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PROTON BREMSSTRAHLUNG AT 140 MEV.

by

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II

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ABSTRACT

The high energy gamma rays arising from 140 Mev proton bombardment of several elements has been studied using a scintillation counter telescope to detect secondary electrons. The angular distribution is consistent with an approximately isotropic distribution in the center of mass system if we assume the bremsstrahlung to come from p-n collisions inside the nucleus. This is in disagreement with a phenomenological potential treatment of the p-n force or the scalar meson theory.

The form of the spectrum is found to be consistent with the $d\nu/\nu$ shape, and the dependence on Z much as would be expected from an opaque nucleus with only the neutrons contributing to the bremsstrahlung.

* This work was assisted by the Atomic Energy Commission.

** Now at Stanford University, Palo Alto, California.

INTRODUCTION

High energy radiation has been detected from cyclotron targets bombarded with protons and deuterons.[1] The energy of the bombarding particle was, in most cases, high enough so that most of the radiation can be attributed to the decay of neutral mesons; only in the case of bombardment by 190 Mev deuterons is this explanation implausible.

It is of interest to investigate the γ radiation directly accompanying nuclear events in the target; this will result from the deceleration of the proton in a field of force, in a similar manner to the well-known electron bremsstrahlung; but in the present case, the force is the nuclear force between the neutron and the proton rather than the coulomb force. Thus a study of the γ radiation should throw light on the character of the p-n force. The radiation is expected to arise only from p-n collisions and not from p-p collisions: calculations have been made for p-n collisions by Ashkin and Marshak[2] and by Simon.[3] Variations might be expected in the angular distribution and spectral shape of the γ rays according to the form of nuclear interaction.

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1 W. E. Bjorklund, R. Crandall, B. J. Moyer, H. F. York, Phys. Rev. 77, 213, 1950.

2 J. Ashkin and R. E. Marshak, Phys. Rev. 75, 58, 1949.

3 A. Simon, Phys. Rev. 79, 573, 1950.

EXPERIMENTAL

A target was set up at 43" radius in the Rochester cyclotron, corresponding to a maximum energy of 145 Mev, in order to be below the threshold for neutral and charged π meson production.[4] The energy is 5 Mev above the threshold for neutral meson production in a heavy element, such as uranium, but the contribution of the γ rays from decay of the neutral particles is expected to be less than 10 % in this case, and for the lighter elements even a big impurity of the heavy elements could not be a cause of the radiation.

Fig. 1 is a plan view of the apparatus; a collimator in the fringing field removes all charged particles, leaving only γ rays and neutrons, to enter the counters. The γ rays are converted on a 0.1 mm Pb sheet placed in front of 4 scintillation crystals (anthracene or stilbene) in coincidence. Absorbers may be placed in front of the collimator to analyse the primary radiation, and absorbers between counters 3 and 4 analyse the range of the secondary particles from the radiator.

The four counters are connected in pairs to two fast (10^{-8} sec) coincidence circuits, modified from a design of Garwin.[5] The outputs of the two coincidence circuits are taken to a slow (2×10^{-7} sec) coincidence circuit.

The crystals are of different sizes, as shown in Fig. 2. The first is thin to avoid production of high energy protons or electrons from neutrons or γ rays in the crystal, and the other crystals

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4 W. H. Barkas, Phys. Rev. 75, 1109, 1949

5 R. L. Garwin, Rev. Sci. Inst., 1950

are thicker; the electron energy loss in the thick crystals is greater, so that the threshold bias may be increased with a reduction of background. The size of the other crystals is increased so that electrons scattered away from the forward direction by multiple Coulomb scattering will still reach the crystals. With no absorber between crystal 3 and crystal 4, they are placed close together in order to avoid scattering losses; when absorber is used, the scattering losses for the electrons which can still penetrate the absorber are less and crystal 4 is removed sufficiently far away to allow room for the absorber.

MONITORS

Two monitors have been used during this experiment. One, axial monitor,[6] is on the axis of the magnet and above the magnet yoke and is an anthracene scintillation counter biassed at 2 Mev; it counts at approximately the same rate at whatever azimuth a target is exposed to the beam. The second, neutron monitor,[6] is a sodium iodide crystal biased at about 5-10 Mev placed in the forward direction from the target and is shielded from scattered protons by 10 cms. of copper. This counts neutrons which are produced in the target and has only a 20 % background from other parts of the cyclotron. During most of the operating runs, the neutron monitor is used to normalize the counts since if the beam conditions change so that the fraction of the beam which hits the target changes, the number of neutrons is expected to

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6 The axial monitor was set up and maintained by J. Norton, the neutron by J. Ferry.

be proportional to the number of γ rays. The neutron monitor is more stable over short periods than the axial monitor. The axial monitor is more permanent, however, and is used to give an indication of absolute beam intensities and for comparison of runs.

RESULTS

A. Proof of Photon Identity

The radiation from several targets has been examined; the absorption curves for radiation from a 1" Beryllium target has been examined in the greatest detail. Fig. (3) shows a log plot of the coincidence counting rate against primary lead absorber showing that most of the counting rate is due to a radiation heavily absorbable in lead. If we assume that the residual effect is due to fast neutrons converting in the first crystal, or the lead radiator, the radiation can be split into the two components shown; the neutron absorption cross section of lead varies little up to 100 Mev, so this separation is likely to be fairly accurate. The γ ray energy found in this way agrees with an energy of 30-60 Mev.

The low absorption in aluminum of the primary radiation confirms the view that it is not merely an absorption of charged particles taking place.

Table I shows the variation of the counting rate for change of radiator with and without 1/2 " of lead primary absorber. The difference between these two is a measure of the contribution due to γ rays. The interpretation of these is difficult; large thicknesses of lead radiator will scatter and absorb the low energy electrons produced, so

Table I

Radiator Change

Radiator	Absorber out	Absorber in
None	.16 ± .01	0.08 ± .004
.5 mm Pb	0.55 ± .1	0.25 ± 0.1
1 mm Pb	1.000	0.34 ± .03
5 mm Pb	1.6 ± 0.2	
1 cm Pb	0.8 ± 0.2	

that the increase of intensity with radiation thickness is not so great as with higher energy γ rays.[7] However, it is not in disagreement with the calculated efficiency for the γ-ray spectra expected. A thickness of 1 mm. was chosen for most experiments in order that the low energy electrons should not be attenuated by scattering. It is worth noting, that the counts without the radiator in position are not heavily reduced by a primary lead absorber and are therefore mainly due to neutrons. Using a radiator equivalent to the first crystal indicates that most of this background comes from events in the first crystal, but a little may come down the collimator (presumably caused by neutrons hitting the sides). A check has been made with an anti-coincidence crystal preceding the telescope to cut out any background from charged particles coming down the collimator. No difference was observed.

Chance coincidence counts are less than 1 per cent of the total ray count except when large thicknesses of secondary absorber are used. The main contribution to this chance coincidence rate comes from genuine events in counters 1, 2 and 3 in chance coincidence with an event in counter 4, and genuine events in counters 2, 3 and 4 in coincidence with an event in counter 1. These are assessed by inserting a delay of 5×10^{-8} sec. in counter 4 and counter 1 channels in turn. The rate caused by chance coincidences between the doubles in channels 1-3 and the doubles in channels 2 - 4 is calculated from the observed doubles rates. The

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[7] J. S. Steinberger, W. K. H. Panofsky and J. Steller, Phys. Rev. 78, 802, (1950)

delay of 5×10^{-8} sec. is the period of the cyclotron oscillator, and therefore of a beam fine structure.[8] A drop of 30 % in chance coincidence rate is observable by using a delay which is not a multiple of the oscillator period.

Approximately 0.1 % of the counts come from other parts of the cyclotron than the target.

In order to check that each counter was counting the electrons, a plot was made of counting rate as a function of pulse height for the various events in the telescope. Fig. 4 shows a curve of (i) the single counting rate in one crystal (ii) quadruples rate against pulse height and also for comparison a curve taken for the quadruples rate (iii) with recoil protons from fast neutrons. The counters are biassed to accept virtually all the fast electrons. Some of the γ ray events give both an electron and a positron through a crystal, which spreads the distribution out.

B. Secondary Electron Spectrum

Fig. 5 shows the secondary electron spectrum obtained from Be and C targets at 90° to the proton beam, the energies being inferred from the absorption in carbon. The absorption in carbon and in the hydrocarbon crystals is obtained from the calculations of Halpern and

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8 I am indebted to Mr. H. Reynolds for communicating to me the importance of this effect in measuring chance coincidences and for instructing me generally in the uses of this type of equipment.

Hall.[9] The doubt which some authors have cast on the accuracy of these calculations is attributable only to confusing observable ionization with energy loss.[10] In this case the energy loss is what matters. The accuracy has been checked by experiment[10].

These spectra are corrected for the neutron component at each point and for the background which is present in the absence of a radiator. These corrections do not alter the shape of the curve as they happen to be proportional to the electron counting rate (to within statistical error) except at the higher energies (70 Mev). Here the corrections due to chance coincidences become appreciable also, and the correction is approximately 30 % of the observed counting rate. The statistical errors shown are standard deviations computed including allowance for the corrections.

Table II gives the angular ratio, 90° to 180° for all eletrons above 20 Mev for several target elements. An angular ratio 90° to 30° is also given for beryllium: this is not very accurate because of the large neutron count found in the forward direction.

RADIATIVE AND SCATTERING CORRECTIONS

Corrections to these data must be applied for electrons which are lost from the telescope due to scattering and radiation. For low energy electrons, the scattering losses in the geometry used are less than 3 % so long as the electron emerges from the third crystal with

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9 O. Halpern and H. Hall, Phys. Rev. 73, 477, 1950.

10 H. Messel and D. M. Ritson, Phil. Mag. 41, 129, 1950.

Table II

Angular Ratio $\frac{90^\circ}{180^\circ}$

Target	Measured	Corrected for Aberration*	Corrected for Doppler Shift and Aberration*
Be	3.0 ± 0.2	1.9 ± 0.2	1.55 ± 0.4
C	2.9 ± 0.3		1.5 ± 0.5
Al	2.8 ± 0.3		1.45 ± 0.5
Cu	3.4 ± 0.3		1.8 ± 0.5
Ag	3.4 ± 0.3		1.8 ± 0.5
W	2.9 ± 0.3		1.5 ± 0.5

* The corrections for aberration assume an n-p collision, and those for Doppler shift take account of the efficiency of the telescope as a function of energy. A spectrum of the shape $d\nu/\nu$ is assumed here, but there is only 5% difference for a $\nu d\nu$ type spectrum.

Angular Ratio for Be	Measured	Corrected for Aberration	Corrected for Doppler Shift and Aberration
$30^\circ/90^\circ$	2.5 ± 1	1.5 ± 0.8	1.0 ± 0.6
$45^\circ/90^\circ$	2.0 ± 0.4	1.3 ± 0.3	1.0 ± 0.4

Ratio of neutron counts at different angles from Be target (due to 80 Mev recoil protons in the forward direction)

$0^\circ/30^\circ$	> 2
$30^\circ/45^\circ$	2.1 ± .1
$45^\circ/90^\circ$	50 ± 20
$90^\circ/180^\circ$	> 2

at least 4 Mev energy. Since a 1 Mev pulse is needed in the fourth crystal, this might introduce a spread in the energy scale of 3 Mev; a spread of 3 Mev is also introduced by radiation and absorption in the radiator, making a total of 6 Mev.

At the higher energies, large thicknesses of absorber are used and appreciable scattering can occur. This has been calculated using the method of E. J. Williams[11], using the Born approximation for the small angle cut-off. Since we are interested only in small scattering angles, the distribution can be taken as Gaussian and the large angle cut off chosen accordingly. Such a calculation of mean square scattering angle has been checked for electrons of 17 Mev and 115 Mev[12]. The detailed multiple scattering calculations including energy loss arise from a simple integration following a method developed by Ritson[13]. It is found that approximately 50 per cent of the 70 Mev electrons can escape from the telescope when a 70 Mev absorber is in position but only 10 per cent of the 80 Mev electrons. These values are considerably less at smaller absorber thicknesses and energies. Thus any electron which has sufficient energy to lose 2 Mev in the last crystal, has only a 5 per cent chance of being scattered out. Radiative losses can be important even in carbon, for we have here nearly half a radiation length for

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[11] E. J. Williams, Phys. Rev. 58, 292, (1940).

[12] L. Voyvodic and E. Pickup, Phys. Rev. 81, 890, (1951). D. R. Corson, Phys. Rev. 80, 303, (1950).

[13] D. M. Ritson, Thesis, Oxford, (1948).

absorbing 70 Mev electrons. Since the electrons are losing energy and the cross section for bremsstrahlung falls, only about 20 % of the 70 Mev electrons are lost from this cause, and these appear as lower energy electrons. Thus the experimental curves may be corrected as shown.

The mean square angle of pair production is calculated from the formulae of Stearns[14] and it is found that the pair products are always within the angle of the telescope.

There is a possibility that an electron which radiates in the first few cms. of absorber might produce γ rays which later count in crystal 4. If the corresponding positron was counted in crystals 1, 2 and 3, it could simulate 70 Mev γ rays. Calculations show that this could account for but 10 % of the high energy electrons. A correction is made for this 10 % in making the correction for radiation and scattering above.

SUMMARY OF CORRECTIONS

The corrections to the secondary electron spectrum are shown as corrections to the theoretically expected spectra. These corrections are unlikely to be in error by more than 25 %. In view of the shape of the curve, this will not affect the conclusions appreciably.

PHOTON YIELDS

The total counting rate for secondary electrons above 20 Mev, from radiation at 90° to the incident proton beam, has been measured

14 M. Stearns, Phys. Rev. 76, 836, 1949.

for several targets and for several maximum proton energies. The targets had approximately equal proton energy loss if recirculation is neglected. The counts were normalized to the axial monitor, which was later calibrated, as a function of target radius, at a time when the cyclotron beam was steady, by moving the targets successively into the beam with a flip coil.

We make the following assumptions. (A) the circulating beam is constant with radius; (B) the recirculation of protons through a target can be calculated from the multiple scattering in the target[15] (C) the target alignment is sufficiently accurate that all protons go through all the target. Assumption (A) might be in error by a factor 2 for a beam energy change from 143 to 240 Mev, though there is no evidence for such a change. (B) is probably accurate to 10 % at 143 Mev, where the vertical oscillation period is large. The accuracy at 240 Mev is likely to be less, and lead to an overestimate of the beam current for the lower targets. The relative accuracy between 100 and 143 Mev is likely to be higher. Assumption (C) has been studied with auxiliary measurements and it is found that $1/10^{\circ}$ change in target alignment can be detected for a 1" copper target. The accuracy of alignment is about 2° and the values in the table could be 20 % higher for the lower when thick targets are used.

The scattering formula used by Knox is not valid for our proton energies. We have taken the appropriate formula of the Williams

15 W.J. Knox, UCRL 883, 1950.

Table III

Relative Yield of Photons. at 90° Lab system.

Target	Max. proton Energy	Recirculation Correction	Yield/neutron	$A^{-1/3}$
Be	100		0.50 ± .02	
Be	120		0.70 ± .02	
Be	143	1.55	1.0	1.0
Be	240		13.5	
C	143	1.6	0.9	0.9
C	240		14	
Al	143	1.35	0.75	0.7
Al	240		11.5	
Cu	143	1.26	0.63	0.5
Cu	240		4.5	
Ag	143	1.13	0.38	0.42
Ag	240		5.8	
W	143	1.08	0.3	0.35
W	240		4.2	

The statistical errors in the counts are small compared with the other errors mentioned in the text.

theory. The discrepancy Knox finds between theory and experiment is probably due to working at a radius where the vertical oscillation period is small. Table III indicates the results. The sharp increase in yield in going from 140 to 240 Mev is presumably due to   rays from π^0 decay. Approximately the same dependence upon Z is found for the π^0 rays as for the bremsstrahlung, although the recirculation correction is likely to be in error here.

The absolute cross section has been estimated by the production of   from polyethylene foils placed on either side of a target. The total cross section for production of γ rays above 20 Mev from 140 Mev protons on Be is 1.3×10^{-29} cm.^{2} to within a factor of 3, or 2.5×10^{-30} cm.^{2}/ neutron in the nucleus. This is a little over $e^2/\hbar c$ times the neutron-proton scattering cross section at 140 Mev which is in agreement with the theoretical order of magnitude.

INTERPRETATIONS

A theoretical study of the radiation to be expected from high energy nucleon-nucleon collisions has been made by Ashkin and Marshak[2] using a phenomenological potential, and by Simon[3] using pseudo-scalar and scalar meson field theory. The field-theoretic calculation indicates that the terms due to the interaction of the electromagnetic field with the meson are expected to be three times as large as the potential terms, so that the phenomenological treatment is expected to be in error if mesons play a part in nuclear forces.

These authors assumed that the bremsstrahlung is due to proton-nucleon scattering with both final nucleons remaining in a free state. It appears, however, that a larger effect is to be expected from the reaction:[16]

The cross section for the inverse process has been calculated by Marshall and Guth[17] and by Schiff[18] with similar results. By using the principle of detailed balancing, the cross section might be expected to be 6×10^{-30} cm.^{2} at 140 Mev, as compared with 4×10^{-30} cm.^{2} for bremsstrahlung. The effect would approximately vary inversely as the energy.

A summary of these predictions is given in Table IV: the angular distribution expected is of the form $a + b \sin^2 \theta$. The energy spectrum for the bremsstrahlung theories will either be of the form $(E_0/2 - h\nu)^{1/2} d\nu/\nu$ or $(E_0/2 - h\nu)^{1/2} \nu d\nu$ in the c. m. system where E_0 is the incident proton energy in the laboratory system. The latter form arises from the important role played by negative energy states in the pseudoscalar meson theory.

These theoretical calculations apply only to proton-neutron collisions. To apply them to proton-nucleus collisions, we regard the nucleus as composed of independent nucleons with an energy distribution given by the Fermi gas model (E^2 dE up to 25 Mev). The first proton-

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16 I am indebted to Dr. Marshak for mentioning this possibility and to Mr. N. Francis for assistance in calculating the magnitude of the effect.

17 J. F. Marshall and E. Guth, Phys. Rev. 78, 738, 1950.

18 L. Schiff, Phys Rev. 78, 733, 1950.

neutron colli ion will give the energetic radiation; for the second collision, th nucleon energies will be reduced and the energies of the γ rays will e correspondingly lower. The second collision has here been ignored; many of the nucleons whould escape from the nucleus for low Z nuclei, so if the effect is important, it will be so only for high Z.

The e are two important effects of the nuclear motion; the first is the ffect on the angle of emission of the γ ray, and the second is the change of energy in the proton-neutron system and therefore a change in cross section and γ ray energies. So long as only the first nuc ear collision need be considered, the nuclear motion cannot alter he angle of γ emission by more than 20° for a nucleon of 140 Mev hi ting a Fermi gas of nucleons. The second scattering may also occu and the angle may be as large as 90° although low energy radiation wil be produced usually.

The effect of angle is expected to be similar, if both primary and secondary effects are included, to the effect on the angular distribution of neu rons from protons on various elements.[19] These indicate that the angu ar spread is greater than 20° and therefore there may be appreciable s condary scattering.

It seems probable also that the interaction between the neutron and the proto in the final state will be perturbed by the presence of other nucl ons in the nucleus so that the reaction $p + n \rightarrow D + \gamma$

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19 R. D. Mil er, D. C. Sewell and R. W. Wright, Phys. Rev. 81, 374, 1951; cf. also the eutron background found in Table III of the present expiment.

Table IV

Summary of Theoretical Predictions for bremsstrahlung in p-n collisions

Theory	Potential	I_{90}/I_0 c.m. system	Proton Energy	Energy Dependence	Form of Spectrum
Phenomenological	1 V(r)	7	250	E_0^{-1}	$\frac{d\nu}{\nu}$
	$P_M V^*(r)$	25	250		
	1/2 $(1 + P_M)V(r)$	15	250		
Scalar Meson Theory		230	180	E_0^{-1}	$\frac{d\nu}{\nu}$
Pseudoscalar Theory		0.8	180	E_0^{2}	$\nu d\nu$
$p + n \rightarrow \gamma + D$		5^{**}	140	E_0^{-1}	70 Mev line

* P_M is Majorana operator

** Depends upon the nuclear forces; see Marshall and Guth loc. cit.

will not take place. One would also expect fewer collisions with emission of any γ ray with an energy within 10 Mev of the maximum. The extra lightly bound neutron in Be^9 as compared with C^{12} might be expected to lead to a large high energy component of the secondary electron distribution. However, there is no appreciable difference between Be^9 and C^{12} in this respect. The effect of the nuclear motion on the energies of the gamma rays assumes a knowledge of the energy dependence of the cross section.

The effect of the nuclear motion on the energies of the gamma rays has been calculated by J. B. French and P. B. Daitch, assuming a Fermi gas of nucleons in the nucleus. I am deeply grateful to Dr. French and Mr. Daitch for performing these calculations and allowing me to quote their results.

The calculation has been carried out for the two assumed spectra for the neutron-proton interactions, one $\left(\frac{E_0}{2}-h\nu\right)^{1/2}\frac{d\nu}{\nu}$ and the other $\left(\frac{E_0}{2}-h\nu\right)^{1/2}\nu\,d\nu$. With the former is assumed a dependence on energy of E_0^{-1} and with the latter a dependence on energy of E_0^{2} corresponding to the predictions of Simon for scalar or phenomenological and pseudoscalar theories respectively. The calculations were also made for two possible assumptions about the angular distribution of the reaction in the neutron-proton system; one that it is isotropic, and the other that it is $\cos^2\theta$; the results are shown in Figure 6. Combinations of the curves can be used to predict the results for a distribution $A+B\cos^2\theta$.

If we thus compute the curves for I_{180} for the $\sin^2\theta$ case, we find that the intensity is about $I_{\frac{90}{40}}$ for a completely $\sin^2\theta$ distribution, compared with $I_{90/2}$ for an isotropic distribution. This confirms the contention that the angular distribution should not be markedly affected by nuclear motions.

The reduction of the intensity by the factor 2 in the 180° direction for isotropic emission in the c.m. system is the Doppler Shift and aberration correction already inserted in Table II.

It is possible to compute the secondary electron spectra theoretically expected from a gamma ray spectrum. This is plotted for comparison with the experimental curves in Figure 5. It is clear that the spectrum $(E/_2 - h\nu)^{1/2}\nu d\nu$ is not consistent with the data whereas the spectrum $(E/_2 - h\nu)^{1/2}\frac{d\nu}{\nu}$ fits well.

There is a marked difference at the low energy end of the spectrum between the radiation from Be^9 and C^{12} or Cu. This presumably arises from a nuclear γ ray of the order of 15 Mev. Thus the portion of the curves below 20 Mev. has been disregarded for angular distribution comparisons for yield curves and for analysis of the spectrum.

If we assume that the rest of the spectrum is due to bremsstrahlung, a fit can best be obtained to the theory by assuming a $d\nu/_\nu$ type spectrum. a $\nu d\nu$ type spectrum could only be made if it were true that secondary nucleon collisions are of importance. This might be true for the heavier elements.

The angular distribution given in Table II shows that the distribution in the c.m. system is nearly isotropic -- as predicted by pseudoscalar theory. If the secondary nuclear collisions are important, an intrinsic $\sin^2\theta$ distribution might simulate an isotropic distribution for the low energy gamma rays where the angles are badly altered by collisions. The $\sin^2\theta$ distribution should still be correct for large angles. The form of the secondary electron spectrum for Be^9 at 180° agrees with the shape at 90° with appropriate Doppler Shift corrections; it would appear, therefore, that this does not occur and that the phenomenological and scalar meson theories will not meet the requirement of isotropy. The reaction $p+n \rightarrow d+\gamma$ will do so under some theoretical arguments. If, however, the $p+n \rightarrow d+\gamma$ reaction were a major contribution to the radiation, the number of secondary electrons above 10 Mev. would be considerably increased.

EXCITATION CURVE

If we consider now the yield of γ rays from Be, as a function of energy, we must apply a correction for the decreased efficiency of γ rays from lower energy protons and, taking the experimental secondary electron spectrum for this correction, it is found that the yield varies as $E^{0.3 \pm 0.5}$. For the low energy protons the Be nucleus is nearly opaque; every proton will therefore make a nuclear interaction. The observed energy dependence should then be the ratio of the probability of radiative to elastic proton neutron scattering. In a phenomenological theory this ratio is $\frac{g^2}{\hbar c}$, and in a scalar meson theory it is also independent of energy. On a pseudoscalar theory the variation will be as E^3 which is discounted by the data.

DEPENDENCE on A and Z

For opaque nuclei we expect the total number of nuclear interactions of the proton with the nucleus to vary as $A^{2/3}$; of these interactions a fraction $(A-Z)/A$ will be with a neutron and liable to give radiation. We would therefore expect a dependence on A and Z of $A^{-1/3}(A-Z)$ for the cross section on the nucleus as a whole, or $A^{-1/3}$ per neutron in the nucleus. The value of $A^{-1/3}$ is tabulated for comparison with the yields for neutron in Table III. It is clear that the dependence on $A^{-1/3}$ is in general correct.

More conclusive data could be obtained from an investigation of bremsstrahlung from proton-neutron collisions. An approximation should be to use proton-deuteron collisions where the neutron is more nearly free than in most nuclei.

I am most grateful for the enthusiasm and cooperation of Dr. James Rouvina in the early stages of the experiment, and for the assistance of Mr. John Ferry in taking data. I would like to thank Dr. Sidney Barnes, Mr. Hugo Logemann, Mr. R. Mortenson and the crew of the 130" cyclotron for their assistance in the experiment, and Dr. R. E. Marshak, A. Simon and J. B. French for innumerable valuable discussions on theoretical aspects of the problem.

FIG 1

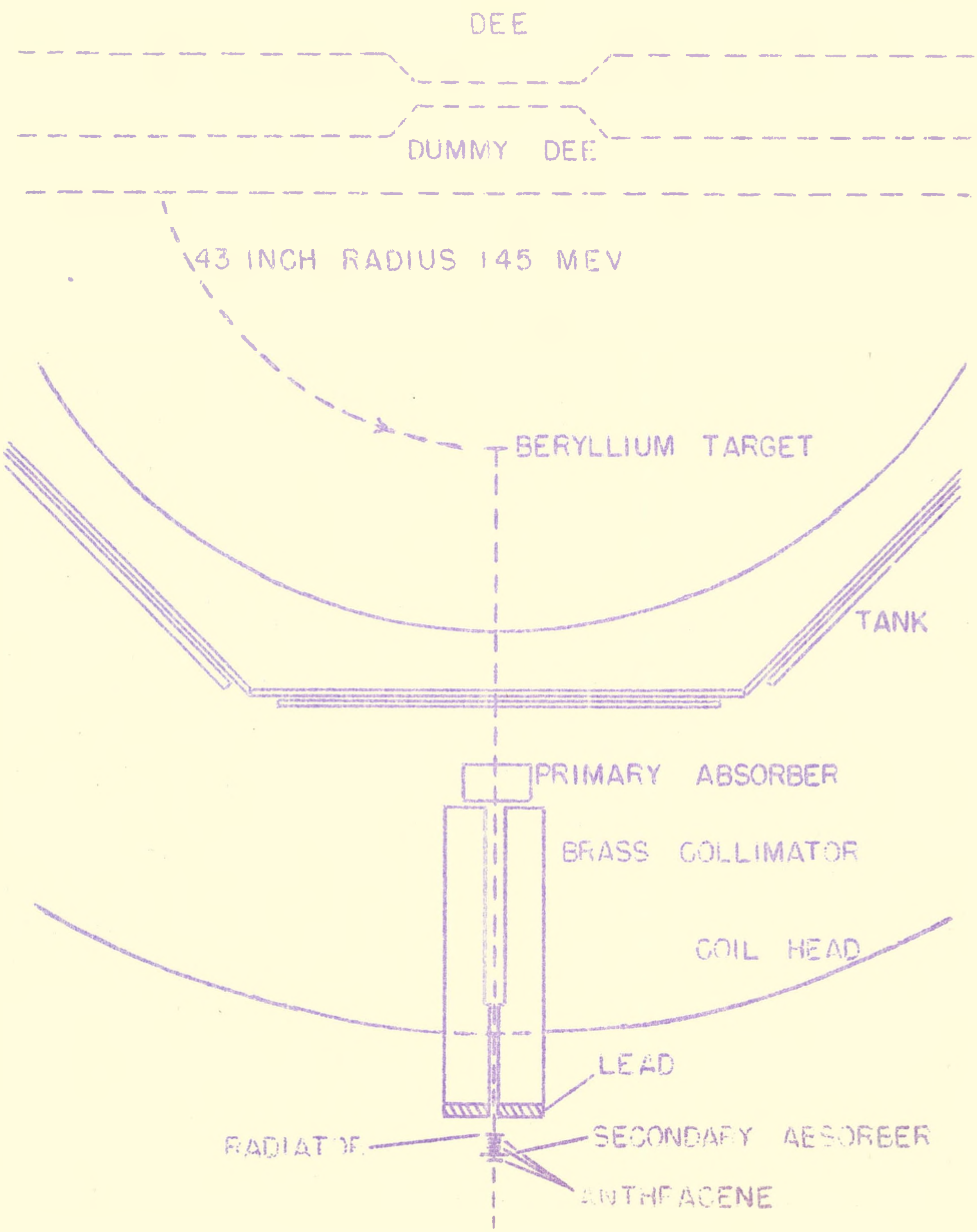
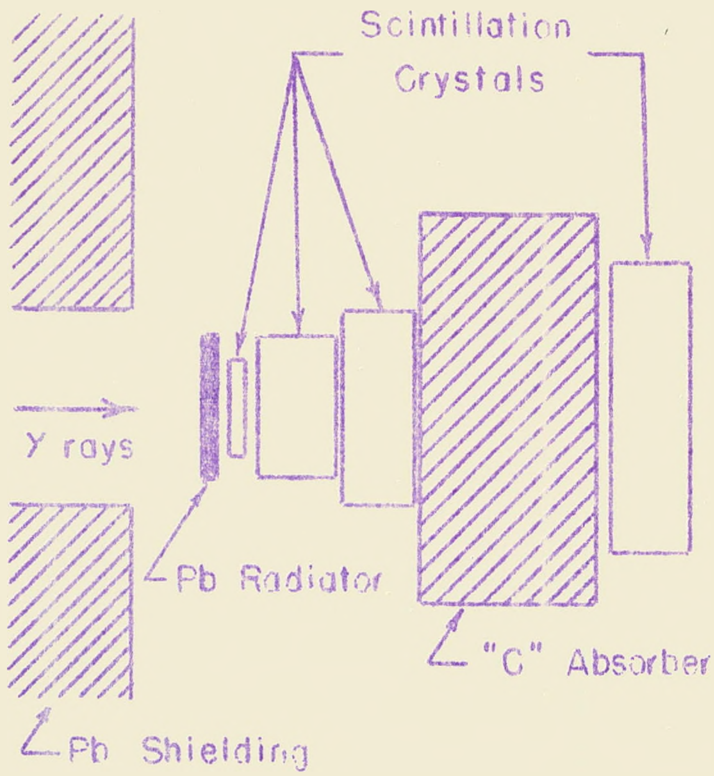

DEE
DUMMY DEE
43 INCH RADIUS 145 MEV
BERYLLIUM TARGET
TANK
PRIMARY ABSORBER
BRASS COLLIMATOR
COIL HEAD
LEAD
RADIATOR
SECONDARY ABSORBER
ANTHRACENE

FIG. 2



Full Scale

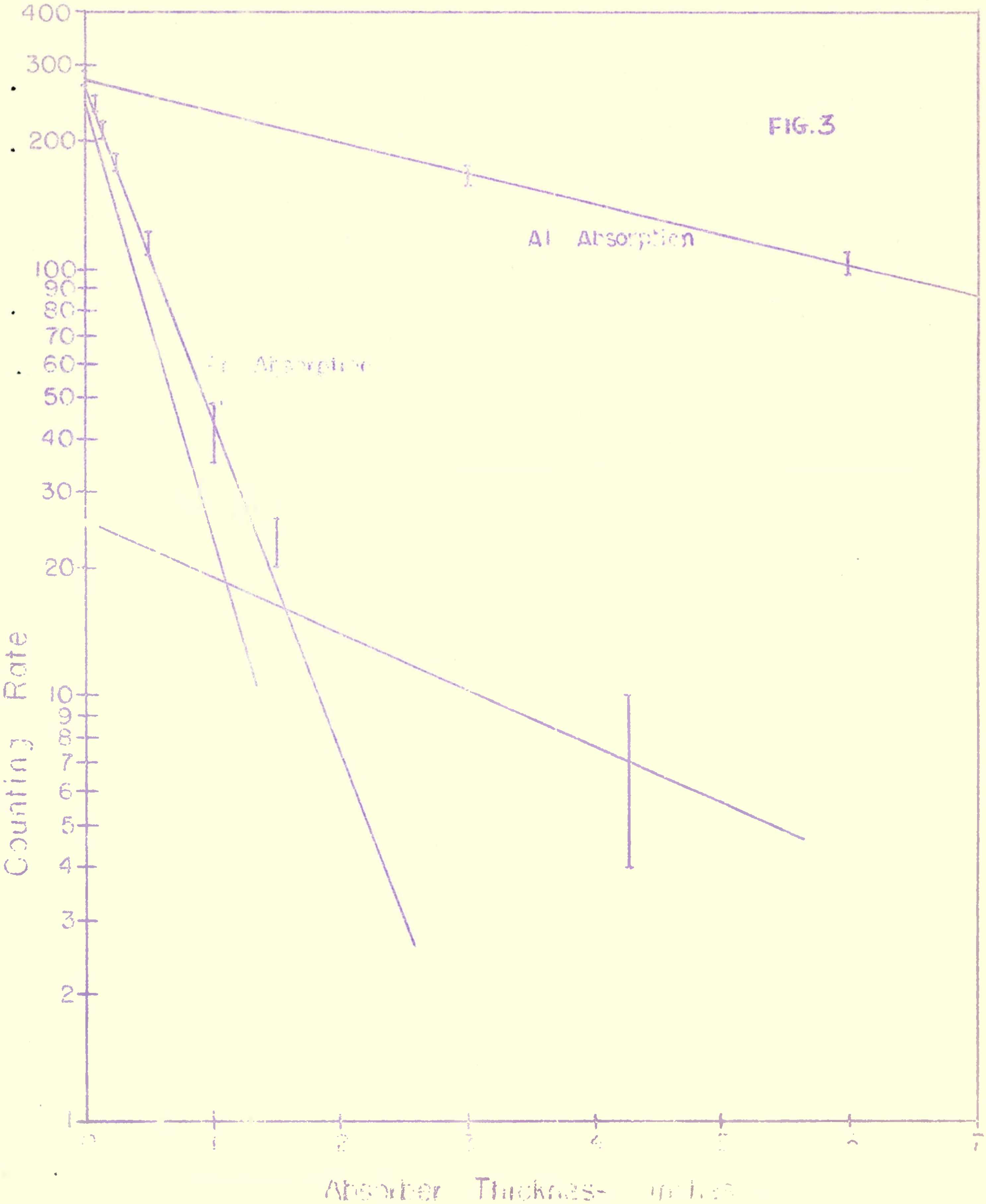
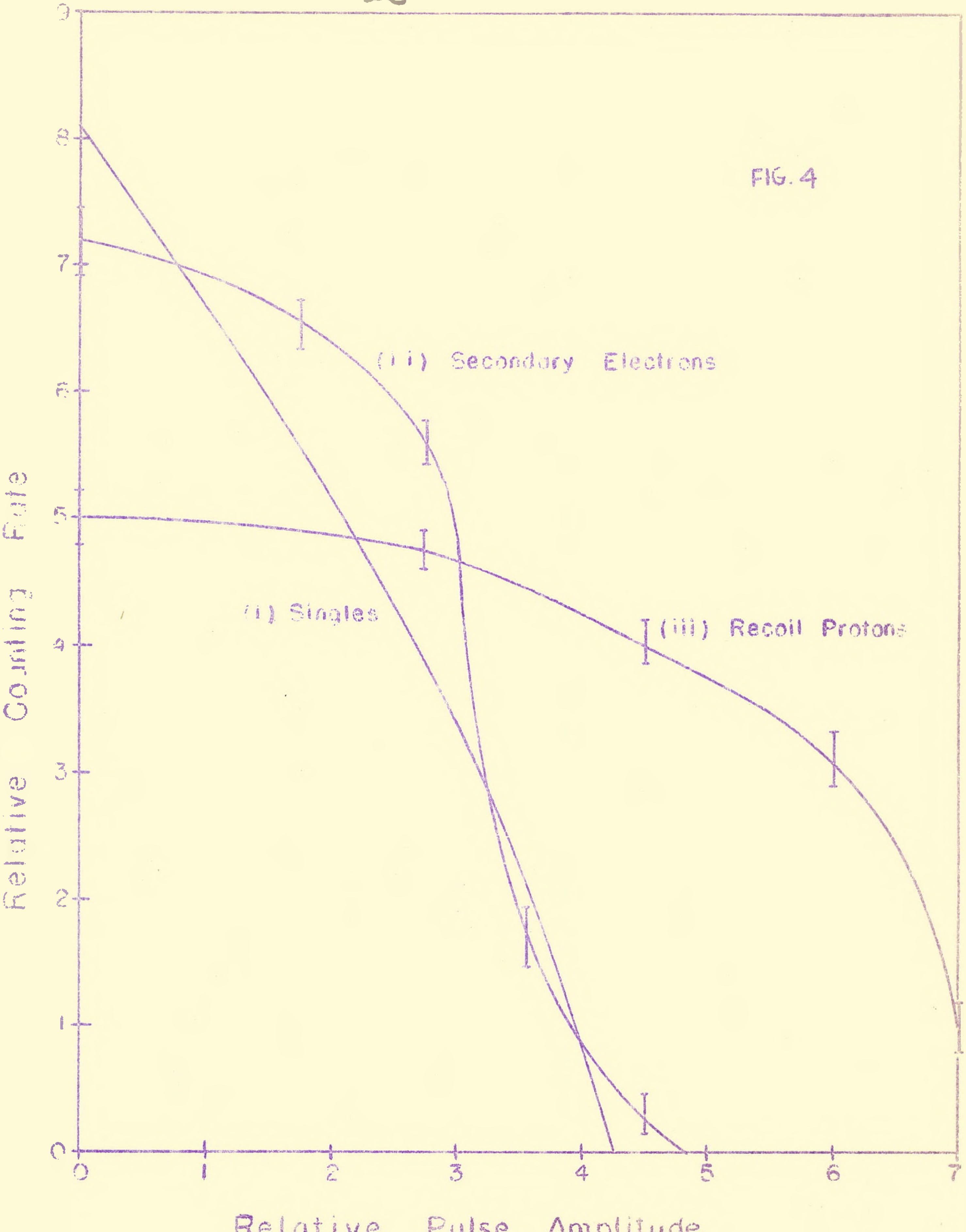
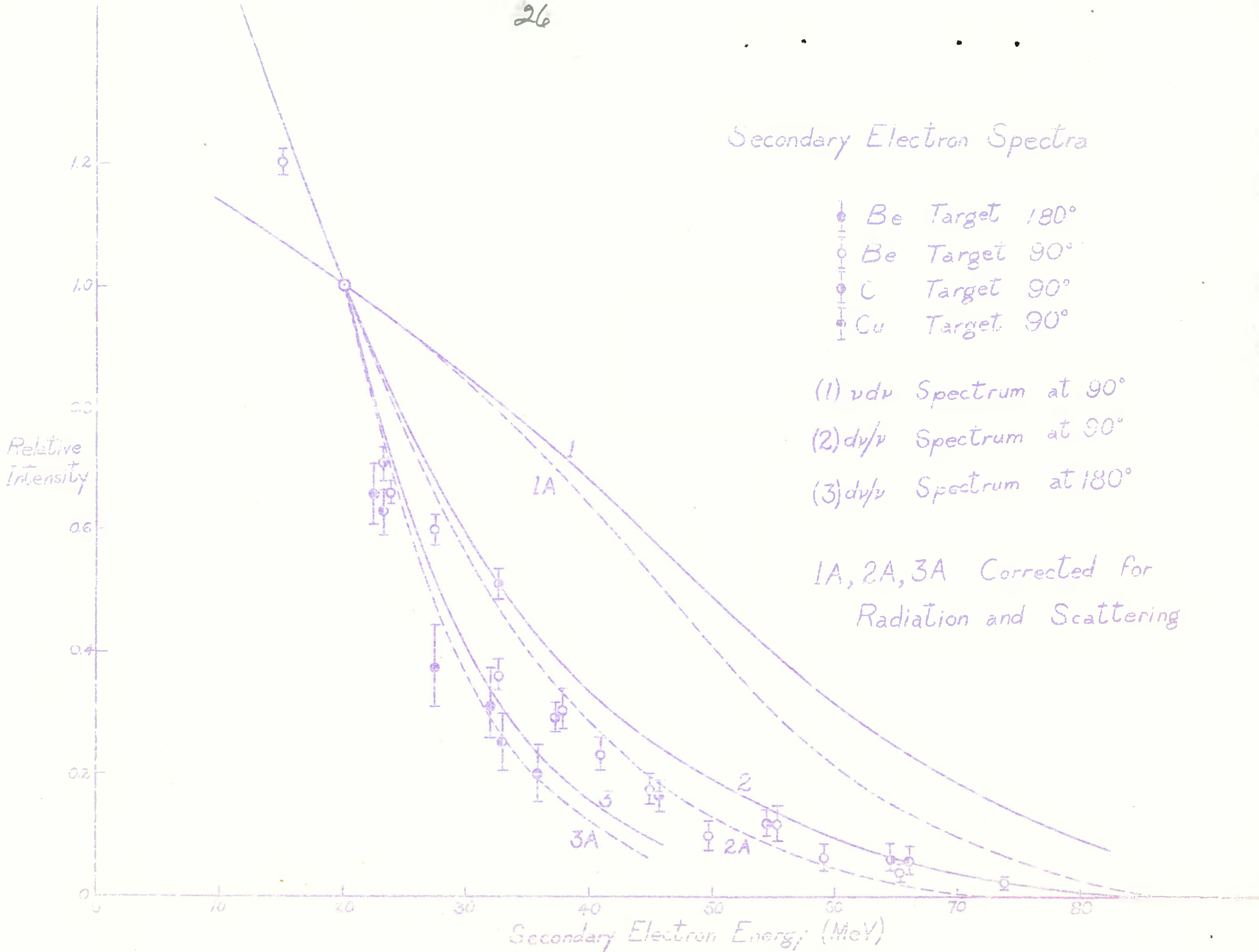

Al Absorption
Counting Rate
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
2
4

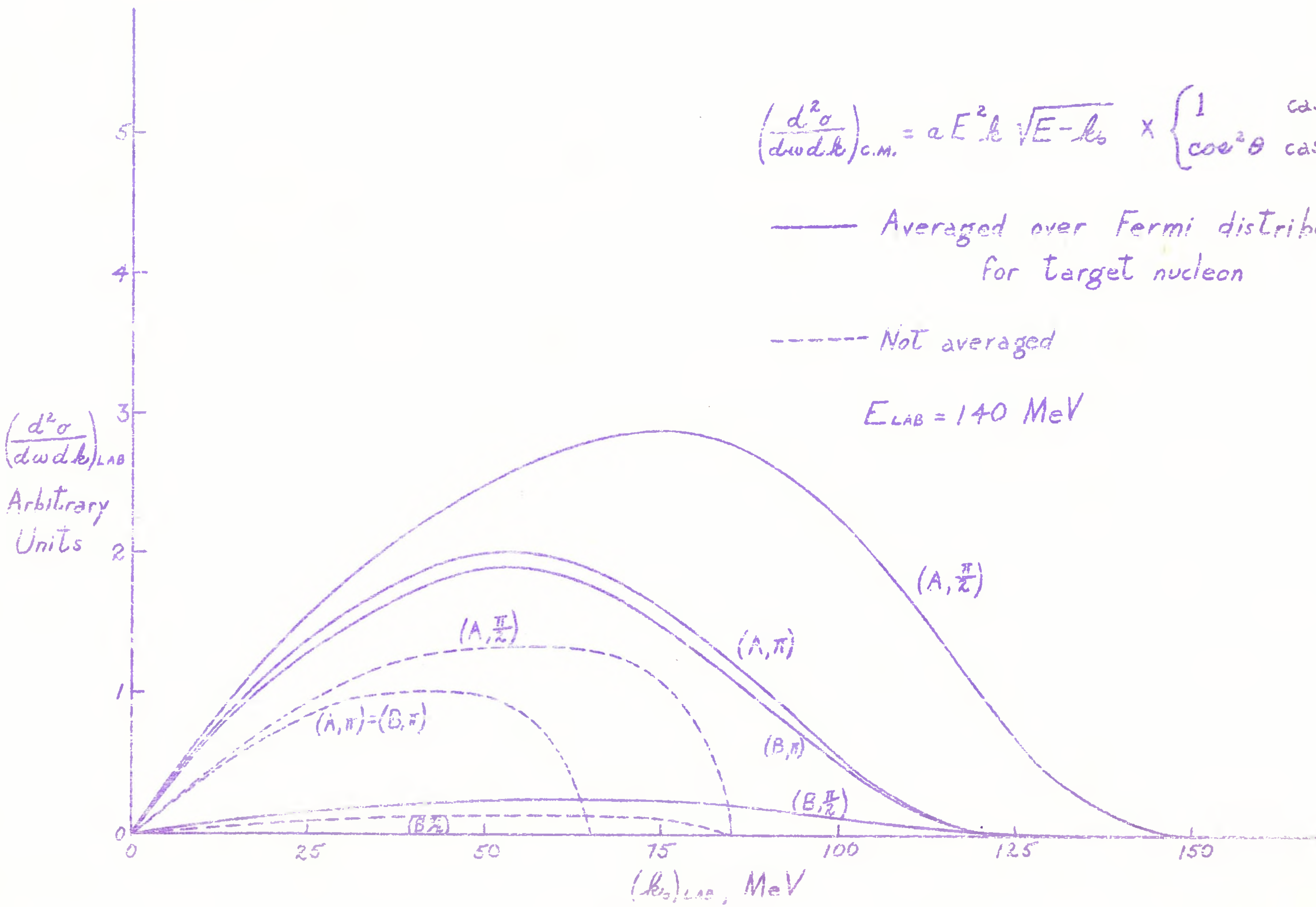
FIG.3



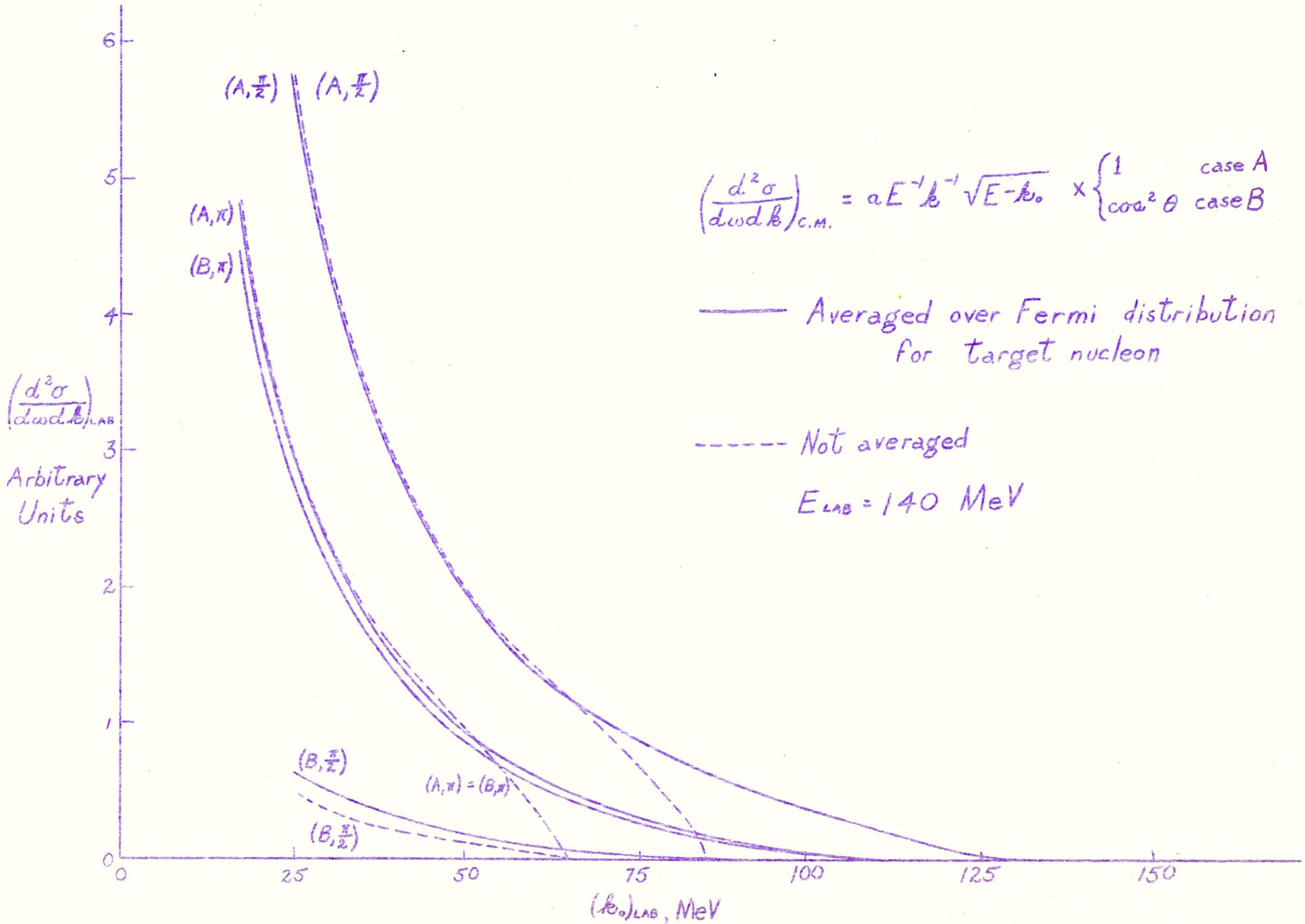
(ii) Secondary Electrons
(i) Singles
(iii) Recoil Protons
Relative Counting Rate
Relative Pulse Amplitude
0
1
2
3
4
5
6
7
8
9

FIG. 4


Secondary Electron Spectra
Be Target 180°
Be Target 90°
C Target 90°
Cu Target 90°
(1) $\nu d\nu$ Spectrum at 90°
(2) $d\nu/\nu$ Spectrum at 90°
(3) $d\nu/\nu$ Spectrum at 180°
1A, 2A, 3A Corrected for Radiation and Scattering
Relative Intensity
1.2
1.0
0.6
0.4
0.2
0
1
1A
2
2A
3
3A
0
10
20
30
40
50
60
70
80
Secondary Electron Energy (MeV)



$\left(\frac{d^2\sigma}{d\omega\, dk}\right)_{C.M.} = a E^2 k \sqrt{E - k_0} \times \begin{cases} 1 & \text{case A} \\ \cos^2\theta & \text{case B} \end{cases}$
Averaged over Fermi distribution for target nucleon
Not averaged
$E_{LAB} = 140$ MeV
$\left(\frac{d^2\sigma}{d\omega\, dk}\right)_{LAB}$
Arbitrary Units
$(A, \frac{\pi}{2})$
(A, π)
(B, π)
$(B, \frac{\pi}{2})$
$(A, \pi) = (B, \pi)$
$(B, \frac{\pi}{2})$
$(k_0)_{LAB}$, MeV
0
1
2
3
4
5
25
50
75
100
125
150



6
5
4
3
2
1
0
$\left(\frac{d^2\sigma}{d\omega dk}\right)_{LAB}$
Arbitrary Units
$(A,\frac{\pi}{2})$
$(A,\frac{\pi}{2})$
(A,π)
(B,π)
$(B,\frac{\pi}{2})$
$(A,\pi) = (B,\pi)$
$(B,\frac{\pi}{2})$
$\left(\frac{d^2\sigma}{d\omega dk}\right)_{C.M.} = aE^{-1}k^{-1}\sqrt{E-k_0} \times \begin{cases} 1 & \text{case } A \\ \cos^2\theta & \text{case } B \end{cases}$
Averaged over Fermi distribution for target nucleon
Not averaged
$E_{LAB} = 140$ MeV
0
25
50
75
100
125
150
$(k_0)_{LAB}$, MeV

Captions to Figures

Fig. 1 Drawing of the cyclotron showing position of the collimator for observing γ rays at 90° to the target.

Fig. 2 The arrangement of the four scintillation crystals. The position of the fourth crystal depends on the amount of absorber used.

Fig. 3 Reduction of quadruple coincidences by lead and aluminum absorption of the primary γ ray beam.

Fig. 4 Integral pulse amplitude distribution in the second crystal; (i) single pulses in the crystals, (ii) Quadruple coincidences from γ rays, (iii) quadruple coincidences from recoil protons.

Fig. 5 Absorption of secondary electrons in carbon compared with theory.

Fig. 6 Theoretical γ ray spectra computed by French and Daitch.