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

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

  ![Diagram](image)

$N^*$ 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

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

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

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

• \( \Gamma^{\mu\nu} \) is chosen to maintain gauge invariance.

• 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 \( E_\gamma = 6 \) GeV.
\( \pi \) and \( \eta \) exchanges

- For \( t \)-channel exchange involving \( \pi \) and \( \eta \), we use

\[
\mathcal{L}_{\gamma\phi M} = \frac{eg_{\gamma\phi M}}{m_\phi} \epsilon^{\mu\nu\alpha\beta} \partial_\mu \phi_\nu \partial_\alpha A_\beta \varphi_M
\]

\[
\mathcal{L}_{MNN} = \frac{g_{MNN}}{2M_N} \bar{\psi} \gamma^\mu \gamma^5 \psi \partial_\mu \varphi_M
\]

with \( M = (\pi, \eta) \).

- We choose \( g_{\pi NN} = 13.26 \), \( g_{\eta NN} = 1.12 \), \( g_{\gamma\phi\pi} = -0.14 \), and \( g_{\gamma\phi\eta} = -0.71 \).

- Form factor at each vertex in the \( t \)-channel diagram is

\[
F_{MNN}(t) = F_{\gamma\phi M}(t) = \frac{\Lambda^2_M - m^2_M}{\Lambda^2_M - t}
\]

- The value \( \Lambda_M = 1.2 \ \text{GeV} \) is taken for both \( M = (\pi, \eta) \).
Resonances

- Only spin 1/2 or 3/2 because the resonance is close to the threshold.

- **Lagrangian densities** that couple spin-1/2 and 3/2 particles to $\gamma N$ or $\phi N$ channels are

\[
\mathcal{L}^{1/2^\pm}_{\phi NN^*} = g_{\phi NN^*}^{(1)} \bar{\psi}_N \Gamma^\pm \gamma^\mu \psi_{N^*} \phi_\mu + g_{\phi NN^*}^{(2)} \bar{\psi}_N \Gamma^\pm \sigma_{\mu\nu} G^{\mu\nu} \psi_{N^*}, \\
\mathcal{L}^{3/2^\pm}_{\phi NN^*} = ig_{\phi NN^*}^{(1)} \bar{\psi}_N \Gamma^\pm (\partial^\mu \psi_{N^*}^\nu) \tilde{G}_{\mu\nu} + g_{\phi NN^*}^{(2)} \bar{\psi}_N \Gamma^\pm \gamma^5 (\partial^\mu \psi_{N^*}^\nu) G_{\mu\nu} \\
+ ig_{\phi NN^*}^{(3)} \bar{\psi}_N \Gamma^\pm \gamma^5 \gamma_\alpha (\partial^\alpha \psi_{N^*}^\nu - \partial^\nu \psi_{N^*}^\alpha) (\partial^\mu G_{\mu\nu}),
\]

where $G_{\mu\nu} = \partial^\mu \phi^\nu - \partial^\nu \phi^\mu$ and $\tilde{G}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^{\alpha\beta}$. The operator $\Gamma^\pm$ are given by $\Gamma^+ = 1$ and $\Gamma^- = \gamma_5$, depending on the parity of the resonance $N^*$.

- For the $\gamma NN^*$ **vertices**, simply change $g_{\phi NN^*} \rightarrow eg_{\gamma NN^*}$ and $\phi_\mu \rightarrow A_\mu$.  

5
• **Current conservation** fixes $g_{\gamma NN^*}^{(1)} \rightarrow 0$ for $J^P = 1/2^\pm$ and the term proportional to $g_{\gamma NN^*}^{(3)}$ vanishes in the case of real photon.

• The **effect of the width** is taken into account in a Breit-Wigner form by replacing the usual denominator $p^2 - M_{N^*}^2 \rightarrow p^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}$.

• The **form factor** for the vertices used in the $s$- and $u$-channel diagrams is

$$F_{N^*}(p^2) = \frac{\Lambda^4}{\Lambda^4 + (p^2 - M_{N^*}^2)^2}$$

with $\Lambda = 1.2$ GeV for all resonances.
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 $\gamma p \to \phi p$

- 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 $\gamma p \to \omega p$. The resonance seems to have a considerable amount of strangeness content.
DCS of $\gamma p \rightarrow \phi p$ at forward angle

Black $\rightarrow J^P = 3/2^-$  Red $\rightarrow J^P = 3/2^+$

Total $\rightarrow$ full, Nonresonant $\rightarrow$ dotted, Resonant $\rightarrow$ dashed
DCS of $\gamma p \rightarrow \phi p$ as a function of $t$

![Graph showing DCS of $\gamma p \rightarrow \phi p$ as a function of $t$.](image)

Black $\rightarrow J^P = 3/2^-$ Red $\rightarrow J^P = 3/2^+$

Total $\rightarrow$ full, Nonresonant $\rightarrow$ dotted, Resonant $\rightarrow$ dashed

10
SDME of $\gamma p \rightarrow \phi p$ as a function of $t$

$1.77 < E_\gamma < 1.97$ GeV
SDME of $\gamma p \rightarrow \phi p$ as a function of $t$

$1.97 < E_\gamma < 2.17$ GeV

![Graph showing SDME of $\gamma p \rightarrow \phi p$ as a function of $t$.](image)
SDME of $\gamma p \rightarrow \phi p$ as a function of $t$

$2.17 < E_\gamma < 2.37$ GeV
\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & $J^P = 3/2^+$ & $J^P = 3/2^-$ \\
\hline
$M_{N^*}$(GeV) & $2.08 \pm 0.04$ & $2.08 \pm 0.04$ \\
$\Gamma_{N^*}$(GeV) & $0.501 \pm 0.117$ & $0.570 \pm 0.159$ \\
$e g_{\gamma NN^*} g_{\phi NN^*}$ & $0.003 \pm 0.009$ & $-0.205 \pm 0.083$ \\
(1) & (1) & (1) \\
$e g_{\gamma NN^*} g_{\phi NN^*}$ & $-0.084 \pm 0.057$ & $-0.025 \pm 0.017$ \\
(2) & (2) & (2) \\
$e g_{\gamma NN^*} g_{\phi NN^*}$ & $0.025 \pm 0.076$ & $-0.033 \pm 0.017$ \\
(3) & (3) & (3) \\
$e g_{\gamma NN^*} g_{\phi NN^*}$ & $0.002 \pm 0.006$ & $-0.266 \pm 0.127$ \\
(1) & (1) & (1) \\
$e g_{\gamma NN^*} g_{\phi NN^*}$ & $-0.048 \pm 0.047$ & $-0.033 \pm 0.032$ \\
(2) & (2) & (2) \\
$e g_{\gamma NN^*} g_{\phi NN^*}$ & $0.014 \pm 0.040$ & $-0.043 \pm 0.032$ \\
(3) & (3) & (3) \\
$\chi^2/N$ & 0.891 & 0.821 \\
\hline
\end{tabular}
\end{table}

- 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.

$$\frac{1}{E_p + E_n - E_1' - E_2 + i\epsilon} = \frac{\mathcal{P}}{E_p + E_n - E_1' - E_2 - i\pi\delta(E_p + E_n - E_1' - E_2)}$$
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 $\phi nn^*$ 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

    $\rightarrow N_{2}^{3-}(2095)[D_{13}]_{5}$ 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 $\gamma d \rightarrow \phi pn$

- 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

![Graphs showing DCS of $\gamma d \rightarrow \phi pn$ for different energy ranges (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). The graphs compare LEPS data with different FSI (full hadronic) and no FSI scenarios.](image-url)
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

![Graphs showing DCS of $\gamma d \rightarrow \phi pn$ for different energy ranges and fitted models](image)

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

- **LEPS data**
- **Free p and n**
- **FSI**
- **FSI on-shell**
- **No FSI**

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

**Legend:**
- **LEPS data**
- **Free p and n**
- **FSI**
- **FSI on-shell**
- **No FSI**

**Table:**

<table>
<thead>
<tr>
<th>$E_\gamma$ Range</th>
<th>$d\sigma_d/dt_\phi$ (\mu b \text{ GeV}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.57 &lt; $E_\gamma$ &lt; 1.67 GeV</td>
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**Note:**
- $t_\phi - t_{max}$ (proton) (GeV^2)

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21
DCS of $\gamma d \rightarrow \phi pn$

Not fitted

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

$-0.6 -0.4 -0.2 0$

$1.97 < E_\gamma < 2.07 \text{ GeV}$

$2.07 < E_\gamma < 2.17 \text{ GeV}$

$2.17 < E_\gamma < 2.27 \text{ GeV}$

$2.27 < E_\gamma < 2.37 \text{ GeV}$

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

Not fitted

$1.65 < E_\gamma < 1.75$ GeV

$d\sigma_d/dt_\phi$ (µb 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})

(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

<table>
<thead>
<tr>
<th>$t_\phi - t_{\text{max}}$ (proton)</th>
<th>(GeV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_{00}^0$</td>
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<tr>
<td>$\rho_{10}^0$</td>
<td>$\rho_{1-1}^0$</td>
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<tr>
<td>$\rho_{11}^1$</td>
<td>$\rho_{00}^1$</td>
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<tr>
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<td>$\rho_{1-1}^1$</td>
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<tr>
<td>$\rho_{11}^1$</td>
<td>$\rho_{00}^2$</td>
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<td>$\rho_{1-1}^2$</td>
</tr>
<tr>
<td>$\rho_{11}^2$</td>
<td>$\rho_{00}^3$</td>
</tr>
<tr>
<td>$\rho_{10}^3$</td>
<td>$\rho_{1-1}^3$</td>
</tr>
<tr>
<td>$\rho_{11}^3$</td>
<td>$\rho_{00}^4$</td>
</tr>
<tr>
<td>$\rho_{10}^4$</td>
<td>$\rho_{1-1}^4$</td>
</tr>
</tbody>
</table>

$|t_\phi - t_{\text{max}}(\text{proton})| (\text{GeV}^2)$
SDME of $\gamma d \to \phi pn$ as a function of $t$

Not fitted

$1.97 < E_\gamma < 2.17$ GeV

Spin-density matrix elements

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

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

$\rho_{11}^1$

$\rho_{1-1}^1$

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

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

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

$\rho_{00}^0$, $\rho_{10}^0$, $\rho_{1-1}^0$, $\rho_{00}^1$, $\rho_{10}^1$, $\rho_{11}^1$, $\rho_{1-1}^1$, $\text{Im}\rho_{20}^0$, $\text{Im}\rho_{21}^0$,

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

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

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

with

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

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

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

A1
\[ M(s, t) = C_P F_1(t) F_2(t) \frac{1}{s} \left( \frac{s - s_{th}}{4} \right)^{\alpha_P(t)} \exp \left[ -i\pi \alpha_P(t)/2 \right] \]

in which

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

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

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

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

• The threshold factor \( s_{th} = 1.3 \text{ GeV}^2 \) is chosen to \textbf{match} the forward differential cross sections data at around \( E_\gamma = 6 \) GeV.

\( \text{A2} \)
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.

B1
DCS of $\gamma p \rightarrow \omega p$ as a function of $t$

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