

components are also shown. When the isotope shift investigation was begun, all the 125 sample had been sputtered in the investigation of the hyperfine structure of 125, and natural tellurium had to be used instead of 125. This explains why the center of gravity of 125 components is located with inferior accuracy in Fig. 2. In the same figure the isotope shift in $\lambda 4049$ is also shown. Within experimental error, the isotope shifts in $\lambda 4006$ and $\lambda 4049$ are quite the same. In heavy elements, isotope shifts in the terms arising from the configuration $5s5p^4$ should be nearly the same and insensitive to the J values in one and the same element. This expectation is in agreement with the observation.

The anomalously large shift at $A=124-126$ namely at $N=72-74$ (A is the atomic weight integer and N the neutron number) is quite conspicuous, and must be connected with the structure of nuclei with $N=72$ or $N=74$.

The classification of the Te II spectrum, which is important in interpreting the hfs, was put at our disposal before publication, by Professor J. E. Mack and Dr. J. C. van den Bosch. We appreciate the deep interest of Professor Mack in our work. One of us (K.M.) would like to express his appreciation to Professor Mack for making it possible to spend this past year at the University of Wisconsin.

Proton Bremsstrahlung at 140 Mev*

RICHARD WILSON†

University of Rochester, Rochester, New York

(Received October 24, 1951)

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 neutron contributing to the bremsstrahlung.

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 180-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 Marshak² 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.

EXPERIMENTAL

A target was set up at 43-in. 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 1 percent in this case, and for the lighter elements even a big impurity of the heavy elements could not be a cause of the radiation.

Figure 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 1.0-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 analyze the primary radiation, and absorbers between counters 3 and 4 analyze 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.

* This work was assisted by the AEC.

† Now at Stanford University, Stanford, California.

¹ Bjorkland, Crandall, Moyer, and York, *Phys. Rev.* **77**, 213 (1950).

² J. Ashkin and R. E. Marshak, *Phys. Rev.* **76**, 58 (1949).

³ A. Simon, *Phys. Rev.* **79**, 573 (1950).

⁴ W. H. Barkas, *Phys. Rev.* **75**, 1109 (1949).

⁵ R. L. Garwin, *Rev. Sci. Instr.* (1950).

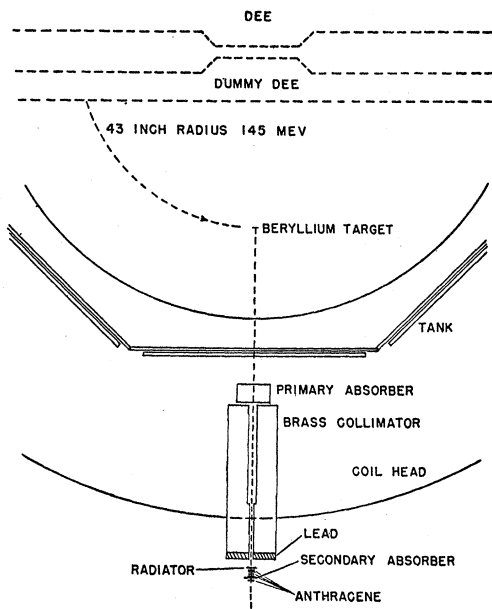


FIG. 1. Drawing of the cyclotron showing position of the collimator for observing γ -rays at 90° to the target.

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 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

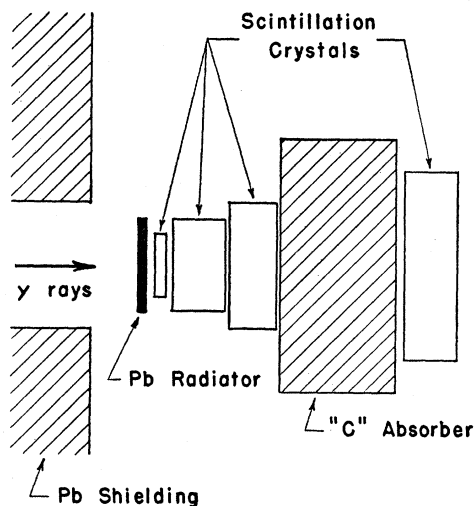


FIG. 2. The arrangement of the four scintillation crystals. The position of the fourth crystal depends on the amount of absorber used.

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 biased 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 percent 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 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.

TABLE I. Radiator change.

Radiator	Absorber out	Absorber in
None	0.16 ± 0.01	0.08 ± 0.004
0.5 mm Pb	0.55 ± 0.1	0.25 ± 0.1
1 mm Pb	1.000	0.34 ± 0.03
5 mm Pb	1.6 ± 0.2	
1 cm Pb	0.8 ± 0.2	

RESULTS

A. Proof of Photon Identity

The radiation from several targets has been examined; the absorption curves for radiation from a 1-in. beryllium target has been examined in the greatest detail. Figure 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 $\frac{1}{2}$ in. of lead primary absorber. The difference between these two is a

⁶ The axial monitor was set up and maintained by J. Norton; the neutron by J. Perry.

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 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 anticoincidence 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 percent of the total γ -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 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 percent in chance coincidence rate is observable by using a delay which is not a multiple of the oscillator period.

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

In order to check that each counter was counting all the electrons, a plot was made of counting rate as a function of pulse height for the various events in the telescope. Figure 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 biased 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 System

Figure 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.

⁷ Steinberger, Panofsky, and Steller, Phys. Rev. 78, 802 (1950).

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.

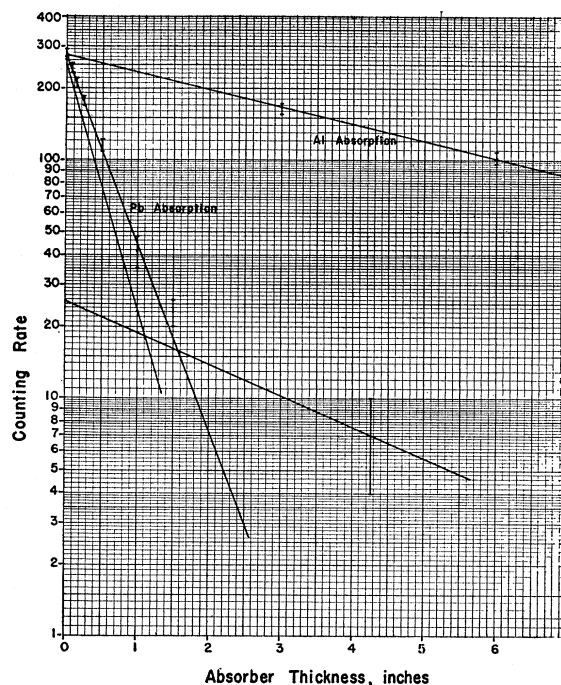


FIG. 3. Reduction of quadruple coincidences by lead and aluminum absorption of the primary γ -ray beam.

The absorption in carbon and in the hydrocarbon crystals is obtained from the calculations of Halpern

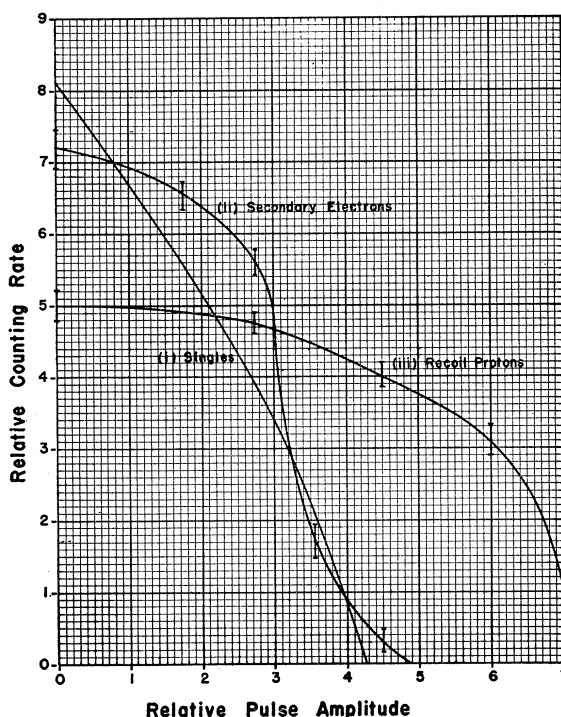


FIG. 4. Integral pulse amplitude distribution in the second crystal; (i) single pulses in the crystals, (ii) quadruple coincidences from γ rays, (iii) quadruple coincidences from recoil protons. The scale for the relative pulse amplitude should read from 2 to 9.

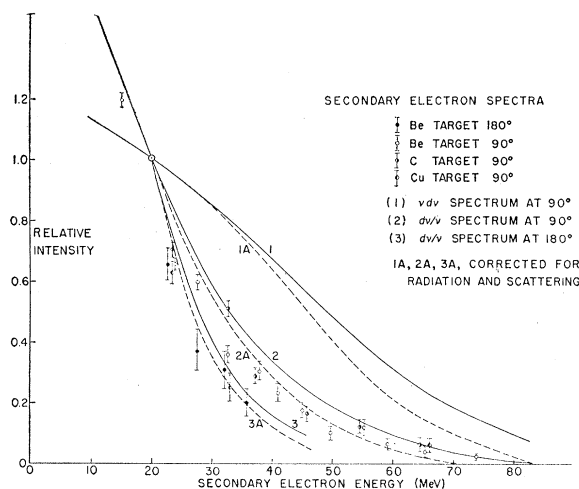


FIG. 5. Absorption of secondary electrons in carbon compared with theory.

and 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.⁹

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

TABLE II. (a) Angular ratio for all secondary electrons above 20 Mev for several target elements. (b) Ratio of neutron counts at different angles from Be target as a result of 80-Mev recoil protons in the forward direction.

(a) Angles	Target	Measured electron ratio	Corrected for aberration ^a	Corrected for Doppler shift and aberration ^a
90°/180°	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
30°/90°	Be	2.5±1	1.5±0.8	1.0 ±0.6
45°/90°	Be	2.0±0.4	1.3±0.3	1.0 ±0.4
(b) Angles		Ratio of neutron counts		
0°/30°		Be	>2	
30°/45°		Be	2.1±0.5	
45°/90°		Be	50 ±20	
90°/180°		Be	>2	

^a 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 dv/v is assumed here, but there is only 5 percent difference for a vdv type spectrum.

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

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

percent 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 electrons 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 percent so long as the electron emerges from the third crystal with 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 Williams,¹¹ using the Born approximation for the small angle cutoff. Since we are interested only in small scattering angles, the distribution can be taken as Gaussian and the large angle cutoff 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 percent of the 70-Mev electrons can escape from the telescope when a 70-Mev absorber is in position but only 10 percent 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 percent chance of being scattered out. Radiative losses can be important even in carbon, for we have here nearly half a radiation length for absorbing 70-Mev electrons. Since the electrons are losing energy and the cross section for bremsstrahlung falls, only about 20 percent 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 formula 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 cm of absorber might produce γ -rays which later count in crystal 4. If the corresponding

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).

¹⁴ M. Stearns, Phys. Rev. **76**, 836 (1949).

positron was counted in crystals 1, 2, and 3, it could simulate 70-Mev γ -rays. Calculations show that this could account for at most 10 percent of the high energy electrons. A correction is made for this 10 percent 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 percent. 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 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 assumption. (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 target¹⁵ (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 percent 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-in. copper target. The accuracy of alignment is about 2° and the values in the table could be 20 percent higher for the lower Z 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 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 γ -rays from π^0 decay. Approximately the same dependence upon Z is found for the π^0 γ -rays as for the bremsstrahlung, although the recirculation correction is likely to be in error here.

¹⁵ W. J. Knox, University of California Radiation Laboratory Report No. 883 (1950).

The absolute cross section has been estimated by the production of C^{14} 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} to within a factor of 3, or 2.5×10^{-30} cm²/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 Marshak² using a phenomenological potential, and by Simon³ using pseudoscalar 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

TABLE III. Relative yield of photons (at 90° , lab system).^a

Target	Max. proton energy	Recirculation correction	Yield/neutron	A^{-1}
Be	100		0.50 ± 0.02	
Be	120		0.70 ± 0.02	
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	

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

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 $p + n \rightarrow \gamma + d$.

The cross section for the inverse process has been calculated by Marshall and Guth¹⁷ and by Schiff¹⁸ with similar results. By using the principle of detailed balancing, the cross section might be expected to be 6×10^{-30} cm² at 140 Mev, as compared with 4×10^{-30} cm² 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

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).

$a+b \sin^2\theta$. The energy spectrum for the bremsstrahlung theories will either be of the form $(\frac{1}{2}E_0 - h\nu)^{\frac{1}{2}}d\nu/\nu$ or $(\frac{1}{2}E_0 - h\nu)^{\frac{1}{2}}\nu d\nu$ 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-neutron collision will give the energetic radiation; for the second collision, the nucleon energies will be reduced and the energies of the γ -rays will be correspondingly lower. The second collision has here been ignored; many of the nucleons should escape from the nucleus for low Z nuclei, so if the effect is important, it will be so only for high Z .

There are two important effects of the nuclear motion; the first is the effect 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 nuclear collision need be considered, the nuclear motion cannot alter the angle of γ -emission by more than 20° for a nucleon of 140 Mev hitting a Fermi gas of nucleons. The second scattering may also occur and the angle may be as large as 90° for low energy radiation.

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 neutrons from protons on various elements.¹⁹ These indicate that the angular spread is greater than 20° and therefore there may be appreciable secondary scattering.

It seems probable also that the interaction between the neutron and the proton in the final state will be perturbed by the presence of other nucleons in the nucleus so that the reaction $p+n \rightarrow d + \gamma$ 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 larger high energy component of the secondary electron dis-

tribution. 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 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 $(\frac{1}{2}E_0 - h\nu)^{\frac{1}{2}}d\nu/\nu$ and the other $(\frac{1}{2}E_0 - h\nu)^{\frac{1}{2}}\nu d\nu$. 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 Fig. 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 $I_{90}/40$ 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 Fig. 5. It is clear that the spectrum $(\frac{1}{2}E_0 - h\nu)^{\frac{1}{2}}\nu d\nu$ is not consistent with the data whereas the spectrum $(\frac{1}{2}E_0 - h\nu)^{\frac{1}{2}}d\nu/\nu$ 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.

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	$1V(r)$	7	250	E_0^{-1}	$d\nu/\nu$
	$P_M V(r)^a$	25	250		
	$\frac{1}{2}(1+P_M)V(r)$	15	250		
Scalar meson theory		230	180	E_0^{-1}	$d\nu/\nu$
Pseudoscalar theory		0.8	180	E_0^2	$\nu d\nu$
$p+n \rightarrow \gamma+d$		5 ^b	140	E_0^{-1}	70-Mev line

^a P_M is Majorana operator.

^b Depends upon the nuclear forces; see reference 17.

¹⁹ Miller, Sewell, and Wright, Phys. Rev. 81, 374 (1951); see also the neutron background found in Table III of the present experiment.

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 fitted if it were true that secondary nucleon collisions are of importance. This could only 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 Be⁹ 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 50 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 $e^2/\hbar c$, 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

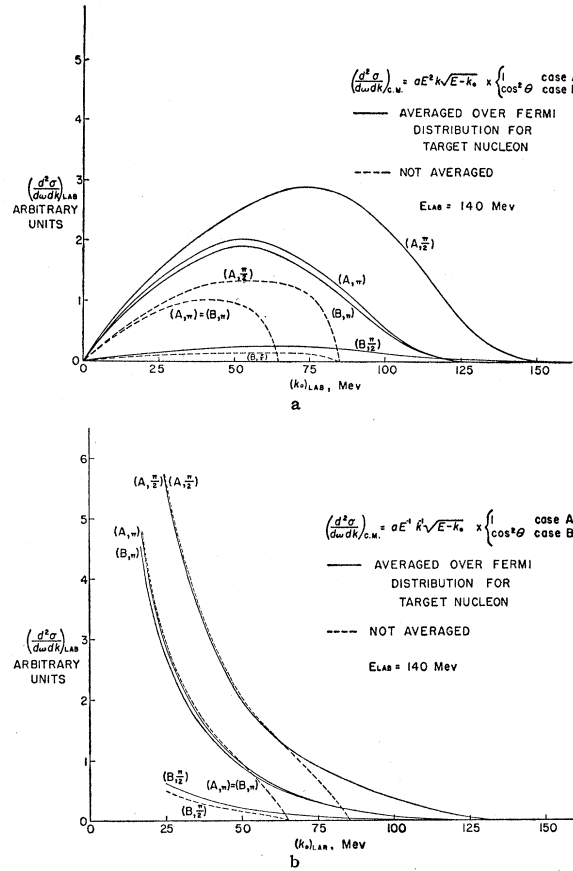


FIG. 6. Theoretical γ -ray spectra computed by French and Daicht.

$A^{-1/3}$ 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 coöperation of Dr. James Rouvina in the early stages of the experiment, and for the assistance of Mr. John Perry in taking data. I would like to thank Dr. Sidney Barnes, Mr. Hugo Logemann, Mr. R. Mortenson, and the crew of the 130-in. 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.