IV. ACKNOWLEDGMENTS

We wish to acknowledge the assistance of various members of the High Voltage Laboratory, particularly Mr. A. Sperduto and Dr. C. G. Stergis, now at Temple University. We are indebted to Mrs. H. Andrews, Miss C. O'Brien, and Mr. W. Tripp for reading the photographic plates.

This work was supported by the joint program of the Office of Naval Research and the Atomic Energy Commission.

PHYSICAL REVIEW VOLUME 76, NUMBER 12 DECEMBER 15, 1949

Investigations of the Capture of Protons and Deuterons by Deuterons

W. A. Fowler, C. C. Lauritsen, and A. V. Tollestrup
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received August 26, 1949)

The capture of protons and deuterons by deuterons has been studied up to energies of 1.5 Mev. An upper limit of $\sim 10^{-31}$ cm^2 has been found for the $D(d\gamma)$ reaction near 1 Mev. The gamma-radiation from $D(p\gamma)$ has been found to have an angular distribution obeying a $\sin^2\theta$ law. The cross section of the reaction is given empirically from 0.5 to 1.5 Mev by $\sigma = 0.74E^{0.72}\times 10^{-29}$ cm^2 for E in Mev.

THE discovery at Los Alamos[1] of 20 Mev gamma-radiation with an angular asymmetry in yield from the capture of protons by tritons led us to investigate the possibility of the emission of similar radiation in the capture of deuterons by deuterons. The excitation of the He^4 nucleus produced in this capture was expected to be 24 Mev, slightly higher than that expected and observed in the capture of protons by tritons. Because of the large number of neutrons produced in the bombardment of deuterons by deuterons a triple coincidence counter arrangement was employed. Thick targets of heavy ice were bombarded by deuterons from the electrostatic generator at an energy of 1.24 Mev. Observations were made at angles from 0° to 135° with the incident beam.

Copious radiation was observed which produced electron secondaries having ranges in aluminum as measured by the coincidence method corresponding to energies up to 8 Mev. This radiation was considerably enhanced by the introduction of paraffin and various materials such as cadmium between target and counter and could be accounted for completely as radiation caused by the capture of neutrons in materials near the experimental set-up. Above 8 Mev it was possible to set an upper limit of 2×10^{-11} quanta per proton for the yield. On the assumption that the effective target width is about 0.5 Mev, the average cross section of the $D(d\gamma)He^4$ reaction near 1 Mev is calculated to be $<10^{-31}$ cm^2. This upper limit is considerably less than that observed[2] in the $T(p\gamma)He^4$ reaction which has a cross section of $\sim 3\times 10^{-28}$ cm^2 at 1.24 Mev rising to $\sim 10^{-27}$ cm^2 at 2.6 Mev. An explanation of the low yield in the $D(d\gamma)$ reaction has been given by Professor R. F. Christy in terms of arguments based on the identity of the incident and target deuterons. The odd ^1P state in He^4 apparently responsible for the radiation in the $T(p\gamma)$ reaction cannot be produced by any combination of deuterons and deuterons.

In the course of the above investigation it was decided to investigate also the bombardment of deuterons by protons. Preliminary measurements with the triple coincidence arrangement indicated gamma-ray emission and since no neutrons were observed measurements were continued with the standard double coincidence

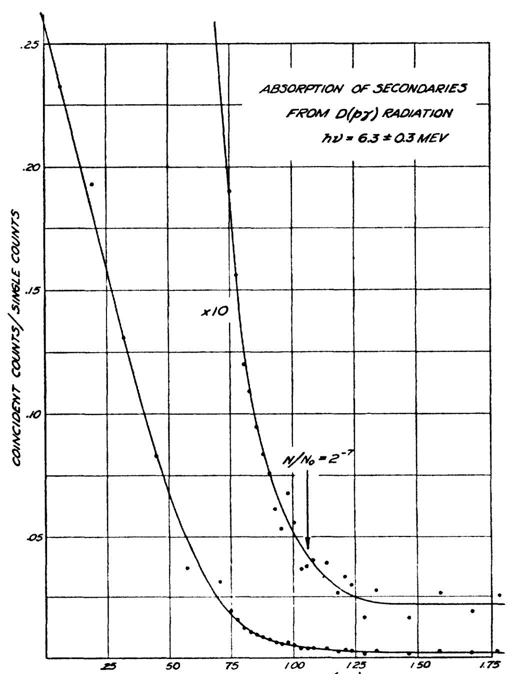

FIG. 1. Coincident counter measurements of the absorption of the secondaries produced in aluminum by the radiation from $D(p\gamma)$. The coincidence counts drop to 2^{-7} at 1.06 ± 0.05 cm of aluminum indicating a gamma-ray energy of 6.3 ± 0.3 Mev.

[1] Argo, Gittings, Hemmendinger, Jarvis, Mayers, and Taschek, Phys. Rev. **76**, 182 (1949). We are grateful to these authors for communicating to us the details of their investigations.
[2] R. F. Taschek, Phys. Rev. **76**, 584 (1949).

arrangement previously used.[3] The results of coincidence range measurements in aluminum made at a bombarding energy of 1.42 Mev with a thick target and at an angle of 90° with the incident beam are shown in Fig. 1. The number of coincidences decreases

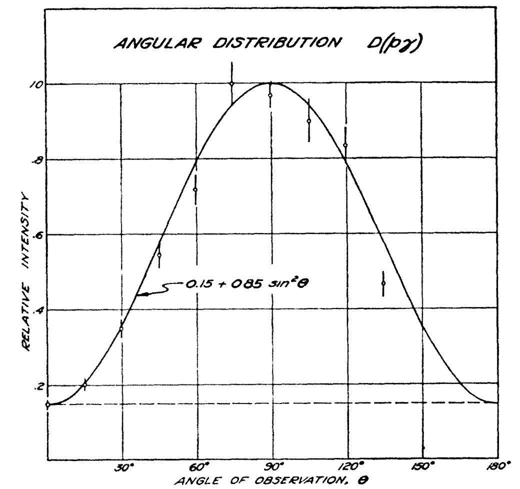

FIG. 2. Angular distribution of the $D(p\gamma)$ radiation as measured by a coincident counter arrangement subtending full angles of 30° and 45° at the target. A value of 0.04 ± 0.02 for the point at 0° was found using an arrangement subtending $18°\times30°$.

by a factor of 2^7 at 1.06 ± 0.05 cm of aluminum corresponding to a gamma-ray energy[3] of 6.3 ± 0.3 Mev. The energy computed from the masses involved in the reaction $D(p\gamma)He^3$ is 6.17 at 1.0 Mev and 6.45 Mev at 1.42 Mev bombarding energy at 90° and we have thus attributed the radiation to the capture of protons by deuterons. Ordinary ice targets gave no radiation above background thus eliminating oxygen under proton bombardment as the source of the gamma-rays.

The angular distribution of the radiation from zero to 135° at a bombarding energy of 1.42 Mev is shown in Fig. 2. The curve shown in the figure is of the form $a+b\sin^2\theta$ with $a=0.15$ and $b=0.85$. This data was obtained with a coincidence counter aperture subtending full angles of 30° vertically by 45° horizontally. With this fairly poor angular resolution it was not possible to exclude the possibility that the angular distribution actually fitted a pure $\sin^2\theta$ law. For this reason the coincidence counter arrangement was moved back from the target until the full aperture angles were 18° vertically by 30° horizontally. A careful study was made of the ratio of intensities at 0° and 90° with this arrangement with the result that $I(0°)/I(90°)=0.04\pm0.02$. Even with the improved resolution the ratio was expected to be 0.03 on the basis of the $\sin^2\theta$ law and hence we conclude that the angular distribution does fit a $\sin^2\theta$ law within a few percent. This would indicate that the radiation emanates from an electric

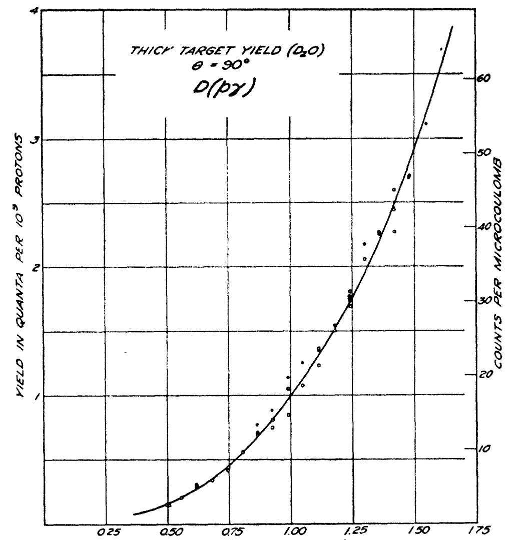

FIG. 3. The thick target yield curve at 90° for the radiation from $D(p\gamma)$. The yield is in quanta per 4π steradians per 10^9 protons.

dipole aligned with the direction of the incident proton beam. As the measurements were made with a thick target it can be concluded that the radiation at 0° is weak at all energies.

The thick target yield curve obtained at 90° as a function of bombarding energy is shown in Fig. 3. Because the single counts were comparable to background at low energies, coincidence counts have been employed in plotting the curve but the right ordinate has been normalized to the number of single counts produced at 1.42 Mev, where the background was small, in an aluminum lined counter 1.8 cm in diameter by 7.6 long at a distance of 3 cm from the target. The thick target yield at 90° in quanta per 4π steradians per 10^9 protons is given as the left ordinate. A logarithmic plot of the data indicates that $Y(90°)=E^{2.59}\times10^{-9}\gamma/p$ for E in Mev. The counting efficiency was assumed to be 4.5 percent independent of bombarding energy.[3] The total cross section obtained by differentiation of the yield curve and summing over all angles is found to be $\sigma=0.74E^{0.72}\times10^{-29}$ cm². In this calculation the variation in the stopping power of water has been taken into account and a small correction has been made for the variation of quantum energy with bombarding energy. Because of the low intensity of this radiation the coefficient in the expression has a probable error of the order of 50 percent near 1 Mev. The exponent indicating the relative variation with energy has a probable error of not more than 15 percent. A more careful determination of the absolute cross section is now underway.

In conclusion we wish to express our appreciation to Professors R. F. Christy and Aage Bohr for enlightening discussions of this problem. This work was assisted by the joint program of the AEC and the ONR.

[3] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 236 (1948).