On the near-threshold incoherent $\phi$ photoproduction on the deuteron: Any trace of a resonance?

MIN16, Kyoto University

July 2016

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Motivation

• Presence of a local peak near threshold at $E_\gamma \sim 2.0$ GeV in the differential cross-section (DCS) of $\gamma p \rightarrow \phi p$ at forward angle by Mibe and Chang, et al. [PRL 95 182001 (2005)] from the LEPS Collaboration.

→ Observed also recently by JLAB: B. Dey et al. [PRC 89 055208 (2014)], and Seraydaryan et al. [PRC 89 055206 (2014)].

• Conventional model of Pomeron plus $\pi$ and $\eta$ exchanges usually can only give rise to a monotonically-increasing behavior.

• We would like to see whether this local peak can be explained as a resonance.

• In order to check this assumption, we apply the results on $\gamma p \rightarrow \phi p$ to $\gamma d \rightarrow \phi pn$ to see if we can describe the latter.
Reaction model for $\gamma p \rightarrow \phi p$

- Here are the **tree-level diagrams** calculated in our model in an **effective Lagrangian** approach.

\[ \begin{align*}
\text{(a)} & \quad \gamma \rightarrow \phi \\
\text{(b)} & \quad \gamma \rightarrow \pi, \eta \\
\text{(c)} & \quad \gamma \rightarrow N^* \\
\text{(d)} & \quad \gamma \rightarrow \phi
\end{align*} \]

$N^*$ is the postulated resonance.

- $p_i$ is the 4-momentum of the **proton** in the **initial** state,
- $k$ is the 4-momentum of the **photon** in the **initial** state,
- $p_f$ is the 4-momentum of the **proton** in the **final** state,
- $q$ is the 4-momentum of the $\phi$ in the **final** state.
• **Pomeron exchange**
  We follow the work of Donnachie, Landshoff, and Nachtmann
  ➔ **Pomeron-isoscalar-photon analogy**

• **π and η exchanges**
  For $t$-channel exchange involving $\pi$ and $\eta$, we use effective Lagrangian approach.

• **Resonances**
  Only spin $1/2$ or $3/2$ because the resonance is close to the threshold.
  ➔ **Effective Lagrangian approach** for the vertices, and Breit-Wigner form for the propagators.
Fitting to $\gamma p \rightarrow \phi p$ experimental data

- We include only one resonance at a time.
- We fit only masses, widths, and coupling constants of the resonances to the experimental data, while other parameters are fixed during fitting.
- Experimental data to fit
  - Differential cross sections (DCS) at forward angle
  - DCS as a function of $t$ at eight incoming photon energy bins
  - Nine spin-density matrix elements (SDME) at three incoming photon energy bins
Results for $\gamma p \rightarrow \phi p$

- Both $J^P = 1/2^\pm$ resonances cannot fit the data.
- DCS at forward angle and as a function of $t$ are markedly improved by the inclusion of the $J^P = 3/2^\pm$ resonances.
- In general, SDME are also improved by both $J^P = 3/2^\pm$ resonances.
- Decay angular distributions, not used in the fitting procedure, can also be explained well.
- We study the effect of the resonance to the DCS of $\gamma p \rightarrow \omega p$. The resonance seems to have a considerable amount of strangeness content.
\begin{table}
\begin{tabular}{|c|c|c|}
\hline
\hline
$M_{N^*}(\text{GeV})$ & 2.08 ± 0.04 & 2.08 ± 0.04 \\
$\Gamma_{N^*}(\text{GeV})$ & 0.501 ± 0.117 & 0.570 ± 0.159 \\
\hline
$eg_{\gamma NN^* g^{(1)}_{\phi NN^*}}$ & 0.003 ± 0.009 & −0.205 ± 0.083 \\
$eg_{\gamma NN^* g^{(2)}_{\phi NN^*}}$ & −0.084 ± 0.057 & −0.025 ± 0.017 \\
$eg_{\gamma NN^* g^{(3)}_{\phi NN^*}}$ & 0.025 ± 0.076 & −0.033 ± 0.017 \\
$eg_{\gamma NN^* g^{(1)}_{\phi NN^*}}$ & 0.002 ± 0.006 & −0.266 ± 0.127 \\
$eg_{\gamma NN^* g^{(2)}_{\phi NN^*}}$ & −0.048 ± 0.047 & −0.033 ± 0.032 \\
$eg_{\gamma NN^* g^{(3)}_{\phi NN^*}}$ & 0.014 ± 0.040 & −0.043 ± 0.032 \\
$\chi^2/N$ & 0.891 & 0.821 \\
\hline
\end{tabular}
\end{table}

- The ratio $A_{1/2}/A_{3/2} = 1.05$ for the $JP = 3/2^-$ resonance.
- The ratio $A_{1/2}/A_{3/2} = 0.89$ for the $JP = 3/2^+$ resonance.
Reaction model for $\gamma d \rightarrow \phi pn$

- We calculate only (a) and (b), as (c), (d), and (e) are estimated to be small.
- We want to know if the resonance would manifest itself in different reaction.
• **Fermi motion** of the proton and neutron inside the deuteron is included using **deuteron wave function** calculated by Machleidt in PRC 63 024001 (2001).

• **Final-state interactions (FSI) of** $pn$ **system is included using Nijmegen** $pn$ **scattering amplitude.**

• **On- and off-shell** parts of the $pn$ **propagator** are included.

\[
\frac{1}{E_p + E_n - E'_1 - E_2 + i\epsilon} = \frac{\mathcal{P}}{E_p + E_n - E'_1 - E_2} - i\pi\delta(E_p + E_n - E'_1 - E_2)
\]
• The **same model** for the amplitude of $\gamma p \to \phi p$.
  
  → **Realistic** model
  
  → **Correct spin structure** is maintained

• A $J^P = 3/2^-$ **resonance** is also present in the $\gamma n \to \phi n$ amplitude
  
  - For $\phi nn^* \text{ vertex}$, $\phi p$ and $\phi n$ cases are **the same since** $\phi$ is an $I = 0$ particle.
  
  - For $\gamma nn^* \text{ vertex}$, we assume that the **resonance** would have the **same properties**, including its coupling to $\gamma n$, as a CQM state with the same isospin, $J^P$, and **similar value of** $A_{1/2}/A_{3/2}$ for the $\gamma p$ decay
    
    → $N^{3/2}_2(2095)[D_{13}]_5$ in **Capstick’s work** in PRD 46, 2864 (1992), the **only one with positive value of** $A_{1/2}/A_{3/2}$ for $\gamma p$ in the energy region.
Results for $\gamma d \to \phi pn$

- Notice that **no fitting is performed** to the LEPS data on DCS [PLB 684 6-10 (2010)] and SDME [PRC 82 015205 (2010)] of $\gamma d \to \phi pn$ from Chang et al.
  
  We use **directly the parameters resulting from** $\gamma p \to \phi p$.

- We found a **fair agreement** with the LEPS experimental data on both observables.

- **Resonance**, **Fermi motion**, and **$pn$ FSI** effects are found to be **large**.
  
  **Without them**, the DCS data **cannot** be described.
DCS of $\gamma d \rightarrow \phi pn$

Not fitted

- $1.57 < E_\gamma < 1.67$ GeV
- $1.67 < E_\gamma < 1.77$ GeV
- $1.77 < E_\gamma < 1.87$ GeV
- $1.87 < E_\gamma < 1.97$ GeV

$\frac{d\sigma}{dt_{\phi}}$ (mb GeV$^{-2}$)

$t_{\phi} - t_{\text{max}}$ (proton) (GeV$^2$)
DCS of $\gamma d \rightarrow \phi pn$

Not fitted

![Graph showing DCS of $\gamma d \rightarrow \phi pn$ for different energy ranges with fits and data points.](image)
DCS of $\gamma d \rightarrow \phi pn$

Not fitted

\[ \frac{d\sigma}{dt_{\phi}} (\text{mb GeV}^{-2}) \]

- $1.57 < E_{\gamma} < 1.67$ GeV
- $1.67 < E_{\gamma} < 1.77$ GeV
- $1.77 < E_{\gamma} < 1.87$ GeV
- $1.87 < E_{\gamma} < 1.97$ GeV

$t_{\phi} - t_{\text{max}}$ (proton) (GeV$^2$)
DCS of $\gamma d \rightarrow \phi pn$

Not fitted

$1.97 < E_\gamma < 2.07$ GeV

$2.07 < E_\gamma < 2.17$ GeV

$2.17 < E_\gamma < 2.27$ GeV

$2.27 < E_\gamma < 2.37$ GeV
DCS of $\gamma d \rightarrow \phi pn$

Not fitted

$1.65 < E_\gamma < 1.75$ GeV

$d\sigma_d/dt_\phi$ (\(\mu\)b GeV\(^{-2}\))

$t_\phi - t_{\text{max (proton)}}$ (GeV\(^2\))
DCS of $\gamma d \rightarrow \phi pn$ and its ratio to twice DCS of $\gamma p \rightarrow \phi p$ at forward angle

Not fitted

$t_\phi = t_{\text{max}}(\text{proton})$
SDME of $\gamma d \rightarrow \phi pn$ as a function of $t$

Not fitted

$1.77 < E_\gamma < 1.97$ GeV

Spin-density matrix elements

$|t_\phi - t_{\text{max}}(\text{proton})| \text{ (GeV}^2\text{)}$

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SDME of $\gamma d \rightarrow \phi pn$ as a function of $t$

Not fitted

$1.97 < E_\gamma < 2.17$ GeV

Spin-density matrix elements

$|t_\phi - t_{\text{max}}(\text{proton})|$ (GeV$^2$)

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SDME of $\gamma d \rightarrow \phi pn$ as a function of $t$

Not fitted

$2.17 < E_\gamma < 2.37$ GeV
Summary and conclusions

• **Inclusion of a resonance is needed** to explain the **non-monotonic behavior** in the DCS $\gamma p \rightarrow \phi p$ near threshold.

• Resonance with $J = 3/2$ of either parity is preferred for $\gamma p \rightarrow \phi p$, while $J^P = 1/2^\pm$ cannot fit the data.

• The resonance seems to have a **considerable amount of strangeness content**.

  → Based on a **separate study** on its effect on $\gamma p \rightarrow \omega p$.

• Agreement to the experimental data on the DCS and SDME of $\gamma d \rightarrow \phi pn$ is only quite reasonable using $J^P = 3/2^-$ resonance.

• **Fermi motion, final-state interaction of $pn$, and resonance effects** are found to be **large** and **important** to describe the data.
THANK YOU!
Pomeron exchange

We follow the work of Donnachie, Landshoff, and Nachtmann

\[ i\mathcal{M} = i\bar{u}_f(p_f)\epsilon^*_\phi M_{\mu\nu} u_i(p_i)\epsilon^\nu \]

\[ M_{\mu\nu} = \Gamma_{\mu\nu} M(s, t) \]

with

\[ \Gamma_{\mu\nu} = k' \left( g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) - \gamma_\nu \left( k_\mu - q_\mu \frac{k \cdot q}{q^2} \right) \]
\[ - \left( q_\nu - \bar{p}_\nu \frac{k \cdot q}{p \cdot k} \right) \left( \gamma_\mu - q_\mu \frac{q \cdot \mu}{q^2} \right) ; \bar{p} = \frac{1}{2}(p_f + p_i) \]

where \( \Gamma_{\mu\nu} \) is chosen to maintain gauge invariance, and

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\[ M(s, t) = C_P F_1(t) F_2(t) \frac{1}{s} \left( \frac{s - s_{th}}{4} \right)^{\alpha_P(t)} \exp \left[ -i\pi \alpha_P(t)/2 \right] \]

in which

\[ F_1(t) = \frac{4m_N^2 - 2.8t}{(4m_N^2 - t)(1 - t/0.7)^2} \]

\[ F_2(t) = \frac{2\mu_0^2}{(1 - t/M_\phi^2)(2\mu_0^2 + M_\phi^2 - t)}; \quad \mu_0^2 = 1.1 \text{ GeV}^2 \]

- \( F_1(t) \rightarrow \text{isoscalar EM form-factor of the nucleon} \)
- \( F_2(t) \rightarrow \text{form-factor for the } \phi-\gamma\text{-Pomeron coupling} \)
- \( \text{Pomeron trajectory } \alpha_P = 1.08 + 0.25t. \)

- The strength factor \( C_P = 3.65 \) is chosen to fit the total cross sections data at high energy.

- The threshold factor \( s_{th} = 1.3 \text{ GeV}^2 \) is chosen to match the forward differential cross sections data at around \( E_\gamma = 6 \text{ GeV} \).
Effects on $\gamma p \rightarrow \omega p$

- From the $\phi - \omega$ mixing, we expect the resonance to also contribute to $\omega$ photoproduction.

- The coupling constants $g_{\phi NN^*}$ and $g_{\omega NN^*}$ are related, and in our study we choose to use the so-called “minimal” parametrization,

\[ g_{\phi NN^*} = -x_{OZI}\tan\Delta\theta_V g_{\omega NN^*} \]

where $x_{OZI} = 1$ is the ordinary $\phi - \omega$ mixing.

- By using $x_{OZI} = 12$ for the $J^P = 3/2^-$ resonance and $x_{OZI} = 9$ for the $J^P = 3/2^+$ resonance, we found that we can explain quite well the DCS of $\omega$ photoproduction.

- The large value of $x_{OZI}$ indicates that the resonance has a considerable amount of strangeness content.
DCS of $\gamma p \rightarrow \omega p$ as a function of $t$

Data from M. Williams, PRC 80, 065209 (2009)

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