Introduction

In the next decade, Brookhaven National Laboratory (BNL) plans to upgrade its Relativistic Heavy Ion Collider (RHIC) to include an electron-ion collider (eRHIC). eRHIC will be a high luminosity collider to study the nucleon and nuclear structure, including spin and flavor physics, and to explore nuclear matter at high parton densities. In addition to studying unpolarized ions colliding with electrons, eRHIC will investigate high-energy spin physics with the collision of polarized protons and ^{3}He ions with polarized electrons.

In the more immediate future, Brookhaven also anticipates an upgrade of their pre-injector to replace the existing Tandem Van de Graaff, which dates back to the 1970s. This new system, based on an Electron Beam Ion Source (EBIS) design, will improve both the performance and the operational simplicity of the machine, as well as allowing flexibility in the type of atomic species used and the ability to deliver beam to multiple users [1]. Brookhaven has built a full power, half-length prototype for EBIS called the Electron Beam Test Stand (EBTS) to demonstrate an EBIS capable of meeting the RHIC requirements [2]. Presently, the EBTS is being used to study the basic physics of a high-intensity source.

In preparation for these upgrades, a collaboration between Caltech, MIT-Bates Laboratory and Brookhaven National Laboratory Accelerator Division is designing and building a polarized ^{3}He beam and investigating the depolarization effects induced in the beam due to ionization in EBIS. These studies are required to test the feasibility of a ^{3}He^{++} beam of 5x10^{11} ions produced by EBIS with a 20 μs pulse duration and polarization in excess of 70% for injection into eRHIC.

Motivation

Polarized deep inelastic scattering (DIS) is one of the most effective means for studying the internal spin structure of nucleon; its continued exploration motivates experiments at eRHIC. The results from previous DIS experiments have been used to measure the polarized parton distributions in the nucleon, to test quantum chromodynamics (QCD) and to solve for the strong coupling constant, $\alpha_s(Q^2)$.

The primary motivation behind polarized DIS experiments is to establish the relationship between the spin of the nucleon and its internal structure. According to the relativistic quark-parton model, we expect around 60% of the nucleon spin to arise from the spin of the three valence quarks. However, the first set of data from the CERN in the late 1980's, combined with earlier data from SLAC, showed that only 12±17% of the nucleon spin could be attributed to the quark spin [3]. These results gave rise to the "Proton Spin Crisis" and a rush of experiments to measure both the proton and neutron spin structure functions. More recent data shows that ∼30% of the nucleon spin can be attributed to the quark spin; a less striking but still significant deviation from the quark-parton model [4]. Table 1 lists previous experiments on polarized deep inelastic scattering. Of particular interest, is the use of polarized ^{3}He to measure the neutron structure function.

Table 1: Deep inelastic scattering experiments.

Experiment	Probe Particle (Energy)	Target Particle	Year
CERN EMC	μ (200 GeV)	proton	1987 - 1988
CERN SMC	μ (100-200 GeV)	proton	1993 - 1998
		deuteron	
SLAC E142	e (22 GeV)	^{3}He	1993 - 1995
SLAC E143	e (29 GeV)	proton	1994 - 1996
		deuteron	
SLAC E154	e (50 GeV)	^{3}He	1997
SLAC E155	e (50 GeV)	proton	1998 - 2002
		deuteron	
DESY HERMES	e^+ (27 GeV)	^{3}He	1995 - 2000
		proton	
		deuteron	
CERN COMPASS	μ^+ (190 GeV)	proton	2001
		deuteron	
BNL RHIC	p-p (200 GeV)	collider	2002 - ?

In addition to studying the neutron spin structure, experiments at eRHIC will test a fundamental prediction of perturbative QCD: the Bjorken sum rule

$$\int_0^1 g_1^p(x)dx - \int_0^1 g_1^n(x)dx = \frac{1}{6}\left(\frac{g_A}{g_V}\right)\left(1 - \frac{\alpha_s(Q^2)}{\pi} - \cdots\right) . \qquad (1)$$

The proton and neutron spin structure functions are $g_1^p(x)$ and $g_1^n(x)$, respectively. The Bjorken variable, x, describes the fraction of the nucleon momentum carried by a particular parton in the infinite momentum frame. The Bjorken variable is defined as $Q^2/(2M(E-E'))$, where Q^2 is the four-momentum transfer, M is the nucleon mass and E is the collision energy. g_A and g_V are axial and vector coupling constants as measured by neutron β-decay. The only free parameter is α_s, the strong coupling constant. Using the measured values for the proton and neutron spin structure function as well as the axial and vector coupling constants, one can solve for α_s. As seen in Table 1, DIS experiments cover different ranges in x and Q^2 owing to their different beam energies and different coverage of scattering angles. After fitting the data from these experiments to the QCD evolution equations, the results are often evolved using the renormalization group to a common scale, generally taken to be the mass of the Z boson, and expressed as $\alpha_s(M_Z^2)$. Presently, the average value for $\alpha_s(M_Z^2)$ is 0.12$\pm$0.009 [5].

The Bjorken sum rule is tested and confirmed to a level of approximately 10%. Measurement uncertainties are limited by systematic uncertainties on the beam and target polarizations, the remaining uncertainty is due to the theoretical extrapolation of of the results to low Bjorken x. Significant improvements to testing the sum rule require a substantially higher-energy experiment and a more precise polarimeter. At higher energies, the theoretical uncertainties coming from the low x extrapolation and from perturbative QCD corrections are reduced. The future experiments will require the polarization of the beam be known at the level of $\sim$1% or better [6].

Previous Polarized ^{3}He Experiments

Although ^{3}He is often used in polarized target experiments, several experiments in the 1970s-1980s also did work with polarized ^{3}He beams. Table 2 lists the well-known experiments from this period.

Table 2: Previous Experiments

Source	Current	Polarization	Beam Energy	Ion
Birmingham	100 nA	55-65%	29 keV	$^3He^{++}$
Laval	100 nA	95%	12 keV	$^3He^{+}$
Rice/ Texas A&M	8 μA	11%	16 keV	$^3He^{+}$

Due to technological constraints, most of these experiments were unable to simultaneously achieve both high polarization as well as high current, however, recent improvements in spin and metastability exchange techniques has reinvigorated interest in the field. One advancement, in particular, has been in the field of NMR tomography of the lungs. Due to the low water content in human lungs, a patient must inhale a gas with sufficient polarization for NMR imaging. Traditionally, the patient inhales a radioactive gas, such as ^{133}Xe, that decays into a spin polarized state. Isotopes of certain non-radioactive noble gases with an odd number of nucleons, such as ^{3}He or ^{129}Xe, can be imaged within the air passages using NMR, however, the signal is extremely weak because of the low spin density. Provided these gases can be hyper-polarized (i.e. obtain a nuclear spin state population difference significantly greater than the equilibrium population difference), they can provide excellent imaging of lungs as well as being a safer alternative to ^{133}Xe [7]. This challenge to create dense hyper-polarized ^{3}He for lung imaging has provided significant progress in the field.

The University of Mainz has pioneered much of the work and are one of the leaders in producing hyper-polarized ^{3}He world-wide. They have achieved polarization close to 80% with commercially available 15 W fiber lasers at 1083 nm (IPG Photonics Corporation, Model: YLD-15-1083) using metastability exchange optical pumping, which is further described in the next section [8]. Figure 1 illustrates the dramatic improvement in polarization between the old 8 W LNA-laser system and the new 30 W fiber laser. The University of Mainz has successfully delivered ^{3}He with polarization of over 70% at a rate 9x10^{18} atoms/s in large volume systems for lung imaging. This rate far exceeds what is required for a polarized ^{3}He beam source at RHIC.

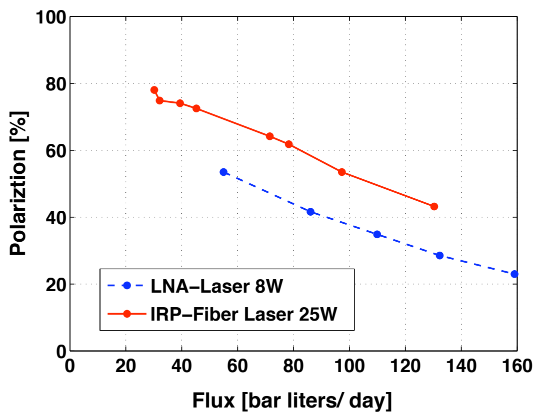


Figure 1: Performance of the Mainz ^{3}He polarizer and compressor with the old (LNA-laser 8W, dashed line) and the new (fiber-laser 30 W, solid line) laser system [8].

Experiment

Polarization

Two techniques exist for producing hyper-polarized ^{3}He: spin exchange with optical pumping (SEOP) or metastability exchange with optical pumping (MEOP). In the case of SEOP, ^{3}He is generally mixed with rubidium (Rb) vapor. The Rb vapor is polarized via optical pumping and the ^{3}He atoms are subsequently polarized through collisions with the polarized Rb vapor. Unfortunately for producing sufficient ions for use in accelerators, this method has long time scales before the ^{3}He gas is fully polarized. Also the Rb vapor needs to be removed from the polarized ^{3}He mixture, adding complexity to the system. The typical pressures for the spin exchange technique is a few bar.

The other method for polarizing ^{3}He, and the method chosen for this experiment, is with MEOP [9]. In this method, a weak RF discharge is maintained in the neutral ^{3}He vapor to produce an initial population of metastable atoms in the long-lived 2^3S_1 state. Circularly polarized 1083 nm pumping light incident on the metastable atoms excite the transition between the $2S_1$ and $2P_0$, shown in Figure , with the selection rule $\Delta m_F = +1$. The laser excites atoms from the metastable $m_F = -\frac{1}{2}$ and $-\frac{3}{2}$ sublevels of the $2S_1$ state to the $2P_0$ state, where they then decay with equal probabilities to all the $2S_1$ states. The atoms

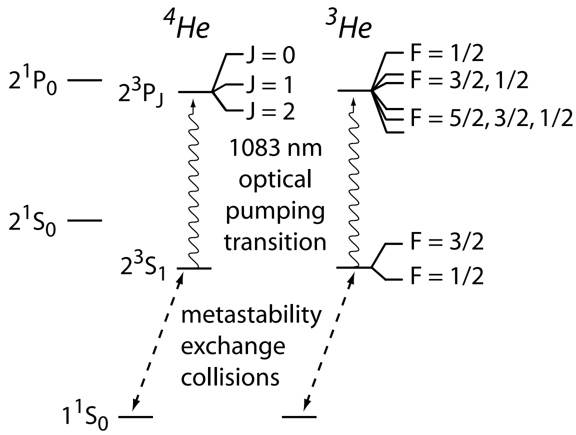


Figure 2: Ground state and first excited state of ^{4}He and ^{3}He (not to scale).

in the $m_F = \frac{1}{2}$ and $m_F = \frac{3}{2}$ states are left untouched. The atoms are converted from states with low magnetic quantum numbers ($m_F = -\frac{1}{2}, -\frac{3}{2}$) to those with high magnetic quantum numbers ($m_F = \frac{1}{2}, \frac{3}{2}$). This interaction requires a weak external magnetic field ($\sim$10 G) and low pressure ($\sim$1 mbar). The polarization of atoms in the 2^3S_1 excited state is transferred to the nuclear spin of the ground state via metastability exchange collisions. Since ^{3}He has a nuclear spin $I = \frac{1}{2}$ and a ground state Zeeman doublet, the metastability exchange collision is of the type:

$$^3\mathrm{He}(m_F = -\tfrac{1}{2}) + {}^3\mathrm{He}^*(m'_F) \Leftrightarrow {}^3\mathrm{He}^*(m'_F - 1) + {}^3\mathrm{He}(m_F = \tfrac{1}{2}) \;, \qquad (2)$$

where ^{3}He* is the metastable atom and m_F is the magnetic quantum number.

In order to measure the degree of nuclear polarization, fluorescence scattering of the 668 nm 1^1S_0 to 2^1S_0 line is monitored with an optical polarimeter. The MEOP method is roughly ten times faster than SEOP, at the price of greater mechanical complexity. Using this technique, the polarized ^{3}He atoms rate for injection into EBIS is on the order $10^{13} - 10^{14}$ atoms/s, well within results demonstrated by the University of Mainz.

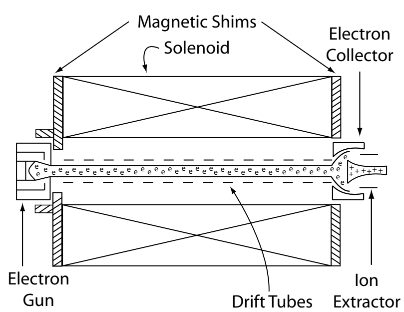
Four critical components seriously impact polarized ^{3}He production: the ^{3}He flow rate, the laser power, the gas purity and the gas extraction line. The flow rate is the time an atom typically spends in the pumping cell. The laser power together with the flow rate determine the maximum polarization. Only a minimal amount of gas impurity is allowed, since impurities lead to depolarization. A well-chosen gas extraction line is crucial because field gradients and wall interactions also lead to depolarization.

To address these key design and experimental considerations, several components of the polarization system are predetermined. First, the high power available with a fiber laser is required to ensure a polarization of $\sim$70-80%.

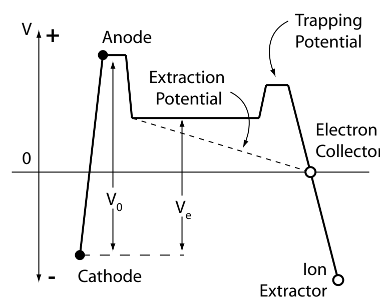
Because eRHIC expects a flow rate of $\sim 10^{15}$ polarized atoms/s, the minimal pumping cell volume must be 10 ml and the resulting time needed to reach maximum polarization is $\sim$100 seconds. Lastly, the ^{3}He path from the pumping cell to the ionization source must minimize large field gradients through EBIS/EBTS as they will lead to depolarization.

Ionization

After production in the cell, the polarized neutral ^{3}He will be fed into Brookhaven's Electron Beam Test Stand (EBTS) to produce doubly ionized ions. The primary physical process used to generate highly-charged ions in EBIS systems is electron impact ionization. Initially, a dense electron beam is produced using an electron gun. An electromagnetic ion trap along the beam is created by applying voltages along the drift tube structures together with a solenoidal magnetic field. Atoms are injected into the trap and become ions though impact ionization with the electron beam. The ions are contained in the potential trap until the polarized ^{3}He is fully ionized. Finally, the $^3He^{++}$ ions are extracted by the rapid application of a high voltage in the trap region. Figure 3 illustrates the main components of the EBIS design as well as the potential variation along its length.



(A)



(B)

Figure 3: (A) A schematic of EBIS and (B) The electric potential along source.

The ionization of ^{3}He occurs in a 50 kG magnetic trapping field. The large magnetic field greatly suppresses the depolarization in the intermediate He^+ single charge state since the critical depolarization field for $^3He^+$(1S) is 3.1 kG. The ionization efficiency to doubly ionize the ^{3}He beam will be close to 100% and the number of ions is limited to the maximum that can be confined in EBIS, which is about 2.5x10^{11} of $^3He^{++}$/store. The resulting expectation is about 10^{11} He^{++} ions/pulse exiting EBIS.

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.

Lamb-Shift Polarimeter

A Lamb-shift polarimeter will be used to measure the polarization of the ^{3}He ion beam after exiting the EBIS. By choosing a polarimeter that functions 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.

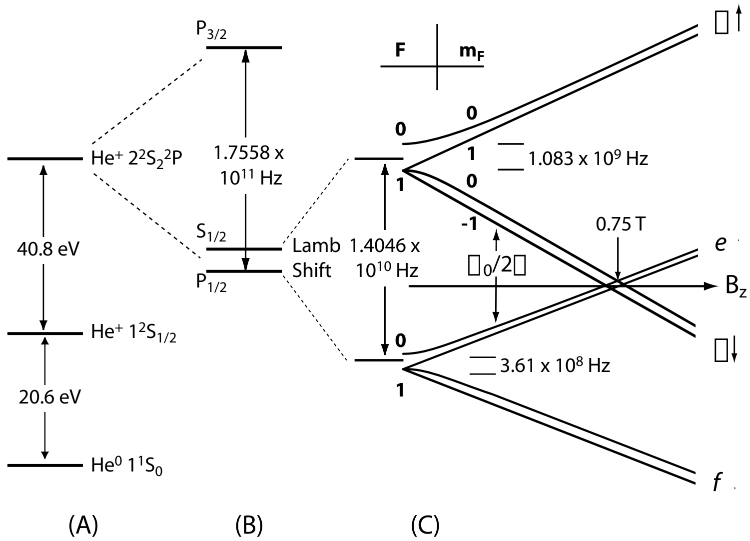


Figure 4: (A) Energy levels of the ground state neutral ^{3}He and the energy levels of the ^{3}He$^+$ ion. (B) The fine structure of the n=2 level of ^{3}He$^+$ and its Lamb shift. (C) Hyperfine structure of the 2S$_{1/2}$ and 2P$_{1/2}$ states of ^{3}He$^+$ showing the Zeeman splitting as a function of external magnetic field.

A Lamb-shift polarimeter (LSP) exploits the difference in lifetimes between the 2S$_{1/2}$ and 2P$_{1/2}$ states, where the term “Lamb-shift” describes the energy difference between them. For reference, the energy separation between the atomic states of a neutral and singly-ionized ^{3}He is given in Fig. 4(A). The fine structure of the n=2 level of ^{3}He$^+$ is shown in Fig. 4(B). Figure 4(C) shows the Zeeman hyperfine splitting of the 2S$_{1/2}$ and 2P$_{1/2}$ energy levels as a function of external magnetic field, B_z. Please note the α, β, e and f naming convention for the four hyperfine states.

As illustrated in Fig. 5, the Lamb-shift polarimeter is comprised of four main components. (1) A hydrogen-filled cell is used to produce ^{3}He$^+$ ions in the metastable 2S-state via charge exchange. Ions in the less stable 2P-state will immediately decay. (2) A bending magnet separates ^{3}He$^+$ ions from the doubly-ionized and neutral atoms. (3) A spin filter quenches the unwanted β-states of the metastable ions. (4) A detector system quenches the remaining ions in the α-state and the resultant 40.8 eV photons are detected to measure the polarization.

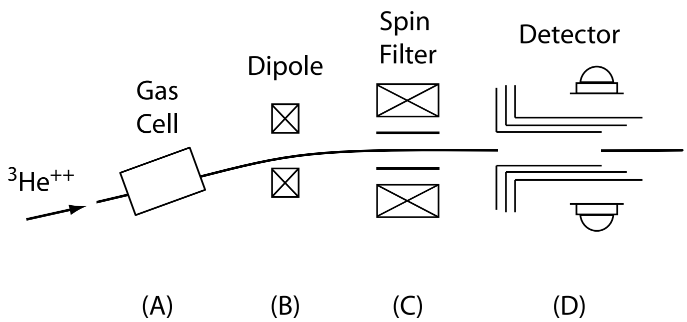


Figure 5: Schematic of the Lamb-shift polarimeter (A) The incoming ^{3}He^{++} ions passes through a hydrogen vapor cell with an external magnetic field to produce ^{3}He$^+$(2S). (B) The bending magnet to ensures a beam of pure ^{3}He$^+$ ions. (C) Spin filter to quench the unwanted states of the metastable ions. (D) Detector to observe the 40.8 eV photons produced by quenching the remaining ions.

(1) Hydrogen-filled Canal

In order to produce a singly-ionized ^{3}He ion beam in a metastable state, the doubly-ionized ^{3}He beam from EBIS passes through a hydrogen vapor cell. The resulting metastable ^{3}He ions are generated via an electron transfer with the hydrogen atoms:

$$^3\mathrm{He}^{++} \ + \ \mathrm{H}_2 \rightarrow \ ^3\mathrm{He}^{+}(2\mathrm{S}) \ + \ \mathrm{H}_2^+ \ . \tag{3}$$

Based on work done by Torres *et al.* with ^{4}He$^+$ and ^{3}He^{++} primary beams, hydrogen produces the largest fraction of singly ionized ^{3}He atoms at 60 keV when compared with argon, nitrogen and neon [10]. At this energy, the charge equilibrium fractions of $\mathrm{F}_{0\infty}$, $\mathrm{F}_{1\infty}$, $\mathrm{F}_{2\infty}$ are 0.806, 0.194 and 0.0004, respectively.

Of particular interest is the fraction of those singly-ionized ^{3}He atoms which are in the 2S metastable state. According to work done by Shah and Gilbody, the cross section for the resonant charge-transfer process which results in a metastable singly-ionized ^{3}He atom is $\sigma_{21*}(\mathrm{H}_2) = 11.6\times10^{-17}$ cm^2 at 58.1 keV [11]. The accuracy of the absolute value for $\sigma_{21*}(\mathrm{H}_2)$ is 15%. Shah and Gilbody also addressed the 1S-2S excitation and found the cross section is about an order of magnitude less at similar energies.

To define the polarization of the metastable helium ions, an external magnetic field is required along the length of the gas cell [12]. The resulting relative populations of the four $2S_{1/2}$ hyperfine sublevels of the $^3He^+$ ions after the charge exchange are given by the following equations:

$$N(F=0, m_F=0) = \frac{1}{4}\left[1 - \frac{P_z x}{\sqrt{1+x^2}}\right] , \tag{4}$$

$$N(1,1) = \frac{1+P_z}{4} , \tag{5}$$

$$N(1,0) = \frac{1}{4}\left[1 + \frac{P_z x}{\sqrt{1+x^2}}\right] , \tag{6}$$

$$N(1,-1) = \frac{1-P_z}{4} , \tag{7}$$

where x is defined as B/B_c and P_z is the longitudinal nuclear polarization of the initial $^3He^{++}$ ions. B is the external magnetic field during charge exchange and the critical magnetic field, B_c, for the $2S_{1/2}$ state of $^3He^+$ is 387 G or 0.0387 T. A small coil is placed around the gas cell to produce the required external magnetic field.

(2) Bending Magnet

In order to create a pure beam of $^3He^+$ ions, a small bending magnet is used to reject neutrals and doubly-ionized ^3He. The neutrals do not bend, while the doubly-ionzed ions bends too much; both species are blocked by a single aperture.

(3) Spin Filter

The spin filter quenches the unwanted β-states (Eqs. 6 and 7) by taking advantage of the lifetime difference between the atoms in the metastable $2S_{1/2}$ state and those in the rapidly decaying $2P_{1/2}$ state. Ions in the $2S_{1/2}$ state have a lifetime of 2×10^{-3} s, while the ions in the $2P_{1/2}$ state only have a lifetime of 10^{-10} s and immediately decay. The long lifetime of the metastable state arises because electric dipole and quadrupole transitions to the ground state are forbidden and the decay rate for magnetic dipole radiation is very small. The long and short states can be mixed in an applied electric field via the stark effect. The metastable lifetime, τ_{2S}, is decreased as a function of the short lifetime, τ_{2P}:

$$\tau_{2S} = \tau_{2P}\left[\nu^2 + \frac{1}{(4\pi\tau_{2P})^2}\right]\left|\frac{h}{V}\right|^2 , \tag{8}$$

where $h\nu$ is the energy difference between the levels involved in the transition. The matrix element of the perturbation energy is $V = (\sqrt{3}/2)eEa_0$, where E is the external electric field in units of V/cm and a_0 is the Bohr radius. Recall from Fig. 4(C) that β-levels of the $2S_{1/2}$ state cross the e-levels $2P_{1/2}$ state at an applied field of 0.75 T. At the level crossing, when $\nu \to 0$, the metastable lifetime is:

$$\tau_{2S} = \frac{1}{16\pi^2 \tau_{2P}} \left| \frac{h}{V} \right|^2 \ . \tag{9}$$

When the external magnetic field is perpendicular to the electric field, the allowed mixing states are those with $\Delta m_J = \pm 1$ or $\alpha - f$ and $\beta - e$. In the case where the electric field is parallel to the magnetic field, the allowed transitions are those where $\Delta m_J = 0$ or $\alpha - e$ and $\beta - f$. In order to selectively quench ions in the β-state, a magnetic field is applied along the direction of motion, while simultaneously applying a transverse electric field. The field strength is chosen such that the flight time through the spin filter is much longer than the lifetime of the β-state but much shorter than that of the α-state.

There are two possible means of quenching the unwanted β-states; either the external magnetic field is sufficiently large to induce mixing or a combination of smaller external magnetic field in conjunction with a radio-frequency (rf) cavity to excite the atoms to transition.

The University of Birmingham successfully implemented a polarized ^{3}He source by using a combination of low magnetic field and rf cavity to induce transitions [13]. Following their source set-up, the beam containing metastable ions enters a radio-frequency cavity situated in an axial magnetic field, $B_z =$ 0.25 T, where the rf cavity is fed with power at a frequency

$$\nu = \omega_0 / 2\pi = 9.4 \times 10^9 \text{ Hz} \ . \tag{10}$$

This frequency corresponds to the energy difference between the β component of the $2S_{1/2}$ state and the e component of the $2P_{1/2}$ state when the external magnetic field is 0.25 T, as illustrated in Fig. 4(C). The cavity provides a transverse electric field, E_x, given by

$$E_x = -\frac{\partial V(x,t)}{\partial x} = E_0 \cos \omega_0 t \ , \tag{11}$$

which induces the transition. The ions in the $2S_{1/2}$ state that are transferred to $2P_{1/2}$ decay rapidly, with probability $\Gamma_{2P}/\hbar$ per unit time, to the ionic ground state and the ion beam is left polarized with electron spin "up".

To calculate the transition probabilities, we will assume any variations of the magnetic field or the rf amplitude are negligible along the beam path. The time-independent energy eigenfunctions of the system are defined as $\phi_n(B_z)$ and the energy eigenvalues are defined as $E_n(B_z)$. The wave function describing the beam of ions at time t is written

$$\Psi(t) = \sum_n c_n(t) \phi \exp(i E_n t / \hbar) \ , \tag{12}$$

where the amplitudes, $c_n(t)$, are given by

$$i\hbar \frac{\partial}{\partial t} c_n(t) = \sum_k c_k \exp[-i\omega_{kn}(B_z)t] V_{nk} - \frac{1}{2} i \Gamma_n c_n \ . \tag{13}$$

The energy difference is $\hbar\omega_{kn} = E_k(B_z) - E_n(B_z)$, $\Gamma_n/\hbar$ is the decay probability of the state ϕ_n and V_{nk} is the matrix element of the perturbation. To approximate the solution, we will assume $\hbar\omega_0 \gg \frac{1}{2}\Gamma_{2P}$ and $|\omega(B_z) - \omega_0| \ll |\omega(B_z) + \omega_0|$. The resulting number of ions that remain in the spin "down" $2S_{1/2}$ state is

$$\begin{aligned} |C_{2S}(t)\text{``down''}|^2 &= \exp\left[-\frac{1.2\times 10^{25} * E_0^2}{(\omega(B_z)-\omega_0)^2 + 2.5\times 10^{19}} t\right] \\ &= \exp\left[-\frac{\Gamma_{\text{Stark}}}{\hbar} t\right] \ , \end{aligned} \tag{14}$$

where $\Gamma_{\text{Stark}}/\hbar$ is the decay constant of the 2S state in the presence of the rf field. This solution is only valid when the decay rate for the 2S state is greater than its natural rate and that the decay is less than that of the 2P state, which implies:

$$500 \ll \Gamma_{\text{Stark}}/\hbar \ll 5\times 10^{-9}\ s^{-1} \ . \tag{15}$$

By substituting for E_0 and ω in Eq. 14, the spin "down" substates decay 68 times faster than the spin "up" substates in an external magnetic field of 0.25 T and $\omega_0 = 2\pi \times 9.4 \times 10^9$ Hz.

Additional quenching, for both spin "up" and spin "down" states arise from off-axis beam particles in their passage through the cavity because of the Lorentz force

$$F = e\vec{v}\times\vec{B} = e\vec{E}_{\text{Lorentz}} \ , \tag{16}$$

which provides an effective electric field, which will lead to some beam loss. For such beams there is also a loss to polarization due to the radial components of the magnetic field, B_z. Neither of these effects have been calculated.

The level crossing method is a simpler solution and was succinctly described by Y.A. Plis at the SPIN98 Conference [14]. According to Fig. 4, the first crossing for the β and e states occurs at approximately 0.75 T. In order to mix the β and e states, an external electric field is applied perpendicularly. With an external magnetic field of 0.75 T, the frequency separation between the α and f state is 28 GHz. Using Eqs. 8 and 9, the lifetimes for the α and β states become:

$$\begin{aligned} \tau_\alpha &= \frac{6.39\times 10^{-2}}{E^2} \ , \\ \tau_\beta &= \frac{5.16\times 10^{-5}}{E^2} . \end{aligned} \tag{17}$$

If L is the length of the magnetic field region, v is the velocity of the ions, then $t = L/v$ is the time of interaction. We'll define ζ as the parameter that describes the quenching of the β-state, where $\exp(-t/\tau_\beta) = \exp(-\zeta)$, and δ is the parameter that defines the quenching of the α-state, such that $\exp(-t/\tau_\alpha) = \exp(-\delta)$. The electric field necessary for quenching the β-state is:

$$E[\text{V/cm}] = 36.2 \cdot \sqrt{\frac{\zeta}{\text{L[cm]}}} \cdot \sqrt[4]{W[\text{keV}]} \ , \tag{18}$$

where W is the energy of the ions. The resulting electric field must also ensure most of the ions in the α state remain unperturbed, so the δ parameter should be less than 10^{-2}.

Assuming the ion beam exiting EBIS is approximately 40 keV, an interaction region of 2 cm and a β decay parameter of $\zeta = 3$, the external electric field must be 110 V/cm, which can be applied with a parallel-plate capacitor. The lifetime of the α-state ions in that electric field is 5.14×10^{-6} s. The total interaction time is 1.25×10^{-8} s, which results in an α decay parameter of $\delta = 2.5 \times 10^{-3}$. In other words, 99.75% of the α-state ions pass through the spin filter without any decay. The population of the remaining ions in the α state, as a function of P_z, is:

$$N(\alpha) = N(0,0) + N(1,1) = \frac{1}{2}\left[1 + \frac{P_z}{2}\left(1 - \frac{x}{\sqrt{1+x^2}}\right)\right] . \tag{19}$$

(4) Detector System

To detect the remaining ^{3}He ions in the α-state, a final external electric field is applied to the beam. By the same Stark mixing process used in the spin filter, the field is sufficiently large such that the lifetime of the $2S_{1/2}$ state decreases and the ions decay to the ground state. The resulting 40.8 eV (304 Å) photons are measured by a photo-multiplier tube which is sensitive to that energy range. Utilizing knowledge garnered by previous experiments, we have chosen a detector design similar to that used by Harrison *et al* and later by Shah and Gilbody [15, 16]. The design, illustrated in Fig. 6, is composed of three cylindrical electrodes coaxial with the beam which provide the required quenching field without transverse deflection of the beam. A potential of up to 3 kV will be applied to the electrode C_2, while both C_1 and C_3 will be held at ground. The cylindrical electrodes will have slits S_1, S_2 and S_3 covered with high transparency, 0.1 μm-thick aluminum (Al) foils. The foils shield the detector from charged particles and are 45% transparent to 40.8 eV photons.

If we measure the photon current for the case of zero polarization (I_0) and for polarized beam (I_+), the polarization equals

$$P_z = \frac{2}{1 - \frac{x}{\sqrt{1+x^2}}}\left(\frac{I_+}{I_0} - 1\right) . \tag{20}$$

Instead of measuring an unpolarized beam, we measure the difference between spin-up and spin-down polarization. By reversing the magnetic field direction in the charge-exchange chamber and the quenching region, the sign of the polarization changes. The projection of the nuclear polarization of the primary beam in the direction of the magnetic field in the polarimeter (before reversal) is:

$$P_z = \frac{2}{1 - \frac{x}{\sqrt{1+x^2}}}\left(\frac{I_+ - I_-}{I_+ + I_-}\right) , \tag{21}$$

where I_+ and I_- are the counts for 40.8 eV photons with the beam in spin-up and spin-down polarizations.

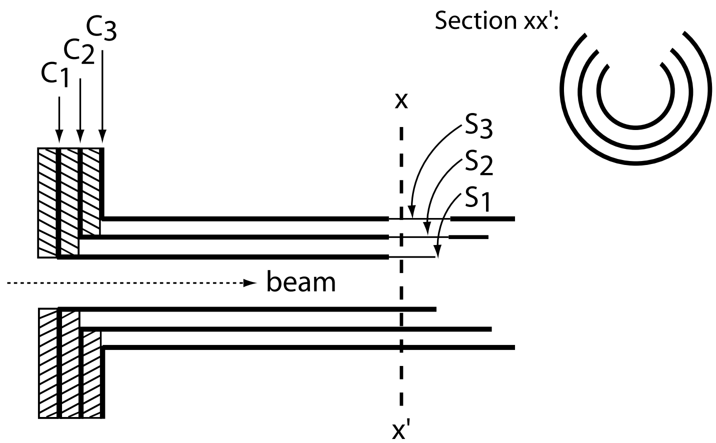


Figure 6: Three cylindrical electrodes coaxial with the beam. 0.1 μm-thick aluminum foils covers the slits S_1, S_2 and S_3. A high potential is applied to C_2, while C_1 and C_3 are held at ground.

Bibliography

[1] J. G. Alessi, E. Beebe, A. Kponou, A. Pikin, K. Prelec, D. Raparia, J. Ritter, and S. Y. Zhang. "A Proposal for an EBIS-Based RHIC Preinjector". *A.I.P. Conference Proceedings*, 572:196–214, 2001.

[2] A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, G. Kuznetsov, and M. Tiunov. "EBTS: Design and Experimental Study". *A.I.P. Conference Proceedings*, 572:3–19, 2001.

[3] G. Altarelli and Ridolfi. "Understanding the Proton Spin Structure: A Status Report". *Nucl. Phys. B (Proc. Suppl.)*, 39B:106–118, 1995.

[4] A. Aipapetian et al. "Precise determination of the spin structure function g_1 of the proton, deuteron, and neutron". *Phys. Rev. D*, 75:012007, 2007. (HERMES Collaboration).

[5] W.-M. Yao et al. "2006 Review of Particle Physics". *J. Phys. G*, 33:1, 2006.

[6] E. W. Hughes and R. Voss. "Spin Structure Functions". *Annu. Rev. Nucl. Sci.*, 49:303–339, 1999.

[7] H.-U. Kauczor et al. "Imaging of the Lungs using 3He MRI: Preliminary Clinical Experience in 18 Patients with and without Lung Disease". *JMRI*, 7:538–543, 1997.

[8] M. Batz et al. "^{3}He Spin Filter for Neutrons". *J. Res. Natl. Inst. Stand. Technol.*, 110:293–298, 2005.

[9] F. D. Colegrove et al. "Polarization of He^3 Gas by Optical Pumping". *Phys. Rev.*, 132:2561–2572, 1963.

[10] P. Torres et al. "Charge Equilibrium Fractions of a Helium Beam in Hydrogen, Nitrogen, Neon, and Argon from 60 to 850 keV". *Phys. Rev.*, 183:216–220, 1969.

[11] M. B. Shah and H. B. Gilbody. "Electron capture and He$^+$(2s) formation in fast He^{2+}-H and He$^+$-H collisions". *J. Physics. B: Atom. Molec. Phys.*, 11:121–131, 1978.

[12] W. Haeberli. "Sources of Polarized Ions". *Annu. Rev. Nucl. Sci.*, 17:373–426, 1967.

[13] W.E. Burcham et al. "A Source of Polarized ^{3}He Ions". *Nucl. Instru. Meth.*, 116:1–7, 1977.

[14] Y. A. Plis. "Lamb Shift Polarimeter for a Helium-3 Ion Beam". In *"13th Symposium on High Energy Spin Physics (SPIN98)"*, Protvino, Russia, 1998.

[15] M. F. A. Harrison, D. F. Dance, K. T. Dolder, and A. C. H. Smith. "Sensitive Detector for Metastable He^{+}(2S) Ions". *Rev. Sci. Inst.*, 36:1443–1447, 1965.

[16] M. B. Shah and H. B. Gilbody. "Charge Transfer in He^{2+}-H collisions in the energy range 6-60 keV". *J. Phys. B: Atom. Molec. Phys*, 7:256–286, 1974.