HIGH INTENSITY SOURCE OF He NEGATIVE IONS

V. Dudnikov [#], Muons, Inc., Batavia, IL 60510, USA, V. Morozov, Jefferson Laboratory, Newport News, VA 23606, USA and A. Dudnikov, BINP, Novosibirsk, Russia

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 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, 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 ^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 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 ^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.

[#] Vadim@muonsinc.com

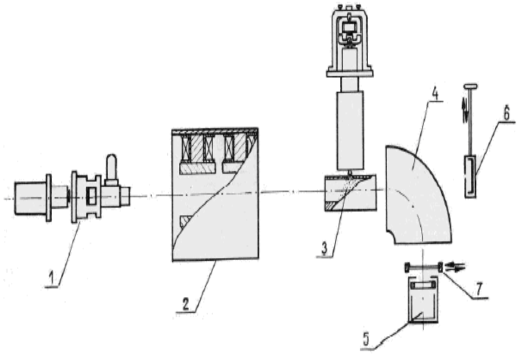

Figure 1: 1 - arc-discharge He$^+$ ion source, 2 - quadrupole lens, 3 -sodium jet charge-exchange target, 4 - magnetic analyzer, 5 - Faraday cup with suppressor, 6 - beam profile monitor, 7 - beam profile monitor (scintillator).

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 ^{3}He$^-$ production as described earlier. We found that these differences indeed exist and therefore make polarized ^{3}He$^-$ 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 ^{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 [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, ±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 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 ^{3}He$^-$ beam (10) as shown in Fig. 4.

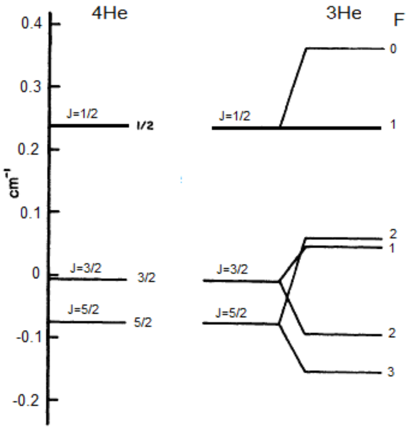

Figure 2: Calculated fine and hyperfine structure of (1s, 2s, 2p) 4P states in ^{4}He$^-$ and ^{3}He$^-$ [12].

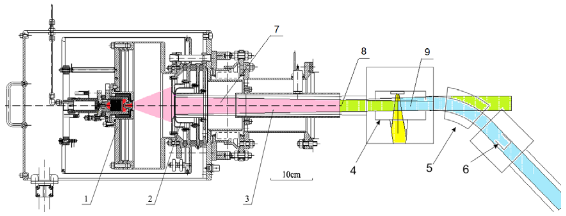

Figure 3: Schematic of an experiment on He$^-$ beam production: 1- He$^+$ source, 2 - extraction system, 3 - space charge compensation, 4 - Cs (Rb, K) jet target, 5 - bending magnet, 6 - decay channel with solenoid and RF transition, 7 - e$^+$ beam, 8 - space-charge compensated beam, 9 - He$^-$ beam.

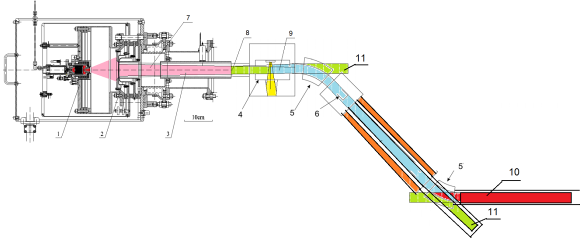

Figure 4: Schematic of a ^{3}He$^-$ ion source: 1 - arc-discharge He$^+$ source, 2 - extraction system, 3 - space charge compensation, 4 - Cs (Rb, K) target, 5 - bending magnet, 6 - decay channel with solenoid and RF transition, 7 - He$^+$ beam, 8 - space-charge compensated beam, 9 - He$^-$ beam, 10 - polarized ^{3}He$^-$ beam, 11 - ^{3}He 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. ^{4}He$^-$ ions in these experiments were produced in double collisions ($^4He^+$ + Cs -- $^4He^*$, $^4He^*$ + Cs -- $^4He^-$) of 2.5 keV $^4He^+$ in a cesium charge-exchange cell.

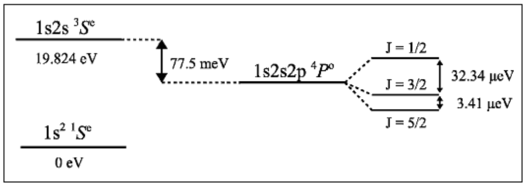

Figure 5: Schematic energy diagram of the ground state and the lowest excited state of ^4He and of the 1s2s2p 4Po state of $^4He^-$ [13].

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 ^4He 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.

REFERENCES

[1] V. Dudnikov, V. Morozov, and A. Dudnikov, "Polarized 3He− ion source with hyperfine state selection", AIP Conference Proceedings 1655, 070006 (2015).

[2] A. Zelenski, J. Alessi, E. Beebe, A. Pikin, M. Farkhondeh, W. Franklin, A. Kocoloski, R.Milner, C. Tschalaer, E. Tsentalovich, E. Hughes, "A proposal for a polarized $3He^{++}$ ion source with the EBIS ionizer for RHIC," SPIN 2004, Trieste, Italy, 2004.

[3] J. Maxwell, "Polarized He-3 source development for RHIC," 2013 International Workshop on Polarized Sources, Targets & Polarimetry (PSTP), Charlottesville, September 2013, http://pos.sissa.it/archive/conferences/182/047/PSTP2013_047.pdf

[4] Yu. I. Bel'chenko, V. I. Davydenko, G. E. Derevyankin, G. I. Dimov, V. G. Dudnikov, I. I. Morozov, G. V. Roslyakov, A. L. Shabalin, Rev. Sci. Instrum. 61, 378-384 (1990).

[5] A. Zelenski et. al., "RHIC polarized source upgrade," 2013 International Workshop on Polarized Sources, Targets & Polarimetry (PSTP), Charlottesville, September 2013.

[6] V. Dudnikov, "Perspectives of highly polarized ion sources development," 2013 International Workshop on Polarized Sources, Targets & Polarimetry (PSTP), Charlottesville, September 2013, http://pos.sissa.it/archive/conferences/182/071/PSTP2013_071.pdf; http://pos.sissa.it/archive/conferences/182/050/PSTP2013_050.pdf

[7] A. Belov, "Production of polarized ions with nearly resonant charge-exchange collisions in plasma," PSTP-2007, BNL, USA, AIP Conference Proceedings 980 (2008), pp. 209-220.

[8] A.N. Zelensky, "Towards 100% polarization in the ion source," BNL report, 2005.

[9] G. Roslyakov, G. Dimov, Pribory i Technika Eksperimenta **3**, 31-35 (1974). English translation in Experimental Instruments and Techniques (1974); G. Roslyakov, PhD thesis, INP, Novosibirsk, 1975.

[10] G. E. Derevyankin, V. G. Dudnikov, and P. A. Zhuravlev, Pribory i Technika Experimenta, 5, 168-169 (1975).

[11] M. Kisaki, et al., Rev. of Sci. Instrum. **79**, 02C113 (2008).

[12] S.T. Manson, Phys. Rev. A **3**, N. 1 (1971).

[13] D. I. Mader and R. Novick, Phys. Rev. Letters 29, 199 (1972).

[14] U.V. Pedersen, M. Hyde, S. P. Moller and T. Andersen, Phys. Rev. A 64, 012503 (2001).

[15] P. Reinhed, A. Orba´n, J. Werner, S. Rose´n, R. D. Thomas, I. Kashperka, H. A. B. Johansson, D. Misra, L. Brannholm, M. Bjorkhage, H. Cederquist and H.T. Schmidt, Phys. Rev. Letters 103, 213002 (2009).

[16] P. Feldman and B. Novick, "Polarization of 3He negative ions," International Congress of Nuclear Physics, Paris, 1964, pp.785-786; P. Feldman and R. Novick, in *Comptes Rendus du Congres International de Physique Nucleaire*, Paris, 1964, edited by P. Gugenberger (CNRS, Paris, 1964), Vol. II, 4a/C144, pp. 785-786.

[17] L. M. Blau, R. Novick, and D. Weinflash, Phys. Rev. Letters 24, 1268 (1970).

[18] A. Szanto de Toledo and O. Salada, Production of Negative Helium ions, Revista Brasileira de Física, Vol. 7, No 1, (1977).