First measurement of coherent double neutral-pion photoproduction on the deuteron at incident energies below 0.9 GeV

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Abstract

The total cross sections were measured for coherent double neutral-pion photoproduction on the deuteron at incident energies below 0.9 GeV for the first time. No clear resonance-like behavior is observed in the excitation function for $W_{\gamma d} = 2.38 - 2.61$ GeV, where the $d^*$ (2380) dibaryon resonance observed at COSY is expected to appear. The measured excitation function is consistent with the existing theoretical calculation for this reaction. The upper limit of the total cross section is found to be $0.034 \mu b$ for the dibaryon resonance at $W_{\gamma d} = 2.37$ GeV (90% confidence level) in the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction.

Keywords: Coherent meson photoproduction, Dibaryon resonance, ABC effect
The internal structure of hadrons is a subject in the non-perturbative domain of the fundamental theory of strong interactions, quantum chromodynamics. The familiar mesons and baryons are composed of $q\bar{q}$ and $qqq$, respectively. More complex quark configurations beyond these are objects of great interest to investigate the effective degrees of freedom describing hadrons and to understand color confinement. The WASA-at-COSY collaboration has recently reported the isoscalar $d^*(2380)$ resonance with mass $M \simeq 2380$ MeV and width $\Gamma \simeq 68$ MeV, which is observed in the $pn \rightarrow \pi^0\pi^0d$ [1] and $pn \rightarrow \pi^+\pi^-d$ [2] reactions. The first indication corresponding to this resonance was observed in the former reaction by the CELSIUS/WASA collaboration [3]. The resonance may be attributed to an isoscalar $\Delta\Delta$ quasi-bound state, $D_{03}^0$, predicted by Dyson and Xuong [4]. In addition to the $\pi^0\pi^0d$ and $\pi^+\pi^-d$ final states, evidence for the $d^*(2380)$ resonance has been confirmed by the WASA-at-COSY collaboration in the $\pi^0\pi^-pn$ [5], $\pi^0\pi^0pn$ [6], and $\pi^+\pi^-pn$ [7] final states. The SAID partial wave analysis, which incorporates the analyzing power for the quasi-elastic $\vec{n}p \rightarrow np$ scattering measured by the WASA-at-COSY collaboration, also supports the existence of the $d^*(2380)$ resonance with quantum numbers $I(J^\pi) = 0(3^+)$ [8, 9]. These experimental results have stimulated intensive theoretical investigations of $D_{03}$ [10, 11]. To date, all the observations have been made using $pn$ collisions. Nearly all the measurements were made by the WASA-at-COSY collaboration.

The $d^*(2380)$ resonance should be observable in photoproduction reactions if it exists. The $\gamma d \rightarrow \pi^+\pi^-d$ and $\gamma d \rightarrow \pi^0\pi^0d$ reactions are expected to be of value when studying the production mechanism of the $d^*(2380)$ resonance. It may be produced as an intermediate state in the $s$ channel, and decays into a final state including a deuteron, where no special treatment is required kinematically for the Fermi motion of nucleons. The $\pi^+\pi^-d$ final state includes the isovector ($I = 1$) component, while the $\pi^0\pi^0d$ has just the isoscalar ($I = 0$) component alone. The Kroll-Ruderman contact term is expected to give a large effect in the $\pi^+\pi^-d$ channel, i.e., the $\gamma N\pi^\pm$ coupling is large. This may hide the $d^*(2380)$ contribution in the $\gamma d \rightarrow \pi^+\pi^-d$ yield. This reaction was studied by the CLAS collaboration at the Thomas Jefferson National Accelerator Facility. Their preliminary result does not show a peak corresponding to the $d^*(2380)$ resonance [12]. The other $\gamma d \rightarrow \pi^0\pi^0d$ reaction is thought to be the best process to investigate the $d^*(2380)$ resonance in photoproduction.

Two series of meson photoproduction experiments [13] were carried out using the tagged photon beam [14, 15] at the Research Center for Electron Photon Science (ELPH), Tohoku University. The photon beam was produced by a bremsstrahlung process with a carbon fiber from the 0.93 GeV circulating electrons in a synchrotron called the STructure Booster (STB) ring [16]. The tagging energy of the photon beam ranged from 0.57 to 0.88 GeV. The target used in the experiments was liquid deuterium with a thickness of 45.9 mm. The incident photon energy gives a $\gamma d$ center of mass energy, $W_{\gamma d}$, from 2.38 to 2.61 GeV, and the lowest photon energy corresponds to the centroid of the $d^*(2380)$ resonance.

All the final-state particles in the $\gamma d \rightarrow \pi^0\pi^0d$ reaction were measured using an electromagnetic (EM) calorimeter complex, FOREST [17]. FOREST consists of three different EM calorimeters: the forward, central, and backward calorimeters consisting of 192 pure CsI crystals, 252 lead scintillating fiber modules, and 62 lead glass Cherenkov counters, respectively. A plastic scintillator (PS) hodoscope is placed in front of each calorimeter to identify the charged particles. The solid angle of FOREST is approxi-
mately 88% in total. The typical tagging rate was 2.8 MHz, and the photon transmittance (so-called tagging efficiency) was approximately 42% [14]. The trigger condition of the data acquisition (DAQ) was

$$\sum_i [ST_i] \otimes [#S3 + #BG \geq 2]$$

(1)
to detect more than one final-state particles in coincidence with a tagging signal, where \(\sum\) indicates the OR signal of signals and \(\otimes\) stands for the coincidence of signals. The \(#S3 + #BG \geq 2\) denotes the signal generated when two output signals out of the groups in the forward and central calorimeters were given. The \(ST_i\) denotes an OR signal of the tagging channels in the corresponding group \(i = 1, \ldots, 16\). The details of the groups are described elsewhere [17]. The average trigger rate was 1.1 kHz, and the average DAQ efficiency was 85%.

Events detected in the final state containing four neutral particles and a charged particle were selected. Each neutral pion in the \(\gamma d \rightarrow \pi^0 \pi^0 d\) reaction was identified via its decay into \(\gamma \gamma\). Photons were detected as a set (cluster) of hit calorimeter modules without any responses of the hit PSs in the front hodoscope. The details of making clusters in FOREST are described in Ref. [17]. The time difference between every two neutral clusters of four was required to be less than \(3\sigma_t\), where \(\sigma_t\) denotes the time resolution for the difference depending on the modules and their measured energies for the two clusters. Deuterons in the final state were detected with the forward hodoscope called SPIDER, and the direction of emission was determined by the hit PSs. Note that the response of the corresponding calorimeter called SCISSORS II was not required. The time delay from the average time response between the four neutral clusters was required to be larger than 1 ns. The energy measured with SPIDER was required to be greater than \(2E_{mip}\), where \(E_{mip}\) denotes the energy that the minimum ionizing particle deposits in a PS. The momentum of deuterons was calculated from the measured time delay assuming that the charged particles had the mass of the deuteron.

A kinematic fit with six constraints (6C) was applied for the further event selection of the \(\gamma d \rightarrow \pi^0 \pi^0 d\) reaction. The kinematic variables in the fit were the incident photon energy, the three-momentum of the five final-state particles, and the reaction vertex point. Even though FOREST did not have a vertex counter, the \((x, y)\) intensity map of the photon beam was measured using a beam-profile monitor [15] day by day. The measured variable and its resolution for the \(x(y)\)-component of the vertex point were assumed to be the same as the centroid and width of the \(x(y)\) distribution of the photon beam at the target position. Because the attenuation of the photon beam flux was negligibly small passing through the liquid deuterium target, the measured variable and its resolution for the \(z\)-component was assumed to be the same as the center and thickness(\(\sigma\)) of the target. The required constraints were energy and three-momentum conservation between the initial and final states and two \(\gamma \gamma\) invariant masses (the neutral-pion rest mass, \(m_{\pi^0}\)).

The 6C kinematic fit is effective at selecting the \(\gamma d \rightarrow \pi^0 \pi^0 d\) reaction. Events in which the \(\chi^2\) probability was higher than 0.4 were selected to prevent contamination from the quasi-free two neutral-pion photoproduction on the proton in the deuteron, \(\gamma p' \rightarrow \pi^0 \pi^0 p\). This quasi-free production is the most competitive background process, having 100 times higher cross section [18]. The lower limit of \(\chi^2\) probability 0.4 makes the contamination less than 5%, which is much less than the statistical error of the measured total cross section (\(~ 20\%)\). Because accidental coincidence events exist between
the photon-tagging counter, STB-Tagger II [14], and FOREST, sideband background subtraction was performed.

An invariant mass distribution of two final-state particles was investigated to give the difference of the measured distributions between the experimental data and pure phase-space simulation. Fig. 1(a) shows the typical $\pi^0\pi^0$ invariant mass ($m_{\pi\pi}$) distribution. The $m_{\pi\pi}$ distribution for the real data is quite different from that for the pure phase-space generation of the three final-state particles. An enhancement is observed in the lower-mass region close to $2m_{\pi0}$, which may correspond to the ABC effect [19]. In addition, another enhancement is observed in the higher-mass region. These two enhancements are observed in all the incident energy regions. Fig. 1(b) shows the typical $\pi^0d$ invariant mass ($m_{\pi d}$) distribution. No significant difference between the real data and the simulation is observed in the $m_{\pi d}$ distribution.

![Figure 1: (a) $\pi^0\pi^0$ and (b) $\pi^0d$ invariant mass distributions at $W = 2.39$ GeV (2.382–2.396 GeV). The data points (blue) are compared with the simulation results. The dashed histogram (magenta) shows the results for pure phase-space event generation, and the solid histogram (red) shows the results for $n = 4.9$ (see text). Normalizations of the simulation results are the same for (a) and (b).]

The total cross section of the $\gamma d \rightarrow \pi^0\pi^0d$ reaction can be obtained from the equation

$$\sigma = \frac{N_{\pi^0\pi^0d}}{N'_\gamma N_\tau \eta_{\text{acc}} \{\text{BR}(\pi^0 \rightarrow \gamma\gamma)\}^2},$$

which uses the number of events for the $\gamma d \rightarrow \pi^0\pi^0d$ reaction, $N_{\pi^0\pi^0d}$, the effective number of incident photons, $N'_\gamma$, the number of target deuterons per unit area, $N_\tau = 0.237\, \text{b}^{-1}$, the acceptance of the final state $\pi^0\pi^0d \rightarrow \gamma\gamma\gamma\gamma d$ detection, $\eta_{\text{acc}}$, and the branching ratio of the neutral pion to the two-photon decay, $\text{BR}(\pi^0 \rightarrow \gamma\gamma)$. The number of incident photons, $N_\gamma$, is determined by multiplying the number of tagging signals after the counting-loss correction by the corresponding photon transmittance. The $N'_\gamma$ is obtained additionally multiplying $N_\gamma$ by the DAQ efficiency. The acceptance of $\gamma\gamma\gamma\gamma d$ detection is estimated by a Monte-Carlo simulation based on Geant4 [20]. Here, the total cross section as a function of the incident energy is assumed to be flat. To reproduce
the measured $m_{\pi\pi}$ distribution, the $m_{\pi\pi}$ distribution for generated events is assumed to have an additional dependence from pure phase-space generation:

$$P = \left(\frac{m_{\pi\pi}^\text{max} - m_{\pi\pi}^\text{min}}{m_{\pi\pi}^\text{max} - m_{\pi\pi}^\text{min}}\right)^n + \left(\frac{m_{\pi\pi}^\text{max} - m_{\pi\pi}^\text{max}}{m_{\pi\pi}^\text{max} - m_{\pi\pi}^\text{min}}\right)^n$$

with $n = 4.9$, where $m_{\pi\pi}^\text{max}$ and $m_{\pi\pi}^\text{min}$ denote the maximum and minimum values for $m_{\pi\pi}$, respectively, at the fixed incident photon energy.

Because the statistics were limited, the tagging channels were divided into 16 groups, and the total cross section was obtained for each group. Fig. 2 shows the total cross section, $\sigma$, for the $\gamma d \rightarrow \pi^0\pi^0 d$ reaction, as a function of the incident energy, $E_\gamma$. The total cross section is rather flat, and a clear resonance-like behavior is not observed in the excitation function for $E_\gamma = 0.57–0.88$ GeV ($W_{\gamma d} = 2.38–2.61$ GeV).

![Figure 2: Total cross section, $\sigma$, as a function of $E_\gamma$. The upper points (blue) show the obtained $\sigma$. The horizontal bar of each point shows the coverage of the incident photon energy, and the vertical bar shows the statistical error of $\sigma$. The lower histogram (red) shows the systematic errors (see text for details). The data are compared with theoretical calculations for the $\gamma d \rightarrow \pi^0\pi^0 d$ reaction given in Ref. [22] (dashed) and Ref. [23] (solid).](image)

To estimate the systematic uncertainty of event yields, we varied the lower limit of event selection in the kinematic fit from 0.2 to 0.6 (from 19% to 3% contamination assuming 100 times higher total cross section for the quasi-free $\gamma p' \rightarrow \pi^0\pi^0 p$ reaction),
and the uncertainty ($\sigma$) was found to range from 5.2% to 10.8% depending on the tagging-energy group. To estimate the systematic uncertainty of the acceptance, we changed the $m_{\pi\pi}$ distribution for event generation in the simulation. The $n$ parameters corresponding to the realistic $m_{\pi\pi}$ distributions give the uncertainty ($\sigma$) from 0.1% to 0.5%. The uncertainty in the acceptance from the uncertainty in the FOREST coverage is 0.7%–4.1%. The uncertainty in the deuteron detection efficiency is 1.0%–5.3% owing to the uncertainty in the density of the vacuum chamber surrounding the liquid deuterium target. The normalization uncertainties resulting from the number of target deuterons and the number of incident photons are 1% and 1.5%–1.9%, respectively. The total systematic uncertainty is obtained by combining all the uncertainties described above in quadrature. The total systematic uncertainty as a function of $E_\gamma$ is also plotted in Fig. 2.

Fix and Arenhövel reported their calculation of the total cross section for the $\gamma d \rightarrow \pi^0\pi^0d$ reaction at $E_\gamma = 0.32$–1.50 GeV [22]. Egorov and Fix recently reported their calculation for the reaction at $E_\gamma = 0.40$–0.70 GeV [23]. The calculated cross sections are also plotted in Fig. 2. For coherent production, the isovector parts in the amplitudes for the $\pi^0\pi^0$ production on the proton and neutron are canceled. Because the fraction of the isoscalar part is thought to be only 8% of the proton amplitude, the cross section for the coherent production is much smaller than that for the quasi-free $\pi^0\pi^0$ production on the nucleon ($\sim 10 \mu b$ at $E_\gamma = 0.60$ GeV). The measured cross section is well reproduced by the calculation given by Fix and Arenhövel except for the lowest incident photon energy region ($\sim 0.57$ GeV). The discrepancy in the lowest energy region may be explained by excitation of the $d^*(2380)$ dibaryon resonance.

Fig. 3 shows the total cross section, $\sigma$, for the $\gamma d \rightarrow \pi^0\pi^0d$ reaction as a function of $W_{\gamma d}$. The $d^*(2380)$ contribution was estimated by fitting the function

$$\sigma(W_{\gamma d}) = \frac{\text{BW}(W_{\gamma d})}{\text{BW}(2.37 \text{ GeV})} \sigma_{d^*} + \sigma_{\text{th}}(W_{\gamma d})$$

(4)

to the data, where $\text{BW}(W_{\gamma d})$ denotes the relativistic Breit-Wigner function [21] corresponding to the expected $d^*(2380)$ contribution with a centroid of $M = 2.37$ GeV and a width of $\Gamma = 68$ MeV. The $\sigma_{\text{th}}$ stands for the calculated cross section given by Fix and Arenhövel. The $\chi^2$/dof of the fit is 10.1/15, and the obtained parameter is

$$\sigma_{d^*} = 0.0184 \pm 0.0091 \mu b.$$  

(5)

The upper limit of the total cross section was found to be 0.034 $\mu b$ at $W_{\gamma d} = 2.37$ GeV (90% confidence level).

The total cross sections for the $\gamma d \rightarrow \pi^0\pi^0d$ reaction were measured for the first time using the FOREST detector at ELPH. The incident energy ranged from 0.57 to 0.88 GeV. No clear resonance-like behavior corresponding to the $d^*(2380)$ resonance with $I(J^\pi) = 0(3^+)$ was observed in the excitation function for $W_{\gamma d} = 2.38$–2.61 GeV. The measured cross section is well reproduced by the calculation given by Fix and Arenhövel [22] except for the lowest incident photon energy region ($\sim 0.57$ GeV). A possible explanation of the discrepancy in the lowest energy region may be attributed to excitation of the $d^*(2380)$ dibaryon resonance. The upper limit of the total cross section in this reaction was found to be 0.034 $\mu b$ for the dibaryon resonance at $W_{\gamma d} = 2.37$ GeV (90% confidence level). A further understanding of the $\gamma d \rightarrow \pi^0\pi^0d$ reaction mechanism is required.
Figure 3: Total cross section, $\sigma$, as a function of $W_{\gamma d}$. The upper points (blue) show the obtained $\sigma$. The horizontal error of each point corresponds to the coverage of the incident photon energy, and the vertical error shows the statistical error of $\sigma$. The lower histogram (red) shows the systematic error of $\sigma$ (see text for details). The dotted curve (green) shows the calculated $\sigma$ given in Ref. [22]. The data are compared with a function shown in the solid curve (green) expressed by the sum of the expected $d^*(2380)$ contribution with a relativistic Breit-Wigner shape with $W = 2.37$ GeV and $\Gamma = 68$ MeV ($0.0184$ $\mu$b at $W = 2.37$ GeV) and calculated $\sigma$ [22].

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