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Coherent neutral-pion and eta-meson photoproduction on the deuteron

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Coherent neutral-pion and eta-meson photoproduction on the deuteron, $\gamma d \to \pi^0 \eta d$, has been experimentally studied at incident photon energies below 1.15 GeV. A rather uniform angular distribution of deuteron emission in the center-of-mass frame suggests that sequential processes take place in the reaction. We have decomposed the ηd and $\pi^0 d$ invariant-mass spectra into the $\eta\mathcal{D}_{12}$ and $\pi^0\mathcal{D}_{01}$ contributions, where $\mathcal{D}_{12}$ denotes a known resonance with $I = 1$ and $J = 2$ in the $\pi^0 d$ channel, and $\mathcal{D}_{01}$ denotes a near-threshold state with $I = 0$ and $J = 1$ in the ηd channel. From the analysis of π^0 and η angular distributions, we have determined the spin-parity of the first intermediate $\eta\mathcal{D}_{12}$ and $\pi^0\mathcal{D}_{01}$ systems. The spin-parity of the major component is found to be 0^- in the $\pi^0\mathcal{D}_{01}$ system, suggesting that some nucleon resonances contribute to $\pi^0\eta$ photoproduction on the nucleon. It should be noted that $\Delta(1700)3/2^-$ is the main contributor for elementary $\pi^0\eta$ photoproduction.

KEYWORDS: Coherent meson photoproduction, Angular correlation, ηd threshold structure, …

1. Introduction

A photon beam with an energy around 1 GeV, which produces baryon resonances from the nucleon, has an important function in Hadron Physics. Their excitation spectrum is important for understanding the non-perturbative behavior of quantum chromodynamics at low energies. Even when a nuclear target is irradiated with such a photon beam, baryon resonances are likely to be produced from the quasi-free (QF) nucleon, which becomes a participant and the residual nucleus becomes a spectator. Since no spectator exists in coherent meson photoproduction where the same nucleus appears in the final state, a meson-nucleus system is expected to be produced. Thus far, no indication of such a system was found in coherent single meson photoproduction on the deuteron, $\gamma d \to \eta d$ for example [1, 2]. We have found that the dominant process in coherent double neutral-pion photoproduction is the $\gamma d \to \mathcal{D}_{\rm IS} \to \pi^0 \mathcal{D}_{\rm IV} \to \pi^0 \pi^0 d$ sequence where $\mathcal{D}_{\rm IS}$ and $\mathcal{D}_{\rm IV}$ denote some two-baryon states with $I = 0$ and $I = 1$, respectively [3, 4]. The important feature is a rather flat angular distribution of deuteron emission in the center-of-mass (CM) frame, which rules out QF $\pi^0\pi^0$ production with deuteron coalescence. In this proceeding, we have experimentally studied $\pi^0 d$ and ηd systems in $\gamma d \to \pi^0 \eta d$.

2. Experiment

The experiment was carried out using a bremsstrahlung-photon beam [5] from 1.20-GeV electrons circulating in a synchrotron [6] at the Research Center for Electron Photon Science (ELPH), Tohoku University, Japan [7]. The energy of a produced photon in bremsstrahlung was tagged from 0.75 to 1.15 GeV by detecting the post-bremsstrahlung electron with a photon-tagging detector. The target used was liquid deuterium with a thickness of 45.9 mm. All the final-state particles in the $\gamma d \to \pi^0 \eta d \to \gamma\gamma\gamma\gamma d$ reaction were measured with the FOREST detector [8] consisting of three different electromagnetic calorimeters (EMCs) and plastic-scintillator hodoscopes (PSHs) placed in front of EMCs.

3. Event selection

The events were initially selected which contained four neutral particles and a charged particle. A neutral particle was given by an EMC cluster without a corresponding PSH hit, and a charged particle was given by a PSH hit regardless of the existence of a corresponding EMC cluster. A kinematic fit (KF) with six constraints was applied for selecting the $\gamma d \to \pi^0 \eta d$ events: the energy and three-momentum conservation, the invariant mass of two photons out of four being the π^0 mass, and that of the other two being the η mass. The most competitive background was from events of deuteron misidentification in the QF $\gamma p' \to \pi^0 \eta p$ reaction. Thus, selected events were additionally required to exhibit χ^2 probability below 0.01 in another KF for the $\gamma p' \to \pi^0 \eta p$ hypothesis. Finally, sideband-background subtraction was performed for accidental-coincidence events detected in the photon-tagging detector and FOREST.

4. ηd and $\pi^0 d$ invariant mass distributions

Fig. 1 shows the differential cross sections $d\sigma/dM_{\eta d}$ and $d\sigma/dM_{\pi d}$ at incident photon energies from 0.95 to 1.01 GeV/c. A clear peak or an enhancement over the phase space is observed near the threshold in $d\sigma/dM_{\eta d}$. Only the S-wave ηd system with isospin 0 and spin 1 ($\mathcal{D}_{01}$) forms a peak close to the threshold in $d\sigma/dM_{\eta d}$. Although the low-mass side of the peak does not change regardless of incident energies, the peak becomes narrower and wider at lower and higher incident photon energies, respectively. Thus another resonance in the $\pi^0 d$ channel contributes to the high-mass side of the peak.

In $d\sigma/dM_{\pi d}$, a significant enhancement is observed over the phase space in the high-mass region. The peak position increases with increase of the incident energy. Owing to the limited phase space, only appears the low-mass side of the known $\pi^0 d$ resonance, $\mathcal{D}_{12}$ with isospin 1 and spin 2.

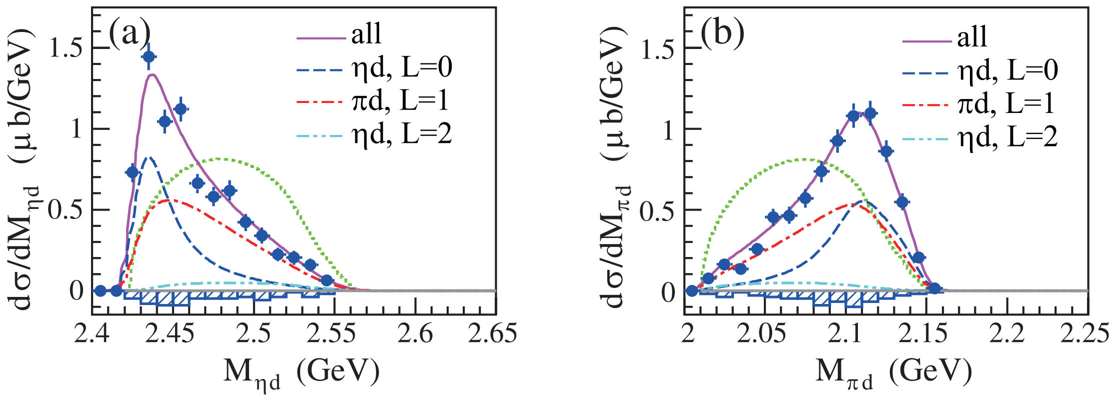

Fig. 1. Differential cross sections $d\sigma/dM_{\eta d}$ (a) and $d\sigma/dM_{\pi d}$ (b) at E_γ = 0.95–1.01 GeV. The dotted curves (green) show the corresponding phase space contribution. The solid curves (magenta) show the fitted distributions. The dashed (blue), and two-dot-dashed (cyan) curves show the S- (blue dashed) and D-wave (cyan double-dotted) decay contributions of $\mathcal{D}_{01}$. Also plotted is the $\mathcal{D}_{12}$ contribution (red dot-dashed). The lower hatched histograms show the systematic errors.

We observed a resonance-like structure near the ηd threshold, and the known $\mathcal{D}_{12}$ resonance. Thus we decomposed $d\sigma/dM_{\eta d}$ and $d\sigma/dM_{\pi d}$ into $\pi^0\mathcal{D}_{01}$ and $\eta\mathcal{D}_{12}$ contributions. Here, the $\mathcal{D}_{01} \to \eta d$ decay was assumed to take place in the S and D waves. We also assumed the mass distribution of $\mathcal{D}_{12}$ takes a Breit-Wigner shape, and that of $\mathcal{D}_{01}$ was expressed by a Flatté parameterization. In Fig. 1, also plotted is each contribution from $\mathcal{D}_{01}$ and $\mathcal{D}_{12}$.

5. π^0 and η angular distributions

To investigate the $\pi^0\mathcal{D}_{01}$- and $\eta\mathcal{D}_{12}$-produced processes, we obtained the angular distributions of π^0 and η for the events with $M_{\eta d}$ < 2.47 GeV. Fig. 2 (a) shows the π^0 angular distribution in the γd-CM frame at E_γ = 0.95–1.01 GeV where z axis is taken along the incident photon direction. Almost flat is the experimentally obtained distribution. Fig. 2 (b) shows the η angular distribution in the ηd rest frame at E_γ = 0.95–1.01 GeV with respect to the opposite direction to π^0 emission. The distribution takes a convex-upward shape, and shows almost symmetry against $\cos\theta_\eta = 0$.

We also decomposed the π^0 and η angular distributions into the contributions from different spins of the first intermediate states. Here, we assumed the two reaction sequences:

$$J_0\,(d) = 1 \xrightarrow{L_0(\gamma)} J_1\left(\pi^0\mathcal{D}_{01}\right) \xrightarrow{L_1(\pi^0)} J_2\,(\mathcal{D}_{01}) = 1 \xrightarrow{L_2(\eta)=0,2} J_3\,(d) = 1, \tag{1}$$

and

$$J_0\,(d) = 1 \xrightarrow{L_0(\gamma)} J_1\,(\eta\mathcal{D}_{12}) \xrightarrow{L_1(\eta)} J_2\,(\mathcal{D}_{12}) = 2 \xrightarrow{L_2(\pi^0)=1} J_3\,(d) = 1, \tag{2}$$

where J_1 and J_2 denote the spins of first and second intermediate states, respectively, and $J_0 = J_3 = 1$ are those of the initial and final deuteron. The L_0 denotes the angular momentum carried by the incident photon. The L_1 and L_2 denote the angular momenta carried by meson emission from the first and second intermediate states, respectively. We calculated the angular distributions by using the

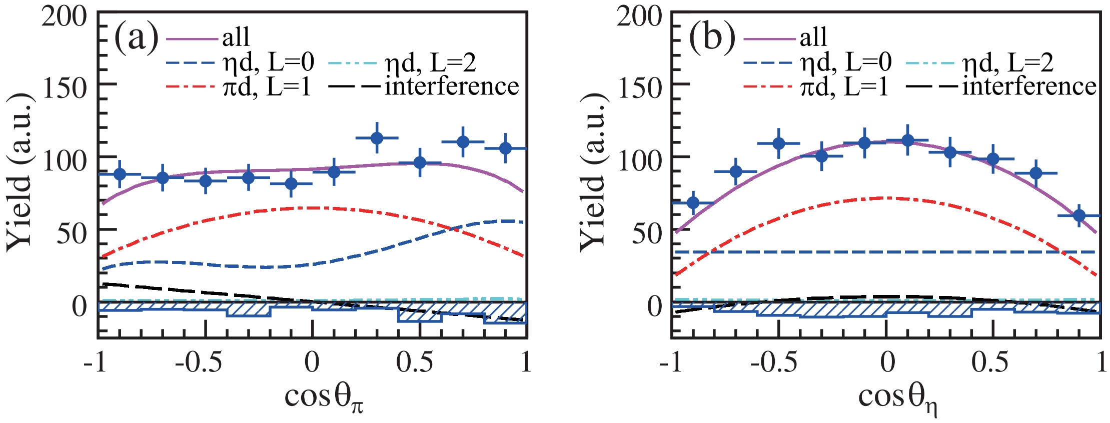

Fig. 2. Acceptance-corrected angular distributions for π^0 (a) and η (b) at E_γ = 0.95–1.01 GeV for the events with $M_{\eta d} \leq 2.47$ GeV. The emitted angles of π^0s are given with respect to the photon beam direction in the γd-CM frame, and those of ηs with respect to the opposite direction to π^0 in the ηd rest frame. The solid curves (magenta) show the fitted angular distributions. The dashed (blue), dot-dashed (red), and two-dot-dashed (cyan) curves correspond to the L_2 = 0, 1, and 2 contributions, respectively. The long-dashed curves (black) represent the interference effects. The lower hatched histograms show the systematic errors.

density matrix (statistical tensor) formalism [9]. The solid curves (magenta) in Fig. 2 show the fitted angular distributions together with other components from $\pi^0\mathcal{D}_{01}$ and $\eta\mathcal{D}_{12}$. The major component of $\pi^0\mathcal{D}_{01}$ is found to be 0^- (∼ 57%). That of $\eta\mathcal{D}_{12}$ is found to be 2^+ (∼ 100%).

Loosely-coupled isovector S-wave molecules N-Δ(1620)1/2$^-$ and N-N(1650)1/2$^-$ would play a role as a doorway to the $\pi^0\mathcal{D}_{01}$ system. It should be noted that neither Δ(1620)1/2$^-$ nor N(1650)1/2$^-$ is considered a contributor to the elementary $\gamma N \to \pi^0\eta N$ reaction, and that the main contributor is Δ(1700)3/2$^-$ [10–14]. Since Δ(1620)1/2$^-$ is located below the $\eta\Delta$ threshold, N-N(1650)1/2$^-$ seems appropriate for the $\pi^0\mathcal{D}_{01}$ system. While N-Δ(1600)3/2$^+$ and N-N(1720)3/2$^+$ are candidate doorways to $\eta\mathcal{D}_{12}$. Since Δ(1600)3/2$^+$ is located much below the $\eta\Delta$ threshold, N-N(1720)3/2$^+$ would play a role as a doorway to $\eta\mathcal{D}_{12}$ although the branching ratio of N(1720)3/2$^+$ $\to \eta N$ is only a few % [15].

6. Summary

We have measured the cross sections for coherent neutral-pion and eta-meson photoproduction on the deuteron, $\gamma d \to \pi^0\eta d$, at incident photon energies below 1.15 GeV. We have decomposed the ηd and $\pi^0 d$ invariant-mass spectra into the $\eta\mathcal{D}_{12}$ and $\pi^0\mathcal{D}_{01}$ contributions. We have determined the spin-parity of the first intermediate $\eta\mathcal{D}_{12}$ and $\pi^0\mathcal{D}_{01}$ systems. The spin-parity of the major component is found to be 0^- in the $\pi^0\mathcal{D}_{01}$ system, suggesting that some nucleon resonances contribute to $\pi^0\eta$ photoproduction on the nucleon. It should be noted that Δ(1700)3/2$^-$ is the main contributor for the elementary $\pi^0\eta$ photoproduction. The detailed analysis and discussion can be found elsewhere [16].

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References

[1] P. Hoffmann-Rothe *et al.*, Phys. Rev. Lett. **78**, 4697 (1997).
[2] J. Weiß *et al.*, Eur. Phys. J. A **11**, 371 (2001).
[3] T. Ishikawa *et al.*, Phys. Lett. B **772**, 398 (2017).
[4] T. Ishikawa *et al.*, Phys. Lett. B **789**, 413 (2019).
[5] T. Ishikawa *et al.*, Nucl. Instrum. Meth. A **622**, 1 (2010); T. Ishikawa *et al.*, Nucl. Instrum. Meth. A **811**, 124 (2016); Y. Matsumura *et al.*, Nucl. Instrum. Meth. A **902**, 103 (2018); Y. Obara *et al.*, Nucl. Instrum. Meth. A **922**, 108 (2019).
[6] F. Hinode *et al.*, in Proceedings of 21st IEEE Particle Accelerator Conference (PAC) (IEEE, Piscataway, 2005), pp. 2458–2460.
[7] H. Hama, AAPPS Bulletin **30**, 41 (2020).
[8] T. Ishikawa *et al.*, Nucl. Instrum. Meth. A **832**, 108 (2016).
[9] L.C. Biedenharn, and M.E. Rose, Rev. Mod. Phys. **25**, 729 (1953).
[10] M. Döring, E. Oset, and D. Strottman, Phys. Rev. C **73**, 045209 (2006).
[11] J. Ajaka *et al.*, Phys. Rev. Lett. **100**, 052003 (2008).
[12] A. Fix, V.L. Kashevarov, A. Lee, and M. Ostrick, Phys. Rev. C **82**, 035207 (2010).
[13] V. Sokhoyan *et al.*, Phys. Rev. C **97**, 055212 (2018).
[14] E. Gutz *al.* (CBELSA/TAPS collaboration), Eur. Phys. J. A **50**, 74 (2014).
[15] P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).
[16] T. Ishikawa *et al.*, Phys. Rev. C **104**, L052201 (2021).