PHYSICAL REVIEW VOLUME 82, NUMBER 5 JUNE 1, 1951

Yields of Photoprotons from Twenty Elements[*]

A. K. MANN AND J. HALPERN
University of Pennsylvania, Philadelphia, Pennsylvania

(Received February 5, 1951)

Scintillation counters have been applied to the study of the yields of photoprotons from twenty elements. The relative yields increase by a factor of approximately one hundred as Z increases from 4 to 28, and then decrease to a value, at $Z=50$, of about one-tenth that of the maximum at $Z=28$. An upper limit is placed on the yields from several heavy elements. The absolute values are compared with the neutron data of Price and Kerst, and the sum of the two yields is compared with theory.

INTRODUCTION

ONE of the general features of photonuclear reactions which is of interest is the dependence of the yields of these reactions on atomic number. The yields of γ-n reactions have been investigated most extensively,[1] because experimental difficulties generally involved in the study of photonuclear disintegrations can be surmounted in many of the γ-n processes. The high background attending the intense x-ray beams required to produce these reactions has limited the use of counters for observing directly and rapidly the emitted particles. Many of the γ-n reactions, however, lead to products which are beta-active and whose half-lives are such that these products can be examined conveniently some time after their formation. There are also available slow neutron detectors such as indium and rhodium foils which are insensitive to the γ-ray background and which have been used in the investigation of γ-n processes. Recently, boron trifluoride counters in conjunction with a moderator have been applied successfully to the detection of γ-n processes.[2] Further, since target absorption is not a factor with neutrons, large samples can be irradiated with consequent large yields. In the main, the products of reactions in which charged particles are emitted are not radioactive; and these reactions have been observed primarily with cloud chambers and nuclear emulsions, which necessarily prohibit a comprehensive survey. However, Wäffler and Hirzel,[3] using the Li 17.6-Mev γ-ray, measured the γ-p cross sections of fourteen isotopes (all of which have an observable beta-decay after proton emission) relative to the γ-n cross section in Cu^{63}. The relatively large γ-p cross sections found by them indicated that these reactions were considerably more probable, especially in the lighter elements, than had previously been assumed and suggested the need for a more complete study.

The present paper describes a method, employing scintillation counters, for the direct detection of protons from γ-p reactions and its application to an investigation of the absolute yields of γ-p processes in 20 elements bombarded by bremsstrahlung from the University of Pennsylvania 25-Mev betatron.

METHOD AND PROCEDURE

Two scintillation counters, to be described in detail below, were contained in a scattering chamber completely shielded by four inches of lead, through which passed the collimated x-ray beam from the betatron. The complete experimental arrangement is shown in Fig. 1. The concrete wall provides shielding against neutrons produced in the betatron target. The lead wall and collimator shield the counters from the direct and scattered x-ray beam. The collimator sharply defines an x-ray beam with an angular divergence of 0.22 degree and a circular cross section at the target position $\frac{9}{32}$ in. in diameter. The thickness of the

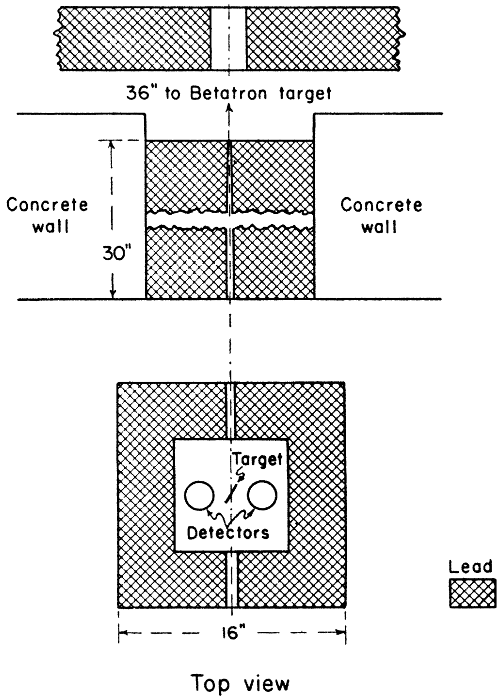

FIG. 1. Diagram of experimental arrangement.

---

[*] Assisted in part by the joint program of the ONR and AEC.

[1] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948); G. Friedlander and M. L. Perlman, Phys. Rev. **74**, 442 (1948); G. Friedlander and M. L. Perlman, Phys. Rev. **75**, 988 (1949); G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950); Johns, Katz, Douglas, and Halsam, Phys. Rev. **80**, 1062 (1950).

[2] McDaniel, Walker, and Stearns, Phys. Rev. **80**, 807 (1950); Sher, Halpern, and Stephens, Phys. Rev. **81**, 154 (1951).

[3] H. Wäffler and O. Hirzel, Helv. Phys. Acta **21**, 200 (1948).

scattering chamber shield was determined from lead absorption measurements of the scattered radiation attending the x-ray beam. The counters and target were mounted on a rotatable table to permit angular distribution measurements. It was possible to align the scattering chamber and the target with the beam by irradiating x-ray film in the target position.

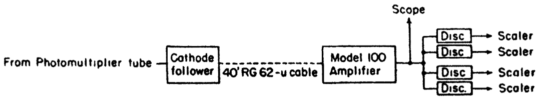

FIG. 2. Schematic diagram of a complete counting channel.

The output pulses from the two counters, operated independently, were fed into identical, separate channels. A complete channel for a single tube is shown schematically in Fig. 2. The cathode followers were mounted on the underside of the table supporting the counters and exhibited a linear response over the range of pulse sizes which were observed. The data of these experiments are integral bias curves. The four scalers allowed four points on a bias curve to be obtained simultaneously. The 5819 photomultiplier tube was operated at approximately 900 volts, divided such that 193 volts appeared between the photocathode and the first dynode, 129 volts between the first and second dynodes, and 65 volts between each remaining pair of dynodes.

In order to count protons from reactions induced in a target in the scattering chamber, it is necessary that the detector be capable of sufficient discrimination against x-rays and secondary electrons scattered from the target. The degree of discrimination depends on the resolving time of the counting system. If the resolving time is such that every incident particle is resolved, then it is necessary only that the counter distinguish between a single proton and a single electron. If, however, the resolving time does not allow the resolution of every incident particle, then the counter must discriminate against pile-up due to two or more electrons arriving within the resolving time. The counter to be described here satisfied the latter requirement. The counter consisted of the photomultiplier tube, a silver-activated ZnS scintillator screen, and an aluminum reflector, arranged as shown in Fig. 3. The scintillator screen was made by depositing powdered crystals on a 0.1 cm thick glass plate, which allowed the screen to be mounted vertically. This orientation of phototube and scintillator was possible because the reflector and the large photocathode surface of the 5819 provided satisfactory light collecting conditions.

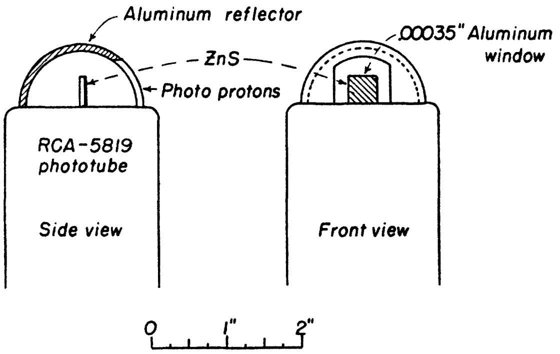

FIG. 3. Diagram of scintillation counter.

The performance of the counter is determined principally by the properties of the scintillator screen. The resolving time is indirectly limited by the decay time of the light pulses from ZnS, and no resolution is attempted within the half-width of the betatron pulses ($\sim 0.5\ \mu$sec). However, powdered ZnS is opaque to its own radiation in a thickness corresponding roughly to the range of million-volt protons. For protons with energies from about 1 to 10 Mev, the light yield from the ZnS screen is approximately independent of energy. This saturation effect also occurs for electrons, but the region of approximately constant light yield begins at a much lower energy. It is known that the energy required for the emission of a light quantum from ZnS is about equal for both protons and electrons.[4] Consequently, except for very low energies, the light yield from the ZnS screen is considerably greater for protons than for electrons, independent of their respective energies. This strong discrimination against electrons is not completely realized because of the pile-up effect mentioned previously. However, if the magnitude of the pile-up is restricted to values below a certain maximum by limiting the intensity of the x-ray beam from the betatron, almost complete discrimination is obtained, as is illustrated by the bias curves in Fig. 4. The steeply rising portion of these curves is due to electron pile-up which increases rapidly with decreasing bias voltage until the betatron pulse recurrence rate (180 sec^{-1}) is reached. This may or may not occur outside the region of phototube noise, depending on the incident x-ray beam intensity and the atomic number of the target. The relatively flat portion of the integral curve is due to protons from a γ-p reaction in the target. The long tail extending to low bias voltages in the differential bias curve results from protons with energies below the flat response region of the counter.

The counter was not sensitive to neutrons. This is indicated by the curves in Fig. 5, which were taken under the following conditions: with the counters in the positions shown in Fig. 1, i.e., at right angles to the direction of the incident x-ray beam, a deuterated paraffin target was irradiated and bias curves were obtained for each of the counters. One of the counters was then shielded by 0.027 in. of aluminum and the target irradiated again. The proton counts from the unshielded counter were the same in both runs. The bias curves obtained from the other counter are those in Fig. 5. In order to insure that the heavy particles

---

[4] H. Kallman, Phys. Rev. 75, 623 (1949).

were not α-particles from the carbon, an experiment similar to that above was performed using a total absorption equivalent to 0.0035-in. aluminum shielding-which is sufficient to absorb almost all α's from a γ-α reaction in C^{12}. The heavy particle counting rate remained the same within statistics in both the shielded and unshielded runs.

The low yields from γ-p reactions required the use of thick (∼5 Mev) targets, which minimized the information to be gained from complete aluminum absorption studies. Nevertheless, several such studies were made on different targets to determine the rough absorption characteristics of the emitted particles. The general features of these absorption curves strongly support the identification of the heavy particles as protons from γ-p reactions. This identification is further substantiated by the excitation functions obtained with the method described here.[5]

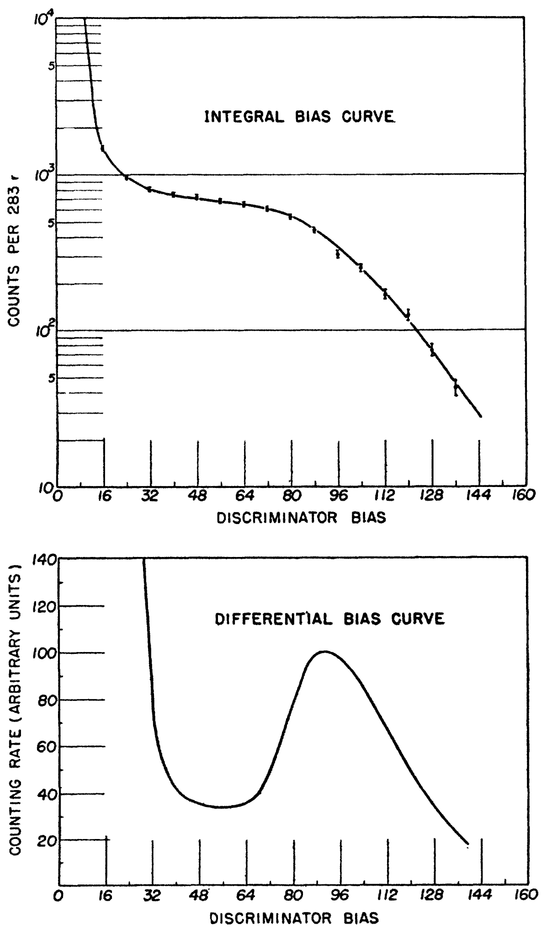

FIG. 4. Bias curves illustrating discrimination against pile-up. The target was nickel.

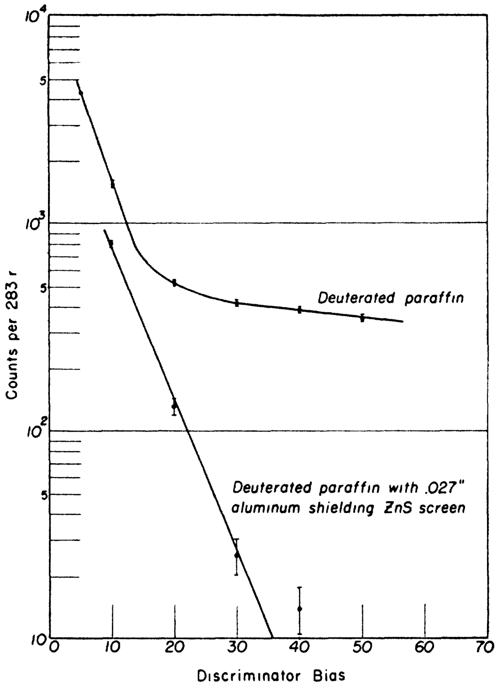

FIG. 5. Bias curves demonstrating the counter insensitivity to neutrons.

In the measurement of γ-p yields, the counters were fixed at 90 degrees with respect to the direction of the x-ray beam. A target holder was installed which allowed targets to be changed conveniently and with a negligible change in the geometry. The targets were in the form of foils of commercial purity and natural isotopic composition. Target thicknesses were determined from weight and area measurements. Each target was irradiated with a bremsstrahlung spectrum having approximately the same maximum energy of 23.5 Mev. The instantaneous intensity of the incident beam was adjusted so that discrimination against the pile-up was maintained essentially independent of the atomic number of the target during the entire course of any run. The total intensity of x-rays striking the target was determined for each run by integrating the current from an ionization chamber in the path of the beam. The chamber and integrator were calibrated against a Victoreen thimble "r" meter imbedded in a Lucite cylinder of 8-cm outside diameter. Several of the targets were used as standards, and all measurements were made by alternating a standard with an unknown element.

Integral bias curves for several elements are shown in Fig. 6, which also includes a curve obtained without a target in the scattering chamber. These curves represent the data from one of the counting channels. In all cases, the two counters agreed within statistical errors. It will be seen that the slope of the pile-up in the background curve is nearly the same as that observed with low Z elements such as deuterium and aluminum.

---

[5] A. K. Mann and J. Halpern, Phys. Rev. **80**, 470 (1950). Excitation functions of several other elements have since been obtained.

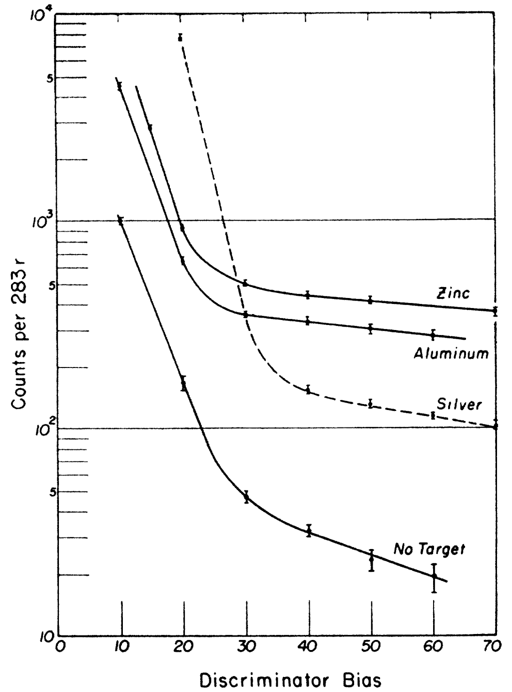

FIG. 6. Typical bias curves for three elements compared with the curve for no target.

That portion of the background curve which extends to higher bias voltages is due to heavy particles, as is shown by comparison with the shielded counter curve in Fig. 5, which exhibits only slight evidence of a heavy particle tail. Because of imperfect control of the incident beam intensity, the magnitude and slope of the pile-up show some increase with increasing atomic number of the target. This in turn results in a steeper slope of the proton regions of curves corresponding to relatively high Z targets, because discrimination against pile-up is lessened. For a given target, the slope of the heavy particle region depends on the relative magnitudes of the pile-up and the heavy particle yield. The low yield accounts for the extreme slope of the heavy particle region of the background curve, while a combination of relatively low yield and high pile-up is responsible for the increased slope of the high Z target curves. In order to facilitate direct comparison of the data for elements of widely different Z, the heavy particle and pile-up components of each of the curves are separated under the assumption that the shape of the pile-up is exponential and independent of its magnitude and, consequently, is the same for all targets.

There are several sources of error which must be considered before the yields can be determined from the reduced data. Since measurements were made only at one angle, it is necessary to make an assumption concerning the angular distributions of protons from those elements for which no information is available. The angular distributions from Al, Mg, Cu, Rh, and Ag have been measured[6] by the photographic emulsion method. We have verified the results for Ag and also made a rough determination of the distribution from Ni with the method of this paper. All of the distributions, except those for Rh and Ag, are spherically symmetric within the accuracy of the experiments. The data for Rh and Ag indicate that, although there is a high energy proton component exhibiting marked assymmetry, the entire energy spectrum shows only small departure from an isotropic distribution. Consequently, we have computed the total yields for all elements from the known geometry of our apparatus, assuming spherical symmetry.

Another source of error arises from uncertainty in the value of the counter efficiency, which was determined from the following experiment. The proton yield from deuterium in a given solid angle at 90 degrees was obtained from the bias curves for normal and deuterated paraffin targets after background corrections were made. The total yield from deuterium can be calculated by numerical integration with respect to energy of the product of the incident x-ray spectrum[7] and the cross section for photodisintegration.[8] This value must be modified to take into account the geometrical conditions of the experiment and target absorption of the emitted protons. The final calculated value and the measured value agree within 20 percent. In view of the errors attached to the quantities involved in the calculation and the measured yield value, closer agreement would probably be fortuitous. On the basis of this experiment, we have assumed the efficiency of our counters to be 100 percent. It should be noted that any error resulting from this assumption will only increase the absolute values of the proton yields.

The largest source of error is that due to absorption of the protons by the target and by the air and aluminum foil (see Fig. 3) in the scattering chamber. When the energy distribution of the protons is known, as in deuterium, it is possible to correct for the absorption with high accuracy. For most of the elements studied here, the energy distributions are not known and only approximate corrections can be made. A first-order relative correction was applied by selecting the thickness of each of the targets to be that corresponding approximately to the range of a 5-Mev proton. The energy distributions from Al, Mg, Cu, Rh, and Ag have been measured[6] with bremsstrahlung excitation using photographic emulsions; but only the data for Cu were obtained under experimental conditions which allow their use directly in the application of absorption

---

[6] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950); M. E. Toms and W. E. Stephens (to be published); P. R. Byerly, doctoral dissertation (University of Pennsylvania, 1950); Curtis, Hornbostel, Lee, and Salant, Phys. Rev. **77**, 290 (1950).

[7] Johns, Katz, Douglas, and Halsam, Phys. Rev. **80**, 1062 (1950).

[8] Collie, Halban, and Wilson, Proc. Phys. Soc. (London) **63**, 994 (1950). This article contains a table of most recent measurements.

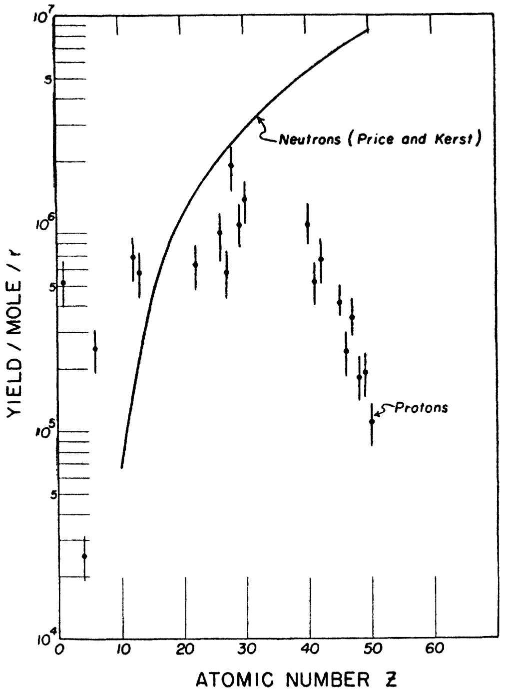

Fig. 7. Plot of the absolute yield values of γ-p reactions in twenty elements as a function of Z.

corrections to the yield data of this paper. However, the experiments with emulsions indicate that the shapes of the distributions do not depend strongly on the atomic number of the target and are closely described by the proton energy distribution predicted by the theory of the compound nucleus.[9] Consequently, for the purpose of absolute absorption corrections, we have used an energy distribution similar in shape to that observed for Cu and of width determined by the γ-p threshold for the element investigated. The calculated corrections increased the observed yield values for all elements except deuterium by about a factor of 2.5.†

RESULTS AND DISCUSSION

The corrected absolute yield values plotted against atomic number are shown in Fig. 7. The estimated errors are indicated by the vertical lines through the points. The errors attached to the relative values of neighboring elements are about one-half as large as those in the figure. In addition to these data, upper limits to the yields of ${}_{73}$Ta, ${}_{74}$W, ${}_{78}$Pt, and ${}_{79}$Au have also been obtained. The yields from these elements are less than or equal to that from ${}_{50}$Sn. For the purpose of comparison, there is also shown in Fig. 7 a portion of the curve which fits the absolute γ-n yield data of Price and Kerst.[10] These values were determined with bremsstrahlung of maximum energy of 22 Mev.

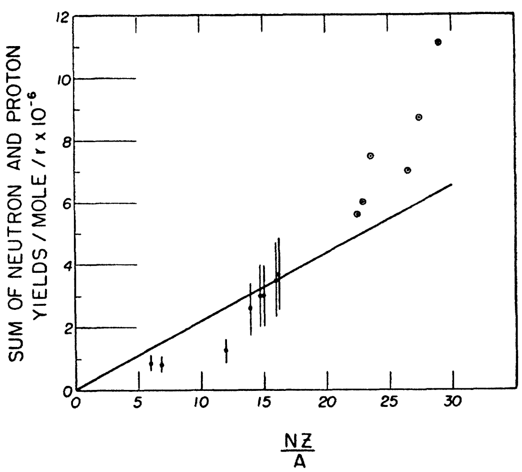

Fig. 8. Plot of the sum of the γ-n and γ-p yields as a function of NZ/A.

The cross section for excitation of a nucleus by photons is known to possess a resonance character.[11] The energy dependence of the resonance and the magnitude of the integrated cross section have been estimated by Goldhaber and Teller[12] and by Levinger and Bethe.[13] Both theories predict that the integrated cross section, $\int \sigma_a dE$, should be proportional to NZ/A. (σ_a is the cross section for photon absorption.) If the spectrum from the betatron contained equal numbers of photons in every energy interval up to the maximum, the neutron yields of Price and Kerst and our proton yields would be exactly proportional to the integrated cross sections of γ-n and γ-p processes, providing also that the maximum photon energy extended beyond the resonance in every element. The yields measured with a betatron are proportional to $\int P\sigma_a dE$, where PdE is the number of photons per cm^2 in the energy interval dE and, to a good approximation, varies as $1/E$. If, however, it is assumed that the half-widths of the cross section resonances are small compared with the energy at resonance and that the variation of the resonance energy with Z is also small, then $\int P\sigma_a dE \approx \text{const} \int \sigma_a dE$. To this approximation, the yields given in Fig. 7 can be taken as proportional to the integrated cross sections. Since $\sigma_a = \sigma_{\gamma-p} + \sigma_{\gamma-n} + \cdots$, it is necessary to add the integrated cross sections for the partial reactions to compare the experimental results with theory. The sum of the neutron and proton yields is plotted as a function of NZ/A in Fig. 8. The neutron yield values were taken directly from the data of Price and Kerst and not from the smooth curve in Fig. 7. Errors have been attached only to those points for which the proton yield

---

[9] V. F. Weisskopf and D. T. Ewing, Phys. Rev. **57**, 472 (1940).

† *Note added in proof:* Since this paper was written, we have determined the effect of absorption with increased accuracy by measuring the yields from several target thicknesses of the same element. The correction factors obtained in this way are less than those used in the present paper by 30 percent, which is just outside the estimated errors given in Fig. 7.

[10] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).

[11] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948); Johns, Katz, Douglas, and Halsam, Phys. Rev. **80**, 1062 (1950).

[12] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).

[13] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).

is an appreciable fraction (>25 percent) of the sum. Comparison with theory depends critically on the validity of the method by which the integrated cross sections are obtained from the yields. The error due to assuming that the resonances are narrow is probably small; but the assumption that the resonance energy is not dependent on Z can introduce large errors, especially with bremsstrahlung of maximum energy in the vicinity of 25 Mev. The error resulting from this approximation will, in general, make the values of the integrated cross sections appear too small. Contributions from other photonuclear processes will also increase the yield values. Further, the γ-n cross section values of Johns *et al.*[11] are consistent with the yield data of Price and Kerst only if it is assumed that, because of the difference in the techniques of measurement, a large fraction of the values from the latter arise from photonuclear reactions other than γ-n.

If we use the data of Johns *et al.* for copper, which include the experimentally determined dependence of the cross section on energy, to normalize the straight line in Fig. 8, the result is $\int \sigma_a dE = 0.044Z$ Mev-barns. This is to be compared with the prediction of Levinger and Bethe that $\int \sigma_a dE = 0.030Z(1+0.8x)$ Mev-barns, where x is the fraction of attractive exchange force for the neutron-proton potential, and N is assumed equal to Z.

ACKNOWLEDGMENTS

Each of us wishes to acknowledge a grant from the Committee on the Advancement of Research of the University of Pennsylvania. Several of the targets used in this experiment were kindly furnished by the Foote Mineral Company and the Lamp Department of the G.E. Company. It is a pleasure to acknowledge the assistance of Mr. R. H. Asendorf in the initial phase of this work and of Mr. G. Werthner, the betatron technician.

PHYSICAL REVIEW VOLUME 82, NUMBER 5 JUNE 1, 1951

On the γ-Ray Spectrum Resulting from the Absorption of π-Mesons in Deuterium*†

KENNETH M. WATSON AND RICHARD N. STUART
Radiation Laboratory, Physics Department, University of California, Berkeley, California

(Received January 22, 1951)

The γ-ray spectrum resulting from the reaction $\pi^- + D \rightarrow 2n + \gamma$ has been shown to depend strongly on the nature of the n–n interaction and has been calculated for several values of the n–n scattering length. A comparison of the theoretical cross section with preliminary experiments by Aamodt, Panofsky, and Phillips indicates: (1) an upper limit of approximately 200 kev can be put on the binding energy of the di-neutron; (2) photomeson production involves an interaction with the nucleon spin.

I. INTRODUCTION

EXPERIMENTAL studies of thec apture of π^- mesons in deuterium[1] indicate that approximately 30 percent of the capture events lead to a high energy γ-ray. This has been interpreted, for instance, as implying that the π-meson is not scalar.[2,3] However, quite apart from its implications as to the nature of the π-meson and as to meson-nucleon interactions, this experiment, as has been noted previously,[2,3] is of interest in that it offers a means of deducing something about the interaction between two neutrons.

This possibility arises through a measurement of the γ-ray spectrum resulting from the radiative decay and may be seen qualitatively as follows. Since the final state contains three particles—a γ-ray and two neutrons—the γ-ray spectrum is not monochromatic; on the other hand, if there were only the γ-ray and one particle (say a bound di-neutron) in the final state, the γ-ray spectrum would be monochromatic. If the two neutrons in the final state are not actually bound, but interact through an attractive potential, we can expect a tendency for them to recoil in the same direction with about equal velocities and thus cause the γ-ray spectrum to be more nearly monochromatic than if there were no n–n (neutron–neutron) force. That is, the effect of an attractive n–n potential should be such as to make the γ-ray spectrum show a pronounced peak near its high energy limit.

We can obtain in a simple manner the shape of the spectrum near this peak. Let us denote the transition matrix for the radiative capture to a singlet spin state for the two neutrons by M^s, and suppose that the singlet n–n wave function is $\psi^s(r)$. Then M^s will have the form (we use as units $\hbar = c = 1$)

$$M^s = \int d^3r\psi^{*s}(r)\times[\text{other factors}]. \qquad (1)$$

Let $\mathbf{p}$ be the relative momentum of the two outgoing

---

* The work described in this report was performed under the auspices of the AEC.

† This work was reported at the New York Meeting of the American Physical Society in February, 1951.

[1] Panofsky, Aamodt, and Hadley, Phys. Rev. **81**, 565 (1951).

[2] Brueckner, Serber, and Watson, Phys. Rev. **81**, 575 (1951).

[3] S. Tamor and R. E. Marshak, Phys. Rev. **80**, 766 (1950).