Interference between $\phi$ and $\Lambda(1520)$ production channels in $\gamma p \rightarrow K^+ K^- p$ reaction near Threshold

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The $\phi$-meson production has the unique feature within gluon dynamics of being a result of OZI suppression due to the dominant $\bar{s}s$ structure.

\[ \gamma p \rightarrow p \rho \]
\[ \gamma p \rightarrow p \omega \]
\[ \gamma p \rightarrow p \phi \]
Bumps in $\phi$ and $\Lambda(1520)$ Photoproduction

- The $\sqrt{s} = 2.1$ GeV bump in $\phi$ photoproduction has not yet been explained in detail $^1$.
- Similar bump in $\Lambda(1520)$ photoproduction $^2$.

$^1$T. Mibe et al. (LEPS), PRL 95, 182001 (2005); H. Seraydaryan et al. (CLAS) PRC 89, 182001 (2005); B. Dey et al. (CLAS) PRC 89, 055206 (2014)

$^2$H. Kohri et al. (LEPS), PRL 108, 092001 (2012)
Bumps in $\phi$ and $\Lambda(1520)$ Photoproduction

- Excitation of missing nucleon resonances $^3$
- Hidden-strangeness pentaquark state (in analogy to $J/\psi p$ pentaquark states $^4$)
- Rescattering processes $^5$
- **Interference effect** between $\phi$ and $\Lambda(1520)$ production channels

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$^3$A. Kiswandhi et al., PLB 691, 214 (2010)
$^4$R. Aaij et al. (LHCb), PRL 115, 072001 (2015)
$^5$S. Ozaki et al., PRC 80, 035201 (2009); H-Y. Ryu et al., PTEP 2014, 023D03 (2014)
Interference between $\phi(1020)$ and $\Lambda(1520)$

$$
\frac{d^2\sigma}{dm_{K^+K^-}dm_{K^-}p} \propto |M_\phi + M_{\Lambda(1520)} + M_{nr}|^2
$$

$$
\approx |M_\phi + M_{\Lambda(1520)}|^2 + |M_{nr}|^2,
$$

where $M_\phi$ and $M_{\Lambda(1520)}$ are the complex amplitudes for $\phi$ and $\Lambda(1520)$ production processes, respectively. $M_{nr}$ represents non-resonant $K^+K^-p$ production.
Interference between $\mathcal{M}_\phi$ and $\mathcal{M}_{\Lambda(1520)}$

Differential cross sections for the $\gamma p \to K^+ K^- p$ reaction via the $\phi$ and $\Lambda(1520)$ resonances:

$$\frac{d^2\sigma}{dm_{K^+ K^-} dm_{K^- p}} \bigg|_{\phi, \Lambda(1520)} \propto \left( \frac{a e^{i\psi_a}}{m^2_{\phi} - m^2_{K^+ K^-} + im_{\phi}\Gamma_{\phi}} \right) \left( \frac{b e^{i\psi_b}}{m^2_{\Lambda^*} - m^2_{K^- p} + im_{\Lambda^*}\Gamma_{\Lambda^*}} \right)^2,$$

where $a$ and $b$ denote the magnitudes of the Breit-Wigner amplitudes for $\phi$ and $\Lambda(1520)$. 
Interference between $\mathcal{M}_\phi$ and $\mathcal{M}_\Lambda(1520)$

The integrated cross sections over the $K^-p$ mass interval in the $\phi$-$\Lambda(1520)$ interference region where the two resonances overlap $^6$:

$$\frac{d\sigma}{dm_{K^+K^-}} \propto \left| \frac{ae^{i\psi_a}}{m^2_\phi - m^2_{K^+K^-} + im_\phi \Gamma_\phi} + B(m_{K^+K^-})e^{i\psi_b} \right|^2$$

where $B(m_{K^+K^-})$ corresponds to the Breit-Wigner lineshape of $\Lambda(1520)$ projected onto the $K^+K^-$ mass axis in the interference region.

Relative Phase $\psi$

\[
I(m_{K^+K^-}) = 2|aB(m_{K^+K^-})| \left( \frac{m^2_{\phi} - m^2_{K^+K^-}}{m^2_{\phi} - m^2_{K^+K^-}} \right) \cos \psi + \Gamma m_{\phi} \sin \psi \left( \frac{m^2_{\phi} - m^2_{K^+K^-}}{m^2_{\phi} - m^2_{K^+K^-}} \right)^2 + m_{\phi}^2 \Gamma^2
\]

where $\psi = |\psi_a - \psi_b|$.

- Consequently, only a single parameter $\phi$, exists in the fit.
- Maximum constructive at $\psi = +\pi/2$
- Maximum destructive at $\psi = -\pi/2$. 
Compton-Backscattered photon beam and a forward LEPS spectrometer at BL33LEP beam line, SPring-8.

\( \gamma p \rightarrow K^- K^+ p \) reactions at forward angles from the \( \phi \) production threshold (1.573 GeV) to 2.4 GeV.
A typical mass resolution is 30 MeV for 1 GeV kaons.
$P(\chi^2)$ Selection from Kinematic Fit

$K^+K^-$ mode

$K^-p$ mode

$K^+p$ mode

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MC Simulation for $\gamma p \rightarrow K^+ K^- p$ in all $E_\gamma$ Ranges

1. $\gamma p \rightarrow \phi p \rightarrow K^- K^+ p$ based on $E_\gamma$-dependent SDME $^7$.
2. $\gamma p \rightarrow \Lambda(1520) K^+ \rightarrow K^- p K^+$ based on the decay angular distributions from LEPS results $^8$.
3. $\gamma p \rightarrow K^+ K^- p$ (non-resonant S-wave production)
4. $\gamma p \rightarrow K(896)^0 \Sigma^+ \rightarrow K^+ \pi^- p \pi^0$ based on SDME results $^9$.

$^7$W.C. Chang et al. (LEPS) PRC 82, 015205 (2010)
$^8$J. Chen, Ph.D thesis (2009)
$^9$S.H. Hwang et al. (LEPS), PRL 108, 092001 (2012)
Template Fits except the Interference Region

$|\mathcal{M}_\phi|^2$ and $|\mathcal{M}_{\Lambda(1520)}|^2$ in the interference region will be estimated from the magnitudes of MC templates for $\phi$ and $\Lambda(1520)$ mass bands.
Fit with MC Templates for $\gamma p \rightarrow K^- K^+(p)$

- The invariant mass spectra for $K^+ K^-$ (left) and $K^- p$ (right) system
- MC data for $\phi(1020)$
- MC data for $\Lambda(1520)$
- MC data for non-resonant $K^+ K^- p$ production
Interference Yields \((K^+ K^-)\)

Dashed lines are from theoretical estimates with \(\psi = \pi/2\) (S. i. Nam et al.)
Integrated Yields and Phases \((K^+K^-)\)

![Graph showing integrated yields and phases](image)

- **Phase \(\Psi\)**

- **Number of events**

**Legend**
- \(\bullet\) \(K^+K^-\) mode
- \(\square\) \(K^-p\) mode
- \(\Delta\) \(K^+p\) mode

Sun Young Ryu — \(\phi-\Lambda(1520)\) Interference — Page 16 of 19
LEPS first observed the $\sqrt{s} = 2.1$ GeV bump in $\phi$ photoproduction (T. Mibe et al., PRL 95, 182001 (2005)).
Differential cross sections for $\gamma p \rightarrow K^+ \Lambda(1520)$ at forward $K^+$ angles ($0.8 < \cos \theta_{K^+}^* < 1.0$).
The $\phi$-$\Lambda(1520)$ interference measurement is a good probe to study the origin of enhanced production cross sections for $\phi$ and $\Lambda(1520)$ near $\sqrt{s}=2.1\text{GeV}$. 
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We reconfirmed the bump structure in the analysis without the $\phi$-$\Lambda(1520)$ interference region. The difference between the cross sections obtained with and without the interference region is not large enough to account for the bump structure.
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The relative phases suggest strong constructive interference for \(K^+K^-\) pairs observed at forward angles.
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The nature of the bump structure could originate from interesting exotic structures such as a hidden-strangeness pentaquark state, a new Pomeron exchange or rescattering processes via other hyperon states.