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 2S1 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 3He 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 3He+ ions are particularly important for efficient electron-ion collider operation.

A review of the polarized 3He ion beam production has been presented in Ref. [2]. Early ion sources have polarized 3He ion beam intensities of nA scale. Since the efficiency of experiments is proportional to the square of the polarization, P2, having the highest possible degree of polarization is very important. For polarized 3He++ production, it was proposed to use ionization of nuclear-polarized 3He+ by electrons in an electron beam ion source (EBIS) [2, 3]:

\[ 3\text{He}^+\rightarrow 3\text{He}^++3e \]

The expected beam intensity is about 2.5⋅10^13 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+ 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+ in a storage tube by an incident 4He+, 4He++ plasma jet produced by an arc-discharge ion source [4]:

\[ 3\text{He}^0++4\text{He}^+\rightarrow 3\text{He}^{++}++4\text{He}^0 \]

The proposed methods of polarized 3He 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 He0 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 He+ 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 3He 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.
A 1 MeV 10 mA He\(^-\) ion source is under development for this purpose (He\(^-\) current should be ~3 A with a low emittance) \cite{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 \(^3\)He\(^-\) production as described earlier. We found that these differences indeed exist and therefore make polarized \(^3\)He\(^-\) production possible \cite{13,16-17}. A theoretical estimation of the auto-detachment lifetimes of the different states of He\(^-\) ions was presented in Ref. \cite{12}.

The calculated fine and hyperfine structures of the (1s, 2s, 2p) 4P states of \(^3\)He\(^-\) and \(^4\)He\(^-\) are shown in Fig. 2.

**PROPOSAL FOR AN EXPERIMENTAL TEST OF \(^3\)He\(^-\) PRODUCTION**

Using the arc discharge source (developed at BINP and used in OPPIS \cite{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. \(^4\)He 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 \(^3\)He\(^-\) ions with components \(5/2, \pm 5/2\>\). Then, using RF to induce a transition of one of the components to the zero state, one can produce a \(^3\)He\(^-\) beam with nuclear polarization close to ~95%. A schematic of the proposed experiment using BNL equipment to measure the \(^3\)He\(^-\) beam production is shown in Fig. 3. A high-brightness \(^3\)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 \(^3\)He\(^-\) beam (10) as shown in Fig. 4.

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 photodetachment.

An experimental detection of the He\(^-\) ion destruction by the blackbody radiation was conducted in \cite{14,15} using a cryogenic electrostatic ion trap. \(^4\)He\(^-\) ions in these
experiments were produced in double collisions ($^4$He$^+$ + Cs $\rightarrow$ $^4$He*, $^4$He* + Cs $\rightarrow$ $^4$He$^-$) of 2.5 keV $^4$He$^+$ in a cesium charge-exchange cell.

Figure 5: Schematic energy diagram of the ground state and the lowest excited state of $^3$He and of the 1s2s2p $^4$Po state of $^4$He [13].

From the measured temperature dependence of the lifetime of the 1s2s2p $^4$Po$^{5/2}$ level of $^4$He$^-$, 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 $^3$He$^-$ 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 $^3$He and of the 1s2s2p $^4$Po state of $^4$He [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 $^3$He$^-$ 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 He$^-$ production in a Rb cell as well as He$^+$ production with a K jet charge-exchange cell.

REFERENCES


