Non-strange dibaryons studied in coherent double neutral-pion photoproduction on the deuteron

Takatsugu ISHIKAWA
Research Center for Electron Photon Science (ELPH),
Tohoku University, Japan

12th International Workshop on the Physics of Excited Nucleons (NSTAR2019)
10~14 June 2019, Bonn, Germany

Contents

1. dibaryons
2. isoscalar dibaryon $\mathcal{D}_{03}(2380)$
3. isovector $\mathcal{D}_{12}(2150)$
4. experimental setup
5. total cross section
   ~ isoscalar dibaryons $\pi^0\pi^0d$
6. differential cross section
   ~ isovector dibaryons $\pi^0d$
7. properties of the dibaryon observed in $\pi d$ system
8. summary

$\gamma d \rightarrow \pi^0\pi^0d$

T. Ishikawa et al.,
PLB772, 398 (2017);
PLB789, 413 (2019).
Dibaryons

a dibaryon

an object with baryon number $B=2$

deuteron is the first dibaryon

proton and neutron bound system

with spin $J=1$ and isospin $I=0$

the quark picture of a dibaryon

is of interest in the non-perturbative

domain of QCD
Dibaryons

a dibaryon ($B=2$ system):
a phase change of its basic configuration

a molecule-like state
consisting of two baryons
such as the deuteron

a hexaquark hadron state

the current problem in hadron physics
insights into the nuclear equation of state
and the interior of a neutron star

$d^*(2380)$, a dibaryon resonance $d^*(2380)$: observed $pn \rightarrow \pi^0\pi^0d$ reaction

$m=2.37$ GeV, $\Gamma=0.07$ GeV, $I=0$, $J^\pi=3^+$

M. Bashkanov et al. (CELCIUS/WASA), PRL102, 052301 (2009).
P. Adlarson et al. (WASA-at-COSY), PRL106, 242302 (2011).

A hexaquark state, and/or an isoscalar $\Delta\Delta$ quasi-bound state, $D_{03}$

F.J. Dyson and N.-H. Xuong, PRL13, 815 (1964).

**$d^*(2380)$**


<table>
<thead>
<tr>
<th>$\mathcal{D}$</th>
<th>$D_0$</th>
<th>$D_{10}$</th>
<th>$D_{12}$</th>
<th>$D_{21}$</th>
<th>$D_{03}$</th>
<th>$D_{30}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BB$</td>
<td>$NN$</td>
<td>$NN$</td>
<td>$\Delta N$</td>
<td>$\Delta N$</td>
<td>$\Delta \Delta$</td>
<td>$\Delta \Delta$</td>
</tr>
<tr>
<td>$M$</td>
<td>$A$</td>
<td>$A$</td>
<td>$A+6B$</td>
<td>$A+6B$</td>
<td>$A+10B$</td>
<td>$A+10B$</td>
</tr>
<tr>
<td></td>
<td>1878</td>
<td>1878</td>
<td>2160</td>
<td>2160</td>
<td>2348</td>
<td>2348</td>
</tr>
</tbody>
</table>

$M = A + \{I(I+1) + S(S+1) - 2\}B$

$A = 1878$ MeV

$B = 47$ MeV

- non-attractive $^1S_0$ states: $pp$, $pn$, $nn$
- deuteron: attractive $^3S_1$ state

---

$d^*(2380)$
total cross section for $\gamma d \rightarrow \pi^0 \pi^0 d$
below the incident energy of 0.88 GeV
T. Ishikawa et al., PLB772, 398 (2017).

Breit-Wigner + theoretical calculation
A. Fix and H. Arenhobvel,

Systematic error

a slight enhancement:
$18.4 \pm 9.2$ nb (upper limit: 34 nb 90% CL)

**$D_{12}$** (2150)  
the excitation spectrum:  
internal structures of dibaryons  

<table>
<thead>
<tr>
<th>DIS</th>
<th>$D_01$</th>
<th>$D_{10}$</th>
<th>$D_{12}$</th>
<th>$D_{21}$</th>
<th>$D_{03}$</th>
<th>$D_{30}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB</td>
<td>NN</td>
<td>NN</td>
<td>$\Delta N$</td>
<td>$\Delta N$</td>
<td>$\Delta \Delta$</td>
<td>$\Delta \Delta$</td>
</tr>
<tr>
<td>M</td>
<td>$A$</td>
<td>$A$</td>
<td>$A+6B$</td>
<td>$A+6B$</td>
<td>$A+10B$</td>
<td>$A+10B$</td>
</tr>
<tr>
<td></td>
<td>1878</td>
<td>1878</td>
<td>2160</td>
<td>2160</td>
<td>2348</td>
<td>2348</td>
</tr>
</tbody>
</table>

WASA-at-COSY, PRL121, 052001 (2018)  

$$pp \rightarrow \pi^- \pi^+ pp$$

WASA-at-COSY, PLB762, 455 (2016)  

$$pp \rightarrow \pi^- \pi^- \pi^+ \pi^+ pp$$

\( \mathcal{D}_{12}(2150) \)

\( \mathcal{D}_{12} \): partial-wave analysis

\( \pi d \to pp \): R. Arndt et al., PRC48, 1926 (1993).

\[ ^3P_2 - \pi d \]

\[ ^1D_2 - pp \]

FIG. 7. Argand plot of the dominant \( \pi d \) partial-wave amplitudes \( ^3P_2, ^3D_3, \) and \( ^3F_4 \) which correspond to the \( ^1D_2, ^3F_3, \) and \( ^1G_4 \) \( pp \) states, respectively. (Compare Fig. 7 of Ref. [3]). The \( X \) points denote 50 MeV steps. All amplitudes have been multiplied by a factor of \( 10^3 \).

\( \pi d \to \pi d \): R. Arndt et al., PRC50, 1796 (1994).

The SAID group provides a pole for \( \mathcal{D}_{12} \) from a combined analysis including \( pp \) elastic scattering.

C.H. Oh et al., PRC56, 635 (1997).

$D_{12}(2150)$

$D_{12}$: partial-wave analysis
dibaryonic interpretation is still questionable

quasi-free $\Delta$ excitation cannot be kinematically separated
$\gamma d \rightarrow \pi^0 \pi^0 d$ to study $\mathcal{D}_{12}$ (2150)

1. Dibaryon production

$$d \xrightarrow{R_{IS}} \pi \xrightarrow{R_{IV}} d$$

Angular distribution of deuteron emission

- Almost flat

2. QF $\pi\pi$ production

$$d \xrightarrow{\Delta} \pi \xrightarrow{\Delta} d$$

Backward peaking

3. QF $\pi\pi$ production

$$d \xrightarrow{\Delta} \pi \xrightarrow{R_{IV}} d$$

Sideway peaking

4. QF $\pi\pi$ production

$$d \xrightarrow{\pi} \pi \xrightarrow{\pi} d$$

Almost flat

Kinematically separable!

Accelerator

Electron Beam
LINAC 150 MeV
Booster Ring 1200 MeV (max)

Photon Beam
Bremsstrahlung
Tagged

1.3 GeV Booster STorage Ring

740~1150 MeV @ 1200 MeV
~20 MHz (photon: 10 MHz)
\[ W_{\gamma d} = 2.50 \sim 2.80 \text{ GeV} \]

570~890 MeV @ 930 MeV
~2.8 MHz (photon: 1.2 MHz)
\[ W_{\gamma d} = 2.38 \sim 2.61 \text{ GeV} \]

T. Ishikawa et al., NIMA 622, 1 (2010); T. Ishikawa et al., NIMA 811, 124 (2016);
Y. Matsumura et al., NIMA 902, 103 (2018); Y. Obara et al., NIMA 922, 108 (2019).

EM calorimeter
Backward Gamma

SCISSORS III  SPIDER  LOTUS  Rafflesia II

192 CsI crystals
3% @ 1 GeV

252 Lead/SciFi modules
7% @ 1 GeV

62 Lead Glasses
5% @ 1 GeV

Target: 45 mm thick LH2 & LD2
T. Ishikawa et al., NIMA 832, 108 (2016).

Event Selection

1. 4 neutral particles and 1 charged particle

2. each neutral pion: $\gamma\gamma$ decay
time difference is less than $3\sigma_t$
between every 2 neutral clusters out of 4

3. $d$ is detected with SPIDER
(response of SCISSORS III is not required)
time delay is larger than 1 ns wrt average $\gamma\gamma\gamma\gamma$ time
energy deposit is higher than $2E_{\text{mip}}$

4. sideband background subtraction
to remove accidental coincidence
between STB-Tagger II and FOREST

Further event selection:
a kinematic fit with 6 constraints is applied
ergy and momentum conservation (4)
each $\gamma \gamma$ invariant mass is $m_{\pi^0}$ (2)
$\chi^2$ probability is higher than $0.4$

$\gamma d \rightarrow \pi^0 \pi^0 d$ (coherent)
$\gamma p' \rightarrow \pi^0 \pi^0 p$ (pQF)
$\gamma n' \rightarrow \pi^0 \pi^0 n$ (nQF)
$\gamma d \rightarrow \pi^0 \pi^0 pn$ (non QF)
Further event selection:
a kinematic fit with 6 constraints is applied
energy and momentum conservation (4)
each $\gamma\gamma$ invariant mass is $m_{\pi^0}$ (2)
$\chi^2$ probability is higher than 0.4

missing momentum is given for the deuteron in these plots

Total cross section

total cross section for $\gamma d \rightarrow \pi^0 \pi^0 d$

at the incident energy $0.55 \sim 1.15$ GeV

resonance-like behavior peaked at around 2.47 and 2.63 GeV
two-peak structure is similar to the excitation function of QF $\pi\pi$ production corresponding to the second- and third-resonance regions of the nucleon naïve interpretation: QF excitation of the nucleon
Differential cross section

\[ \pi^0 d \text{ invariant mass} \]

A peak at \( \sim 2.15 \text{ GeV} \) and its reflection

deuteron emission
rather flat
slight backward peaking at high energies

The data points are compared with calculations by Fix and Arenhövel (FA calculation).

$\pi d$ invariant mass

loci corresponding to $D_{12}$ can be observed in correlation plots.

available region is very limited at a fixed incident energy
\[ \pi d \text{ invariant mass} \]

\[ W_{\gamma d} = 2.70 - 2.80 \text{ GeV} \]

**FA calculation**

**Counts / 0.02 GeV**

<table>
<thead>
<tr>
<th></th>
<th>0.02 GeV</th>
<th>0.04 GeV</th>
<th>0.06 GeV</th>
<th>0.08 GeV</th>
<th>0.10 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>2.2</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>2.4</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>2.6</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
</tbody>
</table>

\[ M_{\pi d} (\text{GeV}) \]

\[ N(m_1) = \int_{m_2} M_{\pi d} (m_1) \left( \alpha \left| L_{M,\Gamma}(m_1) + L_{M,\Gamma}(m_2) \right|^2 + C \right) V_{PS}(m_1, m_2) \, dm_2 \]

**Breit-Wigner amplitude:**

\[ L_{M,\Gamma}(m) = \left( m^2 - M^2 + iM\Gamma \right)^{-1} \]

**D_12 or \Delta + N**

mass \( 2140 \pm 11 \text{ MeV} \) & width \( 91 \pm 11 \text{ MeV} \)

Deuteron angular distribution

\[ W_{\gamma d} = 2.70 - 2.80 \text{ GeV} \]

- LIPS
- QF \( \pi \pi \) production (FA calculation)
- QF \( \pi \) production
- Pure phase space (direct \( \pi \pi \) production)

Experimental data suggests a sequential process:

\[ \gamma d \rightarrow R_{IS} \rightarrow \pi^0 R_{IV} \rightarrow \pi^0 \pi^0 d \]

(rather flat angular distribution & 2.15-GeV peak in \( M_{\pi d} \))

Total cross section for $\gamma d \rightarrow \pi^0 \pi^0 d$
at the incident energy 0.55–1.15 GeV

Resonance-like behavior peaked at around 2.47 and 2.63 GeV

3 dibaryons: 2.38, 2.47, and 2.63 GeV with widths of 0.07, 0.12, 0.13 GeV
Spin and parity sequential process:

\[ \gamma d \rightarrow R_1 \rightarrow \pi_1 R_2 \rightarrow \pi_1 \pi_2 d \]

\[ J^{\pi} = 1^-, 2^-, 1^+, 2^+, 3^- \]

- \( \pi_1 \) emission angle in the \( \gamma d \) CM frame
- \( \pi_2 \) emission angle in the \( \pi_2 d \) rest frame
- \( z \) axis: \( \gamma \)

FA calculation

Two isoscalar dibaryons and an isovector dibaryons are observed in the $\pi\pi d$ and $\pi d$ systems, respectively.

*T. Ishikawa, 11 Jun. 2019 (NSTAR2019)*
$\gamma d \rightarrow \pi^0 \eta d$ TCS

total cross section for $\gamma d \rightarrow \pi^0 \eta d$
at the incident energy 0.74~1.15 GeV

angular distribution of
deuteron emission:
rather flat

isovector dibaryon?

\( \gamma d \rightarrow \pi^0 \eta d \) DCS

Angular distribution of deuteron emission: rather flat

\( \pi d \) invariant mass shows a peak at 2.15 GeV.

Summary

Total cross section of the $\gamma d \to \pi^0 \pi^0 d$ reaction has been measured at $W_{\gamma d}=2.38 \sim 2.80$ GeV for the first time. A slight enhancement corresponding to $d^*(2380) \sim \mathcal{D}_{03}$ candidate is observed.

T. Ishikawa et al., PLB772, 398 (2017).

Additional two dibaryon resonances are observed at 2.47 and 2.63 GeV with widths of 0.12 and 0.13 GeV (A rather flat angular distribution of deuteron emission shows production of dibaryon resonances).

A peak at $M \sim 2.15$ GeV $\sim \mathcal{D}_{12}$ candidate is observed in the $\pi^0 d$ invariant mass distribution for the $\gamma d \to \pi^0 \pi^0 d$ reaction at $W_{\gamma d}=2.50 \sim 2.80$ GeV. $M=2.14 \pm 0.01$ GeV, $\Gamma=0.09 \pm 0.01$ GeV $J^\pi=1^+, 2^+$ or $3^-$

T. Ishikawa et al., PLB789, 413 (2019).