Direct Production of $^3He^+(2S)$ Ions with an rf Ion Source and Nuclear Polarization

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The measurement of photons from the quenching of $^3He^+(2S)$ state ions produced under special conditions by an rf ion source permit one to deduce a polarizable current of 260 nA, close to 5% of the total $^3He^+$ current. Zeeman splitting and quenching of unwanted components can be effected at the ion source yielding directly a $^3He^+$ beam with nuclear polarization.

A polarized ^3He ion source based on the Lamb shift method has become operational[1] yielding on target, after cyclotron acceleration, 0.5 nA with 70% polarization. The interest of continued development and improvement of such a source in general,[2,3] and, in particular, for use at single-ended Van de Graaff accelerators, has been discussed abundantly and need not be commented upon.

The scheme used at the University of Birmingham[1] is based on the production of a $^3He^{++}$ beam in a primary ion source and subsequent capture of electrons in a gas canal in order to produce $^3He^+(2S)$ ions. Considerable simplification of the polarized ion source could be achieved if it were possible to produce the $^3He^+(2S)$ ions directly from a primary ion source. The basic idea pursued here follows directly from the equilibrium equation of ions in the plasma of the ion source:

$$^3He^0 \rightleftarrows {}^3He^+ \rightleftarrows {}^3He^{++}.$$

Clearly the $^3He^+$ population in the ion source will consist of ions in the ground state and excited states. The 2S state is metastable, with a lifetime of 2×10^{-3} s, and thus there will be a stable population of $^3He^+$ ions in that state, from the electron capture by the $^3He^{++}$ ions and from the decay of higher excited states of $^3He^+$ to the 2S state, or from inelastic collisions of electrons and ions. Figure 1 shows the level scheme of $^3He^+$ relevant to the ion source. Axial symmetry is usual in rf ion sources with a magnetic field in the range of 0.05 to 0.1 T, which produces a Zeeman splitting of states as shown in Fig. 1.[2] Taking into account the dependence of the lifetime of the $He^+(2S)$ states on the electric field gradient[4] and Zeeman splitting, it is possible to foresee that, using low extraction voltages, in the range of 10–100 V cm^{-1}, a significant fraction of the $^3He^+$ ions can be obtained in the 2S state, and hence that it should be possible to produce a beam having nuclear polarization. We have performed a series of experiments in order to determine and optimize the current of $^3He^+(2S)$ ions produced and its fraction with respect to the total $^3He^+$ current.

Preliminary measurements were carried out following the method of the preferential ionization of the $^3He^+(2S)$ ions used by Karban, Oh, and Powell[5] and encouraging results were obtained.[6] However, it was felt that a direct measurement of photons of 304 Å, corresponding to the quenching of the metastable 2S state, was preferable. Figure 2 shows a schematic of the experimental setup in its final form. The McPherson monochromator is used to measure the frequency spectrum of photons emitted in the quenching region, by automatic rotation of the diffraction grating. Photons are detected with a Bendix Channeltron. The photon pulses are accumulated on a multichannel analyzer which sweeps the storage channel, while the monochromator sweeps the frequency at a constant speed. Thus, the analyzer records a photon-spectrum histogram. Firstly, a calibration of the system was performed by producing $^3He^+(2S)$ ions via the electron capture by a

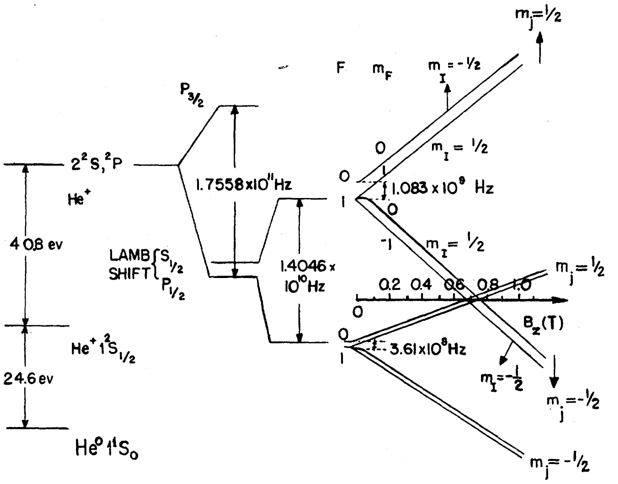

FIG. 1. Scheme of $^3He^+$ states showing the fine and hyperfine structure and Zeeman splitting.

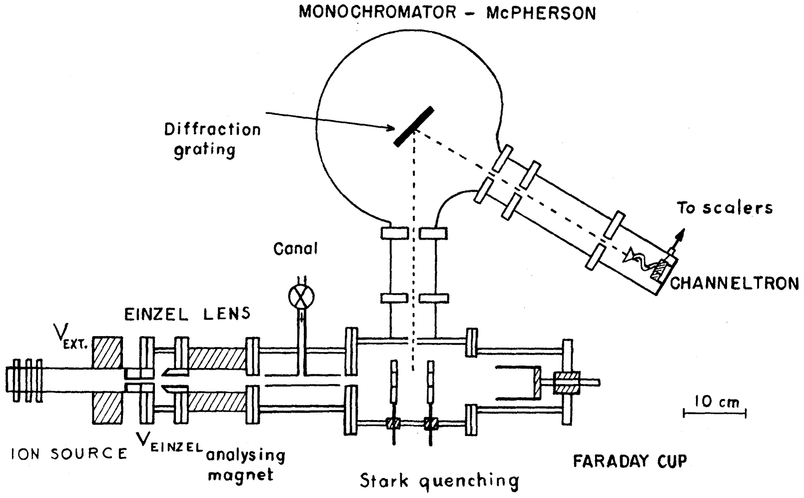

FIG. 2. Schematic of the experimental setup.

^{3}He^{++} beam; the selection of the beam is effected by a 30° analyzing magnet in a plane perpendicular to the horizontal projection shown in Fig. 2. The ^{3}He^{++} beam was accelerated to 30 keV and focused by a gap-einzel lens. Electron capture takes place in the gas canal using H_2. Stark-quenching electrodes producing a 4-kV-cm^{-1} gradient suffice to produce over 95% quenching at the corresponding ion velocities. We have verified that the photon spectrum peaks at 304 Å, as it should, from quenching of the 2S state. The background was small, less than 7%. The flow of H_2 was varied and an optimum yield was obtained, which corresponds to ~30 m Torr cm, as established by Shah and Gilbody,[7] for the maximum electron-capture yield. With the use of their calibration it is possible to convert the photon yield into absolute ^{3}He$^+$(2S) current. In view of the small background, measurements can be carried out placing the diffraction grating at a total reflection angle, and the integral of the photon spectrum is obtained simply by counting Channeltron pulses. The background can be measured after turning off the quenching field.

Given the Stark-effect quenching and the dependence of the lifetime of metastable atoms on the electric field gradient and Zeeman splitting,[6] it is evident that an optimum production of ^{3}He$^+$(2S) ions should be found for rather modest extraction voltages and gap-einzel lens gradients. For the measurements of ion-source-produced ^{3}He$^+$(2S) ions, the analyzing magnet was set to select them and a photon spectrum was obtained, peaking at 304 Å. Subsequently, measurements were carried out in the total reflection condition, yielding the integral of the photon spectrum, with and without quenching field in order to subtract background. The optimum conditions were obtained with an extraction voltage of 0.5 kV. A lower extraction voltage of 0.25 kV also produces a satisfactory yield. The gas flow was higher as compared to the ^{3}He^{++} operation. Figure 3 shows a plot of the current of ^{3}He$^+$(2S) together with the percentage of total ^{3}He$^+$ current as a function of gap-einzel lens voltage. The ion-source emittance at 4 keV of ^{3}He$^+$ is close to 50 mm mrad. A maximum current of ^{3}He$^+$(2S) ions of 260 nA

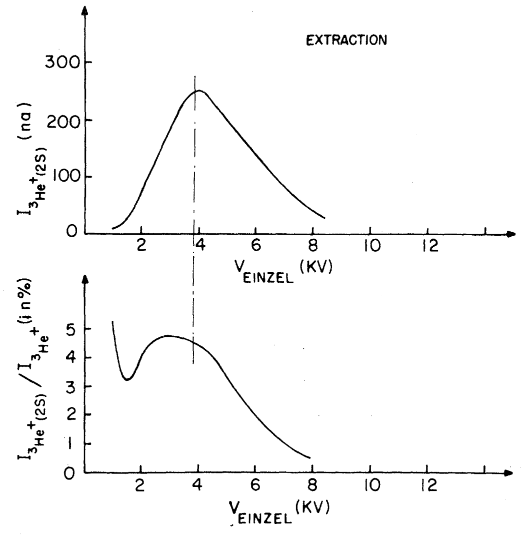

FIG. 3. Optimum ^{3}He$^+$(2S) current and fraction to total ^{3}He$^+$ current as a function of the gap-einzel lens voltage, at an extraction voltage of 0.5 kV. These measurements are precise to 5%.

was measured. These ions can be polarized in electron spin by quenching of unwanted Zeeman components. At a field of 0.7 T there is degeneracy of the two lower S states with the upper P states (see Fig. 1). It appears that a modest superconducting coil can achieve such a field at the ion source. Quenching of the lower S states can then be effected simply with a static electric field, thus producing a beam with electronic polarization and, after restoration of the hyperfine coupling, nuclear polarization (theoretically 50%). Alternatively, C-shaped iron-core coils disposed like orange sections around the source could also reach such fields on the axis, at room temperature. Another quenching scheme that seems feasible can be based on the field emission of electrons in the ion source plasma. At a field of 0.30 T the cyclotron resonance frequency of electrons is 8.4 GHz and the magnetron-type radiation is adequate to induce the transition $2S_{1/2}(m_j=-\frac{1}{2}) - 2P_{1/2}(m_j=\frac{1}{2})$ (see Fig. 1). The subsequent stages of the polarized ion source would consist of a spin-reversal coil followed by a Sona adiabatic transition[8] with a strong axial magnetic field. Ionization of the $^3\text{He}^+$ ions to $^3\text{He}^{++}$ would take place in this strong field with a stripping gas canal. Preferential ionization privileges the $^3\text{He}^+(2S)$ ions with respect to $^3\text{He}^+(1S)$ ions in a proportion of approximately 100 to 1 at the energies investigated by Karban, Oh, and Powell.[5] It should be higher at our ion energies.[2] The ion separation is simple after acceleration at the analyzing magnet. In view of the experience of Allenby and coworkers,[1] the yield curves of Shah and Gilbody,[7] and the simplicity of acceleration in a Van de Graaff accelerator without injection and extraction difficulties, it is estimated that the polarized $^3\text{He}^{++}$ beam intensity on target should be about 20% of the $^3\text{He}^+(2S)$ ion flux with a polarization of 70%, that is, close to 100 nA.

We acknowledge the invaluable assistance of our colleagues, Professor R. Drouin and Professor E. Knystautas, atomic physicists, who lent their equipment for the 304-Å photon spectrometry and taught us how to use it; of Mrs. R. Labrie, the Van de Graaf accelerator engineer, R. Lapointe, R. Bertrand, and H. Pouliot for their keen involvement with electromechanical and electronic aspects of the setup.

Note added.—The field emission of electrons in the ion source plasma in the presence of a magnetic field, at the frequency $\omega_c = eB/mc$, can be estimated from the well-known expression[9] $I = 2e^4B^2v^2/3m^2c^5(1-\beta^2)$ (all the symbols have the usual meaning) and the electron density. This radiation takes place to first order in the plasma parameter $\epsilon = 1/n\lambda_D^3$, where n is the number density of particles and λ_D is the Debye shielding distance.[10] The lines are not sharp because of Doppler effects in the spiraling motion of electrons, but this is advantageous in the present case. On the assumption of an average electron energy of 200 eV the emission is close to 10 eV sec^{-1}. The total radiation produced would be close to 1 mW cm^{-3}. The frequency of this radiation is well below the critical plasma frequency $\omega_p = (4\pi ne^2/m)^{1/2}$, where n is the electron density, and hence it is absorbed. The method of quenching based on transitions induced by this radiation is as yet untested, but it seems worthwhile investigating.

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