The Photodisintegration of the Deuteron by the Gamma-Radiation from Na^{24}

J. REGINALD RICHARDSON* AND LORENZO EMO
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
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The photodisintegration of the deuteron by the gamma-radiation from radioactive sodium Na^{24} has been observed in a cloud chamber filled with deuterium at a pressure of one atmosphere. A sample of NaF was activated by deuteron bombardment in the cyclotron to a gamma-ray strength equivalent to about 12 mg of radium, and was then brought close to the cloud chamber. Pictures were taken with a stereoscopic camera. Of the 100 proton tracks observed on 5000 pictures, only 42 were deemed suitable for range measurement, although the angular orientation of 61 could be determined. The range distribution of these tracks indicates a mean air equivalent range of 4.4 mm, corresponding to a mean energy of 410 kv for the photoprotons. This indicates that the difference between the energy of the Na^{24} gamma-ray and the binding energy of the deuteron is 820 ± 35 kv. Since the new range energy relation for slow protons has thrown doubt upon the binding energy of the deuteron, we can use the value of 3.00 ± 0.05 Mev obtained by the Compton recoil method for the energy of the gamma-radiation from Na^{24}, and obtain 2.18 ± 0.07 Mev for the binding energy of the deuteron. The angular distribution of the tracks indicates that the disintegration is predominantly photoelectric, although a small contribution from the photomagnetic effect is not ruled out. A rough calculation from the yield of tracks indicates a cross section for the disintegration of 1×10^{-27} cm². The possibilities of the method for the determination of the energy of strong gamma-radiation is discussed.

1. INTRODUCTION

A DIRECT interaction between gamma-radiation and the nucleus was discovered by Chadwick and Goldhaber[1] in 1934. At that time they found evidence indicating that the deuteron was disintegrated into a neutron and a proton when it was irradiated with the hard gamma-rays of Th C″. This corresponds to the reaction

$$_1H^2+Q_\gamma\rightarrow{}_1H^1+{}_0n^1.$$

Later,[2] they reported the measurement (with a linear amplifier) of the energy of the protons produced in the reaction. From the energy of the gamma-rays (2.62 Mev) it was then possible to calculate $Q_\gamma=\epsilon$ the binding energy of the deuteron, for which they obtained the value 2.1 Mev. A calculation of the cross section for the process yielded a value of 6×10^{-28} cm², with a possible error of a factor of two.

The photoneutrons produced in the reaction were also observed and their angular distribution was roughly found to have a maximum at right angles to the direction of propagation of the gamma-ray. On the other hand, the neutrons produced by the photodisintegration of beryllium (first reported by Szilard and Chalmers[3]) were found to have a more or less isotropic angular distribution.

A more exact method of measuring the energy of the photoprotons is to measure their range in a cloud chamber. This has been done by Chadwick, Feather and Bretscher,[4] although no details have been published as yet. A value of the range was found which leads Bethe and Bacher to evaluate the binding energy of the deuteron at 2.22 Mev.

It seemed that one could perhaps exploit this phenomenon to measure accurately the energy of the gamma-radiation from strong sources. This could be done by measuring the range of the photoprotons ejected in a deuterium filled cloud chamber. From the energy of the proton and assuming the binding energy of the deuteron one can determine the energy of the gamma-ray which caused the disintegration. Radio sodium, Na^{24}, offers a convenient source of high energy gamma-radiation to use in testing the method.

2. THEORETICAL CONSIDERATIONS

The photoelectric effect is a transition of the deuteron from the ground state ^3S to that ^3P state in the continuum which has no angular momentum around the direction of polarization

* Now National Research Fellow at the University of Michigan.
[1] Chadwick and Goldhaber, Nature **134**, 237 (1934).
[2] Chadwick and Goldhaber, Proc. Roy. Soc. **151**, 479 (1935).
[3] Szilard and Chalmers, Nature **134**, 494 (1934).
[4] Chadwick, Feather and Bretscher, *An Introduction to Nuclear Physics*, N. Feather (1936).

of the gamma-ray. This means that the relative probability of ejecting a photoproton at an angle θ with the direction of polarization of a quantum is proportional to $\cos^2\theta$. If one averages this over all directions of polarization for an unpolarized beam, one obtains that the number of photoprotons will be proportional to $\sin^2\psi$ per unit solid angle, where ψ is the angle between the direction of the incident gamma-ray and the velocity of the proton.

There is another transition, however, which could effect the disintegration of the deuteron by gamma-rays, and that is from the ^3S to an hypothetical ^1S state. This transition is forbidden, of course, for the electric dipole, but it can be accomplished by the magnetic dipole moment if there is an admixture of some spin dependent Heisenberg force in the neutron proton interaction. This assumption was originally introduced to explain the scattering of slow neutrons by protons. Evaluating the matrix elements of the magnetic dipole moment, Bethe and Bacher[5] have calculated its contribution to the cross section, assuming zero interaction range. They find for the total cross section for the photodisintegration

$$\sigma=\frac{4}{3}\frac{e^2}{c}\frac{h}{\mathrm{M}}\left\{\frac{\epsilon^{\frac{1}{2}}E^{\frac{3}{2}}}{(E+\epsilon)^3}+\frac{(\mu_p-\mu_n)^2}{4}\frac{E^{\frac{1}{2}}\epsilon^{\frac{1}{2}}(\epsilon^{\frac{1}{2}}\pm\epsilon'^{\frac{1}{2}})^2}{(E+\epsilon)(E+\epsilon')Mc^2}\right\},$$

where ϵ' is the binding energy of the ^1S level—either real or virtual; μ_p, μ_n are the magnetic moments of the proton and neutron, and $E=h\nu-\epsilon$. The minus or plus sign stands according to whether the singlet state of the deuteron is stable or virtual. For a finite range of interaction the electric contribution is increased by 60 percent, the magnetic contribution by 15 percent. (If $\epsilon'\sim 120$ kv.)

Since the photomagnetic effect corresponds to a transition $^3S\rightarrow{}^1S$, the angular distribution of the ejected protons (or neutrons) will be isotropic per unit solid angle. Thus if τ represents the ratio of the magnetic to the electric contributions, the total distribution per unit solid angle will be $\sigma_\omega d\omega\sim(\sin^2\psi+2\tau/3)d\omega$.

[5] Bethe and Bacher, Rev. Mod. Phys. 8, 83 (1936).

In an investigation of the amount of energy which a proton will receive in the disintegration, it is found that the contribution of the momentum of the gamma-ray cannot be completely ignored. Thus if ψ is the angle between the direction of propagation of the gamma-ray and the velocity of the proton, the conservation of momentum and energy indicates the energy of the proton will be:

$$E_H=\tfrac{1}{2}[h\nu(1-h\nu/2Mc^2)+h\nu\cdot(V/c)\cos\psi-\epsilon],$$

where M and V are the mass and velocity of the proton. Thus it is seen that the energy of the proton will vary with ψ in a symmetrical manner around the mean at $\psi=\pi/2$. If one takes into account the number of protons ejected per unit solid angle, neglecting the term $h\nu/2Mc^2$, the distribution of protons with energy can be obtained. This distribution for the photoelectric effect turns out to be a parabola as shown in Fig. 1. The width of the curve at half-maximum ordinate is seen to be 0.7δ where $\delta=h\nu\cdot(v/c)$ and in particular, for $h\nu=3.0$ Mev, $\delta=85$ kv. The bearing of this result on the measurement of gamma-ray energies will be discussed further in Section 5.

3. Apparatus

The cloud chamber used in these experiments was of the Blackett type, with an aluminum piston mounted in a rubber diaphragm. A source

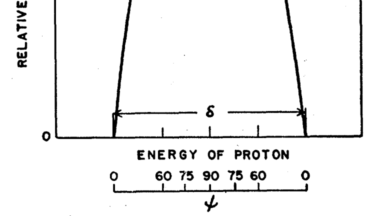

FIG. 1. The energy distribution of the photoprotons ejected by a gamma-ray of energy $h\nu\cdot\psi$ is the angle between the velocity of the proton V and the direction of propagation of the gamma-ray. $\delta=h\nu\cdot v/c$.

of alpha-particles was provided by an active deposit of polonium on the end of a copper wire. The particles were allowed to enter the cloud chamber through a copper foil equivalent in stopping power to 1.1 cm of air. A shutter, mounted on the piston, allowed only fresh tracks to enter the chamber during the expansion. The homogeneity and range of the source was also investigated by means of a linear amplifier.

Since the expected range of the photoprotons was around half a centimeter air equivalent, it was obvious that as much of the stopping power as possible should be due to atoms of deuterium which contribute to the probability of a disintegration. For this reason the chamber was filled with deuterium instead of heavy methane, although the technical difficulties in getting good tracks are somewhat greater with the former. Considerable difficulty was encountered at first in obtaining good heavy particle tracks in the presence of the high electron ionization produced by the strong gamma-ray sources used. As is the usual practice, the clearing field of the chamber was shorted out just preceding each expansion (in order to produce sharp heavy particle tracks). When the clearing field was strong enough to sweep out the general ionization, it was found that a quantity of charge collected on the glass roof of the chamber and so the field could not be taken off. This resulted in an undesirable diffusion of the heavy particle tracks. The most convenient remedy for this condition was found to be a screen of fine wire suspended across the top of the chamber.

The gamma-ray source was a target of NaF which had been bombarded in the deuteron beam of the cyclotron until it had a gamma-ray strength usually equivalent to about 12 mg of radium. The strength of the source was estimated roughly by comparing the gamma-ray ionization it produced in an electroscope with that produced by a known mesothorium source. The NaF was placed in the plane of the cloud chamber at a distance from the walls that was usually about 8 cm.

A stereoscopic camera designed by F. N. D. Kurie[6] was employed in the experiments. This camera uses an f: 4.5 lens and it was found that the light supplied by overloading eight 150-watt 110-volt lamps across 220 volts was quite sufficient for the photography of heavy particle tracks. The tracks were measured by reprojecting the images on the film through the original optical system of the camera. The reprojection image is formed on a table which may be oriented in such a way as to find the angle which a proton track makes with the incident gamma-ray. The length of the image is measured with a pair of dividers and scale. In order to test the reliability of the development and reprojection process, some glass fibers were placed in the chamber, photographed, and then their reprojected images were measured. The distribution of values obtained indicated a probable error of about two percent for the measurement of a clear track.

4. Results

In a total of about 5000 cloud chamber photographs there appeared sixty-one tracks for which the angle made with the direction of propagation of the gamma-ray could be measured. Forty-two of these tracks were deemed of suitable clearness for range measurement.

The tracks were classified into grades according to their clearness in the photographs, their apparent newness in the cloud chamber, and facility with which they could be recombined for measurement. The number of tracks in each class will give an idea of the subjective criteria employed:

Class	1	2	3	4	5
Number	13	29	19	18	20

Class 1 and class 2 included the tracks which were sufficiently clear so that their length could be measured, while in class 3 the ends of the tracks were not quite distinct enough for range measurement but the angular orientation ψ could be determined.

All the experiments were performed after midnight when the cyclotron had been turned off. It was also ascertained that there was no other source of neutrons in the effective neighborhood at the times concerned.

In order to obtain the energy of a proton from the length of its track in a cloud chamber, it is necessary to obtain the stopping power of the gas in the chamber. If this stopping power S_α is the ratio of the range of alpha-particles in air to the range in the gas, one obtains the reduced air

[6] F. N. D. Kurie, Rev. Sci. Inst. 3, 655 (1932).

range by multiplying the length of the proton by S_α. Then it is necessary to find the air equivalent[7] range by multiplying the reduced air range by the appropriate factor in order to take care of the fact that the relative stopping power of hydrogen for slow protons is much larger than for alpha-particles.[8] This factor for the case under consideration is 1.23. The value of S_α was found by measuring the extrapolated range of the alpha-particles in the cloud chamber at the time of the experiment, and performing the corresponding measurement in air (reduced to S.T.P.) with a linear amplifier or cloud chamber. The values for S_α were checked by computation, knowing the composition of the gas in the cloud chamber.

The lengths of the tracks of class 1 and class 2 were multiplied by the appropriate values of S_α to give their reduced air range. These ranges were then segregated into groups of $\frac{1}{4}$ mm width and the number in each group was counted, giving each class 1 track a weight of three class 2 tracks. Normalizing the numbers again to the actual forty-two tracks, one obtains the data plotted in histogram form in Fig. 2. The asymmetry of the curve is at first sight surprising but it is easily explained as follows: In a cloud chamber investigation in which the yield is so small, there are bound to be some old tracks which are included unwittingly with the new. These old tracks will have traversed the chamber before the completion of the expansion so that their length will be somewhat shorter than the majority of the tracks. This could very easily produce the larger tail observed on the short range side.

It is interesting to observe the individual reduced air ranges of the four class 1 tracks which make an angle greater than 80° with the direction of propagation of the gamma-ray. They are: 0.345, 0.349, 0.357, 0.372 cm, giving a mean of 0.356 ± 0.004 cm. This value, together with an inspection of Fig. 2, leads to a choice for the mean reduced air range of the photoprotons of 0.36 cm. Multiplying this by the factor 1.23 mentioned previously, we obtain the value 0.44 cm for the mean air equivalent range of the photoprotons.

Since this work was first reported,[9] an improved determination of the range energy relationship for slow protons has been published by Parkinson, Herb, Bellamy and Hudson.[10] They have measured the extrapolated range in air of protons accelerated in their two million volt generator. Their results indicate an energy for a given range (around 0.5 cm) which is about 30 percent higher than the old value based on the measurements of Blackett and Lees. This probably means that Feather's determination of the binding energy of the deuteron should now yield a lower value close to 2.1 Mev.

Application of the new range energy relationship to our data indicates that the difference between the energy of the sodium gamma-radiation and the binding energy of the deuteron is 820 ± 35 kv. This is the best that can be said toward obtaining the energy of the gamma-radiation until the value for the binding energy of the deuteron is cleared up. Recently,[11] an improved energy determination of the high energy gamma-ray line of Na^{24} has been made using Compton recoil electrons, and yielding the value 3.00 ± 0.05 Mev. We can use this value, together with the difference given above, to make an estimate of the binding energy of the deuteron. It turns out to be 2.18 ± 0.07 Mev.

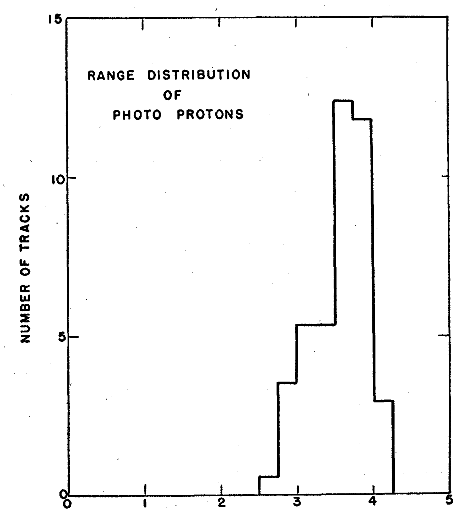

FIG. 2. The range distribution of the photoprotons ejected from deuterium by the gamma-radiation of Na^{24}. The total number of tracks is forty-two.

[7] Blackett and Lees, Proc. Roy. Soc. **134**, 658 (1932).
[8] Blackett, Proc. Roy. Soc. **135**, 132 (1932).
[9] J. R. Richardson and L. Emo, Phys. Rev. **51**, 1014 (1937).
[10] Parkinson, Herb, Bellamy and Hudson, Phys. Rev. **52**, 75 (1937).
[11] J. R. Richardson, Phys. Rev. **53**, 124 (1938).

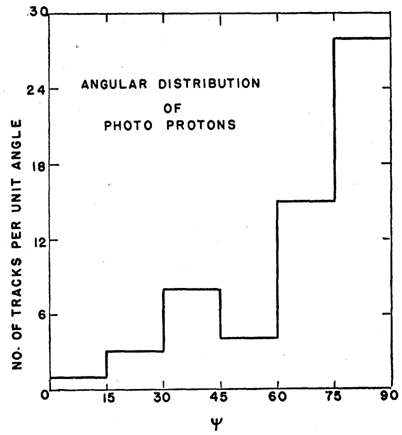

FIG. 3. The experimental distribution of the photoprotons per unit angle. Total number of tracks is sixty-one.

The angular distribution of the photoprotons was also observed. The number of tracks in each fifteen degree interval was counted and the histogram shown in Fig. 3 was drawn. In order to facilitate comparison with theory, the numbers were divided by sin ψ and renormalized, thus obtaining the number of tracks per unit solid angle. The resulting histogram is plotted in Fig. 4. The smooth curve represents the theoretical distribution to be expected from a purely photoelectric effect and has the form $\sin^2 \psi$. Experiments on the scattering of slow neutrons by protons, however, indicate the presence of a probably virtual singlet state of the deuteron at about 120 kv. By substituting this value of ϵ' into the formula of Section 2, the contribution to the cross section of the so-called photomagnetic effect can be determined. Since this effect leads to a ^1S state in the continuous spectrum of the deuteron, the angular distribution of the protons due to it will be isotropic in solid angle. The dotted curves represent the theoretical prediction for a 3.0 Mev gamma-ray and a virtual singlet state of the deuteron at 120 kv. They have been normalized to the area of the experimental histogram. Unfortunately, from the data one cannot say whether the photomagnetic effect exists or not. All that can be said is that the photoelectric effect is predominant at this gamma-ray energy.

One can make a rough estimate of the cross section for the disintegration from the yield of tracks if one knows the sensitive time of the cloud chamber, the gamma-ray strength of the Na^{24} source, the fraction of the strength in the 3.0 Mev line, etc. σ turns out to be 1.1×10^{-27} cm^2. This result is probably uncertain by a factor two. The theoretical prediction for the combined photoelectric and photomagnetic effects at $h\nu = 3.0$ Mev, if one takes into account the finite range of the neutron proton interaction, is $\sigma = 1.8\times 10^{-27}$ cm^2.

5. The Measurement of Gamma-Ray Energies

There are two obvious disadvantages to this method of measuring the energy of gamma-radiation. The first is the condition that there must be very few fast neutrons in the neighborhood, because they will knock forward some of the deuterons in the cloud chamber which will leave tracks indistinguishable from those of the photoprotons. Taking into account the relative cross sections for the two processes one sees that it is necessary that there be less than one neutron per thousand gamma-rays in order to get a reliable distribution of tracks. This precludes any work being done on the transmutation gamma-rays from bombardment by deuterons, neutrons, or alpha-particles. However, it should be possible to investigate the gamma-radiation emitted when various substances are bombarded by low energy protons.

The second disadvantage is the small cross section for the disintegration. In practice this

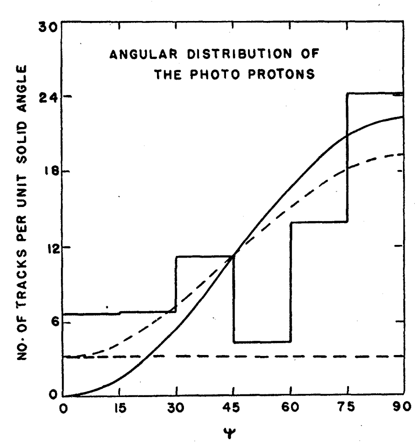

FIG. 4. The distribution of the photoprotons per unit solid angle. Formed by dividing the histogram of Fig. 3 by sin ψ and renormalizing to sixty-one tracks. The solid curve is the distribution to be expected if the disintegration is purely photoelectric. The broken curve is to be expected if there is a singlet virtual state of the deuteron at 120 kv.

TABLE I. *Information relative to the power of the method to resolve gamma-ray lines.*

Energy of gamma-ray $=h\nu$ in Mev	3.0	5.0	10	16
Energy of photoproton $=E_H$ in Mev	0.4	1.4	4	7
h.w. of E_H due to straggling in percent of E_H	7	5	4	3.5
h.w. of E_H in kv due to energy spread for all ψ	60	190	650	1370
h.w. of $h\nu$ in percent of $h\nu$	5	8	14	19
h.w. of $h\nu$ in kv taking $75° < \psi < 105°$	60	150	400	800

means that the source must have a strength of at least two millicuries in the gamma-ray line being investigated.

Whether or not two gamma-ray lines can be resolved by the method, can be determined from the width of the probable energy values of the photoprotons to be expected from a single line. Table I contains the essential information (neglecting instrumental error, which can be made small). The width at half-maximum ordinate (designated in the table by h.w.) is a convenient measure of the difference in the energy of two lines which can be just resolved.

Thus one sees that by using an angular restriction (Fig. 1) it would be possible to resolve lines differing in energy by 60 kv at 3 Mev or 800 kv at 16 Mev. This is probably the best that can be done by any method at present, particularly for the lower energies. There is also a distinct advantage in having the gamma-ray energy depend upon the mean of a distribution rather than its end point (as in the case of the Compton recoils[12] because it makes unnecessary an estimate of the instrumental probable error. Another advantage is the comparatively small dependence on angular variation, so that good results can be obtained under very difficult geometrical conditions. Obviously, the method is only applicable to gamma-radiation of energy greater than 2.2 Mev.

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[12] J. R. Richardson and F. N. D. Kurie, Phys. Rev. **50**, 999 (1936).

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The Scattering of Protons by Protons

L. R. HAFSTAD, N. P. HEYDENBURG AND M. A. TUVE
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
(Received December 13, 1937)

Our measurements of proton-proton scattering during 1936 established the existence of large *nuclear forces* between protons at close distances, in addition to the usual Coulomb forces. These nuclear forces give rise to scattering in excess of the Coulomb prediction, appreciable at 700 kilovolts and very marked at 900 kv. In the energy region between 200 kv and 600 kv the amount of scattering to be expected on the basis of *attractive* nuclear forces is radically different from that to be expected on the hypothesis of *repulsive* nuclear forces since in the first case a decrease and in the second an increase, with respect to the classical scattering, is predicted. We have accordingly extended our measurements to include this energy region, and have obtained results which can only be explained by the assumption of a strong *attractive* force of short range acting in addition to the repulsive Coulomb forces between the particles. The magnitude of the nuclear force required is in approximate quantitative agreement with that deduced from our results of 1936, experimental difficulties due to the low residual energies of the scattered particles, and the very small numbers of counts in some regions of voltage and angle (as low as three percent of the Coulomb prediction) preventing a high precision in these results below 600 kv.

INTRODUCTION

MEASUREMENTS on the scattering of protons by protons made in this laboratory last year[1] showed a considerable excess in the scattering at angles around 45° over that which would be expected for ordinary Coulomb interaction between the particles as assumed by Mott.[2] By a careful mathematical analysis,

[1] Tuve, Heydenburg and Hafstad, Phys. Rev. **50**, 806–825 (1936).

[2] Mott, Proc. Roy. Soc. **A126**, 259–267 (1930).