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

J. Maxwell

for the BNL–MIT Polarized He3 Ion Source Collaboration

International Workshop on Polarized Sources, Targets & Polarimetry
September 16th, 2015
Outline

1. Source Design
   - Electron Beam Ion Source
   - MEOP $^3\text{He}$ Polarization
   - Depolarization Effects
2. Polarization and Relaxation Tests
   - MIT Lab
   - Stray Field Tests
   - High Field Tests
3. Next Steps
Why a Polarized Helium 3 Source?

- Polarized DIS crucial for study of neutron spin structure
  - PPDFs; tests of QCD, Bjorken sum rule; higher energies

<table>
<thead>
<tr>
<th>State</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>88.6%</td>
</tr>
<tr>
<td>S’</td>
<td>1.5%</td>
</tr>
<tr>
<td>D</td>
<td>8.4%</td>
</tr>
</tbody>
</table>

- S-state $^3$He: nuclear spin carried by the neutron
- $^3$He’s magnetic moment close to n, compatible with RHIC spin manipulation
- Polarized $^3$He ions offer a “polarized neutron beam” for RHIC and a future EIC
Polarized $^3$He at RHIC

- $^3$He's anomalous $g$-factor is larger than $p$: more & stronger resonances
- Need 6 siberian snakes per ring$^1$

---

$^1$Bai, Courant et al., BNL-96726-2012-CP, 2012.
Polarized $^3\text{He}$ at RHIC

- $^3\text{He}$’s anomalous $g$-factor is larger than $p$: more & stronger resonances
- Need 6 siberian snakes per ring\(^1\)

\(^1\)Bai, Courant \textit{et al.}, BNL-96726-2012-CP, 2012.
Outline

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

2. **Polarization and Relaxation Tests**
   - MIT Lab
   - Stray Field Tests
   - High Field Tests

3. **Next Steps**
History of $^3$He Ion Sources

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

Our Proposal

- 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

---

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$^2$

- 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

Source Design Goals

- Polarize to $\sim 70\%$ at 1 torr with 10 W laser
- Transfer $\sim 10^{14} \text{ } ^3\text{He}/s$ to EBIS at 5 T & $10^{-7}$ torr
- Deliver $1.5 \times 10^{11} \text{ } ^3\text{He}^{++}$ ions per 20 $\mu$s 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
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/cm² Current Density
- Any species, switch between species in 1 sec

![Diagram of electron beam ion source](image)

**Figure 4.** (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.
EBIS Beams Run to Date

D, $^3\text{He}^{2+}$, $^4\text{He}^{1+}$, $^2+$, Li$^3+$, C$^5+$, O$^7+$, Ne$^5+$, Al$^5+$, Si$^{11+}$, Ar$^{11+}$, Ca$^{14+}$, Ti$^{18+}$, Fe$^{20+}$, Cu$^1+$, Kr$^{18+}$, Xe$^{27+}$, Ta$^{38+}$, Au$^{32+}$, Pb$^{34+}$, U$^{39+}$. Capable of $^3\text{He} \Rightarrow ^3\text{He}^{++}$ at nearly 100%


**3^He Polarization**

- EBIS has done much of the work for us!
- Need polarized $^3$He; 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 or higher
- Pure $^3$He sample, faster than SEOP

---


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

\[ 2^3P_0 \rightarrow 1/2 \quad m_F = -3/2 \]

CP Laser 1083 nm

\[ 2^3S_1 \]

RF Excitation (~1 ppm)

\[ 1^1S_0 \rightarrow F=1/2 \]

\[ 1/2 \]

\[ -1/2 \]

\[ 1/2 \]

\[ 3/2 \]

C_8, C_9

\[ \sigma^+ \]

Equal Probability Decay

Net Polarization

Metastability Exchange

PSTP, Sept 16, 2015
Depolarization Contributions

• Wall Bounces
  • 3 mm long, 0.1mm diameter leak: 1 torr to \(10^{-7}\) torr
  • 1m long, 2mm 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
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
Depolarization Contributions

- **Wall Bounces**
  - 3 mm long, 0.1mm diameter leak: 1 torr to $10^{-7}$ torr
  - 1m long, 2mm 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
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.

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

Map in mm of Transverse Field Gradient
Calculating Relaxation Time in EBIS B field
Calculating Relaxation Time in EBIS B field

Map in mm Relaxation Time ($< 10^{-2}$ torr)
Two Design Options: Low or High Field?

- Two design possibilities present themselves:
  - Polarize at 30 G in EBIS stray field using field correction, then transfer into EBIS
  - Polarize in EBIS, or nearby, extending field region
Outline

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

2. Polarization and Relaxation Tests
   - MIT Lab
   - Stray Field Tests
   - High Field Tests

3. Next Steps
MIT Test Lab

- Magnet, vacuum, laser setup
- 70% polarization achieved
- Allows flow of polarized gas between cells
- Observe polarization diffusion through region of depolarizing gradients\(^6\)
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development\(^7\)

\(^6\) Maxwell, Epstein, Milner, NIM A (777), 2015.
\(^7\) Maxwell, Epstein, Milner, NIM A (764), 2014.
Transferring between B Fields via Diffusion
Relaxation Time Map, Helmholtz and Solenoid
Polarization Transfer via Diffusion

Polarization measured via discharge light in each cell
Relaxation in Both Cells

Fits roughly match relaxation & diffusion model of 2 cells, line...
BNL Test Polarizer

- Polarizer on movable stand
- EBIS 5 T spare solenoid
- Allows polarization at any location in the stray field
- Initial polarization tests with NO field correction
- 30 G solenoid allows small increase of $B_l$
- Tested at two locations on axis of solenoid, one off axis
Stray Field Results

- Spare solenoid at 1 T
- Polarizing sealed cell, which attained 50% in 30 G solenoid
- At location of interest in stray field:
  - Only stray field, 17% with ∼0.5 A pump
  - Only stray field, 28% with ∼10 A pump
  - 6 second relaxation, matches calculation nicely
  - Adding 30 G holding field improves as expected
Low Field Conclusions Thus Far

- Transfer of polarized gas at 1 torr matches calculations
- Polarization and relaxation in the EBIS stray field with no magnetic shielding also agree
- Trusting these calculations, a path into EBIS through the stray field exists in which the path averaged relaxation time is around 0.7 sec (0.01 torr)

Low Field Source with MEOP and EBIS is feasible

- But not necessarily easy or optimal
- Battle must be fought with the stray field both to polarize and to transfer, compromising the achieved polarization, however little
Low Field Conclusions Thus Far

- Transfer of polarized gas at 1 torr matches calculations
- Polarization and relaxation in the EBIS stray field with no magnetic shielding also agree
- Trusting these calculations, a path into EBIS through the stray field exists in which the path averaged relaxation time is around 0.7 sec (0.01 torr)

Low Field Source with MEOP and EBIS is feasible

- But not necessarily easy or optimal
- Battle must be fought with the stray field both to polarize and to transfer, compromising the achieved polarization, however little
MEOP at High Magnetic Field

• European group (Paris, Krakow) researching high pressure MEOP, medical applications

• Pioneering achievements in pumping efficiency at high pressures leveraging fields above 1 T in last ten years

• M. Abboud, Europhys. Lett. 68, 2004
  - 1.5 T; 0.5, 2 W OP laser
  - 1.3, 8, 32, 67 mbar
  - Circles and stars are at 1.5 T, others at low field
MEOP at High Magnetic Field

- European group (Paris, Krakow) researching high pressure MEOP, medical applications
- Pioneering achievements in pumping efficiency at high pressures leveraging fields above 1 T in last ten years

  - 4.7 T, 0.5 W OP laser
  - 1.3, 32, 67, 96, 128, 267 mbar
  - Noted trouble with RF for 1 torr cell
BNL High Field Tests

- EBIS spare solenoid at 1, 2, 3, and 4 T
- Low field polarimetry technique not effective above 10 mT
- High-field polarimetry with low power probe laser
  - AM on discharge for lock-in detection
- Sealed cells at 1 torr with two cell geometries
  - 5 cm OD, 5 cm long
  - 3 cm OD, 10 cm long
Optical Probe Polarimetry

- High or low field, no calibration required
- Sweep low power probe laser through two $^{23}S-^{23}P$ transitions to directly probe states$^8,^9$

---

Optical Probe Polarimetry

• High or low field, no calibration required
• Sweep low power probe laser through two $2^3S - 2^3P$ transitions to directly probe states\textsuperscript{8,9}

Measuring Optical Pumping
Measuring Optical Pumping

Probe Laser Absorption Peaks at Zero and High Polarization

*M = 0*

*M = 0.89*

Preliminary
High Field Polarization Results

- Error set at 10% while measurement is investigated
Thoughts on Probe Measurement Error

- Intense probe can cause over-estimation of polarization
- Talbot: as much as 5% at $M=0\%$ and 1% at $M=10\%$

$$M(r/r_0) = \frac{r/r_0 - 1}{r/r_0 + 1}, \quad \sigma_M(r/r_0) = \frac{2\sigma_{r/r_0}}{1 + (r/r_0)^2}$$
High Field Conclusions Thus Far

- First results for MEOP at 3, 4 T and 1 torr, to near 90%
  - With discharge off, $T_1 = 2.7$ hours
- Not only is this possible but it’s easy!
  - Cell which we struggled to get to 70% at 30 G reach over 80% at high field
  - Field uniformity a given at high field

High polarizations from MEOP over 1 T

- At high field, OP and ME both still work
- Zeeman splitting reduces electron-nucleus spin coupling for polarization, but also inhibits relaxation channels (such as 668 nm line used for low field measurement)
- Transition split allows pumping just one state with laser
High Field Conclusions Thus Far

- First results for MEOP at 3, 4 T and 1 torr, to near 90%
  - With discharge off, $T_1 = 2.7$ hours
- Not only is this possible but it’s easy!
  - Cell which we struggled to get to 70% at 30 G reach over 80% at high field
  - Field uniformity a given at high field

High polarizations from MEOP over 1 T

- At high field, OP and ME both still work
- Zeeman splitting reduces electron-nucleus spin coupling for polarization, but also inhibits relaxation channels (such as 668 nm line used for low field measurement)
- Transition split allows pumping just one state with laser
Outline

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

2 Polarization and Relaxation Tests
   MIT Lab
   Stray Field Tests
   High Field Tests

3 Next Steps
Looking forward

- To corroborate probe polarimeter results, NMR system has been built, under initial tests
- We can polarize near EBIS operating fields, avoiding the transfer through depolarizing gradients
  - High field source design offers best chance of success
- High field source is under initial design process by BNL collider and accelerator team
- Preliminary plan for magnet construction, spare solenoid reinforcement, low energy polarimetry and test
  - Estimated 3-4 years until test source operational and swap with EBIS can be performed
Looking forward

- To corroborate probe polarimeter results, NMR system has been built, under initial tests
- We can polarize near EBIS operating fields, avoiding the transfer through depolarizing gradients
  - High field source design offers best chance of success
- High field source is under initial design process by BNL collider and accelerator team
- Preliminary plan for magnet construction, spare solenoid reinforcement, low energy polarimetry and test
  - Estimated 3-4 years until test source operational and swap with EBIS can be performed
High Field Source Design: EBIS Upgrade

- New solenoid-injector section will improve EBIS operation with all gases, allow polarized $^3$He$^{++}$
- Lengthened ion trap brings increased heavy ion yield
- Test can be built and tested without affecting EBIS operation: goal $> 80\%$ polarization $^3$He$^{++}$ beam
Polarized $^3$He Source for JLab MEIC?

- Two EIC candidates, eRHIC and MEIC
- JLab does not have EBIS
- Revisit Rice source$^{10}$ with modern techniques

$^{10}$Baker, PRL 20, 14 (1968)
BNL–MIT Pol He3 Source Collaboration:

- Brookhaven National Laboratory
- MIT Laboratory for Nuclear Science
  - C. Epstein, J. Maxwell, R. Milner
  - Bates technical support

We gratefully acknowledge the advice of
- P.J. Nacher, G. Collier

Work supported by
- DOE Office of Nuclear Physics, R&D for Next Generation Nuclear Physics Accelerator Facilities
- MIT Department of Physics
Thanks for your attention!
Next Steps

Development of a Polarized $^3$He Beam Source
Maintaining Polarization in a Circular Collider

- Spinor precesses as bent in B field
- Depolarizing resonances
  - Spin precession frequency = frequency of perturbing B field
  - Imperfection: $\nu_s = G\gamma = n$
  - Intrinsic: $\nu_s = G\gamma = Pn + \nu_y$
  - Anomalous $g$-factor $G$
  - Resonances for p in RHIC
- Siberian Snakes to the rescue
  - Rotate spin 180°, allow the wobble to unkink itself
  - Partial snakes can be used for some imperfections

---

Maintaining Polarization in a Circular Collider

- Spinor precesses as bent in B field
- Depolarizing resonances
  - Spin precession frequency = frequency of perturbing B field
  - Imperfection: \( \nu_s = G\gamma = n \)
  - Intrinsic: \( \nu_s = G\gamma = Pn + \nu_y \)
  - Anomalous \( g \)-factor \( G \)
  - Resonances for p in RHIC\(^{11}\)
- Siberian Snakes to the rescue
  - Rotate spin 180°, allow the wobble to unkink itself
  - Partial snakes can be used for some imperfections

\(^{11}\)Bai, Courant et al., BNL-96726-2012-CP, 2012.
RHIC Spin Manipulation

Absolute Polarimeter (H↑ jet) → RHIC pC Polarimeters

Siberian Snakes

PHENIX

Spin Rotators

STAR

Spin Rotators

Pol. H⁻ Source → LINAC → BOOSTER → AGS

200 MeV Polarimeter

Strong AGS Snake

Helical Partial Siberian Snake

AGS pC Polarimeter

Next Steps Development of a Polarized $^3$He Beam Source
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)
Constraints on Path into EBIS
Constraints on Path into EBIS
Constraints on Path into EBIS
Test of Polarization Diffusion Measurement

\[
\begin{pmatrix}
\dot{P}_p(t) \\
\dot{P}_t(t)
\end{pmatrix}
= 
\begin{pmatrix}
- \left( \frac{1}{\tau_p} + \frac{N_t}{N} \frac{1}{t_{ex}} \right) & \frac{N_t}{N} \frac{1}{t_{ex}} \\
\frac{N_p}{N} \frac{1}{t_{ex}} & - \left( \frac{1}{\tau_t} + \frac{N_p}{N} \frac{1}{t_{ex}} \right)
\end{pmatrix}
\begin{pmatrix}
P_p(t) \\
P_t(t)
\end{pmatrix}
\]

- 5 variables describe system (initial pols, decays, transfer)
- Solution is sum of two exponentials
- Relate to 4 fit parameters of measured relaxation curve

\[
P_p(t) = a_s e^{-t/\tau_s} + a_l e^{-t/\tau_l}
\]