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

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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.

1
Reaction model for $\gamma p \rightarrow \phi p$

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

$N^*$ 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
  \[\rightarrow\] **Pomeron-isoscalar-photon** analogy

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

• **Resonances**
  Only spin 1/2 or 3/2 because the **resonance is close to the threshold**.
  \[\rightarrow\] **Effective Lagrangian approach** for the **vertices**, and **Breit-Wigner** form for the **propagators**.

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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.
\[
J^P = \frac{3}{2}^+ \\
\\
\begin{array}{|c|cc|}
\hline
M_{N^*}(\text{GeV}) & 2.08 \pm 0.04 & 2.08 \pm 0.04 \\
\Gamma_{N^*}(\text{GeV}) & 0.501 \pm 0.117 & 0.570 \pm 0.159 \\
\hline
\end{array}
\]

\[
J^P = \frac{3}{2}^- \\
\\
\begin{array}{|c|cc|}
\hline
M_{N^*}(\text{GeV}) & 2.08 \pm 0.04 & 2.08 \pm 0.04 \\
\Gamma_{N^*}(\text{GeV}) & 0.501 \pm 0.117 & 0.570 \pm 0.159 \\
\hline
\end{array}
\]

- The ratio \( A_{1/2}/A_{3/2} = 1.05 \) for the \( J^P = 3/2^- \) resonance.
- The ratio \( A_{1/2}/A_{3/2} = 0.89 \) for the \( J^P = 3/2^+ \) resonance.
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.

$$\frac{1}{E_p+E_n-E_1'-E_2'+i\epsilon} = \frac{P}{E_p+E_n-E_1'-E_2} - i\pi\delta(E_p + E_n - E_1' - E_2)$$
• The **same model** for the amplitude of $\gamma p \rightarrow \phi p$.
  \[\rightarrow \text{Realistic model}\]
  \[\rightarrow \text{Correct spin structure} \text{ is maintained}\]

• A $J^P = 3/2^-$ **resonance** is also present in the $\gamma n \rightarrow \phi n$ amplitude
  
  – For $\phi nn^*$ vertex, $\phi p$ and $\phi n$ cases are the same since $\phi$ is an $I = 0$ particle.
  
  – For $\gamma nn^*$ 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
    
    \[\rightarrow N_{3/2}^3(2095)[D_{13}]_5 \text{ in Capstick’s work in PRD 46, 2864 (1992), the only one with positive value of } A_{1/2}/A_{3/2} \text{ for } \gamma p \text{ in the energy region.} \]
Results for $\gamma d \rightarrow \phi pn$

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

- 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

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

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

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

Not fitted

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

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

Not fitted
DCS of $\gamma d \rightarrow \phi pn$

Not fitted
DCS of $\gamma d \rightarrow \phi pn$

Not fitted

$1.65 < E_\gamma < 1.75$ GeV

$\frac{d\sigma}{d t_\phi}$ (µb GeV$^{-2}$) vs. $t_\phi - t_{\text{max}}$ (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

$$t_\phi = t_{\text{max}} \text{(proton)}$$

(a) 

(b)
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

$\rho_{00}^0$ $\rho_{10}^0$ $\rho_{1-1}^0$

$\rho_{11}^1$ $\rho_{00}^1$ $\rho_{10}^1$

$\rho_{1-1}^1$ $\rho_{1-1}^1$

$\text{Im} \rho_{2-1}^1$

$\text{Im} \rho_{10}^2$

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

Spin-density matrix elements

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

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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

\[ \Gamma_{\mu\nu} = k^\mu \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) - \gamma_\nu \left(k_\mu - q_\mu \frac{k \cdot q}{q^2}\right) \]

\[ - \left(q_\nu - \bar{p}_\nu \frac{k \cdot q}{p \cdot k}\right) \left(\gamma_\mu - q_\mu \frac{q_\mu}{q^2}\right) \]

\[ \bar{p} = \frac{1}{2}(p_f + p_i) \]

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 $JP = 3/2^-$ resonance and $x_{OZI} = 9$ for the $JP = 3/2^+$ 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)