Optical orientation of a dense sodium charge-exchange target for producing polarized protons and H$^-$ ions

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The polarization of protons through the capture of electrons by optically oriented sodium atoms has been studied experimentally. A new method for measuring the polarization of sodium is proposed. A density of 2×10^{13} atoms/cm^2 has been achieved for a charge-exchange target with a $90\pm5\%$ degree of polarization.

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The recent increased interest in accelerator experiments on polarization phenomena at high energies stems from the discovery of two new effects, which depend on the polarization and whose study can yield much new information on the interaction mechanism. Since the cross sections for these processes are relatively small, the intensities of the polarized beams must be raised. A promising approach is to accelerate particles that are polarized in their sources.

The existing sources of polarized ions can produce currents of polarized protons up to 100 μA in the continuous mode or about 200 μA in pulsed operation with an 80% degree of polarization. A further increase in the intensity of pulsed operation is particularly necessary for high-energy accelerators because of the short time the particles remain in acceleration. The development of intense sources of polarized negative hydrogen ions, H$^-$, also raises the possibility of increasing the intensity during multiorbit charge-exchange injection into an accelerator.

In addition to the development of the classical polarization methods,[1] the method of polarizing protons through the capture of polarized electrons, proposed by Zavoĭskiĭ,[2] has recently attracted considerable interest. The efficiency of the polarization process could be raised substantially by using advanced high-power tunable dye lasers to orient the spins of the electrons in the charge-exchange target.[3]

Figure 1 shows a source of polarized ions, which makes use of the optical orientation of electrons in sodium atoms. Sodium was chosen because of its large charge-exchange cross section, $\sigma_{+0}=10^{-14}$ cm^2, and also because of the availability of the transition $3S_{1/2}\rightarrow3P_{1/2}$, which is convenient for optical pumping with dye lasers. Protons from the source (1) capture polarized electrons in a cell filled with sodium vapor (2), which is immersed in the magnetic field of a solenoid (3). A substantial fraction of the hydrogen atoms formed during the capture of electrons from the sodium are in excited $2S$ and $2P$ states.[5] If depolarization due to the spin–orbit interaction in these states is to be avoided, the magnetic field in the charge-exchange region and before the transition to the ground state must be $\sim$1.5–2 T. Then there is a nonadiabatic transition to the region of the oppositely directed field of a second solenoid (5), where the protons are spin-polarized.[4] Inside this solenoid is an ionizer cell (6), filled with either the vapor of alkali metals, in which case the yield of polarized negative hydrogen ions

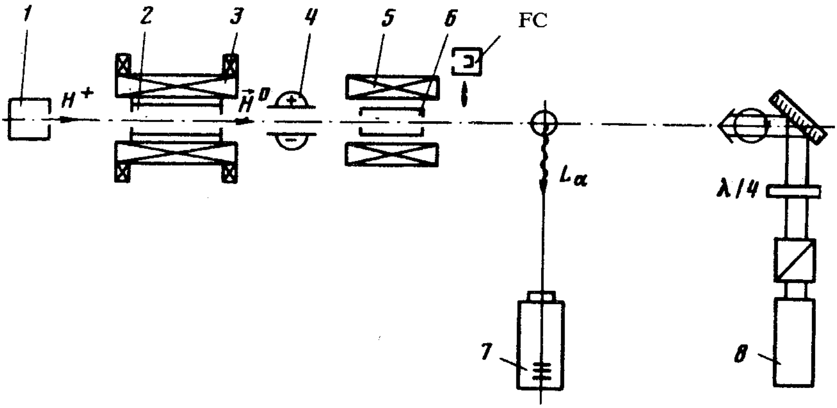

FIG. 1. Polarized-proton source with charge exchange with optically oriented sodium atoms. 4—Plates which remove the ion component from the beam; FC—Faraday cup to measure the beam current and the degree of charge exchange.

is 5–10%, or helium, in which case the proton yield ranges up to 80%. A high density (nl) of the charge-exchange target is important for increasing the overall efficiency of the polarization process. According to estimates by Zavoĭskiĭ,[2] sodium can be polarized to a degree $P_{\mathrm{Na}} \geqslant 90\%$ by using several cw dye lasers with a total power of 5 W, pumped with argon lasers, at a density $nl \simeq 3\times10^{13}$ atoms/cm^2. The atoms are depolarized in collisions with the walls and also in the capture of the unpolarized resonance radiation emitted in spontaneous transitions during the optical orientation. It is thus necessary to experimentally study the conditions for achieving a degree of high polarization with $nl \geqslant 10^{13}$ atoms/cm^2.

A 0.8-W cw dye laser was used in Ref. 6 to polarize sodium. As the target thickness was raised to 2×10^{13} atoms/cm^2, the degree of polarization fell to 20%. In the present experiments, we used a flashlamp-pumped dye laser; as a result, we obtained an output power above 100 W at a line width of 0.5 Å and a pulse length of 20 μs.

The method for measuring P_{Na} makes use of the properties of the metastable hydrogen atoms formed during the capture of polarized electrons from sodium. The apparatus contains the basic units of the source shown in Fig. 1, but the magnetic field in the first solenoid is $B_1 = 0.3\ \mathrm{T} \gg B_{\mathrm{crit}} = 650$ G, sufficient to produce a high P_{Na}. During charge exchange into the metastable state H(2S), the polarization of the electrons is preserved. The particle spin state in which the metastable atoms are formed and thus P_{Na} can be determined by passing the beam through a solenoid (4) with $B_2 = 0.055$ T, in the same direction as B_1, and through a transverse electric field of 20 V/cm. In this field, atoms with $m_J = -1/2$ return to the ground state in a time on the order of the lifetime of the allowed transition $2P \rightarrow 1S$. Atoms in states with $m_J = 1/2$ pass through the fields without any loss. The difference stems from the mixing of the 2S and 2P levels by the electric field at the point at which they intersect, and this difference is exploited in all polarized-proton sources of the Lamb type. The detector (7) thus detects only the atoms with $m_J = 1/2$. This detector uses microchannel plates

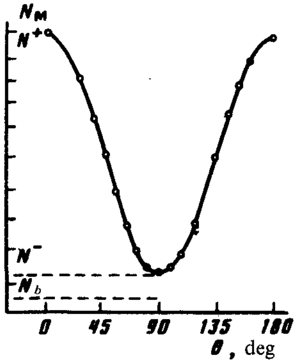

FIG. 2. Dependence of the metastable-atom count rate on the orientation of the $\lambda/4$ plate. N^-—negative circular polarization of the light; N^+—positive circular polarization.

which are sensitive to the emission at 10.2 eV that arises during the quenching of the metastable atoms in an electric field of 300 V/cm (Ref. 7).

The circularly polarized beam from a flashlamp-pumped laser using the dye rhodamine 6G(8) is used to polarize dense sodium vapor in pulses. An interference–polarization filter in the resonator contracts the emission spectrum and provides a conversion to the transition wavelength, $\lambda\ (3S_{1/2}\rightarrow 3P_{1/2}) = 5896$ Å.

Figure 2 shows the dependence of the count rate of metastable atoms, N_M, on the orientation angle of the $\lambda/4$ plate, which determines the polarization of the emission. The polarization of the sodium is related to the count rate by $P = (N^+ - N^-)/(N^+ + N^- - 2N_b)$, where N^+ and N^- are the count rates for positive (σ^+) and negative (σ^-) polarizations of the emission, respectively. The quantity N_b is the background count rate. In this measurement, all the metastable atoms were quenched by the strong electric field before they reached the detection region. The absorption spectrum of sodium in a magnetic field ~0.3 T has a width $\Delta\lambda \cong 0.2$ Å, which reflects the Doppler broadening at the cell temperatre, ~550 K.

To determine the sodium density, we measured the ratio I/I_0, where I is the residual proton current and I_0 is the current from the cold cell; this ratio immediately gives us the charge-exchange efficiency. It is unambiguously related to the density: $I/$

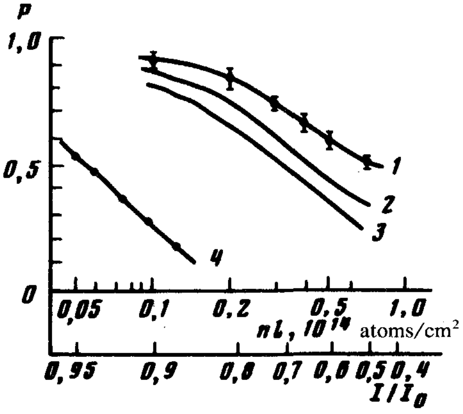

FIG. 3. Dependence of the degree of polarization of the sodium on the charge-exchange efficiency for various power levels of the orienting light. 1—$W_0 = 100$ W/cm², 0.5 Å; 2—$W = W_0/4$; 3—$W = W_0/8$; 4—data from Ref. 6.

$I_0 = \exp(-n\sigma_{+0}l)$, where $\sigma_{+0} = 10^{-14}$ cm^{-2}, and $l = 10$ cm is the length of the cell. The degree of polarization $P_{\rm Na}$ was measured as a function of the target thickness for various levels of the pump power (Fig. 3).

Of importance for the practical use of this result is that the $90 \pm 5\%$ degree of polarization of the charge-exchange target was achieved at a charge-exchange efficiency of 20%.

The use of this polarized charge-exchange target along with the best available protons sources would make it possible to produce a current ~1 mA of polarized negative hydrogen ions and ~10 mA of H^+ ions.

In summary, the optical-orientation method makes it possible to raise the intensity of sources of polarized ions by more than an order of magnitude, makes it possible to improve the control of the polarization direction, and raises new possibilities for polarization experiments on accelerators.

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