Recent $\Theta^+$ and Gamma experiments at the SPring-8/LEPS

Koichi Kino (RCNP)

- $\Theta^+$ experiment
  - LD2 target data

- Gamma experiment
  - Forward gamma detector
  - Preliminary $\gamma+p \rightarrow \eta+p'$ analysis
LEPS beam line

SPring-8 (SuperPhotonRing 8GeV)

8 GeV electron storage ring

Current=100mA
62 beam lines
Bunch=every 2nsec

1.5 – 2.4 GeV real photon available
$\Theta^+$ experiment
LEPS $\Omega^+$ first data

- **Prediction from the chiral soliton model**

- $\gamma+n(^{12}\text{C}) \rightarrow K^+K^-n$

\begin{align*}
\text{nK}^+ \text{ or pK}^0 & \rightarrow \text{Z}^+(\text{uudds}) \\
180 \text{ MeV} & \\
180 \text{ MeV} & \rightarrow \Sigma(1890) \\
180 \text{ MeV} & \downarrow \rightarrow \Xi(2070) \\
\Xi^-\pi^- \text{ or } \Sigma^-K^- & \rightarrow \Xi_{3/2}^- \\
(\text{ddssu}) & \\
q^4\overline{q} & \rightarrow 10 \text{ state}
\end{align*}

\begin{align*}
\Xi^0\pi^+ \text{ or } \Sigma^+K^0 & \\
(\text{uussd}) & \\
\text{peak} = 1.54 \pm 0.01 \text{ GeV/c}^2 \\
\text{width} < 25 \text{ MeV/c}^2 \\
\text{Gaussian significance} = 4.6\sigma
\end{align*}

$^{12}\text{C(Scintillator)}$
Data from other Labs

- **Optimistic data**
  - LEPS \( \gamma+n^{(12)C} \rightarrow nK^{+}+K^{-} \)
  - CLAS \( \gamma+d \rightarrow nK^{+}+p+K^{-} \)
  - CLAS \( \gamma+p \rightarrow nK^{+}+\pi^{+}+K^{-} \)
  - SAPHIR \( \gamma+p \rightarrow nK^{+}+K^{0} \)
  - HERMES \( e+d \rightarrow pK^{0}+X \)
  - ZEUS \( e+p \rightarrow pK^{0}+X \)
  - COSY \( p+p \rightarrow pK^{0}+\Sigma^{+} \)
  - DIANA \( K^{+}+XE \rightarrow pK^{0}+XE' \)
  - JINR \( n+p \rightarrow nK^{+}+p+K^{-} \)
  - SVD \( p+A \rightarrow pK^{0}+X \)
  - \( \nu+A \rightarrow pK^{0}+X \)

- **Pessimistic data**
  - BaBar \( e^{+}+e^{-} \rightarrow pK^{0}+X \)
  - E690(Fermi) \( p+p_{rest} \rightarrow p_{slow}K^{0}+K^{-}+\pi^{+}+p_{fast} \)
  - CDF \( p+\bar{p} \rightarrow pK^{0}+X \)
  - Belle \( K+N \rightarrow pK^{0} \)
  - Belle \( B^{0} \rightarrow pK^{0}+\bar{p} \)
  - HERA-B \( p+A \rightarrow pK^{0}+X \)
  - ALEPH \( e^{+}+e^{-} \rightarrow pK^{0}+X \)
  - DELPHI \( e^{+}+e^{-} \rightarrow pK^{0}+X \)
  - HyperCP \( p+A \rightarrow pK^{0}+X \)
  - BES \( \psi(2S) \rightarrow pK^{0}+\bar{n}K^{-}, \bar{p}K^{0}+nK^{+} \)
  - BES \( J/\psi \rightarrow pK^{0}+\bar{n}K^{-}, \bar{p}K^{0}+nK^{+} \)

\[ E522(KEK) \quad \pi^{-}+p \rightarrow X+K^{-} \]

- **Can the peak seen in the previous LEPS data be seen in the new data again?**

etc.
LEPS new LD2 and LH2 data

- 15cm-long target cell
- $\sim 2 \cdot 10^{12}$ photons on the LD2 target
  - Less Fermi motion effect
- $\sim 1.4 \cdot 10^{12}$ photons on the LH2 target
LEPS Detector

Aerogel Čerenkov counter

Vertex detector (SSD)

Dipole Magnet (0.7 T)

Target

Start counter

LH2, LD2 Target (150mm thick)

TOF wall

MWDC 1

MWDC 2

MWDC 3

1m

γ
Expected reactions

\[ \gamma n(p) \rightarrow \Theta^+K^-(p) \]
\[ \Theta^+ \rightarrow K^+n \]
Exotic

\[ S=+1 \]

\[ \gamma p(n) \rightarrow \Lambda^*(1520)K^+(n) \]
\[ \Lambda^*(1520) \rightarrow K^-p \]
Standard baryon

\[ S=-1 \]

\[ \gamma N \rightarrow \phi(1020)N \rightarrow K^+K^-N \]
Mason resonance
Applied cuts and correction

- $\phi$ meson exclusion cut
- Deuteron elastic reaction cut
- Missing mass cut
- Fermi motion correction
**φ meson exclusion cut**

- **Invariant Mass (K⁺K⁻) (GeV/c²)**
  - Ratio = (Real − MC) / MC
  - Almost Eᵧ independent

- **Missing Mass (γ,K⁻)**
  - MC KKn 3-body phase space
  - 1.8 < Eᵧ < 2.0 GeV  2.2 < Eᵧ < 2.4 GeV
  - M(φ) = 1.019 GeV/c²
  - Relative acceptance
  - = N(1.50 < MM(γ,K⁻) < 1.55) / N(all)
  - Eᵧ dependent

R = “Ratio” × “Relative acceptance”
**φ meson exclusion cut**

- **Energy dependent**
  φ exclusion cut function

- **Effect on MM (γ,K⁺)**

![Graphs showing energy-dependent exclusion cut function](image)

- **Invariant Mass (K⁺K⁻)** (GeV)

- **Eγ (GeV)**

- **MM γK⁺ (GeV/c²)**

- **R=0.20**
  - MM γK⁺ (GeV/c²) = 0.01

- **R=0.05**
  - MM γK⁺ (GeV/c²) = 0.10

- **R=0.01**
  - MM γK⁺ (GeV/c²) = 0.20

- MM γK⁺ (GeV/c²) = 0.50
deuteron elastic reaction cut

- Remove $\gamma d \rightarrow K^+ K^- d$ reaction
- Cut $\text{MM } d(\gamma, K^+ K^-) < 1.89 \text{ GeV/c}^2$
MM n(γ,K⁺K⁻) cut

- Choose 0.89 < MM n(γ,K⁺K⁻) < 0.99 GeV/c²

![Graphs showing distributions for MM n(γ,K⁺K⁻) with LH2 and LD2 labels.]
Fermi motion correction

1 : $\text{MM}^c_{\gamma K^-} = \text{MM}_{\gamma K^-} - \text{MM}_{\gamma K^+ K^-} + M_n$

2 : $(\text{MM}^c_{\gamma K^-})^2 = (\text{MM}_{\gamma K^-})^2 - \frac{P_{(K+n)}}{P_n}(\text{MM}^2_{\gamma K^+ K^-} - M_n^2)$

3 : n(p) momentum = missing momentum
Result of LD2 data and summary

- $K^+K^-$ from LD2 target
- $\phi$ exclusion cut at $R=0.2$
- $MM \, d(\gamma,K^+K^-) > 1.89 \, GeV/c^2$
- $0.89 < MM \, n(\gamma,K^+K^-) < 0.99 \, GeV/c^2$
- Fermi motion correction

LEPS took new data with LD2 target for the search of the $\Theta^+$.

- Energy dependent $\phi$ exclusion cut was designed and its validity was checked with $\Lambda(1520)$ study.
- The "$\Theta^+$" peak was reproduced in the $K^-$ missing mass of LD2 data.
Gamma experiment
Primakov $2\pi^0$ production

- **Polarizability** $(10^{-4}\text{fm}^3)$
  - $\alpha-\beta = -1.4 \pm 1.7 \ (\text{exp.})$
  - $\alpha-\beta = -1.9 \pm 0.2 \ (\chi\text{PT.})$

- **Loop structure in the $\chi$PT theory**
  - No tree diagram because of no charge

Only one similar reaction data exists

\[ e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-\pi^0\pi^0 \]

- Cross Section (nb) $(|\cos \theta|<0.8)$

- 1 loop diagrams
Primakov $2\pi^0$ production

- Contribution of $\sigma$ meson
  - inverse process of $\sigma \rightarrow 2\gamma$ decay
  - $f_0(400-1200)$

- $2\pi^0$ decay: dominant
  - $\Gamma_{\gamma\gamma} = 10 \pm 6$ keV (PDG)
  - $\Gamma_{\gamma\gamma} = 3.8 \pm 1.5$ keV
  (Pennington hep-ph9905241)

\[
\frac{d\sigma}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2 \beta^3 E^4}{M^3} \frac{E^4}{q^4} |F_{e.m.}(q)|^2 \sin^2(\theta)
\]

- $\sigma$ Mass: momentum transfer

Total Cross Section = $1.0 \mu$ barn
$E_\gamma = 0.5$ Mcps $\otimes$ DAQ Live time
$\Rightarrow$ 0.3 event/hr
Gamm-rays distribution

- Simulation of Primakov $2\pi^0$ production
Nucleon resonances

• Gap between theory and experiment
  – $\pi N$ scattering and $\pi$ decay
  – data with other channels and isospin selectivity needed

• This experiment
  – suitable energy
  – various channels $\eta, \omega, \eta', \ldots$
  – photon beam asymmetry
\( \gamma p \to \eta p' \) data by ELSA

\[ \text{Included diagrams} \]

<table>
<thead>
<tr>
<th>( N^* )</th>
<th>( M ) (MeV)</th>
<th>( \Gamma ) (MeV)</th>
<th>( A_{3/2} / A_{1/2} )</th>
<th>( P_{\text{in/out}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1520)D_{13}</td>
<td>1530 ± 7</td>
<td>102 ± 15</td>
<td>&lt;−2.4</td>
<td>0.027±0.015</td>
</tr>
<tr>
<td>PDG</td>
<td>1520±10</td>
<td>120±15</td>
<td>&lt;−6.9 ± 2.6</td>
<td>&lt; 0.07</td>
</tr>
<tr>
<td>N(1535)S_{11}</td>
<td>1505 ± 12</td>
<td>152 ± 15</td>
<td>−6.9 ± 2.6</td>
<td>0.01 − 0.4</td>
</tr>
<tr>
<td>PDG</td>
<td>1505 ± 10</td>
<td>170 ± 80</td>
<td>−6.9 ± 2.6</td>
<td>0.01 − 0.4</td>
</tr>
<tr>
<td>N(1650)S_{11}</td>
<td>1626 ± 10</td>
<td>188 ± 30</td>
<td>0.2 ± 0.06</td>
<td>&lt; 0.07</td>
</tr>
<tr>
<td>PDG</td>
<td>1660 ± 20</td>
<td>160 ± 10</td>
<td>0.1 ± 0.4</td>
<td>0.01 − 0.4</td>
</tr>
<tr>
<td>N(1680)F_{15}</td>
<td>1673 ± 8</td>
<td>98 ± 17</td>
<td>large</td>
<td>0.009 ± 0.007</td>
</tr>
<tr>
<td>PDG</td>
<td>1680±10</td>
<td>130 ± 10</td>
<td>−8.9 ± 3.6</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>N(1720)P_{13}</td>
<td>1734 ± 23</td>
<td>275±70</td>
<td>−4.5±1.7</td>
<td>0.2±0.28</td>
</tr>
<tr>
<td>PDG</td>
<td>1720±30</td>
<td>250 ± 50</td>
<td>−1.1 ± 2.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>N(2080)D_{15}</td>
<td>2079 ± 40</td>
<td>368±100</td>
<td>−0.5 ± 0.3</td>
<td>0.20 ± 0.03</td>
</tr>
</tbody>
</table>

**Fit result**

\( D_{15} \rightarrow 5/2^- \)  \( \chi^2 = 676/630 \)

\( 3/2^- \)  \( \Delta \chi^2 = 59 \)

\( 1/2^+ \)  \( \Delta \chi^2 = 73 \)

\( 5/2^+ \)  \( \Delta \chi^2 = 91 \)

[hep-ex/0311045]
What kind of state?

Deformed Oscillator Quark Model

$D_{15}$

isospin $1/2$

spin $5/2$

$\pi+N$ decay

relative angular momentum

$J^\pi = 5/2^-$

$\rightarrow L = 1$ or $3$

Even parity

Odd parity

Even parity candidates

Odd parity candidates

$E_{\text{DOQ}}(L,N) = E_{\text{int}}(N) + \frac{L(L+1)}{2I} - \left\langle \frac{L^2}{2I} \right\rangle$

$E_{\text{int}}(N) = \frac{L(L+1)}{2I} - \left\langle \frac{L^2}{2I} \right\rangle$
Detector Setup

Backward Detector

\[ \theta = 30-100 \text{ deg} \]
\[ \phi = 0-360 \text{ deg} \]

Forward Detector

\[ \theta = 3-15 \text{ deg} \]
\[ \phi = 0-360 \text{ deg} \]
Backward Gamma Detector

- Lead/SCIFI 252 modules
- Energy resolution 6% @ 1 GeV Gamma-ray
- Each length = 22cm → 13.7 X₀
Forward Gamma Detector

- 252 PWO crystals
  - $22 \times 22 \times 180\text{mm} \ 19.5X_0$
- $\frac{3}{4} \text{ in. PMT}$
- Cockcroft-Walton type H.V. supplier
- Energy resolution 3%
  - @ 1GeV gamma-ray
PbWO$_4$ Crystal

- Development started in 1992
- Property
  - high density
  - short radiation length
  - small Moliere radius
  - fast decay time
  - small light output
- Recent development (1999~)
  - La$^{3+}$,Y$^{3+}$,... doped
    - To suppress 350 and 420nm absorption bands due to Pb$^{3+}$,O$^-$ color centers

<table>
<thead>
<tr>
<th></th>
<th>PWO</th>
<th>BGO</th>
<th>NaI(Tl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>density (g/cm$^3$)</td>
<td>8.2</td>
<td>7.13</td>
<td>3.67</td>
</tr>
<tr>
<td>radiation length (cm)</td>
<td>0.92</td>
<td>1.12</td>
<td>2.59</td>
</tr>
<tr>
<td>Moliere radius (cm)</td>
<td>2.2</td>
<td>2.4</td>
<td>4.5</td>
</tr>
<tr>
<td>decay constant (ns)</td>
<td>10</td>
<td>300</td>
<td>230</td>
</tr>
<tr>
<td>light yield (%)</td>
<td>~0.5</td>
<td>7 - 10</td>
<td>100</td>
</tr>
<tr>
<td>wave length (nm)</td>
<td>430</td>
<td>480</td>
<td>415</td>
</tr>
<tr>
<td>index</td>
<td>2.2</td>
<td>2.15</td>
<td>1.85</td>
</tr>
</tbody>
</table>
Experiment

• Target
  - CH2(0.10X₀), C(0.17X₀), W(0.20X₀)

• Event Trigger
  - (FGor ⊕ BGor) ⊗ TaggerHit ⊗ Bar(VetoCounters)
    • FGor: 30MeV deposit at least in 1 crystal
    • BGor: 10MeV deposit at least in 1 module

• Incident gamma intensity
  - 500-600 kcps

• Trigger rate
  - 350-750 cps
  - 70-80% DAQ live time
FG Base analysis(1)

- **Energy calibration**
  - (1) cosmic-ray MIP
  - (2) iteration method using $\pi^0 \rightarrow 2\gamma$ events

- **Clustering**
  - Energy deposit @ 1 GeV gamma-ray
    - 80% center PWO
    - 20% peripheral 8PWOs

---

**2\gamma event**

![Histogram of invariant mass](image)

2 cluster and no charged particle on FG detector

- real data = 4.9%
- simulation = 4.2%

![Cluster examples](image)

1 cluster
- example1
- example2

2 cluster
- example1
- example2

Energy deposit > 40MeV
FG Base analysis(2)

- Position reconstruction
  - center of gravity method
  - logarithmic weighting

\[ w_i = \max \{ 0, \left[ W_0 + \ln \left( \frac{E_i}{E_{\text{tot}}} \right) \right] \} \]

\[ X = \frac{\sum w_i x_i}{\sum w_i} \quad Y = \frac{\sum w_i y_i}{\sum w_i} \]

Experimental result using e-beam
Examples of invariant mass

2γ event
\[ \pi^0 \rightarrow 2\gamma \ (99\%) \]
\[ \eta \rightarrow 2\gamma \ (39\%) \]
\[ \eta' \rightarrow 2\gamma \ (2\%) \]

3γ event
\[ \omega \rightarrow \gamma \pi^0 \rightarrow 3\gamma \]
\[ \text{(9\%)} \]

kinematical fit applied
$\gamma p \rightarrow \eta p'$ event selection

- 2$\gamma$ and 1 charged particle detected events

**Applied cut**

**Charged particle ID**
Photon Beam Asymmetry (1)

- Photon beam asymmetry: \( \Sigma \)

\[
\begin{align*}
\sigma_\perp &= \sigma + \Sigma \cos(2\phi) \\
\sigma_\parallel &= \sigma - \Sigma \cos(2\phi)
\end{align*}
\]

\[
\Sigma \cos(2\phi) = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}
\]

CM system of \( \gamma p \to \eta p' \) reaction
Photon Beam Asymmetry (2)

- Helicity representation

\[ A_{\mu\lambda}(\theta, \phi) = \sum_j A^j_{\mu\lambda}(2j + 1) d^j_{\lambda\mu}(\theta) e^{i(\lambda - \mu)\phi} \]

initial helicity \( \lambda = \lambda_k - \lambda_1 \)
final helicity \( \mu = \lambda_q - \lambda_2 = -\lambda_2 \)
resonance spin \( j \)

<table>
<thead>
<tr>
<th>( \lambda_1(\lambda) )</th>
<th>( \lambda_k = +1 )</th>
<th>( \lambda_k = -1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu = \frac{1}{2} )</td>
<td>( A_{\frac{1}{2}, \frac{3}{2}} )</td>
<td>( A_{\frac{1}{2}, \frac{1}{2}} )</td>
</tr>
<tr>
<td>( \mu = -\frac{1}{2} )</td>
<td>( A_{-\frac{1}{2}, \frac{3}{2}} )</td>
<td>( A_{-\frac{1}{2}, \frac{1}{2}} )</td>
</tr>
</tbody>
</table>
Photon Beam Asymmetry (3)

Using property:

\[ A_{-\mu, -\lambda} = -e^{i(\lambda - \mu)(\pi - 2\phi)} A_{\mu, \lambda}(\theta, \phi) \]

\[ \varepsilon_\perp = \frac{i}{\sqrt{2}}(\varepsilon_+ + \varepsilon_-) \quad \text{Vertical linear polarization} \]

\begin{align*}
\lambda_1 & \quad \mu \\
-\frac{1}{2} & \quad 1/2 \quad A_{1/2, 3/2} + A_{1/2, -1/2} \quad \rightarrow \quad \sum_j A^j_{1/2, 3/2}(2j + 1)d_{1/2}^j(\theta) e^{i\phi} + \sum_j A^j_{-1/2, 1/2}(2j + 1)d_{1/2}^j(\theta) e^{-i\phi} \\
-\frac{1}{2} & \quad 1/2 \quad A_{-1/2, 1/2} + A_{-1/2, -3/2} \quad \rightarrow \quad \sum_j A^j_{-1/2, 1/2}(2j + 1)d_{1/2}^j(\theta) e^{i\phi} + \sum_j A^j_{1/2, 3/2}(2j + 1)d_{1/2}^j(\theta) e^{-i\phi} \\
1/2 & \quad 1/2 \quad A_{1/2, 1/2} + A_{1/2, -3/2} \quad \rightarrow \quad \sum_j A^j_{1/2, 1/2}(2j + 1)d_{1/2}^j(\theta) - \sum_j A^j_{-1/2, 3/2}(2j + 1)d_{1/2}^j(\theta) e^{-2i\phi} \\
-\frac{1}{2} & \quad -1/2 \quad A_{-1/2, 3/2} + A_{-1/2, -1/2} \quad \rightarrow \quad \sum_j A^j_{-1/2, 3/2}(2j + 1)d_{1/2}^j(\theta) - \sum_j A^j_{1/2, 1/2}(2j + 1)d_{1/2}^j(\theta) e^{-2i\phi}
\end{align*}

Interference terms in the cross section:

\[ = 2Re \left[ \left( \sum_j A^j_{1/2, 3/2}(2j + 1)d_{1/2}^j(\theta) \right) \left( \sum_j A^j_{-1/2, 1/2}(2j + 1)d_{1/2}^j(\theta) \right)^* \right] \cos(2\phi) \]

\[ -2Re \left[ \left( \sum_j A^j_{1/2, 1/2}(2j + 1)d_{1/2}^j(\theta) \right) \left( \sum_j A^j_{-1/2, 3/2}(2j + 1)d_{1/2}^j(\theta) \right)^* \right] \cos(2\phi) \]

\[ \varepsilon_\parallel = -\frac{1}{\sqrt{2}}(\varepsilon_+ - \varepsilon_-) \quad \text{Horizontal linear polarization} \]

Interference terms \rightarrow inverse signs
Example $\gamma p \rightarrow \eta p' @$ low energy

$S_{11} \otimes (D \text{ or } F \text{ or } G)$

$\uparrow$

Large Cross Section

GRAAL data
**cos(2\(\phi\)) dependence**

Example: CH2 target, FG1\(_y\), BG1\(_y\)

\[ E_y = 1.8-2.1\text{GeV}, \; \theta^*\eta = 40-60\text{deg} \]

Very preliminary result with limited data
Obtained Asymmetry

- GRAAL data
- LEPS CH2
- LEPS carbon

Very preliminary result with limited data
Possibility of $\Delta^*$ study

- Resonance isospin $3/2$ selectivity
- Quark model prediction
  - $F_{35}(1990)$
  - $D_{35}(2165)$
- 2 neutral particles in final state
  - $\eta + \pi^0$ or $\eta + n$
    ($\Delta^+ \to p\pi^0, n\pi^+$)
  - $\eta$ detection is important
Summary

• Photoreaction experiment was performed to study Primakov $2\pi^0$ production and nuclear resonances at the SPring-8/LEPS beam line.

• Forward gamma detector was constructed to detect gamma-rays at a forward direction with a minimum angle of 3 degree.

• Preliminary result of $\gamma p \rightarrow \eta p'$ reaction was shown. Photon beam asymmetries have tendency of a forward peaking distribution.

• Data analysis for precise calibration and various physics channels are in progress.
additional pages
Charged particle identification

Reconstructed mass

Mass/Charge (GeV/c$^2$)

$\sigma_{\text{Mass}} = 30$ MeV/c$^2$(typ.) for 1GeV/c Kaon
KKN phase space MC data

- After applying the same cuts
• After applying the same cuts
$\Lambda^{*}(1670)$ MC

- After applying the same cuts
$\text{MM}(\gamma, K^+) \text{ vs } \text{MM}(\gamma, K^-)$

LH2

LD2