Development of a Polarized $^3$He Beam Source for RHIC with EBIS

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for the BNL–MIT Polarized He3 Ion Source Collaboration

Laboratory for Nuclear Science

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Outline

1. Source Design
   - Electron Beam Ion Source
   - MEOP $^3$He Polarization
   - Depolarization Effects

2. Gas Transfer Test Design
   - Magnetic Shielding
   - Test Polarization System
   - Transfer Path

3. Current Progress
   - New Discharge Polarimeter
   - MIT Lab Setup
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Why a Polarized Helium 3 Source?

- Polarized DIS crucial for study of nucleon spin structure
  - Measurements of PPDFs; tests of QCD, Bjorken sum rule; exploration at higher energies
- Targets have proton and neutron surrogates (H, D, $^{3}$He)
- Polarized neutron beam for polarized DIS needed as an Electron Ion Collider becomes new focus
  - Deuterium has small magnetic moment: tough
  - $^{3}$He has a magnetic moment close to the free neutron, will work with RHIC spin manipulation
- Polarized $^{3}$He ions offer a polarized neutron beam for RHIC and a future eRHIC
- Workshop on Opportunities for Polarized He-3 in RHIC and EIC (2011)
History of $^3$He Ion Sources

- Rice University, 1969: MEOP for $^3$He$^+$
  - 16 keV, 8 particle $\mu$A at 11% polarization
- Univ. of Birmingham, 1973: Lamb Shift for $^3$He$^{++}$
  - 29 keV, 50 particle $\mu$A at 65% polarization
- Laval University, 1980: Stern-Gerlach for $^3$He$^+$
  - 12 keV, 100 particle nA at 95% polarization

Our Proposal\(^1\)

- RHIC’s **Electron Beam Ion Source** Preinjector
  - Proven in recent RHIC runs, NASA Space Radiation Lab
- Metastability Exchange Optical Pumping
- Doubly ionize $^3$He$^{++}$ for injection

\(^1\)A. Zelenski, J. Alessi, ICFA Newsletter (2003).
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Source Design Goals

- Polarize to $\sim 70\%$ at 30 G & 1 torr with 10 W laser
- Transfer $\sim 10^{-14} \, ^3\text{He}/s$ to EBIS at 5 T & $10^{-7}$ torr
- Deliver $1.5 \times 10^{11} \, ^3\text{He}^{++}$ ions per 20 $\mu$sec pulse
RHIC’s Electron Beam Ion Source
RHIC’s Electron Beam Ion Source

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm^2 Current Density
- Any species, switch between species in 1 sec
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**Figure 4.** (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.
RHIC’s EBIS Performance

- EBIS has provided He$^{2+}$, Ne$^{5+}$, Ar$^{10+}$, Fe$^{20+}$, and Ti$^{18+}$ for NASA’s SRL
- For RHIC run supplied U$^{39+}$, and both Au$^{32+}$ and Cu$^{11+}$ with rapid switching$^2$
- Capable of $^3$He $\Rightarrow$ $^3$He$^{++}$ at nearly 100%

$^2$Alessi, Beebe, Pikin: BNL-94248-2011-CP and BNL-98867-2013-CP
3He Polarization

- EBIS has done much of the work for us!
- Need polarized 3He; pure sample for injection
- Revisit MEOP technique\(^3\) with modern lasers

Metastability Exchange Optical Pumping

- Mature technique: polarized targets, medical imaging\(^4\)
- Laser technological advances give 10 W @ 1083 nm easily
- Polarize at \(\approx 1\) torr, \(\approx 30\) G (Higher possible)
- Pure 3He sample, faster than SEOP

\(^4\)Kauczor et al. JMRI, 7 (1997).
MEOP Mechanism

$2^3P_0$  

CP Laser 1083 nm

$2^3S_1$  

RF Excitation (~1 ppm)

$1^1S_0$  

F=1/2

$\nu_F = -3/2$

Equal Probability Decay

Net Polarization

Metastability Exchange
Depolarization Contributions

- **Wall Bounces**
  - 3 mm long, 0.1 mm diameter leak: 1 torr to $10^{-7}$ torr
  - 1 m long, 2 mm diameter tube: $\approx 10^6$ bounces, $\approx 1$ msec
  - Negligible depolarization with glass walls

- **Magnetic field gradients from EBIS stray field**
  - Hinder Polarization
  - Depolarization During Transport to EBIS

- **Small Contributions During Ionization:**
  - Charge Exchange: $^3\text{He}^+ + ^3\text{He}^{++} \rightarrow ^3\text{He}^{++} + ^3\text{He}^+$
  - Recombination: $e^- + ^3\text{He}^{++} \rightarrow ^3\text{He}^+$
  - Spin Exchange from Beam
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Depolarization from Field Gradients

From Schearer\textsuperscript{5}, we have:

\[
\frac{1}{\tau} = \frac{2}{3} \frac{|\Delta B_t|^2}{|B_l|^2} \langle v^2 \rangle \frac{\tau_c}{\omega_0^2 \tau_c^2 + 1}
\]

- Transverse gradient $\Delta B_t$
- Holding field $B_l$
- Velocity $v$
- Average time between collisions $\tau_c$
- Resonant frequency $\omega_0$

We can map regions of stray field which should be problematic, but a full-scale test of the source with test solenoid is planned.

\textsuperscript{5}Schearer, Walters, Phys. Rev. 139(5A) (1965).
Relaxation Time in EBIS B field

- Avoiding dark spots will minimize spin relaxation
Depolarization After Entering EBIS

- Simulation by E. Mace
- Number of Bounces before:
  - Trapped
  - Absorbed in wall
  - Exit cylinder
- No particles bounces more than 35 times
- Expect $10^3$ bounces before depolarization
Polarimetry

- Gas Polarization Measurements
  - RF discharge polarimeter\(^6\): Low P, Low B
  - Probe laser absorption polarimeter\(^7\): Wide range of P, B
  - NMR: calibration with water cell
- After Extraction (10-20 keV)
  - Lamb-shift polarimeter\(^8\)
- After RFQ and Linac (\(\sim\) 6 MeV)
  - \(^3\)He–C Foil\(^9\), calibration using:
  - \(^3\)He–\(^4\)He polarized elastic scattering\(^{10}\)

\(^{10}\) Plattner, Bacher, Phys. Letters (1971).
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Polarization and Relaxation Test

- What polarization relaxation do we expect during transfer from pumping cell, through stray field, to EBIS?
- Perform gas transfer to test solenoid following same route
  - **But**: Polarization measurement at $10^{-7}$ torr is difficult

### Polarization Relaxation in Transfer at 1 torr

- Pumping cell and test cell at same pressure, gas exchange via diffusion (worse depolarization than molecular flow)
- Estimate polarization in test cell from discharge polarimetry in pumping cell, observing rates of relaxation
- Secondary polarization measurement in test cell with optical probe and electrical discharge
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Testing Depolarization in Transfer to EBIS
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$^3$He Depolarization Transfer Test Setup

- Allows simple test of quantities we need to study
  - Polarization performance in shielded pumping cell
  - Relaxation in transfer into and inside solenoid
- Works if diffusion time is shorter than relaxation time

Relaxation rate measurements from pumping cell:
- Discharge off, pumping off
- Discharge on, pumping off
- Polarization destroyed with transverse field →

Direct measurements:
- Discharge on in test cell, optical probe laser

C.E. Jones et al. $^3$He(e,e') Quasielastic Asymmetry, Phys. Rev. C, 47 (1993).
Optical Probe Polarimetry
Possible secondary polarization measurement for solenoid cell.

- Optical absorption technique\textsuperscript{11,12} good at high field

- Sweep probe laser through two $2^3S - 2^3P$ transitions

- For common spin temperature $1/\beta$ between metastable and ground state atoms: $P = \frac{e^\beta - 1}{e^\beta + 1}$

- $\beta$ can be deduced from ratio of absorption signals

Optical Probe Polarimetry

Possible secondary polarization measurement for solenoid cell.

- Optical absorption technique\textsuperscript{11,12} good at high field

**Technique Benefits**

- No calibration required
- Can be performed at high, static B field
- High accuracy, signal-to-noise

Polarizing in Stray Field

- Potential sites for our polarizer reside within the solenoid’s 10 G line
- Stray field gradients unsuitable for longer time scales needed to polarize
- In region of polarizing cell, correction necessary: correcting coil, or shield and additional magnet
- Aim for better than 0.03 G/cm in our 30 G holding field
Magnetic Shielding for Pumping Cell

- Soft steel magnetic shield designed by Brookhaven collaborators (Gu, Pikin)
- Simulated in Opera
- Settled on 1/4 inch thick soft steel cylindrical shell
- 3 cm clearance around Helmholtz coils
- Better than $10^{-4}$ field uniformity in cell region
- Tested several extensions to reduce gradients as transfer line exits shielding
Magnetic Shield and Test Stand Design (Farrell)
Helmholtz Pair Magnet

- Weak magnetic field needed
- Uniformity better than $10^{-4}$ to ensure long relaxation time in pumping cell
- Open access for discharge polarimeter, flexibility
- 30 G, 30 cm Helmholtz pair chosen
Glass Design

- Pumping cell inside shielding
- Test cell inside 5 T solenoid, longer path for absorption probe polarimeter
- 100 cm³ > transfer line 4 mm ID
Transfer Path Relaxation Studies

- Investigating possible paths into EBIS with solenoid field map, calculating relaxation time at each point

- Algorithm compromises between relaxation time and transfer length to pick next step in path

- Average inverse relaxation times to qualify path

- Two transfer lines to be made for upcoming test
  - “Best” case, avoiding depolarization
  - Real case, following EBIS feed-throughs

(Color scale in seconds)
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Liquid Crystal Based Discharge Polarimeter

- Nuclear polarization proportional to circular polarization of 668 nm discharge light\textsuperscript{13}
  - Historically measured via light intensity with linear polarizer, rotating 1/4 wave plate. For angle off axis $\theta_m$:
    \[
    M_c = \frac{1}{2 \cos \theta_m} \frac{\text{AC amplitude}}{\text{DC offset}}
    \]

- Advent of nematic liquid crystals offer variable wave plates for light polarimetry\textsuperscript{14} with msec switching times
  - Obviates need for noisy motor and lock-in amplifier
  - Directly observe 1/4, 3/4 wave plate intensities
    \[
    M_c = \frac{1}{\cos \theta_m} \frac{I_{3/4} - I_{1/4}}{I_{3/4} + I_{1/4}}
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Polarimeter Design from Off-the-shelf Parts

- LCR with voltage controller (2 kHz)
- Linear polarizer
- Bandpass filters (10 W of laser light to avoid)
- Rotation mounts for alignment
- Photodiode
  - Extreme sensitivity for discharge light after loss to filters
  - Femtowatt photoreceiver eventually selected
  - Si based photodiode with very high gain and low noise, sacrificing bandwidth (20 Hz)
Polarimeter Performance

- Must subtract small offsets due to ambient light, laser light (sub 1%)
- Time resolution of measurement dependent on LCR switching time
  - Typically 110 msec to switch down to 1/4 wave
  - 60 msec to switch to up to 3/4 wave
- Measures several times a second
- “Warm-up” time, after which voltage calibration should be redone
- Working to tighten error, which is mostly from electronic noise
MIT $^3$He Lab Equipment Tests

- Keopsys 10 W, 1083 nm fiber laser
  - Circularly polarizing, beam expansion
- 30 cm Helmholtz coil magnet
  - 30 G at 16.5 A
  - Independently powered coils
- Agilent 250 l/s compact turbopump
  - Instrutech ion and convection gauges
  - Inficon RGA
- NI USB-6259 BNC
- Discharge polarmeter (Thorlabs)
- Custom glassware (Finkenbeiner)
- Bake-out with heat tape, Omega thermocouple scanner
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MIT $^3$He Lab
DAQ Software

Nuclear Polarization  Optical Polarization

791.7%  99%
DAQ Software

Nuclear Polarization: 1.2%
Optical Polarization: 0.2%
First Polarization Results

- New sealed cell, no getters, moderate bake-out
- 2 s build-up, 20 s relaxation time (discharge on)
Looking forward

- Polarizing in the lab: plenty of power, we now need purity.
- Plan to move polarizer to Brookhaven in the next couple months to start depolarization tests.
- Spare EBIS solenoid undergoing minor refurbishment, will become available in this timeframe.
- Hope to finish initial depolarization in transfer tests by end of year.
- Next: Transfer into and ionization in EBIS.
  - Polarization measurement after extraction: Lamb-shift? He3–He4 elastic scattering?
BNL–MIT Pol He3 Source Collaboration:

- Brookhaven National Laboratory
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