Development of a Polarized $^3$He Beam Source
And Applications in Ghostbusting

J. Maxwell

Jefferson Lab Pizza Seminar
June 8th, 2016
Outline

1 Polarized $^3$He Source
   Source Design
   Polarization and Relaxation Tests
   High Field Tests
   Next Steps

2 Ghostbusters (2016)
   He3 Polarizer on Film
   Proton Pack Design
   Other Fun Stuff
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1. Polarized $^3$He Source
   - Source Design
   - Polarization and Relaxation Tests
   - High Field Tests
   - Next Steps

2. Ghostbusters (2016)
   - He3 Polarizer on Film
   - Proton Pack Design
   - Other Fun Stuff
Polarized Scattering Experiments

- Polarized targets and sources are analogous to polarized lenses in sunglasses
  - Light from the sun is unpolarized
  - Reflected glare from the water or the road is more likely horizontally polarized
  - By selecting only vertically polarized light, we see a different picture
Why a Polarized Helium 3 Source?

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

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<td>D</td>
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• 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
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

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Source Design Goals

- 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
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/cm² 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
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**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%
3He Polarization

- EBIS has done much of the work for us!
- Need polarized 3He; pure sample for injection
- Revisit MEOP technique\(^2\) with modern lasers

Metastability Exchange Optical Pumping

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

\(^3\) 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

m_F = -3/2

-1/2

1/2

σ^+

Equal Probability Decay

Equal Probability Exchange

Net Polarization

Metastability Exchange

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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
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Depolarization from Field Gradients

From Schearer\textsuperscript{4}, we have:

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

- 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{4}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

Map in mm Relaxation Time (1 torr)
Calculating Relaxation Time in EBIS B field

Map in mm Relaxation Time ($<10^{-2}$ torr)
Two Source 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
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\(^5\)
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development\(^6\)

\(^5\) Maxwell, Epstein, Milner, NIM A (777), 2015.
\(^6\) 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

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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
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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 $2^3S - 2^3P$ transitions to directly probe states $^7$,$^8$

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Optical Probe Polarimetry

- High or low field, no calibration required
- Sweep low power probe laser through two $^{2}S_{1/2} \rightarrow {^{2}P_{1/2}}$ transitions to directly probe states$^{7,8}$

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
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
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High Field Source Design: EBIS Upgrade

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

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- DOE Office of Nuclear Physics,
  R&D for Next Generation Nuclear Physics Accelerator Facilities
- MIT Department of Physics
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   He3 Polarizer on Film
   Proton Pack Design
   Other Fun Stuff
Ghostbusters (2016)
He3 Polarizer on Film

Development of a Polarized \(^3\)He Beam Source

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He3 Polarizer on Film
PARTS LIST

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75mm OD, 8mm OD Pyrex tube

PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT
He3 Polarizer on Film

50mm OD cell with optically clear windows

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Ghostbusters (2016)
He3 Polarizer on Film

Development of a Polarized $^3$He Beam Source

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A New Proton Pack
Ghostbusters (2016)
Proton Pack Design
What are Ghosts? How do you catch them?

• ”Unphysical” occurrences isolated in time & space
  • Dark matter? Fields, particles outside Standard model?

• Spectral Ether: a new gauge field through which unknown entities can interact with our world
  • Localized excitation of the ether, ”spectral foam,” results in regions in space and time where significant coupling exists between spectral matter and Standard Model particles
  • ”Ethereal polarization,” good/bad slimes from GB 2

• Proton Pack?
  • Absorbs spectral energy via unidentified secondaries generated by beam of high energy protons
  • “Unlicensed nuclear accelerator” on your back
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Cyclotron: 1932
Synchrotron: 1945
New Proton Pack

- Miniature Superconducting Proton Synchrotron
  - RF plasma ECR proton source
  - Cryogen reservoir with cryocooler for active cooling
  - “Magic” beam steering
  - Plasma beam halo

- Timeline:
  - Saturday night: “Can you label this?”
  - Sunday: PANIC
  - Sunday night: “How’s this?”
  - Monday: Tweet
Development of a Polarized $^3$He Beam Source

Proton Pack Design

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Proton Pack Design
Development of a Polarized $^3$He Beam Source
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Proton Pack Design

Development of a Polarized $^3$He Beam Source

Turbopump Set
Hydrogen Tank
Proton Pack Pump-out Connection
Ectoplasm Analysis Unit
Power Cell
Long-range Psychokinetic Energy (PKE) Scanners
Pumping Lines
Loudspeaker
Positive & Negative Polarized Spectral Foam Detectors
Baseline PKE Reference Cell
Reserve Liquid Helium Dewar
Proton Pack Spectral Charge Grounding Line
Ghostbusters (2016)

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Proton Pack Design
Development of a Polarized $^3$He Beam Source

Proton Pack Design

Ghostbusters (2016)
Ghostbusters (2016)

Other Fun Stuff

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Ghostbusters (2016)
Other Fun Stuff
Development of a Polarized $^3$He Beam Source

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[Image of a person in a lab setting with equipment]
Ghostbusters (2016)
Development of a Polarized $^3$He Beam Source

Other Fun Stuff
Who you gonna call?!
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 $180^\circ$, allow the wobble to unkink itself
  - Partial snakes can be used for some imperfections

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RHIC Spin Manipulation

Absolute Polarimeter (H↑ jet)

RHIC pC Polarimeters

Siberian Snakes

Spin Rotators

PHENIX

STAR

Pol. H⁻ Source

LINAC

200 MeV Polarimeter

BOOSTER

AGS

Helical Partial Siberian Snake

Strong AGS Snake

AGS pC Polarimeter
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\textsuperscript{10}

\textsuperscript{10}Bai, Courant \textit{et al.}, BNL-96726-2012-CP, 2012.
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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

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

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

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

- Atoms consist of electrons around a nucleus
- Nuclei consist of protons and neutrons
- Nucleons consist of 3 quarks
  - Quarks get their mass from the Higgs Mechanism
  - Mass of $u$ quark $\sim 2$ MeV, $d$ quark $\sim 5$ MeV
  - Mass of proton ($uud$) is 938 MeV. *Wait, what?*

- In QCD, the nucleon is made of 3 valance quarks, a sea of virtual quark–anti-quark pairs, all bound by gluons
- Nearly all the mass is generated by flurry of activity from quarks and gluons jiggling at near $c$, and $q-\bar{q}$ pairs springing into and out of existence
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  - Mass of proton ($uud$) is 938 MeV. *Wait, what?*

- In QCD, the nucleon is made of 3 valance quarks, a sea of virtual quark–anti-quark pairs, all bound by gluons
- Nearly all the mass is generated by flurry of activity from quarks and gluons jiggling at near $c$, and $q$-$\bar{q}$ pairs springing into and out of existence
The Makeup of Matter

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- Nuclei consist of protons and neutrons
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Understanding the Strong Force

**Electromagnetic Force (QED)**

Particles of charge (+−) interact via mediating photons, which are neutral
- 1 vertex for radiation/absorption

**Strong Force (QCD)**

Particles of color charge (RGB) interact via mediating gluons, which carry color charge
- Vertex for gluon radiation
- 2 vertices for gluon self-coupling
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In chromodynamics, a bare red charge begets more red charge, serving to “anti-screen” at a distance, leading to “confinement”. A high energy probe with a short distance scale sees smaller charge, “asymptotic freedom.”
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Scattering Probes of Nuclear Structure

- We need a “microscope” to see inside the nucleus
  - But, you can’t see something if it’s smaller than the wavelength of light you are using
  - Need “light” with very small wavelength

- An electron scatters off a proton via a photon
  - An electron beam can provide a beam of “virtual photons”
  - The more 4-momentum exchanged ($Q^2$), the smaller the virtual photon, the higher resolution you can achieve
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Pushing the Frontier

- Once we have enough momentum transfer to see quarks, what’s next?
  - Kinematics determine what we are probing
    \[ Q^2 = 4EE' \sin^2 (\theta/2), \quad x = Q^2/(2M(E - E')) \]
  - Bjorken $x$ is “momentum fraction” of struck quark
- At high $x$, we see a quark with “asymptotic freedom”
- At low $x$, we see a quark bound by a mess of gluons
- The next Nuclear Physics machine will reach the extreme low $x$ region
  - Move from a fixed nuclear target and electron probe beam (SLAC, JLab) to a nuclear beam colliding with an electron beam
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Electron Ion Collider (eRHIC)
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16 GeV polarized electrons and 250 GeV polarized protons
Electron Ion Collider (JLab EIC)
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10-20 GeV polarized electrons and 100-250 GeV polarized protons
Thoughts on Probe Measurement Error

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

\[
M(r/r_0) = \frac{r/r_0 - 1}{r/r_0 + 1}, \quad \sigma_M(r/r_0) = \frac{2\sigma_{r/r_0}}{1 + (r/r_0)^2}
\]