Laser source of polarized protons and H^- ions

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The process by which protons are polarized in the capture of optically oriented sodium atoms in a strong magnetic field has been studied experimentally. A degree of polarization 65 ± 3% has been achieved in charge exchange in a 15-kG field. The development of a source of polarized protons and H^- ions for accelerators on the basis of this new polarization method is reported.

In this letter we report the results of an effort to develop a source of polarized protons of a new type, which implements the polarization method proposed by Zavoĭskiĭ,[1] involving the capture of polarized electrons by protons. The use of laser light for optical orientation in terms of the electron spin of atoms in a charge-exchange target substantially increases the efficiency of the polarization process.[2,3] The optical

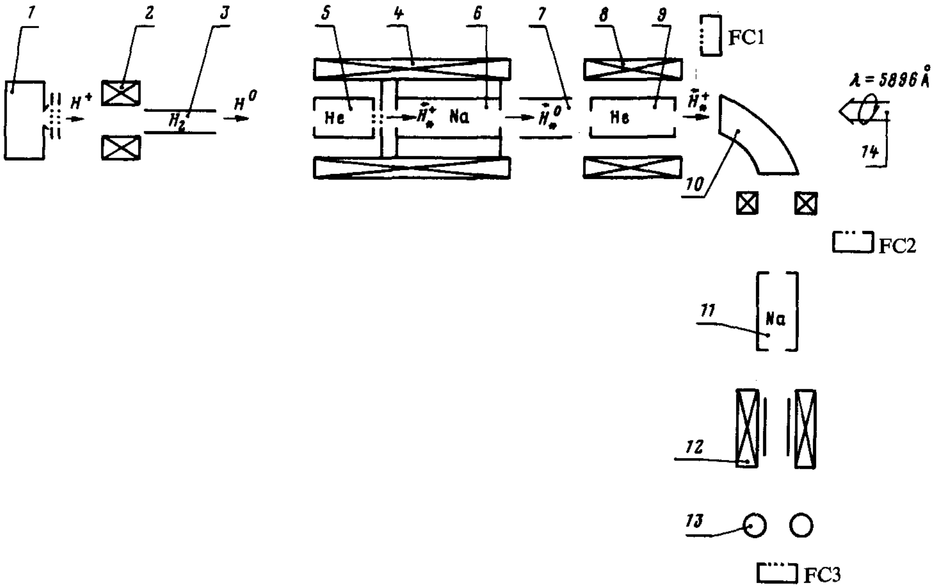

FIG. 1. Schematic diagram of the laser source of polarized protons. 4, 8—Pulsed solenoids; 5, 9—helium-filled cells with pulsed gas injection; 13—detector of metastable hydrogen atoms.

orientation of sodium vapor was studied in Ref. 4. Experiments with a pulsed dye laser yielded a degree of polarization $90 \pm 5\%$ at a target thickness $\sim 3 \times 10^{13}$ atoms/cm^2. When electrons are captured by sodium, a significant fraction of the hydrogen atoms forms in $2S$ and $2P$ excited states. If depolarization caused by the spin-orbit interaction is to be avoided in these states, the magnetic field in the charge-exchange region must be 10–20 kG even before the transition to the ground state.[5,6] Charge exchange in a magnetic field, however, increases the phase volume of the beam and thus causes a significant loss of intensity.[7]

Figure 1 shows the basic arrangement of a polarized-proton source, in which the suggestion made in Refs. 8 and 9 for overcoming this difficulty is implemented. Protons from source 1 are focused by solenoid 2 and neutralized in gas target 3 (Ref. 10). A beam of hydrogen atoms is injected into solenoid 4, where there is an auxiliary helium-filled ionizing cell 5. The protons formed in this cell are retarded by a potential ~ 1 kV and then neutralized again in the capture of polarized electrons in sodium target 6. In this case the beams at the entrance to and at the exit from the solenoid are neutral, and there is no increase in the emittance in the interaction with fringing fields of the solenoid. The retardation of the protons makes it possible to eliminate the unpolarized component of the beam in bending magnet 10. This unpolarized component is formed from neutrals which have passed through cell 5 without undergoing charge exchange. Deflecting plates 7 remove the remaining ions from the beam.

The 1.5-kG magnetic field in the ionizer is directed opposite the field in the sodium cell. Under these conditions, the hyperfine interaction in the hydrogen atom leads to a transfer of the polarization from the electron to the proton during a nonadiabatic passage through the region in which the direction of the magnetic field changes.[11] The atoms are ionized in a second helium cell. The H^- ions can be formed by using either an alkali-metal vapor or xenon in the ionizer.

To measure the polarization, we use charge exchange of protons into $H(2S)$ metastable states in the sodium cell 11 of the polarimeter. The populations of the sublevels of the $H(2S)$ hyperfine structure depend on the polarization of the protons. The distribution in spin states is analyzed by passing the beam through a "spin filter" 12 and detecting the difference caused in the count rates at a Lyman α detector by the change in the proton polarization direction.[9,12] The spin filter is a solenoid with a magnetic field of 570 G, in which plates produce a transverse electric field of 20 V/cm. The mixing of the $2S$ and $2P$ levels by the electric field is intensified at the crossing of the $2S_{1/2}(m_J = -1/2)$ and $2P_{1/2}$ $(m_J = 1/2)$ sublevels in the 570-G field. The atoms with $m_J = -1/2$ go to the ground state in a time on the order of the lifetime of the allowed $2P \rightarrow 1S$ transition, while the atoms with $m_J = 1/2$ pass through without loss.[4] The proton current is measured in the direct beam by detector FC1; after the deflection and energy separation, the current is measured at the entrance to the polarimeter by FC2; the proton current emerging from the polarimeter is measured by the final detector, FC3. The equivalent current I_0 of the original beam of neutral atoms which passes through the polarization system is about 15 mA, according to measurements with ionization in a helium cell. The presence of two helium cells makes it a simple matter to determine the ionization efficiency, $\epsilon_{\rm He} \approxeq 0.7$, at a beam energy of 7 keV. In these measurements the protons produced in the first cell are deflected by the electric field, and the magnitude of the residual neutral component is measured in ionization in the second cell.

The measurements of the degree of polarization of the sodium atoms in electron spin[4] reveal the thickness of the sodium charge-exchange target with a high degree of polarization and thus the efficiency at which polarized electrons are captured, $\epsilon_{\rm Na} \approxeq 0.3$. Taking the three charge exchanges into account, we then find the total efficiency of the polarization process to be $\epsilon = I_t/I_0 = \epsilon_{\rm He}^2 \epsilon_{\rm Na} \approxeq 0.15$, where I_t is the total current of polarized protons. In the experiment, I_t is determined from the increase in the current in FC1 when the sodium cell is heated. At the cell temperature corresponding to the maximum degree of polarization of the protons we have $I_t = 2$ mA. The approximate agreement between I_t and the calculated value implies that there is no intensity loss due to an increase in the beam divergence during charge exchange in the magnetic field. The current I_t does not change when the magnetic field in the first solenoid is increased from 5 to 20 kG. The normalized beam emittance does not exceed 0.5π cm · mrad. The use of these additional charge exchanges thus makes it possible to avoid the difficulty of increasing divergence and to increase the magnetic field in order to raise the degree of polarization.

When the proton beam is extracted, and the energy-separation system turned on, there is a significant loss of intensity. Figure 2 shows the current of polarized protons behind the bending magnet in FC2 versus the temperature of the sodium cell. The current from the cold cell is seen to be less than 2% of the maximum intensity, implying that the method used here to eliminate the background of the residual neu-

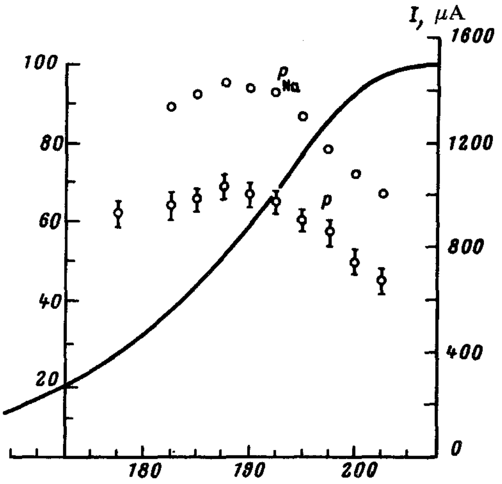

FIG. 2. The current of polarized protons in Faraday cup FC2, I; the polarization of the sodium atoms in electron spin, P_{Na}; and the proton polarization P versus the temperature of the sodium cell, T, °C.

tral component of the beam in the energy separation is working effectively.

Also shown in Fig. 2 are results of measurements of the degree of polarization of the protons. When the cell is heated, and the sodium density increased, the degree of polarization of the protons decreases, as does the degree of polarization of the sodium. The reason for the decrease in the polarization is apparently the capture of resonant radiation emitted in spontaneous transitions during the optical pumping.

Despite the significant loss during the extraction of the beam, these experiments yield a record high current of polarized protons, about 1 mA with $P = 65 \pm 3\%$ and 1.4 mA with $P = 45\%$ when the retarding system is used or 3.5 mA with $P = 30\%$ when there is no energy separation. Optimization of the separation system and of the beam extraction should make it possible to reduce the loss and to raise the intensity of protons with a high degree of polarization toward the value of 2 mA achieved in the direct beam. When the helium in the ionizer is replaced by xenon, we obtain a current

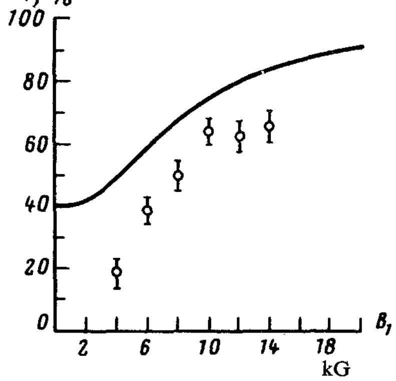

FIG. 3. Degree of polarization of the protons versus the magnetic field in the sodium cell. Curve—Calculations of Ref. 6.

of polarized H^- ions of about 60 μA. The source operates in pulses at a repetition frequency of 1 Hz. The 20-μs length of the current of polarized protons is determined by the length of the pulse from the lamp-pumped dye laser. An effort is under way to develop a cw source with a superconducting solenoid and a cw dye laser.

Further improvements in the proton source and in the system for shaping and extracting the beam will apparently make it possible to produce polarized-proton beams with a current of 10 mA and beams of H^- ions with 1 mA with an emittance acceptable for high-energy accelerators.

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