From LEPS to LEPS2
for the exotic hadron (baryon) study

- 計画研究B01
- What is exotic? (qqqq̅q or qqq+q̅q ……)
- LEPS results for Θ⁺ and Λ(1405)
- LEPS2 project

RCNP M. Yosoi
レーザー電子光ビームを用いたペンタクォークの研究

Photon beam (≒neutral vector meson)
merit: polarization observables
demerit: low interaction rate
$K^+ \pm, \pi^\pm$ beam (charged pseudoscalar meson)

high interaction rate, high resolution
What is ‘exotic’?

Baryon resonances in the mean field approach

(Diakonov arXiv:0812.3418 [hep-ph])

Dirac Hamiltonian for quarks in a baryon:

\[ H = \gamma^0 (i \gamma^i \partial_i + \sigma(x)) + i \gamma^5 \pi(x) + \gamma^\mu V_\mu(x) + \gamma^\mu \gamma^5 A_\mu(x) + \cdots = H_s + H_{ud} \]

\[ [H_s, J] = 0, \quad [H_{ud}, K (= T + J)] = 0 \]

FIG. 1: Filled quark levels for the ground-state baryon \( N(940, \frac{1}{2}^+) \). The two lightest baryon multiplets \( (8, \frac{1}{2}^+) \) and \( (10, \frac{3}{2}^+) \) are rotational excitations of the same filling scheme.

Simultaneous ordinary and isospin space rotation: \( N \rightarrow \Delta \)

\( SU(3) \) flavor rotation: \( \rightarrow \) octet, decuplet
What is ‘exotic’?

A particle-hole excitation for different single particle orbits.

A particle-hole excitation for different single particle orbits.

FIG. 2: $\Lambda(1405, \frac{1}{2}^-)$

FIG. 3: $N(1535, \frac{1}{2}^-)$

FIG. 4: $N(1440, \frac{1}{2}^+)$

FIG. 5: $\Theta^+(\frac{1}{2}^+)$

$m_{\Theta^+}\Sigma(1440)+\Sigma(1535)-\Sigma(1405) = 1570$ MeV
Nuclear Gamow-Teller transitions
\( (\Delta L=0, \Delta S=\Delta T=1) \)

[e.g., \(^{90}\text{Zr}\) \((0^+) \rightarrow \;^{90}\text{Nb}\) \((1^+)\) ]

Energy dependence of \(NN\) \(t\)-matrix
(\(\text{PRC24,1073}(1981)\))

Reaction: \((p,n), (3\text{He},t), \ldots\)
Energy: relatively large \(V_\sigma\)
Angle: very forward
Nuclear Gamow-Teller transitions

$^{90}\text{Zr(}^{3}\text{He,}t)^{90}\text{Nb}$

$E(^{3}\text{He}) = 450 \text{ MeV}$

$\theta = 0^\circ$

$\Delta E = 400 \text{ keV}$

$^{58}\text{Ni(p,n)}$

$E_p = 160 \text{ MeV}, 0\text{-deg.}, \text{IUCF}$

J. Rapaport et al.,

$\Delta E = 35 \text{ keV}$

$^{58}\text{Ni(}^{2}\text{He,}t)$

$E_{^{2}\text{He}} = 140 \text{ MeV/u}, 0\text{-deg}$

2001 RCNP
Quasi-bound $d+t$ cluster state

$^{(6}\text{Li}(p,2p)^{5}\text{He}^* \text{ coincidence with decay particles) }

Ground states of nucleon 5-body system are unbound.
LEPS results for $\Theta^+$ and $\Lambda(1405)$
Super Photon ring – 8 GeV

- 8 GeV electron beam
- Diameter $\approx 457$ m
- RF 508 MHz
- One-bunch is spread within $\sigma = 12$ psec.
- Beam Current $= 100$ mA
- Top-up injection

Osaka – SPring-8: about 120 km, One and half an hour highway drive.
Characteristics of BCS photons
(BCS: Backward Compton Scattering)

- rather flat energy distribution with small spreading
  (Unlike the Bremsstrahlung, where low energy photons are dominated, \( \sim 1/E_\gamma \))
- high linear- or circular-polarization
- photon energy can be tagged by recoil electron

\[ E_e = 8 \text{ GeV} \]
\[ \lambda = 351 \text{ nm} \]
With LEPS, what can be aimed at?

Key words:
1. Forward angle measurement including 0 deg.
2. Polarization observables
3. Strangeness

Threshold region of $\Phi(s\bar{s})$ meson and hyperon resonances

\[\Sigma(1660)\quad \Lambda(1600)\quad \Theta(1540)\quad \Lambda(1520)\quad \Lambda(1405)\quad \Sigma(1385)\quad \Lambda(1405)\quad \Sigma(1192)\quad \Lambda(1520)\quad \Lambda(1116)\]
LEPS forward spectrometer

Same acceptance for the positive and negative charged particles ($\phi \rightarrow K^+ K^-$)

- Target LH$_2$, LD$_2$, etc.
- AC index = 1.03 to reject $e^+e^-$ pairs
- SSD 120$\mu$m pitch
- DCs $\sigma \sim 200$ $\mu$m
- Magnet 135 x 55 cm$^2$, (35° x 15°) B = 0.7T
Particle identification

Reconstructed mass spectra

- TOF: RF signal - TOF wall, $\Delta t = 120$ ps
- Momentum: SSD, DCs, Tracking
  $\Delta p \sim 6$ MeV/c for 1 GeV/c $K$
Experimental setup with TPC

Two types of TPC’s are installed at 2004 and 2007 with a superconducting Solenoid magnet (2 T).

Measure both production and decay simultaneously!
# LEPS experiments (2000 – 2009)

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<thead>
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<th>2001</th>
<th>2002</th>
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<td>photon beam</td>
<td>BL construction &amp; Comissioning</td>
<td>LH2 (short)</td>
<td>nuclear targets</td>
<td>LH2, LD2 (long)</td>
<td>nuclear targets</td>
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<tr>
<td>target</td>
<td>gamma detector</td>
<td>Forward LEPS spectrometer</td>
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<tr>
<td>detector</td>
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</table>

- **Target**
  - LH2, LD2 (long)
  - New target system for TPC (LH2, LD2, LHe)

- **Detector**
  - Forward LEPS spectrometer

- **Photon Beam**
  - LP $E_\gamma < 2.4$ GeV
  - LP $E_\gamma < 3$ GeV

### Development of Polarized HD Target

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<th>year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<td>photon beam</td>
<td>LP $E_\gamma &lt; 3$ GeV</td>
<td>LP $E_\gamma &lt; 2.4$ GeV (8W Paladin x2)</td>
<td>LP $E_\gamma &lt; 3$ GeV</td>
<td>LP $E_\gamma &lt; 2.4$ GeV (test 16W Paladin)</td>
<td>LP $E_\gamma &lt; 3$ GeV</td>
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<tr>
<td>target</td>
<td>LD2, LH2 (long)</td>
<td>new target system for TPC (LH2, LD2, LHe)</td>
<td>LH2 (long)</td>
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<td></td>
</tr>
<tr>
<td>detector</td>
<td>Forward LEPS spectrometer</td>
<td>Fwd spectrometer + TPC–II</td>
<td>Fwd</td>
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</tbody>
</table>
**Θ⁺ search**

- Minimum quark content: 5 quarks \(uudd\bar{s}\)
- Quantum numbers of “Exotic” pentaquarks: not 3-quark

Theoretical Prediction of \(\Theta^+\)

- \(\Theta^+(1530)\)
- \(N(1710)\)
- \(\Sigma(1890)\)
- \(\Xi(2070)\)

\[ M = [1890-180*Y] \text{ MeV} \]


(Chiral Soliton Model)

- Exotic: \(S = +1\)
- Low mass:
  1530 MeV
- Narrow width:
  \(~15\) MeV
- \(J^{\pi}=1/2^+\)
First observation of $\Theta^+$ from LEPS

$$\gamma'n' \rightarrow \Theta^+ K^- \rightarrow K^+ K^- n$$

Target: neutron in Carbon nucleus

Background level is estimated by a fit in a mass region above 1.59 GeV.

Assumption:
- **Background** is from non-resonant $K^+ K^-$ production off the neutron/nucleus
- ... is nearly identical to non-resonant $K^+ K^-$ production off the proton

$M = 1.54 \pm 0.01$ GeV
$\Gamma < 25$ MeV
Gaussian significance 4.6$\sigma$

T. Nakano et al., PRL91, 012002
Both reactions are quasi-free processes.
Fermi-motion should be corrected.
Existence of a spectator nucleon characterize both reactions. \[ p(N_S) < \sim 100 \text{ MeV/c} \]

Data were taken in 2002-2003 (published in PRC79,025210(2009)) and in 2006-2007 (high statistics, still under analysis)
4-momentum of $\gamma$, $d$, $K^+$, $K^-$
→ missing energy and momentum of the $pn$ system
→ calculate the possible minimum momentum of $N_S$
Results of $\Lambda(1520)$ analysis

$pK^-$ invariant mass with MMSA: Fermi motion effect corrected.

Structure with a width less than 30 MeV/$c^2$ requires a physics process or fluctuation.

The total cross section is $\sim 1 \mu$b, which is consistent with the LAMP2 measurements.

$\Delta(-2\ln L) = 55.1$ for $\Delta ndf=2 \rightarrow 7.1\sigma$

$\text{Prob}(7.1\sigma) = 1.2 \times 10^{-10}$
Results of $\Theta^+$ analysis

$nK^+$ invariant mass with MMSA: Fermi motion effect corrected.

Peak position: $1.527 \pm 0.002 \text{ GeV/c}^2$
Signal yield: $116 \pm 21$ events
Differential cross-section: $12 \pm 2 \text{ nb/sr}$

"The narrow peak appears only after Fermi motion correction."

$\Delta(-2\ln L) = 31.1$ for $\Delta ndf=2 \quad \rightarrow \quad 5.2\sigma \quad \text{Prob}(5.2\sigma) = 2 \times 10^{-7}$
We observed a 5-σ peak in the Fermi-motion corrected $nK^+$ invariant mass at 1.527 GeV/c$^2$

New data set with 3-times more statistics was taken. Blind analysis is under way to check the validity of the peak.

A new experiment with a TPC was carried out in 2008-2009: wider angle coverage and $\Theta^+$ reconstruction in $pK_s$ decay mode. (But PI and momentum resolutions are not good.)

→ LEPS2 and J-PARC (formation)
Study of $\Lambda(1405)$

- 3 quark or meson-baryon molecule or 4q-qbar pentaquark?
  qq LS force is too small to explain the mass of $\Lambda(1405)$. meson-baryon molecule has been suggested. 1-pole or 2-pole?
- Low energy K-bar N interaction
  Kaonic nucleus, Kaon condensation in the neutron star
- K-bar K N molecular state?
\( \Lambda(1405) \) photoproduction at LEPS

\[ \gamma p \rightarrow K^+ X \]

Missing mass spectrum can not separate \( \Lambda(1405) \) and \( \Sigma(1385) \)

\rightarrow detect decay products and distinguish two resonances

\[ \gamma p \rightarrow K^+ \Lambda(1405) \rightarrow K^+ \Sigma^\pm \pi^\mp \rightarrow K^+ n(\pi^+ \pi^-) \]

\[ \gamma p \rightarrow K^+ \Sigma(1385)^0 \rightarrow K^+ \Lambda \pi^0 \rightarrow K^+(p\pi^-)\pi^0 \]

- line-shape of \( \Lambda(1405) \) in \( p(\gamma, K^+ \pi^+) \), \( p(\gamma, K^+ \pi^-) \) reactions
  J.K.Ahn et al. NPA 721,715c(2003) (Fwd only)
  Interference of \( \Sigma \pi \) scattering amplitude

- **Differential cross section of \( \Lambda(1405) \) production**
  M.Niiyama et al. PRC78,035202(2008) (Fwd + TPC)
  Enhancement of cross section near threshold.
Lineshape of Λ(1405)

\[ \sigma_{\Sigma^+\pi^-} = \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 + \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^1) \]

\[ \sigma_{\Sigma^-\pi^+} = \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 - \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^1) \]

The interference term depends on π decay angle.

\[ \chi^2 / \text{ndf} = 16.5 / 12 \]

add Σ^+π^- and Σ^-π^+
Spectrum of $\Lambda(1405)$ in 2 $E_\gamma$ bins [CH$_2$-C]

- data
- $\Sigma(1385)$ ($\Lambda \pi^0$ mode)
- $\Sigma \pi$ phase space
- $K^*(892)\Sigma^+$
- theoretical model

$\Lambda^*/\Sigma^* = 0.54 \pm 0.17\, (1.5 < E_\gamma < 2.0)$
$0.074 \pm 0.076\, (2 < E_\gamma < 2.4)$

$1.5 < E_\gamma < 2.0$ GeV
$\chi^2 / \text{ndf} = 43 / 24$
$182 \pm 26$ events

$2.0 < E_\gamma < 2.4$ GeV
$\chi^2 / \text{ndf} = 42 / 24$
$43 \pm 32$ events
Absolute value of the differential cross section

Using the ratio of $\Lambda(1405)/\Sigma(1385)$, the absolute value is obtained from LH2 data.

<table>
<thead>
<tr>
<th>$0.8 &lt; \cos \theta_{kCM} &lt; 1$</th>
</tr>
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</table>

| $1.5 < E_\gamma < 2.0$ GeV | $2.0 < E_\gamma < 2.4$ GeV |
|-----------------------------|

<table>
<thead>
<tr>
<th>$d\sigma/d(\cos \theta)$ [$\mu$b]</th>
</tr>
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<tbody>
<tr>
<td>$\Lambda^*(1405)$</td>
</tr>
<tr>
<td>$0.43 \pm 0.088^{+0.034}_{-0.14}$</td>
</tr>
<tr>
<td>$\Sigma^*^0(1385)$</td>
</tr>
<tr>
<td>$0.80 \pm 0.092^{+0.062}_{-0.27}$</td>
</tr>
</tbody>
</table>

- Strong enhancement of $\Lambda(1405)$ production near threshold. Exotic mechanism may contribute $\Lambda(1405)$ production.
- On going analysis for LH2 data in 2007-2008
  - Obtain more precise differential cross section
  - Photon beam asymmetry
  - $p(\gamma,K^{*+})\Lambda(1405)$
Bump structures around 2 GeV in other reactions

\[ \gamma p \rightarrow \phi p \]

\[ \gamma p \rightarrow K^+ \Lambda(1520) \]

T. Mibe et al. PRL95,182001 (2005)  
LEPS2 project
LEPS new beam line (LEPS2)

**Beam upgrade:**
- **Intensity** --- High power laser, Multi laser(x4)
  --- Laser elliptic focus
  \[2 \times 10^6 \rightarrow 10^7/\text{sec} \text{ for } 2.4 \text{ GeV}\]
  \[2 \times 10^5 \rightarrow 10^6/\text{sec} \text{ for } 3 \text{ GeV}\]
- **Energy** --- Laser with short \(\lambda\),
  \(\text{re-injected Soft X-ray+BCS (2}\text{nd stage)}\), \(\rightarrow\) up to \(~7.5 \text{ GeV}\)

**Detector upgrade:** (reaction process & decay process)
- **Scale &** --- General-purpose large 4\(\pi\) detector \(\rightarrow\) outside of the building
- **Flexibility** Coincidence measurement of charged particles and neutral particles (photons) \(\leftarrow\) BNL/E949 detector
- **DAQ** --- High speed for the minimum bias trigger

**Physics:** Multi-quark (>3)

Workshop on LEPS2 (2005/7, 2007/1)

*statistics, acceptance, momentum and PI resolution, neutral particle detection (especially at large angle)*
Schematic view of the LEPS2 facility

逆コンプトン散乱

8 GeV 電子ビーム 反跳電子 (タギング)

レーザー or 反射X線

実験ホール内

レーザー室

(深)紫外線 レーザー

最良エミッタンス（平行ビーム） ⇒ レーザー電子光が広がらない

実験ホール外

10倍強度のビーム LEPSで開発されたパラレル・レーザー入射システム X線入射による高エネルギー化（将来）

・米国BNL(E949)の400トン スペクトロメーター有効利用
・阪大ブランドの高速データ 収集回路の開発
・LEPSでの膨大なノウハウの蓄積

全方向をカバーする検出器
4πガンマ線検出器（東北大） 崩壊解析用スペクトロメータ 反応同定用スペクトロメータ 高速データ収集システム

実験棟
Divergence of LEP beam

BL31ID $<\sigma_{x'}> = 14 \, \mu\text{rad.}$

BL33B2 $<\sigma_{x'}> = 58 \, \mu\text{rad.}$

Better divergence $\rightarrow$ Better tagging resolution
Smaller beam size at the target
SONY MS
new deep UV laser
LEPS2 Experimental building

LEPS2 Main Spectrometer (E949 solenoid magnet)
Forward Spectrometer
Forward TOF
Beam Dump

H₂, D₂ Buffer
Electronics
Electric Power Equipments
Cooling System

18 m
12 m
27 m
35 m
12 m
10 m
1.4 m
1.5 m
5 m

crane (>10 t)
solenoid (400 t)
LEPS2実験棟
予定地

（参考：BL33XU実験棟）
Detector Setup

Target cell
CFRP
SSD

SSD

Target cell
CFRP

Range and TOF
Barrel γ
Barrel Tracker

γ
TPC or CDC
MWDC

Target and Vertex detector

3 m
Tracking system

- Side way tracker (TPC)
  \[ R = 500 \text{ mm (24-26 layer)}, \]
  \[ \sigma_{r\phi} = 150 \text{um}, \quad \sigma_z = 2 \text{mm}, \]

- Forward MWDC chamber (450mm)
  \[ ^4\text{He} + \text{Ethane} \left( X/X_0 = 1.1 \times 10^{-3} \right) \]
  6 plane (x,x', u(45) u'(-45), y y')
  \[ \sigma_{xy} = 150 \text{um}, \]

- Barrel tracker
  Cathode strip + Anode wire
  \[ \sigma_{r\phi} = 250 \text{um}, \quad \sigma_z = 2 - 3 \text{ mm} \]

- SSD (Cylindrical+ Disk)
  Double side strip sensor
  \[ \sigma = 35 \text{um}, \]
  \[ \Delta Z < 1 \text{ mm at } \theta > 20^0 \]
$\Delta P/P$ at forward region

- $2^\circ < \theta < 17^\circ$
  - Vertex + Fd MWDC
  - No SW tracker
  - At 10 degree
    - $\Delta P/P = 1.3\%$ (He4 gas)
    - 1.9\% (Air)

- $\theta > 17^\circ$
  - MS effect in SW tracker
  - TPC $\Rightarrow$ Ar/CH$_4$ or Ne/CH$_4$
Momentum dep. of $\Delta P/P$
PID
TOF counter
$\Delta t \, 50 \text{ ps}$

TOP or Aerogel Cerenkov

TOF & Cerenkov (TOP, AC, RICH)
Penta-quark $\Theta^+$

Strangeness tagging

$\gamma + n \rightarrow K^- + \Theta^+$

$\rightarrow p \ K^0$

$\rightarrow \pi^+ \ \pi^-$

Invariant Mass measurement

$\Delta M(K^0)=2.4 \text{ MeV}/c^2$

CDC and TPC
MC effect on LH2 target

$\Delta M(\Theta^+)=3.5 \text{ MeV}/c^2$
\[ \gamma p \rightarrow K^* \Lambda(1405) \]

\[ \gamma + p \rightarrow K^{*+} + \Lambda(1405) \rightarrow \Sigma^+ \pi^- \rightarrow n \pi^+ \]

**Missing mass resolution for \( \Lambda(1405) \) 8 MeV/c^2**

![Graph showing missing mass resolution and acceptance for different channels](image)
予算 (全体 ~1000 Myen)

- H22年度施設整備費補助金 (RCNP) □ Myen
  「LEPS2ビームライン及び測定装置」
- 科研費新学術領域「新ハドロン」
  計画研究B01（代表者 野海） ~240 Myen/5年
  (レーザー、検出器)
- 実験棟建設費（理研？） □ Myen
  （18m × 35m (630mm²) → 12m × 27m(324mm²) 1/2縮小案）
- E949検出器&磁石 移設費 □ Myen
  (RCNPサブアトミック科学推進事業 or 阪大学内措置)
- H23年度以降概算要求（サブアトミック科学推進事業）
  (□ Myen × ?年)
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<td>2009FY</td>
<td>Submit LEPS2 proposal</td>
</tr>
<tr>
<td></td>
<td>E949 detector (BNL): Decompose &amp; partially transfer</td>
</tr>
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<td>R&amp;D for high intensity beam</td>
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<tr>
<td></td>
<td>R&amp;D of LEP2 Detector</td>
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<td>Start construction</td>
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<td>Modify SR chamber</td>
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<td>BL construction</td>
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<td>Laser system</td>
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<td>Design &amp; build Exp. hutch</td>
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<td>Infra.</td>
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<td>Rad. shield</td>
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<td>Beam commissioning</td>
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<td>Partially start experiment with $4\pi$ photon &amp; fwd detector</td>
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<td>$4\pi$ photon detector (Tohoku LNS)</td>
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<td></td>
<td>Polarized HD target: R&amp;D and experiment at LEPS</td>
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<thead>
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<th>Year</th>
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<td>2010FY</td>
<td>Construction of the decay spectrometer and forward spectrometer</td>
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<tr>
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<td>Spectrometer commissioning</td>
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<td>Start experiment</td>
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<td>2011FY</td>
<td>R&amp;D of X-ray re-injection system</td>
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<td>LEPS2</td>
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<td>LEPS2</td>
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<td>LEPS2</td>
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Backup
Status of the LEPS2 project

- 2005.6: Discussion for the LEPS2 beamline was started.
- 2005.7: First workshop was held at RCNP → Both physics and technical issues.
- 2005.12: Basic agreement for the movement of the E949 detector was made with BNL and associated laboratories.
  - Numerical consideration for getting the high energy $\gamma$ beam by re-injection of X-ray has been performed. → Need R&D for the mirror.
- Test of the LRNB method for the high intensity LEP → The same intensity as the normal Gauss beam
- 2006.4: Test of the two laser injection → succeed!
- Disassembling work for E949 detector
- Discuss detector design, modification of beamline etc.
- 2007.1: Second workshop @RCNP
- 2008.1: Change the plan of the laser injection place.
- 2008.11: Loan agreement for the E949 detector
- LOI to Spring-8: 2006.12 Hearing → Approved. BL31 was assigned.
- Budget request: 2008,2009 from RCNP → X
- Kakenhi “Exotic Hadron” approved (2009- ), Budget request 2010 O?
BEAM LINE MAP OF SPRING-8

LEPS2 LOI was approved: BL31 was assigned for LEPS2.
$\gamma p \to p \pi \pi$

$\gamma p \to p \pi \pi \pi$

$\gamma p \to p \pi \pi \pi \pi$

$\gamma p \to p \pi^0/\eta/\eta'/\omega$

$\gamma p \to p \eta$
Analysis for 2008A(3 GeV) run

**forward K+ event**

\[ \text{dE/dx} = \text{Average of peak PAD} \]

by Nakatsugawa
$\gamma\ d \to \Lambda(1520)\Theta^+$

$\gamma d \to \Lambda(1520)\Theta^+$

- $K^- p$

$\Delta M(\Theta^+) = 17\ MeV/c^2$

$\Delta M(\Theta^+) = 10\ MeV/c^2$

$\Delta M(\Theta^+) = 3\ MeV/c^2$

$\gamma d \to \Lambda(1520)\Theta^+$

- $K^- p \to K^+ n$

$\gamma d \to \Lambda(1520)\Theta^+$

- $K^- p \to K_s p$

Missing Mass

+ Kinematical fit

Invariant Mass
K/π/p separation by TOF counter

Cerenkov counter is necessary