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Photodisintegration of the deuteron between 100 MeV and 320 MeV

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Abstract. The photodisintegration of the deuteron has been studied for photon laboratory energies from 100 MeV to 320 MeV. Recoil protons were detected in a counter telescope and the effects of more complex reactions investigated by varying the bremsstrahlung end-point energy.

1. Introduction

The photodisintegration of the deuteron, in the energy region below meson threshold, is well accounted for by both theory and experiment (Donnachie and O'Donnell 1964, Partovi 1964, Le Bellac *et al.* 1964). However, in the region between the meson threshold and the (3, 3) resonance, where the reaction is increasingly influenced by mesonic effects, serious differences exist between the most recent experimental data of Kose *et al.* (1967) and those of earlier workers. At present there is no fundamental theory covering this region, and the existing phenomenological calculations (Pearlstein and Klein 1960, Wilson 1956) do not give an unambiguous indication of the validity of any particular set of measurements. Further experimental work seemed indicated, particularly as it has been suggested that a comparison between deuteron photodisintegration in the resonance region and the inverse n–p capture reaction would give information on T-violation effects in electromagnetic interactions.

The most detailed of the earlier investigations was that of Keck and Tollestrup (1956), who measured the energy and emission angle of the recoil protons from the reaction. Protons resulting from pion production reactions were separated from photodisintegration recoils by their characteristic kinematics.

Kose *et al.* employed a neutron counter in coincidence with their proton telescope to discriminate against more complex reactions, and suggested that the difference in their measurements was due to earlier workers' failure to eliminate competing processes. For example, an examination of the kinematics of the possible reactions shows that, at 40° to a 300 MeV bremsstrahlung beam, the spectator neutron process for π^0 production on deuterium will produce a recoil proton of maximum energy 50 MeV which cannot be distinguished from a proton due to simple photodisintegration at a photon energy of 80 MeV. However, the corresponding reaction with the π^0 and neutron recoiling as a single unit (N* production) could produce a recoil proton of maximum energy 120 MeV, identical with that associated with a photon energy of 180 MeV for photodisintegration.

Keck and Tollestrup carried out measurements at bremsstrahlung end points of 500 MeV, 400 MeV and 300 MeV, and may have included protons associated with N* production in their results. It was assumed that the yield of protons from this reaction was negligible as they observed no component having the appropriate dependence on angle and energy. However, the N* resonance is now known to have a width of 120 MeV—sufficient to conceal any effects which they could observe.

The present experiment attempts to determine both the photoproton yield due to photodisintegration and that due to inelastic reactions by measuring the yield per equivalent quantum as a function of the end point of the photon spectrum.

2. Experimental details

The target, consisting of a 1·5 cm thick slice of liquid deuterium contained between walls of thin Melinex film, was placed in the bremsstrahlung beam of the Glasgow synchrotron.

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The beam intensity was monitored by a quantameter of the Wilson (1957) design, calibrated by theoretical calculation to an accuracy of 3%. The shape of the bremsstrahlung spectrum had been measured earlier at 297 MeV end-point energy, and the tables of Penfold and Leiss (1958, unpublished) were modified to reproduce the experimental spectrum at other end-point energies.

In order to minimize corrections for scattering and absorption, the proton detector employed was a dual scintillation counter telescope, in contrast with the multi-element counter/absorber telescopes used by earlier workers. The front counter, consisting of a 0·5 in × 3 in × 6 in NE102A scintillator on a 56 AVP photomultiplier, gave a measure of dE/dx; while the back counter, a 4 in × 4 in NaI (Tl) crystal coupled to a 58 AVP photomultiplier, gave a simultaneous measure of the total energy E. Despite the long decay time of the NaI light output, this crystal was preferred to NE102A for energy measurement because of its superior combination of stopping power and resolution.

The limited anode pulses from the 58 AVP were shaped with an 8 ns shorted delay line, permitting measurements to be made at high counting rates without pile-up affecting the coincidence resolution of the telescope. Coincident energy measuring pulses from both telescope counters were accumulated in a 1024-channel Laben analyser arranged for bi-dimensional analysis. The stored data were formed into a plot of dE/dx against E and the particle discrimination was found to be sufficient to distinguish unambiguously deuterons, protons, pions and the electron background.

Proton spectra were recorded at seven angles between 29° and 140° to the photon beam. At forward angles measurements were made at five bremsstrahlung end-point energies between 210 MeV and 330 MeV to investigate secondary contributions to the photoproton spectrum from other processes such as $N^*_{3/2\,3/2}$ production.

3. Results

Proton yields at an angle of 40° measured with five different bremsstrahlung end-point energies are shown in figure 1 and clearly demonstrate an increasing inelastic contribution,

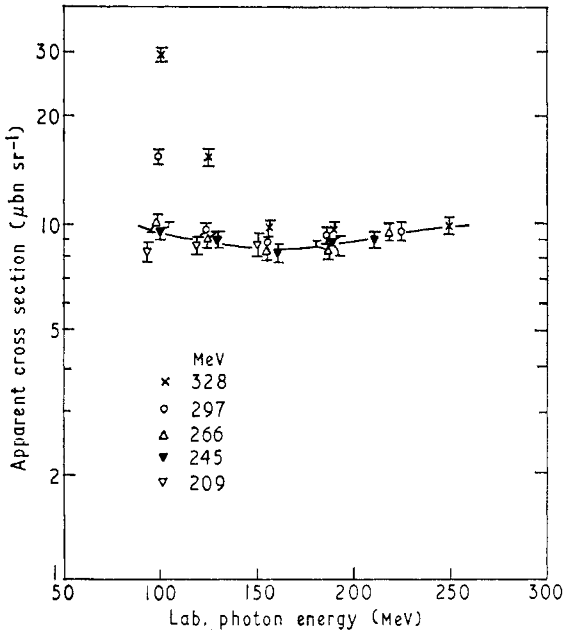

Figure 1. Apparent cross section measured at 40° to the beam for five different bremsstrahlung end-point energies.

which depends upon the value of the end point of the photon spectrum. The photon energy is derived from the kinematics of the photodisintegration reaction, and the curve represents our values of the differential cross section at 40° for the deuteron photodisintegration alone.

These measurements enabled us to select an appropriate bremsstrahlung end-point energy to avoid inelastic contributions to our measured differential cross section at a given angle and photon energy.

As a check on the interpretation of the excitation functions at one angle, the subtraction technique was applied to yield proton spectra due to a narrow energy band of photons. Figure 2 shows the subtracted proton spectra at 40° produced by (*a*) 225 ± 18 MeV photons

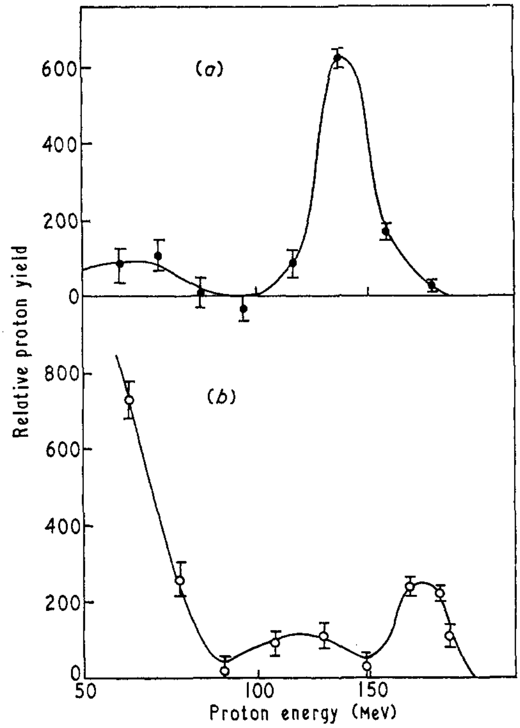

Figure 2. Subtracted proton spectra produced by photons of energies (*a*) 225 ±18 MeV, and (*b*) 280 ±15 MeV.

and (*b*) 280 ± 15 MeV photons. In the former a monoenergetic proton spectrum is obtained, showing that the protons were due to d(γ, p)n, but in the latter there are additional groups of lower-energy protons from competing reactions.

Differential cross sections in the centre-of-momentum system were fitted to an angular distribution of the form

$$\frac{d\sigma}{d\Omega} = a + b\sin^2\theta + c\cos\theta$$

representing the most important terms of the predicted low-energy distribution

$$\frac{d\sigma}{d\Omega} = a + b\sin^2\theta + c\cos\theta + d\cos\theta\sin^2\theta + e\cos^2\theta\sin^2\theta.$$

The total cross section was obtained as

$$\sigma_T = 4\pi(a + \tfrac{2}{3}b).$$

Values of the total cross section and the isotropy ratio, a/b, are shown in figures 3 and 4, respectively, together with previous measurements and theoretical predictions. The present measurements are in excellent agreement with the data of Keck and Tollestrup (1956), and no indication of the smaller cross sections obtained by Kose *et al.* (1967) has been found.

Marked fluctuations in the values of a/b obtained by Kose *et al.* are evident in the region where disparities exist, while the correspondence of the present measurements with the energy variation of the predicted isotropy ratio of Pearlstein and Klein (1960) supports their interpretation of the process.

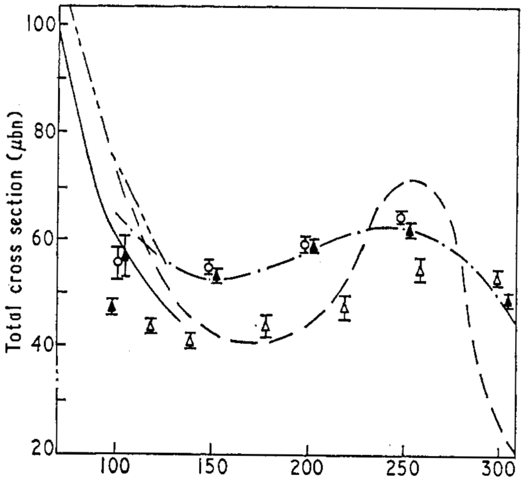

Figure 3. Total cross section. Results: ○ of present experiment; ▲ Keck and Tollestrup 1956; △ Kose *et al.* 1967. Predictions: – – – – Donnachie and O'Donnell 1964; ——— Le Bellac *et al.* 1964; — · — Wilson 1956; — — Pearlstein and Klein 1960.

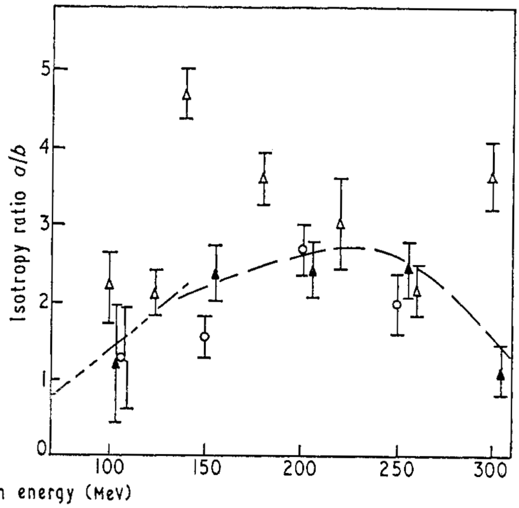

Figure 4. Variation of the isotropy ratio with energy. Results: ○ of present experiments; ▲ Keck and Tollestrup 1956; △ Kose *et al.* 1967. Predictions: – – – – Donnachie and O'Donnell 1964; — — Pearlstein and Klein 1960.

4. Discussion

The close agreement with the earlier measurements of Keck and Tollestrup may at first seem surprising, as we have found contributions to the proton yields from competing processes which they could not have eliminated. However, these contributions are prominent only at forward angles and would not have affected the total cross-section data derived by Keck and Tollestrup above 170 MeV photon energy. Moreover, their results for 105 MeV do not include an angle forward of 56°, thereby minimizing inelastic contributions to their integrated total cross section.

It is difficult to reconcile the marked difference between the measurements of Kose *et al.* and the earlier measurements in terms of unrecognized competition from N* production processes. In addition, it should be noted that under conditions where N* production processes are kinematically excluded (e.g. at 90° with a 300 MeV bremsstrahlung end point) the two sets of results still differ, in contrast with the opinion of Kose *et al.* that differences were entirely due to their elimination of competing processes.

The predicted cross section of Pearlstein and Klein (1960) shows a more pronounced minimum than was observed. This results from the employment of the cross section calculated by de Swart and Marshak (1958) for photon energies up to 80 MeV. A similar study making use of the more extensive recent calculations of Matsumoto (1963) might be expected to provide much better agreement with the observed cross sections. The present measurements are in good agreement with the curve given by Wilson (1956). However, it should be noted that, although these phenomenological calculations can indicate the variation of the cross section with energy, they cannot give the absolute magnitude of the cross section in the region of the (3, 3) resonance.

Note added in proof. Buon *et al.* (1968) have reported an investigation on the photodisintegration of the deuteron from 140 to 400 MeV. They also defined the reaction by recording the recoil proton alone. Although the shapes of their angular distributions below 300 MeV show substantial agreement with those of Keck and Tollestrup and this present experiment, differing markedly from the results of Kose *et al.*, their total integrated cross sections are in better accord with the latter results.

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