3He++ ion source development at RHIC
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J.Maxwell, R.Milner, LNS, MIT

3He++ polarization technique using Electron Beam Ion Source
• 3He metastability-exchange polarization in the high magnetic field
• Optical pumping, polarization measurements.
• Sealed cell
• Open cell, gas purification system
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 eRHIC
eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC including existing RHIC tunnel, detector buildings and cryo facility

Luminosity: $10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- 70% polarized protons
  - 25 - 250 (275*) GeV
- Light ions (d, Si, Cu)
- Heavy ions (Au, U)
  - 10 - 100 (110*) GeV/u
- Pol. light ions (He-3)
  - 17 - 167 (184*) GeV/u

80% polarized electrons:
- 2.6 – 21.2 GeV

Center-of-mass energy range: 20 – 145 GeV

Full electron polarization at all energies
Full proton and He-3 polarization with six Siberian snakes

Any polarization direction in electron-hadron collisions:

* It is possible to increase RHIC ring energy by 10%
3He$^{++}$ spin tracking in eRHIC with 6-snares

- 8 particles on the same betatron amplitude
- Perfect closed orbit
- No momentum spread
Requirements to the $^3\text{He}^{++}$ source

- Intensity $\sim 2 \cdot 10^{11}$ $^3\text{He}^{++}$ ions in 10 us pulse $\sim 4.0$ mA
- Maximum polarization $> 80\%$
- Spin flip every pulse
- Compatibility with the operational EBIS for heavy ion physics
- Polarimetry ?

<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 V MeV$^{1/2}$</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. A number of new ideas were proposed and tested (not successfully).

Spin-exchange and “metastability-exchange” techniques for $^3$He atoms polarization were greatly improved due to laser development and demanding applications.
Injections of $^3$He gas polarized in the external cell into EBIS.

$^3$He polarization inside the EBIS in high magnetic field. No polarization losses during beam transport through gradient magnetic field.

EBIS is used for efficient ionization and accumulation of polarized $^3$He$^{++}$ ions.
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
Radial trapping of ions by the space charge of the electron beam. Axial trapping by applied electrostatic potentials at ends of trap.

- The total charge of ions extracted per pulse is $\sim (0.5 - 0.8) \times (\# \text{ electrons in the trap})$
- 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 $\sim$ independent of species or charge state!
EBIS Beams Run to Date

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

He-3 metastability-exchange polarized cell.

Pumping laser 1083 nm.

He(2S) → He(1S)

EBIS-ionizer, $B \sim 50$ kG

2.5·$10^{11}$ He$^{++}$/pulse

He-transfer line. Valve.

~$50\cdot10^{11}$, $^3\text{He}$/pulse.
P=70-80%.
Principle of Metastability Exchange
Optical Pumping (MEOP) in $^3$He

$^3$He(↓) + $^3$He*(↑) → $^3$He*(↓) + $^3$He(↑)

optical pumping

$2^3P_0$ → $2^3S_1$ (indirect plasma excitation $n_m / N_g \approx 1$ ppm)

$1^1S_0$ (ground state)

$B \approx 10$ G  
$p \approx 1$ mbar

before
after

strong coupling by metastability exchange collisions → efficient transfer of nuclear orientation
MIT-BNL collaboration on polarized $^3\text{He}^{++}$ ion source development

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
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development

BNL Test Polarizer
- Polarizer on movable stand
- EBIS 5 T spare solenoid
- Allows polarization at any location in the stray field
- Initial results from test at 1 T with sealed cell, max 50% polarized
  - 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

$^5$Maxwell, Epstein, Milner, NIM A (764), 2014.
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Injection of polarized 3He-gas in EBIS

- Polarize to $\sim 70\%$ at 1 torr with 10 W laser
- Transfer $\sim 10^{14}$ $^3$He/s to EBIS at 5 T & $10^{-7}$ torr
- Deliver $1.5 \times 10^{11}$ $^3$He$^{++}$ ions per 20 $\mu$sec pulse
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
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 $2^3S - 2^3P$ transitions to directly probe states $^8, ^9$

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Measuring Optical Pumping

Probe Laser Absorption Peaks at Zero and High Polarization

M = 0
M = 0.89

Preliminary
Jan 18, 2016, Sealed cell-Pol.- 88%

Probe laser absorption polarimeter, J. Maxwell-2015
3He polarization in high magnetic field using 5.0 T spare EBIS solenoid at BNL, 2015

80-84 % polarization was measured in experiments with sealed 3H-cell in high magnetic field.
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
Optical pumping laser layout

- **WS6-200**
- **Pumping laser**
- **Probe laser, Toptica, diode laser**
- **Detector**

**Pumping laser** - Keopsys 10 W, 1083 nm, fiber laser
3He Laser system for optical pumping and polarization measurements
Laser wavelength and Line-width control, with wavelength meter WS6-200

276.7558 THz

1083 nm

1.2 GHz
Jan 18, 2016, Sealed cell-Pol.- 94.5%,
Probe laser controller

Pumping laser controller

RF master oscillator and amplifier
High Field Conclusions Thus Far

- First results for high field, O(100 G)
  - With discharge over 90%
- Not only is this achieved in O(100 G),
  - Cell which work over 80%
- Field uniformity over 70%

High polarizations

- At high field, O(100 G)
- 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
New “open” 3He-cell and gas system for 3He-cell preparation and filling
3He-gas purification and filling system

Non-magnetic pneumatic remotely controlled Isolation Valve: IV
He-cell valve closed, RF-33.4 MHz, Amp-0.100, He-3-1.08 torr
He-cell valve closed, RF-33.4 MHz, Amp-0.100, He-3-1.08 torr

Large contamination by H2, H2O, Hydrocarbons, Argon as seen in RGA
3He cryo- purification system built-in CTI-8 cryopump.
3He-gas purification and filling system
June 21, He-fill with CP-pumping at 45deg. K. Very clean spectra, no hydrogen 656 nm line!
Helium Spectrum, 380-900 nm

- 388 nm
- 471 nm
- 447 nm
- 492 nm
- 501 nm
- 558 nm
- 588 nm
- 616 nm
- 668 nm
- 706 nm
- 728 nm
- 778 nm
- 846 nm
3.5 torr, Isolation Valve (IV)-open
3.5 torr, Isolation Valve (IV)-closed, P=63%
“Open cell”, 3He-3.5 torr, Pol-73%
June 30, 3.0 torr, 56%, relaxation time -30 s
RF-discharge in 2.0 T magnetic field.

3He-cell diameter-25mm

RF-discharge parameters strongly affect maximum polarization. Optimization of the 3He-cell geometry (smaller diameter?) and electrodes for RF input should improve polarization.
EBIS upgrade with new “injector” solenoid for polarized $3\text{He}^{++}$ ion production.

BNL-MIT collaboration

Optical pumping in High magnetic field

Polarization and ionization in high magnetic field will produce $3\text{He}^{++}$ ion beam with $P \geq 80\%$

Up to $2 \times 10^{11}$ $3\text{He}^{++}$ ions/pulse
Depolarization due to lower field in the gap between two solenoids.

- Critical field for $\text{He}^+$ ions is 3.1 kG.
- Therefore, about 10 kG field is required at the point of second ionization He$^+$ to He$^{++}$ to minimize depolarization.
- The design of solenoid with this high field in the gap is feasible.
- Due to reduced probability of ionization in the gap (low electron current density), this requirements can be somewhat relaxed.
Extended EBIS

• **Scope**
  • Add superconducting solenoid for trap length extension, expect +40% Au intensity
  • (early completion would shorten time for 2 highest energies in BES-II; also allows for next step in polarized $^3\text{He}$ R&D)

• **Cost and funding**

<table>
<thead>
<tr>
<th></th>
<th>FY2016</th>
<th>2017</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$475k</td>
<td>1350k</td>
<td>1.8M</td>
</tr>
<tr>
<td>(P)</td>
<td>(P)</td>
<td></td>
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</table>

• **Schedule**
  • 2016 start (solenoid acquisition)
  • 2020 planned completion

  largest risk (cost, schedule and performance):
  superconducting solenoid magnet
EBIS center drift tube

He-cell

Valve
He-ionizer cell and three-grid energy separation system
5.3 MeV Helium3–Helium4 Polarimeter

- Transverse polarized $^3$He beam on unpolarized $^4$He at 5 torr\(^{10}\), early design by C. Epstein
- At 5.3 MeV, asymmetry due to polarization goes to 1 at 91\(^\circ\) center of mass → $^3$He at 53.6\(^\circ\) and 2.66 MeV
- Recoil $^4$He as a background at 1.83 MeV, so use 500 $\mu$m partially depleted silicon detector for energy resolution
- At 50\% polarization, expect 3.7\% accuracy in 1 minute

Plan for EBIS upgrade for the Run-2019-20

- EBIS upgrade for higher heavy beams intensities and provisions for polarized $3\text{He}^{++}$ ion beam.
- At first upgraded EBIS will be used for the Gold run in 2019.
- Development of the $3\text{He}$ part in 2016-1018.
- Polarized $3\text{He}^{++}$ beam of $2.0\times10^{11}$ ions/pulse and 80 % polarization in 2020.