Development of a Polarized ^{3}He Ion Source for RHIC

R. Milner
Laboratory for Nuclear Science,
Massachusetts Institute of Technology,
Cambridge MA 02139

Abstract

Funds of $ 150,000 are requested to design and construct a source of polarized ^{3}He atoms for injection into EBIS. This is the initial step in producing polarized ^{3}He beams in RHIC in collaboration with physicists from Columbia University and Brookhaven National Laboratory. These beams can be used to probe the spin structure of the neutron in the existing RHIC complex as as well as to measure precisely the Bjorken Sum Rule at a future eRHIC electron-ion collider. The students and technical support will be provided through the existing Task B and Task L, respectively. This research can attract MIT students into the field of accelerator physics.

Scientific Motivation

Study of the spin structure of the nucleon is a fundamental problem of major current interest. Experiments at SLAC, CERN and DESY over the last two decades have determined that the contribution of the quarks to the nucleon's spin is only about 25%. Major experimental efforts are in progress at CERN and at RHIC to directly determine the contribution of the gluons to the nucleon's spin. A substantial group at MIT-LNS under the leadership of Prof. Bernd Surrow is collaborating in the STAR experiment at RHIC-spin.

In all experimental investigations of nucleon spin to date, it has been essential to carry out measurements on both isospin configurations of the nucleon, namely both the neutron and proton. The neutron contains different combinations of quark flavors and provides a second nucleon system, different from the proton, with (presumably identical) gluon distribution. In the RHIC-spin program, a polarized neutron beam would allow an independent determination of nucleon spin structure, which at a minimum would provide important verification of the proton measurements [1]. It has recently been pointed out [see talk by Z. Kang in 1] that A_N due to the Sivers effect in Drell-Yan processes on polarized neutron will have a much larger magnitude and opposite sign to that on the polarized proton, as shown in Fig. 1.

Further, with the eventual realization of an electron-ion collider, e.g. eRHIC, the ability to have both polarized proton and polarized neutron beams in RHIC is essential for a test of the fundamental Bjorken Sum Rule [2,3]. The Electron-Ion Collider Advisory Committee recently rated [4] polarized ^{3}He production and acceleration in the highest priority category for accelerator R&D. The 2007 NSAC Long Range Plan [5] recommended *the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider.*

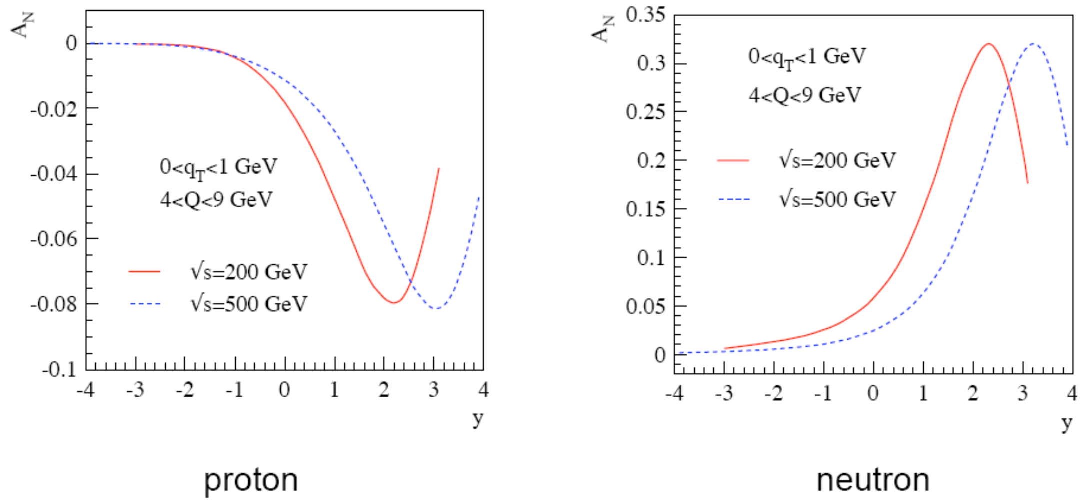

Figure 1. Theoretical calculations of A_N for proton and neutron as reported by Z. Kang in [1].

Nature does not provide us with readily available intense beams of free polarized neutrons. Thus, either polarized deuterium or polarized ^{3}He has been used as an effective polarized neutron target in deep-inelastic scattering measurements to probe the nucleon spin structure. In the case of RHIC, manipulation of the spin of the polarized deuteron is technically formidable because of the small magnitude of the deuteron's magnetic moment. ^{3}He, on the other hand, possesses a magnetic moment close to that of the free neutron and thus in RHIC a polarized ^{3}He beam can be manipulated (up to a sign) similarly to the polarized proton. The ^{3}He mass is substantially larger than that of the proton and this changes the accelerator tune significantly. Thus, to realize a polarized neutron beam in RHIC requires injection of an intense beam of highly polarized ^{3}He ions. It is the goal of this collaborative effort to develop such a source over the next five years.

Polarized ^{3}He ion source

The PI plans to develop at MIT an intense source (~ 500 particle μA, i.e. 3 X 10^{15}/sec) of highly polarized (~ 70%) ^{3}He ions which will be injected into the Electron Beam Ion Source (EBIS) at RHIC. The RHIC polarized ^{3}He source development will be carried out in collaboration with Prof. E. Hughes's group at Columbia University and Dr. J. Alessi and A. Zelenski and their colleagues at Brookhaven National Laboratory, Polarized ^{3}He ions sources have been successfully realized using a number of techniques. A Lamb shift polarized ^{3}He ion source was developed at the University of Birmingham, United Kingdom [6] and delivered 50 particle nA of 65% polarized ^{3}He. A metastability exchange optically pumped source was developed by a Rice University-Texas A&M collaboration [7] and delivered 8 particle μA of 11% polarized ^{3}He. A source based on the Stern Gerlach method was developed at Laval University, Canada [8] and delivered 100 particle nA with high polarization up to 95%. Spin transfer collisions can also be used for polarized $^3He^{++}$ production. This scheme is under development at RCNP (Osaka, Japan) [9].

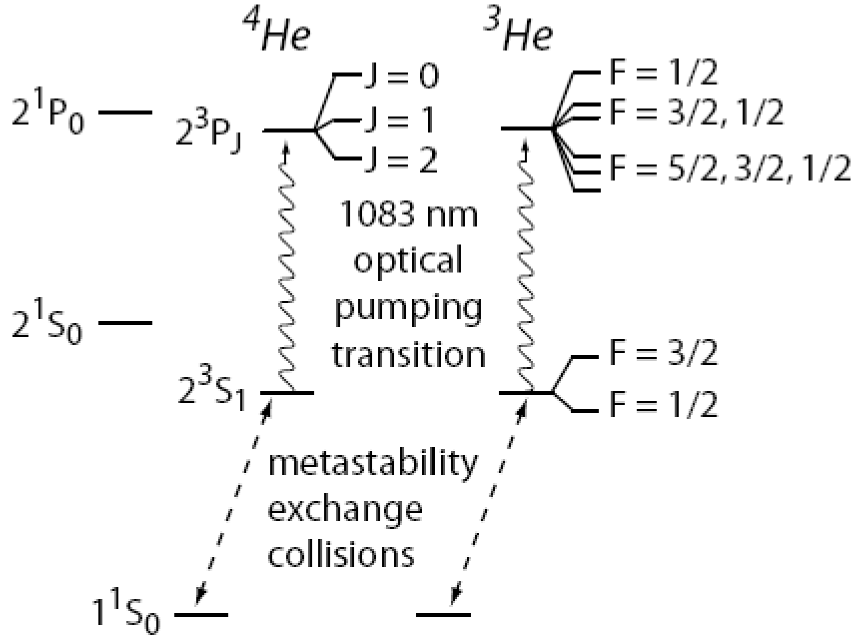

Figure 2. The atomic level structure of ^{3}He and ^{4}He (not to scale).

We propose to develop a source of polarized ^{3}He atoms based on the technique of metastability exchange optical pumping [10]. In this method, ^{3}He gas at typically 1 torr is contained in a glass bulb and a weak RF discharge is maintained in the gas. Metastable atoms in the 2 $^3S_1$ state (see Fig. 2) are produced in the discharge and may be polarized by means of optical pumping with circularly polarized (2 ^{3}P – 2 ^{3}S) 1.083 μm light. This polarization is subsequently transferred to the much more numerous 1 $^1S_0$ ground-state atoms via spin-exchange collisions. Typically, a laser system tuned to the resonance 1.083 μm line is used for the optical pumping. The polarization in the glass cell can be determined using a measurement of the circular polarization of the 667 nm line in the discharge. Modern lasers will allow much higher polarized source figure-of-merit compared to the pioneering efforts described previously.

An internal target based on this principle was developed at MIT-Bates [11] and has been successfully used at IUCF [12], DESY/HERMES [13] and at NIKHEF [14]. The laser used was a modified Nd:YAG system using a flashlamp pumped Nd:LMA . Typical output powers were 2 W at 1.083 μm yielding target polarizations of 50% at flow rates of 2×10^{17} ^{3}He atoms/sec. Recently, ytterbium fiber lasers have produced 20-40 W of 1.083 μm radiation for metastability exchange optical pumping [15]. Large volume systems at the University of Mainz [16] have delivered polarizations of over 70% at a polarization rate of 8×10^{18} atoms/s, as shown in Figure 3.

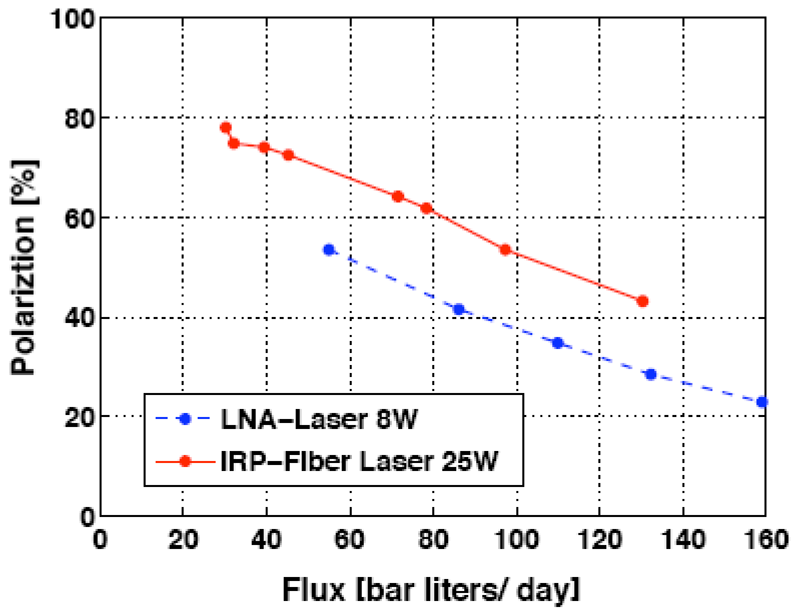

Figure 3. The polarization of the ^{3}He gas as a function of the polarization rate using a 25 W fiber laser system [16].

EBIS source at RHIC

An Electron-Beam Ion Source (EBIS) is under development at BNL as an alternative to the Tandem heavy ion injector for RHIC [17]. It is proposed to use the EBIS to produce $^{3}He^{++}$ by ionization of the polarized ^{3}He gas which is fed from the glass pumping cell. The ionization in the EBIS is produced in a 50 kG magnetic field, which preserves the nuclear ^{3}He polarization while in the intermediate single-charged $^{3}He^{+}$ state. The ionization efficiency to the double-charged $^{3}He^{++}$ will be close to 100% and the number of ions is limited to the maximum charge which can be confined in the EBIS. From experiments with Au^{32+} ion production, one expects about 2.5×10^{11} ions to be produced and extracted for subsequent acceleration and injection to RHIC. Figure 4 shows a schematic layout of the EBIS source. Figure 5 shows a schematic layout of the proposed polarized ^{3}He ion source.

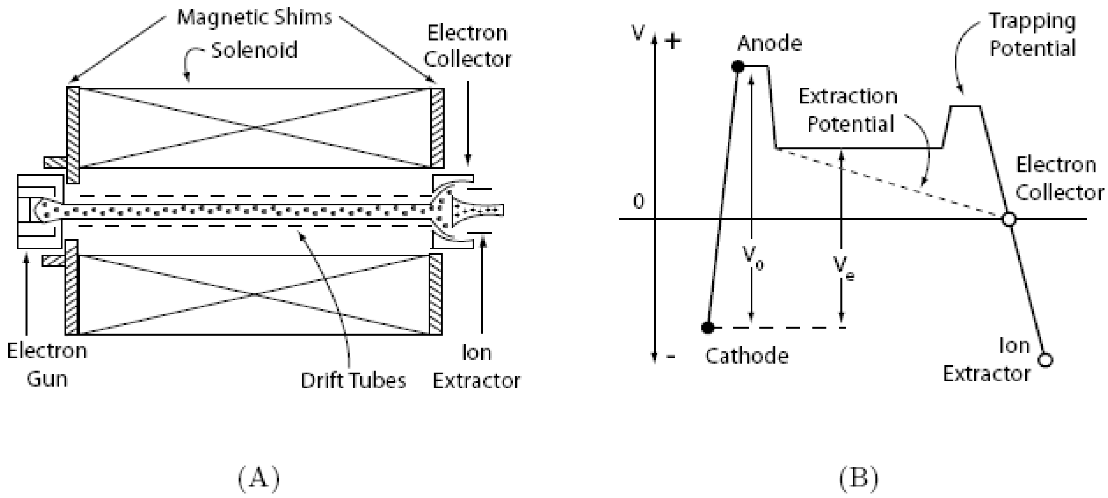

Figure 4. (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.

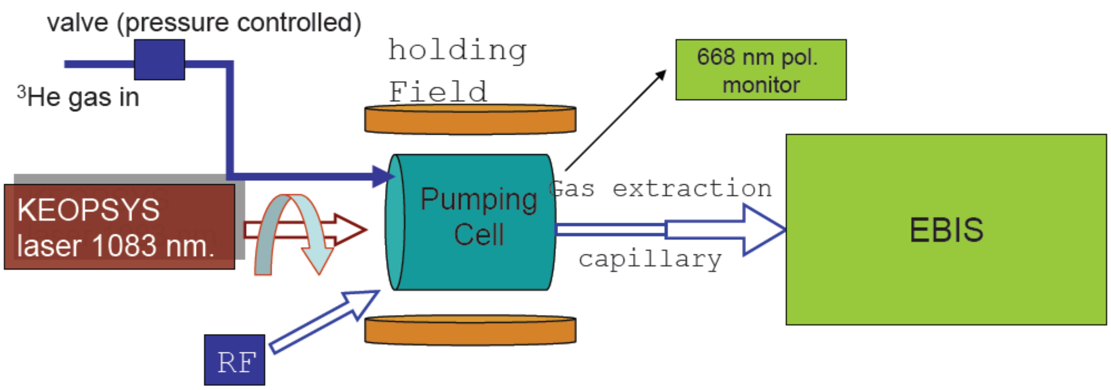

Figure 5. Schematic layout of the polarized ^{3}He source for RHIC.

The path which the ^{3}He atoms take from the pumping cell to the EBIS must be one which does not cause depolarization of the atoms. For example, the presence of magnetic field gradients can lead to depolarization. The Brownian motion of the atoms can lead to an oscillating field with a component of the Larmor frequency in the particle rest frame. The depolarization time constant τ is given by [18]

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

$$\omega_0 = 3.24\ |B_l|\ \text{kHz},\ \tau_c \sim 2.2 \times 10^{-7}\ p^{-1}\ \ [p \text{ in Torr}]$$

Figure 6 shows the calculation by MIT graduate student A. Kocoloski of the effects of the measured EBIS field using the above formula. By transferring the polarized ^{3}He atoms along a line which minimizes the transverse component of the magnetic field, τ can be made much longer than the transfer time. Use of non-magnetic materials such as glass will be required for the transfer line. Special valves will be required to be developed.

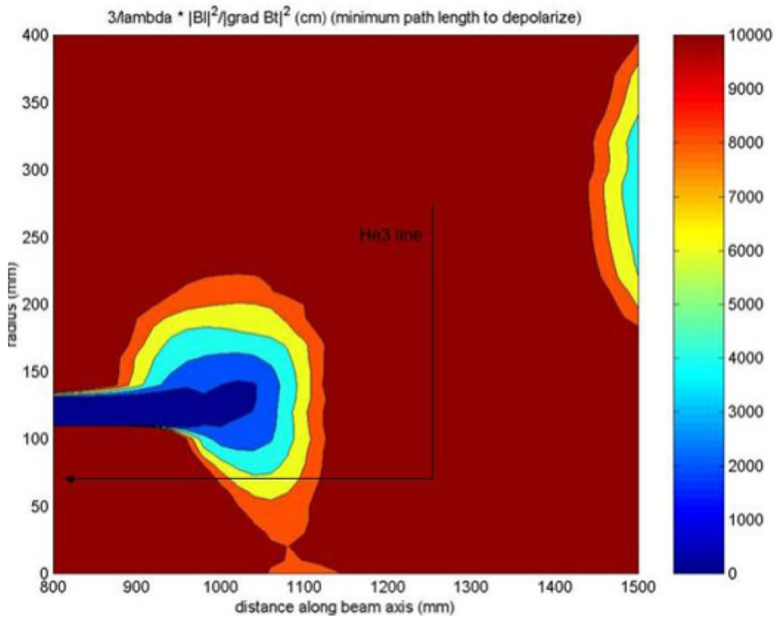

Figure 6. Calculation of the depolarizing effects using the measured magnetic field in EBIS [19].

Polarimetry

The ions exit EBIS and the doubly-ionized ^{3}He are accelerated to 40 keV, after which the ions enter a high-voltage platform which accelerates them to 200 keV and a radio-frequency quadrupole (RFQ) accelerates the beam to 900 keV.

A Lamb shift polarimeter will be used to measure the polarization of the ^{3}He ion beam after exiting EBIS. By choosing a polarimeter that operates at low energy, the system can be installed before the high-voltage platform and without the need for RFQs. This preference for a low-energy polarimeter requires it to be based on atomic interactions rather than nuclear scattering. A detailed concept for the polarized ^{3}He Lamb shift polarimeter has been developed [20].

Research Plan

In the years FY2011 and FY2012 a source of polarized ^{3}He atoms based on the technique of metastability exchange optical pumping using the new generation of fiber lasers will be developed at MIT. The milestones with expected completion dates (assuming November 1st, 2010 start) are as follows:

- Acquire the new laser system (March 1, 2011)
- Design and build the glassware (June 1, 2011)
- Assemble and commission the polarized ^{3}He source at Bates (June 1, 2012)
- Move it to BNL for installation on the EBIS test stand (October 1, 2012)

At MIT-Bates, a test stand for polarized ^{3}He source development exists and is available. Technical support will be provided by the Bates R&E Center at the level for BY 2011 and BY 2012 of 0.75 FTE total, consisting of 0.2 FTE physicists, 0.3 FTE mechanical engineer, and 0.25 FTE mechanical technician. These funds have been requested under Task L.

A major focus of the ion source development will be to attract students at MIT into accelerator physics. The students will be supported by Task B funds. Past experience has shown that this type of table-top development is a strong attractor for students and particularly suitable for undergraduate research projects. It is envisaged that students will play a major role in the eventual commissioning of the source at BNL.

In parallel to the source development at MIT, it is expected that the polarimeter technique for measurement of the $^3He^{++}$ polarization from the EBIS source will be developed.

In FY2012-13, it is anticipated that an experiment can be mounted at BNL in which polarized ^{3}He atoms will be fed into the EBIS prototype source, will be extracted as ions, accelerated and their polarization measured using a polarimeter. The parameters for optimal polarized ^{3}He ion source delivery to RHIC will be established.

Based on the results of this test experiment, in FY2014 design of an optimized polarized ^{3}He source for operation in conjunction with the full scale EBIS could be carried out.

Budget

The costs of the equipment needed to develop the polarized ^{3}He ion source are summarized in Table 1.

Table 1. The budget for the planned research.

Equipment item	**Cost($)**
Keopsys laser system	60,000
Optics	15,000
Polarimeter	20,000
Electronics	20,000
Glassware	15,000
Vacuum equipment	20,000
Total	150,000

References

[1] *RHIC Spin: The Next Decade*, meeting at Iowa State University, May 14-16, 2010: see talks by Marco Stratmann, Anselm Vossen, and Zhongbo Kang at http://www.physastro.iastate.edu/rhic/agenda.html.

[2] J.D. Bjorken, Phys. Rev **148**, 1457 (1966).

[3] Abhay Deshpande, Richard Milner, Raju Venugopalan, and Werner Vogelsang, Ann. Rev. Nucl. and Part. Sci. **55**, 165 (2005).

[4] Report of the 2nd Meeting of the Electron-Ion Collider Advisory Committee, November 2-3, 2009, Jefferson Laboratory, Newport News, Virginia.

[5] *The Frontiers of Nuclear Science*, 2007 NSAC Long Range Plan for Nuclear Science in the United States.

[6] W.E. Burcham, O. Karban, S. Oh, W.B. Powell, Nucl. Instr. and Meth. **116**, 1 (1974).

[7] D.O. Findley, S.D. Baker, E.B. Carter, and N.D. Stockwell, Nucl. Instr. and Meth. **71**, 125 (1969).

[8] R.J. Slobodrian, Nucl. Instr. and Meth. **185**, 581 (1981).

[9] M. Tanaka et al., Phys. Rev. **A1**, 534 (1970).

[10] F.D. Colegrove, L.D. Schearer, and G.K. Walters, Phys. Rev. **132**, 2561 (1963).

[11] K. Lee, J.-O. Hansen, J.F.J. van den Brand, and R.G. Milner, Nucl. Instr. and Meth. **A333**, 294 (1993).

[12] C. Bloch *et al*., Nucl. Instr. and Meth. A **354**, 437 (1995).

[13] D. DeSchepper *et al*., Nucl. Instr. and Meth. A **419**, 16 (1998).

[14] H.R. Poolman *et al*., Nucl. Instr. and Meth. A **439**, 91 (2000).

[15] Thomas R. Gentile, Michael E. Hayden, and Michael J. Barlow, J. Opt. Soc. Am. **B 20**, 2068 (2003).

[16] Private communication, Werner Heil, University of Mainz.

[17] J. Alessi and A. Zelenski, ICFA Newsletter No. 30, p.39, April 2003. See http://www.bnl.gov/cad/ebis/ for latest information.

[18] R.L. Gamblin and T.R. Carver, Phys. Rev. A **138**, 946 (1965)..

[19] A. Kocoloski, private communication.

[20] J. Alessi and E. Hughes, private communication.