ray is negligible is indeed reasonable. For an E2 transition the value of α_K is $\sim 10^{-4}$. Both the half-life (12 days) and the abundance of Zn^{68} from which it was formed make the contribution from Ge^{71} negligible. Self-excitation is negligible in the weak source employed. It will be shown in Part B of the report, under Ge^{68}, that the amount of positron emission from Ge^{68} is <0.4 o/o. This conclusion is supported by beta-decay energy systematics of Way and Wood[20] which predicts a decay energy for $Ge^{68} \rightarrow Ga^{68}$ to be ~ 750 keV or by a plot of $E_{\beta\beta}$ double beta-decay energy versus neutron number (for Zn-Ge). Linear interpolation gives 500 + 150 keV for $Ge^{68} \rightarrow Ga^{68}$ decay if it be assumed that the $Ga^{68} \rightarrow Zn^{68}$ decay energy is 2.9 MeV. The contribution to annihilation radiation due to pairs from the 1.07 gamma ray is certainly negligible[21].

As regards the last assumption about the correctness of the decay scheme, Horen[18] has found very recently weak electron capture branchings (~ 0.37 o/o) to higher excited states in Zn-68. This fact will alter somewhat the value for the ground state electron-capture positron branching ratio. But since the errors are already large, our conclusions remain unaffected.

In the general introduction the expression for the Fierz term was found to be

$$b = \frac{R/R_0 - 1}{2\left[1 + R/R_0 \langle W^{-1} \rangle\right]}$$

in terms of the measured ratio R, the theoretical ratio R_0, and W^{-1}, the average value of W^{-1} over the allowed spectrum. A sufficiently accurate value for W^{-1} can be obtained from an expression due to Gerhart[3]:

$$\langle W^{-1}\rangle \cong \left(\frac{5}{2W_0}\right)\left[\frac{2W_0^3p_0 + 13W_0p_0 - 3(4W_0^2+1)\ln(W_0+p_0)}{2W_0^3p_0 - 9W_0p_0 - 8p_0/W_0 + 15\ln(W_0+p_0)}\right]$$

where $W_o = (E \;\; + M_oc^2)/m_oc^2$
and $P_o = \sqrt{W_o^2 - 1}$.

For the ground state positron group the available values of W_o are 4.70[11, 13], 4.80[12], all from beta-decay, and 4.75[22] from Zn-68 (pn) Ga-68 threshold. For the positron group to the 1.07 MeV level the direct measurement of Mukerji and Preiswerk[11] gives W_o = 2.51. However, the gamma ray energy together with the ground state W_o fix this value uniquely. For the gamma ray measurements we have 1.02 ± 0.02[12], 1.99 ± 0.015[23], 1.088 ± 0.005[24], and our own value of 1.067 ±0.035, all in MeV. We adopt the values W_o = 2.59 to the 1.07 MeV level, and W_o = 4.70 to the ground state. To compute theoretical K/β^+ ratio a numerical integration of the unscreened Fermi function has been carried out using NBS tables[25]. The screening correction for the positron was obtained from the curves of Perlman et al[9]. The screening correction for the K electron was taken into account by putting $Z_K = Z_{parent} - 0.3$. The computed K/β^+ ratios are 1.42 (to the 1.07 MeV level) and 0.09 (to the ground state). After correcting for 8.5 o/o L-capture the Fierz interference terms are obtained as

$$b_{GT} = +0.03 \pm 0.01 \text{ and } -0.03 \pm 0.02$$

to the ground state and first excited state respectively. The large uncertainty in the electron-capture positron branching ratio for the ground state arises, apart from statistics, from the uncertainty in N_o and the uncertainty in the value of $f_\epsilon^{\,1}/f_{\beta^+}^{\,1}$ itself. The more accurate value for the 1.07 Mev level definitely shows the smallness of the Fierz term.

g. <u>Conclusions:</u>

Electron capture positron branching ratios have been measured for the ground state beta-transition and the transition to the 1.07 MeV level in Zn-68, both of which are presumably pure Gamow-Teller transitions. On the basis of the ratio forthe 1.07 MeV level, it is concluded that the Fierz term $b_{GT} = -0.03 \pm 0.02$. Although the measurement is not very accurate, the evidence for the smallness of the Fierz term is unmistakable. This conclusion is indeed consistent with the more accurate results on Co-58 and Na-22, also pure Gamow-Teller emitters, to be described in the following sections.

The measurements on Ga-68 have been presented briefly[26] at the Cambridge Meeting of the American Physical Society and described in detail in Nuclear Physics[27].

2. Electron Capture Positron Branching Ratio in the Decay of Co-58

a. Introduction

72 day Co-58 decays by electron capture and positron emission to the 0.810 MeV level in Fe-58 followed by a gamma ray of this energy to the ground state. Besides, there is a weak electron-capture branch (2 o/o) to the second excited state at 1.63 MeV. This level de-excites itself predominantly by the emission of a gamma ray of 0.820 MeV to the 0.810 MeV level and partly by the emission of a gamma ray of 1.63 MeV to the ground state of Fe-58. The decay scheme as given by Frauenfelder et al.[28] is reproduced in Fig. 4. The end-point of the positron spectrum is measured to be 0.472 ± 0.006 MeV[29]. No positron emission to the 0^+ ground state of Fe-58 has been observed. The spin of 0.810 MeV level is 2^+ from systematics of even-even nuclei[14]. The spin of the second excited state at 1.63 MeV has been assigned 2^+ from angular correlation studies[28]. This is consistent with the presence of a cross-over gamma transition to the 0^+ ground state. The decay of Co-58 to the 2^+ states in Fe-58 and the absence of transition to the 0^+ ground state suggest a spin of 2^+ or 3^+ for Co-58. The spin has been directly measured to be 2 by Bobrov and Jeffries[30] by means of paramagnetic resonance experiments. The assignment of 2^+ to Co-58 makes the beta transition to the 0.810 MeV level allowed by both Gamow-Teller and Fermi selection rules ($\Delta J = 0$, No). However, recent nuclear orientation experiments of Dagley et al.[31] have shown that the angular distribution of the 0.810 MeV gamma ray is consistent only with the beta transition being pure Gamow-Teller, the amount of Fermi admixture being 0.003 ±

0.005. Thus the measurement of electron capture to positron branching ratio to the 0.810 MeV level becomes of obvious interest from the point of view of determining the Fierz term.

Good et al.[32] and Cook and Tomnovec[33] have measured the ratio of total electron capture to positron emission in the decay of Co-58 to be 5.9 $\pm$ 0.2. When account is taken of the weak electron capture branching to the 1.63 MeV level, the K/β^+ ratio to the 0.810 MeV level becomes 5.8 $\pm$ 0.2. This result was obtained by comparison of the intensities of the annihilation radiation and the 0.81-MeV gamma ray, and by a knowledge of the efficiencies. After the work to be described on Co-58 had been completed and briefly published[34] by the author, the work of Konijn et al.[35] on the same subject has come to attention. By using beta-gamma coincidence technique these workers determined the ϵ/β^+ ratio to be 5.67 $\pm$ 0.14.

Neglecting the weak electron-capture branch (2 o/o) to the 1.63 MeV level for the moment, the fraction of positrons in the decay of Co-58 can be expressed as $f_+ = \beta/2c\sigma$, where c is the singles counting rate for the 0.810 gamma ray, β is the coincidence rate between the 0.810 MeV gamma ray and the annihilation radiation, and σ is the efficiency for detecting the annihilation radiation. The value of f_+ when corrected for the presence of the weak branch will give the desired ϵ/β^+ ratio to the 0.810 MeV level.

b. Experimental

Through the courtesy of Dr. R. W. Hayward of the National Bureau of Standards, a Co-58 source was made available for studies. Unfortunately this source contained an appreciable Co-60 impurity. Co-58 was evaporated onto a 0.0003" mylar foil and sealed with cellophane. The sandwich was then squeezed between two lucite slabs each 1.3 mm thick and 1 cm square. The whole assembly was then sealed with black tape. Thus the positrons from Co-58 (0.470 MeV) were completely stopped. The 0.810 MeV gamma ray was detected in a $1\frac{1}{2}$" x 1" NaI(Tl) crystal. Source to detector distances of 1" to $1\frac{1}{2}$" were used. A typical singles gamma spectrum measured in the 2" cube crystal is shown in Fig. 5. Besides the annihilation radiation and the 0.810 MeV gamma ray belonging to Co-58, gamma rays at 1.17 and 1.33 MeV are also prominently seen. The 1.63 MeV gamma ray of Co-58 is too weak to be seen, and no effort was made to observe it. In order to determine the number of counts in the 0.810 MeV photopeak, it is necessary to subtract the Compton background due to Co-60 gamma rays. In order to do this a pure Co-60 source was substituted and its spectrum was carefully normalized to that of Co-58, 60. The dotted curve in Fig. 5 shows the normalized spectrum. For the coincidence measurements a single channel analyzer was set on the photopeak of the annihilation radiation and the spectrum in coincidence was obtained by gating the 20-channel analyzer with the annihilation radiation. The coincidence spectrum thus obtained is shown in Fig. 6. It is observed that the coincident 0.810 MeV gamma ray is superposed on a rather high background due to Co-60. In order to estimate and subtract this background, a coincidence spectrum was taken by replacing Co-58 by Co-60 and the spectrum normalized to the Co-58 spectrum. The resulting background was thus subtracted. In order to check on the reliability of this procedure, the 0.810 MeV gamma ray was measured in triple coincidence with the two annihilation quanta. From this it was concluded that the background had been correctly estimated. The accidentals were about 10 percent of true coincidences in the doubles spectrum.

In order to determine σ, the efficiency for detecting annihilation radiation initially a calibrated Na^{22} source (accurate to 3 o/o) was used. By measuring the area under the photopeak and knowing the source strength one could compute the efficiency. A more accurate efficiency determination was made as follows: A N^{13} source (a pure positron emitter of 10 minutes half life) was produced by bombarding a 2 mil polyethelene foil for 10 minutes with 1 MeV deuterons at The Johns Hopkins University Van de Graaff generator through the courtesy of O. N. Rask. After the bombardment the foil was cut into a tiny piece approximating the dimensions of the Co-58 source and sandwiched between two freshly cleaved NaI(Tl) crystals 1.2 mm thick and 1 cm square, and mounted in the same geometry as the Co-58 course. The beta spectrum observed in this system is shown in Fig. 7. The energy calibration of the counter was made after the N^{13} source was dead by using external gamma ray sources of Co^{57} (0.123 MeV), Cs^{137} (0.661 MeV), and Na^{22} (1.28 MeV). A Fermi plot of the spectrum is shown in Fig. 8. It has an end-point of 1.16 $\pm$0.05 MeV, in good agreement with the value of 1.20 MeV in the literature[29]. By following the decay of the activity for 3 half-lives, it was concluded that no impurities were present. Under the conditions of the bombardment, no other impurities were likely to be formed.

The beta-spectrum was measured in coincidence with the annihilation radiation photo-peak which was detected by the same $1\frac{1}{2}$" x 1" NaI counter whose efficiency was to be determined. A portion of the beta spectrum is shown in Fig. 9. The efficiency for detecting the annihilation radiation is simply the ratio of the beta-spectrum in coincidence and in singles when corrected for decay. Further, since the crystal source was mounted on a light pipe a correction for the absorption of the 0.511 MeV gamma-ray has to be made. This is of the order of 3.7 o/o. Since the positrons from Co-58 (0.470 MeV) and those from N^{13} (1.2 MeV) have different ranges in lucite and NaI respectively used to annihilate them, one might think that a correction for solid angle has to be made. However, the range of 0.470 MeV positrons of Co^{58} in lucite is 1.4 mm and that of 1.2 MeV positrons of N^{13} in NaI(Tl) is 1.16 mm. The actual thickness used to annihilate the positrons were 1.3 and 1.2 mm respectively. A source to detector distance of 25 mm was used. In view of these circumstances the solid angle correction is less than 1 o/o.

c. Results:

Table 2 lists the results obtained. The uncorrected f_+ is 0.147 $\pm$ 0.005. Referring to the Co-58 decay scheme (Fig. 4), it is seen that $1\frac{1}{2}$ o/o of the 0.810 MeV gamma rays arise from the 1.63 MeV level, and another $1\frac{1}{2}$ o/o arise from cascading to the ground state. The uncorrected f_+ has therefore to be multiplied by 0.03 to get the corrected value of f_+. In order to obtain the amount of electron-capture to the 0.810 MeV level, it should be noticed that 2 o/o of the Co-58 transitions lead to the 1.63 MeV level. Hence $\epsilon = 0.98 - 0.151 \pm 0.005$. Thus the ϵ/β^+ ratio to the 0.810 MeV level is computed to be 5.49 $\pm$0.18. The error introduced in the value of 2 o/o for the branching is very small.

d. Discussion:

The ϵ/β^+ ratio computed above has to be corrected for 8 o/o L-capture[12] to give the value of K/β^+ ratio. The value so obtained is 5.08 $\pm$0.17. The theoretical value is 5.15 $\pm$ 0.24 corresponding to maximum beta energy of 0.472 $\pm$0.006 MeV. Thus our value is in excellent agree-

Table 2. Summary of Results on Co^{58}

(For symbols see text)

$c = 91.00 \pm 1.12$ cps

$\beta = 0.242 \pm 0.003$

σ: (a) From Na^{22}

Source strength = N_o = no. of positrons/min = $(3.16 \pm 0.10) \times 10^5 \beta^+/\text{min}$

a = no. of cts. in the 0.511 photo-peak = 47.0 ± 0.0 cps

$\sigma = a/N_o = (8.92 \pm 0.33) \times 10^{-3}$

(b) From N^{13}

$N_{\beta,0.5} = 358.0 \pm 6.0$ cpm

$N_\beta = 23200 \pm 150$ cpm

$$\sigma = \frac{1}{2}\,\frac{N_{\beta,0.5}}{N_\beta} = (9.02 \pm 0.18) \times 10^{-3}$$

f_+ (uncorrected) $= \beta/2c\sigma = 0.147 \pm 0.005$

f_+ (corrected) $= (0.147 \pm 0.005)\, 1.03 = 0.151 \pm 0.005$

$= 0.980 - f_+ = 0.829 \pm 0.005$

$$\epsilon/\beta^+ = \frac{0.829 \pm 0.005}{0.151 \pm 0.005} = 5.49 \pm 0.18$$

$L/K = 0.08$

∴ $K/\beta^+ = 5.08 \pm 0.17$

ment both with theory and with previous measurements. As before, the Fierz term is computed from the expression

$$b = \frac{R/R_0 - 1}{2\left[1 + R/R_0 \langle W^{-1} \rangle\right]}$$

For Co-58 $\langle W^{-1} \rangle = 0.76$ corresponding to $W_o = 1.924$
$b = -0.006 \pm 0.014$

e. Conclusions:

The fraction of Co-58 decays by positron emission has been measured by coincidence methods using NaI crystals. The value is 0.151 ± 0.005. This value leads to a K/β^+ ratio of 5.08 ± 0.17 for the beta transition to the 0.810 MeV level. The theoretical ratio is 5.15 ± 0.24. The Fierz term is computed to be -0.004 ±0.014. It is rather striking that the theoretical value of the K/β^+ ratio has a larger error than the measured value.

It follows then that the Fierz interference term is extremely small. Unfortunately Co-58 is not the best case, since a small admixture of Fermi component in the beta transition may invalidate the conclusions reached so far. However, if it turns out, as is likely, that the Fermi component is zero, then it may be worthwhile to measure the end-point of the positron spectrum more accurately.

3. A Reinvestigation of the Decay of Na-22

a. Introduction

2.60 Year Na-22 decays by positron emission and electron-capture to the first excited state of Ne-22 at 1.28 MeV followed by a gamma ray of this energy to the ground state. The decay scheme is shown in Fig. 10. The spin of Na-22 has been measured to be 3[36] and presumably the parity is even. The spin of the 1.28 MeV state of Ne-22 is 2^+ from life-time measurements[37] and from systematics of even-even nuclei[14]. Hence the transition $3^+ \longrightarrow 2^+$ follows the selection rule $\Delta J = 1$, No and is therefore pure Gamow-Teller. The electron capture to positron branching ratio in the decay of Na-22 has been extensively studied. A summary of previous work is given in a very recent paper by Konijn et al[38]. So far the best value reported is that of Sherr and Miller[6] who obtained $\epsilon/\beta^+ = 0.110 \pm 0.005$ by an elegant experiment, and by comparing with the theoretical value of 0.1135 ± 0.0020 estimated the Fierz interference term to be (-1 ± 2) percent. Since all the present interpretations on Fierz interference are based on this experiment we have been prompted to attempt a more precise determination of the ratio in N-22.

The principle of the present experiment is extremely simple. Suppose we have a gamma counter which detects the 1.28 MeV gamma ray and a beta counter which detects the positrons. Then assuming that all the positrons are counted, we can write for the beta -1.28 coincidences

$$N_{1.28} = N_o f_+ \sigma_{1.28} = a$$

and for the gamma ray

$$N_{1.28} = N_o \sigma_{1.28} = b$$

where N_o is the transition rate

f_+ = the fraction of decays by positron emission

and $\sigma_{1.28}$ = the efficiency for detecting 1.28 MeV gamma ray.

The ratio of a to be then yields f_+, from which the ϵ/β^+ ratio can be computed. This is possible provided the entire positron spectrum can be measured.

We have employed a 4π plastic scintillation counter for detecting the positrons and a NaI(Tl) counter for the gamma ray. The counter is biased to accept only the photopeak. The effectiveness of the 4π scintillation counter for measuring the shapes of beta spectra has been demonstrated by the work of Johnson, Johnson and Langer[39] and more recently by Robinson and Langer[40] and is substantiated by the present experiment.

A Na-22 source from a NCl solution was evaporated on a 0.0001" mylar foil and covered with a similar foil. The 4π counter was formed in the following way. Two plastic cylinders each 3 mm thick and 1 cm in diameter were chosen. One of the cylindres had a depression ½ mm deep and ½ cm in diameter. The Na-22 sandwich was placed in the depression. The two cylinders were pressed together to form the 4π counter. A cone-shaped light pipe 1½" long having a well at the apex was mounted on a DuMont 6292 phototube. To the bottom of the well the 4π plastic scintillation crystal was cemented by means of Canada balsam. The sides of the well had been painted white to ensure good light collection. The top of the well had a thin aluminum foil whitened inside. The gamma counter was a 2" cube NaI(Tl) crystal which had a resolution of 11 o/o for 0.661 Mev gamma ray of Cs-137. The 4π counter had a resolution of 16 o/o for the 0.624 MeV conversion line of Cs-137. The entire assembly of crystal and counters was surrounded by 2" of lead at a distance of 4".

b. Experimental:

The general features of the 4π β counter were investigated by a P^{32} source using plastic cylinders each 5 mm thick and 1 cm diameter. A Fermi plot of the spectrum is shown in Fig. 11. The end-point of 1.72 MeV is in good agreement with the literature[29]. Experiments on Na^{22} were started with plastics of the dimensions described above. The gamma counter was set on the photo-peak of the 1.28 MeV gamma ray. The peak had a width of 3.5 volts at 35 volts. This was used to gate the 20-channel analyzer. The positron spectrum coincident with the 1.28 MeV gamma ray is shown in Fig. 12. Energy calibration of the spectrometer was obtained by using external gamma rays of Na-22 (0.511 MeV) and Cs-137 (0.661 MeV). The Compton edges located at 3/4 of the maximum were used. The calibration is also shown in Fig. 12. The calibration curve intercepted the axis corresponding to zero pulse height at 18 Kev in agreement with similar observations by Johnson, Johnson and Langer[39].

Because of the fact that the plastic chosen had dimensions somewhat greater than the range of positrons, one would expect that the observed beta spectrum may not be the correct one, but somewhat distorted by the simultaneous detection of a beta particle and its associated compton. Thus the effect would be qualitatively to shift the spectrum towards high energy, without changing the area under the spectrum.

In order, therefore, to obtain the undistorted spectrum, the beta spectrum was measured in triple coincidence with the 1.28 MeV gamma ray and the two annihilation quanta. The experimental arrangement and a functional diagram of the electronic circuitry are shown in Fig. 13. Pulses from the two 0.511 MeV counters and the 1.28 MeV counter were fed to a triple coincidence circuit. The output from the triple coincidence circuit was used to gate the 20-channel analyzer. The positron spectrum gated by the triples is shown in Fig. 12, normalied to the doubles spectrum beyond 50 keV. The statistical error for each point varied from 2 to 4 o/o. The spectrum is indeed displaced, as expected. To obtain a quantitative justification for the spectral displacement, the positrons were completely stopped in just enough lucite and the Compton distribution was obtained in coincidence with the annihilation radiation and the 1.28 MeV gamma ray. The spectrum thus obtained is shown in Fig. 12 and is similar to the one that is obtained using an external gamma source except for the absence of edge effects.

If the assertion that the effect of the Compton distribution due to annihilation radiation is simply to shift the doubles spectrum is correct, then it must be possible to express the doubles spectrum d(h) in terms of the triples t(h'), and the Compton distribution C(h - h'). That is, we should be able to write

$$d(h) = \sum_{h'=0}^{h} t(h')\, C(h - h')\, \Delta h.$$

A numerical calculation was carried out to test this assumption. For an assumed compton of 6 o/o the agreement from point to point was 3-4 o/o. The assumption of 6 o/o compton is not inconsistent with the dimensions of the plastic and the compton cross-section. (The choice of 6 o/o is not critical, since the triples spectrum itself was known to 2-4 o/o). The agreement thus obtained provides quantitative justification for the assertion made earlier. It must be pointed out in this connection that the effect of inner bremsstrahlung is to displace the spectrum in a direction opposite to that of the compton distribution, but because of the weakness of the effect the Compton effect predominates. The preservation of areas in the doubles and triples spectrum is indicated by the fact that the two areas could be normalized to within 1/10 of a percent.

Since the lowest energy observed was around 40 KeV, an extrapolation to zero energy has to be made in order to obtain the area under the whole spectrum. To do this the following procedure was adopted: The ideal Fermi spectrum corrected for screening was plotted. The spectrum was distorted for finite resolution (16 o/o in our case) at various points of the spectrum by folding in a gaussian of the proper width. The assumption was made that the half width varied as the square root of the energy over the entire energy range. Choosing various energies (h_{min}), the area to the right of h_{min} was obtained. It was determined that below 50 KeV the area under the beta spectrum with and without resolution correction differed only by 1/10 percent and amounted to 5.3 o/o of the area under the β spectrum beyond 50 KeV. Thus the area under the ideal Fermi distribution was taken as the correct area. This when added to the area due to the remaining portion of the doubles spectrum (which had been corrected by the compton to get the undisplaced spectrum) would give the total area.

In order to test for any possible systematic errors, the ratio of area to the right of h_{min} and the entire area from 50 KeV up to the maximum energy was plotted both for the ideal Fermi spectrum corrected for finite resolution, and the actual observed doubles spectrum corrected to the triples spectrum, as a function of h_{min}. The result is displayed in Fig. 14. It is seen that the data of four different runs are consistent within themselves to $1\frac{1}{2}$ o/o and consistent with theoretical plot within 1 o/o. This gives confidence that there are no systematic errors involved.

The experiments were repeated with and without lead shielding. The effect of channel width on the gamma ray side was next studied. A different source source was made and the experiment repeated. In each case consistent results were obtained. Throughout the course of the experiment the counters were periodically checked. The energy calibration of the beta counter was carried out before and after each run. The overall statistics in each run was 1/10 to 2/10 of a percent. Altogether seven runs were made.

c. Results:

The data from the six runs are assembled in Table 3 together with explanation. The total area in the beta spectrum up to 50 KeV is (64.08 $\pm$ 0.18) cps. This when corrected for the remaining portion of the spectrum becomes (67.52 $\pm$ 0.19) cps. From this area and the area under the 1.28 MeV gamma ray (75.10 $\pm$ 0.11) cps, the value of f_+, the fraction of Na-22 decays by positron emission, is computed to be 0.899 $\pm$ 0.003. This yields an average ratio of

$$\epsilon/\beta^+ = \frac{1 - (0.899 \pm 0.003)}{(0.899 \pm 0.003)} = 0.112 \pm 0.004.$$

Apart from statistical error, the other uncertainty is due to the folding of Compton distribution, and in the estimation of the area under the beta and gamma spectrum. A calculation was made to see how much error would be introduced if the half-width of the gaussian curve deviated from obeying $\sqrt{E}$ law. Dependences proportional to $E^{0.4}$ and $E^{0.6}$ were tried. From this it was concluded that the error introduced is less than 1/10 of a percent in the final result.

An error in the determination of the end-point of the positron spectrum would introduce an error in the value of h_{min}. Because of the assumed linearity in energy scale this would tend to introduce a linear systematic error. In Table II the end-points are tabulated with uncertainties.

Table II

Run No.	End-Point (KeV)
1	546 ± 11
2	541 ± 10
3	548 ± 11
4	539 ± 10
5	540 ± 10
6	544 ± 11

From the above table the systematic error introduced in this way is estimated to be less than 1.2 o/o. Thus allowing for this error, our ratio would at worst become

$$\epsilon/\beta^{+} = 0.112 \pm 0.005$$

resulting in the Fierz term

$$b_{GT} = -0.004 \pm 0.013.$$

d. Discussion:

The computed value of ϵ/β^{+} is somewhat better than that of Sherr and Miller[6]. The theoretical value of ϵ/β^{+} is 0.1135 ± 0.0020 when corrected for screening and 65 o/o L-capture[10]. The value of $\langle W^{-1} \rangle$ for Na-22 for $W_o = 2.061$ is 0.7. The Fierz term is computed as before from the expression

Table 3: Na^{22} Data

Run No.	Conditions	(a) $\beta_{1.28}$ >50 KeV cps	(b) $\beta_{1.28}$ >0 KeV = 1.053(a) cps	(c) $N_{1.28}$ cps	(d) $f_+ = (b)/(c)$
Source #1: 1	2" of Pb shield at 4" γ-ray, ch. width = 3.5 volts	64.08±0.18	67.48±0.19	75.21±0.11	0.898±0.003
Source #1: 2	No shield ch. width 3.5 v	64.23±0.19	67.63±0.20	75.24±0.15	0.900±0.003
Source #1: 3	No shield ch. width = 3 volts	57.82± 0.22	60.88±0.23	67.76±0.15	0.899±0.004
#2: 4	2" of Pb shield at 4" γ-ray ch. width = 3.5 volts	48.31±0.14	50.87±0.15	56.52±0.10	0.900±0.003
#2: 5	No shield ch. width = 3.5 volts	48.07±0.17	50.62±0.18	56.31±.11	0.899±0.004
#2: 6	No shield ch. width = 3 volts	42.78±0.13	45.05±0.14	50.11±0.10	0.899±0.003

Average value of f_+ = 0.899±0.003

$$\epsilon = 1 - f_+ = 0.101 \pm 0.003$$

$$\therefore \epsilon/\beta^+ = \frac{0.101 \pm 0.003}{0.899 \pm 0.003} = 0.112 \pm 0.004$$

$$b_{GT} = \frac{R/R_o - 1}{2\left[1 + R/R_o \langle W^{-1}\rangle\right]} = \frac{\frac{0.112 \pm 0.004}{0.1135 \pm 0.0020} - 1}{2\left[1 + \frac{0.112 \pm 0.004}{0.1135 \pm 0.0020}\right]} \qquad (0.7)$$

The result is

$$b_{GT} = -0.004 \pm 0.012.$$

Na-22 is perhaps the ideal case for determining the Fierz term because of the low Z involved. It is very unfortunate that the end-point of the beta spectrum is not known well enough to attempt any further refinement in experimental techniques to measure ϵ/β^+ ratio. In any case it has been deminstrated that the plastic scintillator can be effectively used in the study of beta spectra and precision results obtained if analyzed with caution.

e. Conclusions:

A reinvestigation of the electron capture to positron branching ratio in the decay of Na-22 has been made with greater precision than has been possible before, using a 4π plastic scintillator and a gamma counter. The measured value for ϵ/β^+ is 0.112 ± 0.004. From this the Fierz interference term is estimated to be $b_{GT} = -0.004 \pm 0.012$. It is suggested that the beta spectrum end-point be measured with greater precision to make much more meaningful estimates of the Fierz term. It would be of interest to measure K/β^+ ratios in unique forbidden transitions allowed only by Gamow-Teller selection rules.

4. Conclusions to Part A.

K-capture to positron branching ratios have been measured in three pure Gamow-Teller transitions (allowed), namely Ga-68, Co-58, and Na-22 using coincidence scintillation spectrometer techniques, special attention being given to the study of Na-22. The measured ratios are 1.28 ± 0.12 (For Ga-68), 5.08 ± 0.17 (for Co-58) and 0.105 ± 0.004 (for Na-22). By comparing these ratios with the theoretical values the Fierz interference term can be computed. The results for b_{GT} are -0.03 ± 0.02 from Ga-68, -0.004 ± 0.14 from Co-58, and -0.004 ± 0.012 from Na-22. Considering the more precise measurements on Co-58 and Na-22, one is led to the conclusion that the Fierz interference term in allowed Gamow-Teller transitions is extremely small, practically zero. The rather less precise results for Ga-68 are consistent with this interpretation. It must be pointed out that our result for K/β^+ ratio in the decay of Na-22 is slightly better than the value of Sherr and Miller, who had obtained the best result so far. Our measurement can be considered as representing a limit on the precision attainable with plastic scintillators. A further refinement in technique can be considered worthwhile only when refinements in the determination of the spectral end-points are made -- when the end-point of Na-22, for example, can be measured to 1/10 percent.

5. Summary of Fierz Interference in Beta-Decay.

In this section the conclusions regarding Fierz interference in Gamow-Teller transitions as indicated by our measurements are summarized (see Table 4).

Table 4. Summary of Results on Fierz Term from This Work

Nucleus	Transition		W_o	b_{GT}
Ga-68	1^+	2^+	4.70	-0.03 ± 0.02
Co-58	2^+	2^+	1.924	-0.004 ± 0.014
Na-22	3^+	2^+	2.061	-0.004 ± 0.012

Gerhart[3] has made an excellent analysis of Fierz interference in Fermi transitions and concludes $b_F = 0.00 \pm 0.12$. A brief review of Fierz interference in beta-decay has been recently given by the author[41]. From the above table one sees that the best evidence for the smallness of the Fierz term in G-T interactions comes from Na-22. Konijn et al.[38] have summarized data regarding the interference term as determined by K/β^+ ratio technique. They conclude that $b_{GT} = -0.007 \pm 0.010$.

From evidence presented above for Gamow-Teller transitions and from Gerhart's analysis of Fermi transitions one can conclude that the Fierz term is practically zero. Before parity non-conservation was discovered, the Fierz term in G-T transitions could be expressed as

$$b_{GT} = \frac{C_A C_T}{|C_A|^2 + |C_T|^2}$$

The smallness of b could be interpreted as implying that either C_A/C_T or C_T/C_A was small. With the discovery that parity is not conserved in beta-decay, the definition of b has acquired the extended form

$$b_{GT} = \frac{\mathrm{Re}(C_A C_T{}^* + C'_A C'^*{}_T)}{|C_A|^2 + |C_T|^2 + |C'_A|^2 + |C'_T|^2}$$

where $C_{A,\,T}$ are the parity conserving coupling constants

$C_{A',\,T'}$ are parity violating coupling constants, and the *s denote complex conjugation resulting from a possible violation of time reversal invariance.

With this new definition the smallness of only means

$$\mathrm{Re}(C_A C_T{}^* + C_{A'} C_{T'}{}^*) = 0.$$

This implies that

$$\frac{C_A}{C_{A'}} = - \frac{C'_T{}^*}{C^*_T}$$

Nothing more can be said concerning the coupling constants unless the relation between the parity conserving and parity non-conserving coupling constants is known, and further a knowledge about the validity of time reversal invariance. The loss of definitiveness regarding the significance of the Fierz term is one of the major consequences of the discovery of parity non-conservation.

PART B

1. Search for A Low-Lying 0^+ State in Ga-68

A. Introduction

The decay of 270 day Ge-68 has been studied by Crasemann[12] and by Horen[18]. The spin of Ga-66 has been measured to be 0[42] and presumably the parity is even. The spin of Ga-68 is most likely to be 1^+ as indicated by allowed log ft values for positron decays to Zn-68. This assignment has been confirmed by a recent direct spin measurement by Hubbs et al[17]. In this region of nucleon numbers 31-37 the $p_{3/2}$ and $f_{5/2}$ are close-lying in energy, as is evident from the measured spins of some stable isotopes in this region[43]. Although the decay energy for Ge-68 - Ga-68 is nearly 700 KeV[20], no gamma rays have been reported in the decay nor any internal conversion electrons. Levels in Ga-68 at 0.17, 0.34, are known through the reaction Zn-68 (p, n)Ga-68[22]. The absence of gamma rays in the decay of Ge-68 means that none of these levels are populated, which in turn implies that the spins of these states must ≥ 2 if of even parity. On the other hand, the closeness of $p_{3/2}$ and $f_{5/2}$ suggests that there might exist a low-lying 0^+ state formed by the same configuration as is found in Ga-66. Such a competition between $p_{3/2}$ and $f_{5/2}$ is in evidence in Cu-62, which has a low-lying 0^+ level very close to the 1^+ ground state[44]. Since no measurements on the low-energy radiations had been reported, it seemed of interest to look for a low-lying 0^+ state. If indeed such a level did exist, it was expected that the electron capture decay from Ge-68 to both 0^+ and 1^+ states would be allowed and would result in a gamma-ray (M1) which could be detected by X-ray-X-Ray and/or X-ray-gamma ray coincidences, if not in the singles gamma spectrum.

An odd-odd nucleus can be looked upon as made up of a superposition of two odd A nuclei, one of them with an odd number of neutrons and the other with an odd number of protons. Since the angular momentum according to the shell model seems to be carried entirely by the last odd nucleon, the study of the spins of odd-odd nuclei throws light on the nature of the nuclear force between the odd proton and the odd neutron. By assuming various forms for the neutron-proton interaction the energy levels of an odd-odd nucleus can be theoretically predicted. The experimental verification of such theoretical predictions is rather hard, since odd-odd nuclei as a rule are unstable. Therefore it would be of interest to study the energy levels of as many odd-odd nuclei as possible. From this point of view the search for a low-lying 0^+ state in Ga-68 seemed more meaningful.

B. Experimental

A Ge-68 source in equilibrium with Ga-68 was produced as described under Ga-68 in Part A of this report. The region (0 to 30 KeV) was studied using very thin (~1 mm thick and 1 cm square) NaI(Tl) crystals. The crystal was mounted with silicone on a DuMont 6292 phototube and sealed with an 0.0001" aluminum foil. The foil besides ensuring a high transmission for the soft radiations, also served as light reflector. Fig. 15 (curve a) shows a typical spectrum. The resolution for 9 KeV K-X-ray varied from 60 to 60 o/o, depending on the crystal. The 5.8 KeV K-X-ray of Fe-55 served as energy standard. Clearly there is no indication of any gamma ray. It is further apparent that the contribution of high energy pulses to the X-ray is appreciable. The region 30 KeV to 1.2 MeV was investigated by a $1\frac{1}{2}$" x 1" NaI(Tl) crystal. Besides the annihilation radiation and the known gamma ray whose energy was measured to be 1.067 ± 0.035 MeV, no other gamma ray was observed (<8 o/o of 1.07 MeV gamma ray). To study X-ray-X-ray coincidences the Ge-68 source was sandwiched between two DuMont 6292 phototubes on which thin NaI(Tl) crystals were mounted, covered with aluminum foil, and sealed with a light shield. Fig. 15 (curve c) shows the coincidence spectrum (0 to 30 KeV). Most of the counts above accidentals are due to crystal to crystal scattering of higher energy pulses. This was confirmed by attenuating the K-X-ray in one of the channels and repeating the spectrum. The 1.07 MeV gamma ray is too feebly converted to give any noticeable coincidences. The X-ray high energy gamma ray (up to 750 KeV) coincidences were performed by replacing one of the counters by a $1\frac{1}{2}$" x 1" NaI(Tl) counter. The results were negative. The region beyond 750 KeV was not studied, since the Ge-68 - Ga-68 decay energy can at most be 750 KeV[22].

A more rigorous search for the 0^+ state was attempted by separating Ge from Ga chemically, using successive ether extractions from 6N HCl. Since an appreciable part of Ge (40-60 o/o) is also extracted[45] into the ether layer, and since the number of extractions could not be done more than twice owing to the fast growth of 68 minute Ge-68, an efficiency of 50 o/o or less was all that could be attained for Ge. The Ge thus separated was converted into the sulphide and rapidly transferred to the counting system. The region 0-30 KeV was studied as a function of time with the 20-channel analyzer using a thin freshly cleaved NaI crystal. At the same time a second counter, $1\frac{1}{2}$" x 1" (NaI(Tl) was set on the photopeak corresponding to the annihilation radiation and its growth in Ga-68 was followed as a function of time. Fig. 15 (curve b) shows the pulse height spectrum taken immediately after the chemical separation. Clearly there is no gamma ray ($<$ 1 o/o of K-X-ray). From the growth curve of annihilation radiation which corresponded to a 70 minute half-life, an upper limit of 0.4 o/o per decay could be set on positron emission by Ge-68. Horen[18] arrived at an upper limit of 0.9 o/o by comparing the gamma spectrum of Ge-68 + Ga-68 with that of Ga-68 alone.

C. Discussion:

The failure to observe any K X-ray K-X-ray, low-energy gamma ray or K-X-ray high energy gamma ray (up to 750 KeV) coincidences suggests that the 0^+ state lies either very close to the ground state at an energy less than the K-binding energy, or very high -- higher than the Ge-Ga decay energy. The absence of transitions to any of the known excited states in Ga-68 confirms that the spins of these states must be $\geqslant 2$ if of even parity.

D. Conclusions:

A search for a possible low-lying 0^+ state in Ga-68 has been made through the decay of Ge-68 using NaI(Tl) crystals. The results were negative. The failure to find the 0^+ state implies that the analogy of Cu-62 does not hold in this case. The absence of positrons in the decay of Ge-68 is consistent with the decay proceeding purely by electron-capture.

Results of this investigation have been published in Nuclear Physics[27].

2. Search for EO Transition from the 2.3 MeV Level in Zn-68

a. Introduction

The decay of Ga-68 has been recently reinvestigated by Horen[18], who found evidence for levels in Zn-68 at 1.07, 1.88 and 2.3 Mev. The decay scheme as given by Horen is reproduced in Fig. 16. The branching percentages to the various levels are indicated, together with the gamma-ray branchings. The levels were assigned the following spins and paritics respectively: (1.07 (2^+), 1.88 (1^+ or 2^+), and 2.3 (2^+). No cross-over gamma ray transition from the 2.3 MeV level to the 0^+ ground state was observed. This fact together with the result of angular correlation studies on the 1.07-1.24 MeV gamma cascade led Horen to suggest 2^+ for the 2.3 Mev level. Since the errors on the angular correlation data were rather large, this spin assignment was considered to be far from unambiguous. It seemed attractive to assign 0^+ for this state. Such an assignment would indeed be consistent with all the observed data. Since 0-0, No transitions throw light on the nuclear structure involved, it seemed worthwhile to look for additional evidence in support of this hypothesis.

0-0, No gamma transitions are strictly forbidden because of the transverse nature of the photon. Hence the de-excitation of the state in question can proceed only through internal conversion. If, however, the energy of the transition exceeds $2m_oc^2$, an alternative mode of decay is possible, namely internal pair formation. The transition probability for an EO transition can be expressed as a product of electronic and nuclear wave functions as in the case of internal conversion for higher multipoles. Thomas[46] has given expressions for the processes of K-conversion and internal pair-creation. The nuclear matrix element is expressed as

$$M = \int \Psi^*_{in} \sum_p r_p^2 \Psi_{fin}$$

where the summation extends over all the protons in the nucleus. M can be conveniently written as $M = \rho R^2$ where R is the nuclear radius and ρ is a measure of the strength of the EO transition, a quantity analogous to the reciprocal of the ft value in beta-decay. The theoretical transition rates for K-conversion and pair formation according to Thomas[46] are given by

$$W_k/\rho^2 = 7.6\times10^{14}\frac{[S+\sqrt{3}(S+2)]^2}{[\Gamma(3+2S)]^3}(\alpha Z)^{3+2S}\,2R^{4+4S}\,\frac{\varepsilon+1+S}{\eta}f_-(\eta,Z)$$

and

$$W_p/\rho^2 = \frac{2.9\times10^{15}}{\pi[\Gamma(3+2S)]^2}\,2R^{4+4S}\int_1^{E-1}\frac{\varepsilon_+\varepsilon_- - (1+S)^2}{\eta_+\eta_-}f_+(\eta_+,Z)f_-(\eta_-,Z)\,d\varepsilon_+$$

where $\varepsilon_+ + \varepsilon_- = E$; $\varepsilon = E + 1 + \rho$; $\eta = (\varepsilon^2 - 1)^{1/2}$; $\rho = \sqrt{1 - \alpha^2 Z^2} - 1$

$f_{\pm}$ is the Fermi function as tabulated in the NBS tables[19], E is the transition energy. All the units are relativistic. $R = 1.3 \times 10^{-13} A^{1/3}$ cm. Church and Weneser[47] have given graphs of W_K as a function of the atomic number, Z, and transition energy E.

0^+ first excited states are known in the doubly magic nuclei - ${}_8O^{16}$, ${}_{20}Ca^{40}$, and ${}_{40}Zr^{90}$ with the neutrons in Zr^{90} completely filling the $p_{1/2}$ shell. 0^+ second excited states occur in ${}_6C^{12}$, ${}_{32}Ge^{72}$ and ${}_{46}Pd^{106}$. 0-0 transitions from higher excited levels are observed in ${}_{84}Po^{214}$, U^{234}, Pu^{238} and ${}_{48}Cd^{114}$. It has been suggested that the 0^+ excited state in doubly magic nuclei may be due to two particle excitation. A similar explanation has been advanced for the second excited state of C^{12}.

b. Experimental

Since the internal pair positron spectrum from the 2.3 MeV level in Zn-68 would be superposed on a rather high background of positrons from the beta-decay of Ga-68, it was decided to look for internal conversion electrons of 2.3 MeV which would appear as a monoenergetic line well beyond the positron end-point of 1.88 MeV. In order to observe the small peak expected due to the conversion electrons, it was necessary to reduce the background to a minimum. In the present investigation this has been accomplished by the use of an anti-coincidence arrangement.

A block diagram of the experimental arrangement is shown in Fig. 17. The Ga-68 source was sandwiched between two plastic scintillators each $1\frac{1}{2}$ cm high and 3 cm in diameter (thus ensuring 4π geometry) and mounted on the face of a DuMont 6292 photomultiplier tube. A second plastic scintillator surrounding the first one was mounted on another phototube ans served as the anti-coincidence counter. The sensitive volume of the counters was surrounded by 4 inches of lead. Pulses in counter 1 not accompanied by pulses in counter 2 operated a gate which admitted to the 20 channel analyzer any pulse in the beta counter (counter 2) occurring in an interval of 3.5 microseconds. The anti-coincidence circuit used here was the same as employed by Tilley[48] with some slight modification. The modification consisted in reducing the duration of the univibrator pulse from 12 to 3 microseconds.

c. Results:

The positron spectrum observed in this system is shown in Fig. 18. The end-point of the spectrum was determined to be 1/89 $\pm$0.06 MeV by comparison with the beta-spectrom of P-32 of end-point 1.71 MeV, also shown in the figure. The resolution of the counter was 18 o/o for the Cs-137 624 KeV conversion line. The search for internal conversion electrons was made by setting the pulse height at 2.1 MeV. The search lasted 105 hours, during which time the apparatus was periodically checked. From the total number of counts observed in the region where the conversion electrons were expected with and without the source, and the total number of counts in the beta spectrum, an upper limit of $(5 \pm 25) \times 10^{-9}$ conversion electrons per decay of Ga^{68} (assuming that the positrons account for 88 o/o of the transitions) could be set. The results are summarized in Table 5.

d. Discussion and Conclusions

One can calculate the expected yield of 2.3 MeV internal conversion electrons as follows (assuming that the state is 0^+). On the basis of the single particle model, the transition probability for an electric quadrupole (E2) gamma transition is given by Moszkowski[49] as $W_\gamma = 1.6 \times 10^8 A^{1/3} E_\gamma^5$. For the 1.24 MeV gamma ray from the 2.3 MeV level to the 1.07 MeV level this is calculated to be $W_{1.24} = 10^{11}$ sec^{-1}. Now the K-conversion probability for the EO transition to the 0^+ ground state is expressed by Church and Weneser[47] as $W_K/\rho^2 = 7 \times 10^8$ sec^{-1} where ρ as already defined is a measure of the strength of the EO matrix element. In Table 6, taken from Deutsch[50] are listed the values of ρ^2 measured for several EO transitions (0 - 0).

If the assumption is made that the EO matrix element for Zn-68 is not much different from that for Ge-70, we can take $\rho = 0.11$, which is the value recently measured by Alburger[51].

Now the conversion yield is expressed as

Table 5. Summary of Results on Search for EO Transition

No. of cts. above 2.1 Mev with source in 105 hours	15 ± 3.7
No. of cts. above 2.1 MeV without source in 105 hours	14 ± 3.6

Total no. of cts. due to conversion electrons if any, in 105 hours $\simeq 1 \pm 5$

Estimated no. of positrons in the beta spectrum ~ 450 cps

No. of disintegrations of positrons $\sim 450 \times 105 \times 3600$

No. of disintegrations of Ga^{68} $\sim \dfrac{450 \times 105 \times 3600}{1.9}$

assuming 0.90 $\sim 1.9 \times 10^{8}$ cts/105 hr.

No. of conv. electrons per disintegration $\sim \dfrac{1 \pm 5}{1.9 \times 10^{8}}$ $(0.5 \pm 2.5) \times 10^{-8}$

or $(5 \pm 25) \times 10^{-9}$ per decay.

Table 6. Transition Probabilities for 0-0 Transitions

Nucleus	Transition Energy, MeV	ρ^2
C^{12}	7.68	0.06
O^{16}	6.06	0.06
Ge^{70}	1.21	0.015
Ge^{72}	0.69	0.014
Zr^{90}	1.75	0.036
Pd^{106}	1.14	0.02
Po^{214}	1.41	0.00257

$$N_K = \frac{(W_K/\rho^2)\rho^2}{\left(\frac{W_K}{\rho^2}\right)\rho^2 + W_{1.24}} \; f\, N$$

where N is the total number of disintegrations and f is the fraction of decays leading to the 2.3 MeV level. From the data of Horen, f is taken to be 10^{-3}. Nf estimated from the positron spectrum is 2×10^5 in 105 hours. Substituting these numbers, the computed yield is $N_K = 8.4 \times 10^{-9}$ conversion electrons per decay, to be compared with the measured value of $(5 \pm 25) \times 10^{-9}$.

If these estimates are indeed correct, then one can conclude that 0^+ is an unlikely assignment for the 2.3 MeV level. This would give rise to the interesting possibility of the existence of a succession of 2^+ levels, if it is assumed on the basis of systematics[52] of even-even nuclei in this region that the 1.88 MeV level is 2^+. The measured upper limit for the internal conversion electrons is indeed consistent with the expected yield of $< 10^{-10}$ conversion electrons per decay for an E2 transition of 2.3 MeV.

We have assumed rather tacitly that the single particle model description is valid in describing the gamma transition. It has been pointed out by Scharff-Goldhaber[53] that the 1.24 MeV gamma ray transition in Ge-70 is ten times faster than expected on the basis of the single particle model. If, by analogy with this, it turns out that the 1.24 MeV gamma ray is equally fast, then our conclusions are somewhat weakened. It is therefore of obvious interest to perform a careful angular correlation of the 1.07 - 1.24 MeV gamma cascade.

3. Conclusions to Part B

A search for a possible low-lying 0^+ state in Ga-68 has been made through the decay of 270-day Ge-68 using NaI(Tl) crystals. The results were negative. An upper limit of 1 o/o could be set on the gamma ray emission in Ge-68 decay. The failure to find the 0^+ state implies that the analogy of Cu-62 does not hold in this case. The absence of gamma rays in Ge-68 decay means that the levels in Ga-68 known from Zn-68 (p, n)Ga-68 reaction must have spins of at least 2 if of even parity.

An upper limit of 0.4 o/o per decay could be set on the amount of positron emission by Ge-68. This is consistent with the decay proceeding purely by electron-capture as preditted by the beta energy systematics of Way and Wood[20].

A search for an electric monopole (EO) transition from the 2.3 MeV level in Zn-68 to the ground state has been made, using plastic scintillators and a shielded anti-coincidence arrangement. Internal conversion electrons of 2.3 MeV arising from the EO modes of de-excitation were sought. An upper limit of $(5 \pm 25) \times 10^{-9}$ conversion electrons per decay of Ga-68 could be set. Assuming a value of 0.11 for ρ, the EO strength parameter, and the single particle model to apply in describing gamma transitions, the theoretically expected yield was 84×10^{-9} conversion electrons per decay. The measured upper limit is interpreted as evidence against a possible 0^+ assignment for the 2.3 MeV level, but the interpretation must be viewed with reservation owing to the assumptions made in computing the theoretical yield. It is suggested that an angular correlation of the 1.07 MeV - 1.24 MeV gamma cascade be made with a strong source to decide between the 0^+ and 2^+ spin assignments.

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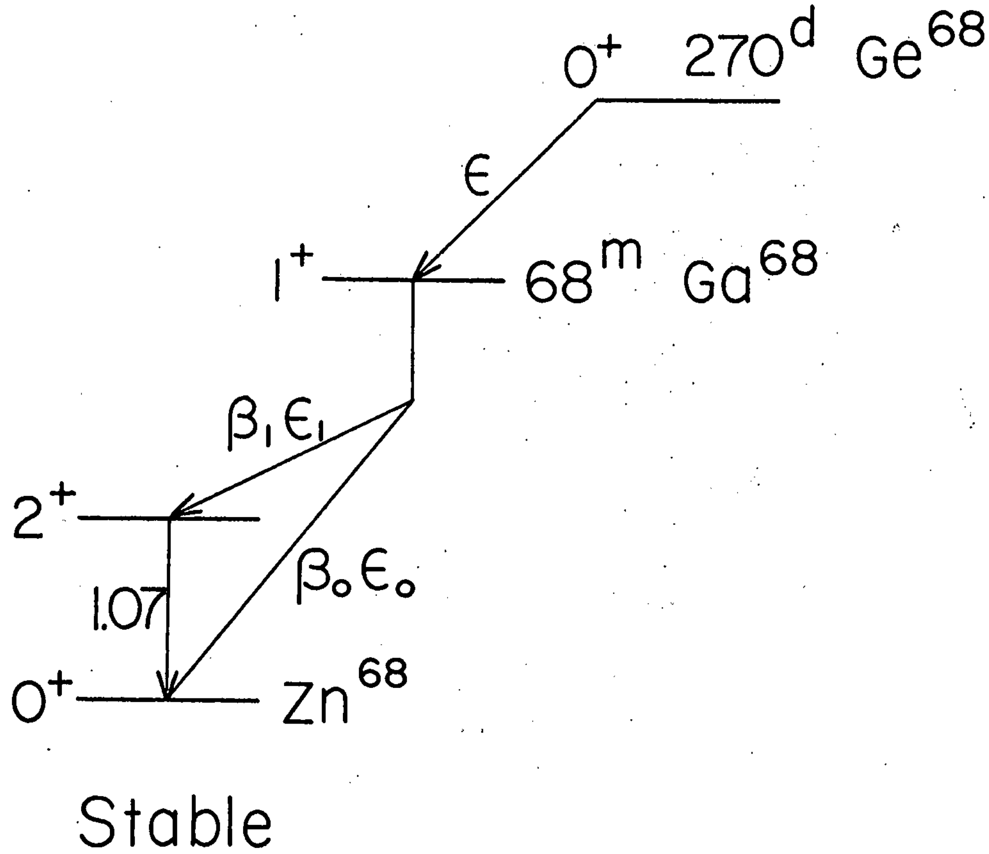
16. Decay scheme of Ga^{68} as given by Horen

17. Block diagram of anti-coincidence arrangement used in the search for EO transition in Zn^{68}. Shielding not shown

18. Positron spectrum of Ga^{68} observed in the anti-coincidence system. Also shown for reference is the beta-spectrum of P^{32} (singles)

Fig 1



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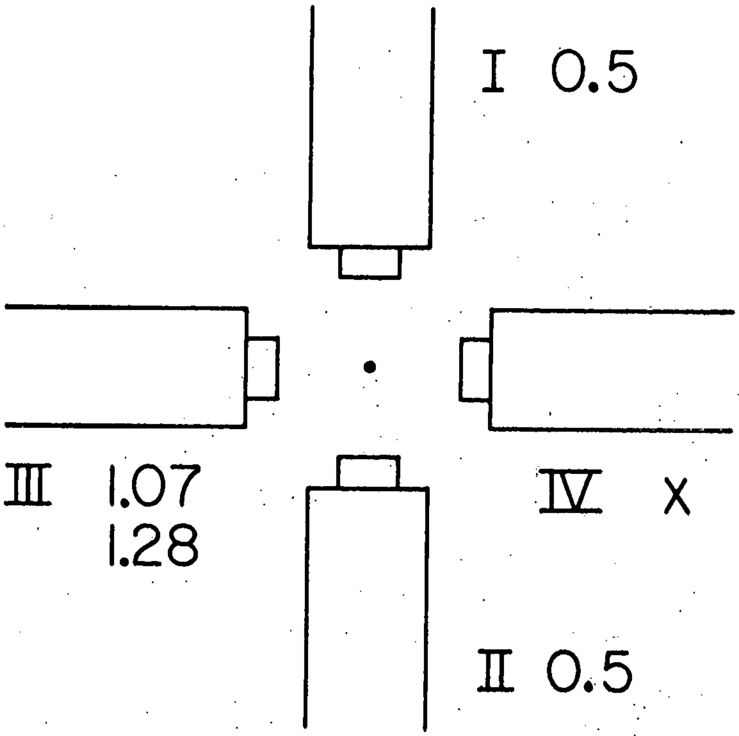
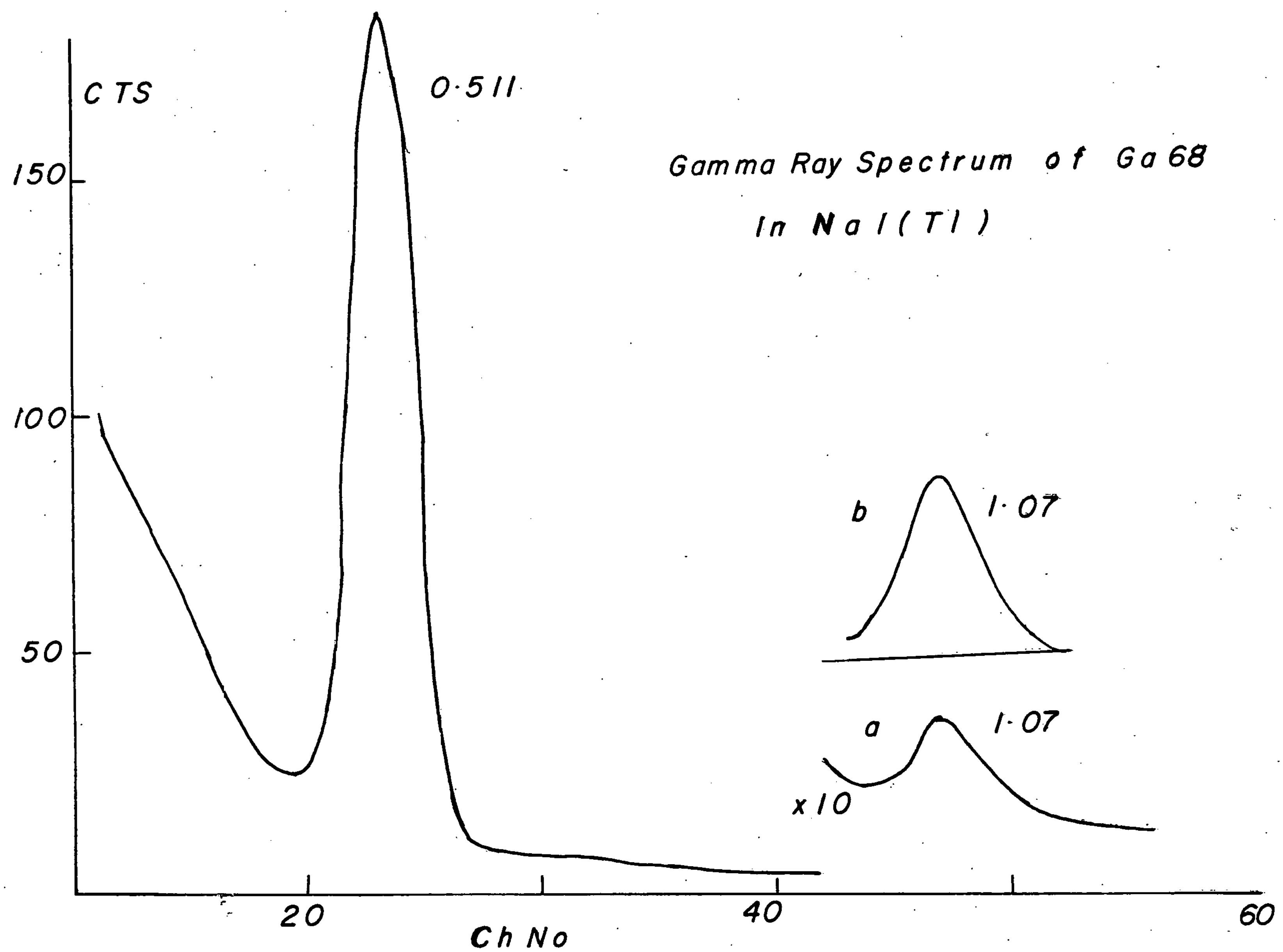


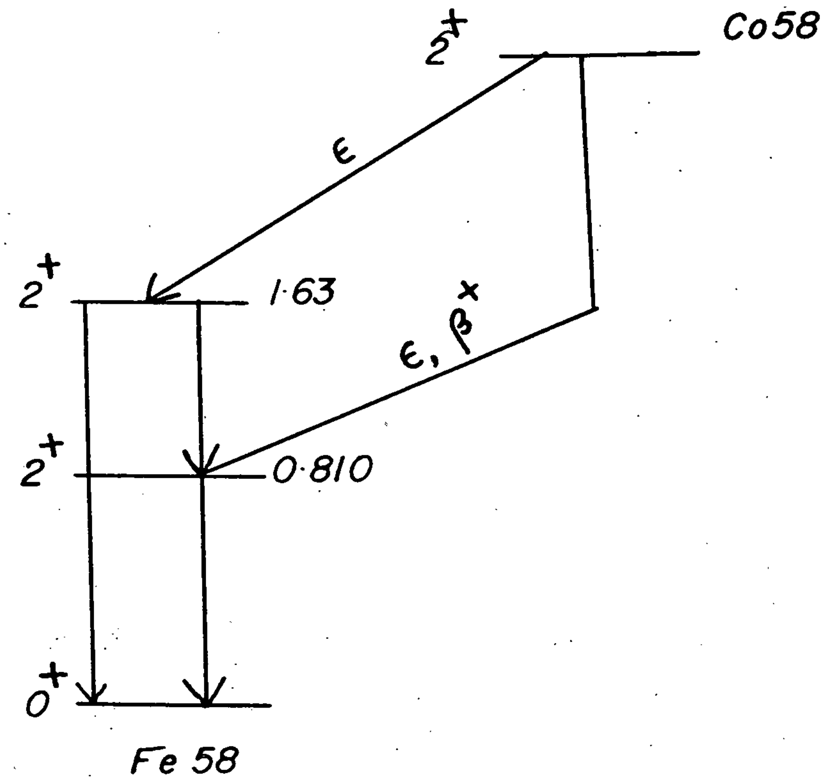
a

3

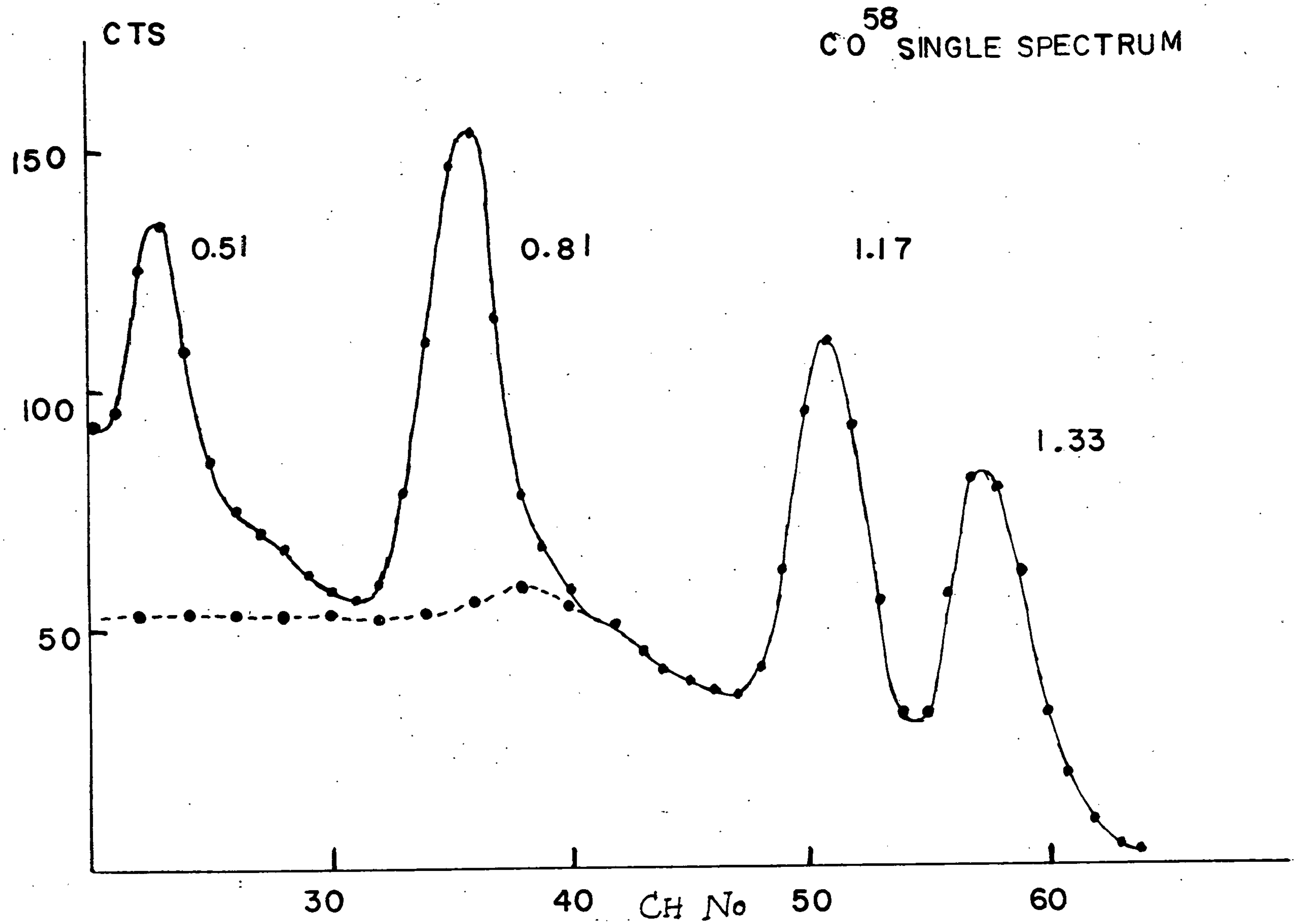


Gamma Ray Spectrum of Ga 68
In NaI(Tl)
CTS
0·511
150
100
50
b
1·07
a
1·07
x10
20
40
60
Ch No

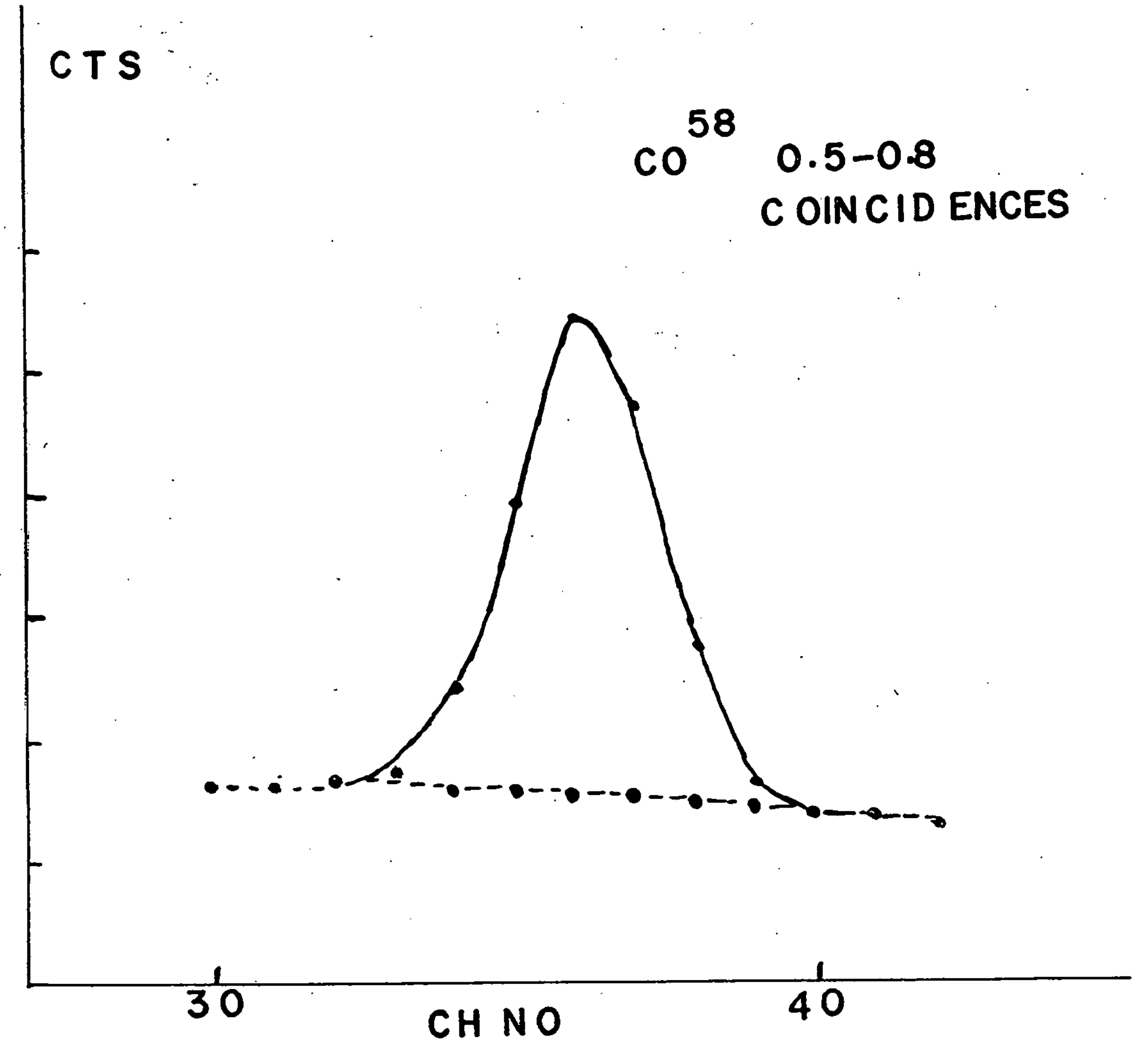
Decay Scheme of Co 58



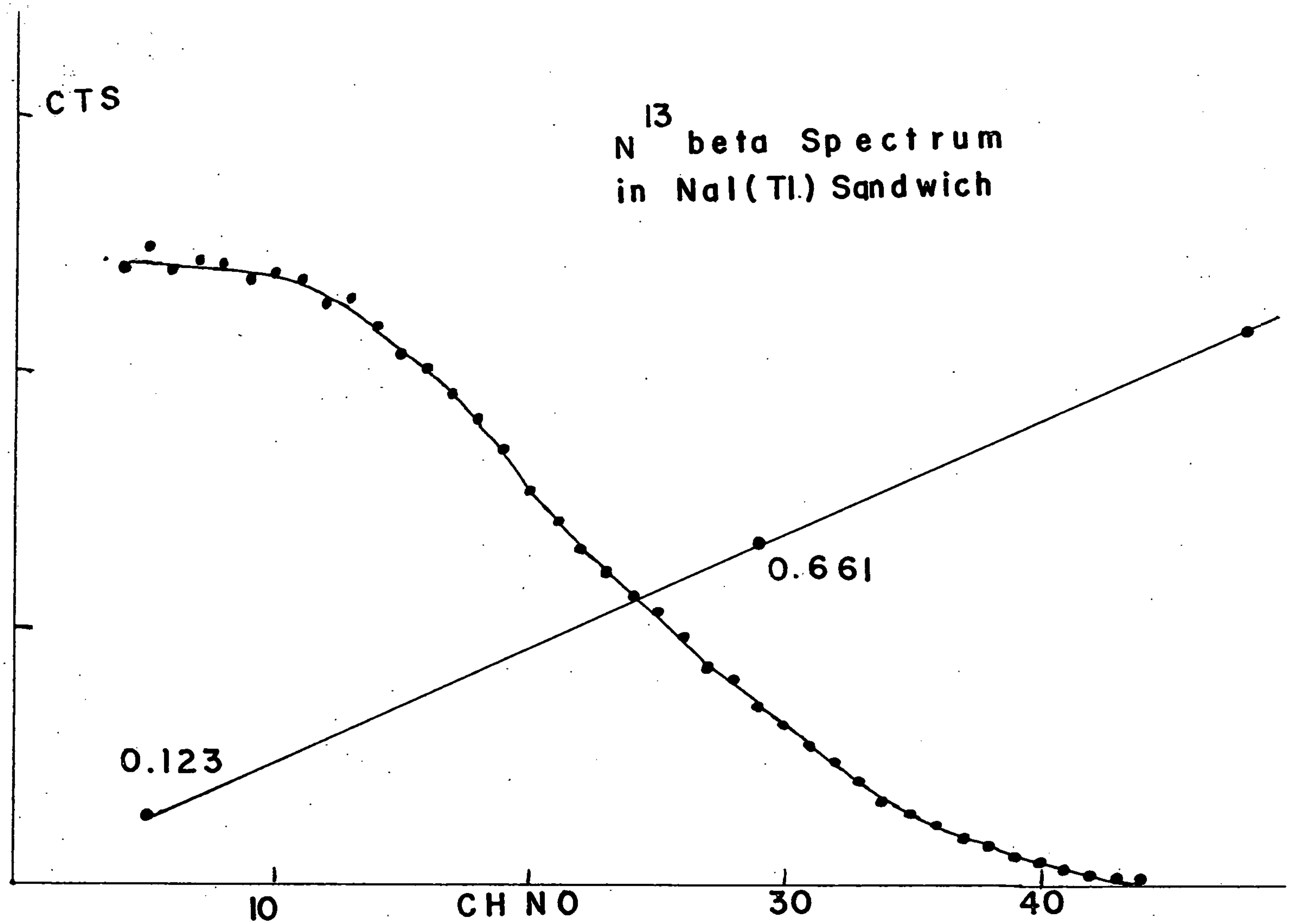
5

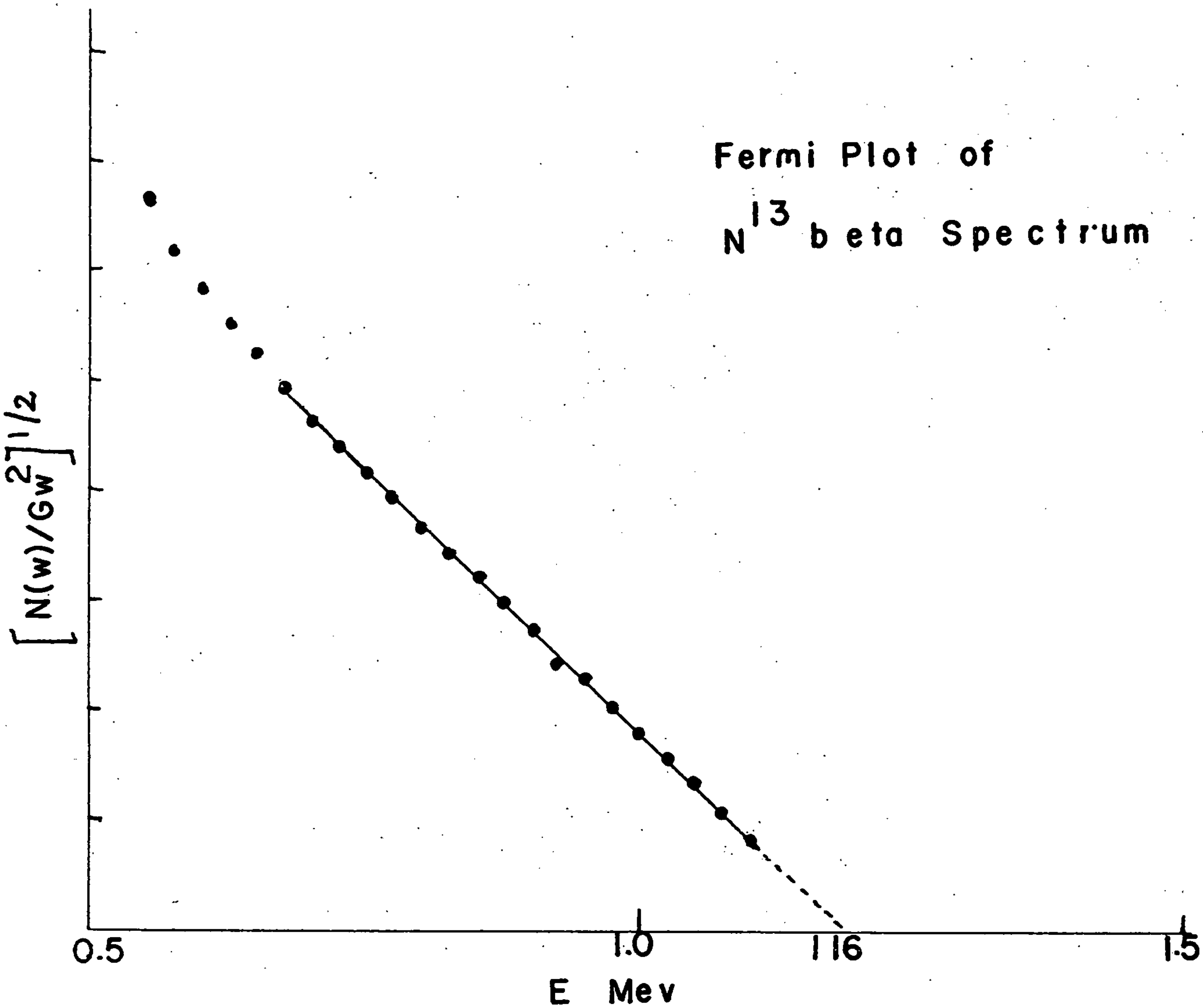


CTS
CO58 SINGLE SPECTRUM
150
100
50
0.51
0.81
1.17
1.33
30
40
50
60
CH No

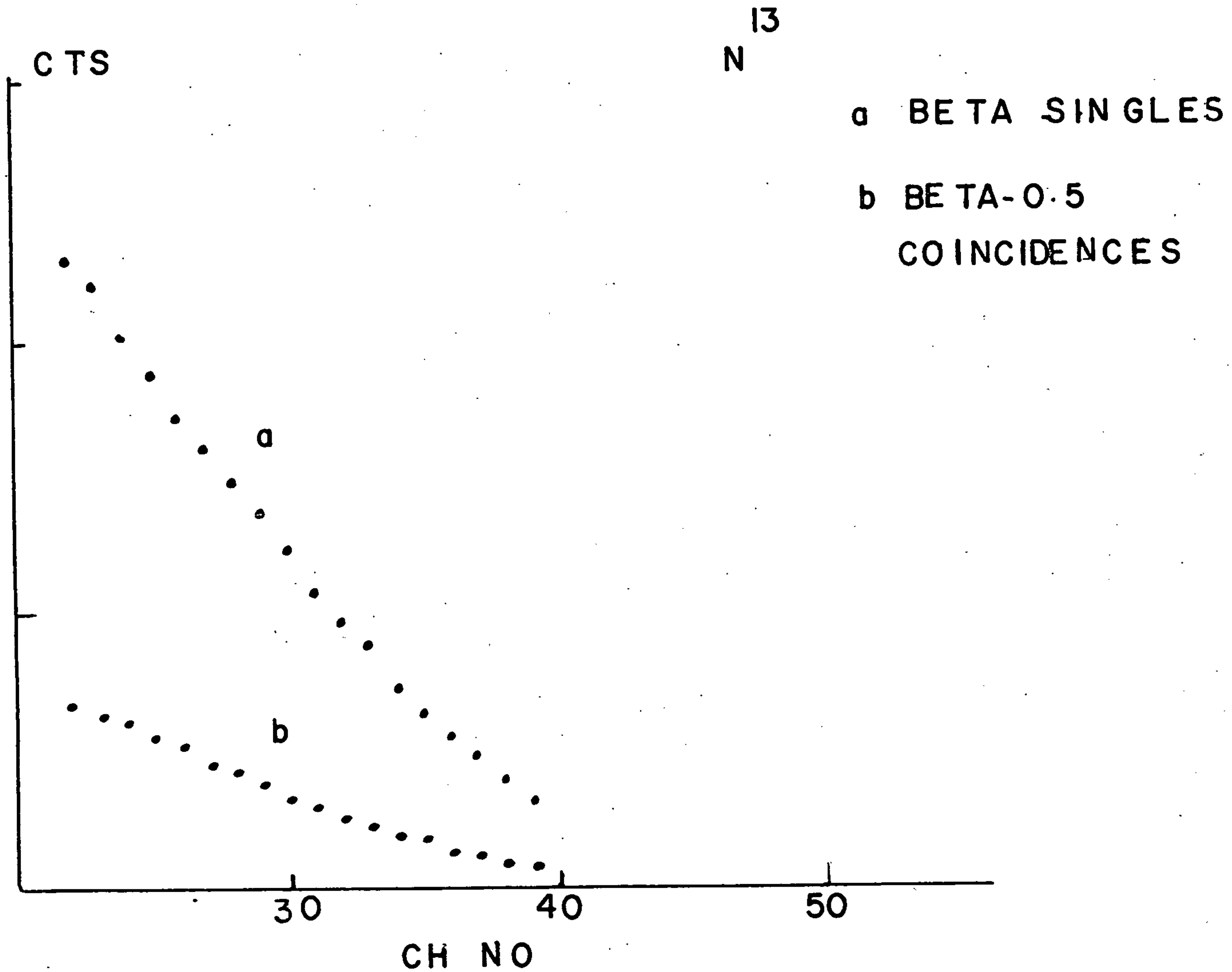

CTS
CO^{58} 0.5-0.8
COINCIDENCES
30
40
CH NO

7

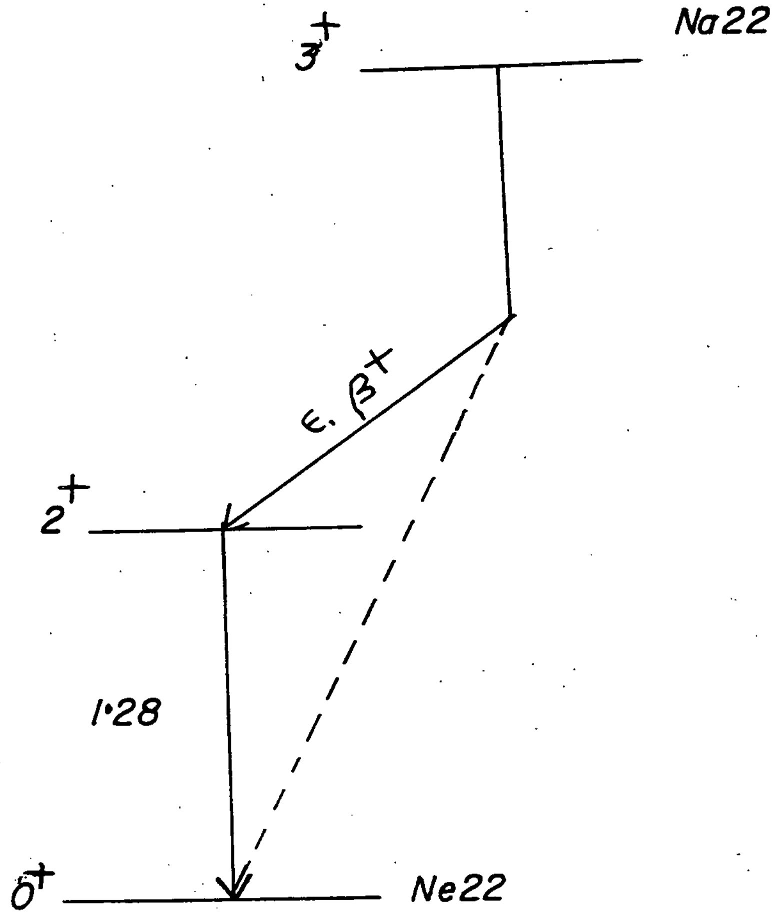

CTS
N 13 beta Spectrum
in NaI(Tl.) Sandwich
0.661
0.123
10
CH NO
30
40


Fermi Plot of
N13 beta Spectrum
[N(w)/Gw2]1/2
0.5
1.0
1.16
1.5
E Mev

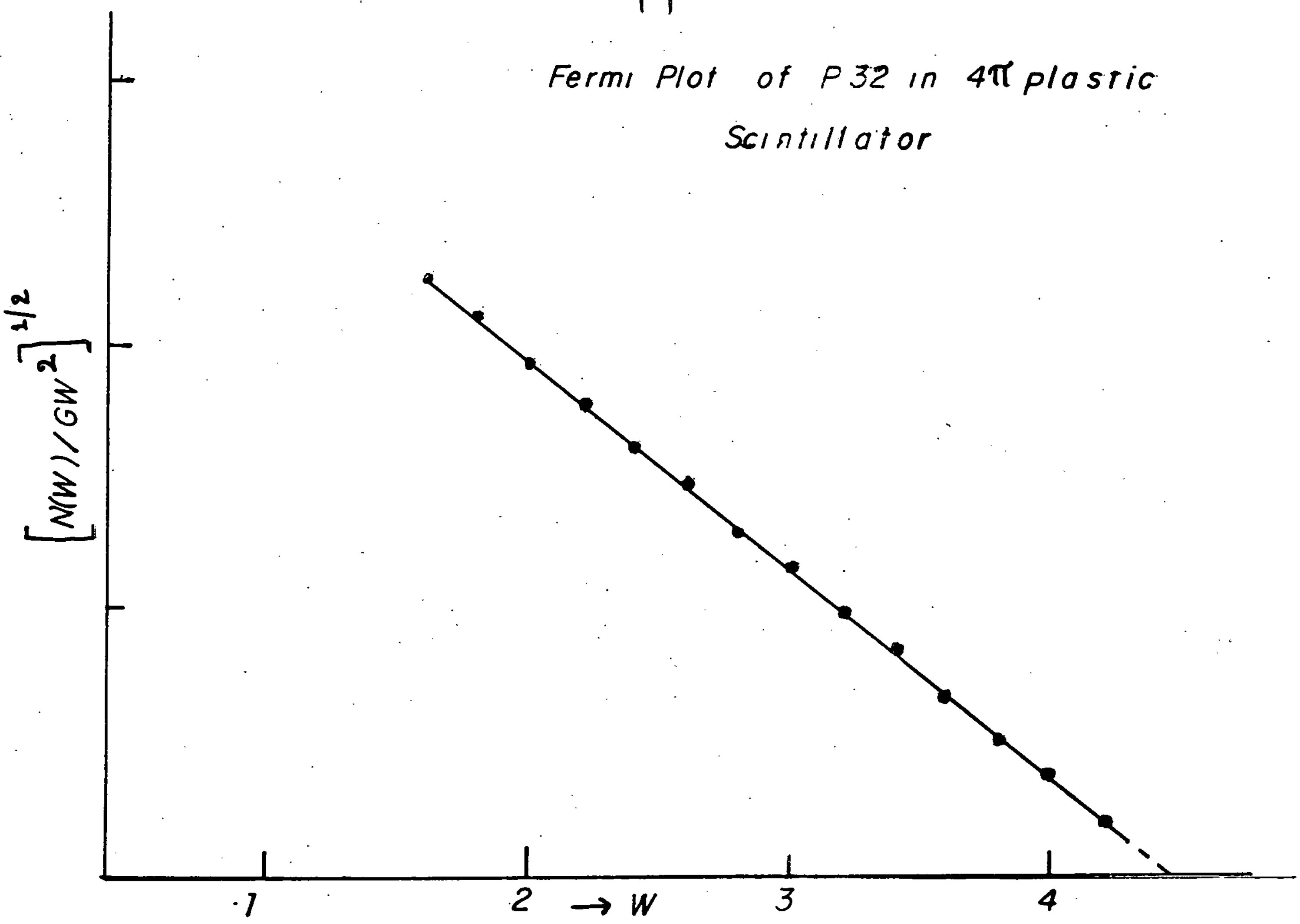
9



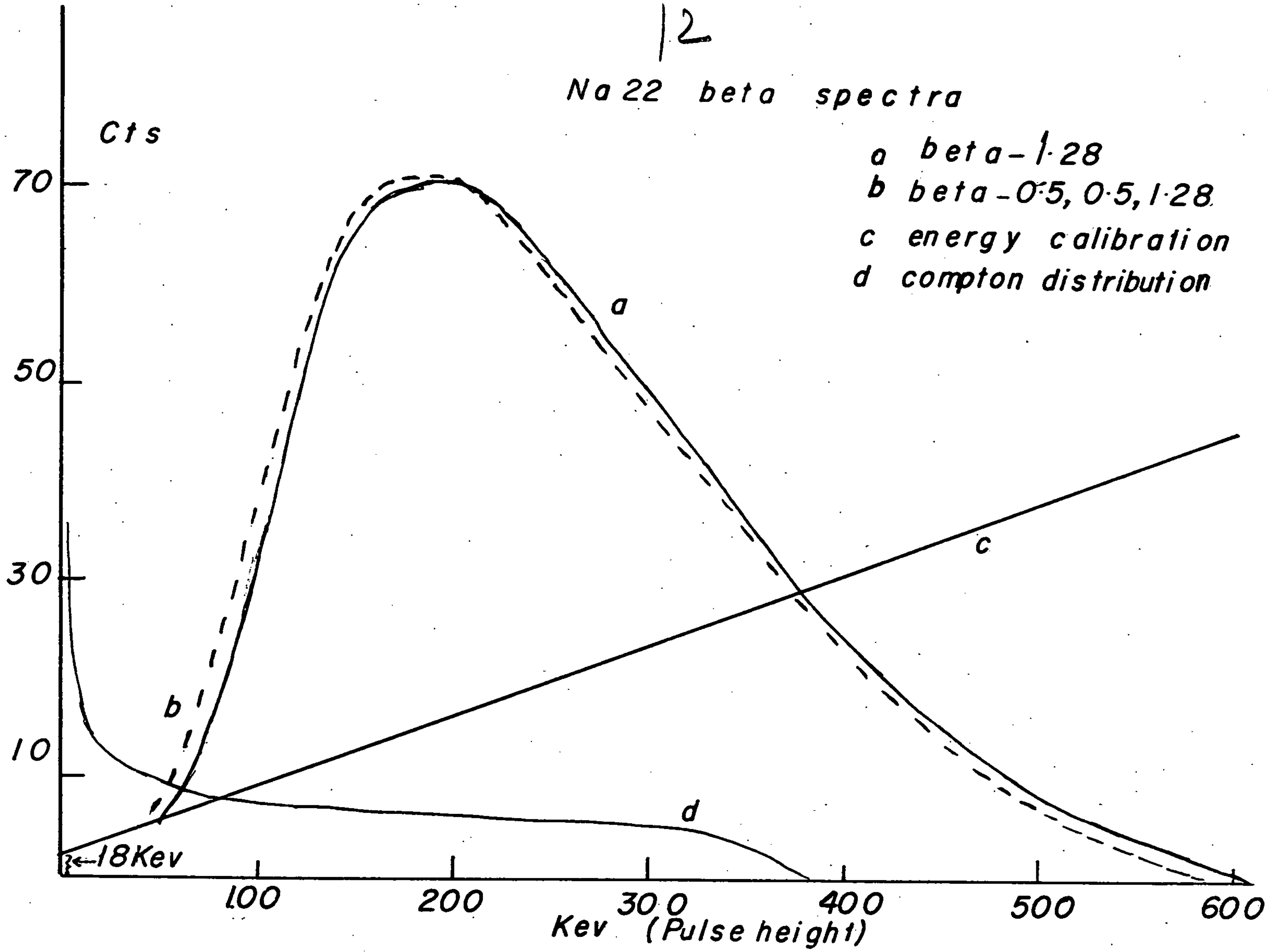
Decay Scheme of Na22

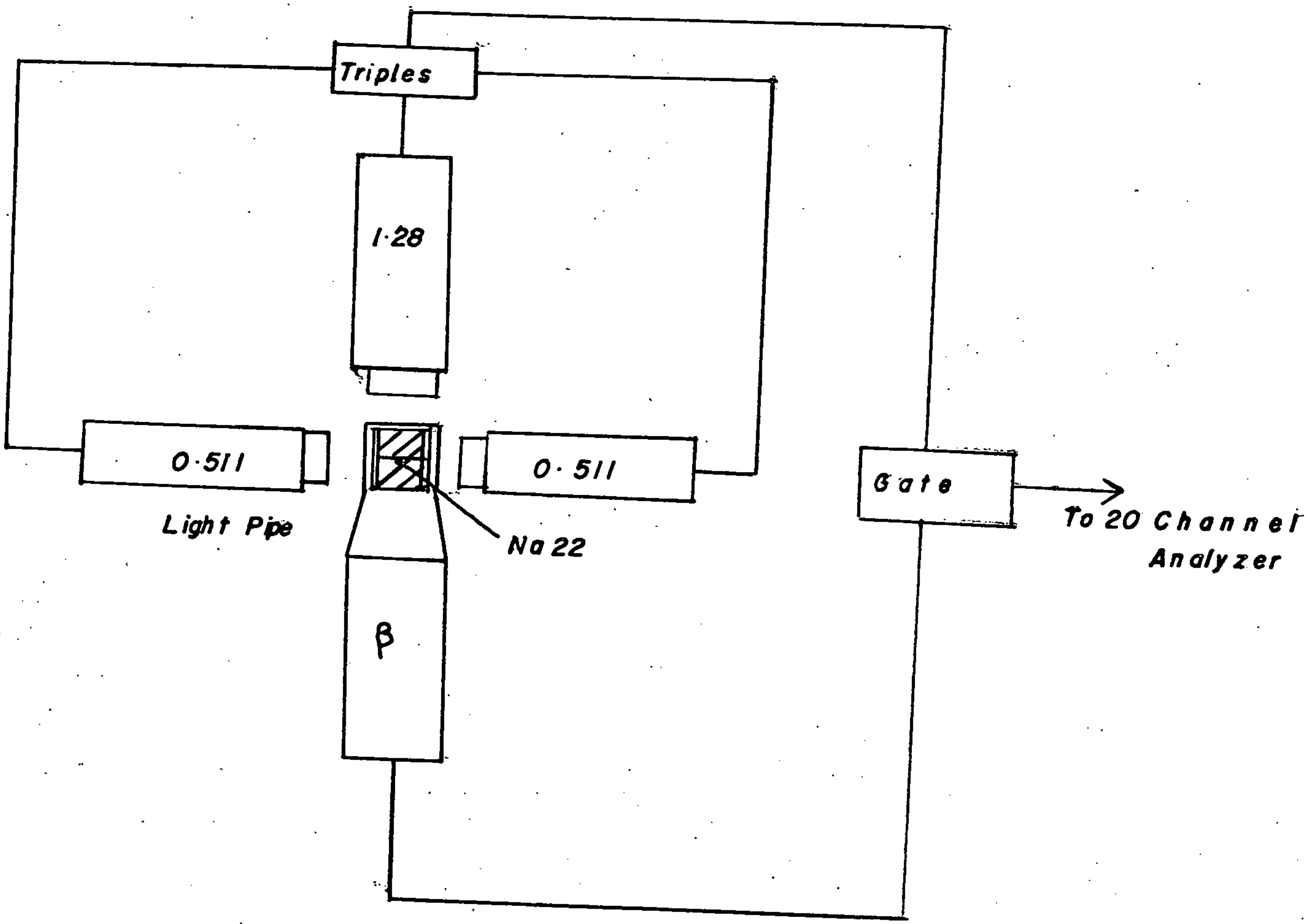


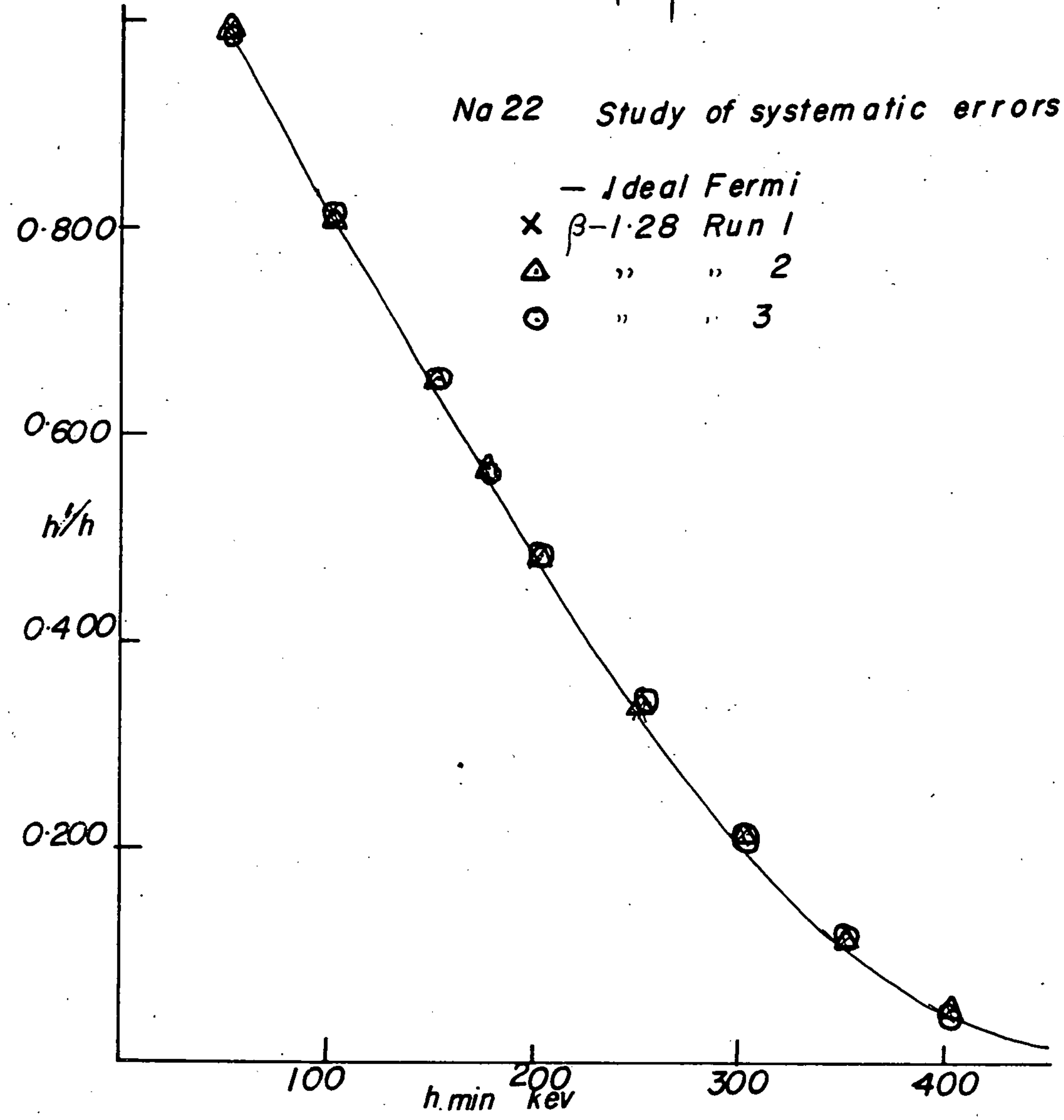
11



12


Na 22 beta spectra
Cts
a beta-1·28
b beta-0·5, 0·5, 1·28
c energy calibration
d compton distribution
70
50
30
10
a
b
c
d
←18Kev
100
200
300
400
500
600
Kev (Pulse height)


Triples
1·28
0·511
0·511
Light Pipe
Na 22
β
Gate
To 20 Channel
Analyzer


Na 22 Study of systematic errors
— Ideal Fermi
× β-1·28 Run 1
△ " " 2
⊙ " " 3
0·800
0·600
0·400
0·200
h'/h
100
200
300
400
h.min kev

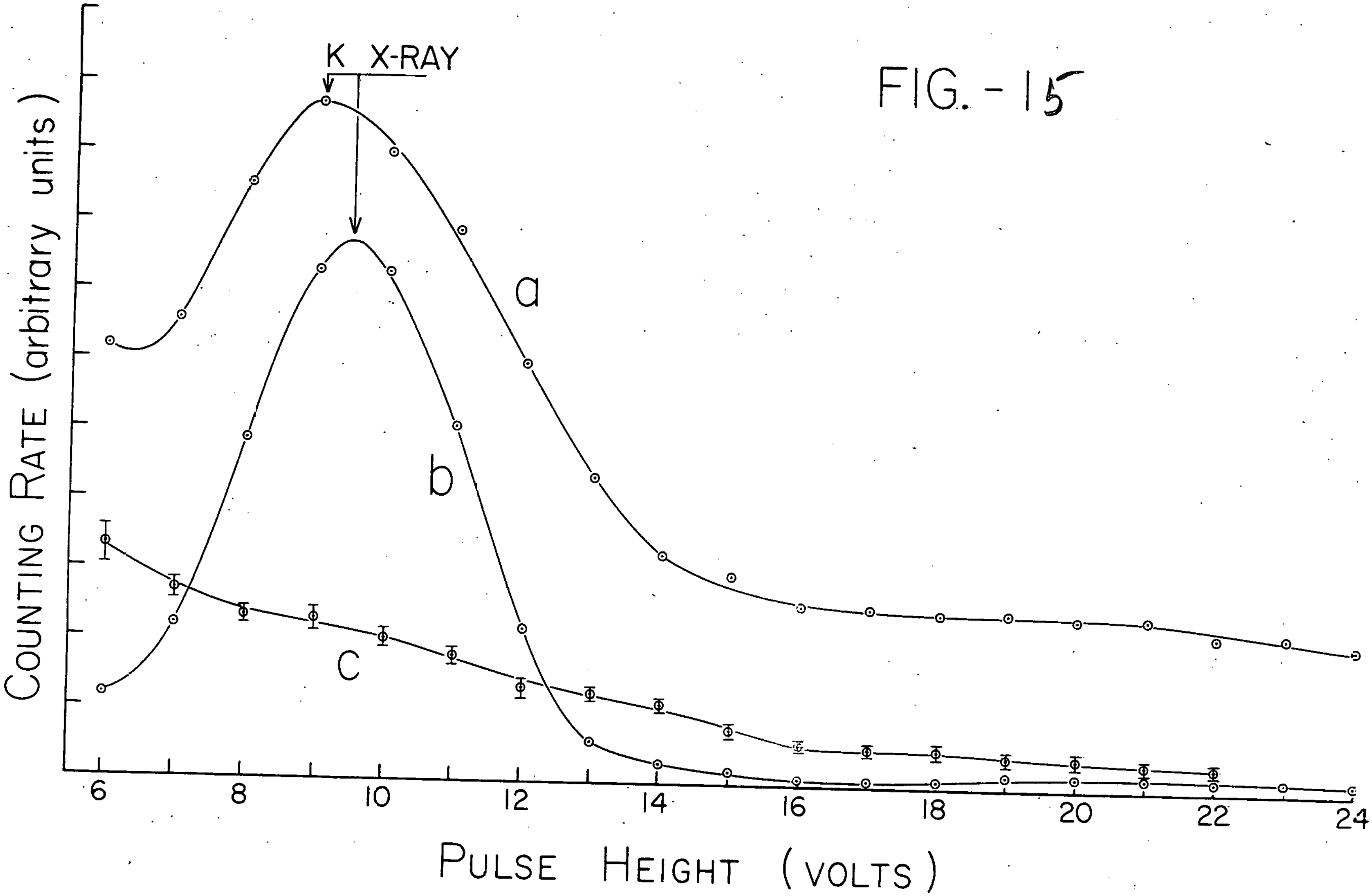
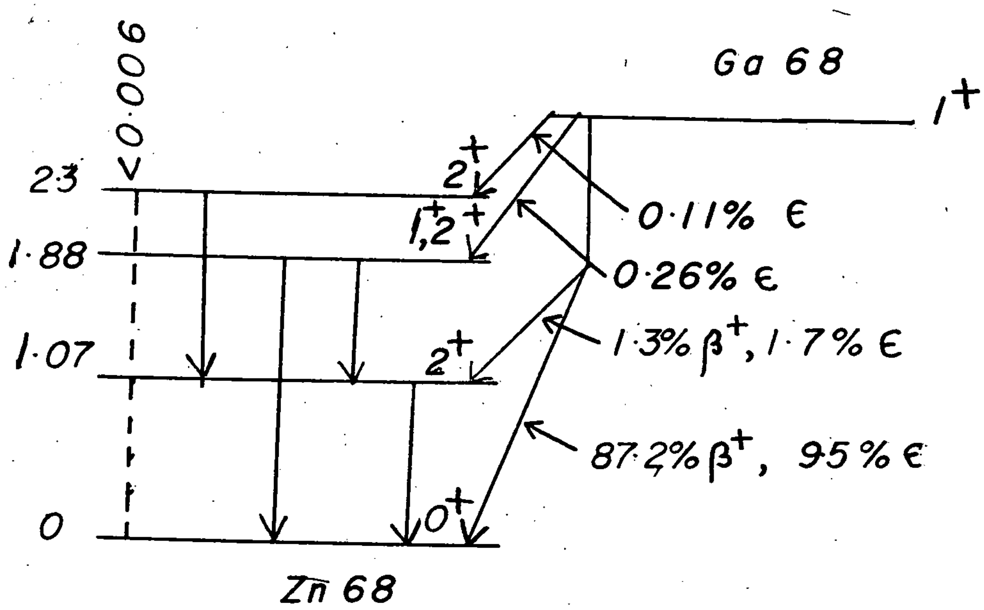
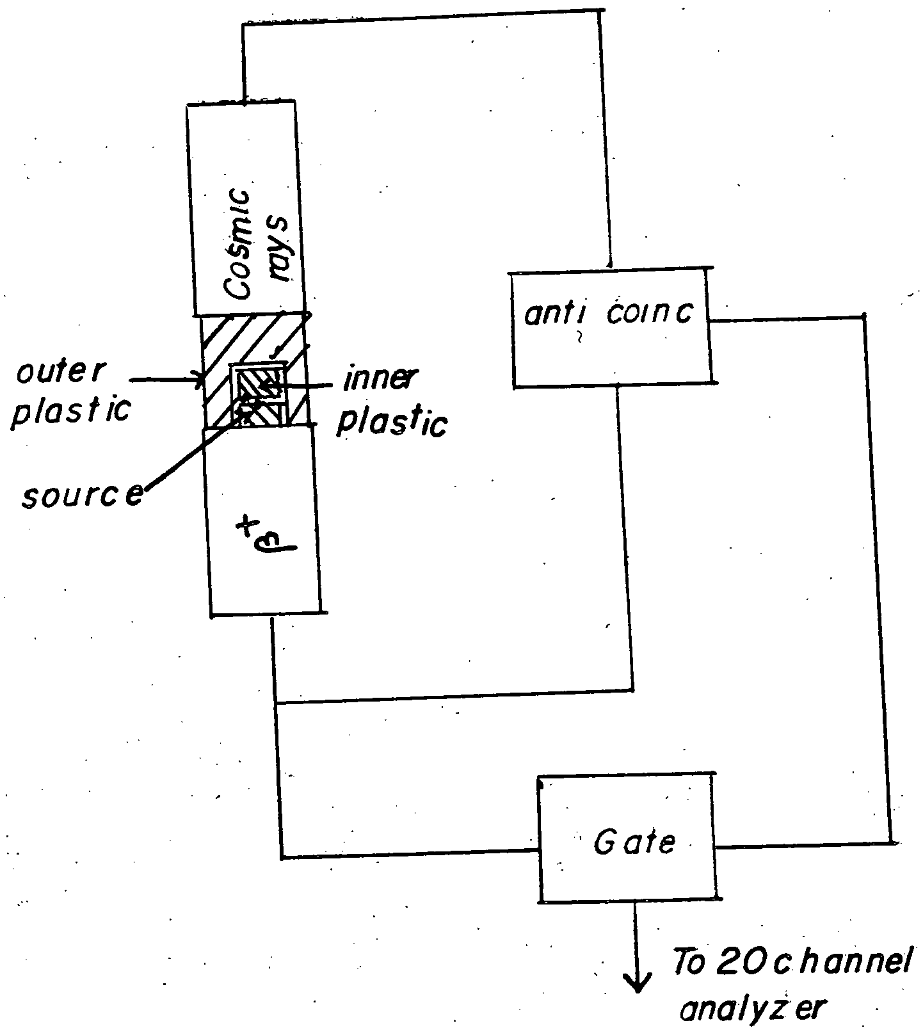

K X-RAY
a
b
c
COUNTING RATE (arbitrary units)
6
8
10
12
14
16
18
20
22
24
PULSE HEIGHT (VOLTS)

FIG. - 15

Decay Scheme of Ga 68 according to Horen




Cosmic rays
outer plastic
inner plastic
source
anti coinc
Gate
To 20 channel analyzer

Beta spectra of Ga 68 and P 32