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HIGH INTENSITY SOURCE OF He NEGATIVE IONS

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Abstract

He- ion can be formed by an attachment of additional electron to the excited metastable 2^3S_1 He atom. Electron affinity in this metastable He^- ion is A=0.08 eV with excitation energy 19.8 eV. Production of He^- ions is difficult because the formation probability is very small but destruction probability is very high. Efficiency of He- ions generation was improved by using of an alkali vapor targets for charge exchange He^- sources. Low current He^- beams were used in tandem accelerators for research and technological diagnostics (Rutherford scattering). The development of high-intensity high-brightness arc-discharge ion sources at the Budker Institute of Nuclear Physics (BINP) has opened up an opportunity for efficient production of more intense and more brighter He- beam which can be used for alpha particles diagnostics in a fusion plasma and for realization of a new type of a polarized $^3He^-$ ion source. This report discusses the high intense He- beams production and a polarized $^3He^-$ ion source based on the large difference of extra-electron auto-detachment lifetimes of the different $^3He^-$ ion hyperfine states.

INTRODUCTION

The parameters of the Electron-Ion Collider projects that are being actively developed by BNL and JLab are discussed in Ref. [1]. Advanced spin control techniques used in these projects should provide very good polarization preservation including ^{3}He and D polarization. This means that the final beam polarization after acceleration will be determined by the beam polarization extracted from the ion source which must be made as high as possible. Polarized ^{3}He ions are particularly important for efficient electron-ion collider operation.

A review of the polarized ^{3}He ion beam production has been presented in Ref. [2]. Early ion sources have polarized ^{3}He ion beam intensities of nA scale. Since the efficiency of experiments is proportional to the square of the polarization, P^2, having the highest possible degree of polarization is very important. For polarized $^3He^{++}$ production, it was proposed to use ionization of nuclear-polarized $^3He^0\uparrow$ by electrons in an electron beam ion source (EBIS) [2, 3]:

$$^3He^0\uparrow + e \rightarrow {}^3He^{++}\uparrow + 3e$$

The expected beam intensity is about $2.5\cdot10^{13}He^{++}$/pulse with nuclear polarization P >70 %.

For polarized $^3He^{++}$ production, one can also use the high-current arc-discharge source (developed at BINP [4] and used in the BNL OPPIS upgrade [5]) with pulsed injection of nuclear-polarized $^3He^0\uparrow$ atoms (polarized by optical pumping) into an arc-discharge plasma source [6]. For protection of the nuclear polarization during the step-by-step ionization, a strong magnetic field can be used.

Another proposed technique [7] is to use resonant charge-exchange ionization of polarized $^3He^0\uparrow$ in a storage tube by an incident $^4He^+$, $^4He^{++}$ plasma jet produced by an arc-discharge ion source [4]:

$$^3He^0\uparrow + {}^4He^{++} \Rightarrow {}^3He^{++}\uparrow + {}^4He^0$$

The proposed methods of polarized ^{3}He ion production were discussed but were never tested.

POTENTIAL OPTIONS FOR PRODUCTION OF POLARIZED $^3He^-$ IONS

An intense beam of polarized $^3He^-$ ions could be produced using the high-brightness arc-discharge ion source with geometrical focusing and low gas consumption developed at BINP and used in the BNL OPPIS upgrade [8]. Earlier this arc-discharge source was used for high-intensity (12 mA) He^- beam production [9]. A schematic of this device is shown in Fig. 1. An intense high-brightness flow of He^+ ions is generated in the arc-discharge source (1) and formed into an ion beam by a multi-grid multi-slit flat extraction system of 4 cm in diameter. This intense space-charge-compensated beam is focused by a magnetic lens (2) into a sodium jet charge-exchange target (3). A part of He^+ ions captures two electrons from Na atoms and forms metastable He^- ions. The beam of He^- ions is deflected from the more intense beams of He^+ and He^0 in an analyzing magnet (4) and detected by a FC (5). The secondary electron emission is suppressed by a suppression electrode. The beam profiles are controlled by profile monitors (6) and (7). Under the optimal conditions at the energy of 12 keV, up to 1.5% of He^+ ions were converted into He^- producing a 12 mA He^- beam. The estimated He^+ beam intensity transferred to the FC is ~ 0.8 A. With a modern spherical multi-aperture extraction system, it is possible to have He^+ beam with an intensity of ~ 2 A.

With a 2 A $^3He^+$ beam current, up to 0.1 A of a $^3He^-$ beam can be produced by charge exchange in an alkali vapors target yielding up to 2 mA of highly polarized $^3He^-$ ions [4, 6].

A pulsed gas valve [10] can provide low gas consumption, which is important because ^{3}He gas is very expensive. The basic idea of this proposal can be traced back to the alpha particle diagnostics that is being developed for the ITER project in France.

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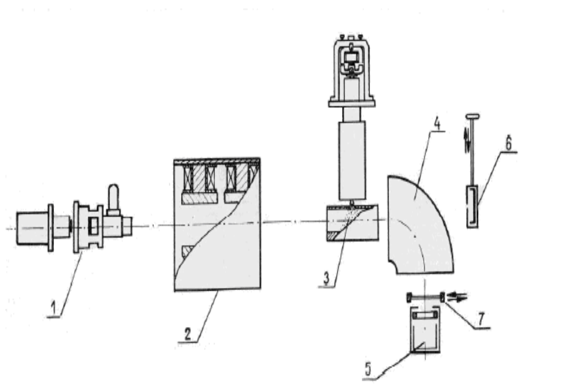

Figure 1: 1 - arc-discharge He^+ ion source, 2 - quadrupole lens, 3 -sodium jet charge-exchange target, 4 - magnetic analyzer, 5 - Faraday cup with suppressor, 6 - beam profile monitor, 7 - beam profile monitor (scintillator).

A 1 MeV 10 mA He^- ion source is under development for this purpose (He^+ current should be ~3 A with a low emittance) [11]. Fast ground-state He^0 is produced by electron auto-detachment from metastable He^- ions. Metastable He^- has three different lifetimes of ~10 μs, ~16 μs, and ~350 μs.

We started by looking for differences of lifetimes of the different hyperfine states to use these differences for polarized $^3He^-$ production as described earlier. We found that these differences indeed exist and therefore make polarized $^3He^-$ production possible [13,16-17]. A theoretical estimation of the auto-detachment lifetimes of the different states of He^- ions was presented in Ref. [12]. The calculated fine and hyperfine structures of the (1s, 2s, 2P) 4P states of $^3He^-$ and $^4He^-$ are shown in Fig. 2.

PROPOSAL FOR AN EXPERIMENTAL TEST OF $^3He^-$ PRODUCTION

Using the arc discharge source (developed at BINP and used in OPPIS [4, 5, 8]), one can extract up to ~2 A of 6-12 keV He^+ with good emittance and obtain up to ~0.1 A of He^- by charge exchange in a potassium jet target. ^4He gas can be used in first experiments on He^- production. After some time of flight (~30 μs, ~30 m) in magnetic field, ions with momentum components 1/2 and 3/2 should be auto-ionized (up to 95%) leaving only $^3He^-$ ions with components |5/2, ±5/2>. Then, using RF to induce a transition of one of the components to the zero state, one can produce a $^3He^-$ beam with nuclear polarization close to ~95%. A schematic of the proposed experiment using BNL equipment to measure the He^- beam production is shown in Fig. 3. A high-brightness He^+ ion beam (7) with an intensity of up to 3 A and an energy of ~10-15 keV is generated by an arc-discharge plasma source (1) and formed by a multi-grid focusing extraction system (2). A pulsed Xe gas target (3) is used for space charge compensation and metastable He* production. A vapor jet target (4) (K, Rb or Cs) can be used for He^+ to He^- beam (9) conversion. Short-lived He^- ions can eject electrons during their flight in the decay channel (6) with solenoid and RF transition producing a polarized $^3He^-$ beam (10) as shown in Fig. 4.

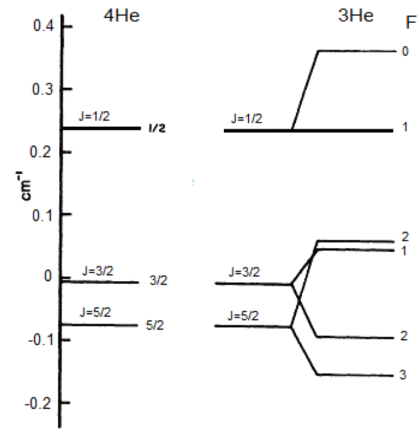

Figure 2: Calculated fine and hyperfine structure of (1s, 2s, 2p) 4P states in $^4He^-$ and $^3He^-$ [12].

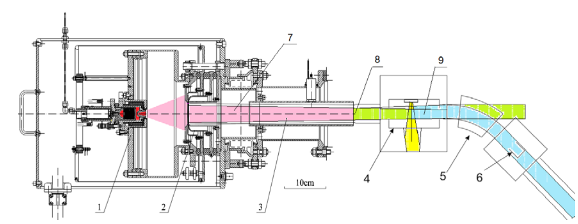

Figure 3: Schematic of an experiment on He^- beam production: 1- He^+ source, 2 - extraction system, 3 - space charge compensation, 4 - Cs (Rb, K) jet target, 5 - bending magnet, 6 - decay channel with solenoid and RF transition, 7 - e^+ beam, 8 - space-charge compensated beam, 9 - He^- beam.

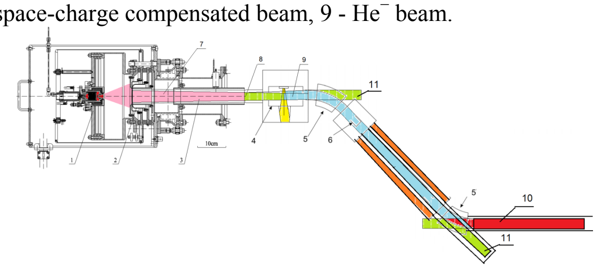

Figure 4: Schematic of a $^3He^-$ ion source: 1 - arc-discharge He^+ source, 2 - extraction system, 3 - space charge compensation, 4 - Cs (Rb, K) target, 5 - bending magnet, 6 - decay channel with solenoid and RF transition, 7 - He^+ beam, 8 - space-charge compensated beam, 9 - He^- beam, 10 - polarized $^3He^-$ beam, 11 - ^3He neutral beam.

To prevent intra-beam stripping, the He^- beam is separated from the intense He^+ and He^0 beams by a bending magnet (5).

He^- ions have an electron affinity A = 0.08 eV. The blackbody radiation with a temperature T of ~300 K ~0.03 eV has some photons in its energy distribution with energies >0.08 eV able to destroy He^- ions by photo-detachment.

An experimental detection of the He^- ion destruction by the blackbody radiation was conducted in [14,15] using a cryogenic electrostatic ion trap. $^4He^-$ ions in these

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experiments were produced in double collisions ($^4He^+$ + Cs -- $^4He^*$, $^4He^*$ + Cs -- $^4He^-$) of 2.5 keV $^4He^+$ in a cesium charge-exchange cell.

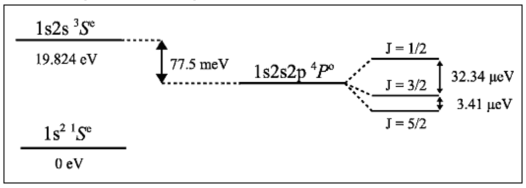

Figure 5: Schematic energy diagram of the ground state and the lowest excited state of ^{4}He and of the 1s2s2p 4Po state of $^4He^-$ [13].

From the measured temperature dependence of the lifetime of the 1s2s2p $4P^o_{5/2}$ level of $^4He^-$, it was determined that, with increase of the trap temperature above 100 K, the He^- lifetime decreases from 360 μs to 280 μs. To prevent photo-destruction of polarized $^3He^-$ by the blackbody radiation, it is necessary to keep the decay channel at a temperature below 100 K. Figure 5 shows schematic energy diagram of the ground state and the lowest excited state of ^{4}He and of the 1s2s2p 4Po state of $^4He^-$ [13].

The He^-/He^+ yield and beam intensity vs He^+ energy with an optimal potassium target presented in [18]. More than 5% of He^+ ions can be converted into He^- ions. With 2 A He^+ current from the BINP arc-discharge source, it is possible to produce ~50-100 mA of He^- ions. Up to ~2 mA of $^3He^-$ with high nuclear polarization can be produced.

For a preliminary feasibility test of He^- ion production, one can use an upgraded BNL OPPIS assembly [6,9] as shown in Fig. 4 with a low solenoid current. The He^+ beam can be generated by an arc-discharge plasma source and formed using a multi-grid extraction system with space charge compensation by a pulsed Xe target. The He^- beam can be generated using charge exchange in a Rb cell in a weak magnetic field with and without optical pumping. Furthermore, other configurations of the BNL OPPIS assembly can be used to study $^4He^-$ production in a Rb cell as well as He^- production with a K jet charge-exchange cell.

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