PHYSICAL REVIEW VOLUME 86, NUMBER 4 MAY 15, 1952

Cloud-Chamber Identification of Photodeuterons from Copper*

WARREN H. SMITH† AND L. JACKSON LASLETT
Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa
(Received January 28, 1952)

The presence of a prominent group of photodeuterons, produced by the irradiation of copper with 65-Mev bremsstrahlung, was demonstrated by experiments employing a 12-in. cloud chamber traversed by a magnetic field. The mean curvature of each acceptable track studied was determined over a fixed range interval; the distribution of the curvatures so obtained provided a clear indication of proton and deuteron groups.

Helium was used as the noncondensible component of the cloud-chamber gas, in order to reduce the effect of scattering. The spread in curvature produced by scattering was determined, for protons, by a control experiment in which essentially only protons were present and the spread expected for deuterons under similar conditions was then readily estimated. The stopping power of the chamber gas was determined from the measured range of polonium alpha-particles and permitted computation of the expected mean curvatures for the unscattered trajectories of protons and of deuterons.

Analysis of the experimental composite distribution curve, representing the particles obtained in the photodisintegration of copper, into proton and deuteron components of the prescribed mean values and widths, was then uniquely possible. The deuteron to proton ratio was thus found to be 0.7_6 for equal range and solid angle intervals. It is estimated that the corresponding ratio for equal intervals of energy is approximately 0.5.

INTRODUCTION

EVIDENCE has been reported for the production of deuterons in the disintegration of copper[1] and sulfur[2] by bremsstrahlung below 24-Mev energy. In the more direct of these investigations,[1] the presence of a deuteron group was inferred on the basis of range and grain-density measurements in nuclear emulsions, and led to a ratio of photodeuterons to photoprotons cited as 0.32 for copper. Because of the bearing which such an abundant deuteron group must have on the theory of photonuclear processes, an independent investigation of the photodeuteron yield from copper was undertaken. The present experiment affords an estimate of the relative yield, in equal range and solid angle intervals, of photodeuterons and photoprotons produced by the irradiation of a thick copper target with 65-Mev bremsstrahlung.

METHOD

A 12-in. cloud chamber traversed by a magnetic field was employed, in conjunction with the Iowa State College Synchrotron, to permit the observation of tracks formed by heavy photoparticles from copper. A determination was made of the mean curvature of each track studied, in a fixed range interval extending between 4 and 14 cm from the end. Thus all protons had, except for straggling, a fixed energy interval and, similarly, the deuterons had another fixed energy interval. The distribution of the curvatures so obtained for such tracks afforded, as will be seen, a clear indication of a deuteron group.

The cloud-chamber arrangement used by Stokes[3] in the measurement of electron pairs was adapted to the measurement of heavy particles. To reduce scattering by the chamber gas, helium was used as the major, noncondensible component, together with ethanol, acetone, and water. A magnetic field of 3440 ± 100 gauss was attained, for a short period coincident with the synchrotron beam, by ignitron switching of the currents used to excite the chamber coils (1057 turns). The photon beam, admitted to the chamber through a coated beryllium window 0.005 in. thick, was approximately $\frac{7}{8}$ in. in diameter and traversed a target of commercial copper, 0.018 in. thick, at an angle of about 10 deg.

The tracks were stereoscopically photographed and reprojected to full size. All tracks ending in the illuminated portion of the chamber at least 1 cm from the wall, longer than 7 cm, and directed away from the copper target, were studied. Portions of track containing observable[4] point scattering were not used; if no section at least 3 cm long and more than 4 cm from the end of a given track could be found free from noticeable point scattering, that track was completely rejected. The average length of track over which the curvature was measured was 7.0 cm. Tracks attributable to alpha-particles or to electrons could be recognized by their appearance and were excluded from measurement. The mean curvature of the projected image was determined for each usable track by choice of the closest fitting circular arc and corrected[3] for the inclination of the track to the magnetic field. The stopping power of the

* Contribution No. 182 from the Institute for Atomic Research and Department of Physics. Work performed in the Ames Laboratory of the AEC. A preliminary account of this work was reported by one of us (W.H.S.) at the Chicago meeting of the American Physical Society in October, 1951.

† Present address: General Electric Company, ANP Project, Oak Ridge, Tennessee.

[1] P. R. Byerly, Jr., and W. E. Stephens, Phys. Rev. **81**, 473 (1951); **83**, 54 (1951).

[2] Harrington, Katz, Haslam, and Johns, Phys. Rev. **81**, 660 (1951); L. Katz and A. S. Penfold, Phys. Rev. **81**, 815 (1951).

[3] R. H. Stokes, Phys. Rev. **84**, 991 (1951).

[4] Point scattering by 0.01 radian may be observed.

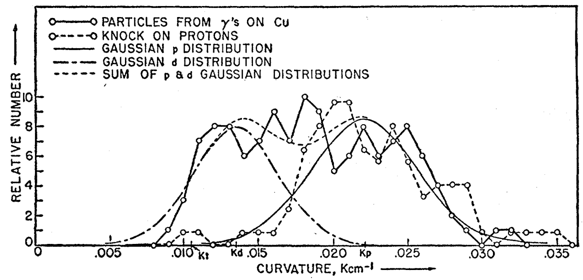

FIG. 1. Experimental curvature distribution obtained for tracks of particles produced by the photodisintegration of copper with 65-Mev bremsstrahlung. The curvature distribution obtained in a control experiment with recoil protons is also shown with the ordinate scale chosen to facilitate comparison of the two curves. The separation of the former curve into deuteron and proton components is indicated. The abscissas designated K_p, K_d, and K_t represent, respectively, the curvatures expected for tracks of unscattered protons, deuterons, and tritons.

cloud-chamber gas was determined from the measured range of polonium alpha-particles. From the stopping power, the energy and momentum were calculated as a function of range for protons and for deuterons, using published range-energy data.[5] The momentum and the magnetic field strength determine the radius of magnetic curvature, which was averaged over the standard interval to give the expected mean curvature for an unscattered path; the values so obtained for a proton and deuteron were 0.022 and 0.014 cm^{-1}, respectively. For those tracks for which the average curvature was not measured directly over the standard range interval, a suitable correction was applied to the curvature. This correction was made without prior identification of the particles and was estimated from the range-energy relation for protons. The correction was less than 12 percent except for 4 tracks; it is fair approximation for deuterons and, as applied, would not give a spurious contribution to the deuteron group.

Because of small-angle multiple scattering in the chamber gas, the measured tracks exhibited a distribution in curvature which, for each type of particle, may be shown to be Gaussian in form. This is deduced from the Gaussian character of the distribution expected for the angle of scattering, which is given by the theory of multiple scattering.[6–10] The width of the distribution in curvature, to be expected for protons under the conditions of the present investigation, was determined by a control experiment. Recoil protons were used for this purpose, and were obtained from irradiation, with polonium-beryllium neutrons, of a plastic enclosure situated within the cloud chamber. Application of scattering theory[6–9] permits a simple evaluation to be made of the width expected for the curvature distribution of deuterons, in terms of that found for protons. In this way 0.005 and 0.004 cm^{-1} were estimated as the $1/e$ half-widths for the proton and deuteron distributions, respectively, as they would occur in the present investigation.

RESULTS

The corrected curvatures of the 67 measurable tracks obtained from photonuclear reactions in the copper target were plotted in the form of a distribution curve to represent the number of tracks in a curvature interval, 0.002 cm^{-1} wide, as a function of curvature. To facilitate the interpretation, points were so plotted at increments of 0.001 cm^{-1} in curvature. This distribution, and that obtained from the control experiment, in which essentially only protons were present, may be compared in Fig. 1 and clearly indicate the presence of a strong deuteron group. By use of the known width and location of the maximum for a pure proton distribution, and the corresponding values expected for a deuteron group, a separation of the composite distribution into proton and deuteron components, also shown in Fig. 1, was performed without ambiguity. Since both the mean curvatures and widths of the separate distributions were known, this analysis involved solely the adjustment of the magnitudes of the proton and deuteron abundances.

The analysis of the distribution curve permitted an estimate to be made of the relative abundance of photodeuterons and photoprotons. The deuteron to proton ratio was thus found to be 0.7_6 for equal range and solid angle intervals. It is estimated that protons originating principally normal to the x-ray beam with energies in the range 1 to 15 Mev and deuterons in the range 1 to 20 Mev are included in this investigation. The sampling favors particles at the high-energy end of the range accepted because the section of target from which they arise is proportional to dR/dE, which increases considerably with particle energy. The deuterons lose energy more rapidly along their range, and the energy interval associated with a given range interval is larger than for protons. It is estimated, accordingly, that the deuteron to proton abundance ratio for equal intervals of energy is approximately 0.5 The large photodeuteron abundance indicated by this ratio is in agreement with the findings of Byerly and Stephens[1] from nuclear emulsion studies of the particles produced by 24-Mev bremsstrahlung.

It is a pleasure to express our thanks to Dr. J. M. Keller for many helpful discussions concerning this work and to Dr. R. H. Stokes for valuable suggestions concerning operation of the cloud chamber. We are also indebted to Mr. L. S. Ring for his very significant help in measuring the tracks.

[5] Aron, Hoffman, and Williams, *Range-Energy Curves* (Technical Information Division, ORE, Oak Ridge, Tennessee, 1949), AECU 663 (1949); UCRL-121 (1949), 2nd revision.
[6] E. J. Williams, Proc. Roy. Soc. (London)**A169**, 531 (1939).
[7] E. J. Williams, Phys. Rev. **58**, 292 (1940).
[8] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941).
[9] H. A. Bethe, Phys. Rev. **70**, 821 (1946).
[10] For the variance of radius of curvature to be expected to arise from scattering under various conditions of curve fitting, see W. Bothe, Sitzber. Heidelberg. Akad. Wiss., Math.-naturw. Klasse **5**, 105 (1948).