

some suggestion of peripheral peaking. [See, for example, B. Musgrave *et al.*, *Nuovo Cimento* **35**, 735

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ANGULAR DISTRIBUTION OF DEUTERON PHOTODISINTEGRATION BETWEEN 240 AND 320 MeV*

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The angular distribution of deuteron photodisintegration has been measured at laboratory photon energies from 240 to 320 MeV in a spark chamber experiment at the Cornell 2-GeV synchrotron. The angular dependence of the cross section is consistent with other recent measurements. A comparison with data on the inverse reaction, $n + p \rightarrow d + \gamma$, should provide a meaningful test of time-reversal invariance in electromagnetic interactions of hadrons.

It has been suggested¹ that a violation of time-reversal invariance in the electromagnetic interactions of hadrons may produce a violation of reciprocity by the angular distributions of the reactions

$$\gamma + d \rightarrow n + p, \quad (1)$$

$$n + p \rightarrow \gamma + d, \quad (2)$$

at energies near the peak in the cross section due to the influence of the $\Delta(1236)$ resonance. In anticipation of forthcoming experimental results for the radiative neutron capture,² new measurements of deuteron photodisintegration have been undertaken in the hope of resolving the substantial discrepancies between the previously published results.^{3,4} Counter measurements have now been made using proton range,³ proton range in coincidence with the recoil neutron,⁴ and magnetic spectrometers.^{5,6} The present Letter reports a new measurement performed at the Cornell 2-GeV electron synchrotron using wire spark chambers.

The experimental arrangement is shown in Fig. 1. Unpolarized bremsstrahlung beams of 350- and 450-MeV maximum energy were produced from an internal target of the synchrotron. The beam, after collimation and sweeping, struck a 3.2-in. long liquid-deuterium target. The momentum of the recoil proton was measured by means of four magnetostrictive-delay-line wire

spark chambers located behind a bending magnet with a 6- by 18-in. pole gap, 36 in. long, mounted so as to bend particles in a vertical plane. Each chamber consisted of a single 0.375-in. gap bounded by two orthogonal planes of copper wires with an interwire spacing of 0.042 in., and had an active region 10 in. wide and 30 in. high. The system was triggered by three large-area scintillation counters in coincidence. The discriminator biases were adjusted to minimize triggers from minimum-ionizing particles. A helium bag extended from the target vacuum chamber through the magnet gap. The counters and chambers were rigidly attached to the magnet, which could

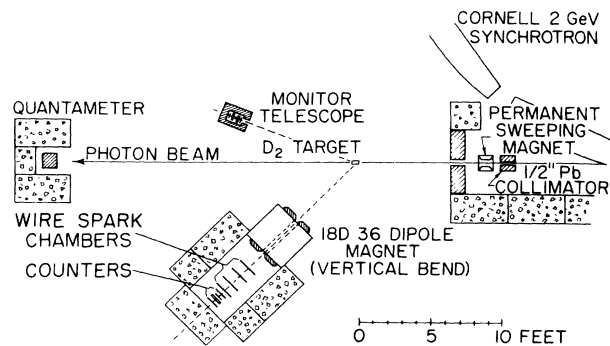


FIG. 1. Experimental layout showing the photon beam, wire-spark-chamber spectrometer, quantameter, and monitor telescope (15° with respect to the beam).

be rotated about the target position. The raw coordinates from the chamber delay lines, together with the pulse heights of the counters and instantaneous counts of various scalars, were written directly on magnetic tape after each event for later analysis.

A totally absorbing ionization chamber (quantameter) was located behind the target and collected virtually all of the incident beam to serve as the primary monitor of beam intensity. A counter telescope consisting of three small scintillation counters monitored the flux from the target at 15° from the beam line on the side opposite the magnet. Its output coincidences were counted in separate scalars which were gated on during the live time and during the 450-msec dead time of the chamber readout system. The ratio of "live-time" pulses to all pulses provided a correction to the quantameter reading for the portions of beam pulses incident on the target during the dead time following a trigger. Dead-time-corrected event rates for equivalent runs taken at widely different beam intensities agreed within their statistical errors, indicating that the correction was well understood.

All desired proton momenta (from 360 to 1000 MeV/c) were detected simultaneously at a single magnetic field setting of 7.4 kG. Data were recorded at six laboratory angles, between 23.8° and 130.0° , with the synchrotron energy at 350 MeV. Additional runs at 450-MeV synchrotron energy, yielding comparable statistics, were taken at three of the angles. For each angle and energy, background runs with the target cup empty were also recorded.

In the analysis of the data a least-squares straight line was fitted to the coordinates of each event which indicated the presence of sparks in three or four chambers. No attempt was made to fit more than one track in events with multiple sparks in three or more chambers, since the number of such events constituted no more than 0.5% of the data in any run. The straight-line trajectory was projected through the magnetic field region to an assumed intersection with the center line of the target cup, and the momentum of the proton was calculated from the trajectory. The momentum of the proton at the point of interaction was obtained by correcting for energy loss in the target, vacuum chamber, and helium bag. The 1-in. diameter of the beam at the target contributed to the momentum resolution through both the original trajectory calculation and the energy-loss correction. The momentum resolution

thus varied with angle and energy, but always had a standard deviation of less than 1.7%. Particle trajectories were required to satisfy geometric cuts which assured that the protons did not scatter from the magnet pole surfaces. The longitudinal position of the interaction in the target, which was not assumed in reconstructing the trajectory, was calculated and plotted, and provided a check on the source of the empty-target background. The empty-target yield, which varied from 10 to 20% of the full-target yield, was found to originate entirely in the windows of the target cup and vacuum chamber, which could be resolved with a standard deviation of 0.6 in. or 0.006 rad.

Using the corrected momentum, the laboratory energy of the incident photon was calculated from the two-body kinematics of deuteron photodisintegration. The low maximum photon energy of the beam precluded other possible final states except for the nonresonant production of single pions, which was shown to be negligible by the good agreement of the data taken at 350- and 450-MeV synchrotron energy.

Each event was assigned to a 20-MeV wide bin of photon energy and weighted by the solid-angle acceptance corresponding to the proton momentum. The solid-angle acceptance $\Delta\Omega(p)$ of the spectrometer was calculated by determining the region in the entry plane of the magnet gap inside which all particles of a specified momentum, originating at a point in the target, would be accepted. This acceptance was averaged over the active volume of the target. Three sets of geometric acceptance cuts were used in the analysis of events, with a separate solid-angle acceptance function calculated for each. The cross sections obtained using the three cuts agreed within their statistical errors, verifying the solid-angle acceptance calculation to within 3%. In the final presentation of data, only the least restrictive of the three cuts was used, in order to minimize the statistical errors. An additional test of the acceptance calculation was provided by plotting the intercepts of accepted trajectories with the magnet entry plane as a function of momentum. The solid angles which were calculated from these data using simple geometry also agree with the original calculation.

The shape of the bremsstrahlung spectrum was determined by a calculation which included the effects of target thickness and collimation.⁷ The results of the experiment were quite insensitive to the details of this calculation.

Table I. Cross sections and angular distribution coefficients for $\gamma + d \rightarrow n + p$. The errors listed are statistical only. Additional systematic errors totaled a maximum of 5.4%.

Photon Energy (MeV)	$E_{c.m.}^{tot}$ (MeV)	$(\frac{d\sigma}{d\Omega})_{c.m.}$ ($\mu\text{b/ster}$)	Laboratory Angle, θ_L						Coefficients of Least Square Fits ^b				
			23.8°	47.5°	68.2°	90.0° ^a	110.2°	130.0° ^a	A	B	C	B/A	C/A
230 - 250	2102		5.45 ±.30	6.59 ±.22	6.22 ±.20	5.60 ±.20	4.42 ±.12	3.89 ±.09	6.03 ±.10	1.41 ±.14	-1.86 ±.26	.234 ±.023	-.309 ±.039
250 - 270	2120		5.83 ±.31	6.38 ±.24	6.33 ±.21	5.88 ±.12	4.83 ±.13	4.12 ±.09	6.25 ±.11	1.23 ±.15	-1.96 ±.27	.197 ±.023	-.313 ±.039
270 - 290	2137		5.62 ±.31	6.05 ±.26	6.05 ±.22	5.38 ±.13	4.58 ±.13	4.12 ±.10	5.79 ±.12	1.13 ±.15	-1.37 ±.28	.193 ±.026	-.237 ±.044
290 - 310	2155		5.04 ±.31	5.60 ±.25	5.45 ±.22	5.19 ±.13	4.26 ±.14	3.79 ±.10	5.48 ±.12	0.91 ±.15	-1.61 ±.28	.167 ±.027	-.293 ±.046
310 - 330	2172		4.41 ±.30	4.93 ±.26	4.74 ±.22	4.30 ±.13	3.61 ±.13	3.21 ±.10	4.65 ±.12	0.90 ±.15	-1.20 ±.26	.193 ±.031	-.257 ±.052

^a Combined cross sections measured at 350- and 450-MeV synchrotron energy. Other angles were measured at 350 MeV only.

^b Assuming $(d\sigma/d\Omega)_{c.m.} = A + B \cos\theta_{c.m.} + C \cos^2\theta_{c.m.}$. The errors in B/A and C/A include correlations between coefficients.

Approximately 4×10^5 events were analyzed, and 80% of these yielded good least-squares straight lines. The remaining events included

faulty magnetic tape records, false triggers due to cosmic rays and low-energy scattered background in the counters, and a 1 to 7% inefficiency in the chamber system which was calculated separately for each run.

Complete angular distributions were obtained at 20-MeV intervals of photon energy between 240 and 320 MeV, a region which includes the broad $\Delta(1236)$ peak at about 275 MeV. The cross sections are displayed in Table I. Least-squares fits of the forms

$$d\sigma/d\Omega_{c.m.} = A + B \cos\theta_{c.m.} + C \cos^2\theta_{c.m.}, \quad (3)$$

$$d\sigma/d\Omega_{c.m.} = A + B \cos\theta_{c.m.} + C \cos^2\theta_{c.m.} + D \cos^3\theta_{c.m.}, \quad (4)$$

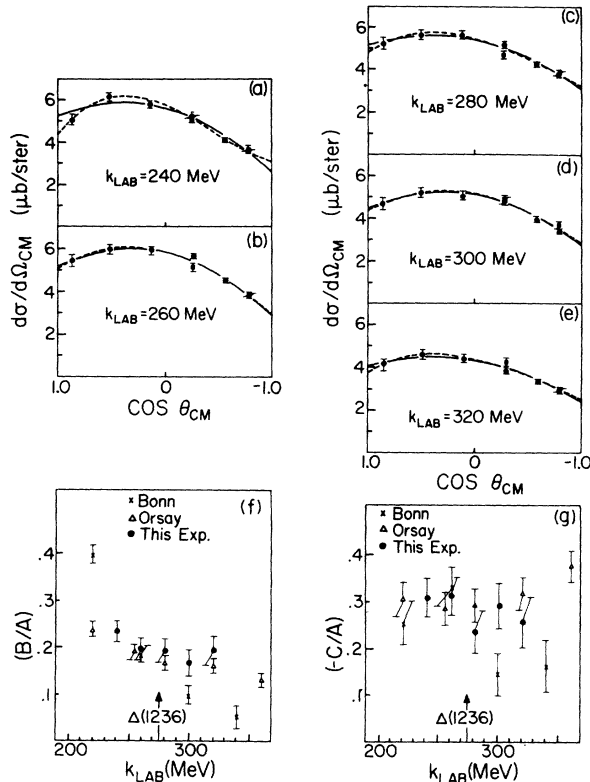


FIG. 2. (a)-(e) $\gamma + d \rightarrow n + p$ angular distributions versus $\theta_{c.m.}$ at various incident energies. The circles represent data taken at 350-MeV synchrotron energy, the squares 450-MeV. The solid curve is a fit with the form $d\sigma/d\Omega = A + B \cos\theta_{c.m.} + C \cos^2\theta_{c.m.}$. The dashed curve is a fit including the term $D \cos^3\theta_{c.m.}$. (f), (g) Normalization-independent ratios B/A and -C/A versus photon energy for least-squares fits with the form $d\sigma/d\Omega = A + B \cos\theta_{c.m.} + C \cos^2\theta_{c.m.}$. The Bonn and Orsay points are fits to the data of Refs. 4 and 5, respectively. The errors include the correlations between coefficients.

were made to the six angles at each energy. The addition of the fourth term did not significantly improve the fit, and had only a slight effect on the other coefficients. The coefficients for fit (3) and the normalization-free ratios B/A and C/A are also presented in Table I.

Although the normalization of the data appears to differ considerably from that of other experiments,^{4,5} the normalization-independent ratios (Fig. 2) are in good agreement over the region of interest. Since a violation of time-reversal invariance would be expected to manifest itself in the ratio C/A ,¹ a meaningful comparison of Reactions (1) and (2) should be possible when data for the latter process become available.

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EXPERIMENTAL CONSISTENCY OF MULTI-REGGEISM IN A HIGH-ENERGY REACTION*

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The reactions $\pi^- + p \rightarrow \pi^- + X + p$, $X \rightarrow \pi^+ + \pi^-$, for incident π^- energy of 25 BeV, has been analyzed within the framework of the multi-Regge exchange model.

It has been conjectured independently by several authors¹ that the multiparticle production amplitude, in a certain well-defined kinematic region, is essentially the product of two-body Regge amplitudes. We shall refer to this as the multi-Regge exchange (MRE) hypothesis. The consistency of this assumption with experimental data has been investigated by several groups,^{2,3} but always in kinematic regions where the validity of application is uncertain and additional assumptions are involved.⁴ We have looked for MRE in the reactions

$$\pi^- + p \rightarrow \pi^- + X + p, \quad (1)$$

$$X \rightarrow \pi^+ + \pi^-, \quad (2)$$

at an incident π^- energy of 25 BeV, always working in a kinematic region where the theoretical assumptions leading to a MRE form for the amplitude are kept to a minimum. Simultaneous with the requirement that the p and π^- momentum transfers be small, we demand that all invariant masses (except that of the X) be large. This is the first time that this particular kinematic region has been investigated experimentally. The events were selected from an 80-in. bubble-chamber exposure at the Brookhaven National Laboratory by the Walker-Erwin group of the University of Wisconsin.

At a fixed incident energy, the amplitude for Reaction (1) will depend on four variables, if we treat X as a stable particle of definite mass. We