Near-threshold behavior of the cross sections of $\gamma p \rightarrow \phi p$ and $\gamma d \rightarrow \phi pn$: A resonance interpretation

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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 by JLAB: Tedeschi et al. and B. Dey dissertation.

- 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.

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

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

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

$N^*$ 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

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

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

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

- \( \Gamma_{\mu\nu} \) 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 \( E_\gamma = 6 \text{ GeV} \).
\( \pi \) and \( \eta \) exchanges

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

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

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

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 \textit{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

$$
\mathcal{L}_{\phi NN^*}^{1/2\pm} = g_{\phi NN^*}^{(1)} \bar{\psi}_N \Gamma^\pm \gamma^\mu \psi_{N^*} \phi_\mu + g_{\phi NN^*}^{(2)} \bar{\psi}_N \Gamma^\pm \sigma_{\mu\nu} G^{\mu\nu} \psi_{N^*},
$$

$$
\mathcal{L}_{\phi NN^*}^{3/2\pm} = ig_{\phi NN^*}^{(1)} \bar{\psi}_N \Gamma^\pm (\partial^\mu \psi_{N^*}^\nu) \tilde{G}_{\mu\nu} + g_{\phi NN^*}^{(2)} \bar{\psi}_N \Gamma^\pm \gamma^5 (\partial^\mu \psi_{N^*}^\nu) G_{\mu\nu}
$$

$$
+ ig_{\phi NN^*}^{(3)} \bar{\psi}_N \Gamma^\pm \gamma^5 \gamma^\alpha (\partial^\alpha \psi_{N^*}^\nu - \partial^\nu \psi_{N^*}^\alpha) (\partial^\mu G_{\mu\nu}),
$$

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 $\phi_\mu \rightarrow A_\mu$. 

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• **Current conservation** fixes \( g_{\gamma NN^*}^{(1)} \to 0 \) 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 \( p^2 - M_{N^*}^2 \to p^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*} \).

• 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 \( \Lambda = 1.2 \text{ GeV} \) 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 $\gamma p \rightarrow \phi p$

- 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.
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 $t$

Black $\rightarrow J^P = 3/2^-$  Red $\rightarrow J^P = 3/2^+$
Total $\rightarrow$ full, Nonresonant $\rightarrow$ dotted, Resonant $\rightarrow$ dashed
SDME of $\gamma p \to \phi p$ as a function of $t$

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

$1.97 < E_\gamma < 2.17$ GeV
SDME of $\gamma p \rightarrow \phi p$ as a function of $t$

$2.17 < E_\gamma < 2.37 \text{ GeV}$

![Graph showing SDME of $\gamma p \rightarrow \phi p$ as a function of $t$ with data points and curves for $\rho_{00}^0$, $\rho_{10}^0$, $\rho_{1-1}^0$, $\rho_{11}^1$, $\rho_{00}^1$, $\rho_{10}^1$, $\rho_{1-1}^1$, $\text{Im} \rho_{10}^2$, and $\text{Im} \rho_{1-1}^2$. The graph is labeled with the energy range and shows the variation of $|t - t_{\text{max}}|$ (GeV$^2$) along the x-axis.]
Decay angular distributions at two energy bins
$[E_\gamma = 2.07 \text{ GeV} \text{ (upper)} \text{ and } E_\gamma = 2.27 \text{ GeV} \text{ (lower)}]$

Not fitted
Decay angular distributions at two energy bins
\[ E_\gamma = 2.07 \text{ GeV (upper)} \text{ and } E_\gamma = 2.27 \text{ GeV (lower)} \]

Not fitted
<table>
<thead>
<tr>
<th></th>
<th>$J^P = 3/2^+$</th>
<th>$J^P = 3/2^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{N^*}$ (GeV)</td>
<td>2.08 ± 0.04</td>
<td>2.08 ± 0.04</td>
</tr>
<tr>
<td>$\Gamma_{N^*}$ (GeV)</td>
<td>0.501 ± 0.117</td>
<td>0.570 ± 0.159</td>
</tr>
<tr>
<td>$e g_{\gamma NN^<em>} g_{\phi NN^</em>}^{(1)}$</td>
<td>0.003 ± 0.009</td>
<td>−0.205 ± 0.083</td>
</tr>
<tr>
<td>$e g_{\gamma NN^<em>} g_{\phi NN^</em>}^{(2)}$</td>
<td>−0.084 ± 0.057</td>
<td>−0.025 ± 0.017</td>
</tr>
<tr>
<td>$e g_{\gamma NN^<em>} g_{\phi NN^</em>}^{(3)}$</td>
<td>0.025 ± 0.076</td>
<td>−0.033 ± 0.017</td>
</tr>
<tr>
<td>$e g_{\gamma NN^<em>} g_{\phi NN^</em>}^{(1)}$</td>
<td>0.002 ± 0.006</td>
<td>−0.266 ± 0.127</td>
</tr>
<tr>
<td>$e g_{\gamma NN^<em>} g_{\phi NN^</em>}^{(2)}$</td>
<td>−0.048 ± 0.047</td>
<td>−0.033 ± 0.032</td>
</tr>
<tr>
<td>$e g_{\gamma NN^<em>} g_{\phi NN^</em>}^{(3)}$</td>
<td>0.014 ± 0.040</td>
<td>−0.043 ± 0.032</td>
</tr>
<tr>
<td>$\chi^2/N$</td>
<td>0.891</td>
<td>0.821</td>
</tr>
</tbody>
</table>

- The ratio $A_{1/2}/A_{3/2} = 1.05$ for the $J^P = 3/2^-$ resonance. → Similarity to $D_{13}(2120)$ is interesting to note.

(PDG lists $A_{1/2}/A_{3/2} = 0.83$)

- The ratio $A_{1/2}/A_{3/2} = 0.89$ for the $J^P = 3/2^+$ resonance.
Predictions for single polarization observables for $\gamma p \to \phi p$

Asymmetries of the polarized beam $\Sigma_x$, polarized target $T_y$, and recoil polarization $P_y'$
Predictions for double polarization observables for $\gamma p \rightarrow \phi p$

Beam-target (BT) asymmetries $C^{BT}_{yx}$, $C^{BT}_{yz}$, $C^{BT}_{zx}$, and $C^{BT}_{zz}$, with the photon beam and the nucleon target polarized
Reaction model for $\gamma d \rightarrow \phi pn$

- **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 $pn$** is included using **GWU-SAID phase-shift data** on $pn$ scattering.
• The **same model** for the amplitude of $\gamma p \rightarrow \phi p$.

• 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 as a CQM state with the same $J^P$ and similar value of $A_{1/2}/A_{3/2}$ for the $\gamma p$ decay

    $\rightarrow N^{3-}_{2}(2095)[D_{13}]_5$ 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.

• $J^P = 3/2^+$ **resonance** has not been calculated yet.

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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 found a very good agreement with the LEPS experimental data on both observables.

- Notice that LEPS DCS data given with error bars are actually processed to remove the effect of Fermi motion.

- Our reconstructed data, given in grey bands, reinstate the removed Fermi motion.
  → We actually discussed this reconstruction with Chang from the LEPS Collaboration.

- Both resonance 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

**Blue** → no resonance, no $pn$ FSI; **Red** → resonance, no $pn$ FSI; **Black** → resonance, $pn$ FSI; **Grey bands** → reconstructed data
DCS of $\gamma d \rightarrow \phi pn$
Not fitted
SDME of $\gamma d \rightarrow \phi pn$ as a function of $t$

Not fitted

$1.77 < E_\gamma < 1.97$ GeV

Blue: No FSI, No resonance; Red: Resonance, No FSI; Black: Resonance, FSI
SDME of $\gamma d \rightarrow \phi pn$ as a function of $t$

Not fitted

$1.97 < E_\gamma < 2.17$ GeV
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

$|t - t_{\text{max}}|$ (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 $J = \frac{3}{2}$ of either parity is preferred for $\gamma p \rightarrow \phi p$, while $J^P = \frac{1}{2}^{\pm}$ cannot fit the data.

- We can also explain the experimental data on the DCS and SDME of $\gamma d \rightarrow \phi pn$ very well using $J^P = 3/2^-$ resonance.  
  \[\rightarrow\text{Final-state interaction of } pn \text{ and resonance effects are found to be large and important to describe the data.}\]

- **Similarity between the** $J^P = 3/2^-$ and $D_{13}(2120)$ is interesting to note.  
  \[\rightarrow\text{Rather similar value of the ratio of helicity amplitudes } A_{1/2}/A_{3/2} \text{ for } \gamma p \text{ (Ours } = 1.05, \text{ PDG } = 0.83).\]

- The resonance seems to have a considerable amount of strangeness content.  
  \[\rightarrow\text{Based on a separate study on its effect on } \gamma p \rightarrow \omega p.\]
Outlooks

- We plan to work out $\gamma d \rightarrow \phi d$ for even more consistent check.

- **Coupled-channel analysis for $\phi N$, $K \Sigma$, and $K \Lambda$** will also be interesting to do.
  → JLAB already has the data.

- More experiments, e.g. measurement of single and double polarizations, would be helpful to check our predictions.
  → Asymmetry of the polarized beam $\Sigma_x$ would be ideal to distinguish the parity since different parities have different signs.
THANK YOU!
Pomeron exchange

We follow the work of Donnachie, Landshoff, and Nachtmann

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

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

with

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

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

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,

$$g_{\phi NN^*} = -x_{\text{OZI}}\tan\Delta\theta V g_{\omega NN^*}$$

where $x_{\text{OZI}} = 1$ is the ordinary $\phi - \omega$ mixing.
- By using $x_{\text{OZI}} = 12$ for the $J^P = 3/2^-$ resonance and $x_{\text{OZI}} = 9$ for the $J^P = 3/2^+$ resonance, we found that we can explain quite well the DCS of $\omega$ photoproduction.
- The large value of $x_{\text{OZI}}$ 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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