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Observation of an Anomalous Structure in Proton Polarization from Deuteron Photodisintegration

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Proton polarization in $\gamma d \to pn$ has been measured at c.m. angle around 90° and photon energies from 325 to 725 MeV. The polarization increases sharply with the photon energy, reaching a high maximum of $(-80 \pm 8)\%$ around 500–550 MeV. Such a high polarization with a sharp energy dependence seems to indicate a new effect in the dibaryon system.

Photodisintegration of the deuteron offers one of the simplest ways for studying a highly excited dibaryon system. Previous measurements have shown that the total cross section has a peak around 300 MeV and decreases monotonically with energy up to 800 MeV.[1,2] These gross features are consistent with the assumption that main contributions come from the Born term and the nucleon-resonance term as shown in Fig. 1.

However, further studies of the differential cross section, the recoil proton polarization, and the polarized photon asymmetry have also revealed the shortcomings of theoretical analyses based on these terms.[3,4] In particular, the analyses failed to explain a sharp increase of proton polarization observed in the energy range of 300 to 450 MeV.[5,6] Since the recoil proton polarization is sensitive to the existence of imaginary interfering amplitudes, the extention of polarization measurements to higher energy ranges is a vital step towards better understanding of this process.

The experimental layout is shown in Fig. 2. Bremsstrahlung photons produced by electrons accelerated in the synchrotron at the Institute for Nuclear Study, University of Tokyo, were brought to a liquid deuterium target. A magnetic spec-

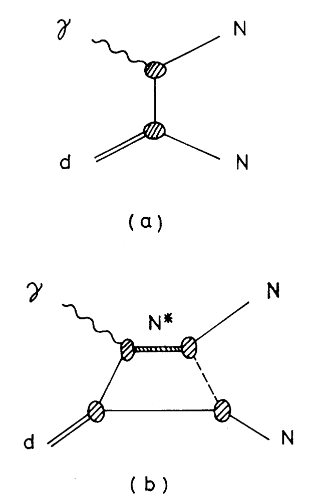

FIG. 1. Dominant diagrams for $\gamma d \to pn$ in the present energy range: (a) nucleon Born term; (b) NN^* term.

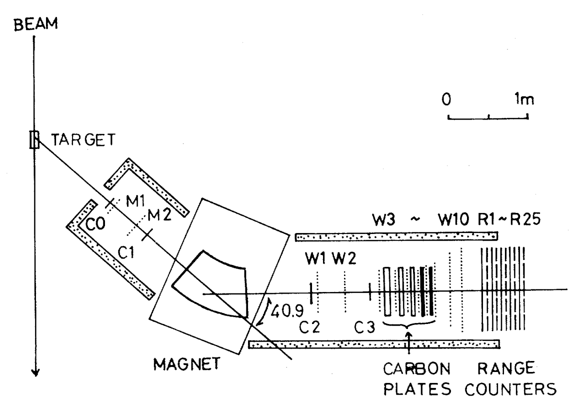

FIG. 2. Experimental layout.

trometer consisting of a sector magnet, two multiwire proportional chambers (M1–M2), four scintillation counters (C0–C3), and three wire spark chambers (W1–W3) was placed on a rotatable table. Seven wire spark chambers (W4–W10), interspersed with three to five layers of carbon (14 to 51 g/cm^2), and a range hodoscope (R1–R25) formed a polarization analyzer which was located behind the magnetic spectrometer. The entire system had angular and momentum acceptance of about 4.2 msr and ± (5.5–10)%, respectively. In the data-taking run, the time-coincidence C0·C1·C2·C3·(R1 + R2 + R3 + R4 + R5) triggered the chambers, and the coordinates of particle tracks on the wire chambers, the hit pattern of the range hodoscope elements, and other relevant information was written on magnetic tapes. Later the reaction point along the photon beam (z), the proton direction (θ_p, φ_p) and momentum (p) in the laboratory system, and the angles (θ_C, φ_C) and energy loss (ΔE) of the proton-carbon scattering were reconstructed. From these, the photon energy (E_γ) was calculated on the assumption that the process was the $\gamma d \to pn$ reaction (zero-constraint fit). The overall measurement errors [full width at half-maximum (FWHM)] were about $\Delta z \cong 0.8$ cm, $\Delta\theta_p \cong 0.35°$, $\Delta\varphi_p \cong 0.6°$, $\Delta p \cong 0.8\%$, $\Delta\theta_C \cong 1.5°$, $\Delta\varphi_C \cong 6.4°$, and $\Delta E_\gamma \cong 1.0\%$.

Background processes such as $\gamma d \to pn\pi^0$, $\gamma d \to \pi^+ nn$, and $\gamma d \to pp\pi^-$, with one positively charged particle entering the spectrometer system, might be registered as an event. However, by setting the top energy of the photon spectrum no more than 100 MeV above the proper value corresponding to the central orbit of the spectrometer, it was possible to prevent most of background events from triggering the spectrometer system. The amount of possible background contamination is estimated to be less than a few percent by reconstructing the photon spectrum from all triggered events based on the $\gamma d \to pn$ kinematics.[7]

The data were taken at five different electron energies, 500 MeV ($\theta_p \sim 71.9°$), 550 MeV ($\theta_p \sim 70.9°$), 600 MeV ($\theta_p \sim 69.9°$), 700 MeV ($\theta_p \sim 68.2°$), and 800 MeV ($\theta_p \sim 66.6°$), where the laboratory angle θ_p was set to correspond to 90° in the c.m. system. About 218 000 events were recorded for the off-line analysis. The following cuts were applied successively and the final sample of 6700 events was used to determine the polarization: (1) various fiducial cuts on the particle coordinates at the target (z), C0–C3, the entrance and exit of the magnet (142 000 retained); (2) the proton momentum and the angle θ_C at the proton-carbon scattering point are to be larger than P_{min}(432.7 MeV/c) and θ_{min}(6°–8.5° depending upon the proton momentum and the total thickness of the carbon plates). This removed events due to the multiple Coulomb scattering (9200 events retained). (3) The cuts (1) and (2) were applied to the "mirror-reflected" event artificially generated from every real event by flipping φ_C to $\varphi_C + \pi$. Unless the mirror-reflected event survived the cuts, the real event was not retained in the sample. This condition served to minimize the possible systematic asymmetry due to the bias in the geometrical acceptance of the apparatus (7600 events retained). (4) The energy loss, ΔE, is to be smaller than 30 MeV (6700 events retained). We note here that the analyzing power of carbon is not well known for larger energy losses.

The final sample of data was divided into $\Delta E_\gamma = 50$ MeV bins and used in calculating the likelihood function. The proton polarization was determined as the value P which maximized the following likelihood function in each energy bin:

$$L(P) = \prod_{i=1}^{N} \frac{[1 + A(p^i, \theta_C{}^i, \Delta E^i) P \cos\varphi_C{}^i]}{\int_0^{2\pi} \eta(p^i, \theta_C{}^i, \Delta E^i; \varphi_C) d\varphi_C}.$$

Here N is the number of events in a 50-MeV bin and $A(p, \theta_C, \Delta E)$ is the analyzing power of carbon as a function[8] of p, θ_C, and ΔE. For $\eta(p^i, \theta_C{}^i, \Delta E^i; \varphi_C)$, $\eta = 1$ is the ith event specified by p^i, $\theta_C{}^i$, ΔE^i, and $\varphi_C{}^i$ passes the trigger conditions and the cuts (1)–(4), and $\eta = 0$ otherwise. The denominator serves to normalize the likelihood function for each event to unity. P is the proton polarization in the 50-MeV bin.

Beside the various cuts described above, the following measures were taken to make a further check for possible biases in our system. (1) For most E_γ bins, polarization was measured twice in two different spectrometer settings; that is, with the proton orbit set at the higher and the lower half of the momentum acceptance. The two measurements were checked to be consistent and then summed together for the final maximum-likelihood fitting. (2) We independently measured the proton polarization in the elastic ep scattering, with the same setup. The measured polarization in our detector was 0.0 ± 0.1 for 695-MeV/c protons and 0.1 ± 0.1 for 808-MeV/c protons. These values are consistent with the previous measurement of (1 – 2)% or less.[9]

The experimental results are listed in Table I and shown in Fig. 3(a) together with the previous data by Liu, Lundquist, and Wiik[5] and by Kose *et al.*[6] Below 450 MeV, our data agree with theirs,

TABLE I. Summary of experimental results. The angular acceptance in the center-of-mass system was about ± 1.0°. The errors in polarization refer to the half-width at half-maximum of the likelihood function.

Energy bin, E_γ (MeV)	Average E_γ (MeV)	Average $\theta_{c.m.}$ (deg)	Polarization, P (%)
350 ± 25	352	87.0	− 35 ± 12
400 ± 25	398	88.4	− 42 ± 9
450 ± 25	448	88.6	− 47 ± 7
500 ± 25	496	90.2	− 80 ± 8
550 ± 25	548	89.2	− 78 ± 7
600 ± 25	597	90.1	− 60 ± 10
650 ± 25	652	89.1	− 53 ± 9
700 ± 25	697	90.0	− 45 ± 9

confirming a sharp increase in this region. A new remarkable feature is that the magnitude of polarization further increases with energy, reaches the maximum value between 500 and 550 MeV, then decreases sharply towards 700 MeV. It should be noted, however, that the available data for differential cross sections at 90° have so far revealed no marked structure in this energy range[1,2] as shown in Fig. 3(b), although the effect of any interfering amplitudes is expected to be less prominent in the differential cross section than in the polarization.

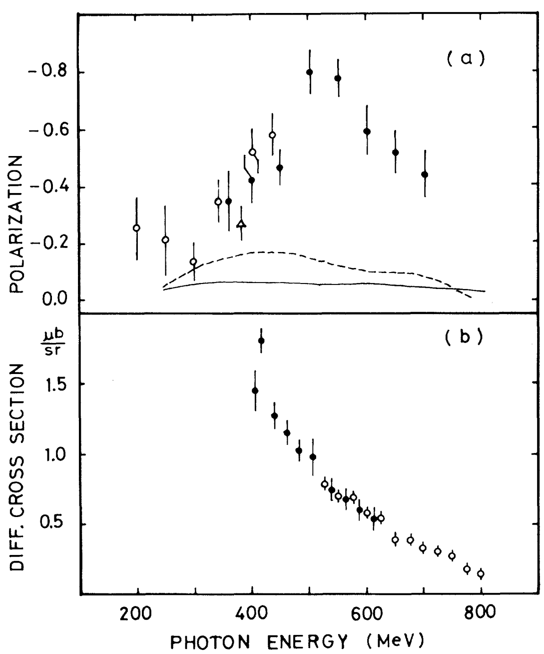

FIG. 3. (a) Proton polarization at 90° c.m. system as a function of the photon energy. The solid and the dashed curves are the results of a relativistic-covariant computation and a phenomenological analysis respectively (see Ref. 10). Data points are from Ref. 5 (open circles), Ref. 6 (triangle), and the present experimental (filled circles). (b) Differential cross section at 90° c.m. system as a function of the photon energy. Data points are taken from Ref. 1 (open circles) and Ref. 2 (closed circles).

Attempts were made to fit the experimental data by computing the helicity amplitudes of the $\gamma d \to pn$ reaction based on the Born term and the resonance term. One is a relativistic covariant computation including several nucleon resonances and the other is a phenomenological approach using the known pion photoproduction helicity amplitudes for a $\gamma N \to \pi N$ vertex of the NN^* term.[10] Within the parameter ranges allowed for fitting the cross section behavior, both attempts completely failed to reproduce the observed structure in polarization as shown by the curves in Fig. 3(a).

The sharpness of the structure and the high value of polarization may imply the existence of an additional imaginary amplitude going through a resonantlike behavior in this energy range. One of the possibilities is the excitation of a dibaryon resonance in the S channel. In fact, based on SU(6) theory, Dyson and Xuong have predicted the D_{03} state, the S-wave Δ-Δ resonance with isospin 0 and spin 3, as one of the possible dibaryon states.[11] Its predicted mass of 2350 MeV corresponds to the photon energy of 536 MeV, where the peak of polarization was observed in this experiment. Another calculation, based on the one-boson-exchange potential model for the Δ-Δ system by Kamae and Fujita, also gives deeply bound states for ($I = 0$, $J = 3$) and ($I = 3$, $J = 0$) combinations.[12]

In order to clarify the situation, further experimental and theoretical studies are definitely needed. In particular, the precise measurements of differential cross sections and polarization in wider-angle ranges for $\gamma d \to pn$ as well as the investigation of the inverse reaction $pn \to \gamma d$ in the corresponding energies may supply useful information.

We wish to thank the staff of the Institute for Nuclear Studies for excellent machine operation and for various assistance in all phases of the experiment. We also thank Mr. T. Kobayashi who participated in the preparation of the detector system. The analyses have been done with extensive use of the computers at the Institute for Nuclear Studies (Japan) computer center and at the National Laboratory for High Energy Physics (Japan) bubble chamber division. This experiment was partly supported by a Grant-in-Aid of the Japanese Ministry of Education, Science, and Culture.

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Possible Existence of a Deeply Bound Δ-Δ System

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Being motivated by the observation of an anomaly in the polarization of protons in $\gamma d \rightarrow pn$, we have investigated the possible existence of deeply bound dibaryon states. The nonrelativistic one-boson-exchange potential model (π, η, ρ, and ω exchanges) for two Δ isobars gives binding energies around 100 MeV for $I=0$, $J=3$ and $I=3$, $J=0$. Existence of this $I=0$ dibaryon resonance reproduces experimentally observed cross sections in the $I=0$, $NN \rightarrow d\pi\pi$ and $NN \rightarrow NN\pi\pi$ channels.

A recent experimental study[1] on the proton polarization in deuteron photodisintegration reports a resonancelike behavior at around 550 MeV in photon energy. The observed polarization increases sharply with photon energy, reaching a maximum of $(-80 \pm 7)\%$. Theoretical analyses by Ogawa *et al.*,[2] by George,[3] and by Hasselmann[4] have failed to reproduce such structure in the polarization. As has been noted,[1] this structure is hard to understand from a composite intermediate state, but is easily understood if there is an appreciable amount of dibaryon resonant amplitudes. That is, a resonance in the two-nucleon system with a mass of approximately 2380 MeV will give an imaginary amplitude of the Breit-Wigner type, as is shown in Fig. 1, which will interfere with almost real amplitudes (Born + NN^*) and will give a structure similar to what has been observed (see Ref. 2 for further details). We looked for nucleon-isobar combinations, which may be deeply bound to give the total mass in this energy range, and discuss here our calculations showing the possible existence of a deeply bound Δ-Δ system. We also discuss what effects this dibaryon resonance might have on other channels, such as $NN \rightarrow d\pi\pi$ and $NN \rightarrow NN\pi\pi$.

The calculation presented here is based on the nonrelativistic one-boson-exchange (OBE) potential model, where the pion, η meson, ρ meson, and ω meson are the exchanged bosons. For simplicity we consider only the S state. The coupling constants are varied around experimentally known