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Angular Dependence of Proton Polarization in the Reaction $\gamma d \to pn$ and a Partial-Wave Analysis of Possible Dibaryon Resonances

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(Received 22 March 1979)

The angular dependence of proton polarization in $\gamma d \to pn$ has been measured at photon energies between 400 and 650 MeV. The polarization and differential-cross-section data are consistently explained by introducing a dibaryon resonance $I(J^P) = 0(3^+)$ or $0(1^+)$ at ≈ 2360 MeV.

In our previous experiment,[1] we measured the proton polarization in the reaction $\gamma d \to pn$ at $\theta_{\text{c.m.}} = 90°$ at laboratory photon energies $E_\gamma = 350-700$ MeV. Unexpectedly large polarization was found at $E_\gamma = 550$ MeV, and this feature was conjectured[2] to be due to the dibaryon resonance with the mass ≈ 2380 MeV, $I(J^P) = 0(3^+)$. Together with other evidences for the dibaryon resonances, both nonstrange[3,4] and strange,[5] much interest has recently been focused on them.[6]

To further investigate the nature of possible dibaryon resonances contributing in the reaction $\gamma d \to pn$, we have measured the angular dependence of the proton polarization at $E_\gamma = 400-650$ MeV. Using the polarization data together with the existing differential-cross-section data, we have been able to perform partial-wave analyses in which dibaryon resonances have been included.

TABLE I. Summary of the experimental results. The positive direction of the proton polarization is defined to be parallel to (photon direction) × (proton direction). The errors are given by the quadratic sum of the 1-standard-deviation error in the maximum-likelihood analysis and the error due to the uncertainty in the analyzing power A of the carbon, $P\Delta A/A \approx 0.05P$.

E_γ (MeV) \ $\theta_{\text{c.m.}}$	45°	70°	90°	120°	135°
400		-0.44 ± 0.09			
450	-0.34 ± 0.08	-0.54 ± 0.10		-0.35 ± 0.21	
500	-0.24 ± 0.09	-0.61 ± 0.11	-0.77 ± 0.13	-0.46 ± 0.12	-0.35 ± 0.24
550	-0.34 ± 0.10	-0.62 ± 0.11	-0.51 ± 0.08	-0.54 ± 0.10	-0.55 ± 0.20
600	$+0.10 \pm 0.13$	-0.42 ± 0.11	-0.58 ± 0.12	-0.59 ± 0.11	
650				-0.38 ± 0.15	

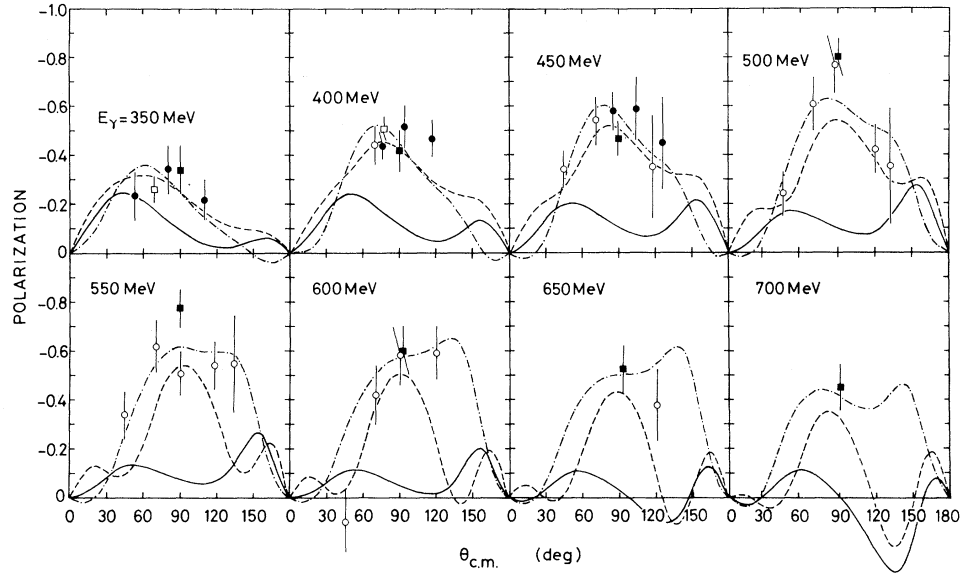

FIG. 1. Angular distributions of the proton polarization. The results of the present experiment (empty circles) are plotted together with the previous data (filled circles, Liu *et al.*, Ref. 12; empty squares, Kose *et al.*, Ref. 12; filled squares, Kamae *et al.*, Ref. 1) used for the χ^2-minimization fits. The dashed curves are the results of the fit including $1(3^-)$ and $0(3^+)$. The dot-dashed curves are the results of the fit including $1(3^-)$ and $0(1^+)$. The solid curves are the calculated results with the nonresonant amplitudes only.

The experiment has been performed at the Institute for Nuclear Study, University of Tokyo, using a bremsstrahlung photon beam from its electron synchrotron. The momentum vector of the proton has been measured by a magnetic spectrometer, and the proton polarization has been determined by using proton-carbon scattering. The apparatus and the method of data reduction are essentially the same as the ones in our previous experiment,[1] and are fully described elsewhere.[7]

Table I summarizes the results of the experiment. They are also plotted in Figs. 1 and 2. These data are based on 6.3×10^5 recorded events, out of which 1.2×10^3 events have been retained for the polarization analysis after various cuts. The cuts applied have been so chosen as to guarantee the bias-free determination of the polarization, and are the same as described in Ref. 1.

We now turn to the discussion of the partial-wave analyses performed to see the effects of dibaryon resonances. The analyses presented here are based on the assumption that the $\gamma d \rightarrow pn$ amplitudes consist of the nonresonant part and the resonant part (dibaryon term).

The nonresonant part consists of the nucleon-exchange Born amplitude and the one-pion–reabsorption amplitude. The deuteron-pole amplitude is believed to be negligible in our energy range, although the lack of the precise knowledge of the *dNN* vertex function for the off-shell deuteron prevents us from demonstrating it unambiguously. The nucleon-exchange Born amplitude is calculated in a covariant way.[8,9] The one-pion–reabsorption amplitude is calculated phe-

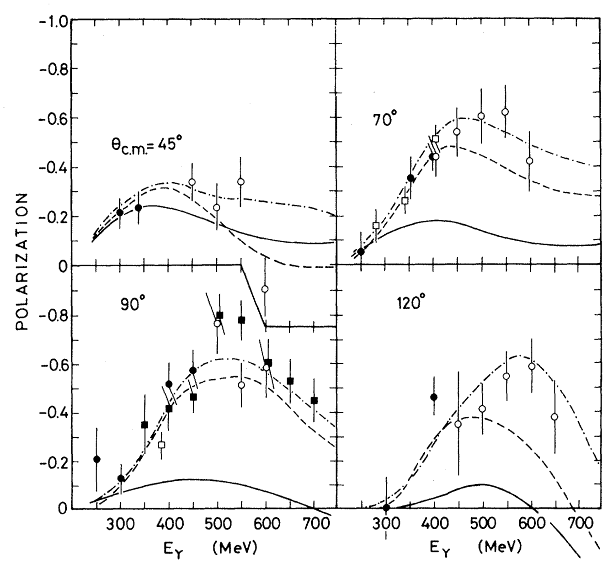

FIG. 2. Proton polarization plotted vs E_γ. The data outside the fitted region are also shown. The curves and symbols are coded as in Fig. 1.

nomenologically, following Ogawa, Kamae, and Nakamura,[10] i.e., the $\gamma N \to \pi N$ vertex is replaced by the single-pion–photoproduction amplitudes given by Moorhouse, Oberlack, and Rosenfeld.[11] In order to make such a replacement consistently, various considerations are needed. Detailed discussion on these calculations is given elsewhere.[10]

To incorporate resonant amplitudes due to an s-channel formation of a dibaryon resonance, we use the multipole expansion of the helicity amplitudes.[8] For example, if there exists a dibaryon resonance in the $I(J^P)=0(3^+)$ state, the multipole transition amplitudes $E_{2,4}(^3D_3)$, $E_{2,4}(^3G_3)$, $M_3(^3D_3)$, and $M_3(^3G_3)$ have chances to show the characteristic behavior. The resonant amplitudes are parametrized as

$$a\frac{\Gamma_1^{1/2}\Gamma_2^{1/2}}{W_0-W-\frac{1}{2}i\Gamma}$$

with

$$\Gamma_1=\tfrac{1}{2}\Gamma(k/k_0)^{2L}[(k_0^2+x^2)/(k^2+x^2)]^L,$$

$$\Gamma_2=\tfrac{1}{2}\Gamma(p/p_0)^{2l+1}[(p_0^2+x^2)/(p^2+x^2)]^l,$$

where k, p, W, Γ, and x are the c.m. photon energy, c.m. nucleon momentum, total c.m. energy, total resonance width, and the angular-momentum barrier parameter, respectively; L and l are the angular momenta of the initial and final states, respectively. The subscript 0 denotes the value at the resonance peak.

The data used for the χ^2-minimization fits are the present results together with the previous polarization data[1,12] and the differential-cross-section data[13] in the range $E_\gamma=350$–700 MeV. A study has shown that the quality of the fit is not very sensitive to the value of x between 100 and 300 MeV, and $x=200$ MeV has been adopted throughout. It has already been shown[1] that the polarization data could not be explained with the nonresonant amplitudes only. The calculated results are shown by the solid curves in Figs. 1–3. In including resonant amplitudes, however, a problem arises because we do not know *a priori* what dibaryon resonances contribute. Moreover, the quality of the data does not seem to allow an elaborate analysis procedure. Thus our guiding principle is to introduce a minimal number of dibaryon resonances whose quantum numbers are to be determined so as to give a good fit to the data.

We have first attempted to fit the data with only one dibaryon resonance at $\sqrt{s}\approx 2380$ MeV and with a reasonable width $\Gamma\approx 200$ MeV, as suggested by Kamae and Fujita.[2] All allowed $I(J^P)$ combinations have been examined up to $J=4$. With this hypothesis, the quality of the fit appears to be quite poor below $E_\gamma\approx 450$ MeV. There is a candidate of a dibaryon resonance in this energy region: the one reported by Auer *et al.*[3] and Hoshizaki[4] [mass = 2260 MeV, $\Gamma=200$ MeV, $1(3^-)$]. Inclusion of this resonance has reduced the χ^2/DF (degree of freedom) typically by about 4. Thus our analysis supports the existence of this resonance.

With two dibaryon resonances, the smallest χ^2/DF (99.4/96) has been obtained for the combination $1(3^-)$ at 2260 MeV and $0(1^+)$ at 2352 MeV, and the next good combination (χ^2/DF of 140.4/94) has been $1(3^-)$ at 2260 MeV and $0(3^+)$ at 2362 MeV. The parameters obtained for these two solutions are listed in Table II and the fitted curves are shown in Figs. 1–3. The former solution gives a good fit to the data in the entire energy and angular ranges where the fit has been performed. The latter solution also reasonably reproduces the experimental data except for the 120° polarization above 550 MeV.

It is worthwhile to note that various models[2,14-17] for the dibaryon resonances with different approaches rather commonly give the $0(3^+)$ resonance at around 2380 MeV. It is also likely that there exists more than one dibaryon resonance in this energy region. In fact the three-resonance fit including $1(3^-)$ at 2260 MeV and $0(3^+)$ and $0(1^+)$ at around 2360 MeV gives a still better fit,[18] and Ueda's model[17] predicts the existence of these nearby dibaryon resonances.

TABLE II. The results of the fits for the two hypotheses giving the smallest χ^2/DF values. The mass and width (in units of MeV) of the $1(3^-)$ resonance are fixed at 2260 and 200, respectively. The coupling parameters a are given for each multipole transition amplitude in the units of $(\mu b)^{1/2}$.

$1(3^-)$ and $0(1^+)$			$1(3^-)$ and $0(3^+)$		
$1(3^-)$	$E_3(^3F_3)$	-72 ± 25	$1(3^-)$	$E_3(^3F_3)$	-85 ± 38
	$M_2(^3F_3)$	-246 ± 14		$M_2(^3F_3)$	-260 ± 22
	$M_4(^3F_3)$	63 ± 35		$M_4(^3F_3)$	11 ± 45
$0(1^+)$	W_0	2352 ± 14	$0(3^+)$	W_0	2362 ± 15
	Γ	342 ± 69		Γ	238 ± 48
	$E_2(^3S_1)$	128 ± 28		$E_2(^3D_3)$	31 ± 65
	$E_2(^3D_1)$	63 ± 46		$E_2(^3G_3)$	-203 ± 22
	$M_1(^3S_1)$	11 ± 23		$E_4(^3D_3)$	-113 ± 43
	$M_1(^3D_1)$	-249 ± 15		$E_4(^3G_3)$	-56 ± 146
				$M_3(^3D_3)$	25 ± 62
				$M_3(^3G_3)$	-7 ± 66

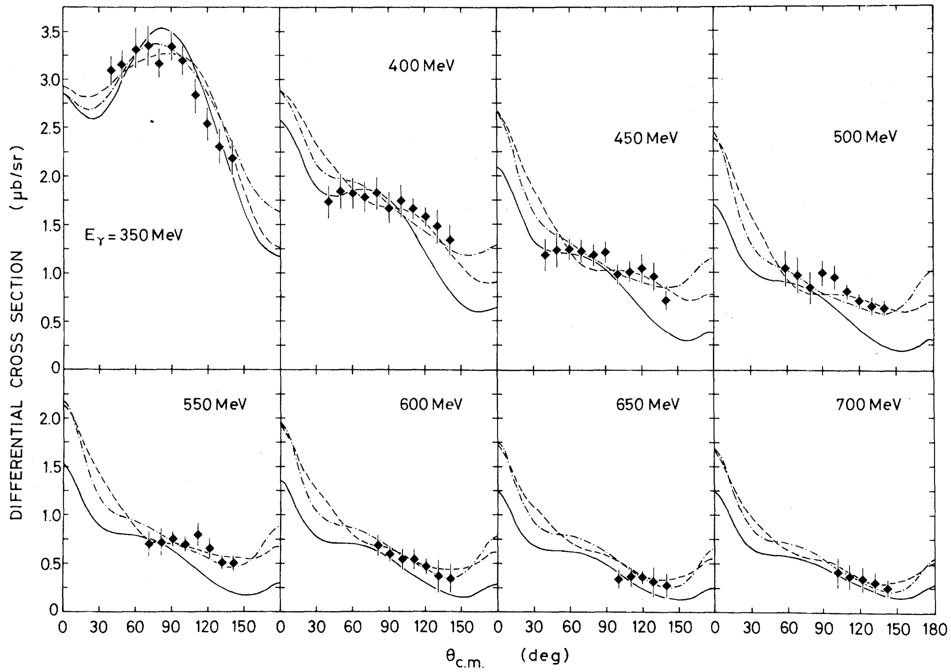

FIG. 3. The differential-cross-section data used for the χ^2-minimization fits and the fitted curves. The curves are coded as in Fig. 1; here the diamonds are data from Dungan *et al.*, Ref. 13.

In summary, our partial-wave analysis based on a phenomenological model has given evidence for a dibaryon resonance with $I(J^P) = 0(1^+)$ or $0(3^+)$ at around 2360 MeV. Our analysis also supports the existence of another dibaryon resonance[3,4] $1(3^-)$ at 2260 MeV.

We wish to express our thanks for the excellent machine operation of the synchrotron crew and for the cooperation and assistance of the high-energy group at the Institute for Nuclear Study.

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