Non-strange Dibaryon Resonances Observed in the $\gamma d \to \pi^0\pi^0d$ Reaction

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Recent, a dibaryon resonance $d^*(2380)$ with $M = 2.37$ GeV/c$^2$, $\Gamma = 0.07$ GeV/c$^2$, and $I (J^p) = 0 (3^+)$ has been observed in the $pn \to \pi^0\pi^0d$ reaction by the CELSIUS/WASA and WASA-at-COSY collaborations. The $d^*(2380)$ may be attributed to an isoscalar $\Delta\Delta$ quasi-bound state $D_{03}$, which was predicted by Dyson and Xuong as a member of the sextet non-strange dibaryons $D_{11}$ with isospin $I$ and spin $J$: $D_{01}$, $D_{10}$, $D_{12}$, $D_{21}$, $D_{03}$, and $D_{30}$. The total cross sections were measured for the $\gamma d \to \pi^0\pi^0d$ reaction below the incident energy of 0.88 GeV at the Research Center for Electron Photon Science (ELPH), Tohoku University. A slight enhancement corresponding to $d^*(2380)$ was observed in the excitation function for the $\gamma d$ center-of-mass (CM) energy $W_{\gamma d} = 2.38–2.61$ GeV although it was not statistically significant.

It is important to establish the excitation spectrum of dibaryons to understand the interior structures of them. So far, only a half of the sextet members seem to be established experimentally: the deuteron $D_{01}$, the $^1S_0$-$NN$ virtual state $D_{10}$, and the $d^*(2380)$ resonance $D_{03}$. Mulders et al. studied the sextet dibaryons using a bag model. They predict that $D_{03}$ has $M = 2.36$ GeV/c$^2$ and strongly (weakly) couples to the $^7S_3$-$\Delta\Delta$ ($^3D_3$-$NN$) state. They also predict that $D_{12}$ has $M = 2.36$ GeV/c$^2$ and couples to the $^1D_2$-$NN$ and $^5S_2$-$NN$ states. Gal and Garcilazo tried to understand $D_{03}$ and $D_{12}$ using three-body hadronic models. They obtain $M = 2.38 (2.15)\text{ GeV/c}^2$ for $D_{03}$ ($D_{12}$) by solving $\pi N\Delta$ ($\pi NN$) Faddeev equations. Experimentally, a hint of $D_{12}$ is given as the $^3P_2$ multipole strength at $M = 2.18$ GeV/c$^2$ in the $\pi^0d$ elastic scattering by a partial-wave analysis. The corresponding $^1D_2$-$pp$ amplitude also shows the same structure in the $\pi^0d \to pp$ reaction although $pp$ elastic scattering does not show any signature. Actually, Dyson and Xuong predicted the masses of the sextet dibaryons using $M = 2.16$ GeV/c$^2$ for $D_{12}$ obtained in the early $\pi^+d \to pp$ experiment as an anchor. Recently, preliminary results for $D_{12}$ candidates observed in the $\gamma d \to \pi^+\pi^-d$ reaction are reported, showing a peak with $M = 2.1–2.2$ GeV/c$^2$ and $\Gamma \simeq 0.1$ GeV/c$^2$ in both the $\pi^\pm d$ invariant-mass distributions. The peak position is close to the sum of the $N$ and $\Delta$ masses.

There is no doubt that the $\pi d$ system has a resonance-like structure around $2.15$ GeV/c$^2$. Once the existence of this resonance $d^*(2150)$ is verified, our understanding of the sextet dibaryons would be strongly deepened. To study $d^*(2150)$, the $\gamma d \to \pi^0d$ reaction is a convenient...
approach. However, the resonance, if observed, can be also understood as a quasi-free (QF) \( \Delta \) excitation out of the two nucleons in the deuteron. To find \( d^*(2150) \) in the \( \pi^0d \) system through the \( \gamma d \rightarrow \pi^0\pi^0d \) reaction is more advantageous, because the QF \( \Delta \) excitation is kinematically separable: the kinetic energy given to the deuteron is very small in most cases for QF \( \pi^0n^0 \) production on a nucleon followed by deuteron coalescence (QFC). In addition, a generated \( \pi^0d \) resonance following \( \pi^0 \) emission requires an isoscalar coupling in the initial \( \gamma d \) state. This constraint in addition to a very small \( \gamma \pi^0 \) coupling may reduce contributions from non-resonance processes. In this Letter, we study the \( \gamma d \rightarrow \pi^0\pi^0d \) reaction, aiming to observe \( d^*(2150) \) in the \( \pi^0d \) system \((I = 1)\) through \( \pi^0 \) decay from a possible higher-mass dibaryon in the \( \pi^0\pi^0d \) system \((I = 0)\).

A series of experiments \cite{16} were carried out using a bremsstrahlung photon beam from 1.20-GeV circulating electrons in a synchrotron \cite{17} at ELPH. The photon beam is provided by inserting a carbon fiber into the circulating electrons \cite{18,19}. The energy of each photon is determined by detecting the post-bremsstrahlung electron with a photon-tagging counter, STB-Tagger II. The tagging energy of the photon beam ranges from 0.75 to 1.15 GeV. The target used in the experiments was liquid deuterium with a thickness of 45.9 mm. All the final-state particles in the \( \gamma d \rightarrow \pi^0\pi^0d \) reaction were measured with the FOREST detector \cite{20}. FOREST consists of three different electromagnetic calorimeters (EMCs): 192 CsI crystals, 252 lead scintillating-fiber modules, and 62 lead-glass counters. A plastic-scintillator hodoscope (PSH) is placed in front of each EMC to identify charged particles. FOREST covers the solid angle of \( \sim 88\% \) in total. The typical photon-tagging rate was \( \sim 20 \) MHz, and the photon transmittance (the so-called tagging efficiency) was \( \sim 53\% \) \cite{18}. The trigger condition of the data acquisition (DAQ), which required to detect more than one final-state particles in coincidence with a photon-tagging signal \cite{21}, was the same as that in Ref. \cite{5}. The average trigger rate was 1.7 kHz, and the average DAQ efficiency was 79%.

Event selection is made for the \( \gamma d \rightarrow \pi^0\pi^0d \rightarrow \gamma\gamma\gamma d \) reaction. Initially, events containing four neutral particles and a charged particle are selected. The time difference between every two neutral EMC clusters out of four is required to be less than thrice of the time resolution for the difference. The charged particles are detected with the forward PSH. The time delay from the response of the four neutral clusters is required to be longer than 1 ns. The deposit energy of a charged particle in PSH is required to be greater than twice of that of the minimum ionizing particle. Further selection is made by applying a kinematic fit with six constraints: energy and three-momentum conservation, and every \( \gamma\gamma \) invariant-mass being the \( \pi^0 \) mass. The momentum of the charged particle is obtained from the time delay assuming that the charged particle has the deuteron mass. Events for which the \( \chi^2 \) probability is higher than 0.4 are selected to reduce those from other background processes. Events from deuteron misidentification in the most competitive QF \( \gamma p' \rightarrow \pi^0\pi^0p \) reaction are less than 3%. Finally, sideband-background subtraction is performed for accidental-coincidence events detected in STB-Tagger II and FOREST.

The total cross section is obtained by estimating the acceptance of \( \gamma\gamma\gamma d \) detection in a Monte-Carlo simulation based on Geant4 \cite{21}. Here, the event generation is modified from pure phase-space generation so as to reproduce the following three measured distributions: the \( \pi\pi \) invariant mass \( M_{\pi\pi} \), the \( \pi d \) invariant mass \( M_{\pi d} \), and the deuteron emission angle \( \cos\theta_d \) in the \( \gamma d\)-CM frame. Fig. \ref{fig:1} shows the total cross section \( \sigma \) as a function of \( W_{\gamma d} \). The data obtained in this work are consistent with the previously obtained data \cite{5} within errors. The systematic uncertainty of \( \sigma \) is also given in Fig. \ref{fig:1}. It includes the uncertainty of event selection in the kinematic fit, that of acceptance owing to the uncertainties of the \( M_{\pi\pi}, M_{\pi d} \), and \( \cos\theta_d \) distributions in event generation of the simulation, that of detection efficiency of deuterons, and that of normalization resulting from the numbers of target deuterons and incident photons.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Total cross section \( \sigma \) as a function of \( W_{\gamma d} \). The squares (blue) show \( \sigma \) obtained in this work, while the circles (cyan) show that presented in Ref. \cite{5}. 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 \( \sigma \). The solid and dotted curves (green) show theoretical calculations given in Ref. \cite{22} and \cite{23}, respectively. The dashed curve (red) shows the fitted function in Eq. \ref{eq:1}: a sum of three BW-peak and phase-space contributions. Each contribution to it is shown in a dash-dotted curve (magenta). The lower hatched histograms (blue and cyan) show the systematic errors of \( \sigma \) in this work and in Ref. \cite{5}, respectively.}
\end{figure}
The excitation function is not monotonically increasing but shows resonance-like behavior peaked at around 2.47 and 2.63 GeV. The two-peak structure is similar to the excitation function of the $\gamma N \rightarrow \pi^0\pi^0N$ reaction with two peaks at the $\gamma N$-CM energy $W_{\gamma N}$ of ~1.5 and ~1.7 GeV \cite{20, 21}, corresponding to the second- and third-resonance regions of the nucleon. A naive interpretation of this behavior may be a QF excitation of the nucleon in the deuteron. The solid line in Fig. 1 shows a calculation performed by Fix and Ahrenhövel (FA) based on the QFC mechanism \cite{22}. The calculation reproduces the data surprisingly well. However, as discussed later, the kinematic condition for the obtained data completely differs from the QFC process. Thus, we consider the possibility that the resonance-like structure might be due to a manifestation of dibaryons. A possible scenario is that one nucleon in the deuteron is excited by photoabsorption but is still interacting with the other nucleon before emitting two $\pi^0$s, forming a dibaryon resonance. We fit a function expressed by a sum of three Breit-Wigner (BW) peak and phase-space contributions to the data. The function is given by

$$\sigma(W_{\gamma d}) = \sigma_{PS}(W_{\gamma d}) \left\{ 1 + \sum_{i=0}^{2} \alpha_i L_{M_i, \Gamma_i}(W_{\gamma d}/c^2) \right\}, \tag{1}$$

where $\sigma_{PS}(W_{\gamma d})$ denotes $\sigma$ for the phase-space contribution, $L_{M_i, \Gamma_i}(W_{\gamma d})$ represents a BW function with the centroid of $M$ and width of $\Gamma$. The $M_0 = 2.37 \text{ GeV}/c^2$ and $\Gamma_0 = 0.07 \text{ GeV}/c^2$ are fixed to the values for $d^*(2380)$ \cite{4}, and the absolute values for $\sigma_{PS}(W_{\gamma d})$ are determined so as to fit the phase-space component in each $M_{\pi d}$ spectrum in Fig. 3. The fitted function and each contribution to it are also plotted in Fig. 1. The obtained parameters for the two peaks are $(M_1, \Gamma_1) = (2.469\pm0.003, 0.120\pm0.002) \text{ GeV}/c^2$ and $(M_2, \Gamma_2) = (2.632\pm0.003, 0.136\pm0.005) \text{ GeV}/c^2$. Isoscalar dibaryons seem to appear not only at 2.38 GeV/c$^2$ but also at 2.47 and 2.63 GeV/c$^2$. It should be noted that each observed peak may be comprised of several overlapping resonances.

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 as shown in Fig. 2. The experimental data are presented by histograms with statistical errors, the systematic uncertainties by hatched histograms and FA calculations by the solid curves. 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 $\pi^0$s are correlated in the QFC mechanism. To coalesce into a deuteron, the second $\pi^0$ should be emitted so as to compensate for the momentum given to the QF participant nucleon by the first emitted $\pi^0$. Therefore, every FA calculation yields an enhancement in the central region of the spectrum. The $d\sigma/dM_{\pi d}$ shows two peaks. The centroid of the low-mass peak is ~2.15 GeV/c$^2$ independently of the incident energy. However, that of the high-mass peak decreases with decrease of the incident energy, and finally the two peaks are merged into a bump. The high-mass peak reflects the appearance of the 2.15-GeV/c$^2$ peak in $d\sigma/dM_{\pi d}$ between the other pion and deuteron (reflection). The FA calculations also show a similar spectrum having two peaks, which are caused by QF $\pi^0\Delta$ production. The $d\sigma/d\Omega_d$ shows a gradually-increasing behavior with decrease of $\cos \theta_d$. The QFC kinematics does not reproduce the measured $d\sigma/d\Omega_d$. The FA calculation shows a strongly backward-peaking distribution accordingly for all the incident energies. This suggests that both the two nucleons participate in the reaction before emitting two $\pi^0$s, and the 2.15-GeV/c$^2$ peak in $d\sigma/dM_{\pi d}$ is due to a dibaryon resonance.

To study the properties of the 2.15-GeV/c$^2$ peak in $d\sigma/dM_{\pi d}$, we have analyzed the $M_{\pi d}$ spectra for the two highest-energy photon-tagging groups as shown in Fig 3 in more detail. Here, we consider the sequential and non-sequential processes of two-$\pi^0$ emission. The contribution from the latter process is assumed to be proportional to the phase space. At first, the mass and width are determined by fitting a function, expressed as a sum of a BW-peak, its reflection, and phase-space contributions, to the $M_{\pi d}$ data. The function is given by

$$N(m) = \alpha N_{PS}(m) \left\{ L_{M, \Gamma}^M(m) + L_{M, \Gamma}^{\sigma}(m') + C \right\}, \tag{2}$$
where \( N_{PS}(m) \) expresses the phase-space contribution, \( I_{M,M'}^{\phi}(m) \) represents the Gaussian-convoluted BW function with \( M, \Gamma \), and the experimental resolution \( \sigma_M = 0.011 \text{ GeV}/c^2 \). The running parameter \( m \) is one of the two \( M_{\pi d} \), and \( m' \) is the other. The acceptance is taken into account depending on \( M_{\pi \pi}, M_{\pi d}, \) and \( \cos\theta_p \) to estimate \( N_{PS}(m) \). The obtained parameters are \( M = 2.153 \pm 0.011 \text{ GeV}/c^2 \) and \( \Gamma = 0.112 \pm 0.011 \text{ GeV}/c^2 \). The mass is slightly lower than the sum of the \( N \) and \( \Delta \) masses (~2.170 GeV/c^2), and the width is almost equal to that of \( \Delta \) (~0.117 GeV/c^2) [24].

![FIG. 3. \( M_{\pi d} \) spectra for the two highest-energy photon-tagging groups. The solid curves (red) show the fitted functions, expressed as a sum of a Breit-Wigner peak (dotted, red), its reflection (dashed, magenta), and phase-space (dash-dotted, green) contributions, to the data.](image)

Both the conventional \( \Delta \) excitation and dibaryon system can form a peak at \( \sim 2.15 \text{ GeV}/c^2 \) in the \( M_{\pi d} \) spectrum. The QFC process makes the angular distribution strongly backward peaking for deuteron emission. The deuterons for most of the events (\( \geq 96\% \)) have the kinetic energy below \( 0.07 \text{ GeV} \), and the acceptance for such events is \( \sim 1.4 \times 10^{-4} \). Thus the QFC process cannot be observed in the present experiment. In addition, the following semi-QF process may be considered: the first \( \pi^0 \) is emitted from the QF nucleon, subsequently the \( NN (\Delta N) \) reaction occurs with the spectator nucleon to generate \( d^*(2150) \), followed by the second \( \pi^0 \) and deuteron emission. The kinematics of this process, however, creates a sideways peak in \( d\sigma/d\Omega_d \) at high incident energies. Such a peak does not exist at all as shown in Fig. 2. We conclude that the peak at \( 2.15 \text{ GeV}/c^2 \) in the \( M_{\pi d} \) spectrum is attributed to a dibaryon state, which can be generated neither in the QFC process nor the semi-QF process. This conclusion provides the following interpretation for the resonance-like structure in Fig. 1 a dibaryon state can be formed from a deuteron and a photon; the generated state might be a loosely-coupled molecular state; it plays a role as a doorway to a more complicated dibaryon state. Of particular importance is the fact that there is no spectator nucleon in the observed reaction.

Information on the spin-parity of the dibaryon states has been deduced from angular distributions of \( \pi^0 \)’s obtained for the events from \( M_{\pi d} = 2.05 \) to 2.25 GeV/c^2 in Fig. 3. Here, we define \( \pi_1 \) and \( \pi_2 \) as follows: \( \pi_1 \) is the first emitted \( \pi^0 \) leaving the \( \pi^0 d \) system behind and \( \pi_2 \) is the one emitted subsequently. We combine the data of the two highest-energy groups to analyze angular distributions. Fig. 3(a) shows the deduced \( \pi_1 \) angular distribution in the \( \gamma d\)-CM frame with the \( z \) axis taken along the incident photon direction. The experimental distribution is mostly expressed by a sum of two terms, constant and proportional to \( \cos\theta \). This \( \cos\theta \) dependence is naturally understood as a result of interference between \( \pi_1 \)-emission amplitudes with different parities. The \( \pi_2 \) angular distribution in the rest frame of the \( \pi d \) system is shown in Fig. 3(b), where the \( z \) axis is defined to be opposite to the \( \pi_1 \)-emission direction. Unlike Fig. 3(a), the distribution shows almost 90° symmetry. This implies that the 2.15-GeV/c^2 resonance is made of a single \( J^+ \) state or mixed states with the same parity. The FA calculation completely fails to reproduce both the angular distributions, due to the difference in the underlying reaction mechanism as already discussed. A sharp peak at 0° in Fig. 3(a) is the reflection of the backward peak in \( d\sigma/d\Omega_d \). In Fig. 3(b), the distribution takes an upward-convex shape being opposite to the experiment.

![FIG. 4. Acceptance-corrected angular distributions for \( \pi_1 \) in the \( \gamma d\)-CM frame (\( z \) axis: the photon beam direction) (a), and for \( \pi_2 \) in the \( \pi d \) rest frame (\( z \) axis: the opposite direction to \( \pi_1 \) (b). Events with \( M_{\pi d} = 2.05-2.25 \text{ GeV}/c^2 \) and \( W_{\pi d} = 2.66-2.80 \text{ GeV} \) are selected. The dashed curves (green) show the corresponding distributions in the FA calculations. The angular distributions are plotted with a shaded band (red) for \( J^* = 1^+, 2^+, \) and \( 3^+ \), and with dotted and dash-dotted curves (black) for \( J^* = 1^- \) and \( 2^- \), respectively. The solid horizontal lines (magenta) show the phase-space contributions.](image)

We calculate the \( \pi_1 \) and \( \pi_2 \) angular distributions for the reaction sequence \( \gamma d \rightarrow R_1 \rightarrow \pi_1 R_2 \rightarrow \pi_1 \pi_2 d \) using the density matrix (statistical tensor) formalism [25], where spins of \( R_1 \) and \( R_2 \) are denoted by \( J_1 \) and \( J_2 \), respectively. A possible contribution from non-sequential \( \pi^0 \) production is assumed to be proportional to the phase-space contribution, of which the fraction is determined from the \( M_{\pi d} \) spectrum in Fig. 3 for each photon-tagging group.
tion is almost symmetric with respect to $\cos \theta_{\pi_2} = 0$, the interference effect may be small. Thus, the contributions from the sequential and non-sequential processes are summed up incoherently. A set of the amplitudes of sequential processes $A_{\Lambda\Lambda}$ is determined for all the $\Lambda = (L_0, L_1, L_2, J_2, L_2)$ combinations to reproduce the measured $\pi_1$ and $\pi_2$ angular distributions simultaneously (20 data points), where $L_0$, $L_1$, and $L_2 \leq 2$ denote angular momenta carried by the incident photon, $\pi_1$ emission, and $\pi_2$ emission, respectively. An amplitude for a mixed state is given by $A_{\Lambda\Lambda} = (A_{\Lambda\Lambda} A_{\Lambda'\Lambda'}^*)^{1/2}$. The $S$-wave $NN^*$ molecular states are assumed to play a role as a doorway to $\Lambda\Lambda$ production. Hence, $J_2^*$ under consideration are $1^+$, $2^\pm$, and $3^\pm$. Additionally, $R_2$ is assumed to be a single resonance, namely $J_2 = J_2^*$ and $L_2 = L_2^*$.

In Fig. 4 also shown are the angular distributions calculated for $J_2^* = 1^\pm$, $2^\pm$, and $3^\pm$. The $J_2^* = 0^\pm$ assignments are already excluded because of an isotropic distribution for $\pi_2$ emission. The assignments of $J_2^* = 1^+$, $2^+$, and $3^-$ show almost the same quality to reproduce the angular distributions ($29 < \chi^2 < 32$). We reject the $J_2^* = 1^-$ and $2^-$ assignments, giving worse distributions ($\chi^2 = 47$ and 55), respectively, with a confidence level of higher than 99.7% (3$\sigma$), and leave the possibility of $J_2^* = 1^+, 2^+$ and $3^-$. Regarding $J_2^*$, major components are $1^+$ ($\sim 70\%$) and $2^-$ ($\sim 20\%$) for the case of $J_2^* = 1^+$ and $2^+$, while they are distributed widely to $J_1^* = 1^+$, $2^\pm$, and $3^\pm$ for $J_2^* = 3^-$. The $J_2^* = 2^+$ assignment not only coincides with energy dependence of the $^3P_2-\pi d$ amplitude, but also supports the existence of the predicted $D_{12}$ state at $2.15$ GeV/$c^2$. The $J_2^* = 3^-$ assignment is consistent with energy dependence of the $^3D_3-\pi d$ amplitude (about a half strength of $^3P_2$). There is no experimental sign for a $1^+$ state, although two isovector $0^-$ and $2^-$ states at $2.2$ GeV/$c^2$ have been reported recently [28].

In summary, the total and differential cross sections have been measured for the $\gamma d \rightarrow \pi^0\pi^0d$ reaction at $E_\gamma = 0.75$–1.15 GeV. The total cross section as a function of $W_{\pi^0d}$ shows resonance-like behavior peaked at around 2.47 and 2.63 GeV. The theoretical calculation based on the QFC mechanism well reproduces its behavior. However, the experimental angular distributions of deuterium emission can never be understood in the QFC mechanism. In the observed reaction, both the two nucleons obviously participate before emitting $\pi^0$s. In $\pi^0d$ invariant-mass distributions corresponding to the state after emitting the first $\pi^0$, a clear peak is observed at 2.15±0.01 GeV/$c^2$ with a width of 0.11±0.01 GeV/$c^2$. The angular distributions for the two $\pi^0$s limit $J^*$ of the state to $1^+$, $2^+$, or $3^-$. The $2^+$ assignment is consistent with the theoretically predicted $D_{12}$ state, and with the resonance structure of the $^3P_2-\pi d$ amplitude. The present work shows strong evidence for the existence of the 2.15-GeV/$c^2$ isovector dibaryon in the $\pi^0d$ channel, and of the 2.47- and 2.63-GeV/$c^2$ isoscalar dibaryons in the $\pi^0\pi^0d$ channel. These findings would give a base to explore dibaryon states lying at higher masses.

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