ABSOLUTE MEASUREMENTS OF INTERNAL CONVERSION COEFFICIENTS

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ABSTRACT

A magnetic lens spectrometer has been used to measure electron yields from the internal conversion of certain nuclear gamma rays. Auxiliary experiments have been performed to determine the effective solid angle of the spectrometer. A technique which has previously proven to be successful has been tested and employed in the measurement of gamma-ray yields by means of a scintillation counter. The combination of conversion electron and gamma yield measurements constitutes an experimental determination of an internal conversion coefficient, and by comparison with theory it is possible to make gamma-ray multipole order assignments.

Bi^{207} decays to an isomeric state of Pb^{207} at 1.63 Mev which emits two successive gamma rays with energies 1.06 and 0.57 Mev, the decay proceeding through a level at 0.57 Mev. Internal conversion lines from both transitions have been observed previously. We have measured the conversion coefficients and found the 1.06-Mev line to be M4 with E2 indicated for the 0.57-Mev line.

Using the reaction $F^{19}(pp')F^{19*}$ we have observed internal conversion lines from the decay of the first two excited states of F^{19}. The transition energies are 109.1 ± 1.0 and 196.8 ± 1.5 kev as determined from the conversion lines. The experimental internal conversion coefficients indicate the following multipole order assignments, in agreement with other

data: 109 kev, E1; 197 kev, E2.

The first excited state of Na^{23} at 440 kev has been produced in $Na^{23}(pp')Na^{23*}$. We have measured the conversion coefficient of the 440-kev transition and assign it either E1 or M1, the experimental uncertainties preventing a definite assignment. Results of other work are cited which indicate M1 is correct.

We have attempted to measure the conversion coefficient of the 470-kev line in Na^{24} produced in $Na^{23}(dp)Na^{24}$. The low intensity of the line, however, permits only the statement that it is of multipole order less than $\ell = 4$.

The lens spectrometer has also been employed to survey the low energy gamma ray spectrum resulting from $N^{15}(dp)N^{16}$ and $F^{19}(\alpha\alpha')F^{19*}$. The electron spectra from external photoelectric converters suggest lines at 118 ± 5 and 275 ± 15 kev from the first reaction and 196.5 ± 4 kev from the latter.

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I. INTRODUCTION

A. GENERAL

An experimental method which sometimes permits unambiguous assignment of gamma-ray multipole orders in nuclear decay schemes is the measurement of an internal K- (or L_I, L_{II}, etc.) electron conversion coefficient and comparison with theoretical predictions. Under favorable conditions (low gamma-ray energy in general), the ratio of electric $(\ell + 1)$- pole or magnetic ℓ-pole to electric ℓ-pole internal conversion coefficients will be of the order of two or more; in such cases, an absolute determination of the coefficient within an accuracy of some 30 percent will lead to a unique multipole assignment. This thesis describes attempts to make such absolute measurements and, in the specific nuclei studied, the extent to which the results establish or confirm the multipole assignments. Also included will be a brief résumé concerning some theoretical treatments of the problem and the limit of their applicability regarding certain simplifying assumptions.

To facilitate discussion, the following terminology will be used throughout this thesis:

$a_K^\ell = Y_e / Y_\gamma$

a_K^ℓ = K-shell internal conversion coefficient for an electric transition of order ℓ.

Y_e = number of K-shell electrons emitted per unit time.

Y_γ = number of gamma rays emitted per unit time.

Similarly,

β_K^{ℓ} = K-shell internal conversion coefficient for a magnetic transition of order ℓ .

Electric (magnetic) transition of order ℓ will be denoted by $E\ell(M\ell)$. a_K will designate a general K-shell internal conversion coefficient.

B. EXPERIMENTAL METHODS FOR MEASURING a_K

Since one requires essentially only two quantities, Y_e and Y_γ, to determine a_K, we will discuss the various possible experimental ways in which they may be determined.

The most frequently used method employed in the measurement of electron yields is the observation of an electron line, or lines, in a beta spectrometer; since this procedure was used in the experiments to be described, it will be discussed in detail later. A further possibility, at least in high-z nuclei, is the measurement of the de-excitation atomic x-rays following the internal conversion process; this can be most easily accomplished by means of scintillation spectroscopy techniques.

Among the several methods for determining gamma ray yields are

(1) External conversion in a beta spectrometer.

(2) Pulse height analysis in a scintillation counter.

(3) Crystal diffraction spectrometer.

(4) Measurement of the frequency of population of the excited state in question (e.g., beta decay or K-capture yields).

Of these, the first two are most frequently applicable and we compare their merits. Since the most intense conversion lines occur for a transition energy of about 1 Mev or less, method (1) above is usually limited to photoelectric conversion; it then appears that the second method is superior for two reasons. It is well known that a yield determined from photoelectric conversion is not generally more accurate than about twenty or twenty-five percent, mainly due to uncertainties in the angular distribution of the photoelectrons. As will be shown later, we believe yields as measured in a scintillation counter are accurate to within perhaps half this error when the pulse height spectrum is reasonably free from extraneous lines. Secondly, there are two opposing factors in photo-conversion in a beta spectrometer which serve to limit the maximum obtainable detection efficiency. On the one hand, the photoelectron yield is proportional to the thickness of converter; however, the electron energy losses increase with increasing converter thickness and, if excessive, will lead to a poorly defined photopeak, and it is the area under the latter which determines the gamma yield. If the so-called "full-energy" peak in the pulse height spectrum of a scintillation counter is being used in the yield determination, the efficiency is limited only by the thickness of crystal available. It is not unusual to find the scintillator efficiency to be some two orders of magnitude better than that of a beta spectrometer in this respect.

The customary procedure in measuring a conversion coefficient is to determine electron and gamma yields relative to

those from a transition for which the internal conversion coefficient is assumed to be known from theory, for example, the 1.33-Mev transition in Ni^{60}.[1] Many gamma rays of known multipole order occur in the "pure" transitions between rotational levels in the even-even medium-heavy and heavy nuclei[2], and these offer convenient internal conversion standards.

II. PROCEDURES FOR DETERMINING Y_γ AND Y_e

A. MEASUREMENT OF GAMMA RAY YIELDS IN A SCINTILLATION COUNTER

The pulse height spectrum from a NaI crystal exhibits a prominent full-energy peak for gamma-ray energies up to several Mev, the limit increasing with increasing crystal size. If one is presented with a spectrum consisting of several gamma lines of the order of hundreds of kilovolts apart, and of comparable intensities, yield measurements can be made most easily and accurately from the full energy peak. This is due to the difficulty of separating the low energy portion of the pulse height distributions (consisting of Compton electrons) of two or more gamma lines. In order to make reliable yield measurements, one needs a measure of the efficiency of the crystal for producing pulses in the full-energy peak, or "photopeak" as it is customarily called. This efficiency, which we denote by η_ϕ, cannot be conveniently calculated from the known cross sections for the possible conversion processes which take place within the crystal.

The primary process by which a pulse appears in the full-energy peak is the photoelectric absorption of a primary gamma ray which thus expends its total energy in the crystal. In addition, the probability is quite high that a quantum scattered from a Compton event will be absorbed; on the other hand, if this quantum escapes a pulse will appear in the Compton distribution (see Fig. (1)). At energies $> 2\, m_o c^2$, a primary gamma ray may produce an electron-positron pair and both positron annihilation quanta be absorbed in the crystal, thus producing a pulse in the full-energy peak.

In obtaining η_ϕ empirically, we have followed a procedure which has previously proven to be successful. The description and results which follow pertain to either a $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in. cylindrical or 1 in. square by $\frac{1}{2}$ in. thick NaI crystal, both of which were employed in the gamma yield measurements.

A typical pulse height spectrum (Cs^{137}, E_γ = 661 kev) taken with a $1\frac{1}{2}$" by $1\frac{1}{2}$" NaI crystal is shown in Fig. (1). The ratio of the area under the photopeak to the total area under the spectrum is η_ϕ/η_T, where η_T is the total crystal efficiency. The latter quantity is calculable, and a discussion of it will be found in the Appendix. Thus, from an experimental determination of η_ϕ/η_T and the calculated η_T, one obtains η_ϕ for a certain gamma ray energy. This has been done for several sources of gamma lines, with energies ranging from 511 kev to 2.6 Mev, and the results are summarized below. In all cases the shape of the photopeak on the low energy side was obtained by reflecting the high energy side about the bias which gave the position of the peak.

Table (1)

		$1\frac{1}{2}$ in. diameter by $1\frac{1}{2}$ in. crystal	1 in. by 1 in. by $\frac{1}{2}$ in. crystal
Source	E_γ (kev)	η_ϕ (%)	η_ϕ (%)
Na^{22}	511	24.8	
Cs^{137}	661	19.8	5.90
Co^{60}	1250	9.08	
Na^{22}	1280	8.68	1.95
Th C"	2615	3.48	0.535

The 1.25-Mev figure for Co^{60} is a result of obtaining an average efficiency for the two lines at 1.33 and 1.17 Mev.

It has been found empirically that over energy regions of the order of 1 or 2 Mev, η_ϕ varies approximately as E_γ^{-k}, where k is a constant depending on the crystal. Thus, if one plots log η_ϕ against log E_γ, a straight line is obtained, from which interpolations can easily be made. Fig. (2) shows this plot for the $1\frac{1}{2}$ in. crystal. In some cases, an intense low energy background in the pulse height spectrum, produced by backscattering (and other gamma lines in the case of Th C''), prevented a complete knowledge of the Compton distribution at low biases, and the bias curve had to be extrapolated, using the theoretical electron energy distribution of the Compton effect. In addition, edge effects in the crystal were neglected. These two factors were the most likely sources of uncertainty in the determination of η_ϕ. It was assumed that the ratio η_ϕ/η_T varies only slowly, if at all, with the source-to-crystal distance, as long as the latter is several crystal diameters. Further experiments are being planned to verify this. We have found that it is possible to reproduce the results of Table (1) to an accuracy of better than ten percent, and we believe values of η_ϕ read from Fig. (2) should have at most ten percent uncertainty.

Investigations have been made to check both the absolute and relative values of η_ϕ obtained by the foregoing procedure. The yield of 1.33-Mev gamma rays from a Co^{60} source was determined from the area under the photopeak and η_ϕ. Using a geiger counter, we also measured the source strength by comparison with an NBS standard Co^{60} source. The two methods gave source strengths

which differed by 2 percent, indicating that the photopeak efficiency curve is correctly normalized at 1.33 Mev. To check the relative values of η_ϕ, the photopeaks of the 1.28-Mev line and 511-kev annihilation radiation from a Na^{22} source were measured. When the 511-kev gamma yield is corrected for the known branching ratio[3] in the Na^{22} decay, these two measurements give independent values for the strength of the source, and these agreed to better than one percent.

B. DETERMINATION OF EFFECTIVE SPECTROMETER SOLID ANGLE

If $S(B\rho)$ is the number of counts per unit time in an internal conversion line at the momentum setting $B\rho$, then the K-shell internal conversion coefficient may be determined from

$$Y_\gamma \alpha_K \Omega_{eff} = \frac{1}{1.064\, p} \int_{K\text{-peak}} \frac{S(B\rho)}{B\rho}\, d(B\rho) \qquad (2)$$

where

Y_γ = gamma ray yield per unit time

Ω_{eff} = effective spectrometer solid angle for the internal conversion process

p = resolution (taken as the width at half maximum divided by the line momentum of a conversion line).

We have used $p = 2.15$ percent. The factor $1.064\, pB\rho$ is a normalization constant resulting from the assumption that the spectrometer resolution curve is a gaussian, $\exp - (1.67\, \Delta B\rho / pB\rho)^2$, where $\Delta B\rho$ is the departure from a given momentum setting $B\rho$, and p is defined above. The factor 1.67 results from the requirement that

the exponential shall be 1/2 when $\frac{\Delta B\rho}{B\rho} = \frac{1}{2}$ p. Thus, the area under the resolution curve is

$$\int_0^\infty e^{-\left[\frac{1.67\,(B\rho - B\rho')}{pB\rho}\right]^2} dB\rho' = 1.064\, pB\rho$$

An internal conversion line is monoenergetic prior to the "window" folding, and such a line spectrum should represent accurately the shape of the resolution curve. Since our yield measurements depend on the assumption of a gaussian window, a gaussian, normalized to the same peak height, was plotted on an experimental spectrum for comparison. The particular case chosen was the 1.06-Mev conversion line in Pb^{207}, shown in Fig. (16). The calculated points lay very close to the experimental curve, and the areas under the two curves agreed to 2.5 percent.

As in the case of most beta ray spectrometers, uncertainty in any yield measurement arises primarily from a lack of knowledge concerning the effective solid angle. Thomas[4] has made both experimental and theoretical studies of this problem for external Compton and photoelectric conversion. An expression, based on Thomas' results, relating the gamma ray yield and solid angle for thick converter Compton conversion has been given by Mackin[5]. For brevity, the spectrum obtained from this type of experiment is called the thick Compton spectrum, S(Bρ).

$$Y_\gamma \Omega_{eff} = A(k)\ S(B\rho)/F(x) \qquad (3)$$

$$F(x) = \frac{2}{k} - \frac{1}{2(1+2k)^2} + \frac{(1+2k)x}{k^2} + (1 - \frac{2}{k} - \frac{2}{k^2})\log(1+2k)x + \tfrac{1}{2}x^2 - \frac{1}{k^2 x}$$

$$x = 1 - \frac{T}{k}$$

$$\frac{1}{A(k)} = N\pi r_o^2 \frac{m_o c^2}{k\mu_e} 1.064\, pB\rho \frac{dT}{dB\rho}$$

N = number of electrons per cm^3 of converter

πr_o^2 = cross section of a classical electron, $0.250 \times 10^{-24} cm^2$

k = gamma ray energy in units of $m_o c^2$

μ_e = effective stopping force for electrons in the converter material

T = electron kinetic energy in units of $m_o c^2$

μ_e is determined from an expression given by Landau[6] for the distribution of energy losses for electrons passing through matter, as modified by Bohr[7] to include the effects of polarization forces.

The customary procedure for determining Ω_{eff} has been to measure the upper 10 percent of the thick Compton spectrum from a gamma ray source of known intensity (1.33-Mev line in Ni^{60} for the Kellogg instrument), the source strength being determined by comparison with a National Bureau of Standards calibrated Co^{60} source. Comparing the experimental spectrum with the theoretical spectrum then gives Ω_{eff} from equation (3). A typical run is shown in Fig. (3) from which Ω_{eff} was determined to be $(1.23 \pm 0.10) \times 10^{-2}$ of a sphere.

One possible error in internal conversion electron yield measurements is the fact that when the solid angle is determined from a thick Compton spectrum, one is actually measuring the quantity Ω_{eff}/μ_e, since once the yield is known, all quantities in equation (3) are given except Ω_{eff} and μ_e. Thus it seemed

that an absolute error in μ_e would lead to a corresponding error in Ω_{eff} which would show up in a process such as internal conversion. Two experiments were performed to measure the relative values of μ_e for two different converter materials and the value of μ_e for a particular gamma-ray energy and converter.

A Co^{60} source was obtained in the form of a small piece of cobalt wire. The thick Compton spectrum from the 1.33-Mev gamma ray was run using a 46-mil thick aluminum converter. The same source was then placed on a 41-mil thick beryllium converter and the 1.33-Mev Compton spectrum repeated. According to equation (3) the spectrum with one converter should be a multiple of the spectrum with the other, the ratio being the inverse ratio of A(k) for the two converters. The calculated ratio $A(k)_{Be}/A(k)_{Al}$ is 1.06. The measured ratio of the aluminum to the beryllium spectrum is 1.07 ± 0.08.

The second experiment relevant to the μ_e investigation was a repetition of one which was carried out by Mackin[5]. In the reaction C^{12} (dp) C^{13*}, a very intense 3.1-Mev gamma ray is observed[8], attributed to a transition from the 3.1-Mev level in C^{13} to the ground state. An alternative mode of decay of an excited nuclear state with excitation energy $> 2\, m_o c^2$ is the emission of an internally formed electron-positron pair. Just as in internal conversion, the internal pair formation coefficient depends on the multipole order of the transition. It is usually most convenient to measure the positron spectrum. One can show that, if the corresponding gamma yield has been determined by the thick Compton method, the spectrum of positrons $P_{\substack{El \\ (M)}}(B\rho_+)$

is given by

$$P_{\underset{(M)}{E\ell}}(B\rho_+) = \frac{5.868 \times 10^{-4}\ S(B\rho)/F(x)}{N\pi r_0^2 m_0 c^2\ dx/dB\rho}\ \mu_e\, \Gamma_{\underset{(M)}{E\ell}}(B\rho_+) \qquad (4)$$

where $\Gamma_{\underset{(M)}{E\ell}}(B\rho_+)$ is a theoretical distribution depending on multipole order[9]; other quantities in equation (4) are defined under equation (3).

A 14 mg/cm^2 graphite flake was bombarded by 1.46-Mev deuterons and the 3.1-Mev Compton spectrum from a 50-mil aluminum converter measured. At the same bombarding energy the positron spectrum was run, the results being shown in Fig. (4). The solid curves are theoretical spectra, proportional to $\Gamma_{\underset{(M)}{E\ell}}(B\rho_+)$ and normalized to the measured gamma yield and a calculated value of μ_e.

The 3.1-Mev level has been assigned $J = \frac{1}{2}^+$ [8] and the ground state is $\frac{1}{2}^-$. Using the areas under the spectra, calculated from 38 to 53.8 m.v., as a figure for comparison purposes, we obtain the following numbers for the ratio of the theoretical curves to the experimental spectrum:

E1	E2
0.861	0.510

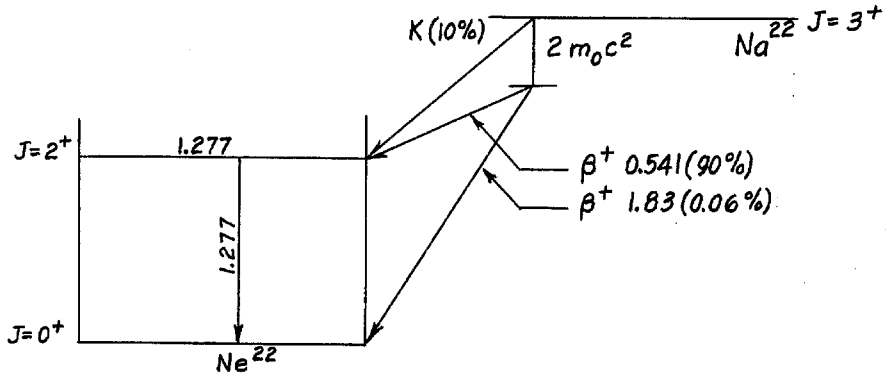
A further check was obtained by measuring this gamma yield in the $1\frac{1}{2}$ in. NaI crystal. The efficiency of the crystal was obtained by extrapolating the empirical efficiency curve of Fig. (2). The 3.1-Mev gamma yield obtained was $(9.9 \pm 0.95) \times 10^8\ \gamma/14.4\ \mu$coul.

This is to be compared with $(11.8 \pm 0.95) \times 10^8 \gamma / 14.4$ μ coul. obtained from the thick Compton spectrum. This measurement constitutes a check on the ratio μ_e (1.33 Mev)/μ_e(3.10 Mev).

This experiment and previous measurements[10][5][11] give internal pair coefficients higher than the theoretically expected ones by 5 to 15 percent. It appeared that this might be caused by an absolute error in the calculated value of μ_e.

In order to determine the spectrometer solid angle by a procedure which does not involve assumptions concerning μ_e, we have performed the following experiment. A Na^{22} source of high specific activity was obtained in the form of NaCl and evaporated onto a 0.2 mg/cm^2 aluminum foil, the source spot being 3 mm in diameter.* This source will be designated "S".

Na^{22} decays to Ne^{22} as shown below[8]:



As is seen from above, the positron spectrum consists almost entirely of the 0.541-Mev branch. In addition, the total positron yield is 90 percent of the 1.28-Mev gamma yield. If one measures the positron spectrum in the spectrometer, the product

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*The author would like to thank Drs. F. Boehm and P. Marmier for their assistance with the preparation of this source.

$Y_S^{\beta^+} \Omega_{eff}$ is obtained according to

$$Y_S^{\beta^+} \Omega_{eff} = \frac{1}{1.064\, p} \int \frac{F(B\rho)}{B\rho}\, d(B\rho)$$

where $Y_S^{\beta^+}$ denotes the total positron yield from the S source per unit time and $F(B\rho)$ is the experimental positron spectrum. If Y_S represents the total number of Na^{22} decays per unit time, then $Y_S^{\beta^+} = 0.90\ Y_S$ from the decay branching ratio. Thus, a determination of Y_S together with a total positron yield gives Ω_{eff}.

The positron spectrum was run in the spectrometer and the resulting Kurie plot is shown in Fig. (5), where it is seen that a straight line appears to fit the points for positron energy above 200 kev. The deviation below this energy is presumably due to backscattering in the aluminum backing. Other investigation has shown the Kurie plot to be linear down to 25 kev[12]. Assuming the straight line in Fig. (5), the total momentum spectrum has been extracted and is shown in Fig. (6), the curve having been normalized to include the window fold. When this curve is integrated, we obtain $Y_S^{\beta^+} \Omega_{eff} = 282$ positrons/sec.

The strength of the S source, Y_S, has been determined by two chains of intercomparisons with other sources, as discussed below. The following notation will be used:

Y_A = strength of Na^{22} "A" source

Y_M = strength of Na^{22} "M" source

Y_F = strength of Co^{60} "F" source

Y_{NBS} = strength of National Bureau of Standards Co^{60} source

The first chain of intercomparisons proceeds as follows:

(1) Determine Y_S/Y_M in NaI crystal from the ratio of the 1.28-Mev gamma ray photopeaks - same geometry and crystal efficiency for S and M sources.

(2) Determine Y_M/Y_A as in (1).

(3) Determine Y_A/Y_F in NaI crystal from photopeaks of 1.28- and 1.33-Mev lines, using the same geometry for each source and making the small correction for different crystal efficiencies.

(4) Determine Y_F/Y_{NBS} by means of a geiger counter.

The intermediate source M was employed because of the large difference in the S and A source strengths ($Y_A/Y_S = 57.4$). These two could not conveniently be compared using the same source to crystal distance for each.

The NBS source is given as $Y_{NBS} = 1.59$ rd on July 25, 1947. Using $\tau_{\frac{1}{2}} = 5.26$ yrs. for Co^{60}, we get $Y_{NBS} = 0.573$ rd on April 22, 1955. Y_F/Y_{NBS} is measured as 4.84 by the geiger counter. The various photopeaks from the crystal are shown in Figs. (7) and (8). The shape of the low energy side of each peak was obtained by reflecting the high energy portion around the bias which gave the peak position. From the areas under the photopeaks, the following ratios were obtained:

$$Y_A/Y_F = 0.495\ \eta_F/\eta_A = 0.495 \times \frac{9.1}{9.4}$$

$$= 0.480$$

$$Y_M/Y_A = 0.281$$

$$Y_S/Y_M = 0.0700$$

From these, a value of 0.0262 ± 0.0025 rd is obtained for Y_S.

This chain was repeated to check for consistency and we obtained $Y_S = 0.0250 \pm 0.0025$ rd.

The second chain of intercomparisons is:

(1) Determine Y_S/Y_M with a geiger counter - same geometry and efficiency for each source.

(2) Determine Y_M/Y_A as in (1).

(3) Determine Y_A/Y_F by comparison of thick Compton spectra from the same converter of 1.28- and 1.33-Mev lines; calculated values of μ_e for the two energies were used.

(4) Determine Y_F/Y_{NBS} with a geiger counter.

Y_F/Y_{NBS} and Y_{NBS} are given in the first chain. The F source Compton spectrum is shown in Fig. (3) and the A source spectrum is shown in Fig. (9). From these, we obtain $Y_A/Y_F = 0.509$, using $\left[\frac{A(k)}{F(x)}\right]_A \Big/ \left[\frac{A(k)}{F(x)}\right]_F = 1.018$. The geiger counter comparisons gave

$$Y_M/Y_A = 0.280$$

$$Y_S/Y_M = 0.0650$$

There results $Y_S = 0.0257 \pm .0025$ rd.

From each of these and the positron yield measurement, a value of Ω_{eff} may be determined. The summary below gives the

Determination	Ω_{eff}
Co^{60} Comptons	$(1.23 \pm 0.10) \times 10^{-2}$
Positron yield and NaI crystal source intercomparisons	$(1.25 \pm 0.15) \times 10^{-2}$
	$(1.20 \pm 0.15 \times 10^{-2}$
Positron yield and geiger counter source intercomparisons	$(1.22 \pm 0.15 \times 10^{-2}$

results obtained with the chains together with the solid angle determined from the Co^{60} thick Compton spectrum.

The good agreement among these measurements indicates that the solid angle as measured by Compton conversion is correct, and we have used $\Omega_{eff} = (1.24 \pm 0.07) \times 10^{-2}$, the average of the above values.

As a final point, mention must be made of the fact that it is necessary to correct the experimental electron yields for absorption in the 1.4-mg/cm^2 mica window of the geiger counter detector. In all of our experiments, this correction was made on the basis of curves given by Feather, Kyles, and Pringle[32].

III. THEORETICAL CONVERSION COEFFICIENTS

The primary purposes of this section are to discuss a simplified theory of internal conversion in order to bring out fundamental principles involved, and to present the results of more accurate approaches, thus providing ready comparisons for the experimental coefficients.

A. ELEMENTARY TREATMENT

The simplified treatment given here, following that in Blatt and Weisskopf,[13] makes use of the following approximations:

(1) Only K-conversion is considered.

(2) The approach will be non-relativistic.

(3) We use the Born approximation for the ejected electron; this is equivalent to neglecting the binding of the K-electrons.

Consider a nuclear transition from initial nuclear state i, energy E_i, wave function ψ_i, to a final nuclear state f, energy E_f, wave function ψ_f. Assume the initial K-electronic wave function to be

$$v_i = \frac{1}{\sqrt{\pi a^3}} e^{-\frac{R}{a}}, \quad a = \frac{a_o}{Z}$$

a_o = Bohr radius of hydrogen atom

and the final electron wave function, normalized to a box of volume V, to be

$$v_f = \frac{1}{\sqrt{V}} e^{i\vec{k}\cdot\vec{R}}$$

$\vec{R}$ = position vector of electron

$\vec{k}$ = wave vector of ejected electron

The transition probability per unit time between initial and final states is

$$\frac{2\pi}{\hbar}\left|\left(\psi_i\, v_i \,\middle|\, O \,\middle|\, \psi_f\, v_f\right)\right|^2 \rho(k)$$

O is an operator which describes the interaction between nucleus and electron, here assumed to be the Coulomb field. $\rho(k)$ is a density of final states factor:

$$\rho(k) = V\,\frac{m_0 \hbar k}{(2\pi\hbar)^3}$$

The total transition probability is obtained by integrating over all ejected electron directions.

$$T_e(i,f) = \frac{4\pi}{\hbar}\,\rho(k)\int |O_{if}|^2\, d\Omega \qquad (5)$$

A factor of two has been included for the possibility of ejection of either of two K electrons.

Assume that

$$O = \sum_{j=1}^{Z} \frac{e^2}{|\vec{R} - \vec{r}_j|}\,, \qquad \vec{r}_j = \text{coordinate vector of j'th proton}$$

Then,

$$O_{if} = \frac{1}{\sqrt{\pi a^3 V}} \sum_{j=1}^{Z} \int d^3R \int e^{-i\vec{k}\cdot\vec{R}} \psi_f^* \frac{e^2}{|\vec{R} - \vec{r}_j|} e^{-\frac{R}{a}} \psi_i \, d\tau \qquad (6)$$

where $d\tau$ includes all pertinent nuclear variables. From the behaviour of the function $e^{-\frac{R}{a}}$, we note that the main contribution to the integration over R comes from values of $|\vec{R}|$ larger than the nuclear radius. For $|\vec{r}_j| < |\vec{R}|$ we can write, from a well-known expansion theorem,[13]

$$\frac{1}{|\vec{R} - \vec{r}_j|} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} \frac{4\pi}{2\ell+1} \frac{r_j^\ell}{R^{\ell+1}} Y_{\ell m}(\Theta, \Phi) Y_{\ell m}^*(\theta_j, \phi_j)$$

Θ, Φ = polar angles of $\vec{R}$

θ_j, ϕ_j = polar angles of $\vec{r}_j$

Substitution into equation (6) gives

$$O_{if} = \frac{e}{\sqrt{\pi a^3 V}} \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} \frac{4\pi}{2\ell+1} Q_{\ell m}(i,f) J_{if}$$

where

$$J_{if} = \int e^{-\frac{R}{a}} e^{-i\vec{k}\cdot\vec{R}} \frac{Y_{\ell m}(\Theta, \Phi)}{R^{\ell+1}} d^3R$$

and $Q_{\ell m}$ is a nuclear electric multipole matrix element:

$$Q_{\ell m}(i,f) = e \sum_{j=1}^{Z} \int r_j^{\ell} Y_{\ell m}^{*} (\theta_j, \phi_j) \psi_f^{*} \psi_i \, d\tau$$

Since we have assumed that the energy of the ejected electron is much larger than the K-shell binding energy, the wavelength of the outgoing electron is much smaller than the Bohr radius of the K-shell; $\lambda\!\!\!^{-} << a$ or $ka >> 1$. Then, if $e^{-\frac{R}{a}}$ is taken as unity, the matrix element J_{if} can be explicitly evaluated. When this is done, the resulting expression substituted in equation (5), and the final integration performed, there results

$$T_e(i,f) = 128\pi \frac{m_0 e^2}{\hbar^3 a^3} \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} \frac{k^{2\ell-3}}{\left[(2\ell+1)!!\right]^2} \left|Q_{\ell m}(i,f)\right|^2$$

If we assume the major contribution in the first summation arises from one ℓ value, then

$$T_e(i,f) = 128\pi \frac{m_0 e^2}{\hbar^3 a^3} \frac{k^{2\ell-3}}{\left[(2\ell+1)!!\right]^2} \sum_{m=-\ell}^{+\ell} \left|Q_{\ell m}(i,f)\right|^2$$

The rate of gamma emission for the transition, under the above assumption of a specific ℓ value, is

$$T_\gamma(i,f) = \frac{8\pi(\ell+1)}{\ell[(2\ell+1)!!]^2}\,\frac{\left(\frac{\omega}{c}\right)^{2\ell+1}}{\hbar}\sum_{m=-\ell}^{+\ell}\left|Q_{\ell m}(i,f)\right|^2$$

Thus,

$$\alpha_K^\ell = \frac{T_e(i,f)}{T_\gamma(i,f)} = 16\,\frac{\ell}{\ell+1}\,\frac{Z^3}{a_0^4}\,\frac{k^{2\ell-3}}{\left(\frac{\omega}{c}\right)^{2\ell+1}}$$

Using our initial assumption (3), we may write

$$\frac{\hbar^2k^2}{2m_0} \approx \hbar\omega$$

Then,

$$\alpha_K^\ell = \alpha^4 Z^3\,\frac{\ell}{\ell+1}\left(\frac{2m_0c^2}{\hbar\omega}\right)^{\ell+5/2} \qquad (7)$$

α = fine structure constant.

This very approximate expression exhibits the three salient features of the internal conversion process for electric radiation; i.e., increasing probability with (1) increasing Z, (2) increasing ℓ, (3) decreasing gamma ray energy. Internal conversion of magnetic radiation shows the same gross properties.

The above result is of little value in an actual case due to the failure of assumptions (2) and (3) being satisfied.

B. MORE ACCURATE RESULTS

Dancoff and Morrison[14] have carried out rather complete calculations for both relativistic and non-relativistic cases. They neglect the K-binding and the effect of screening by atomic electrons. Using Coulomb wave functions for the outgoing electrons, the non-relativistic conversion coefficient for an electric multipole transition of order ℓ is

$$\alpha_K^{\ell} = 16\alpha \frac{\ell}{\ell+1} \left[\Gamma(\ell+1/2)\right]^2 \left(\frac{2}{\nu}\right)^{\ell+1} \frac{n^4}{(1+n^2)^{\ell-2}} \quad X$$

$$\frac{\left[(\ell+1)(1+n^2)^{\ell-2} e^{-2n \cot^{-1} n} - V_\ell\right]^2}{(\ell^2+n^2)\left[(\ell-1)^2+n^2\right] \cdots (1+n^2)(1-e^{-2\pi n})} \quad \left\{\frac{V}{c} << 1\right\}$$

where

$$\nu = \frac{E_\gamma}{m_0 c^2} \quad , \quad n = \frac{Z\alpha}{\left[2\nu - (Z\alpha)^2\right]^{1/2}} \quad ,$$

α = fine structure constant.

$V_0 = 0$

$V_1 = 0$

$V_2 = 1/3$

$V_3 = \frac{4}{15}(3 + 2n^2)$

$V_4 = \frac{1}{105}(71n^4 + 168n^2 + 141)$

V_ℓ for $\ell \geq 5$ can be obtained from a recursion formula.[14]

In the limit of low Z,

$$\alpha_K^{\ell} = Z^3\alpha^4 \frac{\ell}{\ell+1} \left(\frac{2}{\nu}\right)^{\ell+5/2}$$

The relativistic coefficients, using plane waves for the outgoing electrons, are

Electric:

$$\alpha_K^{\ell} = \frac{2Z^3\alpha^4}{\nu^3}\left(\frac{\nu+2}{\nu}\right)^{\ell-1/2}\left[\frac{(\ell+1)\nu^2+4\ell}{\ell+1}\right] \qquad \left\{\frac{Ze^2}{\hbar v} << 1\right\}$$

Magnetic:

$$\beta_K^{\ell} = \frac{2Z^3\alpha^4}{\nu}\left(\frac{\nu+2}{\nu}\right)^{\ell+1/2} \qquad \left\{\frac{Ze^2}{\hbar v} << 1\right\}$$

In the limit $\nu << 1$,

$$\alpha_K^{\ell} = Z^3\alpha^4 \frac{\ell}{\ell+1}\left(\frac{2}{\nu}\right)^{\ell+5/2}$$

$$\beta_K^{\ell} = Z^3\alpha^4\left(\frac{2}{\nu}\right)^{\ell+3/2}$$

Thus, in the proper limits, both relativistic and non-relativistic electric coefficients approach equation (7).

Rose[15] has performed more exact calculations, the first of which neglects only screening, and the second including this effect by the insertion of a Fermi - Thomas - Dirac central potential

in the Dirac equations for the radial part of the wave function. The unscreened coefficients have been calculated numerically for a wide range of gamma ray energies and Z values; Thomas[4] has plotted the ratio of the unscreened coefficients to the relativistic Born approximation results, where it is seen that the latter differ from the former by rather large percentages except for low Z and large E_γ.

Unfortunately, as yet the screened calculations are rather incomplete as regards Z values, K-shell calculations having been done for Z = 25, 35, 75, and 85. Nevertheless, it was felt desirable to make some attempt to extrapolate the screened calculations to other Z values. To this end, the ratio of screened coefficients to Born approximation coefficients was calculated for the available values of the former. The ratio was plotted as a function of Z, a family of curves being obtained corresponding to various gamma ray energies. It was assumed that the ratio is unity at Z = 0, although there is some doubt as to whether this occurs at Z = 0 or Z = 1. The extrapolation to low Z values is relatively insensitive to this uncertainty.

The curves are shown in Figs. (10), (11), (12), and (13) for E1, M1, E2, and M2 radiation. Until further screened calculations become available, namely, for low Z, these extrapolations should probably be regarded as uncertain by about 10 percent for Z less than 25.

IV. THE 0.570- AND 1.06-MEV CONVERSION LINES FROM Pb^{207}.

Bi^{207} is a long lived ($\sim$ 50 years) isotope produced by bombarding lead with cyclotron accelerated deuterons. Recently, Alburger[16] has made a study of the spectrum of Pb^{207} which is the decay product resulting from K-capture in Bi^{207}. His tentative level and decay scheme is shown in Fig. (14). The 0.570- and 1.06-Mev lines are by far the strongest in the gamma spectrum, and, if the level configuration assignments are correct, should be E2 and M4 transitions, respectively. Such solitary intense lines provide a convenient standard, once the multipole orders are known, for checking the method which we have used for measuring internal conversion coefficients. Dr. Alburger was kind enough to provide us with a 5 microcurie source prepared at the Brookhaven Laboratory.

The internal conversion lines were run in the magnetic lens beta spectrometer. The detector of focussed electrons was an Amperex 200C end window Geiger counter with a 1.4-mg/cm^2 mica window. The K- and unresolved L- and M-conversion peaks from the 0.570- and 1.06-Mev lines are shown in Figs. (15) and (16). The resolution of each K peak is 2.1 percent in momentum. By comparing equations (1) and (2), one sees that

$$Y_e^K = \frac{1}{.064\, p\, \Omega_{eff}} \int_{K\text{-peak}} \frac{S(B\rho)}{B\rho}\, d(B\rho)$$

is the yield of K-conversion electrons, and similarly for the L + M line. Table (2) below lists the pertinent yields and ratios which

were obtained.

Table (2)

E_γ (Mev)	Y_e^K (e/sec)	Y_e^{L+M} (e/sec)	Y_e^K / Y_e^{L+M}
0.570	$(1.70 \pm 0.18) \times 10^3$	$(0.670 \pm 0.074) \times 10^3$	2.54 ± 0.20
1.06	$(8.03 \pm 0.85) \times 10^3$	$(2.49 \pm 0.28) \times 10^3$	3.22 ± 0.25

Alburger in a similar investigation[16], obtained $Y_e^K / Y_e^{L+M} = 3.00 \pm 0.25$ for the 1.06-Mev line. This ratio has recently been measured by Marmier and Boehm who obtain 3.14 ± 0.1.

The 0.570- and 1.06-Mev gamma ray yields were measured in a $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in. NaI crystal which was mounted on the end of a Dumont 6292 photomultiplier tube; after being amplified, the pulses were fed into a ten-channel pulse height analyzer. Photo-peaks from the two lines are shown on the differential bias curves in Fig. (17).

The photopeak efficiencies, η_ϕ, of the crystal for the two lines were taken from the curve of Fig. (2). From these, the solid angle subtended by the crystal, and the area under the photopeaks, the following yields were obtained:

$E_\gamma = 0.570$ Mev: $Y_\gamma = (1.27 \pm 0.25) \times 10^5$ γ/sec.

$E_\gamma = 1.06$ Mev: $Y_\gamma = (8.54 \pm 1.0) \times 10^4$ γ/sec.

Using these and the K-conversion electron yields, we have

$a_K = (1.33 \pm 0.30) \times 10^{-2}$ (0.570-Mev line)

$a_K = (9.40 \pm 1.5) \times 10^{-2}$ (1.06-Mev line)

At these gamma ray energies, it is expected that screening will have only a small effect on the theoretical conversion coefficients. Rose's unscreened calculations were used and a screening correction

estimated from the screened calculations, the correction amounting to only a few percent. Table (3) lists the theoretical coefficients for various multipole orders.

Table (3)

	E1	M1	E2	M2	E3	M3
$E_\gamma = 0.570$ Mev	.00632	.0840	.0171	.194	.0430	.425
	E3	M3	E4	M4	E5	M5
$E_\gamma = 1.06$ Mev	.0107	.0591	.0210	.103	.0389	.174

Wapstra[17] has also measured these conversion coefficients by studying the conversion electrons and Auger electrons in a beta spectrometer, and the gamma rays and K x-rays in a scintillation counter. The coefficients were obtained by measuring the ratios $\alpha_A : \alpha_{K_1} : \alpha_{K_2} = A_K/X_K : K_1/\gamma_1 : K_2/\gamma_2$, where A_K, K_1, and K_2 are the relative intensities of the K Auger electrons and the conversion electrons, and X_K, γ_1, and γ_2 are the relative intensities of the K x-rays and the gamma rays. The Auger conversion coefficient α_A is assumed to be known from theory. Wapstra's results are $\alpha_K = 0.113 \pm 0.040$ and 0.018 ± 0.0063 for the 1.063- and 0.570-Mev lines, respectively. It should be mentioned that the only experimental value for the Auger conversion coefficient in this region of the periodic table gave a value which is 2.5 times that used by Wapstra[17].

V. INTERNAL CONVERSION LINES FROM F^{19}

A. SUMMARY OF PREVIOUS RESULTS.

Internal conversion is generally quite weak in light nuclei, since the probability is proportional to Z^3. However, the coefficients for the ground-state transitions from the first two excited states of F^{19} should be readily measurable since the gamma ray energies are 109 and 197 kev; it was felt that the two levels might be excited in sufficient intensity to allow observations on both conversion lines. Added impetus was given this problem from the fact that further confirmation was needed of the spins and parities assigned to these states on the basis of other investigations. The papers of C. A. Barnes,[18] and F. Ajzenberg and T. Lauritsen[8] summarize the previous work, and we mention here only the points pertinent to later discussion.

Lifetime measurements by Thirion, Barnes, and Lauritsen[19] indicate that the 109-kev transition is E1 and the 197-kev line is E2. Similarly, the Coulomb excitation work of Sherr, Li, and Christy[20] gives E1 excitation for the 109-kev level and E2 excitation for the 197-kev level. Angular distribution measurements made by Barnes[18] are consistent with the assignments of $J = 1/2$, odd parity for the 109-kev state, and $J = 5/2$, even parity for the 197-kev level. The existence of an odd parity state so near the ground state is in seeming contradiction to the shell model which predicts s- and d-shell configurations in the low excitation energy region. In view of this, a further confirmation of the spin and parity assignments, which would be provided by internal

conversion measurements, was desirable.

In addition, at the time this experiment was begun, there was some discrepancy among the various level energy measurements which had been made. The internal conversion lines offered opportunity for a precise determination of the excitation energies.

B. EXPERIMENTAL TECHNIQUES

It was decided to excite the levels in question by inelastic proton scattering, as there are many pronounced resonances leading to these states in the excitation function of $F^{19}(pp')F^{19*}$. (18) A thin fluorine target was required in order that the conversion lines should not be excessively distorted due to electron energy losses in the target. Also, it was anticipated that the major contribution to the background would arise from nuclear pairs produced in the decay of the 6.05-Mev level in O^{16} formed by the competing $F^{19}(p\alpha)O^{16*}$ reaction. The pair yield increases rapidly with energy above $E_p \approx 1$ Mev, suggesting that measurements be made at the resonances below this energy. The 935-kev resonance was used for the 109-kev line measurements, and the 873-kev resonance for the 197-kev line (see ref. (18) for a discussion of the excitation function).

A target was prepared by sticking a piece of 0.2 mg/cm^2 aluminum leaf to a 4 mil aluminum frame which had a 1/4 in. hole punched in the center. This assembly was then held over a bottle of HF acid for about a minute, the fumes producing an Al_2F_3 layer on one side upon interaction with the foil. The beam spot was kept trimmed so as to be well inside the area of the hole in

the thick foil; thus, the conversion electrons had to pass through only the 0.2 mg/cm^2 leaf. This technique gave a very stable target which showed no appreciable loss of fluorine after many hours of bombardment. The effective target thickness was estimated to be 8.4 kev for 873-kev protons.

The protons were accelerated in the Kellogg 3 million volt electrostatic generator and analyzed in a 90^o magnet. The target was bombarded at the focal point of the lens spectrometer, charge collection being measured by a standard current integrator accurate to about one percent.

By extrapolation (to sufficiently low energies) of energy loss curves for electrons in aluminum given by Thomas,[4] it was estimated that the conversion electrons from both the 109- and 197-kev lines would suffer less than 0.5 kev energy loss in passing through the 0.2 mg/cm^2 aluminum leaf. However, as this quantity is subject to some uncertainty, it was decided to make electron energy and yield measurements in two separate experiments. In determining line energies, the fluorided side of the target was faced away from the incident proton beam, and bombardment took place after the beam passed through the aluminum (estimated to be approximately 30 kev thick for the proton energies used). Thus, the conversion electrons suffered essentially zero energy loss, as that due to the thickness of the fluorine layer was negligible. For the electron yield measurements, the fluoride layer was bombarded directly in order that straggling effects in the aluminum should not excessively spread the energy of the protons before bombardment.

Also, due to the rather long lifetimes of the excited states[19] (109 kev, $\sim 10^{-9}$ sec; 197 kev, $\sim 10^{-7}$ sec) there existed the possibility that, if the fluorided side of the target were faced away from the beam, some of the excited F^{19} nuclei might, in recoiling, escape from the target and pass out of the electron acceptance angle of the spectrometer before decaying.

The choice of bombarding energies, as mentioned previously, was motivated primarily by background considerations, assuming the major contribution was electrons from the 6.05-Mev nuclear pairs. In support of this assumption, it was found that the background under the 109-kev conversion line increased by a factor of two in going from the 935- to the 1431-kev resonance. Also, the yield of high energy (6 and 7 Mev) gamma rays from O^{16} is high at 873 and 935 kev; we found it convenient to employ these gamma rays for monitoring purposes.

The gamma monitor was set up as follows. A $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in. NaI (Tℓ) crystal was mounted on an RCA 6292 photomultiplier tube. The pulses were fed into an amplifier and then to a discriminator. An integral bias curve was run using the 2.6-Mev gammas from Th C'', and the bias set just above the cut-off for this line. The crystal was placed in line with the target and at 90 degrees to the direction of the incident proton beam. With the monitor thus biased to count primarily the high energy O^{16} gamma rays, an excitation curve was run and the proton energy fixed at the peak of the resonance to be used. It was required that the monitor counts remain constant while running either electron lines or pulse height spectra.

The momentum spectrum of each internal conversion line was run several times and sample spectra of each are shown in Figs. (18) and (19). The results of averaging several runs on each line gave 109.1 ± 1 and 196.8 ± 1.5 kev for the gamma ray energies.

For the conversion electron yield measurements, the experimental procedure was identical to the line energy measurements, save for the target being reversed as mentioned.

For the gamma ray yield determinations, a 1 in. square by $\frac{1}{2}$ in. thick NaI (Tℓ) crystal and 6292 photomultiplier were used together with a ten-channel pulse height analyzer. The crystal was placed immediately outside the spectrometer vacuum tube wall, approximately 7 in. from the target, and perpendicular to the beam direction. The solid angle was determined by a collimator consisting of a 3/4 in. inner diameter ring of 1/4 in. thick lead backed by 2 mm. of cadmium to absorb x-rays produced in the lead.

Due to the fact that the gamma rays had to pass through the 0.148 in. brass spectrometer wall before entering the crystal, it was felt desirable to make an experimental check on the absorption of the two low energy lines, since this correction to the yield was calculated to be 70 percent for the 109-kev and 39 percent for the 197-kev line. For this purpose, the 113- and 206-kev lines in the decay of Lu^{177} (33) and 511-kev annihilation quanta were used. A source was placed at the target position inside the spectrometer and the pulse height spectrum run; this geometry

was reproduced with no absorber between source and crystal and the pulse height spectrum taken again. Thus, the ratio of the yields with and without absorber gave a direct measure of the absorption in the brass which was 68, 37, and 22 percent for 113, 206, and 511 kev, respectively. These three values agreed within a few percent with those read off an absorption curve calculated from the composition of the brass, and it was felt that sufficient accuracy could be obtained by using the calculated absorption for the fluorine gammas.

The effective solid angle of the collimator has been calculated geometrically. The calculated efficiency of the crystal has been checked in previous experiments[18] by comparing the cross sections obtained in observations on the 109- and 197-kev gamma rays to those given by Peterson, et al.[21], as determined from inelastic proton studies in $F^{19}(pp')F^{19*}$.

Sample bias curves are shown in Figs. (20) and (21). The small bump on the low energy side of the 109-kev spectrum is presumably the escape peak from the 109-kev line[18]. It is not known what causes the background under the 197-kev line to rise abruptly toward the low energy side; the major uncertainty in the measured yield of this line is due to lack of knowledge concerning the background under the peak.

C. RESULTS AND DISCUSSION

Before calculating an experimental internal conversion coefficient, several factors must be considered. Since the K- and L- conversion peaks from the F^{19} lines are only 0.7 kev apart,

the resolution at which the spectrometer was operated would not allow their separation; in fact, only a slight broadening of the single observed peak could be expected. In order to apply a correction for the amount of L conversion present, L-shell conversion coefficients were calculated from expressions given by Hebb and Nelson.[22] α_L was obtained using the non-relativistic treatment; β_L was calculated from the relativistic Born approximation results. The theoretical ratios α_K/α_L and β_K/β_L are given in Table (4).

Table (4)

E_γ(kev)	E1	M1	E2	M2
109	7.87	7.95	7.35	7.89
197	8.10	7.96	7.93	7.95

As is seen from the table, the K/L ratios are all about 8 to within 10 percent, so it seemed sufficient to apply a constant correction to the measured electron yields, amounting to a reduction by 11 percent.

A correction must also be made for the expected anisotropic angular distribution of the 197-kev gamma rays and conversion electrons (the 109-kev electrons and gammas are isotropic), since the gamma yield was measured at 90 degrees and the mean angle of electron acceptance for the spectrometer is 20 degrees to the beam direction. The 197-kev gamma ray distribution has been discussed by Christy[23]; two extreme distributions are obtained, for the 873-kev resonance, corresponding to the two possibilities $j_{p'} = 1/2$ or $3/2$ for the total angular momentum of the unobserved

outgoing proton. These are

$$j_{p'} = 1/2: \quad W(\theta) = 1 + 0.75 \cos^2\theta$$

$$j_{p'} = 3/2: \quad W(\theta) = 1 + 0.23 \cos^2\theta$$

The distribution has been measured by Barnes[18] who finds $W(\theta) = 1 + 0.17 \cos^2\theta$ implying $j_{p'} = 3/2$. The reduction in the amount of anisotropy, as predicted above, presumably arises from effects associated with the long lifetime of the $5/2^+$ state.[19] The 197-kev gamma yield, measured at 90°, was corrected to the total yield over 4π steradians, using $W(\theta) = 1 + 0.17 \cos^2\theta$.

According to the theory of angular correlations,[24] if a gamma ray distribution is of the form $W(\theta) = \sum_k A_k P_k(\cos\theta)$, the corresponding distribution with an internal conversion electron replacing the gamma is given by $W(\theta) = \sum_k A_k b_k P_k(\cos\theta)$, where the b_k depend on the multipole order of the transition, Z of emitting nucleus, and energy of the conversion electrons. Numerical values of b_k are given in Ref. (24), from which it is found that $b_2 = 2$ ($b_o = 1$) for the 197-kev line; no higher value of k is present in the distribution. Considering the reduction in the coefficient of $\cos^2\theta$ due to the lifetime effects, we get for the extreme electron distributions

$$j_{p'} = 1/2: \quad W(\theta) = 1 + 1.29 \cos^2\theta$$

$$j_{p'} = 3/2: \quad W(\theta) = 1 + 0.36 \cos^2\theta$$

Using the result for $j_{p'} = 3/2$, the electron yield was normalized to the total yield over 4π steradians.

As a final possible correction, one must consider whether, at the time of the nuclear decay the probability is 100 percent that the K-shell is occupied by two electrons, since all theoretical treatments assume this. As Thomas[4] has pointed out, there are three aspects to this problem:

(1) There is a good probability that the bombarding particle will knock out one or both K electrons in the nuclear reaction; (2) after the break-up of the compound system, the recoiling nucleus may not have its K electrons; (3) as the recoil nucleus travels through matter, the probability of occupation of the K-shell will be governed by capture and loss phenomena.

In the F^{19} decay, the long lifetimes for both transitions are fortuitous in regard to the above problem. A rough estimate which should be good to about a factor of 10, gives 10^{-14} sec. for the stopping time of the fluorine nuclei recoiling through the aluminum backing. Since the lifetimes of the states are 10^{-9} and 10^{-7} sec., the nucleus is at rest and presumably all atomic rearrangements have occurred prior to the emission of gamma rays or conversion electrons. We assume that the K-shell is occupied with 100 percent probability.

Table (5) below summarizes the yield measurements and the experimental coefficients. In addition, we give the ratio of the experimental conversion coefficients to the theoretical ones to indicate the degree of agreement with various multipole assignments.

Table (5)

E_γ (kev)	Y_γ (γ/14.4 μcoul)	Y_e (e/14.4 μcoul)	a_K
109	$(5.68 \pm 1.15) \times 10^6$	$(11.9 \pm 1.8) \times 10^3$	$(2.10 \pm 0.45) \times 10^{-3}$
197	$(2.69 \pm 0.80) \times 10^6$	$(5.15 \pm 0.80) \times 10^3$	$(1.91 \pm 0.60) \times 10^{-3}$

	a_K (Experimental) / a_K (Theoretical)			
	E1	M1	E2	M2
109	1.14 ± 0.24	2.89 ± 0.62	0.089 ± 0.019	0.282 ± 0.060
197	6.84 ± 2.1	10.8 ± 3.4	0.888 ± 0.28	1.79 ± 0.56

The assignment of E2 to the 197-kev line is consistent with $J = 5/2^+$ for the 197-kev level, made on the basis of results from the previously mentioned experiments (see Ref. (18)). The assignment of $5/2^+$ to this state is not unreasonable since, from the shell model, one expects just such a level in the vicinity of the ground state.

The results shown in Table (5) exclude any other pure multipole order besides E1 for the 109-kev line. This eliminates the possibility of $1/2^+$ for the 109-kev level, which would allow only pure M1 radiation. In addition, it has been argued that a $3/2^-$ assignment should lead to competition between E1 decay to this state and E2 decay to the ground state from the 197-kev level. It has been stated that the 88-kev transition is less than about one percent of the intensity of the cross-over transition, which would require the 88-kev transition to be somehow inhibited by a very large factor.[18]. The assignment of $3/2^+$ to the 109-kev level would allow a mixture of M1 and E2 in the decay. Sherr, Li, and Christy[20] have shown that the Coulomb excitation of this state must be E2 if the assignment

$3/2^+$ is correct. From the excitation cross section, the E2 matrix element may be calculated and gives a lifetime for the state of 7.7×10^{-5} sec. The observed lifetime is 1.0×10^{-9} sec., so the ratio of E2 to M1 in the decay is 1.3×10^{-5}, making it almost pure M1. This conclusion is excluded by our experiments. The possibilities $5/2^{\pm}$ can be eliminated on the basis of the observation that the 109-kev gammas are isotropic and the disagreement with E2 or M2 as given by the conversion coefficient. Thus, $1/2^-$ seems to be the only assignment consistent with this and the previous experiments.

Recently, Flowers and Elliot[25], have made calculations based on an intermediate coupling scheme which, it is claimed, should predict the level positions of all even parity states in F^{19}. The 197-kev level and a level at 1.57 Mev are accounted for quite well, but the 109-kev state is conspicuous by its absence, in agreement with the odd parity assignment. Christy and Fowler[26] consider the $1/2^-$ level as a proton hole in the $p_{\frac{1}{2}}$ shell with four (s, d) particles outside it, coupled to give $T = J = 0$. Their approximate calculation places the state within 0.75 Mev of the F^{19} ground state.

VI. CONVERSION COEFFICIENT OF THE 440-KEV TRANSITION IN Na^{23}

A. PURPOSE OF EXPERIMENT

The first excited state of Na^{23} lies at 440 kev above the ground state; Temmer and Heydenburg have studied the excitation of this state by $Na^{23}(\alpha\alpha')Na^{23*}$ and $Na^{23}(pp')Na^{23*}$[27]. The alpha particle Coulomb excitation cross section curve agrees well with that predicted for E2 excitation of this level, although the shape of the theoretical E1 curve also allows a fit to within 5% of the experimental curve. In addition they have bombarded pairs of thin targets with alpha particles and protons, in an energy region where resonant contributions are very small, and have obtained the ratio of 440-kev gamma yield as produced by alpha particle Coulomb excitation to that produced by proton Coulomb excitation. This ratio is sensitive to the multipole order of the excitation; Temmer and Heydenburg state that their experimental ratio is in agreement with the theoretical one for E2 excitation ($Y_\alpha/Y_p \sim 11$), whereas the E1 ratio would be around 7.

They have also given the ratio of the transition probability as determined experimentally from the alpha particle Coulomb excitation to that predicted from the single particle model for E2 Coulomb excitation, obtaining a ratio of 71. This is a rather surprising result for such a light nucleus where it is thought that collective nuclear motions, which greatly enhance transition rates in medium and heavy nuclei, are relatively unimportant.

The ground state of Na^{23} is $3/2^+$; assuming the excitation is E2 there result the possibilities $1/2^+$, $3/2^+$, $5/2^+$, or $7/2^+$

for the 440-kev state. It was with the hope of getting further information concerning this level that we undertook to measure the internal conversion coefficient.

B. CONVERSION EXPERIMENT

A thin Na^{23} target was prepared by evaporating NaCl on to 0.2 mg/cm^2 aluminum foil. Bombardment took place at a proton energy of 2270 kev; this choice of energy was made to give as high a yield of 440-kev radiation as possible consistent with a low yield of 1.63-Mev gamma rays from Ne^{20} produced in $Na^{23}(p\alpha)Ne^{20*}$, which would give an unwanted background in the 440-kev gamma spectrum. The particular choice of bombarding energy was made by observing that, on an excitation function given by Stelson and Preston[28], the above conditions would be met at E_p=2270 kev.

Upon making an initial search for the internal conversion electrons, it was found that the general counting rate was much higher than expected. Investigation showed the count rate to be independent of spectrometer field setting and independent of bombarding energy down to around 1200 kev where it started decreasing and became zero at about 860 kev. It was suggested that we were counting protons which had passed through the target and backing, and had scattered into the geiger counter. The cut-off at 860 kev corresponded to the minimum proton energy which would permit transmission of protons through the mica window of the counter. This supposition was checked by bombarding bare 0.2 mg/cm^2 and 1.7 mg/cm^2 aluminum foils. The proton energy at which the count rate rose from zero was observed to shift

from 860 kev for the thin foil to 1030 kev for the thick one, the difference being very nearly the expected difference in proton energy loss in the two foils. This difficulty was eliminated by placing a 15.5 mg/cm^2 aluminum foil directly over the geiger window, the foil being thick enough to stop scattered protons but thin enough to pass the conversion electrons.

The only high energy gamma ray present which could be used for monitoring purposes was the 1.63-Mev line in Ne^{20}. When we attempted to use a scintillation counter for a monitor, it was found that the count rate was dependent on the machine background. Thus, the monitoring technique used in the fluorine experiment could not be used here, due to the necessity of a low discriminator bias in order to detect the 1.63-Mev gamma rays. A heavily shielded geiger counter monitor was placed approximately 8 inches from the target and these counts used to normalize the electron and gamma yields.

The 440-kev internal conversion line is shown in Fig. (22). The expected conversion coefficient for this transition is $\sim 10^{-5}$, thus giving a small electron yield and rather large resulting statistical fluctuations in the count rate. The electron yield, corrected for L-conversion, is $Y_e = (2.01 \pm 0.60) \times 10^3$ e/14.4μ coul.

The gamma ray yield was measured in the 1 inch square by $\frac{1}{2}$ inch thick NaI crystal at 7 in. from the target position, the differential bias curve being shown in Fig. (23). The photopeak efficiency for this energy was determined from a curve similar to the one shown in Fig. (2), a series of sources having been run in the $\frac{1}{2}$ inch crystal in exactly the same manner as has been described

for the $1\frac{1}{2}$ inch crystal. Correcting for the small amount of absorption in the spectrometer wall, the yield of 440-kev gammas is $Y_\gamma = (5.00 \pm 1.0) \times 10^7\ \gamma\ /14.4\ \mu$ coul.

The expected lifetime of this state, based on the single particle model, is given below for E1, M1, E2, M2 multipole orders:

	E1	M1	E2	M2
τ (Sec)	1.5×10^{-14}	6×10^{-13}	1×10^{-8}	4×10^{-7}

The estimated nuclear stopping time is approximately 10^{-14} sec. Thus, if the transition is E2 or M2, the possibility that the K-shell is occupied by two electrons at the time of decay should be 100%, implying the conversion coefficient is correct as measured.

If there is uncertainty as to whether the decay takes place before or after the nucleus is stopped, it is necessary to consider the so-called "capture and loss ratio" for the ion in question. Thomas[4] has given an estimate of this quantity which is

$$\frac{\sigma_\ell^{1-2}}{\sigma_c^{1-2}} \sim 4 f_{1-0} \left(\frac{I_{1-0}}{I_{2-1}} \frac{E}{E_o} \right)$$

where

$\frac{\sigma_\ell^{1-2}}{\sigma_c^{1-2}}$ = ratio of cross sections for loss and capture in the exchange from one to two K-electrons.

I_{2-1} = ionization potential for removal of first K-electron

I_{1-0} = ionization potential for removal of second K-electron

E = average kinetic energy of the ion

E_o = kinetic energy of ion at which its velocity is $\frac{Z_2 e^2}{\hbar}$

Z_2 = nuclear charge of the ion

f_{1-0} is an experimental function which Thomas has plotted.

In the case in question, the above estimate gives $\sigma_{\ell}{}^{1-2}/\sigma_{c}{}^{1-2} < 0.02$; thus, the experimental coefficient needs no correction, and we have obtained $\alpha_K = (4.03 \pm 1.5) \times 10^{-5}$.

The theoretical conversion coefficients are shown below:

10^5	E1	M1	E2	M2
α_K	4.85	5.31	20.0	18.6

The experimental result indicates either E1 or M1, and M1 may be inferred if the excitation is E2. Thus, the possibility of $7/2^+$ for the 440-kev level may be eliminated. Further experiments are being planned (angular distribution and Doppler-shift measurements) which it is hoped will lead to a definite assignment for the spin and parity.

VII. INCONCLUSIVE LENS SPECTROMETER EXPERIMENTS

A. $N^{15} + D^2$

Three excited states of N^{16} have recently been discovered by detecting the alpha-particle groups from the reaction $O^{18}(d\alpha)N^{16}$; the level excitation energies are 113, 300, and 391 kev[8]. The reaction $N^{15}(dp)N^{16}$ (Q = 0.27 Mev) has been shown to yield proton groups leading to the first four states of N^{16} [29]. Preliminary investigation of the gamma spectrum by means of a scintillation counter has indicated lines at 116 ± 5 and 280 ± 20 kev (C. A. Barnes, private communication). The presence of other lines is suggested by the pulse-height spectrum, but they are too weak to identify.

We have bombarded a thick N^{15}-enriched TiN target with 1.2-Mev deuterons, and have surveyed the spectrum from a 6.67-mg/cm^2 Th photoelectric converter. Tentative results give an L-conversion peak corresponding to a gamma ray energy of 118±5 kev and a K-peak of a line at 275 ± 15 kev. In addition, the presence of a line at 302 ± 20 kev is suggested. The conversion lines were badly distorted due to large electron energy losses in the photoconverter.

Further experiments are being planned with improved targets in the hope that internal conversion lines may be detected and further information obtained concerning the energy, spin, and parity of some of the levels.

B. $F^{19} + He^4$

Prior to the F^{19} (pp') F^{19*} experiment discussed in Section

V, an attempt was made to excite the 197-kev level in F^{19} by alpha-particle Coulomb excitation, and to observe the 197-kev line by external photo-conversion. A thick CaF_2 target was bombarded with 2.15-Mev singly-charged He^+ ions. The electron spectrum from a 1 - mg/cm^2 uranium converter was investigated and a K-peak observed corresponding to a gamma ray energy of 196.5 $\pm$ 4 kev, in good agreement with the value 196.8 $\pm$ 1.5 kev obtained in the $F^{19}(pp')F^{19*}$ experiment. The intensity of the line was quite low, precluding any other measurements besides the energy determination. The 109-kev line was not searched for, as the converter was much too thick for the L-conversion electrons from that gamma ray.

C. $Na^{23} + D^2$

In the reaction Na^{23} (dp) Na^{24}, proton groups are observed leading to the first two excited states of Na^{24} at 0.47 and 0.56 Mev[30]. At E_d = 3 Mev, Butler analysis of the angular distribution of the unresolved proton groups leading to these two levels indicates ℓ_n = 0 and 2, with the choice ℓ_n = 0 for the 470-kev state being favored[31]. If this is true, then $J = 1^+$ or 2^+ for this level, since the ground state of Na^{23} is $3/2^+$. The ground state of Na^{24} is $J = 4^+$, so it appeared that the 470-kev line might be of a high multipole order and the internal conversion electrons measurable.

A thick NaCl target, similar to that used in the $Na^{23}(pp')$ Na^{23*} experiment, was bombarded with 1.07-Mev deuterons. A 1 in. square by $\frac{1}{2}$ in. thick NaI crystal was placed 7 in. away from the target which was at the spectrometer focal

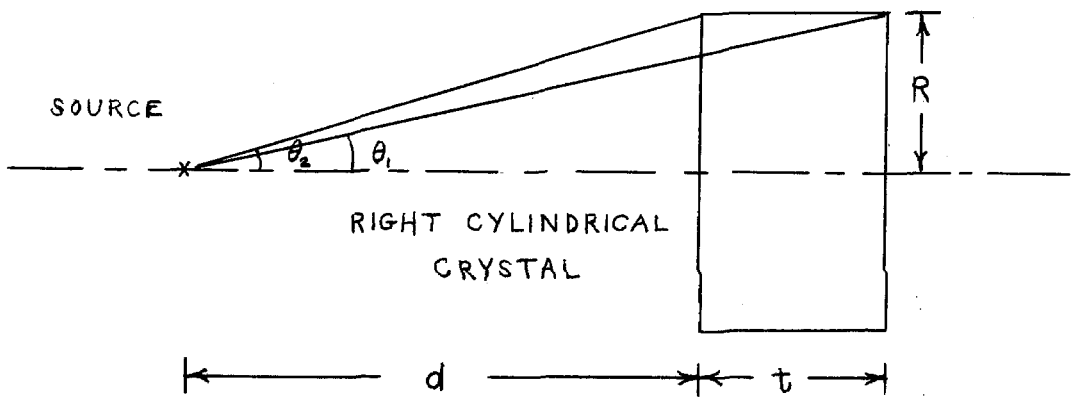
point. When the pulse height spectrum was taken, the 470-kev line was found to give a fairly well-defined photopeak, although the background was high due to neutrons and gamma rays produced by the accelerated deuterons.

When a search was made for the 470-kev internal conversion line, a high background and large count rate variations rendered identification impossible. An upper limit of 6×10^{-4} was placed on the K-conversion coefficient, eliminating multipole orders of $\ell = 4$ and higher.

APPENDIX

CALCULATION OF TOTAL CRYSTAL EFFICIENCY

Consider the following geometry:



Assume that the source isotropically emits N gamma rays per unit time per unit solid angle. Define the total crystal efficiency for the detection of gamma rays as follows:

$$\eta_T = \frac{\text{Number of gamma rays absorbed in crystal}}{\text{Number of gamma rays incident on crystal}}$$

A gamma ray is absorbed if it produces a scintillation from any conversion process. For the purpose of calculating η_T, the crystal may be divided into two regions: I, the region subtended in the solid angle $\Omega_1 = 2\pi\ (1 - \cos\theta_1)$; II, the region subtended in $\Omega_2 - \Omega_1$.

The number of gammas incident on the crystal is $N\Omega_2$. The number absorbed in the element of solid angle $d\Omega_\theta$ is

$N\left[1 - e^{-\mu x(\theta)}\right] d\Omega_\theta$ where

μ = linear absorption coefficient in crystal

$x(\theta)$ = path length in crystal

The conical element of solid angle is $d\Omega_\theta = 2\pi \sin\theta d\theta$. Then the total number of gammas absorbed is

$$2\pi \int_0^{\theta_2} N\left[1 - e^{-\mu x(\theta)}\right] \sin\theta \, d\theta = 2\pi N \int_0^{\theta_1} \left(1 - e^{-\frac{\mu t}{\cos\theta}}\right) \sin\theta \, d\theta$$
$$+ 2\pi N \int_{\cos\theta_2}^{\cos\theta_1} \left[1 - e^{-\mu\left(\frac{R}{\sin\theta} - \frac{d}{\cos\theta}\right)}\right] d(\cos\theta)$$

If R, t $<<$ d, then $\cos\theta \approx 1$ and the first integral on the right is $2\pi N(1-\cos\theta_1)(1-e^{-\mu t})$. With the above approximation, the second integral contributes around 10 percent or less to the total absorption. We have plotted the integrand for a typical case (d = 11 in., R = 0.75 in., t = 1.5 in.), and the resulting curve is linear within 15 percent or better. Thus, since the second integral contributes only a small amount, one is justified in approximating it by

$$2\pi N \frac{1}{2} \left\{\left(1 - e^{-\frac{\mu t}{\cos\theta_1}}\right)(\cos\theta_1 - \cos\theta_2)\right\}$$
$$= 2\pi N \left\{\frac{1}{2}(1 - \cos\theta_2) - \frac{1}{2}(1 - \cos\theta_1)\right\}\left(1 - e^{-\frac{\mu t}{\cos\theta_1}}\right)$$

If $\cos\theta_1 \approx 1$, this becomes

$$\frac{N}{2}(\Omega_2 - \Omega_1)(1 - e^{-\mu t})$$

Thus, the total number of gammas absorbed is

$$N(1 - e^{-\mu t})\left[\Omega_1 + \frac{1}{2}(\Omega_2 - \Omega_1)\right]$$

Therefore,

$$\eta_T = \frac{N\left(1-e^{-\mu t}\right)\left(\frac{\Omega_1+\Omega_2}{2}\right)}{N\,\Omega_2} = \frac{1}{2}\left(1+\frac{\Omega_1}{\Omega_2}\right)\left(1-e^{-\mu t}\right)$$

If the source to crystal distance is more than about eight times larger than both the radius and thickness of the crystal, the expression for η_T should be accurate to better than five percent.

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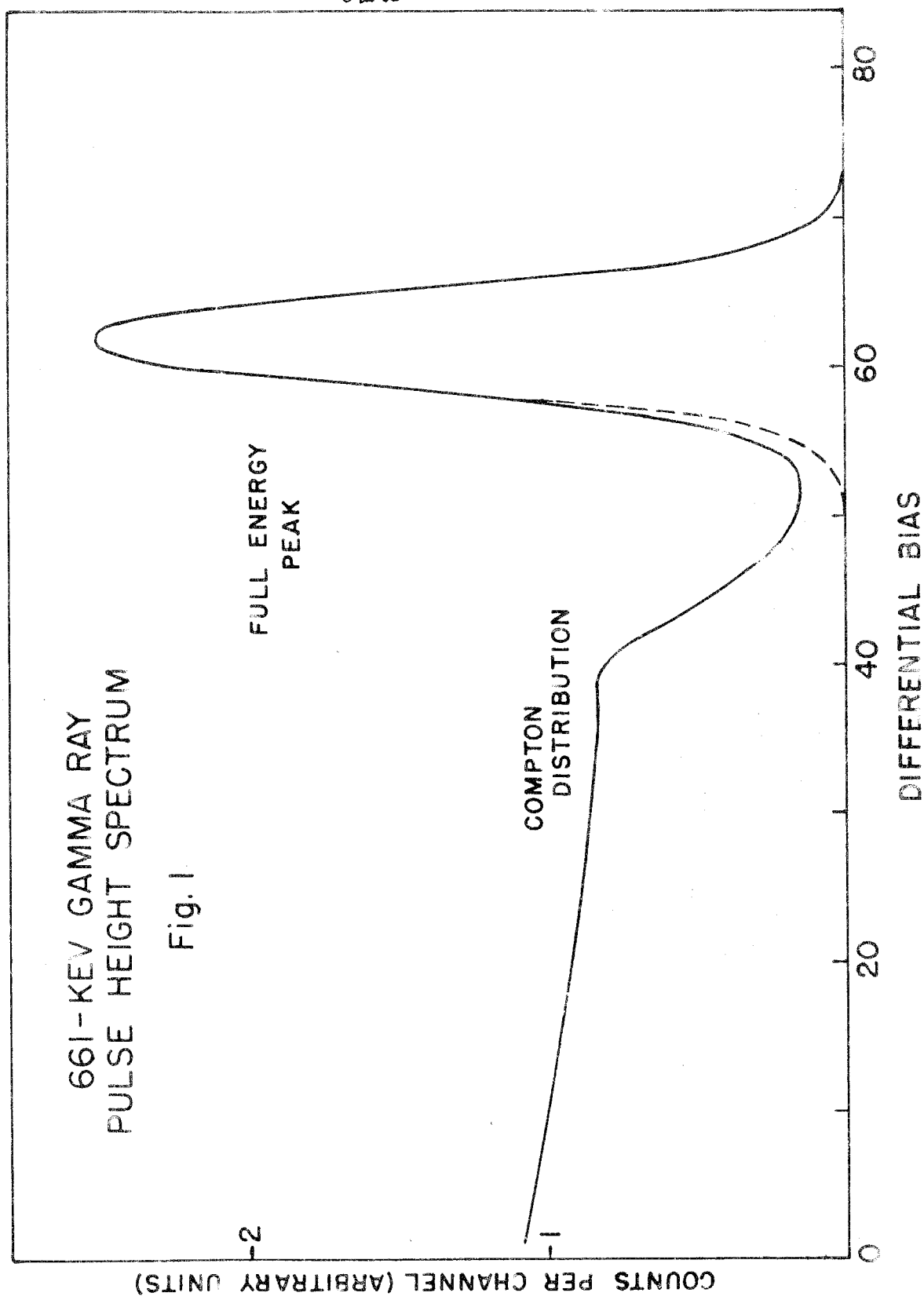

661-KEV GAMMA RAY
PULSE HEIGHT SPECTRUM
FULL ENERGY PEAK
COMPTON DISTRIBUTION
COUNTS PER CHANNEL (ARBITRARY UNITS)
DIFFERENTIAL BIAS
0
20
40
60
80
1
2

Fig. 1

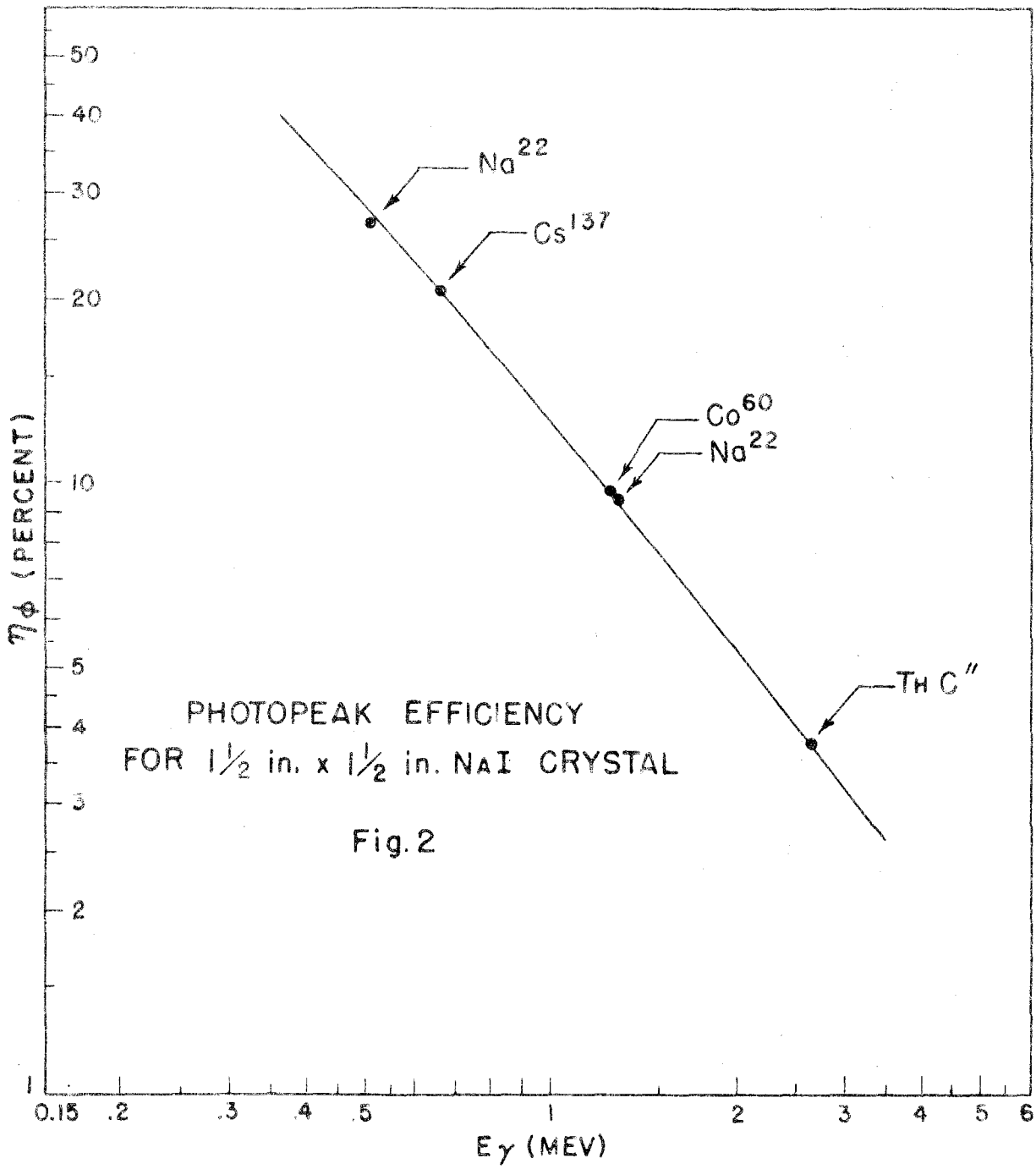
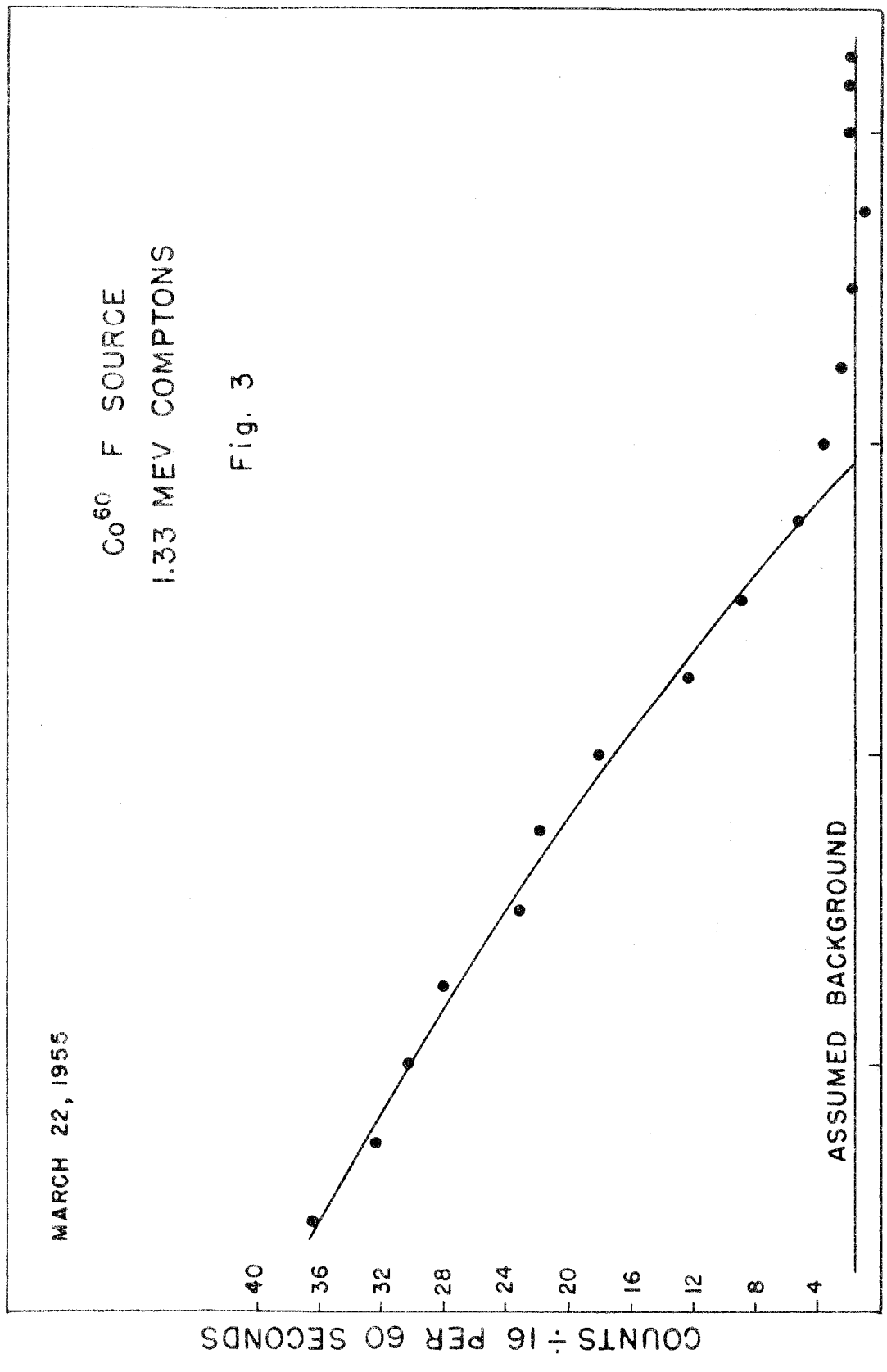
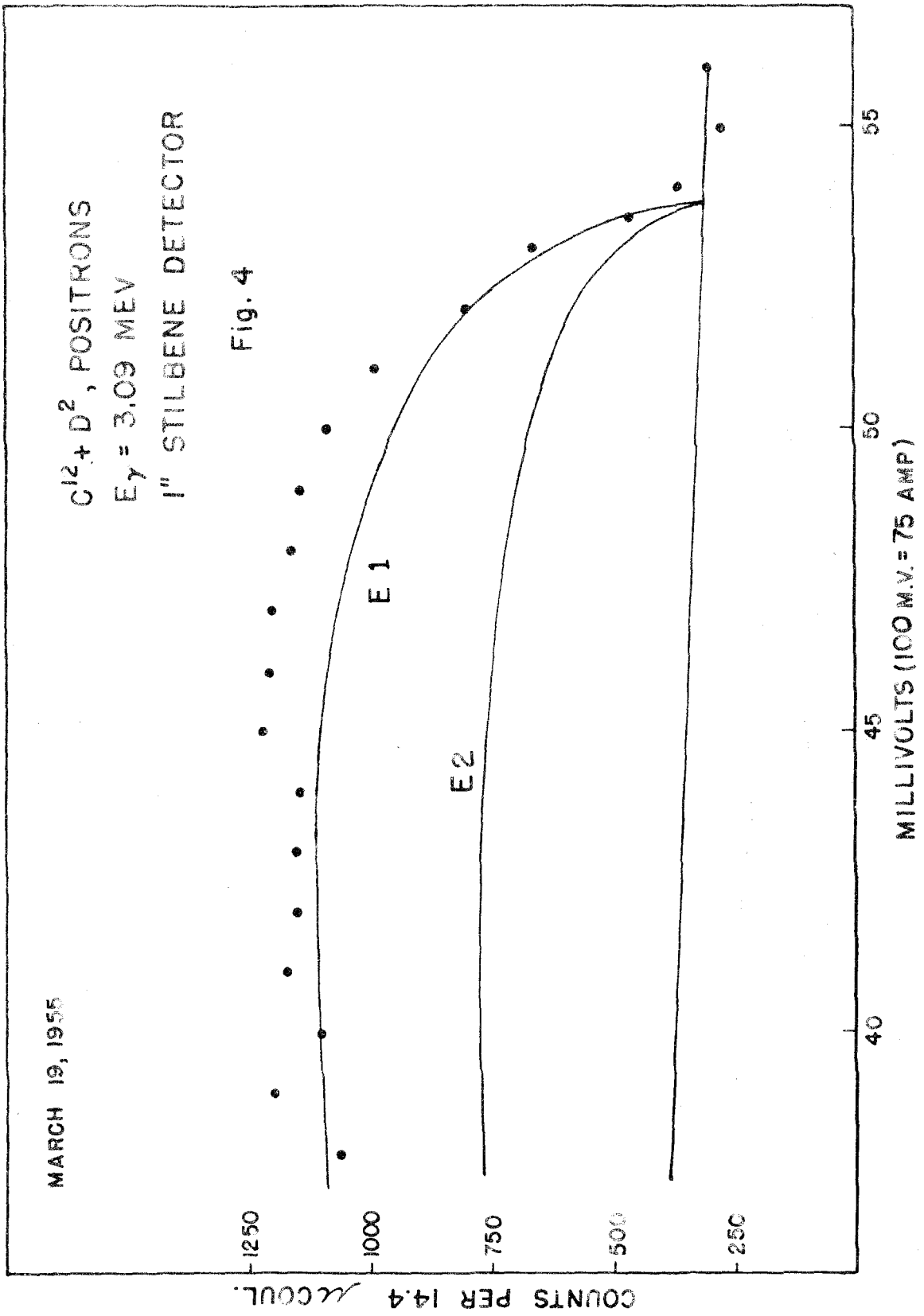
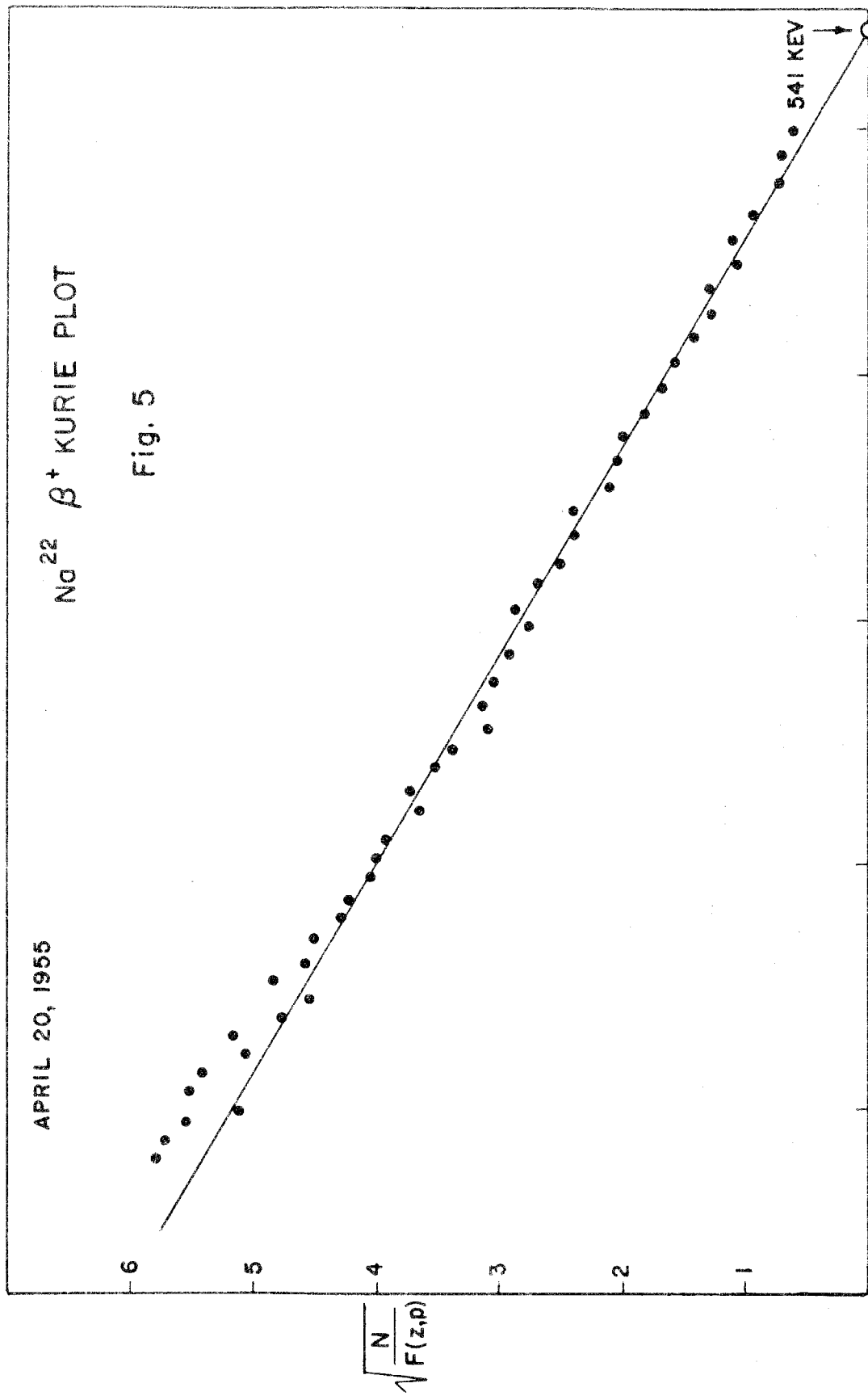
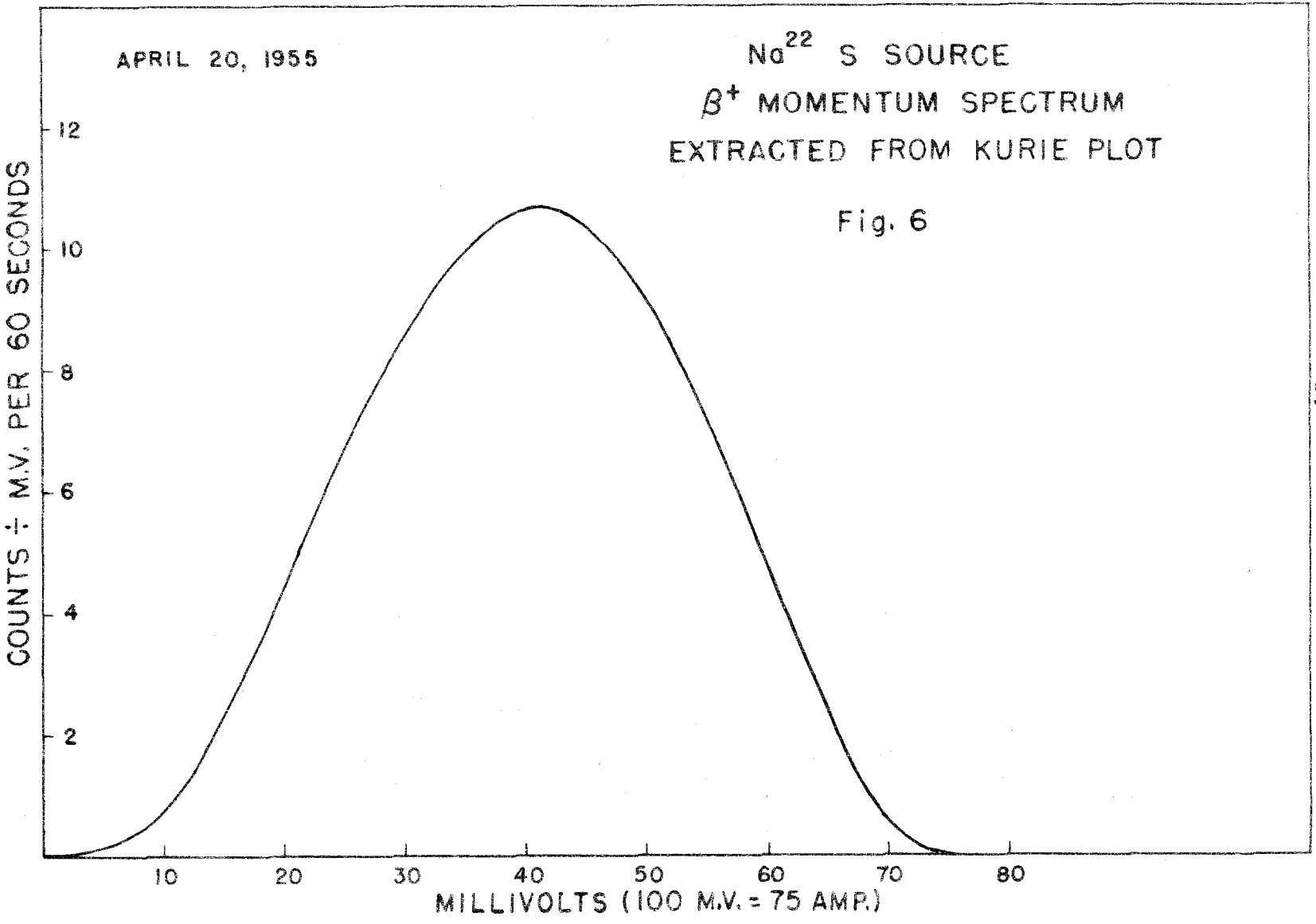

50
40
30
20
10
5
4
3
2
1
$\eta\phi$ (PERCENT)
Na^{22}
Cs^{137}
Co^{60}
Na^{22}
Th C''
PHOTOPEAK EFFICIENCY
FOR 1½ in. x 1½ in. NaI CRYSTAL
0.15
.2
.3
.4
.5
1
2
3
4
5
6
$E\gamma$ (MEV)

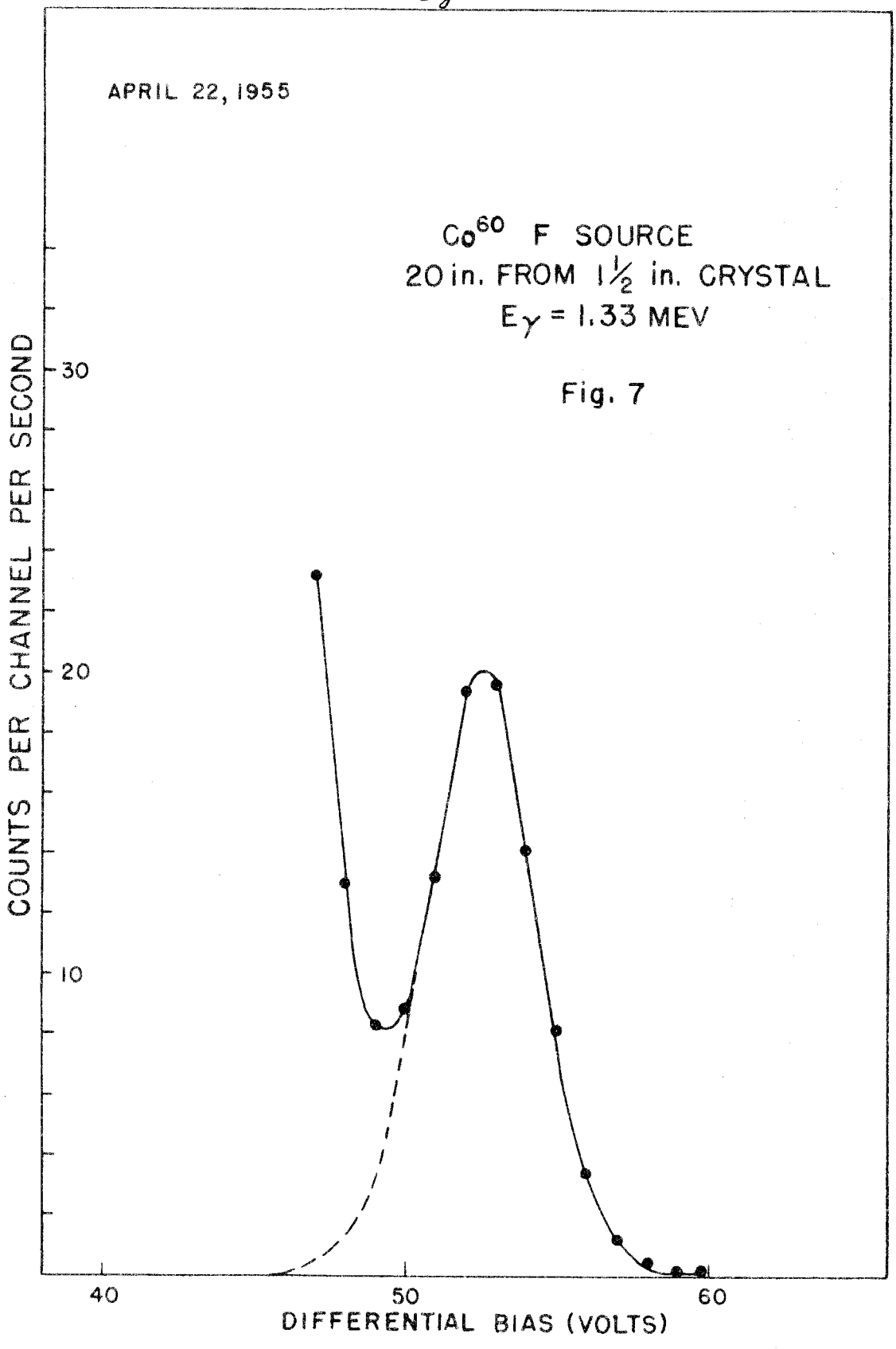
Fig. 2


MARCH 22, 1955
Co^{60} F SOURCE
1.33 MEV COMPTONS
Fig. 3
COUNTS ÷ 16 PER 60 SECONDS
40
36
32
28
24
20
16
12
8
4
ASSUMED BACKGROUND
31
32
33
34
MILLIVOLTS (100 M.V = 75 AMP)


$C^{12} + D^2$, POSITRONS
E_γ = 3.09 MEV
1" STILBENE DETECTOR
Fig. 4
MARCH 19, 1955
E 1
E 2
COUNTS PER 14.4 μCOUL.
1250
1000
750
500
250
40
45
50
55
MILLIVOLTS (100 M.V. = 75 AMP)


APRIL 20, 1955
Na^{22} β^+ KURIE PLOT
Fig. 5
541 KEV
POSITRON ENERGY (KEV)
100
200
300
400
500
1
2
3
4
5
6
$\sqrt{\frac{N}{F(z,p)}}$


APRIL 20, 1955
Na^{22} S SOURCE
β^+ MOMENTUM SPECTRUM
EXTRACTED FROM KURIE PLOT
Fig. 6
COUNTS ÷ M.V. PER 60 SECONDS
12
10
8
6
4
2
10
20
30
40
50
60
70
80
MILLIVOLTS (100 M.V. = 75 AMP.)


APRIL 22, 1955
Co^{60} F SOURCE
20 in. FROM 1½ in. CRYSTAL
E_γ = 1.33 MEV
Fig. 7
COUNTS PER CHANNEL PER SECOND
30
20
10
40
50
60
DIFFERENTIAL BIAS (VOLTS)

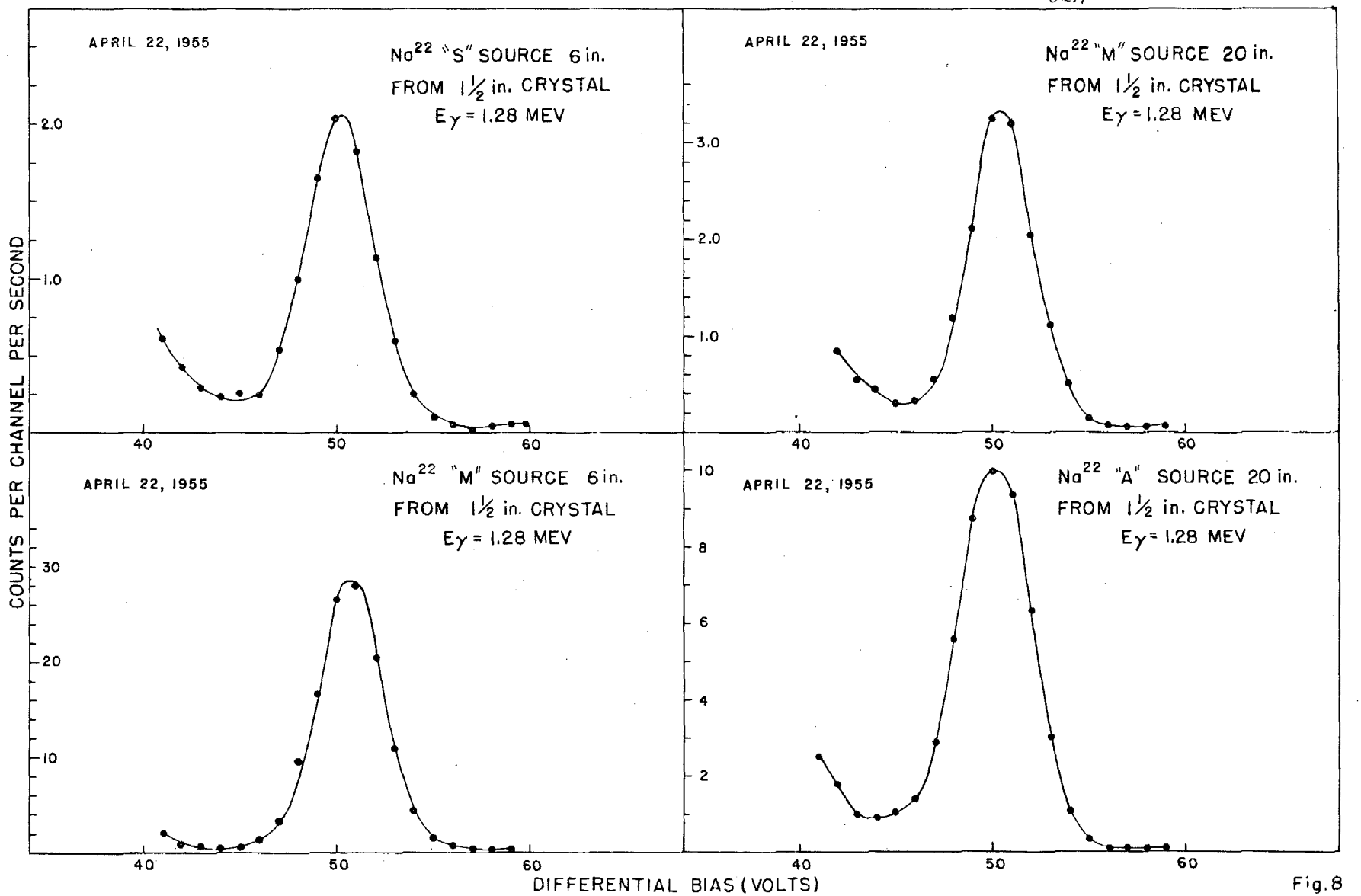
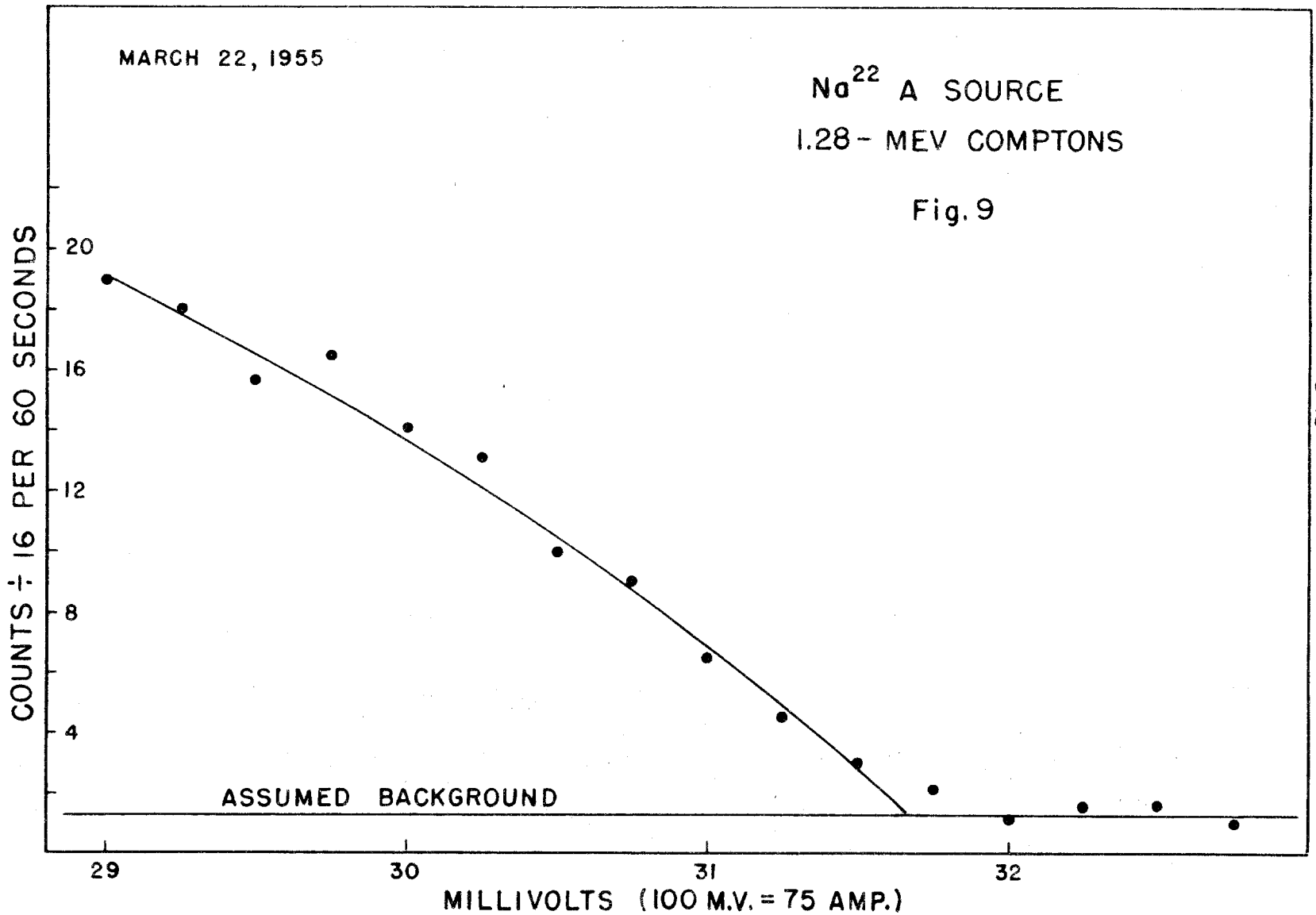
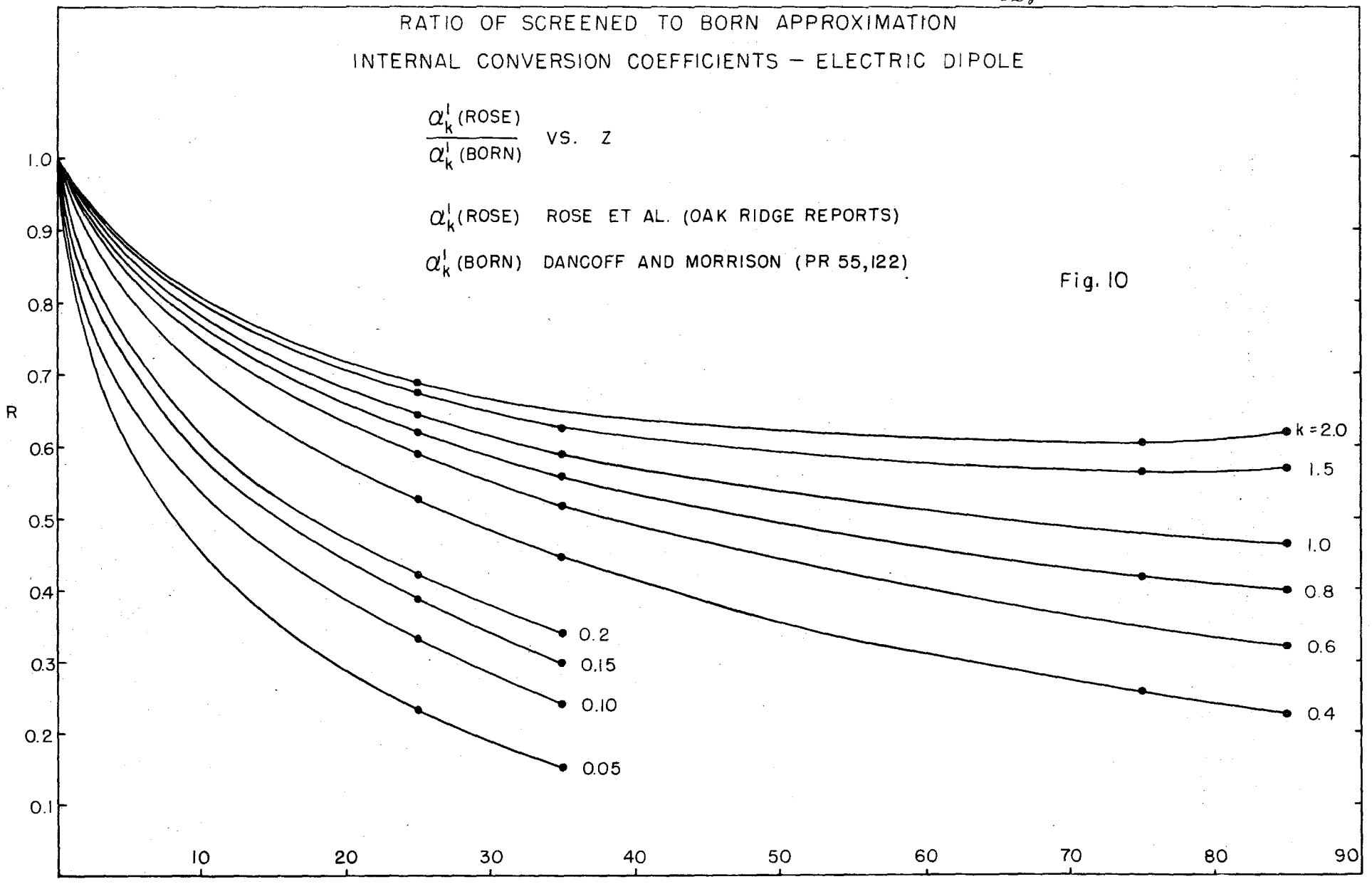

APRIL 22, 1955
Na22 "S" SOURCE 6 in.
FROM 1½ in. CRYSTAL
Eγ = 1.28 MEV
APRIL 22, 1955
Na22 "M" SOURCE 20 in.
FROM 1½ in. CRYSTAL
Eγ = 1.28 MEV
APRIL 22, 1955
Na22 "M" SOURCE 6 in.
FROM 1½ in. CRYSTAL
Eγ = 1.28 MEV
APRIL 22, 1955
Na22 "A" SOURCE 20 in.
FROM 1½ in. CRYSTAL
Eγ = 1.28 MEV
COUNTS PER CHANNEL PER SECOND
DIFFERENTIAL BIAS (VOLTS)
40
50
60
1.0
2.0
3.0
10
20
30
2
4
6
8
10

Fig. 8


MARCH 22, 1955
Na^{22} A SOURCE
1.28 - MEV COMPTONS
Fig. 9
COUNTS ÷ 16 PER 60 SECONDS
20
16
12
8
4
ASSUMED BACKGROUND
29
30
31
32
MILLIVOLTS (100 M.V. = 75 AMP.)


RATIO OF SCREENED TO BORN APPROXIMATION
INTERNAL CONVERSION COEFFICIENTS – ELECTRIC DIPOLE
$\frac{\alpha_k^l(\text{ROSE})}{\alpha_k^l(\text{BORN})}$ VS. Z
$\alpha_k^l(\text{ROSE})$ ROSE ET AL. (OAK RIDGE REPORTS)
$\alpha_k^l(\text{BORN})$ DANCOFF AND MORRISON (PR 55,122)
Fig. 10
R
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10
20
30
40
50
60
70
80
90
k = 2.0
1.5
1.0
0.8
0.6
0.4
0.2
0.15
0.10
0.05

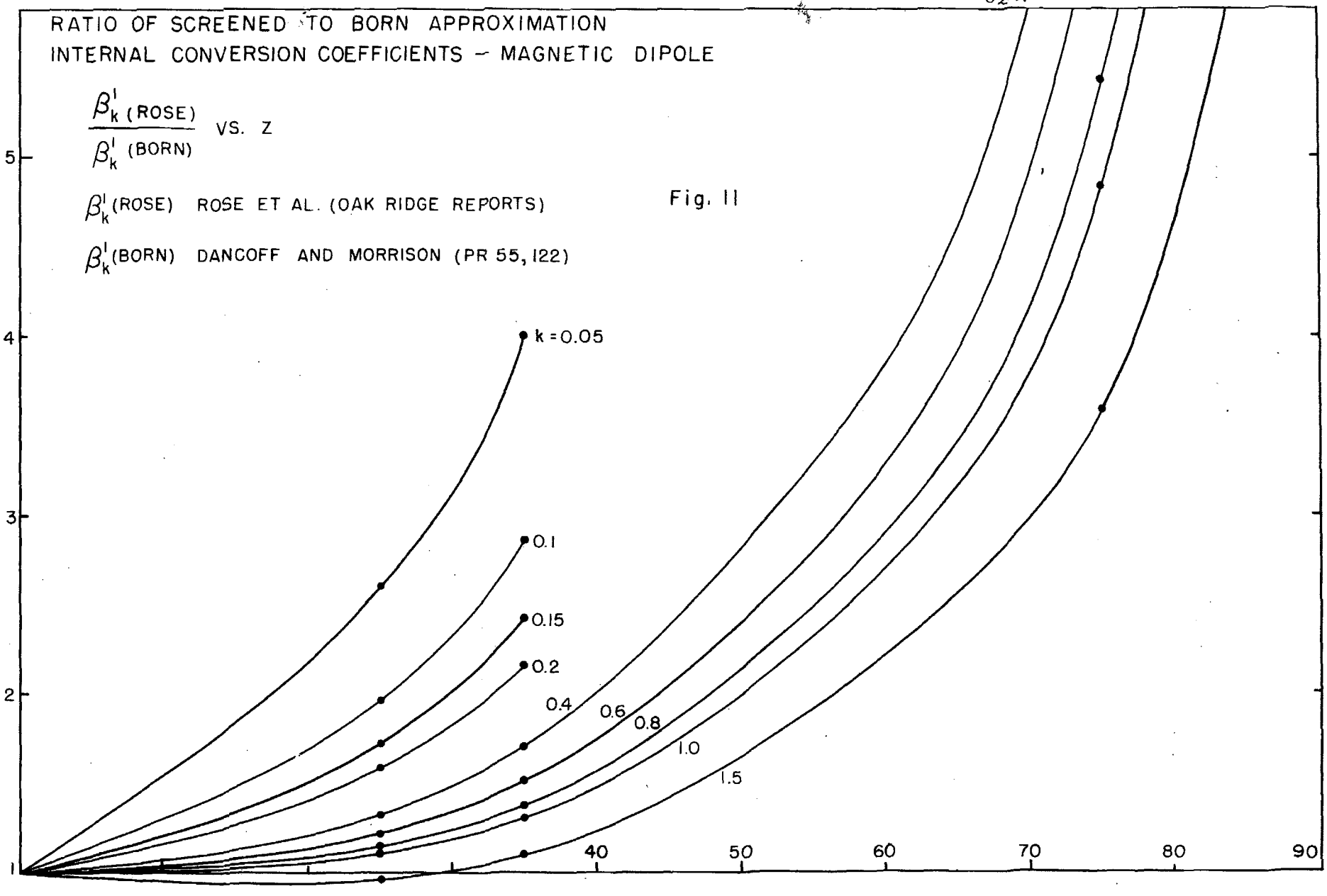
RATIO OF SCREENED TO BORN APPROXIMATION
INTERNAL CONVERSION COEFFICIENTS – MAGNETIC DIPOLE

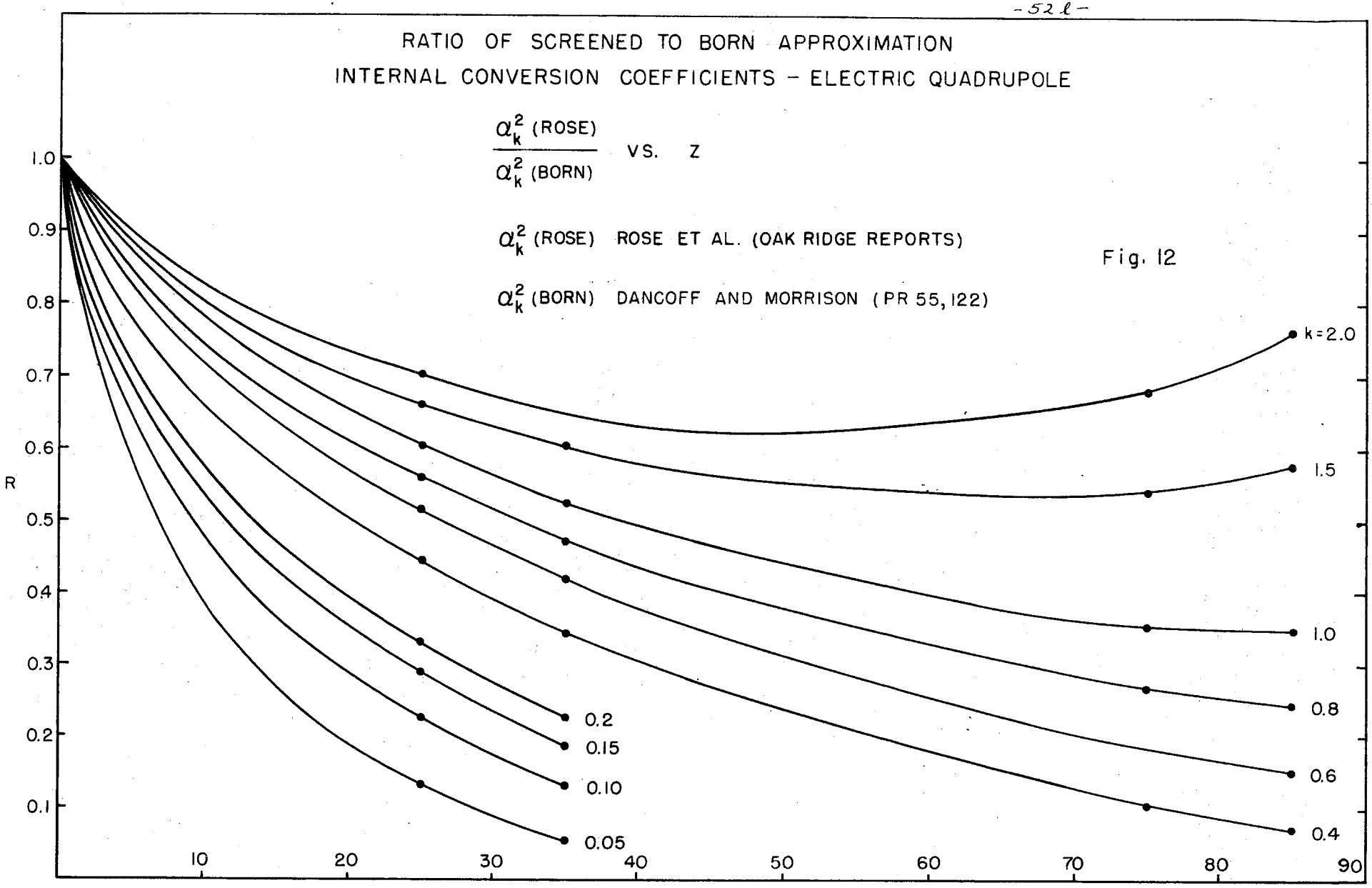
$\frac{\beta_k^1\,(\text{ROSE})}{\beta_k^1\,(\text{BORN})}$ VS. Z

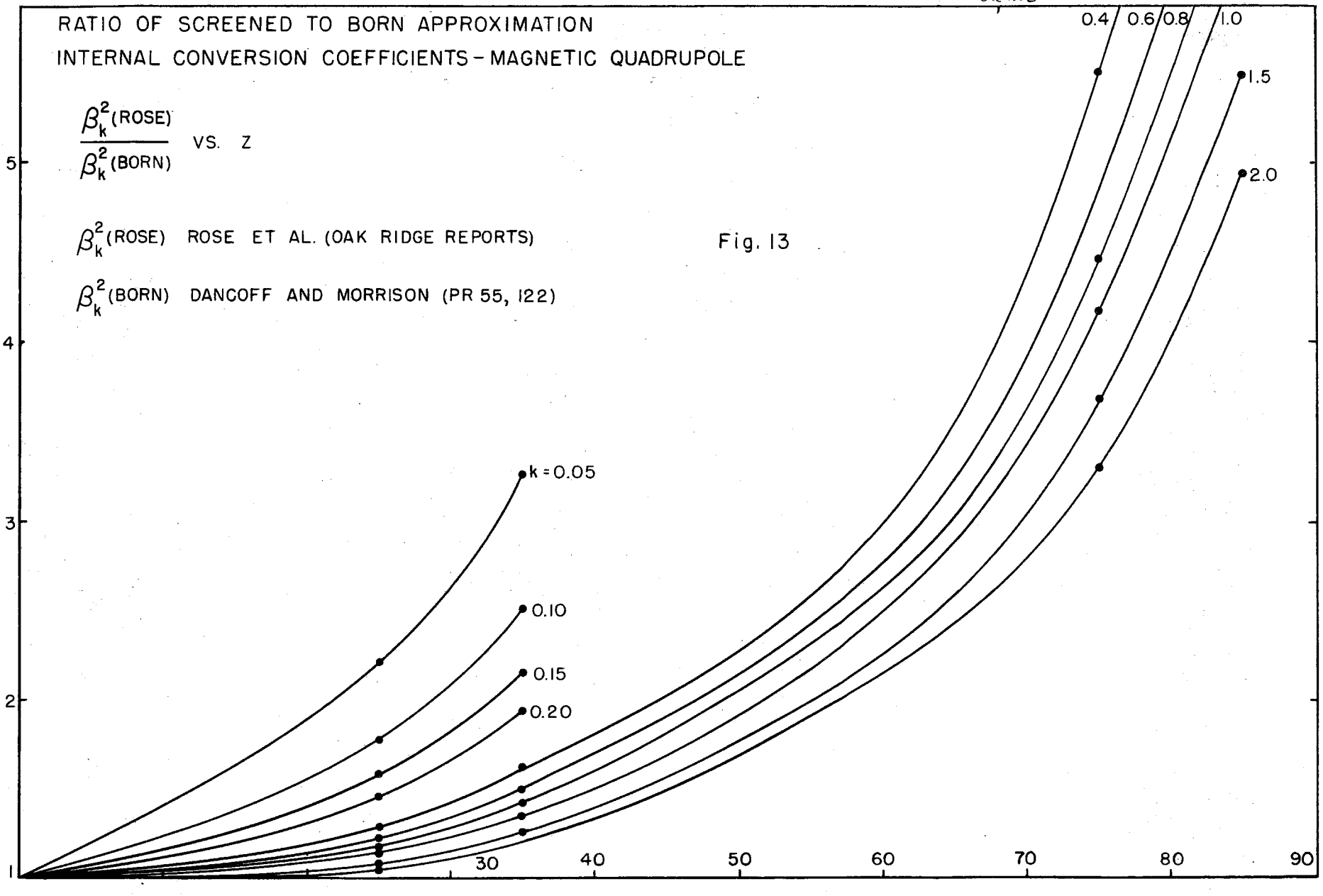
β_k^1(ROSE) ROSE ET AL. (OAK RIDGE REPORTS)

β_k^1(BORN) DANCOFF AND MORRISON (PR 55, 122)

Fig. 11




RATIO OF SCREENED TO BORN APPROXIMATION
INTERNAL CONVERSION COEFFICIENTS - ELECTRIC QUADRUPOLE
$\frac{\alpha_k^2 (ROSE)}{\alpha_k^2 (BORN)}$ VS. Z
α_k^2 (ROSE) ROSE ET AL. (OAK RIDGE REPORTS)
α_k^2 (BORN) DANCOFF AND MORRISON (PR 55, 122)
Fig. 12
R
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10
20
30
40
50
60
70
80
90
k=2.0
1.5
1.0
0.8
0.6
0.4
0.2
0.15
0.10
0.05


RATIO OF SCREENED TO BORN APPROXIMATION
INTERNAL CONVERSION COEFFICIENTS - MAGNETIC QUADRUPOLE
$\frac{\beta_k^2(\text{ROSE})}{\beta_k^2(\text{BORN})}$ VS. Z
β_k^2(ROSE) ROSE ET AL. (OAK RIDGE REPORTS)
β_k^2(BORN) DANCOFF AND MORRISON (PR 55, 122)
Fig. 13
R
k = 0.05
0.10
0.15
0.20
0.4
0.6
0.8
1.0
1.5
2.0
1
2
3
4
5
30
40
50
60
70
80
90

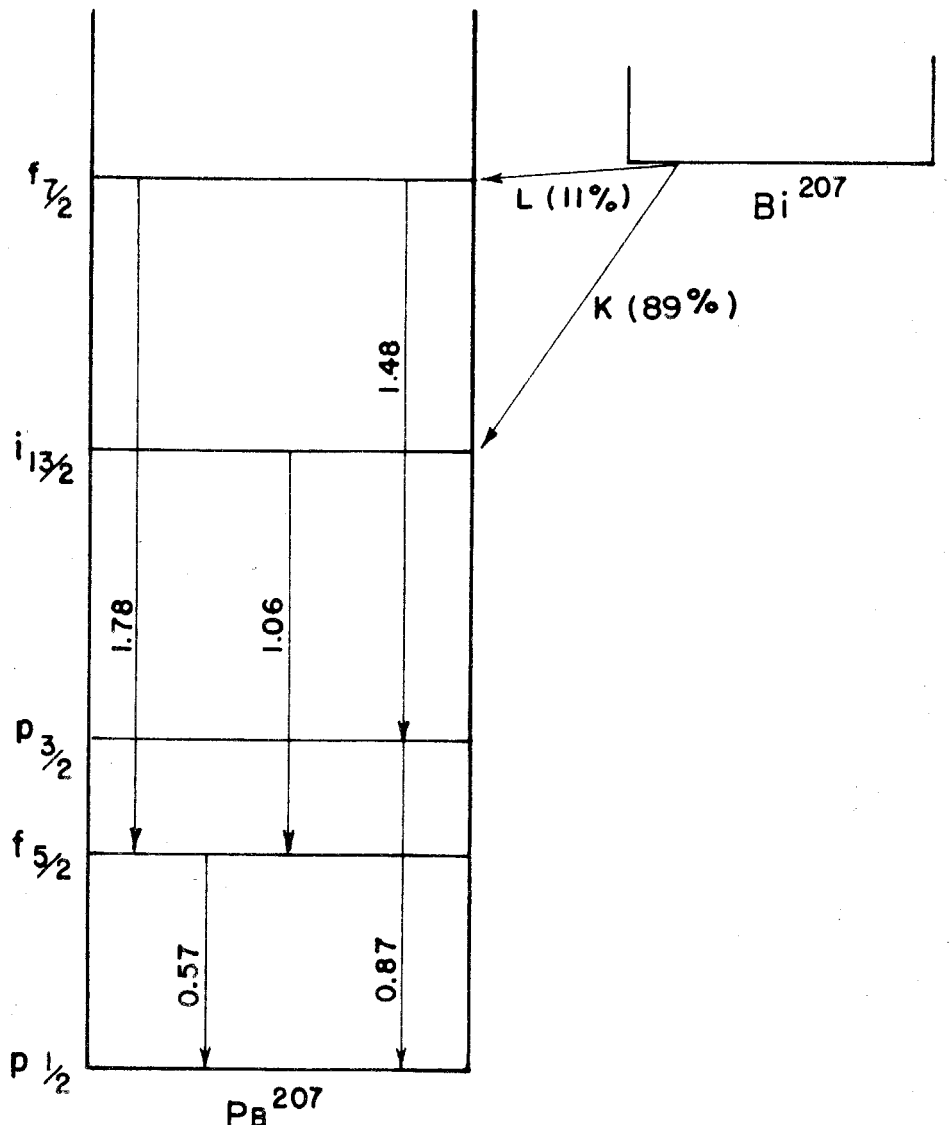
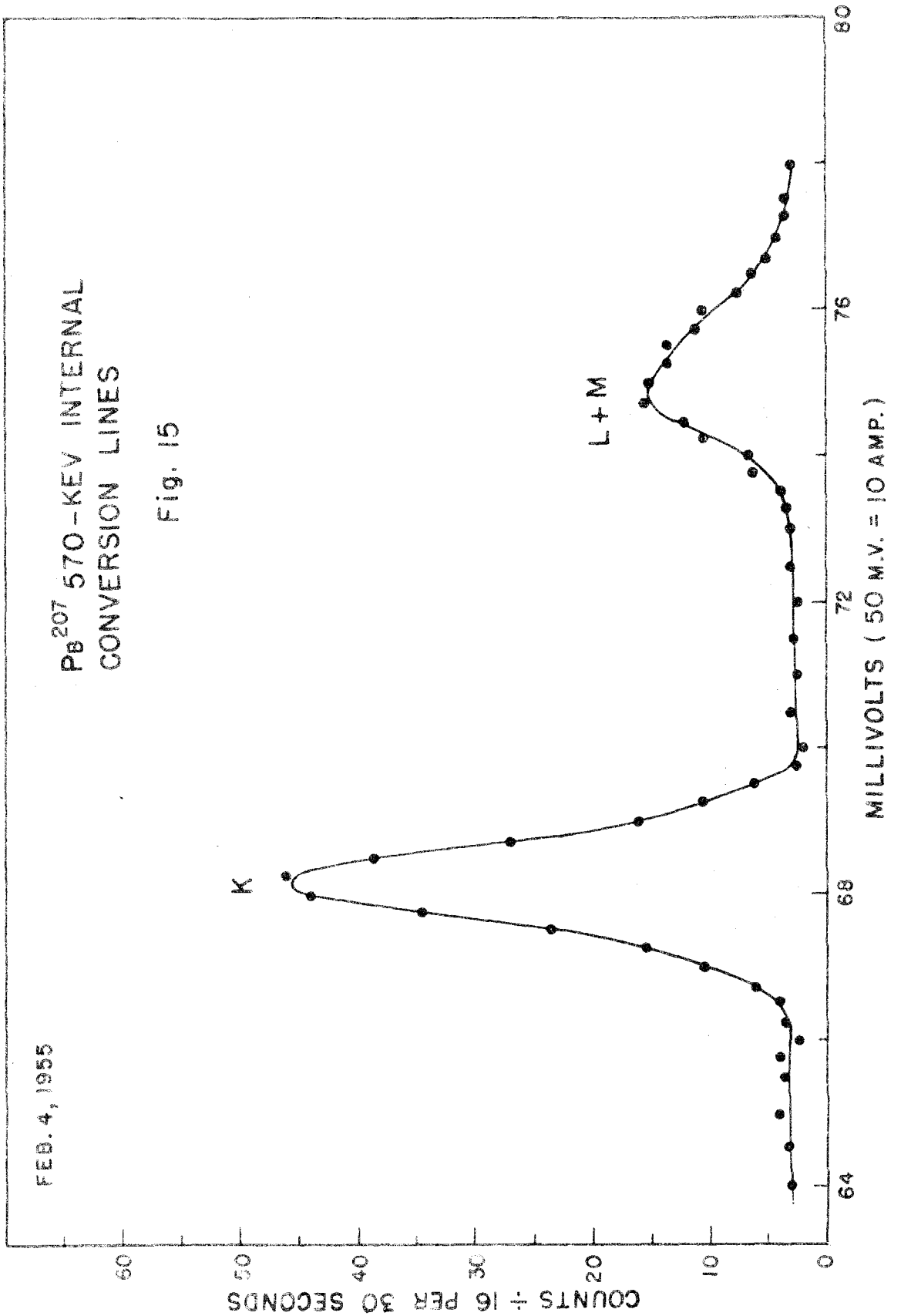
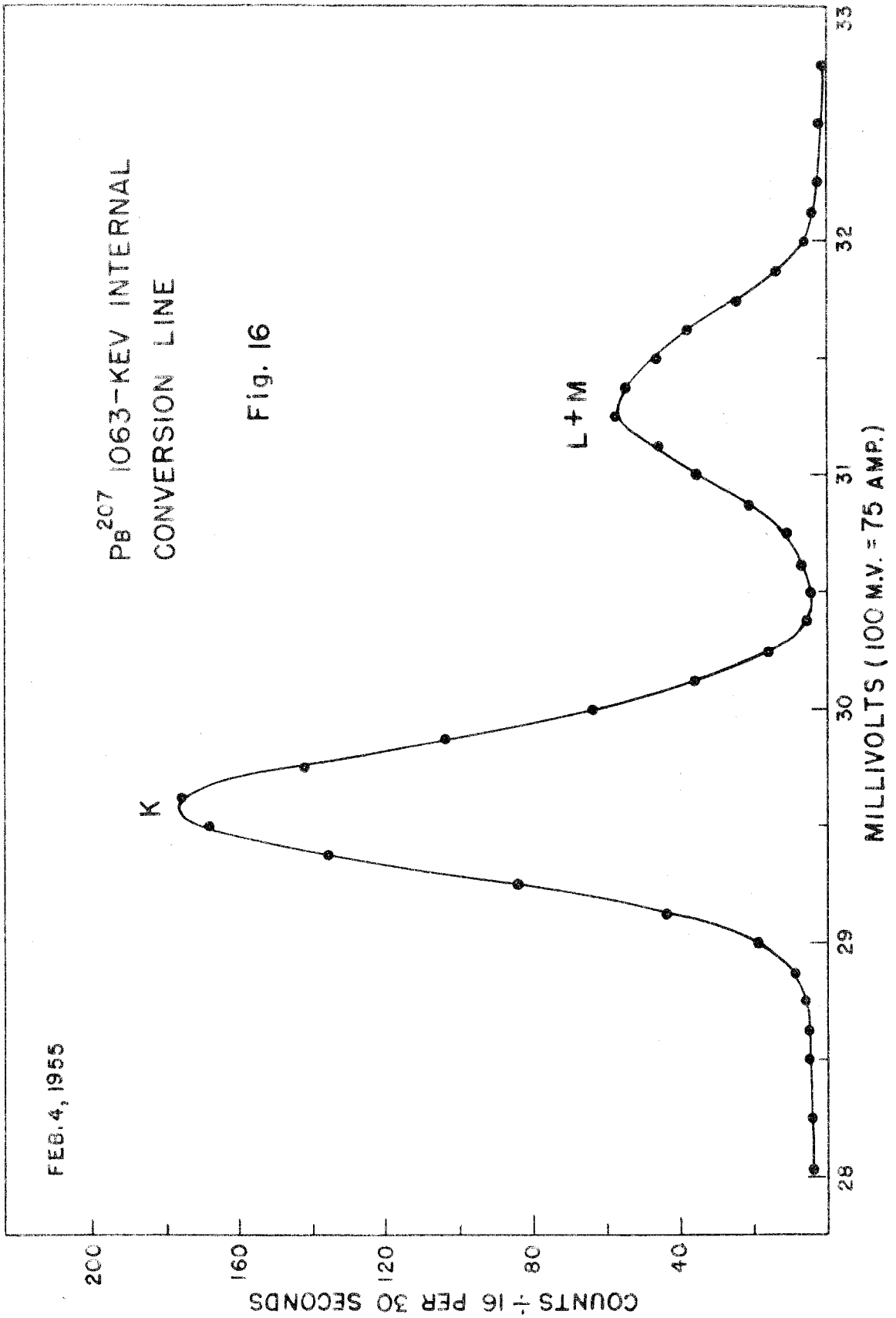
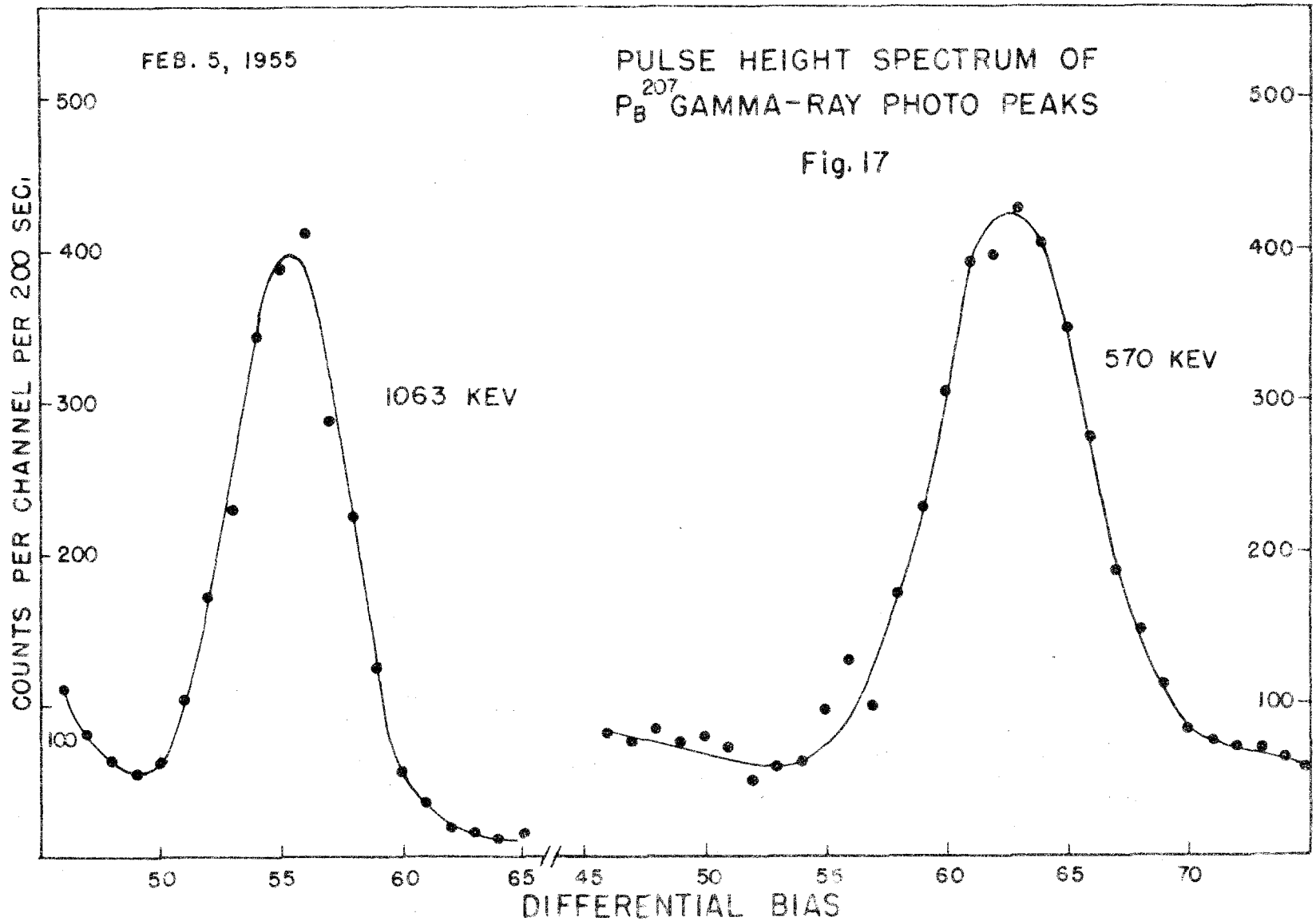
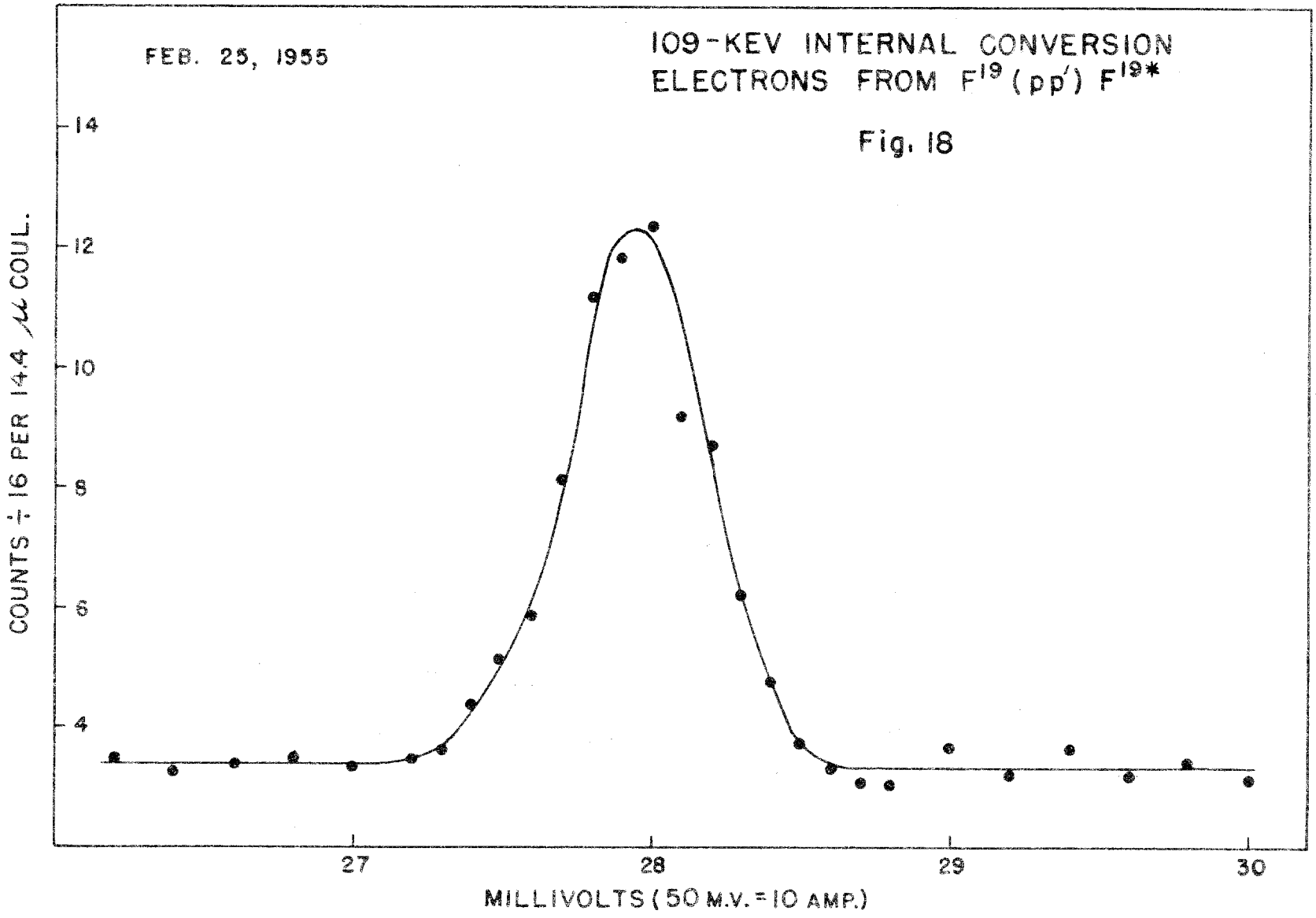


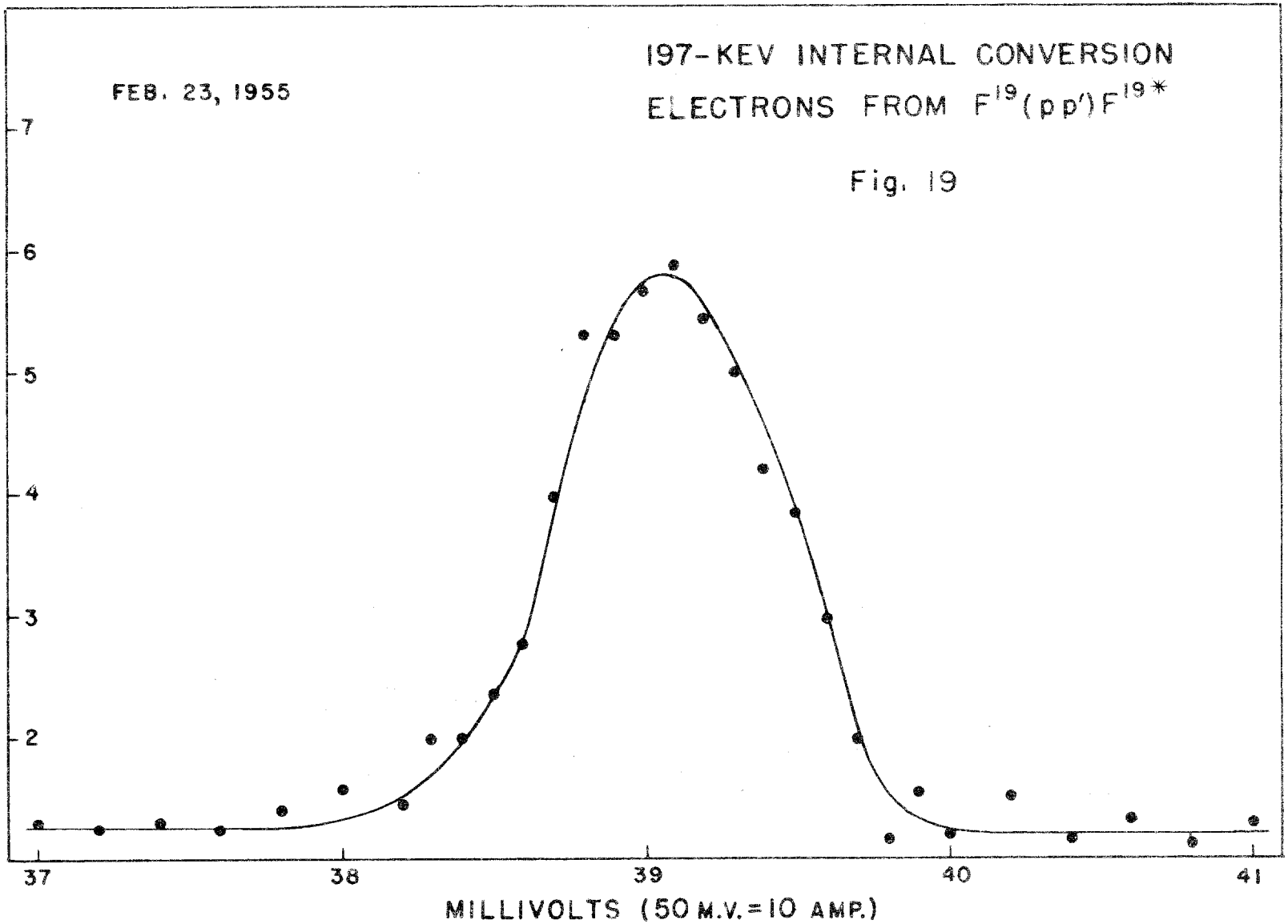
Fig. 14

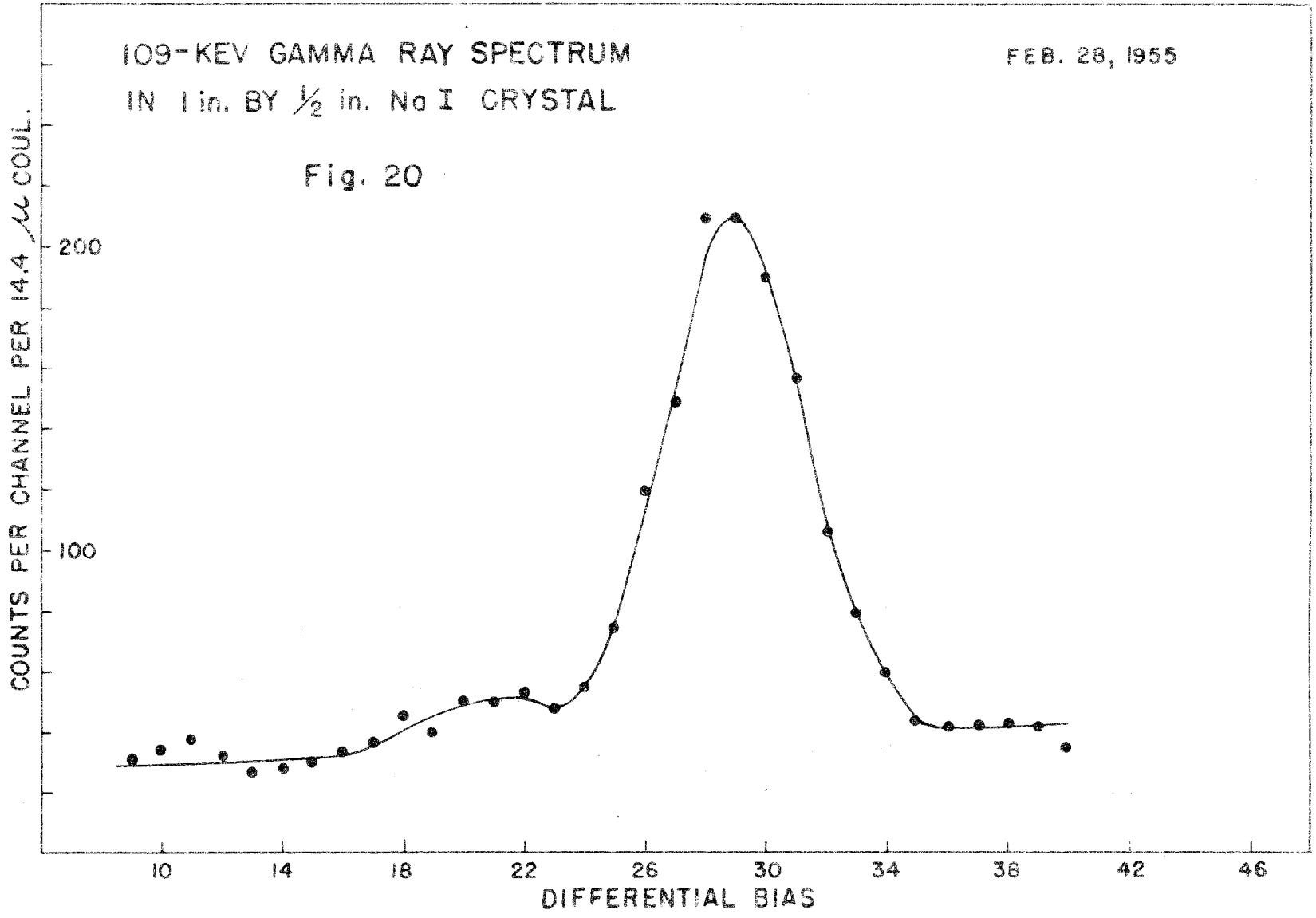

Pb^{207} 570-KEV INTERNAL CONVERSION LINES
Fig. 15
FEB. 4, 1955
K
L+M
COUNTS ÷ 16 PER 30 SECONDS
MILLIVOLTS (50 M.V. = 10 AMP.)
0
10
20
30
40
50
60
64
68
72
76
80


Pb^{207} 1063-KEV INTERNAL
CONVERSION LINE
Fig. 16
FEB. 4, 1955
K
L + M
COUNTS ÷ 16 PER 30 SECONDS
200
160
120
80
40
28
29
30
31
32
33
MILLIVOLTS (100 M.V. = 75 AMP.)


FEB. 5, 1955
PULSE HEIGHT SPECTRUM OF
P_B^{207} GAMMA-RAY PHOTO PEAKS
Fig. 17
1063 KEV
570 KEV
COUNTS PER CHANNEL PER 200 SEC.
COUNTS PER CHANNEL PER 100 SEC.
DIFFERENTIAL BIAS
500
400
300
200
100
50
55
60
65
45
70


FEB. 25, 1955
109-KEV INTERNAL CONVERSION ELECTRONS FROM $F^{19}(pp')F^{19*}$
Fig. 18
COUNTS ÷ 16 PER 14.4 μ COUL.
14
12
10
8
6
4
27
28
29
30
MILLIVOLTS (50 M.V. = 10 AMP.)


197-KEV INTERNAL CONVERSION
ELECTRONS FROM $F^{19}(p\,p')F^{19*}$
FEB. 23, 1955
Fig. 19
COUNTS ÷ 16 PER 14.4 μ COUL.
7
6
5
4
3
2
37
38
39
40
41
MILLIVOLTS (50 M.V. = 10 AMP.)


109-KEV GAMMA RAY SPECTRUM
IN 1 in. BY ½ in. Na I CRYSTAL
FEB. 28, 1955
Fig. 20
COUNTS PER CHANNEL PER 14.4 μ COUL.
200
100
10
14
18
22
26
30
34
38
42
46
DIFFERENTIAL BIAS

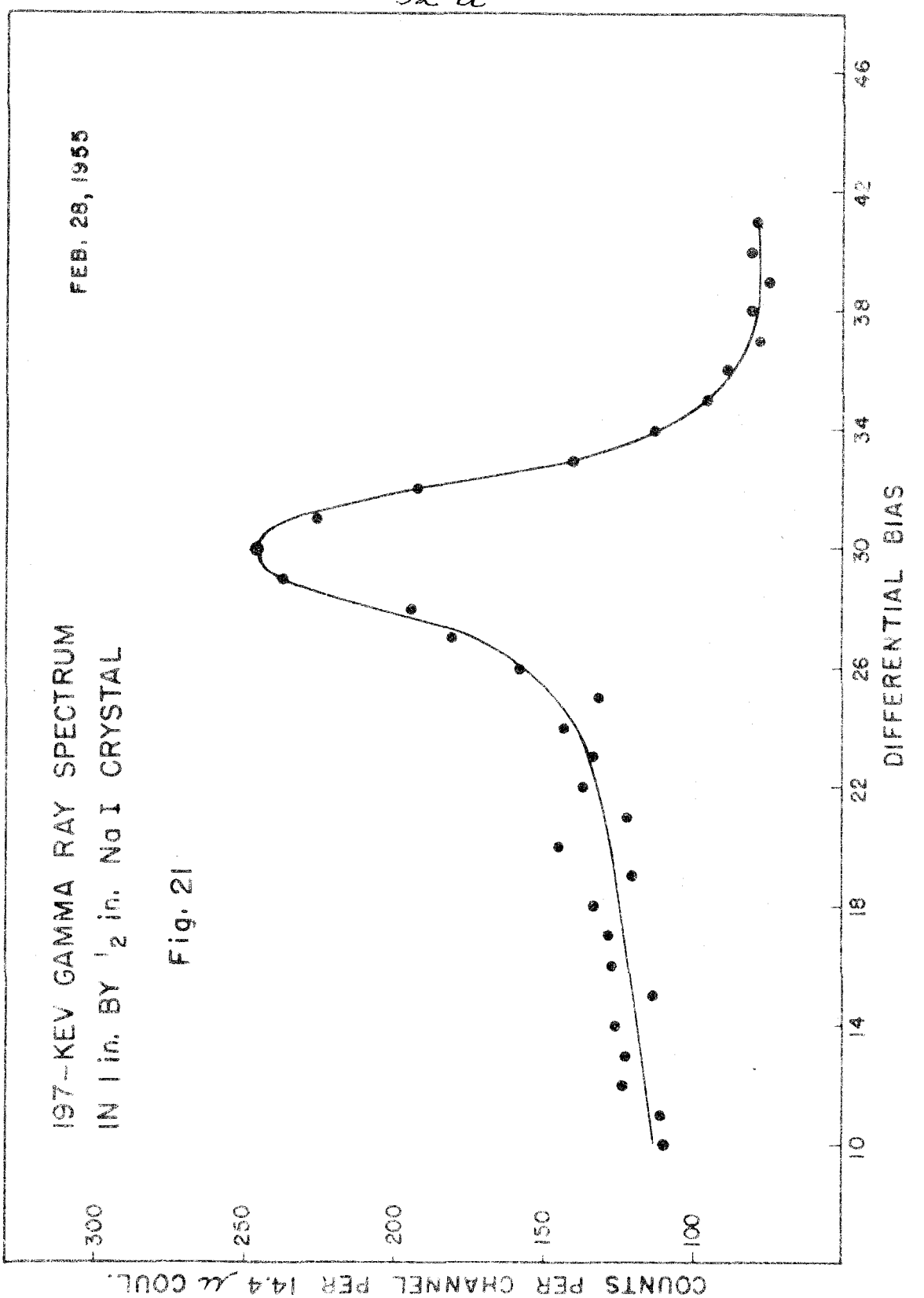
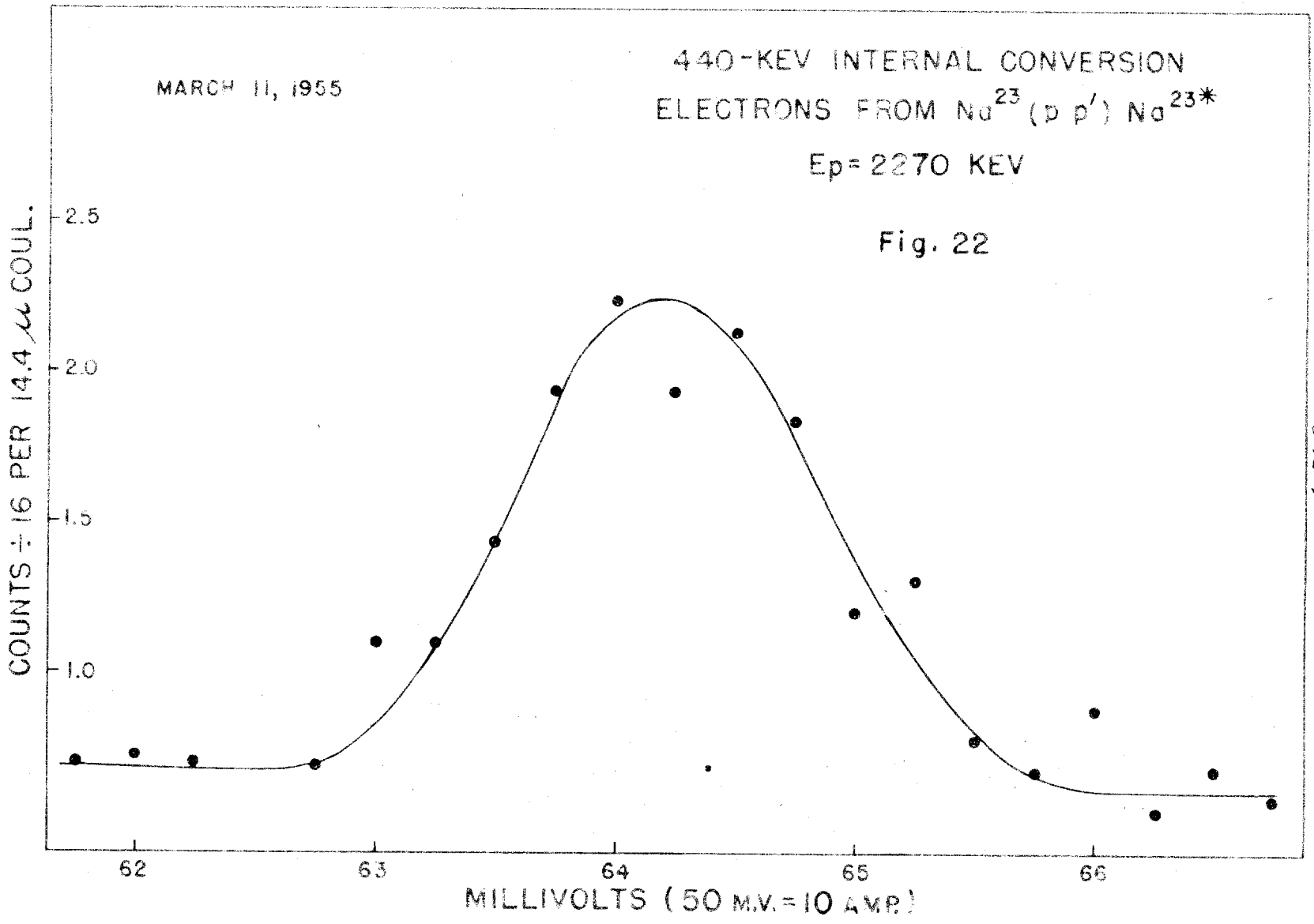
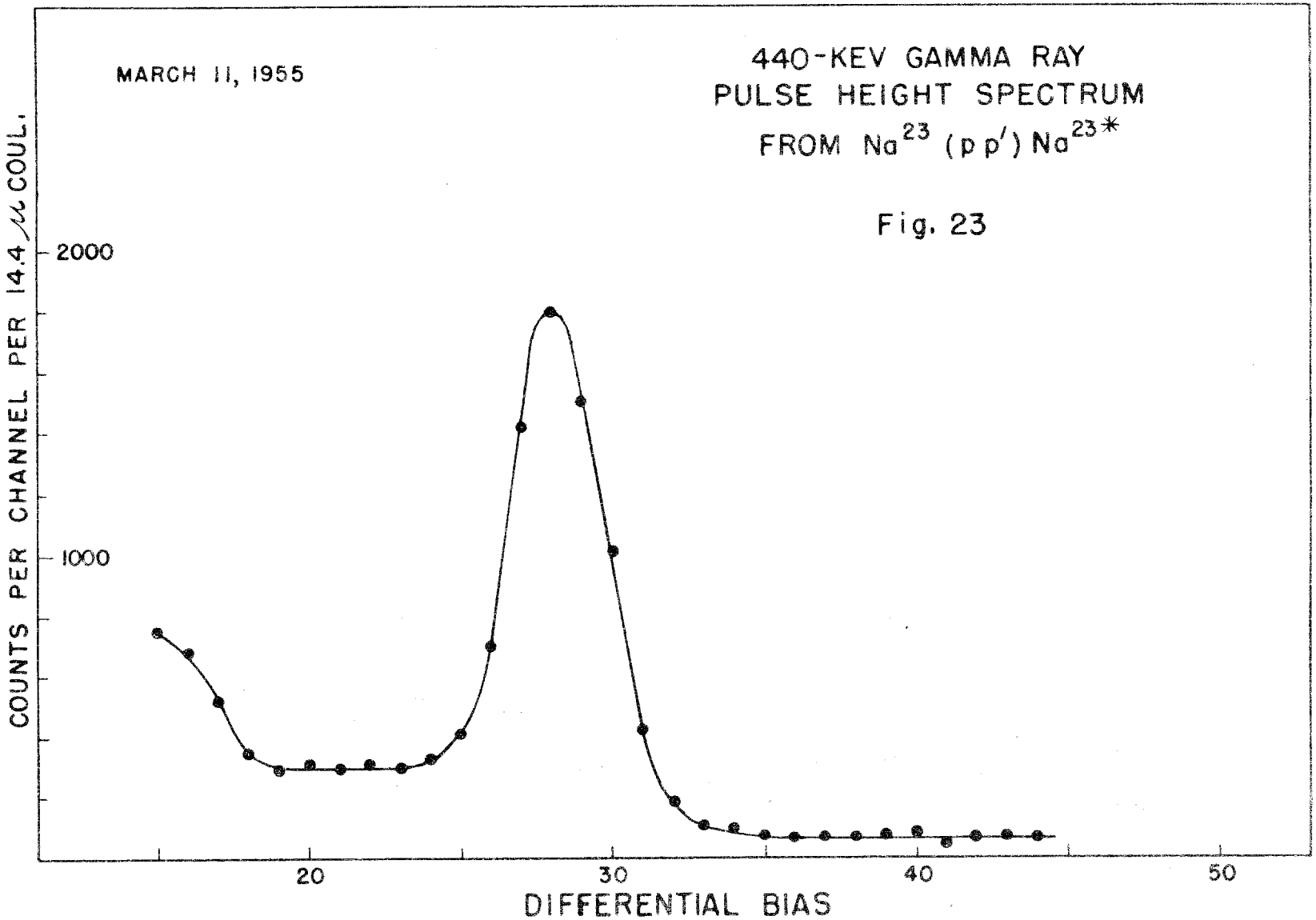

197-KEV GAMMA RAY SPECTRUM
IN 1 in. BY 1/2 in. NoI CRYSTAL
FEB. 28, 1955
COUNTS PER CHANNEL PER 14.4 μ COUL.
300
250
200
150
100
10
14
18
22
26
30
34
38
42
46
DIFFERENTIAL BIAS

Fig. 21


MARCH 11, 1955
440-KEV INTERNAL CONVERSION
ELECTRONS FROM Na^{23} (p p') Na^{23*}
Ep = 2270 KEV
Fig. 22
COUNTS ÷ 16 PER 14.4 μ COUL.
2.5
2.0
1.5
1.0
62
63
64
65
66
MILLIVOLTS (50 M.V. = 10 AMP.)


MARCH 11, 1955
440-KEV GAMMA RAY
PULSE HEIGHT SPECTRUM
FROM Na^{23} (p p′) Na^{23*}
Fig. 23
COUNTS PER CHANNEL PER 14.4 μ COUL.
2000
1000
20
30
40
50
DIFFERENTIAL BIAS

THE FOLLOWING PAPER WAS PUBLISHED IN

THE PHYSICAL REVIEW 95, 1206, (1954)

Observations on the 4.43-Mev Gamma-Rays from C^{12} †

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Abstract

A scintillation spectrometer has been used for "fore and aft" measurements to demonstrate that the 4.43-Mev gamma radiation from $Be^{9}(\alpha, n\gamma)C^{12}$ exhibits a Doppler shift as the result of motion of the emitting nucleus. This implies a lifetime for the C^{12} excited state less than 3×10^{-13} seconds. The Compton electron spectrum from a thin converter has been studied in a magnetic lens spectrometer to produce a value for the level excitation of 4.425 ± 0.020 Mev. The spectrum of internal pairs has been found to agree most closely (to 5 percent) with the (known) assignment of the radiation as electric quadrupole.

† Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

INTRODUCTION

The only gamma radiation of substantial intensity produced by the bombardment of beryllium with low-energy alpha particles is the 4.43-Mev line from $Be^9(\alpha, n\gamma)C^{12}$. The excitation energy of the emitting level is well known: 4.432 ± 0.008 Mev is the average of figures quoted by Ajzenberg and Lauritsen[1]. The angular momentum of the level is 2^+: this is the only assignment which is consistent with all of 13 angular distribution and correlation measurements quoted by the above authors as well as the observed branching ratio of the B^{12} beta decay[2]. Such a well investigated solitary gamma line constitutes a useful standard for the evaluation

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[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 24, 321 (1952).

[2] G. Vendryes, Compt. rend. 233, 391 (1951).

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of techniques of gamma-ray spectroscopy. This paper presents evidence that the line exhibits a Doppler shift due to motion of the emitting nucleus. This is followed by an energy measurement based on the spectrum of Compton electrons from a thin converter, and a multipole-order determination from the internal pair spectrum. Only the first datum provides new information about the excited nuclear state; the others may be regarded primarily as demonstrations of method.

DOPPLER SHIFT

This experiment consisted of a measurement of the energy difference of gamma-rays emitted at different directions with respect to a beam of He^+ ions from a 3-Mev electrostatic accelerator.

Such a difference is expected to be caused by the net forward motion of the emitting nuclei (imparted by the bombarding particles) unless these are stopped before the emission. The beam energy was adjusted by electrostatic analysis to give maximum gamma-ray yield from an 0.09 mg/cm^2 Be target at a strong resonance[3] at 1.90 Mev. The gamma rays were studied with a scintillation

[3] F. L. Talbott and N. P. Heydenburg, Phys. Rev. 90, 186 (1953).

spectrometer employing a cylindrical NaI(Tl) crystal (1.5" dia. x 1.5" long), a Dumont type-6292 photomultiplier, and a 10-channel pulse analyzer. The counter was placed 15 centimeters from the target, in turn at 0 degrees and at 155 degrees with respect to the beam. At each position, the "full-energy" peak produced by the 4.43-Mev line was studied. The stability of the system was checked frequently by measurements on the 2.62-Mev line from ThD.

One of three sets of spectra is shown in Figure 1. The average distance between the peaks corresponds to an energy difference of 2.1 $\pm$ 0.3 percent of the line energy, or about 93 kev. The maximum shift expected to result from center-of-mass motion, given (to first order) by

$$v/c(\cos 0^\circ - \cos 155^\circ)$$

where v/c is the velocity of the center-of-mass relative to light, is 1.88 percent. From this good agreement, it appears that the lifetime of the 4.43-Mev level is less than the stopping time for the recoiling C^{12*} in the tantalum backing, about 3×10^{-13} seconds.

The single-particle model[4] suggests a lifetime of about 1.5×10^{-13} seconds.

[4] J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley and Sons, Inc., New York, 1952)

GAMMA-RAY ENERGY.

In the following measurements, a magnetic-lens spectrometer was used in a manner described in earlier communications.[5,6]

[5] R. G. Thomas and T. Lauritsen, Phys. Rev. 88, 969 (1952); this paper will be referred to as TL.

[6] R. J. Mackin, Jr., Phys. Rev. 94, 648 (1954)

The detector of focused particles was an Amperex type-200C Geiger counter with a 1.2 mg/cm^2 mica end window. The He^+ beam energy was set at 2.2 Mev.

Figure 2 shows the spectrum of Compton electrons produced in a 19 mg/cm^2 Be target-converter. The solid curve is a theoretical spectrum expected from gamma radiation of energy 4.465 Mev. It was computed by folding the Klein-Nishina momentum distribution (TL, Eq. 4a)[5] with functions representing the spectrometer window (a gaussian of width 1.9 percent of electron momentum), energy losses in the converter, and Doppler shift distribution (computed from nuclear motion in the center-of-mass system). The calculations were simplified by approximating the last two functions by gaussians (widths 0.5 percent and 1.1 percent of electron momentum at 15.3 kilogauss-cm, respectively). The Doppler shift distribution

is expected to be uniform, since the gamma emission follows the emission of s-wave neutrons (see Reference 1), so the approximation is adequate. Account was taken of the variation of the spectrometer window with momentum setting and of the effect of the Compton recoil angle (TL, Eq. 7a), though the latter correction amounted to less than 1.5 percent over the range covered. Multiple scattering corrections were estimated to be negligible.

The energy of gamma radiation emitted at 20^{o} with respect to the beam (the spectrometer acceptance angle) is thus found to be 4.465 ± 0.020 Mev, in good agreement with other data. An earlier measurement at this laboratory[5], employing a thick converter, gave a level energy 4.443 ± 0.020 Mev.

INTERNAL PAIRS

The same target was used to investigate the positron spectrum (shown in Figure 3, solid circles). It was then backed with a thick (700 mg/cm^2) Al converter to measure the gamma-ray yield, employing the method[5,6] of comparison of experimental points with a theoretical spectrum. This yield value (uncertain to about 8 percent) was then used to normalize the theoretical positron spectra corresponding to the various multipole orders shown in Figure 3 (where E1 designates the electric dipole curve, etc.). The Born approximation spectra[7] have been corrected at the end point,[8] although the fold with the spectrometer window would largely offset this adjustment.

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[7] M. E. Rose, Phys. Rev. 76, 678 (1949); 78, 184 (1950).

[8] M. E. Rose and G. Uhlenbeck, Phys. Rev. 48, 211 (1935).

As a test of the effect of target thickness on the spectrum, the positron measurement was performed on an unbacked 0.25 mg/cm^2 Be target. The points, arbitrarily normalized to match the earlier ones at 11 kilogauss-cm, are shown as crosses in the figure. They show no discernible deviation from the others.

The ratios of the area under the theoretical curves to the area under the experimental curve (between 2 and 13 kg-cm) give a measure of agreement between data and theory. They are:

E1	1.33	$\pm$ 0.12
E2	0.95	$\pm$ 0.09
M1	0.83	$\pm$ 0.08
Others	0.78	$\pm$ 0.07

where the assigned errors include the yield uncertainty. The comparison shows to what extent assignments other than E2 may be excluded by the present data. The total internal pair coefficient (which is proportional to the area under a curve of counts/momentum) was found to be 4.0 percent greater than that predicted for E2 radiation. This is not felt to be as significant as the previous comparison because of the extra weight given the low-momentum points.

The authors are grateful to J. Thirion for considerable assistance with the first part of the experiment, and to T. Lauritsen for valuable discussions.

FIGURE CAPTIONS

Fig. 1. Pulse height spectrum in NaI(Tl) from $Be^{9}(\alpha, n\gamma)C^{12}$ in the region of the "full-energy" peak for the 4.43-Mev gamma radiation. Circles represent readings taken with counter in line with the beam; crosses correspond to 155 degrees. Peak heights have been drawn equal.

Fig. 2. Spectrum of Compton electrons produced by 4.43-Mev gamma radiation in a 19 mg/cm^2 Be converter. The solid curve represents a theoretical line shape. All points near peak correspond to same total bombardment.

Fig. 3. Positron spectrum. Internal pairs from the 4.43-Mev transition. Solid curves represent theoretical spectra normalized on measured gamma-ray yield. E1 represents electric dipole; E2, electric quadrupole; etc. Circles represent points taken with a 19 mg/cm^2 target; crosses, those from an 0.25 mg/cm^2 target (arbitrarily normalized at 11 kilogauss-cm).

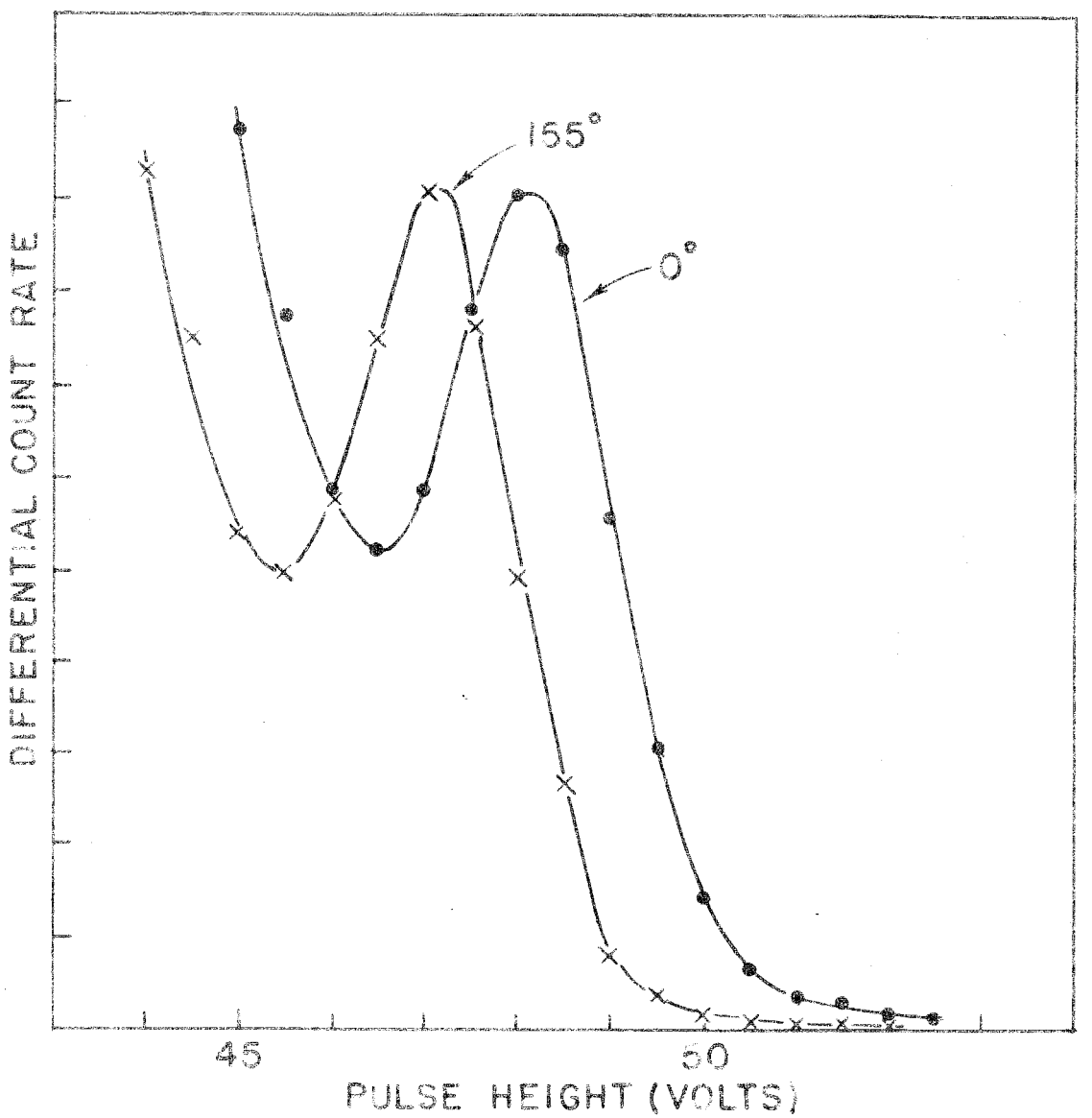

Fig. 1

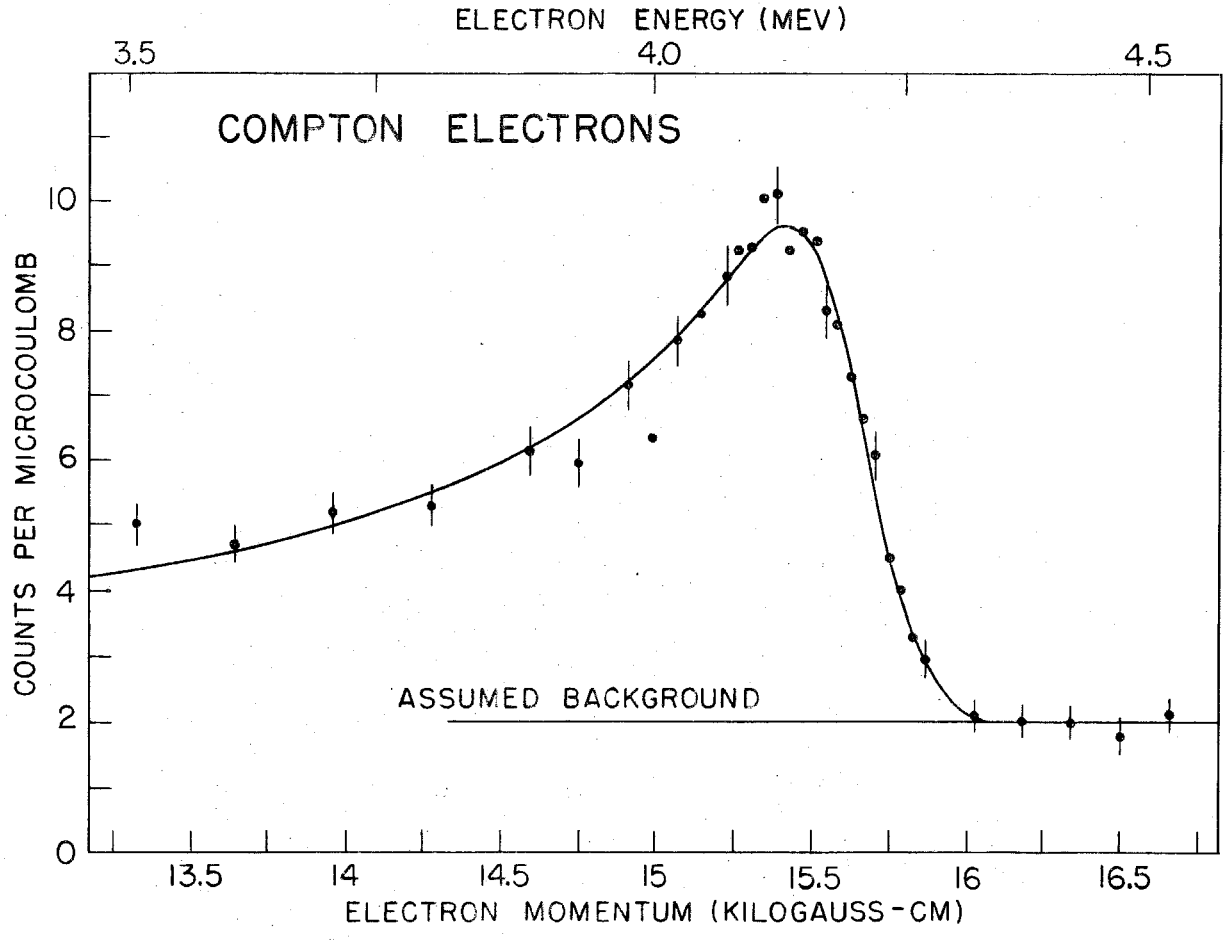
ELECTRON ENERGY (MEV)
3.5
4.0
4.5
COMPTON ELECTRONS
COUNTS PER MICROCOULOMB
0
2
4
6
8
10
ASSUMED BACKGROUND
13.5
14
14.5
15
15.5
16
16.5
ELECTRON MOMENTUM (KILOGAUSS-CM)

Fig. 2

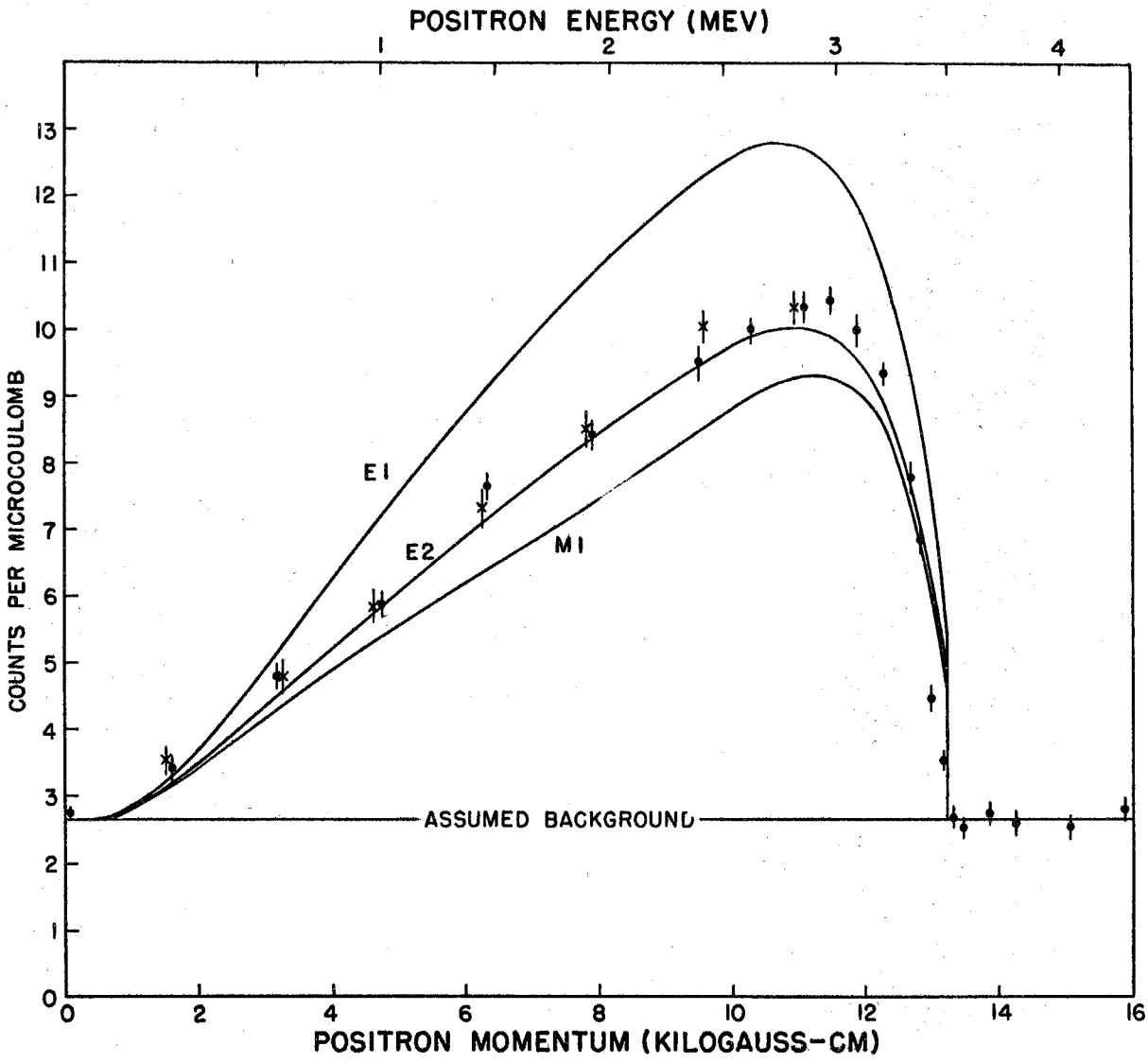
POSITRON ENERGY (MEV)
1
2
3
4
COUNTS PER MICROCOULOMB
0
1
2
3
4
5
6
7
8
9
10
11
12
13
E1
E2
M1
ASSUMED BACKGROUND
0
2
4
6
8
10
12
14
16
POSITRON MOMENTUM (KILOGAUSS-CM)

Fig. 3

THE FOLLOWING PAPER WAS PUBLISHED IN

THE PHYSICAL REVIEW 98, 43 (1955)

Gamma Rays from the Deuteron Bombardment of Carbon 13

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Pasadena, California

ABSTRACT

A magnetic lens spectrometer was used to investigate the gamma radiation produced by the deuteron bombardment of C^{13}-enriched carbon targets. A study of the Compton electron spectra from a thin Al converter at E_d = 1.42 Mev revealed the following gamma lines (energies in kev, not corrected for possible Doppler shift): 4930 $\pm$ 40, 5130 $\pm$ 30, 5730 $\pm$ 30, 6120 $\pm$ 25. A weak line at 3910 $\pm$ 50 kev was established with the spectrum from a thick Al converter. At E_d = 1.9 Mev, additional lines appeared at 6450 $\pm$ 50, 6730 $\pm$ 40, and 811 $\pm$ 3 kev. The last named was identified by photoelectrons from a thorium converter. No new lines were discovered at E_d = 2.7 Mev. The well-known 6.12 Mev-line is from C^{14*}, as are probably the 6.73- and 0.811-Mev lines. All others correspond to known levels of N^{14}.

Assisted by the joint program of the U.S. ONR and AEC.

* National Science Foundation Fellow, now at ONR, Washington 25, D.C.
** Commonwealth Fund Fellow, now at the Clarendon Laboratory, Oxford, England.

I. INTRODUCTION

Information about the levels of N^{14} below 7 Mev has been derived principally from investigations of neutron groups[1] and gamma rays[2] from $C^{13} + D^2$, and more recently from measurements on gamma rays[3] from $C^{13} + H^1$. In view of difficulties which have attended attempts to infer a consistent level scheme, it appeared worthwhile to re-examine certain controversial portions of the gamma-ray spectrum from the former reaction. Additional measurements were made at bombarding energies up to 2.7 Mev in a search for new gamma lines.

[1] R. E. Beneson, Phys. Rev. 90, 420 (1953).

[2] R. G. Thomas and T. Lauritsen, Phys. Rev. 88, 969 (1952).

[3] H. H. Woodbury, R. B. Day, and A. V. Tollestrup, Phys. Rev. 92, 1199 (1953).

II. EXPERIMENTAL PROCEDURE.

A magnetic lens spectrometer[2, 4] was used to study Compton electron spectra produced by gamma rays from $C^{13} + D^2$. A C^{13}-enriched, compressed soot target at the spectrometer focal point was bombarded by magnetically analyzed deuterons from a 3-Mev electrostatic accelerator. Because several closely-spaced gamma lines were anticipated, a 20 mg/cm^2 target was backed with an

[4] W. F. Hornyak, T. Lauritsen, and V. K. Rasmussen, Phys. Rev. 76, 731 (1949).

aluminum converter of minimum thickness consistent with adequate counting statistics, 21 mg/cm^2. Additional runs were made with a 125 mg/cm^2 converter to detect any weak lines.

The spectrometer was operated with 1.9 percent resolution (gaussian window) and an effective solid angle of 2.3 percent of a sphere. The momentum calibration for the Compton spectra was based on the ThD X-line at 9988.4 gauss-centimeters[5]. A helical baffle permitted separation of electrons and positrons. The detector of focussed electrons was a magnetically compensated transstilbene scintillation counter[6] which made possible energy discrimination

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[5] W. Brown, Phys. Rev. 83, 271 (1951).

[6] C. Wong, Phys. Rev. 95, 761 (1954).

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against scattered electrons. The customary beam currents (0.5 - 1.5 μ amp) provoked copious emission from the soot of thermal electrons or positive ions, depending on the target potential. In view of this difficulty, no attempt was made to measure beam current, and the detector count readings were normalized by means of a gamma-ray monitor. The monitor consisted of two thin-wall Geiger counters in coincidence, set along a line from the target perpendicular to the incident beam and separated from one another by 1/32-inch Al so as to record only radiation above 1 Mev. The system was thus insensitive to the delayed (annihilation) radiation from N^{13}, produced by $C^{12}(d,n)N^{13}$. Tests with natural sources confirmed that monitor and detector sensitivity were independent of the magnetic field. Measurements were made at bombarding

energies of 1.42, 1.90, and 2.7 Mev.

A special search was made for gamma lines in the region 0.5 to 1.0 Mev with a carbon foil target[7] (about 0.3 mg/cm^2), backed with a 20.2 mg/cm^2 thorium photo-electric converter.

[7] J. D. Seagrave, Phys. Rev. 85, 197 (1952), E. A. Milne, Phys. Rev. 93, 762 (1954).

III. RESULTS AND ANALYSIS

Because internal conversion pairs contributed a significant background to the Compton electron spectrum, it was necessary to measure the positron spectrum. It is expected for light nuclei (and has been roughly verified in work at this laboratory)[8] that the electron and positron internal pair spectra will be practically identical. Accordingly, the difference of electron and positron curves was regarded as consisting entirely of Compton electrons. This spectrum is shown in Fig. 1, along with the positron data.

[8] Dougherty, Hornyak, Lauritsen, and Rasmussen, Phys. Rev. 74, 712 (1948).

The spectrum above 20.5 kilogauss-centimeters (at E_d = 1.42 Mev) was analyzed by comparison with a theoretical Compton spectrum[2] which was derived from the Klein-Nishina formula. The theoretical curve included the effects of Doppler line broadening, electron energy losses in the converter, and the spectrometer

resolution window.[9] In addition to the gamma-ray energy and yield

[9] W. R. Mills, Jr. and R. J. Mackin, Jr., Phys. Rev. 95, 1206 (1954).

determination, the theoretical line shape permitted extrapolation to lower momenta and made possible separation of the contributions from succeeding gamma lines. The solid curves in Fig. 1 were produced in this way and resulted in the line energies and relative yields given in Table I.

The discrepancy between points and curve below 16 kilogauss-cm. may reflect the presence of a gamma line at 4.5 Mev reported by the Rice Institute group [10] and assigned by them to the reaction

[10] Bent, Bonner, and Sippel, Phys. Rev. 95, 649A (1954).

$C^{13}(d, \alpha)B^{11*}$. It was not found possible to accentuate this line with a thicker converter.

Analysis of the data taken at E_d = 1.9 Mev, also shown in Fig. 1, involved the same procedure. The spectrum shows clearly the existence of a line at 6.73 Mev; the deviation from the calculated line shape below 22.5 kilogauss-cm. is taken to indicate the presence of a line whose energy is 6.45 Mev. The establishment of the 6.45-Mev line was dependent upon certainty that it was not a part of the 6.1-Mev line spectrum; the end point of the latter was carefully determined at E_d = 1.4 Mev.

Fig. 2 shows a 3.91-Mev line (suspected earlier[2]) whose presence was confirmed by measurements with a 125 mg/cm^2 Al

TABLE I. SUMMARY OF RESULTS.

Gamma Ray Energy (kev)	Maximum Doppler Shift (kev)	Relative Yield (E_d = 1.42 Mev)	Assigned Level (kev)		Reaction and Reference	
3910 ± 50	19	0 0.14	N^{14}	3945 ± 15	$N^{14}(p, p')N^{14*}$	(a)
4930 ± 40	24	0.37	N^{14}	4910 ± 10	$N^{14}(p, p')N^{14*}$	(a)
5130 ± 30	25	0.34	N^{14}	5104 ± 10	$N^{14}(p, p')N^{14*}$	(a)
5730 ± 30	28	0.45	N^{14}	5687 ± 20	$C^{13}(d, n)N^{14}$(cascade)	(b)
6120 ± 25	30	1.00	C^{14}	6095 ± 15	$C^{13}(d, p)\ C^{14*}$	(c)
6450 ± 50	36		N^{14}	6440 ± 20	$C^{13}(p,)\ N^{14}$	(d)
6730 ± 40	38		C^{14}	6723 ± 15	$C^{13}(d, p)\ C^{14*}$	(e)
729 ± 3	4		N^{14}	5810 ± 20	$C^{13}(p,)\ N^{14}$	(d)
811 ± 3	4.5		C^{14}	6894 ± 15	$C^{13}(d, p)\ C^{14*}$	(e)
869 ± 3	5		O^{17}	870.5 ± 2	$O^{16}(d, p)\ O^{17*}$	(b)

(a) Bockelman, Browne, Buechner, and Sperduto, Phys. Rev. 92, 665 (1953).

(b) Reference 2.

(c) Sperduto, Holland, Van Patter, and Buechner, Phys. Rev. 80, 769 (1950).

(d) Reference 3.

(e) Sperduto, Buechner, Bockelman, and Browne, MIT Progress Report, May (1954).

converter. The end point of the 3.4-Mev line immediately below was fixed by comparison with a theoretical line shape.

The photoelectron spectrum between 0.5 and 1.0 Mev (taken at E_d = 2.6 Mev) appears in Fig. 3. Three gamma lines at 729, 811, and 869 kev are indicated therein by their K-photopeaks. The expected L-peak of the 729-kev line is shown as a dashed curve. Correction for electron energy loss in the thorium converter[4] was checked by study of the Cs^{137} gamma rays at 661.60 $\pm$ 0.14 kev[11] with the same converter. The 811-kev line was found to have an apparent threshold near E_d = 1.9 Mev.

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[11] Muller, Hoyt, Klein, and Du Mond, Phys. Rev. 88, 775 (1952).

All of the line energies are given in Table I, where also appear the relative yields (at E_d = 1.45 Mev) and the maximum possible Doppler shifts produced by center-of-mass motion. The actual line-shifts may differ from these if the distribution of the motion of the emitting nuclei in the center-of-mass system is asymmetric about 90^o, as in a stripping reaction, or if the mean life for emission is comparable with the nuclear stopping time. Other columns in the table suggest the most likely source of each line and give current values for the excitation energies of the assigned levels as reported by other investigators.

Measurements made at E_d = 2.7 Mev revealed no further lines above 16 kilogauss-cm., although such lines are reported at E_d = 4 Mev.[10]

IV. DISCUSSION.

The 869-kev line at the end of Table I is attributed to the reaction $O^{16}(dp)O^{17*}$, presumably produced by bombardment of oxygen in the surface of the thorium converter. The line did not appear when a copper foil was interposed between target and converter. The line energy confirms the value given by Thomas and Lauritsen.[2]

The other assignments in the table are based on energy agreement with known levels together with threshold considerations. In particular, the yield of the 6.73-Mev line at E_d = 1.9 Mev is believed to be too great to permit assignment to the 6.76-Mev level of B^{11}, since the bombarding energy is less than a hundred kilovolts above threshold for the production of this level.

The assignment of the 3.91-Mev line to the 3.95-Mev level of N^{14} is consistent with the value given by Woodbury, et al.[3] for the branching ratio of that level. The assignment of the line as a cascade from the 6.23-Mev level to the 2.31-Mev level would appear to be excluded on the basis of the observation[3] that the former level decays only to the ground state.

The existence of a 5.82-Mev level in N^{14} is manifested only in the (p,γ) data[3] and in the assignment of the 729 kev-line. For this assignment, a best level excitation value is 5.104 + 0.729 = 5.833 $\pm$ 0.013 Mev. Our failure to observe a line of this energy sets its intensity as less than 0.2 that of the 5.73-Mev line and suggests a cascade branching ratio greater than earlier supposed.[3]

From observations on the gamma rays[3] in $C^{13}(p,\gamma)N^{14}$ and elastically scattered protons[12] in $C^{13}(p, p)C^{13}$, it has been reasonably well established that the 8.06, 8.70 and 9.17-Mev levels in N^{14} have spins and parities 1^-, 0^-, and 2^- respectively. Because of the large γ-width for the ground state radiation from the 8.06-Mev level, and the absence of a transition to the 2.3-Mev level ($J = 0^+$, $T = 1$), it has been suggested[13] that the 8.06-Mev state has $T = 1$. Similarly, the 8.70-Mev level has been assigned $T = 1$ on the basis of the large ground state γ-ray width.[14]

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[12] E. A. Milne, Phys. Rev. 93, 762 (1954).

[13] A. B. Clegg and D. H. Wilkinson, Phil. Mag. 44, 1269 (1953).

[14] D. H. Wilkinson, Phil. Mag. 44, 450 (1953).

Calculation shows that the analogue states of the 6.1, 6.7, and 6.9-Mev levels in C^{14} should lie near 8.4, 9.0, and 9.2 Mev in N^{14}. It has been suggested, on the basis of the internal pair spectrum,[2] that the radiation from the 6.1-Mev level in C^{14} to the ground state is E1 (M1 and E2 are not excluded), implying $J = 1^-$ for this state. Thus, one might identify the 6.1-Mev level in C^{14} as the analogue of the 8.06-Mev level in N^{14}. The absence of a ground state transition from the 6.9-Mev state in C^{14} suggests $J = 0$ for it, and a correspondence with the 8.70-Mev level in N^{14}. The apparent absence of levels between 8.06 and 8.70 Mev in N^{14} (except one with $J = 0$) then suggests that the analogues of the upper two C^{14} levels are inverted. A possible choice for the analogue of the 6.73-Mev level is the level at 9.17 Mev whose large ground state gamma-ray width is characteristic of electric dipole radiation, which would

be inhibited if that level had T = 0. Finally, it must be remembered that the analogue level may thus far be unobserved. If its reduced proton width is a large fraction of the so-called sum rule limit, the observed width may be of the order of Mev, and the level may be lost in the background.

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FIGURE CAPTIONS

Fig. 1. Compton electrons from 20 mg/cm^2 C plus 21 mg/cm^2 Al converter.

Fig. 2. Compton electrons from 20 mg/cm^2 C plus 125 mg/cm^2 Al converter.

Fig. 3. Spectrum of photolines from 20.2 mg/cm^2 Th converter.

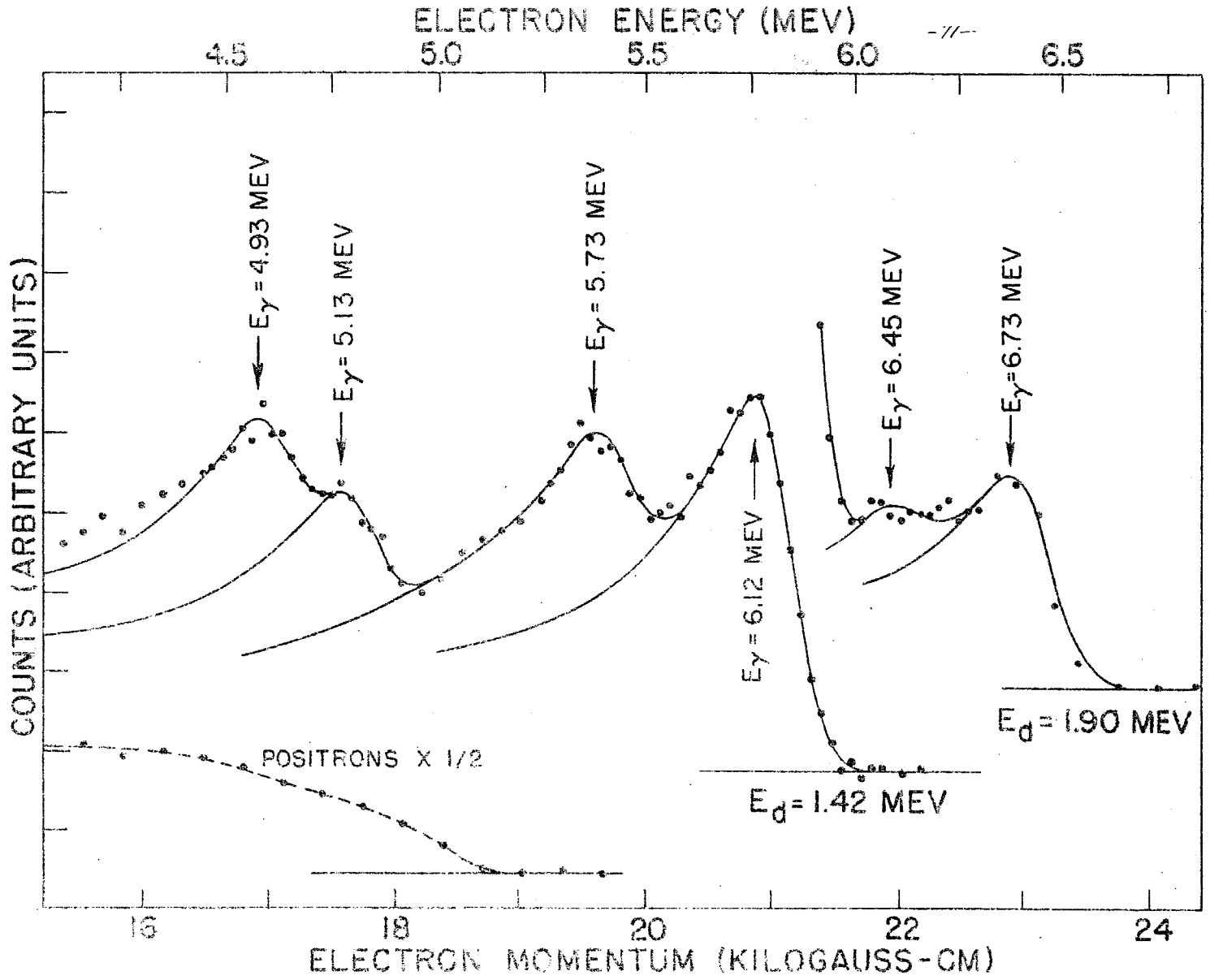
ELECTRON ENERGY (MEV)
4.5
5.0
5.5
6.0
6.5
COUNTS (ARBITRARY UNITS)
E_γ = 4.93 MEV
E_γ = 5.13 MEV
E_γ = 5.73 MEV
E_γ = 6.12 MEV
E_γ = 6.45 MEV
E_γ = 6.73 MEV
POSITRONS X 1/2
E_d = 1.42 MEV
E_d = 1.90 MEV
16
18
20
22
24
ELECTRON MOMENTUM (KILOGAUSS-CM)

FIG. 1

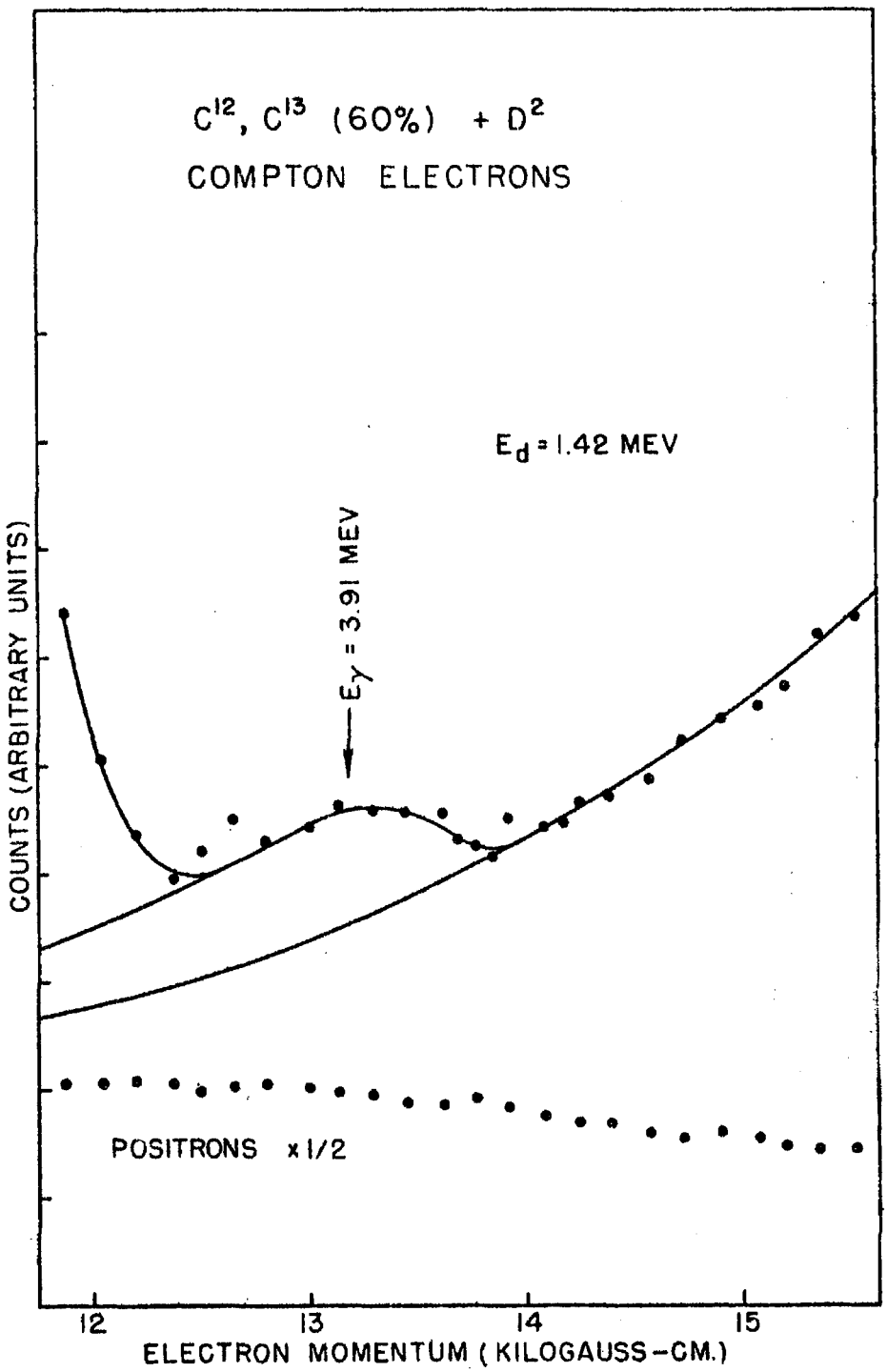
C^{12}, C^{13} (60%) + D^2
COMPTON ELECTRONS
E_d = 1.42 MEV
E_γ = 3.91 MEV
COUNTS (ARBITRARY UNITS)
POSITRONS x 1/2
12
13
14
15
ELECTRON MOMENTUM (KILOGAUSS-CM.)

FIG. 2

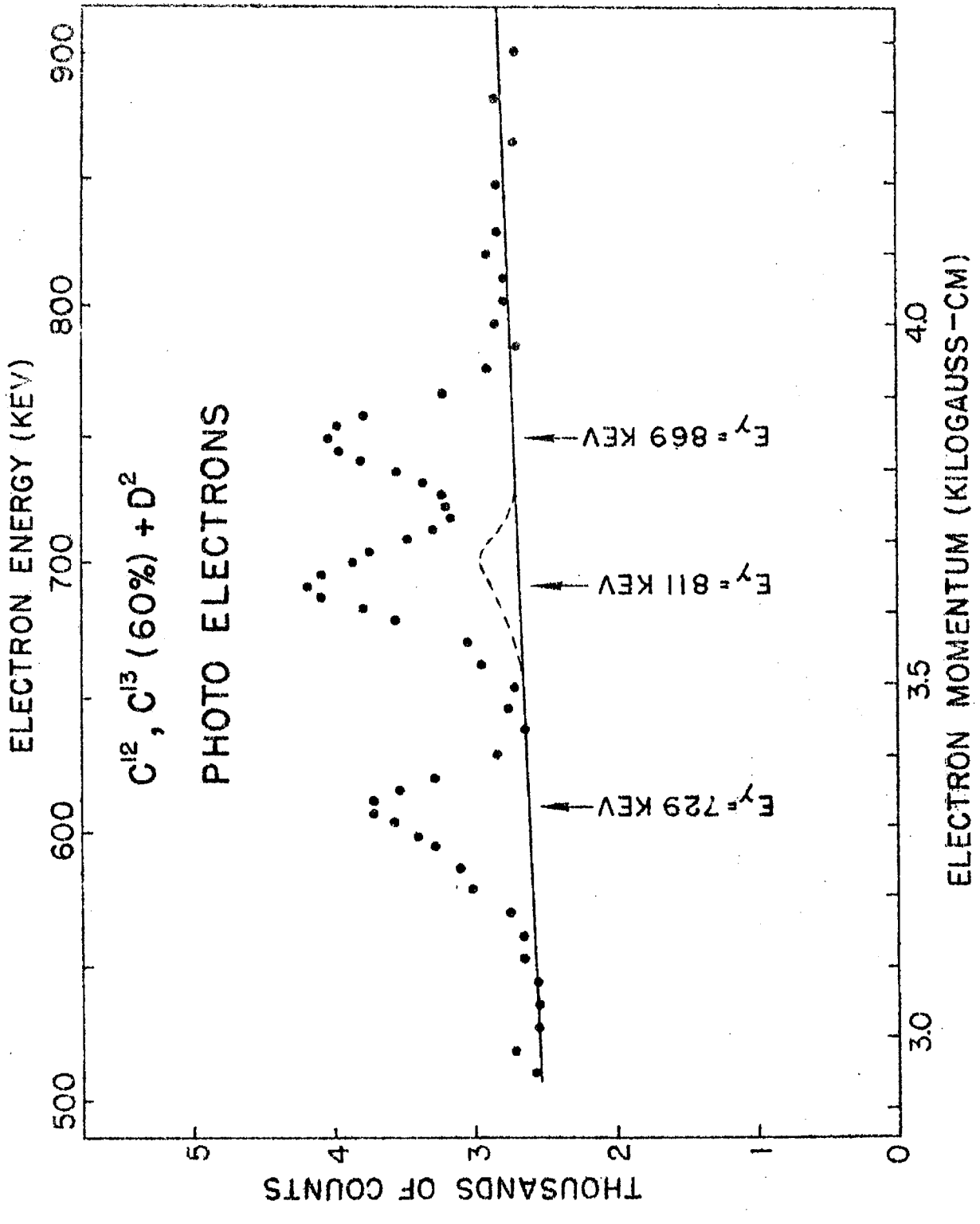
ELECTRON ENERGY (KEV)
500
600
700
800
900
THOUSANDS OF COUNTS
0
1
2
3
4
5
ELECTRON MOMENTUM (KILOGAUSS-CM)
3.0
3.5
4.0
C^{12}, C^{13} (60%) + D^2
PHOTO ELECTRONS
E_γ = 869 KEV
E_γ = 811 KEV
E_γ = 729 KEV

Fig. 3