Developing tools for high energy spin physics experiments

*Spin flipper rf dipole magnet*

*And*

*Ultra-cold polarized Hydrogen gas jet target*

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What tools I was developing?

• Spin flipper rf dipole magnet
  – Manipulate spin direction

• Ultra-cold polarized Hydrogen gas jet target
  – Use for very high intensity beam
  – Use for polarimeter
    • p-p asymmetry by Coulomb Nuclear Interference
Ultra-cold polarize Hydrogen Gas Jet Target*

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Polarization in $p$-$p$ elastic scattering

- Leading order pQCD cannot explain this phenomenon.
  - pQCD can only predict the interaction mechanism at $|t| \& |s| \gg m^2$

- It is necessary to test pQCD theory by polarized $p$-$p$ elastic scattering.

Need highly polarized proton target at high $P_{\perp}^2$ region

(D.G. Crabb et al. PRL 65, 3241 (1990))
Advantages of Ultra-cold Polarized Atomic Hydrogen Gas Jet Target

• Highly polarized proton/electron

• Pure atomic hydrogen
  – No background in scattering experiments

• No radiation damage

• Very monochromatic beam
  – Very small spot size
  – High density compared to other gas jet target
Energy diagram of atomic hydrogen in Strong Magnetic Fields

Schematic Breit-Rabi diagram for atomic hydrogen
**Beam Formation**

**Acceleration by solenoid magnet**
\[ F \sim - \mu_e \frac{\partial B_z}{\partial z} \]

**Focusing by sextupole magnet**
\[ F \sim - \mu_e \frac{\partial B}{\partial r} \]
• **RF dissociator:**
  Produces unpolarized atomic-hydrogen

• **12T Solenoid:**
  Separates electron-polarized states

• **Separation cell:**
  Cools down atomic-hydrogen

• **Mirror:**
  Makes beam parallel

• **RF transition unit:**
  $|2\rangle$ to $|4\rangle$ transition

• **Sextupole magnet:**
  Focuses $|1\rangle$
  Defocuses $|4\rangle$

• **Catcher:**
  Cryocondensation pump
  $1.2 \times 10^7$ l/sec

• **H Maser Polarimeter:**

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**Proposed Michigan Ultra-Cold Jet**

![Diagram of the Michigan Ultra-Cold Jet](image-url)
Parabolic mirror makes hydrogen beam parallel:

- *Coated with superfluid $^4$He film to suppress depolarization and recombination of hydrogen atoms*
- *80 % mirror reflection of cold hydrogen from a helium-film-covered surface*  
  
  *(J.J. Berkhout et al. PRL 63, 1689 (1989))*
- *Beam intensity increases by a factor of 3.*
Present Test Assembly

Now being constructed and tested

RF transition unit
Maser polarimeter

(R.S. Raymond, PST Proceedings, Erlangen, Germany (1999))

Electron polarized Hydrogen gas jet target is available
Hydrogen Flow Rate vs Sextupole Magnet Current
(February 2000)

\[ I_{\text{max}} = 5.7 \text{ Amps} \]
(0.3 T on pole tip)
Compression Tube Covers

Top Cover

Bottom Cover

Holes
Ø = 1.4 mm
Rotation bottom cover

Long slot

0 mm hole (center hole)

10 mm hole
Radial Beam Distribution

$T_{\text{nozzle}} = 30 \text{ K}; \ H_2 \text{ flow} = 0.52 \text{ sccm}; \ CT \text{ angle} = 135 \text{ deg}$

(August 2002)
Film Burner assembly

Cross-sectional view of Film Burner

- Film Burner (1 of 3)
- Nozzle
- Mixing Chamber
- Bolometers
- Mirror
- Superfluid $^4$He film
- Knife Edge
CT signal vs Film Burner Voltage
(August 2003)
Long Term Hydrogen Flow Stability
(August 2002)

Average H flow = $1.3 \times 10^{15}$ H/sec

$\Rightarrow$ H thickness = $8 \times 10^{11}$ H/cm$^2$
Present status of Michigan Jet

• Basic parameters
  – *Velocity of atomic hydrogen at CT (interaction region)* \( \sim 280 \text{ m/sec} \)
  – *Electron polarization* \( \sim 100 \% \) (in high field)
  – *Proton polarization* \( \sim 50 \% \) (in low field)

• Summary of long term flow stability
  – *Average hydrogen flow* \( 1.3 \times 10^{15} \text{ H/sec} \)
  – *Average hydrogen jet thickness* \( 8 \times 10^{11} \text{ H/cm}^2 \)
  – *Longest running time* \( 18 \text{ hours} \)

• Maximum hydrogen jet thickness \( 1.1 \times 10^{12} \text{ H/cm}^2 \)
Spin-Flipping Polarized Deuterons at COSY*

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Motivation for the Research

In scattering asymmetry experiments with polarized beams in storage rings, the systematic error may be greatly reduced by frequently reversing the stored beam’s polarization direction.

Artificial rf-induced spin resonances can be used to cause such reversals, or spin-flips, in a well-controlled way.
Spin motion in an accelerator ring

- Unperturbed spin motion can be seen as precession of the spin-polarization vector around vertical fields of the ring’s dipoles.

- The number of precessions during one turn around the ring is the spin tune:
  \[ \nu_{sp} = G \gamma, \]
  - \( G \) is a gyromagnetic anomaly
  - \( \gamma \) is the Lorentz energy factor.

- Horizontal rf magnetic fields can cause a spin resonance whenever the rf field’s frequency \( f_{rf} \) is correlated with the spin precession frequency as:
  \[ f_{rf} = f_c(k \pm \nu_{sp}), \]
  - \( f_c \) is a circulation frequency
  - \( k \) is an integer.
The Idea of Spin-Flipping

The final vector polarization of the beam $P_f$, after an adiabatic linear crossing of an isolated spin resonance, is given by the Froissart-Stora formula:

$$P_f = P_i (2e^{-\frac{\pi|\varepsilon|^2}{2\alpha}} - 1)$$

where $P_i$ is the initial vector polarization, $\varepsilon$ is the resonance strength, and $\alpha$ is the resonance crossing rate:

$$\alpha = \frac{1}{2\pi f_c^2} \frac{df_{rf}}{dt}$$

In the extreme case of a strong resonance and a low crossing rate, one has:

$$\frac{\pi |\varepsilon|^2}{2\alpha} >> 1.$$ 

Then $P_f \approx -P_i$; thus the polarization is flipped by $180^0$ with almost no depolarization.

The spin-flip efficiency is defined as:

$$\eta = \frac{-P_f}{P_i}$$
Concept sweeping frequency

Resonance

Single spin flipping
## Properties of particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>( G )</th>
<th>( \mu )</th>
<th>( \mu_B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>( 1.1597 \times 10^{-3} )</td>
<td>( 1.0011597 \mu_B )</td>
<td>( 5.79 \times 10^{-11} \text{ MeV/T} )</td>
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<tr>
<td>Proton</td>
<td>( 1.7928 )</td>
<td>( 2.7928 \mu_N )</td>
<td>( 3.15 \times 10^{-11} \text{ MeV/T} )</td>
</tr>
<tr>
<td>Deuteron</td>
<td>( -0.14299 )</td>
<td>( 0.8574 \mu_N )</td>
<td>( 3.15 \times 10^{-11} \text{ MeV/T} )</td>
</tr>
<tr>
<td>Muon</td>
<td>( 1.1659 \times 10^{-3} )</td>
<td>( 1.0011659 \mu_B )</td>
<td>( 2.80 \times 10^{-13} \text{ MeV/T} )</td>
</tr>
</tbody>
</table>
The measured radial proton polarization at 120 MeV is plotted against the number of spin flips. The measured spin-flip efficiency is $99.93 \pm 0.02\%$. [1,2]

The efficiency of spin-flipping the electron beam at 669.2 MeV is plotted against the rf dipole’s ramp time $\Delta t$. The measured spin-flip efficiency is $94.5 \pm 2.5\%$. [3]

Spin-flipping the vector and the tensor polarization of 270 MeV deuterons. The vector and tensor polarization are each measured, and are then plotted against the rf solenoid’s ramp time $\Delta t$. Note that both are flipped, but at different $\Delta t$ values. [4]

The measured vector and tensor deuteron polarizations at 270 MeV are plotted against the number of frequency sweeps. The measured vector polarization spin-flip efficiency is $94 \pm 1\%$. [4]

What’s happen for higher $\gamma$ Deuteron beam?
Polarization of a Beam of Spin-1 Deuterons

• A spin-1 particle has three possible spin states \( |P_z\rangle \) along the vertical axis: \( |+1\rangle, |0\rangle, |-1\rangle \).

• The degree of vector polarization is given by

\[
P_z = \frac{N_+ - N_-}{N_+ + N_0 + N_-}.
\]

• The degree of tensor polarization is given by

\[
P_{zz} = 1 - \frac{3N_0}{N_+ + N_0 + N_-},
\]

where \( N_+, N_0 \) and \( N_- \) are the number of particles in the \( |+1\rangle, |0\rangle, \) and \( |-1\rangle \) states.

• To reduce the systematic error we normally cycled COSY’s deuteron source through the four vertical polarization states:

\[ |P_z P_{zz}\rangle \text{ of } |11\rangle, |-11\rangle, \frac{1}{3} |-1\rangle, \text{ and } -\frac{2}{3} 0\rangle. \]
• Momentum of deuterons was 1.85 GeV/c.
• RF dipole magnet was installed around the Fast Quadrupole magnet.
• We used EDDA as the polarimeter.
• We monitored the injected polarization with the Low Energy Polarimeter.
COoler-SYNchrotron COSY
COSY ABS polarized H⁻/D⁻ ion source
COSY ABS polarized $\text{H}^-/\text{D}^-$ ion source
EDDA polarimeter

- two-layered cylindrical scintillator structure
  - Outer Layer (→ trigger!)
    D: 32 overlapping slabs of triangular cross-section
      \( \Delta \phi = 11.25^\circ \)
    F,R: 2x29 semirings \( \Delta \theta_{\text{lab}} = 2.5^\circ \)
    left semirings \( \phi \in [-90^\circ, 90^\circ] \)
    right semirings \( \phi \in [90^\circ, 270^\circ] \)
  - Inner Layer (H): 640 scintillating fibers
    \( \rightarrow \) vertex reconstruction (\( \sigma \approx 1\text{mm} \))
- Acceptance: \( \theta_{\text{lab}} \in [10^\circ, 72^\circ] \)
- Targets: \( \text{CH}_2 \) and C fiber targets, polarized H and D atomic beam target.
EDDA Polarimeter
COSY RF Dipole Magnet

- $\int B \cdot dl = 0.2 \, T \cdot mm$
- Air-core type
- Ceramic vacuum tube
Resonance frequency search

- Resonance frequency: $f_r = 916.85$ kHz
- Frequency deviation: $\Delta f = \pm 50$ Hz
- Time deviation: $\Delta t = 19$ sec
Resonance mapping with fixed frequency

$f_r = 916.85 \text{ kHz}$
Measured Asymmetry vs $\Delta t$

$\Delta f = \pm 50$ Hz
$P_f / P_i$ vs $\Delta t$

$\Delta f = \pm 50$ Hz

$P_f / P_i$ vs $\Delta t$ (sec)

$\Delta f = \pm 50$ Hz
Average $P_f/P_i$ vs $\Delta t$

$\Delta f = \pm 50$ Hz

$P_f/P_i = (1 + \eta_{\text{max}}) \exp\left[-\left(\frac{\pi \varepsilon f_c}{\Delta f}\right)^2 / \left[\frac{\Delta f}{\Delta t}\right]\right] - \eta_{\text{max}}$

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Error</th>
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<tr>
<td>$(\pi \varepsilon f_c)^2 / \Delta f$</td>
<td>0.01150</td>
<td>0.00018</td>
</tr>
<tr>
<td>$\eta_{\text{max}}$</td>
<td>0.4796</td>
<td>0.0075</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>48.29</td>
<td>NA</td>
</tr>
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</table>
Concept sweeping frequency

Resonance

Multiple spin flipping
Spin-flip efficiency vs Frequency range

$\Delta t = 400 \text{ sec}$
Conclusion

• Deuteron spin-flip efficiency at maximum RF power was about 48 ± 2 %.

• We plan to add a ferrite box to the RF magnet
  - should increase the RF magnetic field by almost 50 %.

• We plan to increase the maximum RF power by using cooling water in the coils
  - should allow further increase of the RF magnet field.