Design of a Lamb-shift polarimeter for pulsed intense polarized H+/D+ ion sources

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Abstract

An intense spin polarized $H^{+/D}+$ ion source (SPIS) based on the principle of atomic beam source and resonant plasma ionizer is under development at Institute of Modern Physics (IMP, CAS) for the future Electron-ion collider in China (EicC). In order to measure the polarization of the pulsed $H^{+/D}+$ beam extracted from the SPIS at an energy of 25 keV, a Lamb-shift polarimeter (LSP) has been designed. Compared with the polarization measurement utilizing nuclear reactions that demands polarized ion beam accelerated to the MeV level, LSP operated at a low energy is evidently more convenient. Moreover, thanks to its principle, LSP can function normally even in the presence of a mixed H_2^+ component in the extracted polarized D^+ beam, which is inevitable for the polarized ion source utilizing resonant plasma ionizer. An ion beam transport system aiming at modifying the beam spin orientation and decelerating the beam from 25 keV to 2.5 keV is incorporated into the LSP, which enables the LSP to be used directly at downstream of the SPIS. In this work, all of the involved critical physical processes and components of the LSP have been modeled, analyzed and designed carefully to ensure high efficiency at each stage of its operation. Even for a low duty factor pulsed ion beam, the LSP is capable of measuring the polarization with a precision of 1% in a few seconds.

Full Text

Preamble

Design of a Lamb-shift polarimeter for pulsed intense polarized H^+/D^+ ion sources

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An intense spin-polarized H^+/D^+ ion source (SPIS) based on the principle of an atomic beam source with a resonant plasma ionizer is under development at the Institute of Modern Physics (IMP, CAS) for the future Electron-Ion Collider in China (EicC). To measure the polarization of the pulsed H^+/D^+ beam extracted from the SPIS at an energy of 25 keV, a Lamb-shift polarimeter (LSP) has been designed. Compared with polarization measurements utilizing nuclear reactions that require acceleration of the polarized ion beam to the MeV level, the LSP operates at low energy and is evidently more convenient. Moreover, thanks to its operating principle, the LSP can function normally even in the presence of a mixed H_2^+ component in the extracted polarized D^+ beam, which is inevitable for polarized ion sources utilizing a resonant plasma ionizer. An ion beam transport system designed to modify the beam spin orientation and decelerate the beam from 25 keV to 2.5 keV/u has been incorporated into the LSP, enabling it to be used directly downstream of the SPIS. In this work, all critical physical processes and components of the LSP have been carefully modeled, analyzed, and designed to ensure high efficiency at each stage of operation. Even for a low-duty-factor pulsed ion beam, the LSP is capable of measuring polarization with a precision of 1% within a few seconds.

Keywords: Spin polarization, Polarized ion source, Lamb-shift polarimeter

Introduction

The electron-ion collider has been recognized as an ideal tool for exploring the inner structure and interactions of nucleons and nuclei. The Electron-Ion Collider in China (EicC) has been proposed and is currently in the conceptual design phase [1, 2]. The EicC is suggested to be built by upgrading the High Intensity heavy-ion Accelerator Facility (HIAF), which is currently under construction [3, 4]. The featured physics programs at EicC include the emergence of proton spin and mass, nucleon partonic structure, exotic hadron states, and more. To pursue these scientific goals, the EicC is conceptually designed to deliver high-luminosity collisions involving highly polarized electrons, protons, and light ions [5-7]. Therefore, it is essential for the EicC to achieve production, acceleration, and preservation of polarized ion and electron beams. Several research and development (R&D) projects, including key technology prototyping, have already been initiated to support these objectives [8]. As one of these R&D projects for EicC, a spin-polarized ion source (SPIS) to produce intense H^+/D^+ beams with high polarization is under development at the Institute of Modern Physics (IMP, CAS).

Technologies for polarized ion sources have undergone significant development since the 1960s, culminating in considerable progress to the present day. Modern polarized ion sources generate polarized ion beams with intensities at the mA level and polarization of about 80%. In polarized ion sources, the process always involves generating atoms with polarized nuclei followed by ionization to produce polarized ions. Currently, atomic beam-type and optically pumped polarized ion sources (ABPIS and OPPIS), classified by their polarized atom generation method, are primarily used to provide polarized ion beams to accelerators. Various ionization schemes are available for ABPIS and OPPIS to produce positive or negative polarized ions. The performances of several typical polarized ion sources are listed in Table 1 . The status of polarized ion source development has been reviewed in refs. [9, 10].

The SPIS developed at IMP is based on the principle of an atomic beam source with a resonant plasma ionizer. It is designed to produce a polarized H^+/D^+ ion beam of 1 mA at 25 keV, with a pulse width of 100 µs, repetition frequency of 5 Hz, and polarization of no less than 80%. The layout of the SPIS is shown in Fig. 1 [Figure 1: see original paper]. Hydrogen molecules are injected into a dissociator (1) through a pulsed solenoid valve (15) and dissociated into atoms via radio-frequency (RF) discharge. The flow channel of the dissociator is wrapped by a cold copper clip (2) cooled to 70 K by a refrigerator (3) to reduce the velocity dispersion of the atoms. The atomic beam is collimated by a skimmer (4). Two permanent sextupole magnets (5 and 7) and three RF transition units (6, 8, and 9) are used to polarize the atomic beam. By switching on specific sets of RF transition units, beams of desired polarization modes can be produced. The polarized H atoms and D^+ ions from a deuterium plasma jet produced by an arc plasma source (14) are injected toward each other and intersect in a storage cell (13), where polarized protons are formed through quasi-resonant charge exchange reactions [16]: $H + D^+ \rightarrow H^+ + D$.

To avoid depolarization during charge exchange, the storage cell is placed in a solenoid magnet (12) that generates a magnetic field of about 0.3 T, much stronger than the critical field of ground-state hydrogen (deuterium) atoms (B_1S^c,H = 50.7 mT, B_1S^c,D = 11.7 mT) [17]. Both the polarized protons and the unpolarized deuterons are extracted by a beam extraction system (11) and spatially separated by a bending magnet (10). Their currents are measured by a Faraday cup (17) or a beam dump (16), respectively. The beam polarization is then measured by a Lamb-shift polarimeter (18) assembled downstream of the SPIS. When the SPIS operates for a polarized deuteron beam, the inlet gas of the atomic beam source and plasma ionizer are switched. However, it is inevitable that the extracted polarized D^+ beam will be mixed with an unpolarized $H_2{}^+$ component, as D^+ and $H_2{}^+$ ions cannot be separated by the bending magnet. Only after the beam is pre-accelerated can the $H_2{}^+$ ions be stripped into protons and then swept out [13].

Beam polarization is one of the main quantities characterizing a polarized ion beam. For proton (spin-1/2) beams produced by an axially symmetric polarized ion source, it is sufficient to describe the polarization with the vector polarization, P__z = n - n , where n± are the occupation numbers of protons with spin parallel and antiparallel to the quantization axis along z. For deuteron (spin-1) beams, the tensor polarization, P_{zz} = 1 - 3n_0, is required in addition to fully describe their polarization states, where n_0 is the occupation number of deuterons with spin perpendicular to z.

It is necessary to measure the beam polarization quickly and accurately downstream of the SPIS for precise investigation of spin depolarization during subsequent acceleration and for SPIS operation itself. Utilizing suitable nuclear reactions with known and adequate analyzing power and cross-section, beam polarization can be determined from the angular asymmetry of reaction products. However, at a beam energy of 25 keV, there are hardly any competent nuclear reactions unless the beam is pre-accelerated before polarization measurement [13, 18]. This approach requires expensive accelerator time for optimizing and tuning the SPIS.

A Lamb-shift polarimeter (LSP) based on atomic processes sensitive to nuclear spin polarization is preferred in the energy range of several keV [19, 20]. Moreover, an LSP can function normally despite the mixed H_2^+ component within the extracted polarized D^+ beam from the plasma ionizer. Therefore, an LSP is under intense development at IMP for measuring the polarization of beams produced by the SPIS.

II. Principles of Lamb-Shift Polarimeter

The spin filter is the core component of an LSP. It was originally invented for the Lamb-shift polarized ion source (LSPIS) at Los Alamos National Laboratory (LANL) in the late 1960s [21]. The spin filter consists of a solenoid magnet providing a uniform magnetic field B_s parallel to the beam, and a cylindrical RF resonant cavity providing a longitudinal RF electric field E_{rf}, a transverse RF magnetic field B_{rf}, and a transverse static electric field E_s. Installed inside and coaxially with respect to the solenoid, the RF resonant cavity operates in the TM_{010} mode with a frequency of 1610 MHz. It is divided into two pairs of opposing quadruplets: one pair is used for RF power coupling and signal pick-up, while the other pair has a DC voltage applied symmetrically.

The spin filter utilizes a three-level resonance interaction among the n = 2 hyperfine states of hydrogen (deuterium) atoms, first reported in 1951 by Lamb and Retherford [22]. Hydrogen (deuterium) atoms in the 2S state are metastable with a lifetime of 1/7 s, while atoms in the 2P state undergo an allowed electric-dipole decay with a lifetime of 1.6 ns. Fig. 2 [Figure 2: see original paper] shows the $2S_1/_2$ and $2P_1/_2$ levels of the hydrogen atom in an external magnetic field with nuclear hyperfine structure included. The levels are labeled α, β, e, and f based on the nomenclature first introduced by Lamb and Retherford [23]. The notation |m_j, m_I indicates the spin projections of the electron and proton in a strong magnetic field. The energies of states α and e (with electron spin parallel to the magnetic field, m_j = +1/2) increase with magnetic field, while those of β and f (m_j = -1/2) decrease.

In the region around 57.5 mT, the β and e levels cross each other, and the splitting between states α and β(e) is about 1610 MHz. The transverse electric field E_s mixes states β and e, while the longitudinal RF electric field E_{rf} mixes α and e, causing the lifetimes of the metastable α and β states to decrease sharply. In general, all metastable atoms in this region will be quenched into the ground state before exiting the spin filter. Exceptions occur when the α-β resonance is induced by the transverse RF magnetic field B_{rf}, which reduces the α-e resonance, allowing about 50% of atoms in the α state to survive. Note that the width of the α-e resonance is approximately 7 mT depending on the lifetime of state e, whereas that of the α-β resonance is only about 0.5 mT. In other words, superposition of the α-β resonance on the α-e resonance—the α-β-e three-level resonance interaction—makes it possible for atoms in α states to pass through the spin filter without quenching. The three-level resonance is so sharp that it can be observed for each hyperfine state.

As shown in the enlargement of Fig. 2, there are two resonances for hydrogen at 54.0 and 61.0 mT, corresponding to m_I = $±$1/2, respectively. For deuterium, the resonances are at 56.4, 57.4, and 58.4 mT, corresponding to m_I = +1, 0, -1, respectively. With B_s at resonant values, all metastable atoms are quenched within the spin filter except those in the resonant m_I state due to the three-level resonance. Thus, the spin filter can select metastable atoms with a specific m_I by varying the magnetic field B_s.

The layout of the LSP at IMP is shown in Fig. 3 [Figure 3: see original paper]. To make it feasible for the polarized H^+/D^+ beams extracted from the SPIS, an ion beam transport system designed to modify the spin orientation and energy of the beam is incorporated into the LSP, including an Einzel lens, a Wien filter, and a deceleration lens. The polarized proton beam extracted from the SPIS is focused by the Einzel lens into the Wien filter, where the spin orientations of the protons are rotated to align with the beam direction. In the deceleration lens, the beam is decelerated from 25 keV to 2.5 keV/u to ensure sufficient dwell time of metastable atoms in the spin filter, which is a prerequisite for proper spin filter operation [24]. After the deceleration lens, a portion of the protons are converted into metastable hydrogen atoms through charge exchange as they pass through a sodium oven, where a strong magnetic field is employed to prevent depolarization. Subsequently, a spin filter is utilized to quench all metastable atoms except those with the selected m_I, depending on the magnetic field B_s of the spin filter. The residual metastable atoms are later quenched by a quenching lens, and the Lyman-α photons (121 nm) emitted by the transitions are registered by a photomultiplier tube (PMT). As metastable atoms with different m_I are selected in the spin filter, the number of photons counted by the PMT is proportional to the number of metastable atoms with the selected m_I, which in turn is proportional to the number of protons with the selected m_I in the primary ion beam, allowing direct determination of beam polarization. When the LSP is used to measure deuteron beam polarization, the mixed ${H_2}^+$ ions can also be converted into metastable atoms at the sodium oven, and corresponding resonances will appear in the spin filter. However, these resonances are clearly separated due to the distinct resonance values of the magnetic field B_s, allowing measurement of deuteron beam polarization without interference. Because the beam produced by the SPIS is pulsed with an average intensity of 0.5 µA, each component of the LSP has been carefully designed to ensure high efficiency throughout the measurement process in order to achieve adequate statistical precision as quickly as possible [25].

III. Ion Beam Transport

The ion beam transport line, shown in Fig. 4 [Figure 4: see original paper], is located between the ionizer and the sodium oven. As mentioned above, it modifies both the energy (velocity) and spin orientation of the ion beam. Simultaneously, it is optimized to maximize the number of ions entering the acceptance of the downstream sodium oven and spin filter, enabling higher statistical precision to be achieved in shorter time.

The red arrows in Fig. 4 represent the spin orientations of the polarized protons (deuterons). The original spin orientation S_i^(H/D) is determined by the magnetic field in the ionization region. After being bent by the dipole magnet, not only is the beam direction changed, but the spin orientation is also altered. According to the Larmor precession equation, dS/dt = $\times$ B = g(q/2m)S $\times$ B, where S is the spin angular momentum, and , g, q, m are the magnetic moment, g-factor (g_p = 5.586, g_D = 1.714), electric charge, and ion mass of the particle, respectively. Therefore, S precesses around the opposite direction of the magnetic field with angular frequency ω = g(q/2m)B , where B is the component of the magnetic field perpendicular to S. Supposing the effective length of the magnetic field is L and the particle' s speed is v, the precession angle of S can be written as ϕ = ωL/v = g(q/2m)B L/v = gB L/2[B], where relativity is ignored and [B] represents the particle magnetic rigidity. From this equation, it is easy to see that if the dipole magnetic field deflects the ion beam by an angle , the spin orientation will precess around the opposite direction of the dipole magnetic field by an angle of g /2. As depicted in Fig. 4, after being bent by the dipole magnet, the spin orientation is rotated from S_i^(H/D) to S_m^(H/D). Based on the same principle, the Wien filter is used to rotate the spin of protons (deuterons) by a well-defined angle, from S_m^(H/D) to S_f^(H/D), making it parallel (antiparallel) to the beam direction.

Space charge effects during low-energy (25 keV) high-current ion beam transport are inevitable [26]. Based on the quasi-resonant charge exchange ionization scheme, it is estimated that extraction of a 1 mA polarized proton beam is accompanied by an unpolarized deuteron beam of about 50 mA [27]. Although the unpolarized deuterons can be separated in the bending magnet, and almost all space charge effects in the bending magnet can be compensated by electrons produced through collisions between ions and residual gas molecules or beam loss at the vacuum chamber wall [28, 29], there is almost no compensation for space charge in subsequent electrostatic elements, as neutralization electrons are rapidly repelled by the electric fields. For polarized deuteron beams, the space charge effect is more serious because they are always accompanied by unseparated H_2^+ ions.

To determine the optimal configuration of the ion beam transport line, a beam transport simulation was conducted. In the simulation, the beam was considered to be direct current (DC) rather than pulsed. Fig. 5 [Figure 5: see original paper] shows the calculated evolution of the double RMS envelope of a 6 mA deuteron beam (equivalent to D^+ and accompanying H_2^+ with intensities of 1 mA and 5 mA, respectively) at 25 keV from the exit of the ion beam extraction system to the quenching gap facing the PMT window. At the exit of the ion beam extraction system, the beam is cylindrically symmetric with KV distributions in vertical and horizontal directions, and the initial Twiss parameters are set as follows: α_x,y = 0, $\beta x,y = 0.169\ \pi \cdot mm \cdot mrad^{-1}$, {norm},rms,x,y = 0.375 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, adopting results from previous experiments with similar devices [27]. After the exit of the ion beam extraction system, there is a drift section of 100 mm before the dipole magnet. The dipole magnet bends the beam by 90° with a radius of 100 mm and provides focusing force in both vertical and horizontal directions with a pair of inclined pole faces and a field decline indicator of 0.5 [30]. Subsequently, the beam drifts 425 mm to reach the entrance of the Einzel lens. The ion beam transport in this section is calculated using the TraceWin code [31]. The three-dimensional magnetic field of the dipole magnet calculated by OPERA [32] is imported, and the space charge effect is ignored. After the dipole magnet, the deuteron beam passes through the Einzel lens, Wien filter, deceleration lens, and arrives at the sodium oven. At the middle plane of the sodium oven, the deuterons are assumed to be converted to metastable atoms. Following this, the atoms drift through the spin filter and reach the quenching chamber. Simulation for beam transport in this section was performed using the IBSimu code [33]. Space charge effects are accounted for through multiple iterations. Particle trajectories are initially calculated without considering space charge. Subsequently, the corresponding space charge is incorporated based on the previously calculated trajectories, and this process is repeated until the solution converges to the required precision. The ion beam transport through each element is simulated sequentially, with the beam phase space distribution from the end of each element being used as the initial condition for the next element. The transmission efficiency of the ion beam transport is defined as the ratio of the number of particles arriving at the quenching gap to the initial number of particles at the exit of the beam extraction system. According to the simulation, the transmission efficiency of the deuteron beam can be optimized to 4%. For the proton beam, the maximum transmission reaches 8%.

IV. Sodium Oven

In the sodium oven, a portion of protons (deuterons) is converted to metastable atoms through charge exchange. The sodium oven is shown schematically in Fig. 6 [Figure 6: see original paper]. To avoid depolarization, the sodium oven is installed in a solenoid producing a magnetic field of up to 70 mT, which is stronger than the critical field of metastable hydrogen (deuterium) atoms (B_2S^c,H = 6.3 mT, B_2S^c,D = 1.5 mT) [17]. Metal sodium is loaded into a reservoir made of copper. As the reservoir is heated by a coil heater, sodium vapor emerges into a cell channel through openings. Two end plates with central holes of 10 mm limit sodium vapor flow into neighboring elements. Thermal insulation material (ZrO_2) is employed between the end plates and the reservoir. Additionally, cooling water is added to the two end plates. In this way, the temperature of the end plates is always below the melting point of sodium (98°C), which helps reduce sodium vapor diffusion into neighboring elements.

For protons (deuterons) at 2.5 keV/u, the charge exchange cross-section for metastable atom production is about 1×10^{-15} cm^2 [34, 35]. The metastable atom yield depends on the thickness of the sodium target Π. According to previous experimental results, the optimal target thickness Π should be 2×10^{14} cm^{-2}, and the maximum yield is about 0.1 [36, 37]. With a thinner target, protons are more likely to pass through without colliding with sodium atoms. However, with a thicker target, multiple collisions may occur before protons exit, leading to collisional de-excitation of metastable atoms.

The target thickness Π depends on the reservoir temperature. To determine a suitable reservoir temperature for achieving the optimal target thickness Π, sodium evaporation has been simulated using the Molecular Flow Module of COMSOL [38-40]. In the simulation, the bottom of the reservoir is set as an evaporation surface. The evaporation rate–the number of sodium atoms evaporated from the surface per unit area per unit time–is determined by the surface temperature as Q = αN_A√(M/2πRT)P_s(T), where N_A is Avogadro's number, M = 23 g/mol is the molar mass of sodium, R = 8.314 $J \cdot K^{-1} \cdot mol^{-1}$ is the gas constant, T [K] is the temperature of the evaporation surface, α is the evaporation coefficient, and P_s(T) is the saturated vapor pressure of sodium as a function of temperature T [K]. The dependence of P_s on temperature is given by [41]: log_{10}P_s [mmHg] = -5300/T[K] - 0.5log_{10}T[K] + 9.235.

Fig. 7(a) shows the simulated number density distribution of sodium atoms along the oven axis for different reservoir temperatures. Outside the cell channel (-40 to 40 mm), the number density of sodium atoms decreases rapidly. The integration of atom number density along the axis–that is, the target thickness –is shown in Fig. 7(b) [Figure 7: see original paper] as a function of reservoir temperature. At 525 K, the sodium atom thickness is about 2×10^{14} cm^{-2}, a suitable value for metastable atom production, and the average pressure in the reservoir is about 0.2 Pa. The actual operation temperature of the reservoir should be higher than 525 K because the evaporation coefficient is set to the ideal value of 1 in the simulation.

A steady-state thermal analysis of the sodium oven has been performed with ANSYS [42]. The thermal conductivities of copper and ZrO_2 are set to 400 and 2 $W \cdot m^{-1} \cdot K^{-1}$, respectively. The cooling water loop on the end plate is carefully designed. At the inlet, water speed and temperature are specified as

1.5 m/s and 20°C, respectively. At the outlet, water pressure is set to 0 Pa. When the coil heater power is 300 W, the simulated steady-state temperature distribution is shown in Fig. 8 [Figure 8: see original paper]. With a reservoir temperature of 250°C, the periphery of the sodium oven maintains a significantly lower temperature. According to further simulations, even with higher heater power and reservoir temperature (such as 450°C), the periphery of the sodium oven remains below 50°C.

V. Spin Filter

The spin filter is shown schematically in Fig. 9 [Figure 9: see original paper]. It consists of a solenoid magnet and an RF resonant cavity. Because the spin filter is based on three-level resonance interaction, inadequate homogeneity of the static magnetic field (B_s) provided by the solenoid magnet can cause unexpected quenching of metastable atoms. A successful spin filter for polarimetry requires an axial magnetic field uniform to $±$0.05 mT over the central region of the spin-filter cavity [43]. The solenoid magnet comprises five windings (C1, B1, A, B2, and C2) wound around copper skeletons. The winding system has been optimized with OPERA [32]. As shown in the inset of Fig. 10 [Figure 10: see original paper], the fluctuation of the solenoid magnetic field is less than $±$0.02 mT at 60 mT over the central region of the spin filter cavity. To shield against interference with magnetic field uniformity caused by external fields—especially the fringe field from the upstream sodium oven—all windings are enclosed by iron yokes. In addition, to avoid frequency shifts of the RF resonant cavity due to thermal expansion, an interlayer for water cooling is designed in the copper skeleton, which effectively prevents heat transfer from the windings to the cavity. It should be noted that the magnetic field in the spin filter must be parallel to the field in the sodium oven; otherwise, unwanted Sona transitions may occur in the zero-crossing region, distorting the polarization measurement results [44].

The RF resonant cavity is a cylindrical cavity with a length of 82 mm and a radius of 75 mm. Each end of the cavity is fitted with an end pipe of smaller radius (30 mm). The cavity is split into four sectors. One pair of opposing sectors are grounded and serve for RF feeding and sampling. The other two sectors have symmetric voltages applied, generating a transverse electric field inside the cavity. The slots between these sectors can be manipulated to fine-tune the cavity' s resonance frequency to 1610 MHz. Fig. 10 [Figure 10: see original paper] illustrates the simulated distribution of the longitudinal RF electric field (dash-dotted E_{rf} line). Similarly, the two end pipes are also divided into four sectors. The sectors adjacent to the RF feeding and sampling sectors of the cavity are grounded, while the other two are floated and can have symmetric voltages applied. This setup allows the static electric field within the cavity and end pipes to be altered independently. As shown by the dotted (E_{s1}) and dashed (E_{s2}) lines in Fig. 10, besides the transverse static electric field of 10–20 V/cm inside the cavity, an enhanced field of about 50 V/cm is established in the end pipes. This stronger field is designed to deflect protons (deuterons) that fail to capture an electron in the sodium oven. This deflection is essential because these protons (deuterons) can reach the downstream quenching chamber and induce a non-linear background signal in the PMT that fluctuates with the magnetic field of the spin filter, making signal processing challenging.

An effective spin filter should possess two key characteristics. First, it should exhibit high transmission for metastable atoms in resonant m_I states, facilitating acquisition of high statistical precision in shorter measurement times. Second, a good spin filter must demonstrate high selectivity for metastable atoms with different m_I values, which is fundamental for accurate beam polarization measurement. Both transmission and selectivity depend on various factors, including the velocity of metastable atoms, uniformity of the axial static magnetic field, and distributions of the static electric fields and RF fields. While established general principles exist from prior calculations and experiments, an effective spin filter design requires quantitative and comprehensive evaluation of transmission and selectivity under various design parameters.

These calculations can be conducted using a time-dependent quantum mechanical approach to analyze the atomic four-level system (α, β, e, and f levels), as done in refs. [45, 46]. The spin filter operates in a magnetic field (50–60 mT) much stronger than the critical magnetic field B_c of hydrogen (deuterium) atoms in 2S and 2P states. Therefore, the quantum number m_I is conserved, and each group of four atomic levels associated with the same m_I can be considered individually. The perturbed Schrödinger equation may be written as:

$(\hat{H}_0 + \hat{H}' \ ) \ = i\hbar \ / \ t$

where H_0 is a Hamiltonian including the influence of an ideal uniform static magnetic field, whose eigenfunctions satisfy H_0u_n = E_{nu}n, and H' symbolizes perturbations from the RF fields, static electric field, and fluctuating static magnetic field. Expanding the atomic wave function with u_n, the coefficients a_k(t) satisfy the differential equations:

= Σ_n a_n(t)u_n e^(-iE_{nt}/ħ)
iħȧ_k = Σ_n H' *{kn} a_n e^(iω*{kn} t)
ω{kn} = (E_k - E_n)/ħ
H' {kn} = u_k*Ĥ' u_n dτ

The perturbation matrix elements H' _{kn} can be calculated and are given in ref. [46]. Damping terms accounting for spontaneous decay of the e and f states can also be included. A Python code has been written to calculate the time evolution of individual α, β, e, and f state amplitudes (denoted as a, b, c, and d) by numerical integration.

The left plot of Fig. 11 [Figure 11: see original paper] shows the time evolution of $|a|^2$ and $|a|^2 + |b|^2$ for three different field configurations as an α-state deuterium atom with m_I = 0 passes through the spin filter with an energy of 2.5 keV/u.

Case has a uniform electrostatic field of 15 V/cm, the realistic RF electric field, and static magnetic field shown by the dash-dotted (E_{rf}) and solid (B_s) curves in Fig. 10, respectively. In cases and , the uniform electrostatic field is replaced with realistic fields shown by the dotted (E_{s1}) and dashed (E_{s2}) curves in Fig. 10, respectively. The central values of E_{s1} and E_{s2} are 15 and 6 V/cm, respectively. Comparing the time-evolution curves, due to deflection electric fields at the entrance and exit of the spin filter, the decay of metastable atoms in cases and is more rapid than in case . The adiabatic variation of $|b|^2$ with E_{rf}, as described in ref. [46], is clearly evident in the time-evolution curves. From the entrance to the exit of the spin filter, as E_{rf} increases gradually, the deuterium atom becomes a coherent mixture of α and β states; then as E_{rf} slowly decreases to zero, the α and β mixture is transformed back into a pure α state. There is severe adiabatic loss for case . As the central value of E_s increases from 6 to 15 V/cm, the adiabatic loss gradually diminishes, leading to increased transmission.

The calculated transmission of metastable atoms, represented as $|a|^2 + |b|^2$ at the exit of the spin filter, is a function of the B_s value. The B_s value is swept from 55.5 to 59.5 mT while maintaining its distribution as shown in Fig. 10. The variations of transmission for metastable deuterium atoms with different m_I in these three cases are illustrated in the right plot of Fig. 11, which also indicates the measurement spectra. Based on the calculated spectra, increasing the central value of E_s leads to higher transmission but also produces a spectrum with larger width and worse selectivity. Although transmission in case is higher, it is unsuitable for separating metastable deuterium atoms with different m_I due to overlapping resonant peaks. Case , however, is more favorable for separating metastable hydrogen atoms because their two resonant peaks are more distant.

VI. Detection for Metastable Atoms

At the end of the transport line, surviving metastable atoms are quenched by the electric field of a quenching lens, and the emitted Lyman-α photons (121 nm) are registered by a PMT sensitive only to photons with wavelengths of 110–200 nm. The lifetime of metastable hydrogen (deuterium) atoms with a moderate electric field can be approximated as:

$$\tau = 1.6 \times 10^{-9} \text{ s} \times (1 + 2.6 \times 10^{-9} \text{ E}^2) \,/\, (2.6 \times 10^{-9} \text{ E}^2)$$

where E is the magnitude of the electric field in V/cm [23]. The kinetic energy of the atomic beam is 2.5 keV/u (7×10^7 cm/s). To achieve high detection efficiency for metastable atoms at this energy, the first gap width and electric field of the quenching lens are set to 2 cm and 200 V/cm, respectively. Under these conditions, the lifetime of metastable atoms (9 ns) is much shorter than the drift time in the gap (30 ns), ensuring that all metastable atoms are quenched in the first gap. The PMT window is located 8 cm from the beam axis with an effective diameter of 23 mm, giving a geometric acceptance of 0.5%. The quantum efficiency of the photocathode (made of CsI) is considered to be 10%. Overall, the detection efficiency for metastable atoms is about 0.05%.

VII. Results and Discussion

Based on quantitative analyses of all critical processes in the LSP, the number of Lyman-α photons detected at the quenching chamber can be calculated. A beam of protons (deuterons) with intensity of 1 mA (6×10^{15} ions per second) enters the ion beam transport line. Due to severe space charge effects, only 8% (4%) of protons (deuterons) can pass through the downstream elements. At the sodium oven, 10% of protons (deuterons) are converted to metastable atoms. Half of the metastable atoms remain in α states (the other half in β states), as there is no polarization at the sodium target. Additionally, the fractions of α-state atoms with m_I = $±$1/2 (m_I = $±$1, 0) are 1/2 (1/3) under the assumption that the proton (deuteron) beam is unpolarized. After traversing the spin filter, 45% (25%) of α-state hydrogen (deuterium) atoms with the selected m_I remain in the metastable state. Considering the detection efficiency of 0.05% for metastable atoms at the quenching chamber, the expected peak count rate of the PMT will be around 3×10^9 (5×10^8) photons per second. For each 100 µs beam pulse, the number of detected photons is 3×10^5 (5×10^4) per pulse, yielding a statistical error of about 0.4%. To achieve a spectrum as depicted in the right plot of Fig. 11, it is necessary to ramp the magnetic field of the spin filter from 50 to 65 mT in increments of 0.3 mT. The time allocated for each step should be 200 ms, ensuring at least one beam pulse occurs during each step. This approach allows the entire spectrum to be recorded within a total duration of 10 s.

The background is considered to be dominated by collisions between ground-state atoms produced by charge exchange in the sodium oven and residual gas [20]. The flux of ground-state atoms from the sodium oven is N 10^{14} atoms per second, which is three times that of metastable atoms [37]. If the pressure in the quenching chamber is $p = 1 \times 10^{-6}$ mbar, the collision rate in front of the PMT window can be calculated as $n = N \cdot \pi d^2 \cdot L \cdot p/kT$ 2×10^9 collisions per second, where $d = 1 \times 10^{-10}$ m is the atom diameter, L = 2 cm is the length facing the PMT window, $k = 1.38 \times 10^{-23}$ J/K is Boltzmann' s constant, and T = 300 K is room temperature. Estimating that 10% of collisions produce 110–200 nm photons and that 0.05% of them are detected by the PMT, the background count rate is about 10^5 s^{-1} during beam duration. The signal-to-background ratio is expected to be 10^3–10^4.

Some corrections are necessary due to systematic factors, and these corrections depend on the properties of LSP components. The corrections can be determined with the polarimeter itself. A systematic error of about 0.4% in the correction factors is reasonable [20]. Therefore, it is feasible to measure the pulsed polarized proton (deuteron) beam using the designed LSP with a precision of 1% in a few seconds.

VIII. Summary

A Lamb-shift polarimeter tailored for the pulsed high-current polarized H^+/D^+ ion source has been systematically investigated in this study. Beam transport in the ion beam transport line, engineered to match the polarized beam extracted from the ionizer with the LSP, has been simulated and optimized. The design of the sodium oven for converting protons (deuterons) to metastable atoms has been completed, and its operating status has been characterized through evaporation and thermal simulations. A spin filter has been designed, including a system of solenoidal windings with homogeneity better than 0.05% and a specific RF resonant cavity. The time evolution of the wave function of metastable hydrogen (deuterium) atoms in the spin filter has been calculated through numerical integration. A metastable atom detection unit has also been designed. Based on these calculations, it is expected that proton (deuteron) beam polarization can be measured with a precision of 1% within a few seconds using the designed LSP assembled directly downstream of the polarized ion source. The LSP is being fabricated and will be integrated in a test bench with the SPIS in 2025. It will be an indispensable tool for tuning and optimizing the SPIS at IMP to produce proton (deuteron) beams with higher polarization. In fact, the LSP is capable of measuring the polarization of $H\pm/D\pm$ [25] and even ${H_2}^+/{D_2}^+$ ion beams [47]. Coupled with an ionizer, the LSP can also be employed to measure the polarization of H/D gas targets.

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