Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)
JPS Conf. Proc. **26**, 022014 (2019)
https://doi.org/10.7566/JPSCP.26.022014

Non-strange Dibaryon Resonances Observed in Coherent Double Neutral-Pion Photoproduction on the Deuteron

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(Received January 17, 2019)

A $B = 2$ system (dibaryon) is an interesting object to investigate a phase change of the basic configuration from a molecule-like state (such as the deuteron) to a spatially-compact hexaquark hadron state. To study dibaryon resonances, we have investigated coherent double neutral-pion photoproduction on the deuteron in which non-resonant processes are suppressed. The total cross section as a function of the γd center-of-mass energy shows resonance-like behavior peaked at around 2.47 and 2.63 GeV. The measured angular distribution of deuteron emission is rather flat, which cannot be reproduced by kinematics for quasi-free $\pi^0\pi^0$ production with deuteron coalescence. In $\pi^0 d$ invariant-mass distributions, a clear peak is observed at 2.14 ± 0.01 GeV with a width of 0.09 ± 0.01 GeV. The present work gives strong evidence not only for the 2.14-GeV isovector dibaryon, which is a key state to establish the theoretically predicted dibaryon sextet, but also for 2.47- and 2.63-GeV isoscalar dibaryons.

KEYWORDS: Coherent double meson photoproduction, dibaryon resonances

1. Introduction

The study of $B = 2$ systems (dibaryons) has a long history [1]. A dibaryon is an interesting object to study its basic configuration from a molecule-like state consisting of two baryons (such as the deuteron) to a hexaquark hadron state, which is expected to appear as a spatially-compact exotic particle. An early work by Dyson and Xuong [2] predicts the sextet of non-strange dibaryons $\mathcal{D}_{IJ}$ with isospin I and spin J ($\mathcal{D}_{01}$, $\mathcal{D}_{10}$, $\mathcal{D}_{12}$, $\mathcal{D}_{21}$, $\mathcal{D}_{03}$, and $\mathcal{D}_{30}$) based on the first known dibaryon, deuteron ($\mathcal{D}_{01}$), the $^1S_0$-NN virtual states ($\mathcal{D}_{10}$), and a resonance-like structure (a candidate for $\mathcal{D}_{12}$) at M=2.16 GeV/c^2 for the $^1D_2$-pp amplitude of the partial wave analysis for the $\pi^+ d \rightarrow pp$ reaction [3]. The recent observations of the $d^*(2380)$ ($\mathcal{D}_{03}$) by the CELSIUS/WASA and WASA-at-COSY collaborations [4, 5] have made us pay attention to this classification. It is important to establish the excitation spectrum of dibaryons in order to understand their internal structures and basic building blocks of hadrons. Many experimental investigations of the sextet members have been made, and candidates for almost all the members seem to be found [6–10]. However, the dibaryonic interpretations of the experimental data for some members are still questionable.

The candidate for the $\mathcal{D}_{12}$ state is given as the $^3P_2$ multipole strength at M=2.18 GeV/c^2 in $\pi^\pm d$ elastic scattering by a partial-wave analysis [6]. The corresponding $^1D_2$-pp amplitude also shows the same structure in the $\pi^+ d \rightarrow pp$ reaction [7]. The SAID group provides a pole for $\mathcal{D}_{12}$ [8] from a combined analysis of these reactions. Although the πd system has a resonance-like structure at approximately 2.15 GeV/c^2, the structure can be also understood as a quasi-free (QF) Δ excitation from a nucleon in the deuteron. It is important to confirm whether the 2.15-GeV/c^2 resonance can be interpreted as a dibaryon or not. The $\mathcal{D}_{12}$ is a key state to understand the sextet of dibaryons.

In photoinduced reactions, the $\gamma d \rightarrow \pi^0 d$ reaction is a convenient approach to study $\mathcal{D}_{12}$. Even if it is observed, it can be also understood as a quasi-free (QF) Δ excitation from a nucleon in the deuteron similarly to the $\pi^+ d \rightarrow pp$ and $\pi^\pm d \rightarrow \pi^\pm d$ reactions. The $\gamma d \rightarrow \pi^0\pi^0 d$ reaction is more advantageous to study $\mathcal{D}_{12}$ in the $\pi^0 d$ subsystem because the QF Δ excitation is kinematically separable as discussed later. Thus, we study the $\gamma d \rightarrow \pi^0\pi^0 d$ reaction, aiming to observe isovector $\mathcal{D}_{12}$ in the $\pi^0 d$ system through π^0 decay from a possible higher-mass isoscalar dibaryon in the $\pi^0\pi^0 d$ system.

2. Kinematics

An important concept is discussed first to separate the mechanisms for QF π^0 production and dibaryon production before moving on to the experiments. Possible mechanisms for the $\gamma d \rightarrow \pi^0\pi^0 d$ reaction can be classified in the following three:

(a) QF $\pi^0\pi^0$ production on a nucleon followed by deuteron coalescence (QFC),
(b) the first π^0 is emitted from the QF nucleon, subsequently the NN (ΔN) reaction occurs with the spectator nucleon to generate an isovector resonance R_{IV}, followed by the second π^0 and deuteron emission, and
(c) both one π^0 is emitted from a photo-produced isoscalar dibaryon R_{IS}, leaving an isovector dibaryon R_{IV}, successively another π^0 is emitted from R_{IV}.

In (a), the second π^0 should be emitted to compensate for the momentum given to the QF participant nucleon by the first emitted π^0 to coalesce into a deuteron. In this case, the angular distribution of deuteron emission in the center-of-mass (CM) frame shows strongly backward peaking. As for (b), the condition to coalescence of R_{IV} make the distribution sideway peaking at the incident photon energy around 1.2 GeV. A rather flat distribution is obtained in (c). Since the three mechanisms give completely different angular distributions, we can separate (or distinguish) the three mechanisms. Fig. 1 shows the diagrams for the three possible mechanisms for the $\gamma d \rightarrow \pi^0\pi^0 d$ reaction. The calculations performed by Fix and Ahrenhövel (FA) [11] are based on a QFC mechanism, and the angular distribution of deuteron emission actually shows strongly backward peaking as shown later in

Fig. 3. The behavior of an angular distribution in each mechanism can also be given by a Monte-Carlo simulation easily.

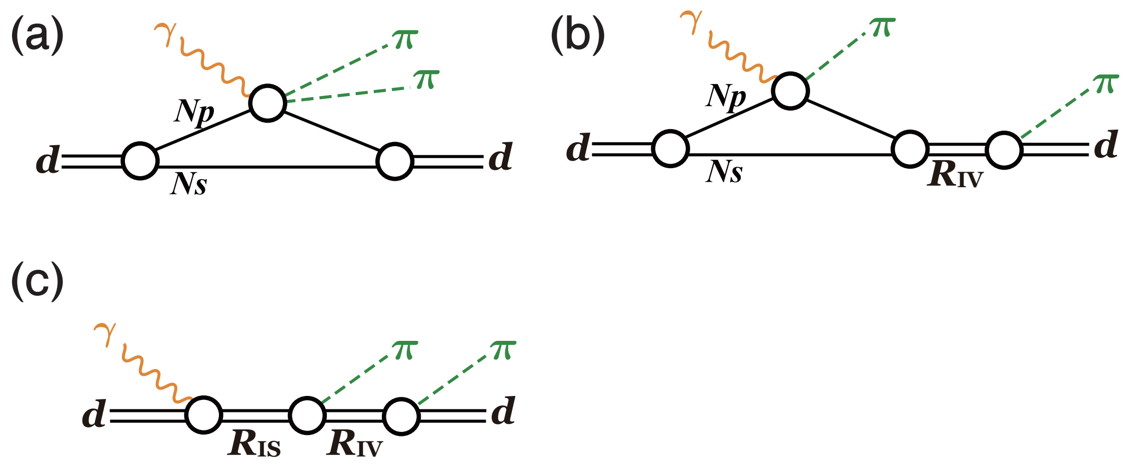

Fig. 1. Possible mechanisms for the $\gamma d \to \pi^0\pi^0 d$ reaction. (a) Two neutral pions are photoproduced on the QF participant nucleon N_p, followed by coalescence of N_p and spectator nucleon N_s into a deuteron. (b) One pion is photoproduced on N_p, successively coalescence of N_p (or Δ produced from N_p) and N_s into an isovector resonance R_{IV}, decaying into a pion and deuteron. (c) An isoscalar resonance R_{IS} is photoproduced from the deuteron. The R_{IS} decays into R_{IV} by emitting a pion, and successively R_{IV} decays into the deuteron by emitting another pion.

3. Experiments

The total and differential cross sections were measured for the $\gamma d \to \pi^0\pi^0 d$ reaction at the Research Center for Electron Photon Science (ELPH), Tohoku University [12]. A bremsstrahlung photon beam was provided by inserting a carbon fiber into the 1.2-GeV circulating electrons [13–16] in a synchrotron at ELPH. The energy of each photon was determined by measuring the trajectory of the corresponding post-bremsstrahlung electron. The tagging energy of the photon beam ranged from 0.75 to 1.15 GeV, and the typical tagging rate was 20 MHz. The target used in the experiments was liquid deuterium with a thickness of 45.9 mm. All the final-state particles in the $\gamma d \to \pi^0\pi^0 d$ reaction were measured with the FOREST detector [17]. FOREST consists of three different electromagnetic calorimeters (EMCs), and a plastic-scintillator hodoscope (PSH) is placed in front of each EMC to identify charged particles.

4. Results

The analysis of the $\gamma d \to \pi^0\pi^0 d$ reaction was made in the same way as in Ref. [19]. We selected the events containing four neutral particles and a charged particle, and applied a kinematic fit with six constraints: energy and three-momentum conservation, and every $\gamma\gamma$ invariant-mass being the π^0 mass. Events for which the χ^2 probability is higher than 0.4 are selected to reduce those from other background processes. A rather higher lower limit for the probability was introduced to suppress the events from deuteron misidentification in the most competitive QF $\gamma p' \to \pi^0\pi^0 p$ reaction.

The total cross section as a function of γd center-of-mass system $W_{\gamma d}$ shown in Fig. 1 is not monotonically increasing but shows resonance-like behavior peaked at around 2.47 and 2.63 GeV. A naive interpretation of this behavior may be a QF excitation of the nucleon in the deuteron. Looking into differential cross sections, the kinematic condition for the obtained data is found to completely differ from the QFC process.

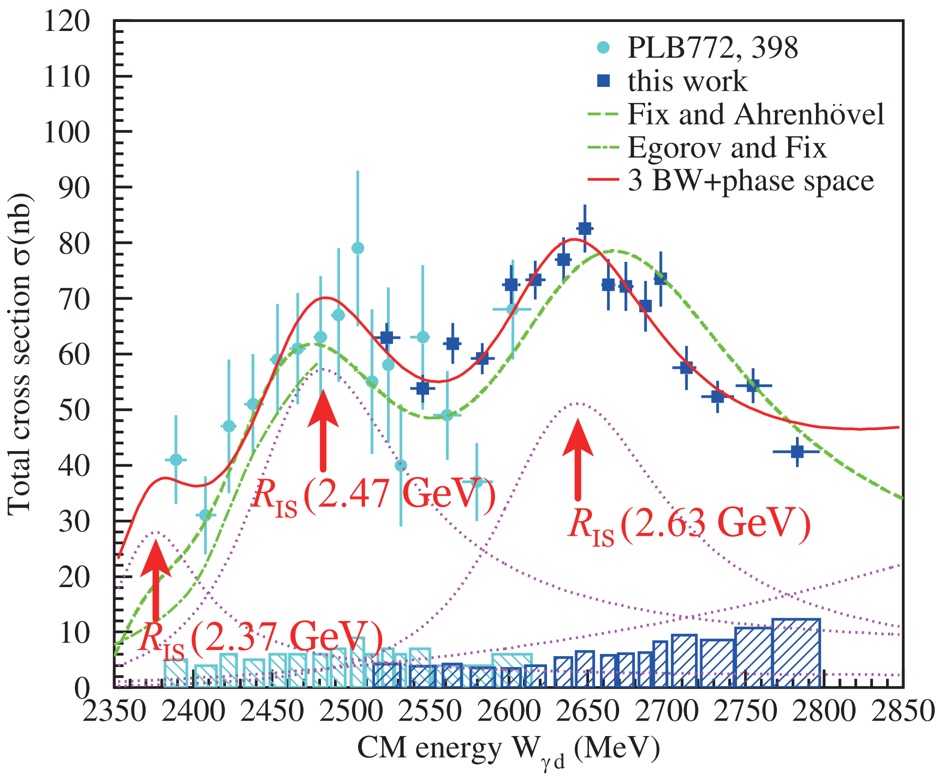

Fig. 2. Total cross section σ as a function of $W_{\gamma d}$. The blue squares show σ obtained in this work, while the cyan circles show that presented in Ref. [19]. The horizontal error of each data point corresponds to the coverage of the incident photon energy, and the vertical error shows the statistical error of σ. The solid and green dotted curves show theoretical calculations given in Ref. [11] and [18], respectively. The dashed red curve) shows the fitted function: a sum of three BW peaks and phase-space contributions. Each contribution to it is shown in a dash-dotted magenta curve. The lower hatched blue and cyan histograms show the systematic errors of σ in this work and in Ref. [19], respectively.

The differential cross sections, $d\sigma/dM_{\pi\pi}$, $d\sigma/dM_{\pi d}$, and $d\sigma/d\Omega_d$, are obtained for each group of photon-tagging channels divided into four groups. Fig. 3 shows $d\sigma/dM_{\pi\pi}$, $d\sigma/dM_{\pi d}$ and $d\sigma/d\Omega_d$ for the photon tagging group corresponding to $W_{\gamma d}$ = 2.7–2.8 GeV. The angular distribution of deuteron emission ($d\sigma/d\Omega_d$) is rather flat, and the kinematic condition for the obtained data completely differs from the QFC (dashed green curve: strongly backward peaking) and semi-QF (dotted magenta curve: sideway peaking) processes. Thus, we consider the possibility that the resonance-like structure in Fig. 2 might be due to a manifestation of isoscalar dibaryons. In the observed reaction, both the two nucleons obviously participate before emitting π^0s. The differential cross section $d\sigma/dM_{\pi d}$ as a function of πd invariant-mass $M_{\pi d}$ shows two peaks. The centroid of the low-mass peak is ~2.14 GeV/c^2 independently of the incident energy. However, that of the high-mass peak decreases with a decrease of the incident energy, and finally the two peaks are merged into a bump. The high-mass peak reflects the appearance of the 2.14-GeV/c^2 peak in $d\sigma/dM_{\pi d}$ between the other pion and deuteron (reflection). The $d\sigma/dM_{\pi\pi}$ shows no prominent feature, increasing monotonically with increase of

$M_{\pi\pi}$ from the minimum to the maximum of the available energy. In contrast, the momenta of the two π^0s are correlated in the QFC mechanism. This is partly because the quasi-free $\gamma n \to \pi^0\pi^0 n$ reaction shows an enhancement in the central part of the $M_{\pi\pi}$ spectrum [21, 22]. Additionally, to coalesce into a deuteron, the two π^0s should be emitted so as to compensate for the momentum given to the QF participant nucleon. Therefore, every FA calculation yields an enhancement in the central region of the spectrum.

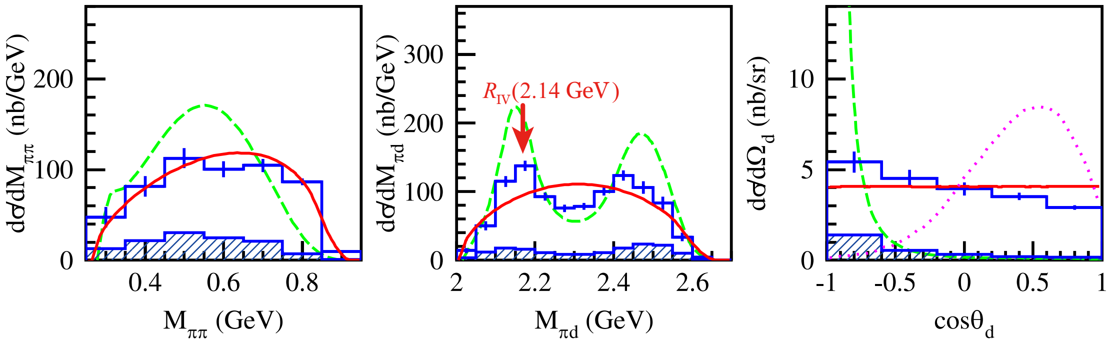

Fig. 3. Differential cross sections $d\sigma/dM_{\pi\pi}$ (left), $d\sigma/dM_{\pi d}$ (central), and $d\sigma/d\Omega_d$ (right) for $W_{\gamma d}$ = 2.7–2.8 GeV. The lower hatched cyan histograms show the corresponding systematic errors. The dashed green curves show the FA calculations based on the QFC mechanism. The solid red and dotted magenta curves correspond to the pure phase-space and semi-QF processes, respectively, where their yields are normalized so that the total cross section should be the same.

The resonance-like structure $R_{\rm IV}$ in Fig. 3 gives a mass of 2.14±0.01 GeV/c^2 with a width of 0.09±0.01 GeV/c^2. The mass is slightly lower than the sum of the N and Δ masses (∼2.170 GeV/c^2), and the width is narrower than that of Δ (∼0.117 GeV/c^2) [23]. This may suggest that the peak is interpreted as an $N\Delta$ quasi-bound state. The angular distributions for the two π^0s limit J^π of the state to 1^+, 2^+, or 3^-. The 2^+ assignment is consistent with the theoretically predicted $\mathcal{D}_{12}$ state, and with the resonance structure of the $^3P_2$-πd amplitude. The details of the analysis for the 2.14-GeV peak in $d\sigma/dM_{\pi d}$ are discussed in Ref. [20].

5. Discussion

A preliminary result for the excitation function of the total cross section obtained by the A2 collaboration at the Mainz MAMI accelerator also apparently showed a similar enhancement above an incident energy of 0.41 GeV ($W_{\gamma d}$ = 2.22 GeV) [24]. A set of differential cross sections is awaited to confirm the dibaryonic interpretation of the observed peaks in the excitation function. Recently, preliminary results for $\mathcal{D}_{12}$ candidates observed in the $\gamma d \to \pi^+\pi^- d$ reaction are reported [25,26], showing a peak with M = 2.1–2.2 GeV and $\Gamma \simeq$ 0.1 GeV both in the $\pi^\pm d$ invariant-mass distributions. The peak position is close to the sum of the N and Δ masses. The observed peak seems to be interpreted as $\mathcal{D}_{12}$, and the final results are strongly desired to study a production mechanism of $\mathcal{D}_{12}$.

6. Summary

The total and differential cross sections have been measured for the $\gamma d \to \pi^0\pi^0 d$ reaction at ELPH with incident energies from 0.75 to 1.15 GeV. The total cross section as a function of $W_{\gamma d}$ shows resonance-like behavior peaked at around 2.47 and 2.63 GeV. The experimental angular distributions of deuteron emission are rather flat, and they can never be understood in the QFC mechanism. A peak with $M = 2.14 \pm 0.01$ GeV and $\Gamma = 0.09 \pm 0.01$ GeV are observed in the $\pi^0 d$ invariant-mass distribution. The present work shows evidence for the existence of the 2.14-GeV/c^2 isovector dibaryon in the $\pi^0 d$ channel, and of the 2.47- and 2.63-GeV isoscalar dibaryons in the $\pi^0\pi^0 d$ channel. The details including figures can be found in Ref. [20].

Acknowledgments

The authors express their gratitude to the ELPH accelerator staff for stable operation of the electron synchrotron and its injector linac during the FOREST experiments. They also acknowledge Mr. Kazue Matsuda, Mr. Ken'ichi Nanbu, and Mr. Ikuro Nagasawa for their technical support. This work was supported in part by the Ministry of Education, Culture, Sports, Science and Technology, Japan through Grants-in-Aid for Scientific Research (B) No. 17340063, for Specially Promoted Research No. 19002003, for Scientific Research (A) No. 24244022, for Scientific Research (C) No. 26400287, and for Scientific Research (A) No. 16H02188.

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