Status of the HD polarization Project for SPring-8

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1. SPring-8 Facility
2. Motivation of Physics
3. Present Status of Polarized proton and deuteron target: HD target project

Super Photon ring – 8 GeV

- 8 GeV electron beam
- Diameter .457 m
- RF 508 MHz
- One-bunch is spread within $\sigma_{12}$ psec.
- Beam Current = 100 mA
- Life time 30.50 hours
LEPS facility

Collision
8 GeV electron
Recoil electron
Electron tagging
Laser light
Inverse Compton $\gamma$-ray

a) SPring-8 SR ring

b) laser hutch

c) experimental hutch

RCNP, JAERI, JASRI collaboration

Laser System

- 351 nm Ar laser
  multi-line UV, 4 W.
  $10^6$ photons/sec on target
- Linearly polarized laser beam
  Polarized LEP beam
  ~95% at 2.4 GeV
Back Compton Scattering

Energy of BCS photons

\[ E_\gamma = \frac{E_e (1 - \beta \cos \theta_e)}{1 - \beta \cos \theta + E_e \left( \frac{\gamma}{E_\gamma} - \cos \theta - \theta \right)} \]

- \( \beta \): Electron velocity /c
- \( \theta_e \): Incident angle of laser photon
- \( \theta \): Scattered angle of photon

Head-on collision (\( \theta_e = 0 \))

\[ E_\gamma \approx \frac{4 \gamma^2 E_e}{1 + \left( \frac{\gamma}{E_\gamma} \right)^2 + 4 \gamma^2 E_e / mc^2} \]

ex. \( E_e = 8 \text{ GeV}, (\text{Laser } \lambda = 351 \text{ nm}) \)

\[ \rightarrow 2.4 \text{ GeV Maximum} \]
LEPS spectrometer

\[ \text{AC}(n=1.03) \]

\[ \gamma \text{ ray beam} \]

\[ \text{LH}_2 \text{ Target} \]

\[ \text{Start Counter} \]

\[ \text{Dipole Magnet 0.7 Tesla} \]

\[ \text{SVTX DC1} \]

\[ \text{TOF DC2 DC3} \]

Charged particle identification

Reconstructed mass for CH\( _2 \) target

\[ \sigma(\text{mass}) = 30 \text{ MeV (typ.) for 1 GeV/c Kaon} \]

4 \( \sigma \) cut for \( K^+/K^-/\text{proton PID} \)
Vertex distribution

Vertex distribution (KK, Kπ tracks)

LH₂ target : -1100 < z < -910 mm
BG from target cell : (z < -960 mm, x < -15 mm)

Missing mass spectrum

- p(γ,K⁺)Λ (1116)
- 72,500 events
- p(γ,K⁺)Σ⁰ (1193)
- 48,900 events
- 1.5 ~ 2.4 GeV
- 0.6 < cosθₑm < 1

Photon beam asymmetry
Photon beam asymmetry $\Sigma$

Vertical
$$\frac{d\sigma}{d\Omega_v} = \frac{d\sigma}{d\Omega_{unpol}} [1 + P_{\gamma}\Sigma \cos(2\phi)]$$

Horizontal
$$\frac{d\sigma}{d\Omega_h} = \frac{d\sigma}{d\Omega_{unpol}} [1 - P_{\gamma}\Sigma \cos(2\phi)]$$

$$N = F_{\text{acc}} \frac{d\sigma}{d\Omega}$$

$$\frac{nN_v - N_h}{nN_v + N_h} = P_{\gamma}\Sigma \cos(2\phi)$$

N : K$^+$ photoproduction yield
$\phi$ : K$^+$ azimuthal angle
$P_{\gamma}$ : Polarization of photon
n : Normalization factor for $N_v$

For all events

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Long standing Naïve Question: What is the reason for the existence of two quark systems (Mesons) and three quark systems (Baryons)?

There is no reason of QCD to exhibit 4-, 5-, 6-, multi-quark systems

- Baryonium hunting
- Dibaryon search (H-dibaryon etc..)
**Pentaquark (5 quark) system**

- QCD does not forbid \( qqqq\bar{q} \) states, but so far only baryons (\( qqq \)) and mesons (\( q\bar{q} \)) have been found.

- \( \Lambda(1405) \)?
  - 3-quark particle (uds)
  - 5-quark particle (uuds\( \bar{u} \))
  - still poor data / ambiguous interpretation

- \( \Theta^+ \)
  - 5-quark state (uudd\( \bar{s} \))
    - meson-baryon resonance
    - exotic S=+1 particle

Nakano et al., PRL 91, 012002 (2003)
Summary of positive results in 2004

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Theta^+$ Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEPS/SPring-8</td>
<td>1540 ± 10 ± 5</td>
<td>25</td>
</tr>
<tr>
<td>DIANA</td>
<td>1539 ± 2 ± few</td>
<td>9</td>
</tr>
<tr>
<td>CLAS(d)</td>
<td>1542 ± 2 ± 5</td>
<td>21</td>
</tr>
<tr>
<td>SAPHIR</td>
<td>1540 ± 4 ± 2</td>
<td>25</td>
</tr>
<tr>
<td>ITEP(n)</td>
<td>1533 ± 5</td>
<td>20</td>
</tr>
<tr>
<td>CLAS(p)</td>
<td>1555 ± 1 ± 10</td>
<td>26 ± 7</td>
</tr>
<tr>
<td>HERMES</td>
<td>1528 ± 2.6 ± 2.1</td>
<td>19 ± 5 ± 2</td>
</tr>
<tr>
<td>ITEP(p)</td>
<td>1526 ± 3 ± 3</td>
<td>24</td>
</tr>
<tr>
<td>ZEUS</td>
<td>1527 ± 3</td>
<td>10 ± 2</td>
</tr>
</tbody>
</table>

Note: Many positive results have been changed to “Negative” in 2005!

http://www2.yukawa.kyoto-u.ac.jp/~mquark04/index.html

Correlated di-quark model

$\Theta^+$ Pentaquark particle

Alpha Cluster

by Yamazaki & Akaishi
\[ \gamma D \rightarrow K^- p X; \quad M(K^- p) = \Lambda^+(1520) \]

By Nakano et al., 2005

What is the spin and party of $\Theta^+$?

Diquark correlations?

Jaffe-Wilczek

Quark bag surrounded by the pion cloud


Naïve quark model

\[ s^4 \bar{s} \]

\[ ps^3 \bar{s} \]

Negative

Positive
Spin observables? Beam asymmetry

\[ \sum B = \frac{\sigma_\perp - \sigma_\|}{\sigma_\perp + \sigma_\|} \]

Nakayama & Tushima:

*for the positive parity* of \( \Theta^+ \) the beam asymmetry is significantly positive,
*whereas for the negative parity* of \( \Theta^+ \) beam asymmetry is significantly negative

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**Physics motivation**

**Nucleon Spin Sum Rules**
Gerasimov-Drell-Hearn (GDH)

\[ \frac{-2\pi\alpha}{m^2} \kappa^2 = \int_{v_0}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{v^3} dv \]

Forward Spin-Polarizability

\[ \gamma_0 = \frac{1}{4\pi^2} \int_{v_0}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{v^3} dv \]

\( s\bar{s} \) contents in nucleon

\[ \gamma p \to \phi p \]

\( \Theta^+ \) spin-parity

\[ \gamma N \to \Theta^+ K \]

\( p p \to \Sigma^+ \Theta^+ \)
**Θ⁺ spin-parity determination**
Zhao and Al-Khalili PLB585(2004)91

\[ \gamma + n \rightarrow \Theta^+ + K^- \]

Beam-target double polarization asymmetry

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**ϕ-meson photoproduction @ LEPS of SPring-8**

Studying diffractive channels as a tool for non-perturbative QCD

(Pomeron structure, search for glueball, \(f_2\)-meson trajectories, etc)

Non-polarized observables are not suitable for this study

Search for exotic processes as s̅s-knockout

Henley et al. [94]
Titov, Yang, Oh [94-98]
**ss** - contents in proton

\[ \phi \text{-meson: } \sim ss^- \]

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

pomeron exchange

+ \[ \pi \text{ exchange} \]

+ \[ ss \text{ knock-out} \]

Study small amplitudes by interference

\[ \rightarrow \text{ double polarization asymmetry} \]

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**Reconstructed \( \phi \) events (K+K- event)**

Selections for \( \phi \) event (KK mode)

\[ |M(KK) - M_\phi| < 10 \text{ MeV} \]

\[ |MM((\gamma K^+K^-)X) - M_{\text{proton}}| < 30 \text{ MeV} \]
beam-target double spin asymmetry for $\gamma p \rightarrow \phi p$

Titov et al. PRC58(1998)2429

FIG. 10. The double spin asymmetry (a) $C_{\gamma p}^{(s)}(\theta)$ and (b) $C_{\gamma p}^{(d)}(\theta)$ at $W^2=2.155$ GeV with $\theta^p=0^\circ$, i.e., the VDM and OPE (solid lines), 0.25% (dashed lines), and 1% (dot-dashed lines) assuming that $|b_1|=|b_2|$. The phases ($\varphi_1, \varphi_2$) are explicitly given in each graph.

Polarization observables with linearly polarized photon (in $\phi$ meson rest frame)

- $\gamma \rightarrow K^+ K^-$
  - Decay direction //
  - to direction of beam
  - Spin-flip processes in
  - Pomeron and $f_2^*$…

- $\gamma \rightarrow K^+ K^-$
  - Decay Plane // $\gamma$ 
  - natural parity exchange $(-1)^l$
  - (Pomeron, Glueball, scalars*)

- $\gamma \rightarrow K^+ K^-$
  - Decay Plane \(\gamma\)
  - unnatural parity exchange $(-1)^l$
  - (Pseudoscalar mesons $\pi, \eta$)
\[ \cos \theta_{K^+} \text{ distribution} \]

For spin-conserving processes:

\[ W(\cos \Theta) \sim \sin^2 \Theta \]

\(-0.2 \leq t < -|t|_{\text{min}} \text{ GeV}^2, \ 2.2 < E_\gamma < 2.4 \text{ GeV} \)

\[ W^0(\Phi) = \frac{1}{2\pi} \left(1 - 2\text{Re}\rho_{1-1}^0 \cos 2\Phi\right) \]

\[ \rho^0_{1-1} = \sqrt{\frac{\sigma(\lambda_\gamma=-\lambda_\gamma)}{\sigma_{\text{tot}}}} \]

\(\text{Distribution on azimuthal } K^- K^- \text{ decay angle } \Phi \)

(tool for double spin-flip processes)

Raw data

CLAS/LEPS
$\phi_{K^+}$-$\Phi_{\text{pol}}$ distribution
(tool for unnatural parity exchange processes)

$|t|_{\text{min}} < |t| < 0.2 \text{ GeV}^2$, $2.2 < E_\gamma < 2.4 \text{ GeV}$

What we can study?

\[ \gamma + p \rightarrow \phi + p \]
\[ \gamma + p \rightarrow K^+ + \Lambda, K^+ + \Sigma^0 \]
\[ \gamma + p \rightarrow \omega + p \]
\[ \gamma + n \rightarrow K^+ + \Sigma^- \]
Quark Dynamics from Jlab (D.S. Carman et al., PRL 90, 131804 (2003))

CERN Courier June 2003

$S = 1^3P_0$ operator: 2:1

Quark-pair creation operator?
Missing resonances?

Weak decay of $\Lambda$
Large Anisotropy due to weak decay

$s\bar{s}$-quark content of proton and neutron

$|p> = \alpha |uud> + \beta |uud\bar{s}\bar{s}>$

$\Theta^+(1530)$
$N(1710)$
$\Sigma(1890)$
$\Xi(2070)$
This simple picture depicts pairs of strange quarks as they pop in and out of existence alongside the permanent quark residents of the proton. Nuclear physicists have found that strange quarks, though present for just tiny fractions of a second at a time, also contribute to the proton's properties.

Image: JLab

**G0 experiment at JLAB: Anapole moment**


**Double polarization asymmetry**

Beam-target asymmetry and exotic processes with unnatural parity exchange (ss-knockout)

LEPS, Spring-8 (calculated by Titov) with 1% ss-bar content

\[
C_{BT} = \frac{\sigma_p (1) - \sigma_A (1)}{\sigma_p (1) + \sigma_A (1)} \Rightarrow \frac{\sigma_p - \sigma_A}{\sigma_p + \sigma_A - 2\sigma_{BG}}
\]

Error estimation for \( C_{BT} \) measurement

\[
\left( \frac{\Delta C_{BT}}{C_{BT}} \right)^2 = \left( \frac{1-C_{BT}^2}{2C_{BT}(1-R)} \right)^2 + \frac{\Delta \sigma_p}{\sigma_p}^2 + \frac{R^2}{(1-R)^2} \left( \frac{\Delta \sigma_{BG}}{\sigma_{BG}} \right)^2
\]
Polarization in thermal equilibrium

\[ H = -\mu \cdot B = -g\mu_B N(B) I_z B \]

If \( I = 1/2 \),

\[ \Delta E = g\mu_B B \]

\[ P = \frac{N_+ - N_-}{N_+ + N_-} = \frac{e^{\Delta E / 2kT} - e^{-\Delta E / 2kT}}{e^{\Delta E / 2kT} + e^{-\Delta E / 2kT}} = \tanh(\frac{\Delta E}{2kT}) \]

proton: \( g_p \mu_B B / 2kT = 0.00101 \ B(T)/T(K) \)
electron: \( g_e \mu_B B / 2kT = 0.67 \ B(T)/T(K) \)

Spin Hamiltonian

\[ H = H_J + H_I + H_D + H_{LS} \]

\( H_J, H_I: \) Zeeman terms

\[ H_D = a(\vec{J} \cdot \vec{I}) - 3(\vec{J} \cdot \vec{r})(\vec{I} \cdot \vec{r}) \]

\( : \) dipole-dipole int.

\[ H_{LS} = -b\vec{J} \cdot \vec{L} - c\vec{I} \cdot \vec{L} \]

\( L: \) rotational angular momentum

\[ \hbar \omega_I \]

red: forbidden transition
Principle of HD

- Longstanding effort at Syracuse, LEGS/BNL ORSAY
- 10-20 mK
- 15-17T
- 80% for H, 20% for D (vector)
- 20% $\rightarrow$ 70% in D with DNP
<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>M. Bixon</td>
<td>An important relaxation mechanism for the protons in solid HD-... is “impurity” ortho-H₂ molecules.</td>
</tr>
<tr>
<td>1966</td>
<td>W.N. Hardy and J.R. Gaines</td>
<td>The above relaxation mechanism with α-H₂ was confirmed by relaxation time measurements in very pure HD at 1.2 K → 4.2 K. → proton relaxation time of many hours was obtained by aging a solid HD with a small α-H₂ impurity.</td>
</tr>
<tr>
<td>1967</td>
<td>A. Honig</td>
<td>Proposed for a free-nu-spin target: polarizing the HD at... low temperature (near 10 mK).</td>
</tr>
<tr>
<td>1968–1970</td>
<td>A. Honig, et al.</td>
<td>Study of the relaxation times, depending on temperature, magnetic field, ortho-H₂ and para-H₂ concentration. At Syracuse University... T = 0.4 – 10 K, H = 0 → 1 T.</td>
</tr>
<tr>
<td>1971–1972</td>
<td>H.M. Boerker, E.H. Grab, et al.</td>
<td>At SUNY Stony Brook... T = 25 mK → 4 K, β = 1.5 – 10 T.</td>
</tr>
<tr>
<td>1975</td>
<td>H. Maeno and A. Honig</td>
<td>Radiation damage was studied at... ERL 28 GeV proton synchrotron and Cornell 3.54 GeV electron synchrotron.</td>
</tr>
<tr>
<td>1976</td>
<td>A. Honig and H. Maeno</td>
<td>RF forbidden transition adiabatic rapid passage... Proton-neutron polarization transfer.</td>
</tr>
<tr>
<td>1985 late 1990s</td>
<td>A. Honig, et al.</td>
<td>The first application of polarized HD... produced at Syracuse for fusion study.</td>
</tr>
<tr>
<td>2003.11</td>
<td>LEGS collaboration</td>
<td>The first double-polarization data of meson photoproduction with polarized HD target.</td>
</tr>
</tbody>
</table>

Present status

LEGs/BNL (←Syracuse)

Orsay → GRAAL/ESRF

RCNP (→ Spring-8)  
goal: 10m K, 17 T
**HD target cycle:**

- Target injection into dilution fridge: 
  - ~min 45 days at 15 Tesla / 12 mK

**Loading In-Beam-Cryostat**
- 0.25 K and 1.00 Tesla

**Extraction with Transfer-Cryostat**
- 2.5 K and 0.120 T

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**In-beam Relaxation Time**

- November '01 (T=3.3 K)
  - H² : 1.5
  - D² : 360

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**Target Polarization**

<table>
<thead>
<tr>
<th></th>
<th>P₀₀</th>
<th>P₀₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov '01</td>
<td>30%</td>
<td>6%</td>
</tr>
<tr>
<td>June '04</td>
<td>54%</td>
<td>21%</td>
</tr>
</tbody>
</table>

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3 γm solid HD + 20% Al by weight (2050 × 50 γm wires)

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**LEGs: γ + HD**

- Eγ = 330 MeV

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**Yield**

- γ⁺ H → γ⁺ p
- γ⁺ H (born) → γ⁺ p
FROM PST05 Nov. 14-17 2005, Tokyo by KAGEYA et al.,

**LEGS production run #2, DeepI/H-1 (Spring'05)**

\[ D(p,n') \quad P_\gamma = 92\% \quad P_\delta = 31\% \]

\[ E_y = 341 \text{ MeV} \quad \theta_{\text{col}} (n') = 105^\circ \]

- target cell and Al wires contain the only unpolarizable nucleons;
- background is sampled in runs with an empty cell

**very preliminary**

\[ D(p,n') \quad P_\delta = 30\% \text{ (avg)} \]

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**Spring'05**

2\(^{nd}\) Production run

\[ E_y = 349 \pm 3 \text{ MeV} \]

\[ E_y = 395 \pm 7 \text{ MeV} \]

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**p and d Polarizations for Target #3 in QBC, 11/2004**

- \( T_1 = 8 \text{ min} \)
- \( T_1 = 13 \text{ min} \)
- \( T_1 = 18 \text{ min} \)
- \( T_1 = 12 \text{ min} \)
HYDILE target @Orsay

- Liquid $^4$He (4.2 K)
- Al Wires
- Saddle coils
- NMR Coils
- 70 K Shield
- Liquid $^4$He (0.5 K)
- Solenoid Coil
- Polarized HD

Proton Relaxation times versus Aging time:

Double distilled HD from LSC

$T_1 (0.5K; 0.07)$

$T_1 (0.5K; 1.07)$

$T_1 (1.0K; 1.07)$

$T_1 (0.5K; 0.07) \sim e^{-0.5}$

$T_1 (0.5K; 1.07) \sim e^{-0.5}$

$T_1 (1.0K; 1.07) \sim e^{-1.5}$
Liq. He Facility RCNP

- Use existing House
- Power line
- Close to the RCNP office
Mixing Chamber

1K Pot

12.20mm

600mm

170mm

400mm

Null Coil

Correction Coil

Main Coil

NbTi joints & Switch

Nb3Sn joints & Protection Circuit

Rough dimensions of the magnet

Field profile around Magnet Center

Field profile around Mixing Chamber
**Road map (5 years from 2005 fiscal year) for Studies of Hardron structures**

<table>
<thead>
<tr>
<th>Fiscal year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>After 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR, SC magnet, HD gas, IBC, TRC, others</td>
<td>92,507 kyen</td>
<td>103,000</td>
<td>103,000</td>
<td>93,000</td>
<td>93,000</td>
<td>total</td>
</tr>
<tr>
<td>IBC cryostat and new Data taking system</td>
<td>83,505</td>
<td>96,000</td>
<td>96,000</td>
<td>96,000</td>
<td>96,000</td>
<td>86,000</td>
</tr>
<tr>
<td>TPC, NMR, DR+IBC</td>
<td>total About 480,000 kyen</td>
<td>total</td>
<td>total</td>
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<td>total</td>
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<tr>
<td>SRC, New DR</td>
<td>total</td>
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<tr>
<td>Scintillator ball, TPC</td>
<td>total</td>
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</tr>
</tbody>
</table>
Summary

1. Some results from LEPS at SPring-8

3. $c_{BT}$ measurements with polarized target

\[ \gamma + p \rightarrow \phi + p \]
\[ \gamma + p \rightarrow K^+ + \Lambda, \ K^+ + \Sigma^0 \]
\[ \gamma + p \rightarrow \omega + p \]
\[ \gamma + n \rightarrow K^+ + \Sigma^- \]

4. HD at SPring-8