PHOTODISINTEGRATION OF DEUTERON AT ENERGIES FROM 50 TO 150 Mev

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Photodisintegration of the deuteron was studied with the 265 Mev synchroton of the Physical Institute of the Academy of Sciences, using D_2O and H_2O targets. Protons were counted with a telescope of two proportional counters. The differential cross section was measured at angles of 22.5, 45, 67.5, 90, 112.5, 135 and 157.5° for γ-ray energies of 54, 70, 88, 110, 129 and 148 Mev in the laboratory system. The approximate angular distribution obtained is compared with results of the calculations of Marshall and Guth.

INTRODUCTION

THE reaction of photodisintegration of the deuteron by high-energy γ-rays has been studied in a series of experiments. The first work[1-5] already showed that the behavior of the total cross section diverged quantitatively from the results of theoretical calculations[6,7] for energies higher than ~ 50 Mev. In later work,[8-12] published in the period during which the present investigation was carried out, much more precise information has been obtained about the behavior with energy of the total cross section and angular distributions for the process, in the energy range from 20 to 450 Mev.

The results of the present work, which was carried out using proportional counters, are compared with theoretical calculations and with the results of Ref. 11, obtained by means of photo emulsions, in an analogous energy range and a somewhat narrower angular range.

1. EXPERIMENTAL ARRANGEMENT

The reaction of photodisintegration of the deuteron

$$\gamma + d \rightarrow p + n \tag{1}$$

was studied for γ-ray energies from 50 to 150 Mev on the 265 Mev synchrotron of the Physics Institute of the Academy of Sciences with targets of heavy and ordinary water by counting the protons. Measurements of the energies of protons emerging at a given angle made it possible to determine the energies of the γ-rays producing the photodisintegration. The upper limit of the γ-ray spectrum in the main measurements was 264 Mev. Measurements at 22.5, 45, and 67.5° for γ-ray energies below 80 Mev were carried out for an upper limit of 170 Mev. The manner of measurement indicated separated the protons arising in the reaction (1) and the recoil protons arising in photo-production of mesons.

The separation of protons from other particles and measurement of their energies was carried out by a telescope of two proportional counters. In front of the counters there was an aluminum filter, the thickness of which was varied from 0.4 to 8.0 g/cm^2, depending on the energy of the protons being counted. The filter placed between the counters had a thickness of 0.13 g/cm^2. The angular resolution of the telescope was better than ± 3°.

Pulses from the counters were transmitted after amplification to a threshold counter and then to a coincidence scheme with a resolving time ~ 1 μsec.

The track lengths of the counted protons were determined from the value of the threshold of the second counter and the total amount of material before it. The width of the track lengths constituted 0.2 g/cm^2 of aluminum, constituting an energy width of 4.0 to 1.0 Mev, depending on the mean energy of the registered protons. Protons were separated from mesons by the magnitude of specific ionization in the first counter. Deuterons could, in principle, be counted by the telescope; however, the energy of the recoil deuterons arising in production of neutral mesons, was insufficient for them to reach the second counter.

Cylindrical proportional counters were filled to a pressure of 200 mm Hg with argon containing an admixture of 1% CO_2. For absolute calibration, a collimated source of α-particles Po^{210} was inserted. In the process of measurement, the apparatus was periodically switched over to count α-particles; this permitted control of the stability of the counting interval.

The targets were in the form of flat thin-walled containers, filled with ordinary and heavy water. The target thicknesses were determined with a given energy resolution and constituted 0.2 to 0.9 cm in different measurements. Measurement of the proton yield at a given energy was carried out in the form of successive counts from D_2O and H_2O targets, placed in turn in the γ-ray beam; this made it possible to diminish the effect of instability in the working of the measuring apparatus and synchroton. All measurements were carried out with alternating filling of each of the containers with heavy and ordinary water.

Relative measurements of the γ-ray beam were carried out with a thin-walled monitoring ionization chamber placed in the beam. Absolute calibration of the thin-walled chamber was carried out using a thick-walled graphite chamber.

2. PROCESSING OF RESULTS

The differential cross section for photodisintegration of the deuteron was calculated from the experimental results by the formula

$$\frac{d\sigma}{d\Omega}(\overline{W}) = \frac{n_p}{\Omega_{\text{eff}}\, n_{\text{nuc}}\, n_\gamma}\,\eta_{\text{ms}}\eta_{\text{nuc}}. \tag{2}$$

The number of protons n_p arising as a result of photodisintegration of deuterium nuclei, was determined by the difference in yields from the D_2O and H_2O targets. The contribution from the Compton effect on water was negligible. The standard statistical error in the number of protons constituted, on the average, 10%.

The effective solid angle for counting, Ω_{eff}, was calculated for the extended target taking into account edge effects in the counters. The accuracy of calculation was ~ 5%. Besides this, the error in measurement of the edge effects in the counters can lead to a systematic error of about 5%. The number of deuterium nuclei in one cm^2 of target, n_{nuc}, was determined to an accuracy of 3%.

The number of γ-rays n_γ incident on the whole area of the target and leading to the n_p protons, was calculated from the formula

$$n_\gamma = k\int_{W_1}^{W_2} f(W)\,\eta(W)\,dW.$$

The factor k is connected with the absolute calibration of the monitoring ionization chamber which was carried out to an accuracy of ~ 10%. The distribution of γ-rays with energy $f(W)$ was calculated from the Bethe-Heitler formula with correction for the thickness of the target and it was averaged over the energies of the electrons incident on the synchrotron target. The energy resolution was determined by the ionization slowing of the protons in the target and the finite width of the telescope interval. The resolution function $\eta(W)$ was approximately an isoceles trapezium. The width at the base $(W_2 - W_1)$ was ~ 20 Mev and the width at half-maximum, approximately 15 Mev. The error in the determination of the value of n_γ, which was not connected with the systematic error in the quantity k, did not exceed 3%. The value of the differential cross section calculated by Eq. (2) was related to the mean γ-ray energy by $\overline{W} = \frac{1}{2}(W_1 + W_2)$.

Corrections taking into account multiple scattering and nuclear interaction of the protons in the filters of the telescope enter into Eq. (2). In the calculation of corrections for multiple scattering η_{ms}, the actual extended target was replaced by a point one. Results given in Refs. 13 and 14 were used in the calculation. The size of the correction grew with increasing energy of the protons counted and usually lay in the interval from 1 to 1.2. The restrictions introduced in the calculation cannot lead to an error in the value of η_{ms} exceeding 5%.

In calculating the influence of nuclear interactions, account was taken only of inelastic proton interactions, the cross section for which was taken equal to half the total cross section measured for neutrons of the corresponding energies. The value of this correction never exceeded 1.15. The error in evaluating η_{nuc} connected with the neglect of elastic interactions was less than 5%. An estimate of the number of secondary protons created by the neutrons in the telescope filters showed that this effect could be neglected.

The error in the differential cross section, Eq. (2), was determined by the statistical error in the number of protons and the total random error from other quantities entering into Eq. (2), which did not exceed 10%. In addition, there was a systematic inaccuracy of about 15% connected with the absolute calibration of the monitor of the ionization chamber. In the future, only statistical errors will be taken into account.

3. RESULTS OF THE EXPERIMENT AND DISCUSSION

As a result of the experiment, values of the differential cross section were obtained for angles of 22.5, 45, 67.5, 90, 112.5, 135 and 157.5° in the laboratory system (l.s.). This data was split into six groups corresponding to mean γ-ray energies of 54, 70, 88, 110, 129 and 148 Mev. laboratory system. The spread of energy inside each group was substantially less than the width of the energy resolution, constituting, on the average, about ± 7.5 Mev. Values of the differential cross section obtained by averaging within each group and converted to the c.m.s. are given in Fig. 1. The total cross section is given in Fig. 2.

TABLE I. Values of the parameters obtained in approximating the angular distributions by $d\sigma/d\Omega = (A + B\sin^2\theta)(1 = 2\beta\cos\theta)$.

W_{lab}, Mev	2β	A, $\frac{\mu\text{barn}}{\text{sterad.}}$	B, $\frac{\mu\text{barn}}{\text{sterad.}}$
54	0.30	3.9	8.6
70	0.40	3.4	6.7
88	0.36	4.7	4.1
110	0.40	4.4	2.5
129	0.40	5.0	0.0
148	0.36	5.0	0.7

For comparison of our data with the results of Ref. 11, which were obtained for the same energy range and somewhat smaller angular range by photo emulsions, we approximated the angular distribution in the form

$$\frac{d\sigma}{d\Omega}\,(A + B\sin^2\theta)(1 + 2\beta\cos\theta), \tag{3}$$

connected with the choice of three parameters. The values of the parameters A, B, β (see Table I) and the value of the total cross section obtained by us agree, within the limits of error, with the results of Ref. 11.

Theoretical calculations of photodisintegration of the deuteron for energies of 20 to 150 Mev have been carried out by Schiff[6] and Marshall and Guth.[7] The total cross section and angular distribution were calculated under the assumption of a half-exchange, central force, acting between proton and neutron, for several potentials. The main term in the total cross section, according to Refs. 6 and 7, comes from electric dipole transitions. Corresponding to this, the angular distribution has a $\sin^2\theta$ character, with some asymmetry relative to 90°, caused by the interference of dipole (E1) and quadrupole (E2) electric transitions. The contribution of the magnetic quadrupole transitions (M2) calculated in Ref. 7 is small. In these articles the magnetic dipole transitions in the $^1S_0$- state leading to an isotropic yield of photo protons from deuterium are not calculated. Results of the calculations of Nagahara and Fujimura[15] for E1, E2 and M2 transitions differ little from Refs. 6 and 7; however, in Ref. 15 the M1 transition connected with the interaction with the exchange

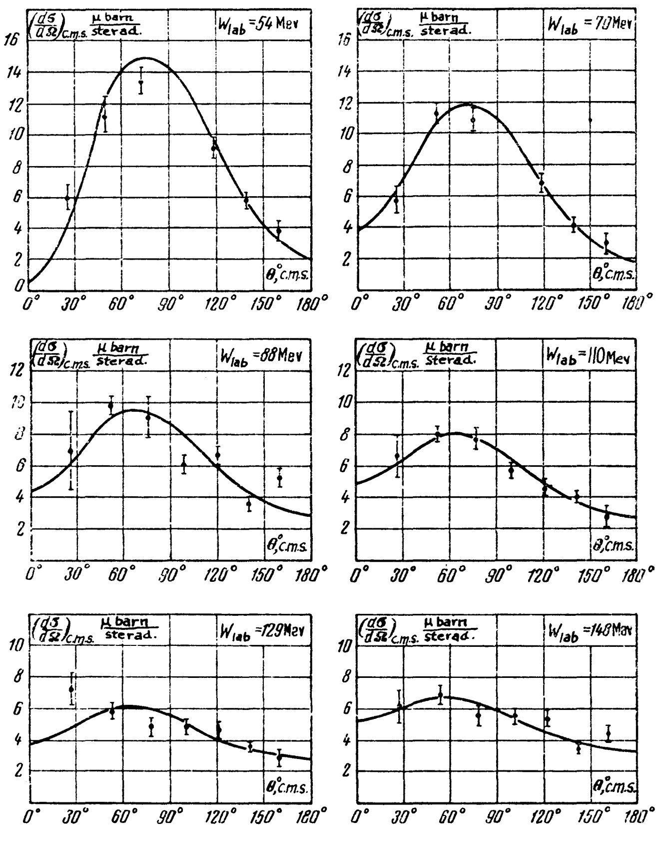

FIG. 1. Differential cross section vs. angle of the emitted proton in the c.m.s. for γ-rays of various energies (W_{lab} = 54, 70, 88, 110, 129 and 148 Mev, respectively). The solid curve corresponds to the approximate form $d\sigma/d\Omega = (d\sigma/d\Omega)_{M.G.} + P + Q\cos\theta$. Energy values have a definition of approximately 7.5 Mev. Errors of the experimental points are standard statistical errors.

magnetic moments, which are introduced phenomenologically, is also calculated.

In Fig. 2 we show our experimental points for the total cross section and curves of the total cross section calculated by Wilson[16] and Marshall and Guth.[7] Divergences from the results of Ref. 7 begin to become noticeable, apparently, at energies ~ 40 Mev, and at an energy of 150 Mev the experimental cross section exceeds that of Ref. 7 by a factor of about 5. The experimental angular distributions in this energy range also show differences, which increase with γ-ray energy, from the distributions of Ref. 7. They are characterized by a large isotropic component and a substantial asymmetry about 90°.

In view of the indicated difference between the experimental data and the results of Marshall and Guth, we approximated our angular distributions in the form

$$d\sigma / d\Omega = (d\sigma / d\Omega)_{\mathrm{M.G.}} + P + Q \cos\theta, \tag{4}$$

TABLE II. Values of the parameters, obtained in approximating the angular distributions by $d\sigma/d\Omega = (d\sigma/d\Omega)_{\mathrm{M.G.}} + P + Q\cos\theta$. The uncertainty in the parameters correspond to the standard statistical error in the proton yield.

W_{lab}, Mev	P, $\frac{\mu\mathrm{barn}}{\mathrm{sterad.}}$	$\pm\Delta P$	Q, $\frac{\mu\mathrm{barn}}{\mathrm{sterad.}}$	$\pm\Delta Q$
54	1.30	0.41	−0.76	0.55
70	2.72	0.28	0.92	0.41
88	3.50	0.37	0.81	0.56
110	3.80	0.28	1.11	0.43
129	3.27	0.29	0.42	0.43
148	4.27	0.32	1.00	0.48

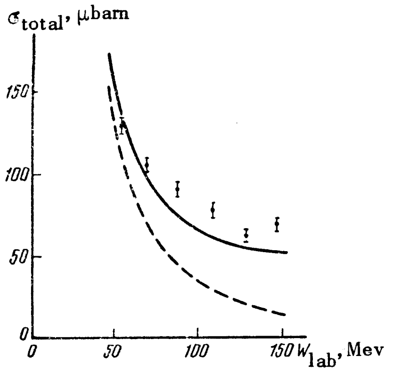

FIG. 2. Total cross section as a function of γ-ray energy W in the l.s. The solid curve is from the calculation of Wilson;[16] the dotted one, from the calculation of Marshall and Guth.[7] The errors in the experimental points are standard statistical ones.

where $(d\sigma/d\Omega)_{\mathrm{M.G.}}$ is the differential cross section of Marshall and Guth and P and Q are parameters of the approximation. Curves of the form Eq. (4), obtained by the method of least squares, are given in Fig. 1, and the values of the parameters with their errors, in Table II. The total cross section, calculated as $\sigma_t = (\sigma_t)_{\mathrm{M.G.}} + 4\pi P$, is shown on Fig. 2.

The angular distribution Eq. (4) describes well the experimental data in the energy region studied. We note that the approximation with the expression not containing the term with $\cos\theta$ is obviously unsatisfactory.

The result, Eq. (4), can be seen to be quite natural, if account is taken of the fact that, in addition to the processes calculated in Ref. 7 (E1, E2 and M2) for the energies considered, magnetic dipole M1 transitions not calculated there can be added. These transitions, beginning from the S-state, give an isotropic term in the angular distribution and their interference with M2 transitions gives a term proportional to $\cos\theta$. As noted in Ref. 6, there is no interference between magnetic and electric transitions. The total cross section for magnetic dipole transitions, equal to $4\pi P$, obtained in this interpretation, is compared in Fig. 3 with the theoretical calculations of Nagahara and Fujimura.[15] The experimental values are several times larger than the calculated result. This indicates that the particular interpretation in which magnetic dipole transitions are added to those calculated by Marshall and Guth, is, evidently, unsatisfactory.

Another possible explanation of the large isotropic component in the distribution, Eq. (4), is the supposition that, in the energy range considered, there is also the process of absorption of a dipole electric γ-ray, for which the transition into the $^3P_0$–state is large compared with transitions into $^3P_1$– and $^3P_2$–states. This process should give an isotropic yield of protons from deuterium.[17] In order to explain the forward peaking in this case, it is necessary to assume the existence of magnetic dipole transitions in the triplet state of the proton-neutron system, i.e.,

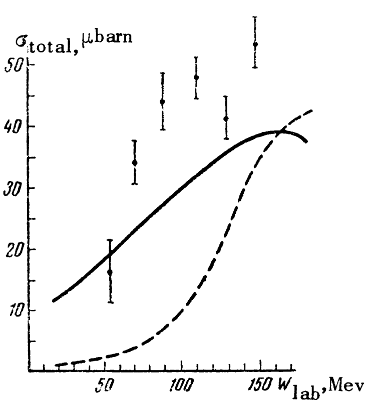

FIG. 3. Magnitude of $4\pi P$ as a function of γ-ray energy in the l.s. The experimental points are given with standard statistical errors. The solid curve comes from the results of Wilson's calculations[16] for photodisintegration by way of re-absorption of mesons. The dotted curve was calculated by Nagahara and Fujimura for magnetic dipole transitions caused by interaction of the γ-ray with the phenomenological exchange magnetic moment.

in the $^3S_1$–state. The interference of these transitions with transitions into the $^3P_0$–state gives a term proportional to $\cos\theta$.

A possible model for transitions into the $^3P_0$–state is photodisintegration of the deuteron connected with photo production of virtual mesons in an S–state on one of the nucleons of the deuteron and their successive absorption by the same deuteron. On Fig. 3 the total cross section for such processes calculated by Wilson[16,18] is compared with experimental data for the isotropic part of the cross section. The experimental points lie closer to this calculation than to the results of Ref. 15; however, the agreement is not complete.

As noted above, the model of re-absorption should be supplemented by magnetic dipole transitions into the $^3S_1$–state, which leads by itself to an isotropic distribution. Evaluation of the total cross section for magnetic dipole transitions, carried out with the experimental data using the cross section of Wilson, showed that the cross section of such transitions does not exceed 5 μbarn. We note that M1 transitions can also lead to the $^1S_0$–state; in this case they lead to an isotropic distribution, but do not interfere with the transitions into the $^3P_0$–state.

Thus, in the energy region considered, the total cross section and angular distributions for the process of photodisintegration of the deuteron can be satisfactorily described if, to the transitions calculated by Marshall and Guth, and by Wilson, magnetic dipole transitions are added, with a cross section lying within the limits of the theoretical estimates of Refs. 15 and 17.

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