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INTERMEDIATE-ENERGY PHOTODEUTERONS FROM C^{12} *AND* Be^9

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The energy distributions of deuterons and protons and the energy dependences of the ratios of the deuteron to proton yields in the photodisintegration of C^{12} and Be^9 are presented. Bremsstrahlung from a synchrotron was used, with $E_{\gamma\,max} = 80$ Mev in the case of C^{12} and $E_{\gamma\,max} = 90$ Mev in the case of Be^9. The angular distributions of deuterons and protons from Be^9 are also given. A semi-empirical analysis of the results for deuterons is carried out on the assumption that the deuterons are formed in the so-called "pick-up" process. The experimental results obtained by other investigators are also analyzed.

1. INTRODUCTION

INVESTIGATIONS of deuterons produced in photonuclear reactions usually establish the ratio of the deuteron yield to the proton yield over a single and often quite broad energy range.[1,2] Only reference 3 has reported the ratio of the deuteron yield to the proton yield as a function of the energies of these particles for a few elements. We possess extremely scanty information on the angular distributions of photodeuterons.

In the investigations that have been mentioned it was determined that the ratio between the photodeuteron and photoproton yields ranges from a few percent to a few tens percent. Such large ratios cannot be accounted for by the statistical theory of nuclear reactions. The authors of reference 3 suggest without obtaining numerical estimates that the experimental results may be accounted for if deuterons are produced by the so-called pick-up process.*

It was necessary to make a detailed study of the relative photodeuteron yields as a function of energy, as well as of the energy and angular distributions. We shall give these relations for deuterons produced through the photodisintegration of C^{12} by bremsstrahlung with $E_{\gamma\,max} = 80$ Mev and of Be^9 with $E_{\gamma\,max} = 90$ Mev. The results are interpreted by means of the pick-up deuteron reaction, which means that a two-stage mechanism is assumed for the (γ, d) reaction. In the first stage the quantum is absorbed by a single nucleon in the nucleus. In the second stage, this nucleon, which is now regarded as free, snatches a complementary nucleon from the same nucleus with sufficient momentum so that a deuteron can be formed and escape from the nucleus as a bound system.

2. EXPERIMENTAL TECHNIQUE AND RESULTS

Particles ejected from nuclei as a result of photodisintegration were detected and identified by means of two independent telescopes, each of which consisted of two scintillation counters connected in coincidence and serving as spectrometers. In each recorded event, therefore, a particle passed through the thin crystal of the first counter, losing the energy $\Delta E \sim dE/dx$, and lost its residual energy E in the second crystal. The pairs of pulses, which

*The term "pick-up" is used in the foreign literature to designate the capture of a nucleon.

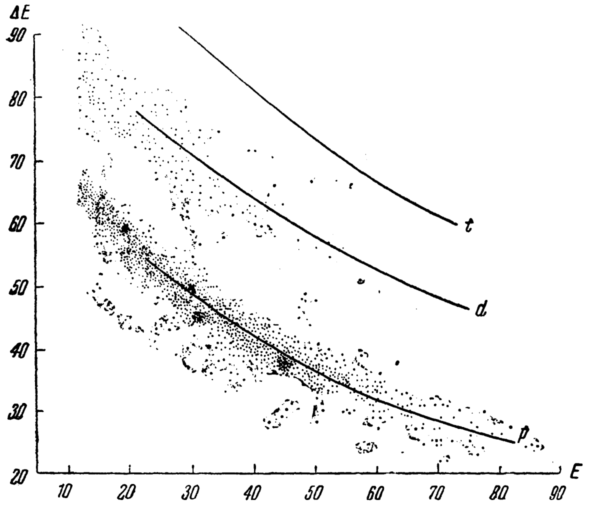

FIG. 1. Relation between energy ΔE absorbed in first telescope crystal and energy E absorbed in second crystal for particles of different masses: p – protons, d – deuterons, t – tritons.

were proportional to ΔE ~ dE/dx and E, respectively, were separated in time by a delay line, after which they passed to the oscilloscope plates and were finally photographed. The switching circuit provided for triggering of the oscilloscope beam only when a gamma-ray beam was associated with coincident pulses from the telescope counters.

When the energy resolution of the scintillation counters is sufficiently good, rapid and reliable particle identification results from an analysis of pulses proportional to E and ΔE, respectively. Adequate energy resolution for this purpose was achieved only by using NaI(Tl) crystals as scintillators. The thin crystal of the first counter had a thickness of about 0.8 mm and the energy resolution for alpha particles from a polonium source was better than 10%. The crystal of the second counter was thick enough to stop protons with energy ~ 60 Mev and the energy resolution for the gamma-ray line of the Cs^{137} source was 10 – 12%. Figure 1 gives a typical picture of the separation of protons and deuterons from Be^9. Each point represents a particle which lost the energy ΔE in the first crystal and its entire residual energy E in the second crystal. The solid curves were calculated for protons, deuterons and tritons. Points representing electrons differ markedly from all other points and are not shown in the figure. It is evident that points which can be ascribed to tritons make an extremely small contribution. In this experiment protons with energies above 50 Mev and deuterons with energies above 18 Mev are analyzed; these thresholds make it unnecessary to supply a correction for the absorption of energy in the target, air and materials protecting the NaI(Tl) crystals.

Some of our experimental data were reported at a conference on nuclear reactions at low and intermediate energies.[4] Figure 2 shows the energy distributions of deuterons and protons from Be^9 with the telescope at 90° to the direction of the gamma-ray beam. The abscissas are particle energies E in Mev and the ordinates are the numbers of protons $N_p(E_p, \theta = 90°)$ and of deuterons $N_d(E_d, \theta = 90°)$ in arbitrary units per 1-Mev energy interval and per unit radiation dose. Analogous data for C^{12} using the same notation are shown in Fig. 3. In both figures the heights of the rectangles represent the maximum statistical errors while the widths represent the particle energy in-

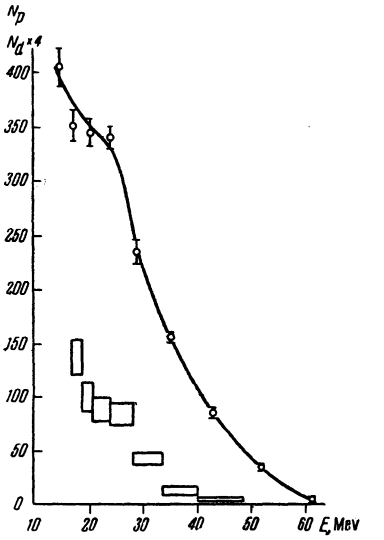

FIG. 2. Energy distributions; o – photoprotons and □ – photodeuterons from Be^9 with $E_{\gamma\,max}$ = 90 Mev. The scale of the ordinate axis for deuterons is enlarged by a factor of 4.

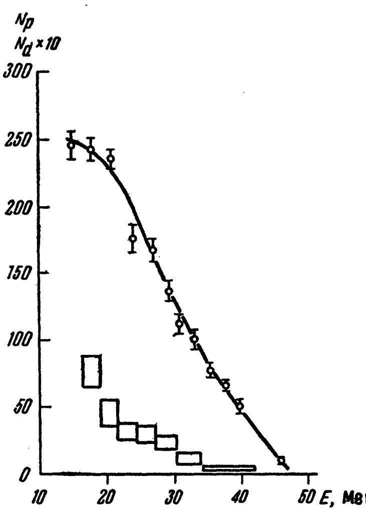

FIG. 3. Energy distributions: o – photoprotons and □ – photodeuterons from C^{12} with $E_{\gamma\,max}$ = 80 Mev. The scale of the ordinate axis for deuterons is enlarged by a factor of 10.

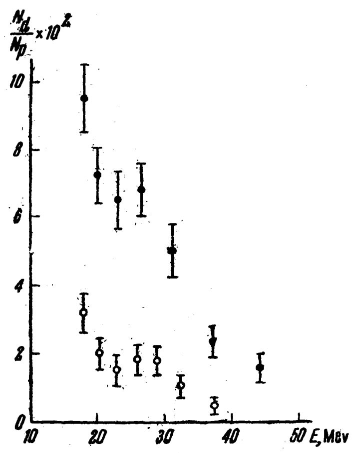

FIG. 4. Ratio of the number of photodeuterons to the number of photoprotons with the same energy, as a function of energy: o – for C^{12} and • – for Be^9.

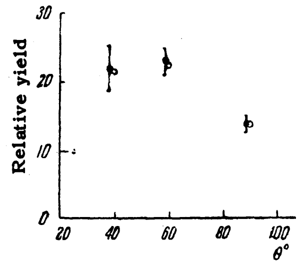

FIG. 5. Angular distributions of photodeuterons (solid circles) and of photoprotons (open circles) from Be^9.

tervals. The continuous lines are smoothed curves of experimental proton energy distributions.

Figure 4 gives the ratio

$$\frac{N_d(E_d, \theta = 90^\circ)}{N_p(E_p, \theta = 90^\circ)}$$

with $E_p = E_d$, as a function of the energy $E = E_p = E_d$ of these particles for Be^9 and C^{12}. The relative yield of deuterons from Be^9 is seen to be considerably greater than that from C^{12}. Figure 5 gives three points of the angular distributions of photodeuterons and photoprotons from Be^9 in the laboratory coordinate system. Normalization was performed by superimposing the points for deuteron and proton emission at 90° to the gamma-ray beam. The measurements include deuterons with $E_d > 18$ Mev and protons with $E_p > 16$ Mev. Figure 5 shows that the angular distributions of deuterons and protons are similar with their peaks shifted to at least 50 – 60°.

3. DISCUSSION OF EXPERIMENTAL RESULTS

As has been stated in Sec. 1, we are assuming a two-stage mechanism for the (γ, d) reaction with a gamma quantum absorbed by a single nucleon of the nucleus in the first stage, after which this nucleon is regarded as free. We may then represent the second stage of the deuteron production process as the pick-up by the free proton or neutron of its complement in the same nucleus, following Chew and Goldberger,[5] who give the angular dependence of the pick-up cross section and the dependence on incident nucleon energy. Following these authors we can write the cross section $d\sigma_{pd}/d\Omega$ for nucleon pick-up by another nucleon to form a deuteron as

$$d\sigma_{pd}/d\Omega \sim \frac{K}{k} N(\mathbf{n}) F(q), \qquad (1)$$

where K and k are, respectively, the momentum of the outgoing deuteron and of the incident nucleon, $N(\mathbf{n})$ is the distribution function of nucleon momentum $\mathbf{n}$ inside the nucleus and $F(q)$ is a function of relative nucleon momentum in the outgoing deuteron. The last factor possesses much weaker angular and energy dependence than $N(\mathbf{n})$ and will represent a constant in our subsequent applications of (1). The energy distribution of deuterons produced through the bombardment of light nuclei by monoenergetic protons and neutrons[6,7] indicates that in (p, d) and (n, d) reactions deuteron production mainly leaves the residual nucleus in its ground state or in weakly excited states (roughly speaking, up to 5 or 6 Mev). The cross section for the production of deuterons which leave the nucleus in higher excited states falls off sharply, and, as the excitation energy of the residual nucleus increases, it reaches an approximately constant value at $\kappa \approx 0.1 - 0.5$ of the cross section for the production of deuterons that leave the nucleus in its ground state or a weakly excited state. Equation (1) has been confirmed experimentally to a certain extent.[6,7] At present we have no detailed experimental data showing the dependence of the pick-up cross section on incident nucleon energy and shall use (1) as a rough approximation. In our case of continuous bremsstrahlung (also giving the proton energy distributions in the form of the continuous spectra shown in Figs. 2 and 3) the deuterons in any narrow energy interval from E_{d_0} to $E_{d_0} + \Delta E_d$ detected by a telescope at $\theta = 90°$ to the gamma-ray beam are formed by protons and neutrons emitted from nuclei at all angles and at all energies above some minimum. There is no ground for assuming that the (γ, n) cross section[8] is very different from the (γ, p) cross section or that the (n, d) cross section[7] is very different from the (p, d) cross section.[6]

We shall also assume that the energy distribution of high-energy photoneutrons does not differ greatly in shape from that of the photoproton energy distribution and we shall hereinafter speak only of (γ, p) and (p, d) reactions. In virtue of the foregoing we can then estimate the (γ, d) cross section and the deuteron energy distribution from the following expressions:

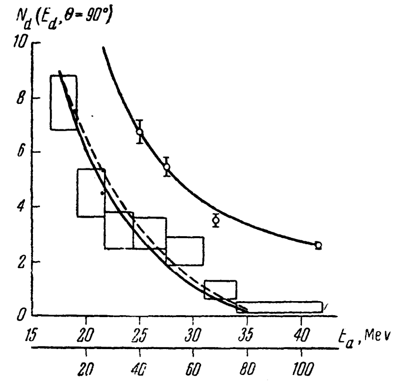

FIG. 6. Experimental and calculated energy distributions of photodeuterons from C^{12}: o – experimental values for $E_{\gamma max}$ = 300 Mev (lower abscissas), rectangles – for $E_{\gamma max}$ = 80 Mev (upper abscissas); the heights of the rectangles represent the statistical errors and the widths represent the energy intervals.

$$\int_0^{\vartheta_0}\int_0^{2\pi}\int_{E_{d_0}}^{E_{d_0}+\Delta E_d} \frac{d\sigma_{\gamma d}(E_d, \vartheta', \varphi')}{d\Omega dE_d} d\Omega dE_d$$

$$= \int_0^{\pi}\int_0^{2\pi}\int_{E_{p\,\min}}^{E_{p\,\max}} \frac{d\sigma_{\gamma p}(E_p, \vartheta, \varphi)}{d\Omega dE_p} P_{pd} d\Omega dE_p; \qquad (2)$$

$$P_{pd} = \frac{\varkappa}{\pi R^2}\int_0^{\vartheta_0}\int_0^{2\pi}\int_{E_{d_0}}^{E_{d_0}+\Delta E_d} \frac{d\sigma_{pd}(E_p, E_d)}{d\Omega dE_d} d\Omega dE_d. \qquad (3)$$

Here P_{pd} is the pick-up probability, $d\sigma_{pd}(E_p, E_d)/d\Omega\, dE_d$ is the cross section for the production of deuterons of energy E_d emitted at the angles ϑ', φ' by nucleons with energy E_p emitted at angles ϑ, φ; $\kappa = 1$ when the residual nucleus is in its ground state or is weakly excited (up to 5 Mev). For more strongly excited residual nuclei $\kappa \approx 0.1 - 0.5$. $E_{p\,min}$ is determined from the equation for the Q reaction.[9] It has been shown experimentally[6] that κ is more or less constant for the angles between proton and deuteron directions that are essential for our calculations. Making the arbitrary assumption that κ is independent of proton energy, and using (1) as the pick-up cross section in (2) with N(n) given experimentally,[6] we obtain roughly the expected energy distribution of photodeuterons from the (γ, d) reaction in C^{12}. Figure 6 gives the calculated and experimental deuteron energy distributions from the (γ, d) reaction in carbon for our case $E_{\gamma max}$ = 80 Mev (the lower solid curve for κ = 0.5 and the dashed curve for κ = 0.25) and for $E_{\gamma max}$ = 300 Mev (the upper solid curve for κ = 0.5). Experimental values were obtained from references 3 and 10 for the last case. The calculated curves were arbitrarily normalized to correspond to the experimental results, which were plotted on an arbitrary scale for each case. It is evident from Fig. 6 that the calculated and experimental deuteron energy distributions are in agreement.

From (2) we can calculate the ratio of the (γ, d) and (γ, p) reactions, $N_d(E_{d_0}, \theta = 90°)/N_p(E_{p_0}, \theta = 90°)$ for $E_{d_0} = E_{p_0}$, which is usually obtained experimentally. Then after arbitrarily normalizing the calculated ratio for $E_{\gamma max}$ = 80 Mev to the experimental results obtained by using gamma rays with $E_{\gamma max}$ = 80 Mev we determine uniquely the ratio of the number of deuterons to the number of protons for $E_{\gamma max}$ = 300 Mev. Figure 7 gives $N_d(E_d, \theta = 90°)/N_p(E_p, \theta = 90°)$ for equal proton and deuteron energies as a function of particle energy E. The lower continuous and dashed curves represent the calculated ratios for $E_{\gamma max}$ = 80 Mev using κ = 0.5 and 0.25, respectively. These curves were normalized at an arbitrary point. The upper continuous and dashed curves represent, after the first normalization, the uniquely determined ratio $N_d(E_d, \theta = 90°)/N_p(E_p, \theta = 90°)$ for $E_{\gamma max}$ = 300 Mev with κ = 0.5 and 0.25, respectively. The experimental values for $E_{\gamma max}$ = 300 Mev were taken from reference 3. It is evident from Fig. 7 that the calculation based on the two-stage (γ, d) mechanism that N_d/N_p shows a considerable tendency to grow as the maximum gamma-ray energy increases, which is also in agreement with experiment.

A more direct test of the pick-up mechanism in (γ, d) reactions would be provided by comparing with experiment the ratio N_d/N_p calculated from (2) after substituting the experimental values of the pick-up cross section $d\sigma_{pd}/d\Omega\, dE_d$. This would require experimental values of the pick-up cross section over broad intervals of proton energy val-

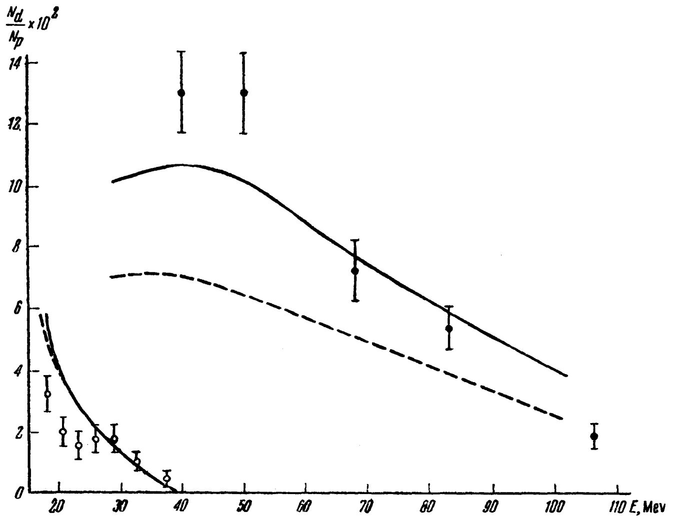

FIG. 7. Experimental and calculated ratios of the number of photodeuterons to the number of photoprotons from C^{12} as functions of particle energy: o – with $E_{\gamma max}$ = 80 Mev and • – with $E_{\gamma max}$ = 300 Mev.

ues and angles, which we unfortunately do not yet possess. However, we may attempt a rough estimate of the (γ, d) cross section in C^{12}, using experimental values of the (p, d) reaction from reference 6 or reference 11 extrapolated by means of (1) to the proton energies and angles required in (2). If (1) represents the actual energy and angular dependences of the (p, d) cross section even roughly, we may expect that the calculated and experimental values of the ratio N_d/N_p for C^{12} will agree in order of magnitude. Some indication that this extrapolation may be justified lies in the fact that when we use (1) to extrapolate the cross sections obtained from references 6 and 11 to the cross sections for the same proton energy and deuteron emission angle the numerical values are very close. The accompanying table gives the experimental values of $N_d(E_d, \theta = 90°)/N_p(E_p, \theta = 90°)$ which were represented in Fig. 7 and the corresponding calculated ratios using the experimental value of the (p, d) cross section[11] with $\kappa = 0.25$ and $r_0 = 1.4 \times 10^{-13}$ cm. The average statistical error of the experimental ratios is ± 20%, while the minimum of the (p, d) cross section taken from Ref. 11 is ± 50%. Assuming identical photoproton and photoneutron contributions to deuteron production, it is better to compare the calculated ratios given in the table with halved values of the experimental results in the table. The calculated and experimental ratios are seen to be of the same order of magnitude.

All of the foregoing estimates agree qualitatively with experimental results. Further study of the angular distributions of photodeuterons may provide additional information on the (γ, d) reaction.

$E_{\gamma\,max} = 80$ Mev			$E_{\gamma\,max} = 300$ Mev		
E_p, E_d, Mev	$N_d(E_d, \theta = 90°)/N_p(E_p, \theta = 90°)$, %		E_p, E_d, Mev	$N_d(E_d, \theta = 90°)/N_p(E_p, \theta = 90°)$, %	
	Experimental	Calculated		Experimental	Calculated
18	3.2	7.3	40	13	10.4
20.5	2	5.2	50	13	9.5
23	1.5	4.0	68	7	7.3
26	1.8	3.0	83	5.4	5.6
29	1.8	2.0			
32.5	1	1.2			

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