Electron-Polarized N^{4+} Ion Beam Formed by Electron Capture to N^{5+} in a Polarized Sodium Target

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Electron-polarized N^{4+} ions were produced via electron capture by a beam of N^{5+} ions in an optically pumped polarized sodium target. The polarization of the ions was detected by measuring the circular polarization of the N V $1s^2 2s\ ^2S$-$1s^2 2p\ ^2P$ (124-nm) transition taking place after the electron capture. These studies point to the feasibility of a general method for the production of polarized multicharged heavy-ion beams.

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We have obtained a beam of electron-polarized N^{4+} ions by charge exchange of a beam of N^{5+} in an optically pumped sodium target. This experiment demonstrates the general applicability of the optical-pumping technique for producing beams of polarized highly charged ions.

Experiments with beams of polarized atoms or nuclei have long been of interest in atomic, nuclear, and high-energy physics. In atomic physics, ions with significant electronic polarization can be used for fundamental experiments such as tests of parity nonconservation.[1] Another application is the study of spin-dependent effects in the scattering of polarized electrons by polarized ions. The long-range attractive Coulomb force, which brings the two collision partners closer together than in the case of the scattering of polarized electrons by neutral atoms, can enhance the effect of the short-range spin-orbit interaction and the exchange interaction. Also, measurement of the polarization of the photons emitted after charge exchange by a polarized ion in an atomic target is an important means of testing the theory of charge-exchange excitation.[2] Use of nuclear-spin-polarized beams allows study of spin-dependent interactions and of symmetries and invariances in nuclear and particle physics.[3]

A recently developed technique for the production of polarized beams for use in nuclear physics is based on charge exchange in an alkali-vapor target which has been polarized by optical pumping.[4,5] Efforts have been primarily focused on light ions such as H^- and D^-.[5,6] In a related technique, polarized beams of $^3He^+$,[7] Li^-, and Na^- (Ref. 8) for injection into a cyclotron or a tandem accelerator have also been generated by direct optical pumping of a discharge source[7] or of an atomic beam.[8] Optical-pumping techniques offer the prospect of providing higher beam intensities[6] than the conventional atomic-beam method.[9] Our work was motivated by the possibility that an optically pumped alkali target could be used to produce polarized beams of many heavy ions.[4] Another means for obtaining an electron-spin-polarized target is to use the surface of a ferromagnet. Highly polarized beams have been obtained by grazing-incidence scattering on both magnetic and nonmagnetic surfaces.[10]

For the optically pumped polarized-H^--ion sources, a charge-exchange cell is required to provide adequate target thickness to ensure good beam intensity. However, radiation trapping and wall relaxation limit the possible target thickness.[11] For multiply charged heavy ions, the electron-capture cross section can be several orders of magnitude higher.[12] An atomic-beam target is, therefore, better suited and was used in our experiments. An advantage of the beam target is that the polarization axis is not restricted to be collinear with the beam axis as in the cell geometry. An important feature of the polarized-H^--ion sources is that a strong magnetic field (≥ 10 kG) is used to decouple the electron orbital and spin angular momenta of the excited hydrogen atoms formed in the charge-exchange cell. This is necessary to eliminate depolarization caused by the spin-orbit interaction. Since the relevant fine-structure splittings in the N^{4+} ion are much larger, it is not possible to decouple the spin-orbit interaction with available laboratory magnetic fields and this source of depolarization cannot be eliminated in our experiments.

Our experimental arrangement is shown in Fig. 1. The sodium beam is produced from a two-stage oven described previously.[13,14] The ion beam comes from the Argonne PII ECR ion source at the ATLAS heavy-ion linac. This source is located on a high-voltage platform so that beam energies up to $350Q$ keV are available for ions of charge state Q. For the present experiment the beam energy is varied from 60 to 210 keV. Typical N^{5+} beam currents are 10 μA. The ion-beam diameter is ~ 1 cm.

The sodium beam is optically pumped by a CR699-21 ring dye laser. In order to pump both ground-state hyperfine levels ($F=2$ and 1) and to cover the complete Doppler profile, we impose both frequency modulation and noise modulation on the laser spectral-density distribution. The frequency of the laser is first tuned midway between the $F=1$ and 2 ground-state hyperfine level res-

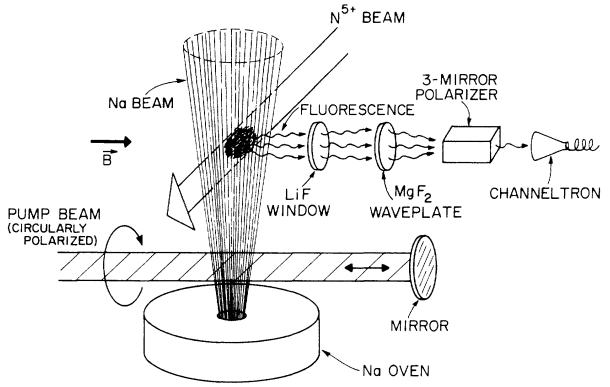

FIG. 1. Schematic of the experimental setup.

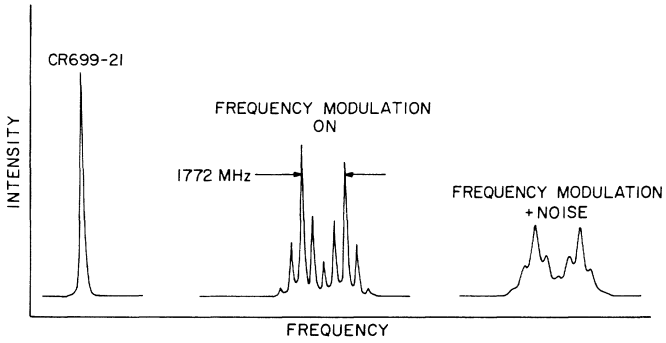

FIG. 3. The laser spectral-density profiles with and without the frequency and noise modulations. Because of the bandwidth (500 MHz) of the available EOM crystals, we apply a modulation frequency of 443 MHz and adjust the rf power applied to the electro-optic modulator so the second sidebands are largest.

onances of the $D2$ line. The output of the actively stabilized ring dye laser is then passed through two electro-optic modulators (EOM) configured in a traveling-wave mode as a ~ 50-Ω transmission line (see Fig. 2). The output of an uhf generator is fed into a rf-power amplifier, sent to the first EOM, and finally terminated in a high-power 50-Ω load. The second EOM is driven by a white-noise source, and fed through a 0–12-dB step attenuator into a rf-power amplifier. The laser spectral density with and without modulation is shown in Fig. 3.

In off-line studies, the polarization of the target was measured by analyzing the circular polarization of the fluorescence induced by a weak linearly polarized laser probe beam. We measured the ratio of the $F=1$ to 2 ground-state hyperfine level populations by scanning the laser and observing the fluorescence peak intensities. These tests indicated high ($\geq 85\%$) target polarization for a target thickness of $\sim 2\times 10^{10}$ atoms/cm^2.

The polarization of the N^{4+} produced in electron pickup from the polarized Na target was measured through detection of the N V resonance transition $2s\,^2S$-$2p\,^2P$ at 124 nm. The vacuum-ultraviolet (vuv) photons of this transition are analyzed by an optical polarimeter consisting of a rotatable MgF_2 retardation plate, followed by a three-mirror linear polarizer[15] and a channeltron (see Fig. 1). The polarimeter and the target chamber are independently pumped and separated by a LiF window. The MgF_2 retardation plate cuts off at wavelengths shorter than 115 nm and the quantum efficiency of the channeltron drops off rapidly at wavelengths longer than 150 nm. Thus the overall system conveniently isolates the N V $2s$-$2p$ emission line. The circular polarization of the emitted photons was observed by first setting the polarimeter at maximum analyzing power for circularly polarized photons. The circular polarization of the pumping laser was alternated and the observed alternating intensity of the emitted N V light was recorded (see Fig. 4). Thus the recorded asymmetry is a signature of the polarization transfer from the target to the ion beam. A raw asymmetry of $(2.18\pm 0.27)\%$

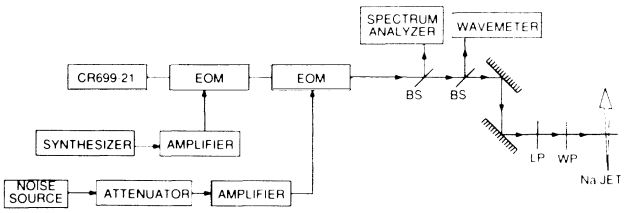

FIG. 2. Schematic for components of the pump beam. Two beam splitters (BS) are employed to direct a small fraction of the laser beam into diagnostic devices (spectrum analyzer and a Burleigh wave meter). The laser beam is circularly polarized by a linear polarizer (LP) and a quarter-wave plate (WP) for the sodium $D2$ line. The two electro-optic modulators (EOM) are used to control the laser spectral density (see text).

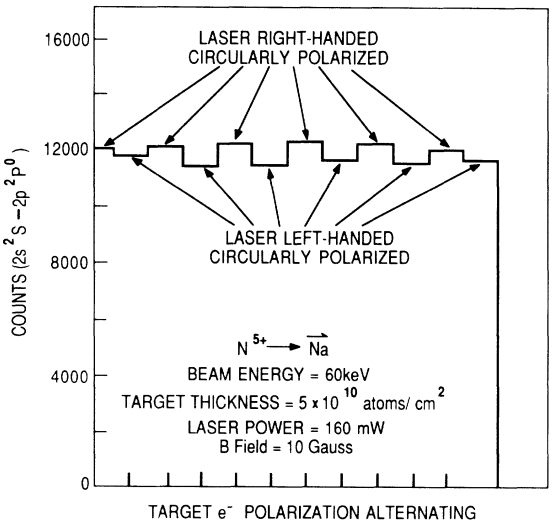

FIG. 4. Observed asymmetry in the $2s$-$2p$ emission counts for a fixed accumulated beam charge vs the change of the target electron-spin polarization. From this, the circular polarization of the line was determined to be $(5.7\pm 0.7)\%$ (see text).

was observed with the N^{5+} beam energy at 60 keV. The MgF_2 phase plate is a quarter-wave plate at Lyman α, 121.6 nm, and thus its phase was $145° \pm 15°$ at 124 nm, the wavelength of the light being observed. This latter phase was checked experimentally and from the theoretical refractive indices of MgF_2. In addition, the coatings of the mirrors in the linear polarizer were not perfect, resulting in a reduced polarization which was measured separately. The combination of these two efficiencies leads to a total polarizing power of 0.38 at 124 nm. Thus a circular polarization (S/I) of $(5.7 \pm 0.7)\%$ was deduced. The linear polarization (M/I) of the line (124 nm) was also determined to be $\sim(10 \pm 1)\%$ at 60 keV and $\sim(6 \pm 1)\%$ at 210 keV beam energy. The linear polarization (M/I) was measured by rotating the retardation plate in the polarimeter and observing the characteristic pattern of four peaks in one complete revolution of the plate.

Using the sudden approximation,[16] we have calculated the expected circular polarization (S/I) of the $2s$-$2p$ transition for capture from a 100% electron spin-polarized target, and the electron and nuclear polarizations of the ground-state N^{4+} beam.[17] The effects of the hyperfine interaction were included for the ground state and $2p$ states and neglected in the higher-excited levels. Since the incoming N^{5+} ion has no unpaired electron or hole, the spin orientation during the collision can be assumed space fixed ("frozen") during collision.[16,18] The fine- and hyperfine-structure interactions after the capture depolarize the electron spin and couple the spin-angular momentum into electron orbital-angular momentum and nuclear spin ($I=1$ for ^{14}N). Part of the angular momentum in the system is carried away by the photons emitted in the deexcitation processes. The calculated results for S/I and M/I are shown in Table I for general different angular momentum capture channels and alignments[19] in the capture process. A simple classical over-barrier model predicts that exit channels with the principal quantum number $n=5$ should be dominantly populated.[20] We observed spectroscopically[13] that the $5d\,^2D$ and $5g\,^2G$ and $4f\,^2F°$ states are the predominant states populated in the capture process. The observed M/I indicates that the capture process strongly favors the $m_L=0$ magnetic substates. Our calculations[16] indicate that the maximum expected electron and nuclear polarization for N^{4+} is 10%. With a magnetic field in the capture region strong enough to decouple the nuclear spin, a maximum electron-spin polarization of 25% for N^{4+} is possible.

Based on our observed circular polarization, we estimate that electron and nuclear polarizations of approximately 4% were obtained in our experiments for ions which reached the ground state via the $2s$-$2p$ transition. The reasons for the lower than expected polarization of the N^{4+} beam are not fully understood and several factors may have contributed. These include (a) low Na polarization, (b) depolarization in the charge-exchange process, (c) the presence of Na dimers in the target, (d) electron capture from (unpolarized) background gas, and (e) incomplete overlap between the laser beam and the sodium beam. These issues will be investigated in future experimental work. The Na polarization was not measured in the on-line experiments because the visible polarimeters used for these measurements had to be removed to make room for the vuv polarimeter. The on-line polarization may have been lower than that obtained off-line because the conditions for the optical pumping were different. In order to obtain adequate signals from the excited N^{4+} ions, a higher sodium density (5×10^{10} atoms/cm^2) was used on-line and the laser power was lower, in part, because of losses in transporting the laser light to the accelerator beam line; in addition, the laser frequency tended to drift during the long integrations (several hours) required for the on-line work.

TABLE I. Expected circular and linear polarization of the s-p transition line as a function of the original capture-state orbital-angular-momentum quantum number (L) and its initial alignment ($A_0^{(0)}$) as a result of electron capture by N^{5+} ions in a polarized target. The electron-spin polarization in the target is assumed to be 100% and perpendicular to the ion-beam axis. Only dipole transitions where the angular momentum changes by one unit in each step are considered.

Capture channel L	$A_0^{(0)}$	S/I (%)	M/I (%)
1	0	34	0
1	−1	31	14
1	0.5	35.5	−7.5
2	0	22.8	0
2	−1	24.1	10.5
2	1	21.5	−11.3
3	0	18.3	0
3	−1	20.5	9.3
3	1.25	15.4	−12.4
4	0	15.9	0
4	−1	18.4	8.6
4	1.4	12.0	−12.9
5	0	14.4	0
5	−1	17.2	8.2
5	1.5	9.8	−13.2

The population difference among the $|F,M_F\rangle$ magnetic substates of ground-state N^{4+} resulting from the capture of polarized electrons can be exploited to measure the hyperfine splitting. The importance of data on the ground-state hyperfine splitting of lithiumlike ions has recently been stressed by Panigraphy *et al.*[21] The hyperfine structures of $^9Be^+$ and $^{19}F^{6+}$ have been measured by direct optical pumping[22] and nuclear quantum beats,[23] respectively. In our scheme with a completely polarized target assumed, the $|\frac{1}{2},-\frac{1}{2}\rangle$ state would be $\sim$20% more populated than the $|\frac{3}{2},-\frac{1}{2}\rangle$ state, while the $|\frac{3}{2},\frac{1}{2}\rangle$ state is $\sim$2% more populated than the $|\frac{1}{2},\frac{1}{2}\rangle$ state. A microwave frequency of $\sim$4.2 GHz (Ref. 21) could be applied to induce transitions $|\frac{1}{2},$

$-\frac{1}{2}\rangle \rightarrow |\frac{3}{2},-\frac{1}{2}\rangle$ and $|\frac{3}{2},\frac{1}{2}\rangle \rightarrow |\frac{1}{2},\frac{1}{2}\rangle$ and change the electron-spin polarization of the N^{4+} ion. The change could be monitored by observing a change in the circular polarization of the 124-nm radiation emitted following electron-impact excitation ($2s$-$2p$).[24] Alternatively, the resonance could be detected by observing a change in the N IV $2s2s\,{}^1S_0$-$2s2p\,{}^1P_1$ [76.5-nm (Ref. 25)] line intensity after electron capture in a second polarized target.

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