Coherent $\phi$-meson photoproduction from helium-4

Toshihiko Hiraiwa
RCNP
for the LEPS collaboration
Outline

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  • Coherent $\phi$ photoproduction from deuteron
  • Coherent $\phi$ photoproduction from helium-4

• Coherent $\phi$ photoproduction from helium-4 at LEPS
  • Measurements of the spin density matrix elements.
  • Differential cross section as a function of momentum transfer
  • Energy dependence of the $d\sigma/dt$ at $t=t_{\text{min}}$

• Summary
Introduction
Vector meson photoproduction from protons

Pomeron exchange: \( \sigma \propto s^{0.08} \)

Meson exchange: \( \sigma \propto s^{-0.45} \)

Forward $\phi$-meson photoproduction from protons

**Pomeron exchange:**
- Positive power law of $s$.
- Dominant at high energies.
- Natural-parity ($=+1$).
- Not well understood, especially at low energies.
- Similar aspects to multi-gluon exchanges.

**Pseudo-scalar meson exchange:**
- Negative power law of $s$.
- Appear near the threshold.
- Unnatural-parity ($=−1$).
- Well-established processes.
- Exchange $\pi$, $\eta$-mesons.
Decay angle measurements with linearly polarized photon beam

\[ \phi \rightarrow K^+K^- \]

\( \varepsilon^\gamma \)

Decay Plane //\( \gamma \)
natural parity exchange \((-1)^J\) (Pomeron, 0+ glueball, scalar mesons)

Decay Plane \( \perp \gamma \)
unnatural parity exchange \(-(-1)^J\) (Pseudoscalar mesons \(\pi, \eta\))

→ Act as a parity-filter in t-channel exchange!!
Definition of the Gottfried-Jackson (GJ) frame

- z-axis: beam direction
- y-axis: perpendicular to the production plane
- X-axis: $\vec{x} = \vec{y} \times \hat{z}$
- $\theta$: polar angle of K+
- $\phi$: azimuth angle of K+
- $\phi$: azimuth angle of the polarization vector of photon

On the $\phi$-meson rest frame
Decay asymmetry: \( W(\phi - \Phi) \)

- Azimuthal angle distribution \( \phi - \Phi \) @ GJ frame:

\[
W(\phi - \Phi) = \frac{1}{2\pi} \left( 1 + P_\gamma (\rho_{1-1}^1 - \text{Im} \rho_{1-1}^2) \cos 2(\phi - \Phi) \right)
\]

- For helicity-conserving processes:

\[
\rho_{1-1}^1 = -\text{Im} \rho_{1-1}^2, \quad \rho_{1-1}^1 = \frac{1}{2} \frac{|I_0^N|^2 - |I_0^U|^2}{|I_0^N|^2 + |I_0^U|^2}
\]

\( \checkmark \) Pure natural-parity exchange: \( (\rho_{1-1}^1 - \text{Im} \rho_{1-1}^2)/2 = +0.5 \)

\( \checkmark \) Pure unnatural-parity exchange: \( (\rho_{1-1}^1 - \text{Im} \rho_{1-1}^2)/2 = -0.5 \)

The SDM element \((\rho_{1-1}^1 - \text{Im} \rho_{1-1}^2)/2\) gives the relative contribution of natural and unnatural-parity exchanges!!

\( \Phi \): K\(^+\) azimuth angle

\( \phi \): azimuth angle of photon polarization vector

Related to the spin-density-matrix elements
The data show a bump-like structure around $E_\gamma = 2.0$ (GeV), which cannot be explained by the model of the Pomeron, $\pi$ and $\eta$ exchanges!!

Theor. curve for Pomeron, $\pi$ and $\eta$ exchanges.
Decay angular distribution for $\gamma p \rightarrow \phi p$

- $W(\cos \theta) \sim (3/4)\sin^2 \theta$ \rightarrow Helicity-conserving processes are dominant.
- $\rho_{1-1}^1 \sim 0.2 \rightarrow N/(N+UN) \sim 70\%$ (No energy dependence).

Forward angle: $-0.2 < t + |t|_{\text{min}} < 0 \text{ GeV}^2$

- On the bump
  - $\rho_{1-1}^1 = 0.197 \pm 0.030\text{(stat.)} \pm 0.022\text{(syst.)}$

- Off the bump
  - $\rho_{1-1}^1 = 0.189 \pm 0.024\text{(stat.)} \pm 0.006\text{(syst.)}$
Coherent $\phi$ photoproduction from deuteron: 
$\gamma D \rightarrow \phi D$

- From the $\rho^{1}_{1-1}$ for $\gamma p \rightarrow \phi p$, there exists a non-negligible contribution (~30%) of the unnatural-parity $\pi$ exchange ($g_{\pi NN} > g_{\eta NN}$).
- With the use of the isoscalar target, the iso-vector $\pi$ exchange process is forbidden.

*The Pomeron exchange process is expected to be dominant in $\gamma D \rightarrow \phi D$ channel!!*
\[ \frac{d\sigma}{dt} \text{ at } t = t_{\text{min}} \text{ for } \gamma D \to \phi D \]

The measured SDM elements show a significant dominance of the helicity-conserving and natural-parity exchanges. $\eta$ exchange is negligibly small.

- Large systematic errors (larger error bars) come from disentanglements of the coherent process (due to the smallness of the deuteron binding energy).

The theoretical model for the Pomeron and $\eta$ exchanges underpredicts the experimental data!!
\[ \frac{d\sigma}{dt} \text{ at } t = t_{\text{min}} \text{ for isoscalar nucleon target} \]

- In the single-scattering approximation, one can deduce the \( \frac{d\sigma}{dt} \) for isoscalar channel from the deuteron data:

\[
\frac{d\sigma^{\gamma N}}{dt} \approx 4Z(t) \frac{d\sigma^{\gamma N; T=0}}{dt}
\]

\( Z(t) = |F_D(t)|^2 \): Deuteron form factor

Different behaviors at higher energies!!
Coherent $\phi$ photoproduction from helium-4:
\[ \gamma^4\text{He} \rightarrow \phi^4\text{He} \]

- In $\gamma^D \rightarrow \phi^D$ channel, there is still room for the pseudo-scalar $\eta$ exchange process although the $\eta$ exchange is expected to be small.

- With the use of the scalar-isoscalar target, not only the $\pi$ exchange, but also the $\eta$ exchange are eliminated.

$\gamma^4\text{He} \rightarrow \phi^4\text{He}$ channel is an unique way for studying the Pomeron exchange process at low energies!!
Coherent $\phi$ photoproduction from helium-4
LEPS/SPring-8 facility

Linearly polarized photon beam is produced via the backward Compton scattering. ($E_\gamma = 1.5 - 2.4$ GeV)

Polarization ~ 0.94 @ Compton edge ($P_{\text{laser}} = 1$)
• Photon energy: 1.5 – 2.4 (GeV)
• Target: Liquid helium-4
• Apparatus: LEPS spectrometer + Time Projection Chamber
  (\(K^+K^-\) pairs were detected by LEPS spc, not TPC. \(\rightarrow\) Acceptance is limited to very forward region, compared to the old LEPS measurements.)
• Integrated # of photons: 2.25 x 10^{12} (horizontal)
  2.30 x 10^{12} (vertical)
How to get coherent $\phi$ yields?

- Total $\phi$ yields by template fit on $M(K^+K^-)$:
  - $\phi \rightarrow K^+K^-$
  - Non-resonant $K^+K^-N$
  - $\Lambda(1520) \rightarrow K^+p$
    (dominating in large $t$)

- Ratio of coherent $\phi$ by template fit on $MM(K^+K^-)$:
  - Coherent $\phi$
  - Incoherent $\phi$
    (Full off.s. corr., s-dep)

- Systematic studies with semi-coherent process:
  ex) $\gamma + "D" \rightarrow \phi + "D"$
    ("D" means a deuteron inside helium-4.)
Decay angular distributions for $\gamma^4\text{He} \rightarrow \phi^4\text{He}$

- Measure five decay angles ($\cos\theta$, $\phi$–$\Phi$, $\phi$+$\Phi$, $\Phi$) at GJ frame:

  **Parametrization:**

  $$
  W(\cos \theta) = N_0 \left( \frac{1}{2} (1 - \tilde{\rho}_1) \sin^2 \theta - \rho_{00} \cos^2 \theta \right)
  $$

  $$
  W(\phi) = N_0 (1 - 2 \tilde{\rho}_2 \cos 2\phi)
  $$

  $$
  W(\phi - \Phi) = N_0 (1 + 2 P_{\gamma} \tilde{\rho}_3 \cos 2(\phi - \Phi))
  $$

  $$
  W(\phi + \Phi) = N_0 (1 + 2 P_{\gamma} \tilde{\rho}_4 \cos 2(\phi + \Phi))
  $$

  $$
  W(\Phi) = N_0 (1 - P_{\gamma} \tilde{\rho}_5 \cos 2\Phi)
  $$

  $\tilde{\rho}_1 = \rho_{00}^0$

  $\tilde{\rho}_2 = \rho_{1-1}^0$

  $\tilde{\rho}_3 = (\rho_{1-1}^1 - \text{Im}\rho_{1-1}^2)/2$

  $\tilde{\rho}_4 = (\rho_{1-1}^1 + \text{Im}\rho_{1-1}^2)/2$

  $\tilde{\rho}_5 = 2\rho_{11}^2 + \rho_{00}^1$

  $\theta$, $\phi$: polar and azimuth angles for $K^+$

  $\Phi$: azimuth angle of photon polarization vector

- Photon energy bins;  
  E1: $1.985 < E_\gamma < 2.185$ (GeV)  
  E2: $2.185 < E_\gamma < 2.385$ (GeV)

- Only at forward region: $0.0 < \tilde{t} = |t| - |t|_{min} < 0.2$ (GeV²)
Decay angle distribution: $W(\cos \theta)$

<table>
<thead>
<tr>
<th>$E_\gamma$ bin</th>
<th>Par</th>
<th>Err</th>
<th>Chi2</th>
<th>ndf</th>
<th>Chi2/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E1$</td>
<td>-0.015</td>
<td>0.016</td>
<td>4.68</td>
<td>8</td>
<td>0.59</td>
</tr>
<tr>
<td>$E2$</td>
<td>0.016</td>
<td>0.012</td>
<td>3.54</td>
<td>8</td>
<td>0.44</td>
</tr>
</tbody>
</table>

$\approx 0$ for $E1$ and $E2$ bin

Helicity-conserving, or non-conserving?
Decay angle distribution: $W(\phi)$

Related to the so-called spin-double-flip transition.

![Graphs showing decay angle distribution for $E1$ and $E2$](image)

<table>
<thead>
<tr>
<th>$E_\gamma$ bin</th>
<th>Par</th>
<th>Err</th>
<th>Chi2</th>
<th>ndf</th>
<th>Chi2/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E1</strong></td>
<td>0.116</td>
<td>0.030</td>
<td>11.36</td>
<td>8</td>
<td>1.42</td>
</tr>
<tr>
<td><strong>E2</strong></td>
<td>0.054</td>
<td>0.020</td>
<td>11.38</td>
<td>8</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Non-zero values
Decay angle distribution: \( W(\phi - \Phi) \)

Natural / unnatural-parity exchange?

<table>
<thead>
<tr>
<th>( E_\gamma ) bin</th>
<th>Par</th>
<th>Err</th>
<th>Chi2</th>
<th>ndf</th>
<th>Chi2/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>0.454</td>
<td>0.024</td>
<td>5.78</td>
<td>8</td>
<td>0.72</td>
</tr>
<tr>
<td>E2</td>
<td>0.436</td>
<td>0.014</td>
<td>8.90</td>
<td>8</td>
<td>1.11</td>
</tr>
</tbody>
</table>

\( \approx 0.5 \), but \( \neq 0.5 \)
Decay angle distribution: $W(\phi+\Phi)$

<table>
<thead>
<tr>
<th>$E_\gamma$ bin</th>
<th>Par</th>
<th>Err</th>
<th>Chi2</th>
<th>ndf</th>
<th>Chi2/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>-0.111</td>
<td>0.033</td>
<td>11.69</td>
<td>8</td>
<td>1.46</td>
</tr>
<tr>
<td>E2</td>
<td>-0.034</td>
<td>0.017</td>
<td>17.86</td>
<td>8</td>
<td>2.23</td>
</tr>
</tbody>
</table>
Decay angle distribution: $W(\Phi)$

<table>
<thead>
<tr>
<th>$E_\gamma$ bin</th>
<th>Par</th>
<th>Err</th>
<th>Chi2</th>
<th>ndf</th>
<th>Chi2/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E1</strong></td>
<td>0.132</td>
<td>0.066</td>
<td>9.52</td>
<td>8</td>
<td>1.19</td>
</tr>
<tr>
<td><strong>E2</strong></td>
<td>0.074</td>
<td>0.041</td>
<td>4.91</td>
<td>8</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Comparison of the SDM with other LEPS data

- $\tilde{\rho}_1 \sim 0$ for all data → Helicity-conserving.
- $\tilde{\rho}_3 \approx 0.5$, but $\neq 0.5$ for $^4$He data (4.6σ deviation at E2 bin), even though pure natural-parity exchange was expected.
  - Naturally understood by the so-called spin-double-flip transition ($\lambda_\phi \rightarrow -\lambda_\gamma$, higher-order effect in two-gluon exchange model). It was also supported by the observed non-zero values of $\tilde{\rho}_2$ (at finite $|t|$).
  - PS exchanges → Not contribute to $\tilde{\rho}_2$
  - Tensor $f'_2$ exchange has the same effect, but smaller by an order of $10^{-1}$.


$(\tilde{\rho}_1 \approx 0)$

These observations would be helpful for understanding the diffractive mechanism in detail.
Differential cross section $d\sigma/d\tilde{t}$ for $\gamma^4{\text{He}} \rightarrow \phi^4{\text{He}}$

- Measured as a function of momentum transfer $\tilde{t}$.
- Six photon energy bins:

<table>
<thead>
<tr>
<th>$E_\gamma$ bin</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-1</td>
<td>$1.685 &lt; E_\gamma &lt; 1.885$</td>
</tr>
<tr>
<td>e-2</td>
<td>$1.885 &lt; E_\gamma &lt; 1.985$</td>
</tr>
<tr>
<td>e-3</td>
<td>$1.985 &lt; E_\gamma &lt; 2.085$</td>
</tr>
<tr>
<td>e-4</td>
<td>$2.085 &lt; E_\gamma &lt; 2.185$</td>
</tr>
<tr>
<td>e-5</td>
<td>$2.185 &lt; E_\gamma &lt; 2.285$</td>
</tr>
<tr>
<td>e-6</td>
<td>$2.285 &lt; E_\gamma &lt; 2.385$</td>
</tr>
</tbody>
</table>

- Momentum transfer $\tilde{t}$ was sliced with the bin width of 0.02 GeV$^2$. ($t-1$, $t-2$, ......, $t-8$ bin)
Results of the $d\sigma/d\tilde{t}$ measurements

Fit results by:

$$\frac{d\sigma}{d\tilde{t}} = N_0 \exp(-b\tilde{t})$$

, with constant slope $b$.

All the $d\sigma/d\tilde{t}$ can be expressed by the constant slope parameter.
Energy dependence of the $t$-slope

- No significant energy dependence was observed.
- Weighted mean of the $t$-slope: $23.81 \pm 0.95$ (stat.)$^{+5.15}_{-0.00}$ (syst.)
  (w/ semi-coherent)

$\rightarrow$ Consistent with; $b(\gamma p \rightarrow \phi p) + b(FF) = 3.38 \pm 0.23$ (GeV$^{-2}$) + 22 (GeV$^{-2}$)

ELPH workshop Dec. 1-2

PRL95 (2005) 182001.
Comparison with scaled proton data

- $^4\text{He}$ data can be compared with LEPS LH$_2$ data (mibe) using the relation:

$$\frac{d\sigma}{dt}\gamma^4\text{He} = 16 Z(t) \frac{d\sigma}{dt}\gamma^N I, J = 0$$

, where $Z(t) = |F_e(t)|^2$.

(4He charge FF)

For the overlapped region, $^4\text{He}$ data are consistent with the scaled LH$_2$ data!!

(The scaled LH2 data lie on the fit curve.)
Energy dependence of the $d\sigma/dt$ at $t = t_{\text{min}}$

- Compared with the phase volume evolution ($\Phi(s)$) including the 4He form factor ($Z(t_{\text{min}})$):
  \[ \text{chi2 / ndf} = 11.8093/5 \]
  \[ 2.7\sigma \text{ from the curve}. \]

The rise of the cross sections can be almost explained by the phase volume evolution. The energy dependence is weak. But ..
Comparison with deduced curve from proton data

- Energy dep. of $d\sigma/dt$ at $t_{\text{min}}$ was deduced from the proton data:

$$\frac{d\sigma}{dt} = 16Z(t) \frac{d\sigma}{dt}$$

$t = t_{\text{min}}^{4\text{He}}$ (4He at rest), assuming scalar-isoscalar nucleons.

A hint of the dip structure can be seen (2.7s). It may suggest another reaction process.

NOTE: The bump-like structure seen in $\gamma p \rightarrow \phi p$ channel is somehow obscured by the $^4\text{He}$ form factor.

ELPH workshop Dec. 1-2
Natural-parity exchange other than Pomeron ($P_1$)

$P_1 + S \ (a_0(980), f_0(980), \sigma = f_0(500))$

$P_1 + P_2$, inspired by the glueball ($J^P = 0^+, M^2 \sim 3 \text{ GeV}^2$)

A.I. Titov et. al., PRC60, 035205 (1999).

Too small contributions!!

Does not make a bump structure.
Summary

• We measured the SDM elements and differential cross sections for coherent $\phi$ photoproduction from helium-4 for the first time.

• The measured SDM elements show a dominance of the helicity-conserving and natural-parity exchanges, and are consistent with the Pomeron exchange.

• The observations of the non-zero $\tilde{\rho}_2$ and the deviations of the $\tilde{\rho}_3$ from 0.5 would be helpful for understanding the diffractive mechanism in detail.

• In the $d\sigma/dt$ measurements, the extracted $t$-slope was consistent with the sum of the slopes for $\gamma p \rightarrow \phi p$ and 4He’s FF. No significant energy dependence was observed.

• Energy dependence of the $d\sigma/dt$ at $t_{\text{min}}$ shows the similar structure to that for the deduced curves from proton data, originating from the bump-like structure in $\gamma p \rightarrow \phi p$ channel. Its significance was within a statistical fluctuation, and it may be a hint for another reaction process.

• New LEPS data for $\gamma p \rightarrow \phi p$ channel upto $E_{\gamma} = 3$ GeV would clarify this situation!!