Development of a Polarized $^3$He$^{++}$ Ion Source for the EIC

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Why a Polarized $^3$He Ion 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
Source Concept


Requirements

• Polarized $^3$He using optical pumping and injection into EBIS at 5 T
• Maximum polarization >70%
• Intensity $2.5 \times 10^{11} \; ^3$He++ ions in 20 $\mu$s pulse (~4 mA peak current)
• Spin-flip in the beam transport line
History of Polarized $^3$He Ion Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Current</th>
<th>Polarization</th>
<th>Emittance</th>
<th>Beam Energy</th>
<th>Energy Spread</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birmingham</td>
<td>50 pnA</td>
<td>55-65%</td>
<td>70 mm mrad.</td>
<td>29 keV</td>
<td>100 eV</td>
<td>$^3$He$^{++}$</td>
</tr>
<tr>
<td>Laval</td>
<td>100 nA</td>
<td>95%</td>
<td>25 mm mrad.</td>
<td>12 keV</td>
<td></td>
<td>$^3$He$^+$</td>
</tr>
<tr>
<td>Rice/Texas A&amp;M</td>
<td>8 µA</td>
<td>11%</td>
<td>10 mm m/M eV$^{1/2}$</td>
<td>16 keV</td>
<td>10-50 eV</td>
<td>$^3$He$^+$</td>
</tr>
</tbody>
</table>

- No new operational $^3$He ion sources were built since 1984. A number of new ideas were proposed and tested (not successfully).
- Spin-exchange and metastability-exchange optical pumping techniques for $^3$He polarization were greatly improved due to laser development and new applications.
• 5T solenoid B Field; 1.5 m ion trap
• 20 keV electrons up to 10 A
• 5 Hz maximum repetition rate
Principle of EBIS Operation

- Radial trapping of ions by the space charge of the electron beam
- Axial trapping by applied electrostatic potentials at ends of trap
- Ion output per pulse is proportional to the trap length and electron current
- Ion charge state increases with increasing confinement time
- Output current pulse is independent of species or charge state

\[ C = \frac{I}{e} \times l \times \sqrt{\frac{m_e}{2E}} \]
Extended EBIS Upgrade

- Add a second 5 T superconducting solenoid for trap length extension: 40% increase in Au intensity
- Install $^3$He polarization and injection system into the upstream solenoid
- Opportunity for various vacuum and other minor improvements
• 5.0 Tesla field, about 1.0 Tesla at field minimum in solenoid separation (~30 cm)
• Electron beam successfully propagated through both solenoids in May 2019.
Polarized $^3$He Ion Source

- 1083nm laser
- $^3$He reservoir
- Pneumatic valve
- $^3$He polarizing cell
- High speed pulsed valve
- Mirror
- Gas ionization cell
- e$^-$ gun
- e$^-$ beam
- Vacuum pump
- Differential pumping
- Ion accumulation region
- 5T solenoid
- 46 cm long, 1 cm diameter gas ionization cell
- 3 cm long, 0.5 cm diameter downstream barrier (blue)
- Electron beams of 6 Amps were successfully propagated through the assembly.
Metastability Exchange Optical Pumping

\[ 2^3P_0 \]

CP Laser 1083 nm

\[ 2^3S_1 \]

RF Excitation (~1 ppm)

\[ 1^1S_0 \]

Net Polarization

\[ m_F = -3/2 \]

\[ 1/2 \]

\[ -1/2 \]

\[ 1/2 \]

\[ 3/2 \]

\[ \sigma^+ \]

Equal Probability Decay

Metastability Exchange
RF Discharge at Multi-Tesla Fields

• RF discharge parameters strongly affect maximum polarization.

• RF discharge power needs to be reduced as $^3\text{He}$ polarization increases.

• Optimization of the $^3\text{He}$ cell geometry and placement of RF electrodes should improve polarization.
High Field MEOP System in EBIS Spare Solenoid

- $^3$He polarization measured with low power probe laser
- Operated at magnetics fields of 1, 2, 3, and 4 T
- Tested sealed cells at 1 mbar: 5cm OD by 5cm long and 3 cm OD by 10 cm long
- Tested open cell system connected to $^3$He purification system
OPPIS (RHIC’s polarized proton source) was converted into a high field MEOP system for polarizing $^3$He.
Open $^3$He Cell and Gas Purification System

$^3$He cyro-purification and storage system was built from a modified cryo-pump. Pump everything except helium!
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$^7,^8$

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Optical Probe Polarimetry

- Wavemeter
- Pumping laser
- Probe laser, Toptica, diode laser
- Detector
- ^3He cell
- Pumping laser-Keopsys 10 W 1083 nm- fiber laser
Zeeman shifting at magnetic fields of several Tesla shifts the pump lines of $^3$He.

An ideal pump laser will need to have broad wavelength tuning and a 2 GHz linewidth to match the thermal Doppler broadening of the absorption peak.
• $^3$He pressure can be controlled with the cryo-pump temperature.

• Polarizations have been measured >80% at 2 torr and higher pressures have similar results.

• Relaxation time of 30 s measured in open cell. Relaxation rate is limited by metal surfaces of the fill valve and gas contamination.

• Valve construction and open cell design will be optimized to improve relaxation rate and maximum polarization.
High Speed Pulsed $^{3}$He Valve

- Pulsed current causes valve to open by Lorentz Force to the conducting plate in high magnetic field.
- Valve design has successful long-term operation in OPPIS: $B=3$ T, $I=100$ A, $L=5$ cm, $F=15$ N, $\tau=100\mu$s.

\[ d\vec{F}_A = I\, d\vec{l} \times \vec{B} \]
High Speed Pulsed $^3$He Valve

- Test of high speed pulsed valve in a 2.5 T field in the OPPIS solenoid.
- $B = 2.5 \text{T}, I = 12 \text{ A}, \; ^3\text{He reservoir pressure} = 2 \text{Torr}$

*Actual valve open time may be longer than the electric current pulse width.*
Extended EBIS Parameters

**Timing & Trap Capacity**
- Maximum EBIS pulse time = 200 ms
- Charge Capacity = ~$10^{12}$ elementary charges
- $^3$He++ Capacity = ~$2.5\times10^{11}$ $^3$He++

**Electron Beam**
- Diameter: 1 mm
- Current: 10 Amp
- Energy: 25 keV

**Pressure**
- During gas injection: $1\times10^{-6}$ mbar
- Standard operation: $1\times10^{-10}$ mbar
### Vacuum Simulations of EBIS with MolFlow

<table>
<thead>
<tr>
<th>Timing &amp; Trap Capacity</th>
<th>Electron Beam</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum EBIS pulse time = 200 ms</td>
<td>1 mm diameter</td>
<td>1x10^-6 mbar during gas injection</td>
</tr>
<tr>
<td>Charge Capacity = (\sim10^{12}) elementary charges</td>
<td>10 Amp</td>
<td>1x10^-10 mbar standard operation</td>
</tr>
<tr>
<td>(^3\text{He}^{++}) Capacity = (\sim 2.5 \times 10^{11}) (^3\text{He}^{++})</td>
<td>25 keV</td>
<td></td>
</tr>
</tbody>
</table>

### Electronics Beam

- Diameter: 1 mm
- Current: 10 Amp
- Energy: 25 keV

### Vacuum

- Injection pressure: \(1 \times 10^{-6}\) mbar
- Standard operation pressure: \(1 \times 10^{-10}\) mbar
Electron Beam Ionization of $^3$He

For an e-beam of 25 keV there is a ≈0.5% probability that $^3$He is ionized during traverse of the e-beam.

Therefore, treat the e-beam as an ideal pump with 99.5% transparency.

\[
S = \frac{16I\sigma}{3\pi^2er_e\nu_{gas}}
\]
Proportion of $^3$He ionized after 20 ms

<table>
<thead>
<tr>
<th>Length:</th>
<th>10 cm</th>
<th>20 cm</th>
<th>30 cm</th>
<th>50 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm (0.5 cm ends)</td>
<td>0.142</td>
<td>0.263</td>
<td>0.372</td>
<td>0.537</td>
</tr>
<tr>
<td>1 cm (1 cm ends)</td>
<td>0.0556</td>
<td>0.132</td>
<td>0.224</td>
<td>0.411</td>
</tr>
<tr>
<td>2 cm (0.5 cm ends)</td>
<td>0.123</td>
<td>0.184</td>
<td>0.218</td>
<td>0.257</td>
</tr>
<tr>
<td>2 cm (1 cm ends)</td>
<td>0.0382</td>
<td>0.0695</td>
<td>0.0997</td>
<td>0.155</td>
</tr>
<tr>
<td>2 cm (2 cm ends)</td>
<td>0.0176</td>
<td>0.0355</td>
<td>0.0557</td>
<td>0.101</td>
</tr>
<tr>
<td>3 cm (0.5 cm ends)</td>
<td>0.097</td>
<td>0.121</td>
<td>0.131</td>
<td>0.141</td>
</tr>
<tr>
<td>3 cm (1 cm ends)</td>
<td>0.0349</td>
<td>0.0576</td>
<td>0.0747</td>
<td>0.0988</td>
</tr>
<tr>
<td>3 cm (2 cm ends)</td>
<td>0.0158</td>
<td>0.0278</td>
<td>0.039</td>
<td>0.06</td>
</tr>
</tbody>
</table>

\[ S = \frac{16I\sigma}{3\pi^2er_eu_{gas}} \]

- For an e-beam of 25 keV there is a $\approx 0.5\%$ probability that $^3$He is ionized during traverse of the e-beam.
- Therefore, treat the e-beam as an ideal pump with 99.5\% transparency.
Gas Diffusion and Pumping in Ionization Cell

- $6.18 \times 10^{11}$ $^3$He atoms injected
- 10 A, 25 keV e-beam
- Ionization Cell
  - 30 cm long
  - 2 cm diameter
  - 1 cm constrictions

![Graph showing pressure over time for Ionization Cell, Upstream Solenoid, and Downstream Solenoid.](attachment:graph.png)
Electron Beam Ionization of $^3\text{He}$

Step sequence | Time
--- | ---
$^3\text{He}$ gas injection | 0.5 ms
Diffusion into ionization cell | 2 ms
Injected gas pressure falls 50% | 3 ms
Ionization of $^3\text{He}$ to $^3\text{He}^+$ | $\sim$10 ms per gas injection
Time constant for $^3\text{He}^+ \rightarrow ^3\text{He}^{++}$ conversion | 1 ms
Pump down to $10^{-9}$ torr | 100-150 ms
5 Hz EBIS pulse repetition rate | 200 ms
Switching time between species | 1 second
Feasibility Experiment

• Use extended EBIS and extract fully stripped polarized $^3\text{He}^{++}$ ions accelerated to 6 MeV

• Measure $^3\text{He} + ^4\text{He} \rightarrow ^3\text{He} + ^4\text{He}$ elastic scattering

• Analyzing power has been measured to be 100% at $91^\circ_{\text{CM}}$ at $\sim 5.3$ MeV

• Process yields 2.66 MeV $^3\text{He}$ at $53.6^\circ_{\text{lab}}$ and 2.64 MeV recoil $^4\text{He}$ at $44.5^\circ_{\text{lab}}$
• 1st dipole magnet rotates $^3$He spin into the horizontal transverse plane.
• Spin-flip solenoid selectively rotates $^3$He spin into the vertical transverse plane (spin-up or spin-down).
• 2nd, 3rd, & 4th dipole magnets direct the $^3$He beam into either the 6 MeV polarimeter or back into the transport line to RHIC.
6 MeV $^3$He$^{++}$ Polarimeter Design

- Measure 2.66 MeV $^3$He at 53.6°$_{\text{lab}}$ and 2.64 MeV recoil $^4$He at 44.5°$_{\text{lab}}$ after $^3$He + $^4$He $\rightarrow$ $^3$He + $^4$He elastic scattering.
- Asymmetry of detector signals for opposite spin states will yield $^3$He polarization.

$^3$He polarimeter test setup to measure null signal asymmetry.
Summary

- Extended EBIS upgrade is ongoing and electrons were propagated through two 5 T solenoids.
- $^3$He was successfully polarized to >80% in a 3 T field.
- An optical probe polarimeter to measure $^3$He polarization was developed.
- A prototype high-speed pulsed valve has been tested.
- Gas injection & ionization simulations show promising results.
- The $^3$He spin-rotator is being designed and equipment purchased.
- The 6 MeV $^3$He polarimeter has been designed and the concept was tested with an alpha source.

Now all the parts need to be put together. We plan for partial installation in the summer of 2020 and complete installation followed by polarization measurements in the summer of 2021.
MIT-BNL Polarized $^3$He Ion Source Collaboration

This work was supported by DOE Office of Nuclear Physics, R&D for Next Generation Nuclear Physics Accelerator Facilities.
Depolarization Contributions in the Electron Beam

- Charge exchange. $^3\text{He}^+ + ^3\text{He}^{++} \rightarrow ^3\text{He}^{++} + ^3\text{He}^+$
  
  This has a cross section of $\sigma \approx 10^{-16} \text{ cm}^2$, and is thus thought to occur at a low rate.

- Recombination. $^3\text{He}^+ + e \rightarrow ^3\text{He}; ^3\text{He}^{++} + e \rightarrow ^3\text{He}^+$

  This is a 3-body process and thus thought to be unlikely. The cross section is lowered by a factor of $\alpha^2$, thus $\sigma < 10^{-20} \text{ cm}^2$

- Spin-exchange collisions. These are thought to occur at a low rate. The cross section for neutral Hydrogen spin-exchange collisions is approximately $10^{-14} \text{ cm}^2$; for $^3\text{He}$ ions it is expected to be even lower. It is expected that due to coulomb interactions, the ions will not even approach close enough for spin-exchange to occur.

See MIT Senior Thesis of Charles S. Epstein:

Development of a Polarized Helium-3 Ion Source for RHIC using the Electron Beam Ion Source , June 2013.
Measuring Optical Pumping

Probe Laser Absorption Peaks at Zero and High Polarization

\[ M = 0 \]
\[ M = 0.89 \]

Preliminary
Before purification with cryo-pump

Large contamination by H2, H2O, Hydrocarbons, Argon as seen in RGA

After purification with cryo-pump

RGA spectra very clean He signal