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Forward- and Backward-Angle Differential Cross Section for $^2H(\gamma,p)n$ at 170 and 210 MeV

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The $^2H(\gamma,p)n$ cross section was measured for the first time simultaneously at $\theta_p^{c.m.}=0°$, 90°, and 180°. The photon energies were 170 and 210 MeV. A quasimonochromatic photon beam was used and the photon spectrum measured on line by a pair spectrometer. The results confirm the consistency among all experimental data from monochromatic photon beams and indicate that the angular distributions are less isotropic than predicted by theory. This problem might be solved by the introduction of relativistic corrections.

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The study of the differential cross sections for deuteron photodisintegration with the proton emerging in the forward and backward directions is a sensitive probe of the nucleon-nucleon interaction and of the electromagnetic properties of the two-nucleon system. In particular, it provides important information about spin-dependent transition operators, the deuteron D state, noncentral forces in the excited states, and possible exotic (nonnucleonic) phenomena.

The revival of the photodisintegration of the deuteron as a source of information on the nucleon-nucleon interaction is due in part to the disagreement between the measurements by Hughes *et al.*[1] of the 0° differential cross section over the photon energy range 20–120 MeV and the standard Partovi[2] calculation which, it was believed, should have been accurate within a few percent if conventional ideas about the two-nucleon interaction were at all correct. This result[1] was later confirmed by a few independent radiative-capture measurements[3–5] and by the experiment with bremsstrahlung photons by Zieger *et al.*[6] at 10.7 MeV. As a consequence, a number of attempts to reconcile theory with data were initiated, leading to the important observation made by Cambi *et al.*,[7] who, for the first time, showed the importance of the relativistic correction to the impulse-approximation cross section.[7–9]

Apart from the above-mentioned experiments of Hughes *et al.*[1] and Zieger *et al.*,[6] at 0°, and that of Althoff *et al.*,[10] at 180° over the photon energy range 180–730 MeV, all previous data concerned with the angular distributions of the deuteron photodisintegration process have been taken between the laboratory angles of $\approx 20°$ and $\approx 150°$. Analytic forms of the angular distributions were then assumed and extrapolations made to complete the plot of differential cross section versus center-of-mass angle at a fixed photon energy. The c.m. angular-distribution laws often assumed for this purpose were $(d\sigma/d\Omega)_{c.m.}=\sum A_L(k)P_L(\cos\theta)$, where θ is the angle between the incoming photon and outgoing proton momenta in the center-of-mass system and k is the laboratory photon energy. This form was usually chosen because the orthogonality of the Legendre polynomials P_L ensures the relative dependence of the fitted coefficients A_L.

In a previous paper,[11] we compared the behaviors of the coefficients A_L (with $L=3$) obtained by fitting of data from monochromatic photon beams[11–14] with those deduced by fitting of recent theoretical angular-distribution calculations.[7,15,16] The experimental total cross section $4\pi A_0$, as well as the interference coefficients A_1 and A_3, is reasonably well reproduced by the theoretical predictions while $-A_2$ is strongly underestimated at energies greater than 100 MeV. The coefficient A_3 cannot be determined as accurately as the other parameters: Considering the error bars, its experimental values appear in reasonable agreement with the calculations. However, the theory[15,16] predicts a different shape for the angular distributions—in particular predicts too large values at forward and backward angles and too small at 90°—compared to experiment. It is therefore evident that a nonambiguous determination of the shape of the angular distribution at photon energy above the π-production threshold can be very significant.

In this Letter we present the results of a new measurement of the differential cross section for the photodisintegration of the deuteron at laboratory photon energies $k=170$ and 210 MeV, performed to get a deeper insight into the process by a combination of forward and backward cross-section data in a new experimental approach. We have detected simultaneously the protons ejected at $\theta_p^{c.m.}=0°$, 90°, and 180°. In this way it is possible to determine the forward-to-backward ratio of the cross section with reduced systematic errors and to check the absolute cross-section normalization by means of the 90°

detector.

The experiment was carried out at Frascati with the LEALE (Laboratorio Esperienze Acceleratore Lineare Elettroni) quasimonochromatic photon beam produced by positron in-flight annihilation on a liquid-hydrogen target.[17] In addition to monochromatic annihilation photons, bremsstrahlung was also produced: in order to increase the annihilation-to-bremsstrahlung photon ratio, measurements were carried out by the collection of photons at an angle of 0.8° with respect to the positron axis. The cleaned and collimated photon beam was momentum analyzed by a pair spectrometer[18] and its integrated flux was measured by a quantameter.[17] The simultaneous measurement of the beam total energy and spectrum allowed a 3% uncertainty in the determination of the annihilation peak intensity. The photon flux used was equal to about 5×10^6 annihilation photons per second. The deuterium target consisted of a vertical Mylar cylinder (40-mm diam, 0.08-mm wall thickness), filled with liquid deuterium, inserted in the center of a dipole magnet (cylindrical in shape, 120-cm diam, 20-cm gap) which produced a uniform (within $\pm0.5\%$) magnetic field inside a cylindrical volume 20 cm high and 42 cm in diameter. The protons were magnetically deflected out of the photon beam and detected by three dual-scintillator-counter telescopes set at $\theta_p^{\mathrm{c.m.}}=0°$, 90°, and 180°, respectively. The front counters (respectively, 3-mm-, 3-mm-, and 1-mm-thick Ne 102 scintillators) gave a measurement of the energy loss ΔE. The back counters (10.4-cm-diam and 12-cm-thick NaI crystals) gave a measurement of the kinetic energy E. The gain stability of each telescope was checked on line every 10 min with two pulses generated by a green-light–emitting diode positioned on the edge of each scintillator, as described by Anghinolfi *et al.*[19] In order to correct for background protons from (γ,p) reactions in the target walls, windows, etc., measurements were performed with and without liquid deuterium in the target cell. The average contribution under the peak of these background sources turned out to be, for $k=210$ MeV (170 MeV), about 17% (13%), 4% (2%), and 25% (24%), at $\theta_p^{\mathrm{c.m.}}=0°$, 90°, and 180°, respectively.

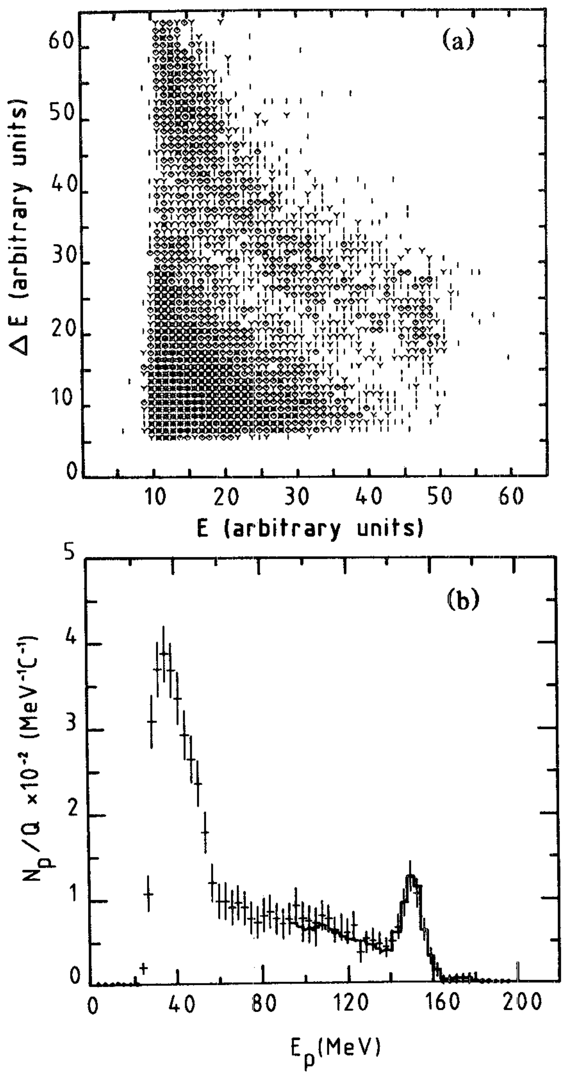

FIG. 1. (a) ΔE-vs-E plot of the events, and (b) proton energy spectrum measured at $E_{e^+}=210$ MeV from the 0° telescope. As seen in (a), protons are clearly separated from electrons and pions appearing in the low-ΔE, low-E region. The histogram in (b) is a result of a Monte Carlo calculation (see text).

Proton spectra were recorded at two positron energies, 180 and 220 MeV, and simultaneously at the three angles. The stored data were presented on line as a plot of ΔE against E and the mass discrimination was found to be sufficiently good to distinguish unambiguously protons from other particles. Figure 1(a) shows, as an example, the ΔE-vs-E plot of the events registered from the 0° telescope at $E_{e^+}=220$ MeV: In spite of the very forward angle, the separation of protons from pions and electrons is very clean, especially in the high-energy region. The relevant proton energy spectrum (after subtraction for the empty cell contribution) is given in Fig. 1(b): The peak due to the annihilation photon contribution is clearly evident. The sharp rise on the tail of the spectrum reflects the opening of the pion-production channel. The histogram, drawn for energies $k>80$ MeV, is a result of a Monte Carlo simulation used to account for the effects on the proton detectors due to finite photon beam size and extended target geometry. The program simulated the experimental photoproton spectra including for each event all the corrections, such as track reconstruction, solid angle, multiple scattering, and energy losses in the target and scintillators, rescattering by the collimators, nuclear absorption, and edge effects in the NaI crystals. Input data were the measured photon spectrum, the complete geometry of the apparatus, and a trial photodisintegration cross section which was iterated until the simulated spectra became compatible, within statistical errors, with the measured ones. The final iteration gave the true experimental photodisintegration cross section with its uncertainty. As shown in the figure, the agreement between computed and measured spectra is excellent.

The values of the differential cross sections obtained at $\theta_p^{\mathrm{c.m.}}=0°$, 90°, and 180°, by use of only the peaks in the photon and proton spectra, are shown in Fig. 2. The errors quoted are statistical only and do not include a $\pm4.5\%$ systematic uncertainty (SU) on the absolute values. Also given in the figure are the data from our previous work[11] (SU $=\pm5\%$), from Arends *et al.*[13] (SU $=\pm4\%$), and from Althoff *et al.*[10] (SU $=\pm6\%$). As is seen from the figure, the present 90° value is in good agreement within the statistical error with previous values.[11,13] This result confirms the reliability of the deuteron photodisintegration differential-cross-section values measured by use of monochromatic photon beams. These values, therefore, represent a reasonable basis of experimental data to compare with theoretical calculations.

Also in Fig. 2 the experimental data are compared with recent calculations by Laget[15] and Leidemann and Arenhövel.[16] Laget used a diagrammatical approach considering one-body currents as well as meson and isobar degrees of freedom. The final-state interaction was treated approximately in S and P waves using as an *Anstaz* a separable NN T matrix of different types. Leidemann and Arenhövel have studied the importance of Δ-isobar degrees of freedom in NN scattering, by using a coupled-channels approach, and have analyzed especially the effect of various models for the potential and Δ width. For normal and meson-exchange contributions they have considered multipoles up to $L=4$ and for the isobar part, in order to save computing time, only up to $L=3$, having checked that inclusion of higher multipoles is negligible. It is seen that neither calculation describes the experimental shape well, the theoretical cross sections being too large at forward and backward angles and too small at $\theta_p^{\mathrm{c.m.}}=90°$.

Figure 3 shows all the 0° and 180° differential-cross-section data presently available as functions of the photon energy. Where available, we also show the theoretical results from Laget[15] (dashed curves) and Leidemann and Arenhövel[16] (dot-dashed curves). The dotted curve is a result of a recent calculation by Laget[20] obtained after the inclusion of D-wave final-state interactions. As shown, this inclusion improves the agreement with data at low energies (< 120 MeV), while at higher energies the theoretical results are lower at 0° and higher at 180°. Leidemann and Arenhövel[21] have assumed that the spin-orbit current gives the dominant relativistic contribution also in the Δ region, as already shown below 140 MeV by Cambi *et al.*[7] Therefore they have included this effect in their calculation as a first step toward an

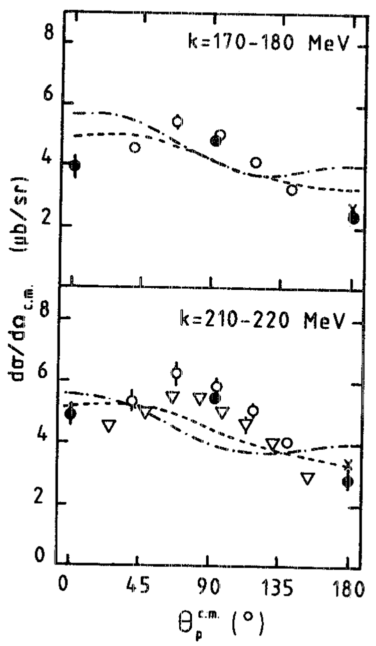

FIG. 2. Experimental and theoretical angular distributions for the process $^2\mathrm{H}(\gamma,p)n$ at the given photon energies: filled circles, present work; open circles, Ref. 11; triangles, Ref. 13; crosses, Ref. 10. The quoted errors are statistical only; where not visible they are smaller than the sizes of the points. Theoretical curves: Ref. 15 (dashed curve) and Ref. 16 (dot-dashed curve).

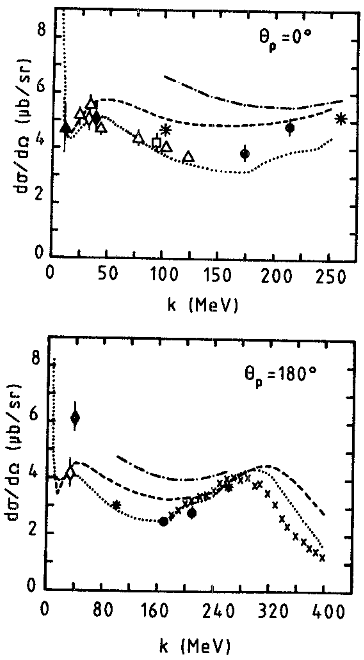

FIG. 3. The excitation functions, at $\theta_p=0°$ and 180°, for the process $^2\mathrm{H}(\gamma,p)n$: circles, present work; open triangles, Ref. 1; open lozenges, Ref. 3; filled lozenges, Ref. 4; square, Ref. 5; filled triangles, Ref. 6; crosses, Ref. 10. The quoted errors are statistical only; where not visible they are smaller than the sizes of the points. Theoretical curves: Ref. 15 (dashed curves), Ref. 16 (dot-dashed curve), Ref. 20 (dotted curves), and Ref. 21 (asterisks).

improved version of their theory. The resulting differential-cross-section values obtained in such a way at 100 and 260 MeV are shown as asterisks in Fig. 3: One notes a significant reduction of the calculated values, in better agreement with the experimental data.

In conclusion: (i) We have measured for the first time the cross section for the photodisintegration of the deuteron simultaneously at 0° and 180°. (ii) The result of this measurement confirms the consistency of the deuteron photodisintegration differential-cross-section values obtained with monochromatic photon beams. (iii) Our 180° cross-section values are in agreement, within total errors, with the data of Althoff *et al.*[10] (iv) A major problem remains in that the angular distributions predicted by presently available theories are of different shape compared to experiment. (v) This problem might be solved by the introduction of relativistic corrections, as was seen in the energy region below the pion threshold.[7-9]

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