Search for the $\Theta^+$
with a Low Momentum $K^+$ Beam

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- Objectives of $\Theta^+$ search at J-PARC
- Considerations on experimental setup
Photoproduction from deuteron

$\Theta^+$

LD$_2$ data (preliminary)
$1.50 < M(pK^-) < 1.54$ GeV/c$^2$

1.6 GeV bump

mass $\sim 1.53$ GeV/c$^2$, $s/\sqrt{s+b} = 4-5\sigma$,
Details are being shown at INPC.

No indications at CLAS, but acceptance coverage is different from LEPS.
(No sensitivity of $\Lambda^*$ detection in extremely forward region)
Isospin Asymmetry in quasi-free $\Theta^+$ Photoproduction


$\gamma N \rightarrow K^0 \Theta^+$: contact term (3/2) or no $K^*$ exchange (1/2)

neutron target $>$ proton target (CLAS-p)

$\gamma N \rightarrow K \Lambda^*$: neutron $<$ proton

Indication is seen in LEPS data.

$\theta_{CM}(K-p) < 60^\circ$

$\sigma_{\gamma p \rightarrow \Theta^+ K^0} < 1.25$ nb @ 1.54 GeV/c$^2$

$\gamma N \rightarrow K \Theta^+$

$\cos \theta_{CM}(K^0) > 0.5$

$\Lambda(1520)$

Counts

$M(K-p)$ GeV/c$^2$

Counts

$M(nK^0)$ (GeV)

$M(nK^0)$ (GeV)

Counts

Counts

$\Theta^+(1540)$ ?

$\cos \theta_{CM}(K^0) > 0.5$

proton target

M(K-p) GeV/c$^2$

deuteron target

M(K-p) GeV/c$^2$
Energy Dependence?

Null results in high energy experiments. (BES, BaBar, Belle, LEP, HERA-B, SPHINX, HyperCP, CDF, FOCUS, PHENIX)

⇒ \( \sigma(\Theta^+)/\sigma(\Lambda^+) < 2-3\% \) [Quark Fragmentation]

**Quark fragmentation**

**Baryon fragmentation**

Needs fewer quark pairs from the vacuum

Pentaquark strongly suppressed?

Pentaquark less suppressed?
Objectives of $\Theta^+$ search at J-PARC (and LEPS2)

- $\Theta^+$ is not established yet.
- Affected by reaction mechanism?
  - Isospin asymmetry in $\gamma N \rightarrow \overline{K}\Theta^+$
  - Angle dependence in $\gamma d \rightarrow \Lambda^*\Theta^+$
  - Energy dependence in $\sigma(\Theta^+)/\sigma(\Lambda^*)$
- Width/spin/parity is not determined.

$\Rightarrow$ Systematic studies of $\Theta^+$ photoproduction at LEPS2
  - Understand reaction mechanisms with high intensity photon beam ($\sim 10^7$/sec) and large volume detector
$\Rightarrow$ $\Theta^+$ formation experiment by $K^+n$ resonance at J-PARC
  - Direct confirmation of $\Theta^+$ existence
  - Independent from reaction mechanism
  - Width can be measured from cross section
**K⁺n Scattering Experiments**

**DIANA**
- Old bubble chamber experiment
- \( K^+ Xe \rightarrow K_S^0 pX \)

**Belle**
- \( K^+ \) is ‘reconstructed’ from the reaction \( D^{*-} \rightarrow D^0 \pi^- \rightarrow (K^+\pi^-)\pi^- \)

**Need a modern experiment with high intensity K⁺ beam**
Basic Concepts

Originally considered at BNL-E949
- sophisticated for K⁺ beam experiment
- large 4π volume with good resolutions

Similar but optimized experiment is possible at J-PARC.

- Resonance formation reaction:
  \[ K^+ n \rightarrow \Theta^+ \rightarrow K_S^0 p \rightarrow \pi^+ \pi^- p \]
  - \( P(K^+) = 417 \) (442) MeV/c for \( M=1.53 \) (1.54) GeV/c²
  - neutron in scintillation fiber target
- \( \pi^+ \pi^- \) detection at Drift Chamber and proton detection at Sci. Tgt.
  \( M(\pi^+ \pi^-) = M(K_S^0) \Rightarrow M(K_S^0 p) = M(\Theta^+) \)
- \( \Lambda^* \) formation for calibrations and checks of data quality and analysis procedure with the same beamline and detectors: \( K^- p \rightarrow \Lambda(1520) \rightarrow \Lambda \pi^+ \pi^- \)
  (It is worth to do even if K⁻ intensity is a bit lower.)
K0.8 (Sharing w/ stopped K⁺ exp.)

Fitch-type Cherenkov
Beam Wire Cherenkov
Aerogel Cherenkov

K0.8

BeO degrader ~40 cm
(high dens. and low A)

K⁺: ~420 MeV/c (β~0.648→n₁₅₈~1.54)
π⁺: ~600 MeV/c (β~0.974→n₁₀₃~1.03)

E787 Year
95
96
97-98

K⁺ momentum (MeV/c)
790
730
710

Stopping Fraction
20%
25%
28%
- $K^+$ travels inside a target until momentum becomes appropriate to produce $\Theta^+$.
- Proton is emitted in forward directions, and tends to stop inside the target.
- Kinetic energy and polar angle measurements of proton.
- Mometum correction for pions.
⇒ Active target w/ fine segmentation
Spectrometer Considerations

- Pions are emitted in side directions.  
  \[ \Rightarrow \text{Cylindrical drift chamber inside a solenoid.} \]
- In case that a 1 m-long drift chamber is placed at -40 cm to 60 cm of the target, geometrical acceptance is an order of 40%.
- PID by TOF would be enough.
  (See right figure: green R=50 cm, red R=90 cm in case of charged particles are emitted at 90°. \( \Delta t=50 \) psec is assumed.)
Mass resolution studies were done assuming BNL-E949 detector resolutions. Invariant mass of $\pi\pi p : 7.6$ MeV/$c^2$ (assuming $\Delta P/P=1.4\%$ at $P=200-300$ MeV/$c$, $\Delta E/E=8.3\%$ at $E_{\text{kin}}=100$ MeV, proton angle mes. error = 6 degree)

Kinematic fit (using correlation with $K_S^0$ mass) : 6.2 MeV/$c^2$

(Note that initial neutron mass is also correlated with the reconstructed mass deviation, but it depends on $K^+$ momentum resolution.)
Although mass resolution with kinematic fit is not sensitive to momentum resolution, it is better to construct a spectrometer with \(~1\%\) resolution. Tracking chambers with such resolutions are under considerations at LEPS2.
Other possibilities of detector setup

- Inactive target + proton detection at spectrometer
  - Need studies of proton momentum resolution.

- Only $\pi^+\pi^-$ detection at Side Tracking Chamber
  - $M(\pi^+\pi^-) = M(K_S^0)$ & $MM(K^+, \pi^+\pi^-) = M(p)$
  - $\Rightarrow M(K^+n)$ with Fermi-correction

\[
\left[ M^C (K^+n) \right]^2 = \left[ M (K^+n) \right]^2 - \frac{\left| P_{K^+} \right|}{\left| P_{K^+} - P_{K_S^0} \right|} \times \left\{ MM (K^+, \pi^+\pi^-) \right\}^2 - \left[ M_p \right]^2
\]

- Mass res. $\sim 15.4$ MeV with $K^+$ beam mom. res. 8.4 MeV/c (LESB3)
- Select backward production of $K_S^0$: 6.7 MeV (135°-180° in CMS)
- Need to measure $K^+$ beam momentum with TOF. (L$\sim$4 m)
Expected Yield (BNL case) and Backgrounds

- LESB3: $10^{12}$ proton/pulse
  \[\Rightarrow 3 \cdot 10^5 \text{K}^+\text{pulse} @710 \text{ MeV/c}\]
  \[\Rightarrow 3 \cdot 10^4 \text{K}^+\text{pulse} @475 \text{ MeV/c} \text{ w/o degrader}\]
- \[Y = \rho \cdot l \cdot \sigma \cdot N_A \cdot F_K \cdot f_n = 1.032 \text{ g/cm}^3 \cdot 25 \text{ cm} \cdot 10^{-27} \text{ cm}^2 \cdot 6.022 \cdot 10^{23} \cdot 3 \cdot 10^4 /\text{pulse} \cdot (6/13) = 200 /\text{mb/pulse}\]
- \[\sigma_{BW}(E) = \pi/(4k^2) \cdot \Gamma^2/[(E-M)^2+\Gamma^2/4] \text{ for spin1/2}\]
  \[\Rightarrow 26.4 \cdot \Gamma \text{ mb/MeV}\]
- \[\Lambda^*: \Gamma = 15.6 \text{ MeV} \Rightarrow \text{order of 100 mb}\]
- CEX BG: 7 mb [PRD15(1977)1846] & forward peaked
- $\pi^+n \rightarrow \pi^+\pi^-\rho$: Pion contamination in beam can be removed by Cherenkov detectors, $K_S^0$ reconstruction, and 4-momentum conservation.
Letter of Intent for
Study of Exotic Hadrons with \( S = +1 \)
and Rare Decay \( K^+ \to \pi^+ \nu \bar{\nu} \)
with Low-momentum Kaon Beam
at J-PARC

Collaboration of
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High Energy Accelerator Research Organization(KEK)
Kyoto University
Osaka University
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National Defense Academy(NDA)
Laboratory of Nuclear Science(LNS), Tohoku University
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K0.8 as K1.1BR at Day-1 ?
K0.8 w/ double separated beam at Day-2 ?

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Summary

• Existence of $\Theta^+$ can be confirmed in $K^+n$ resonance reaction at J-PARC. $P(K^+) \sim 420$ MeV/c
• $\Theta^+$ is identified by invariant mass of two pions and proton.
  Mass resolution $\sim 8$ MeV w/ $\Delta P/P=1.4\%$
  (Better resolution is expected with kinematic fit and/or large volume tracking chamber.)
• $\Theta^+$ signal should be distinguishable from charge exchange background and contaminated pion reaction.
• Width can be measured from cross section. $(26x\Gamma \text{ mb/MeV})$
• $\Lambda(1520)$ formation with $K^-$ beam is useful as a reference reaction.
• Beamline and detector system can be shared with rare kaon decay experiments.