Anomalous effects in the charge exchange of a proton beam in a dense sodium target in resonant 3*S*–3*P* laser light

A. N. Zelenskiĭ, S. A. Kokhanovskiĭ, V. G. Polushkin, and K. N. Vishnevskiĭ
Institute of Nuclear Studies, Academy of Sciences of the USSR

(Submitted 21 May 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 1, 21–23 (10 July 1986)

A significant modulation of the effectiveness of the charge exchange of protons has been found, along with the formation of neutral atoms and H^- ions, during the excitation of 3*S*–3*P* transitions by laser light in a sodium target with a density above 10^{13} atoms/cm^3.

Significant progress has recently been achieved in the development of sources of polarized protons and H^- ions for accelerators.[1–3] The suggestion of using beams of polarized deuterons in thermonuclear-fusion devices[4] has given further impetus to the effort to increase the intensity of sources.

Anderson *et al.*[5] have proposed a method of "collisional pumping" of nuclear polarization through multiple charge exchange accompanied by trapping of polarized electrons. When the thickness of the charge-exchange target exceeds 10^{16} atoms/cm^2, the degree of polarization of the protons should reach $\sim 90\%$, according to calculations.[6] The beam intensity might reach hundreds of milliampers in this approach. A pulsed dye laser with a power $\sim 10^3$ W has been proposed for the optical pumping of targets with a density of 10^{14}–10^{15} atoms/cm^3.

As part of the effort to develop a laser source of polarized protons we have made a detailed study of the optical pumping of a dense sodium charge-exchange target.[7] A lamp-pumped pulse dye laser was used for the optical pumping. We achieved a degree of electron-spin polarization of the sodium atoms greater than 90% at a total target thickness $\sim 10^{14}$ atoms/cm^2. In the present letter we are reporting experimental results on "collisional pumping" in a laser source at an elevated target density and an elevated laser beam power. We will describe the distinctive features observed in the charge exchange in a excited target in this case.

Figure 1 shows the layout of the laser source of polarized protons. The primary proton beam is focused and then neutralized in a hydrogen target. In a first helium cell the atoms are ionized. This cell is held at a potential of $+1$ kV, so that the protons formed in it are retarded. They are then separated from the background component, which has passed through the cell without undergoing charge exchange, in a turning magnet. The protons then pass through a sodium target, which is illuminated by a laser beam with a wavelength at resonance with the 3*S*–3*P* transition. In a measurement of the charge exchange of the protons to form neutral atoms, the deflecting plates remove the residual ions from the beam, and a second helium cell is turned on. In this cell, the neutral atoms are ionized and directed by a turning magnet to a Faraday cup. When the deflecting plates and the ionizer are turned off, we observe the residual beam of protons and H^- ions. The total thickness of the sodium charge-exchange target is

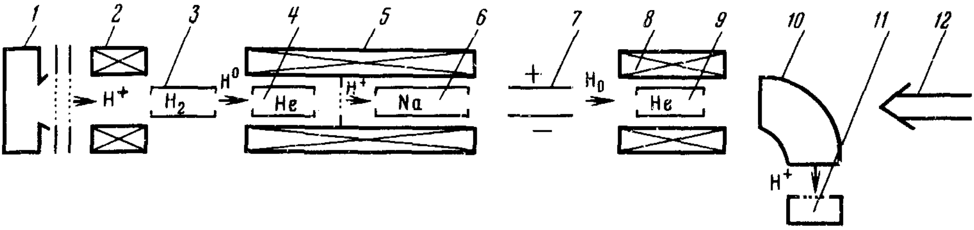

FIG. 1. The experimental layout. 1—proton source; 2—focusing lens; 3—neutralizer; 4, 9—helium targets; 5, 8—pulsed solenoids; 6—sodium cells, 7—deflecting plates; 10—turning magnet; 11—Faraday cup; 12—laser beam.

determined from the efficiency of the charge exchange of the proton beam and the known cross sections for the charge exchange of protons resulting in the formation of neutral atoms and H^- ions. The laser beam power was varied up to 10^3 W/cm^2 at a linewidth of 1.6×10^{10} Hz. The pulse length was 20 μs at the base.

In measurements of the charge exchange of protons resulting in the formation of H^- ions in an oriented target, at densities below 10^{13} atoms/cm^3, we observed a decrease in the intensity of the H^- beam synchronized with the laser pulse (the degree of polarization of the sodium atoms was determined independently through an analysis of the spin states of metastable atoms formed in the same target[7]). The reason for this effect is that the electrons in the H^- ions are in a $1S_0$ state. Consequently, the successive capture of two identically oriented electrons is forbidden. This effect can be exploited to study polarization transfer.[8] When the density was increased above 10^{13} atoms/cm^3, we expected that this modulation would fall off because of the reduction in polarization of the electrons. What the experiments revealed, in contrast, was a significant increase in the modulation of the intensity, which cannot be explained in terms of polarization effects.

Figure 2a shows an oscilloscope trace of the pulse of H^--ion current. The modulation here reaches 90% at a target density above 10^{14} atoms/cm^3. To eliminate the effect of the polarization, we measured the transmission of a proton beam through the target (Fig. 2b). The laser beam causes a "brightening" of the charge-exchange target,

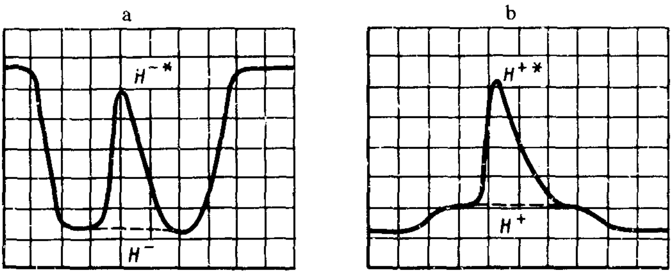

FIG. 2. Oscilloscope traces of pulses. a—current of H^- ions; b—proton current. Dashed lines—currents in the absence of the laser beam; $H^{+}*$, $H^{-}*$—currents with the laser beam.

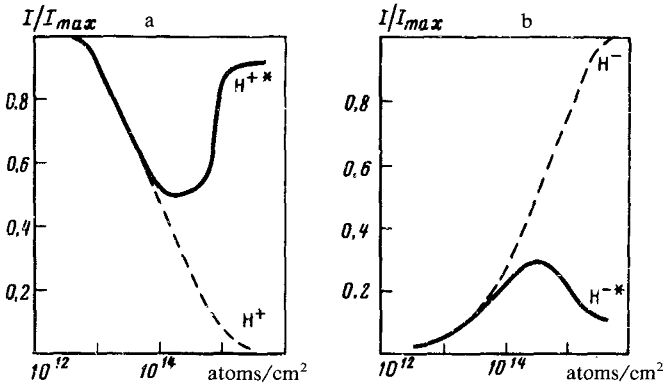

FIG. 3. Relative currents I/I_M versus the total thickness of the sodium target (the cell is 20 cm long). a—proton current; b—current of H^- ions. Dashed lines—currents in the absence of the laser beam; $H^{+}*$, $H^{-}*$—currents with the laser beam.

whose effective thickness falls off by nearly two orders of magnitude (Fig. 3). When the laser wavelength is tuned away from the $3S_{1/2}$–$3P_{1/2;3/2}$ transitions, the modulation disappears completely. (At laser power levels up to 10^3 W/cm^2, the photoionization of H^- ions does not exceed 1% of the current.) There is a threshold involved in the dependence of the magnitude of the effect on the laser power: The modulation disappears at power levels below 100 W/cm^2. A weak magnetic field in the charge-exchange region (saturation at 50 G) increases the modulation level and the relaxation time, furnishing evidence that slow electrons and ions formed in the target play a significant role in the charge exchange.

The electron-capture probabilities of sodium atoms in the ground and excited states differ only negligibly. The probability for many-photon ionization of sodium at a laser power of 10^3 W/cm^2 is negligibly small, so that the observed effects of a greater magnitude are not a trivial matter. The decrease in the charge-exchange efficiency is apparently due to a transition of a large fraction of the sodium atoms into other states of Na_2^+, Na^+, Na_2, for which the charge-exchange cross sections are much smaller than for the atoms. These processes, which occur at high target densities, are associated with an interaction of atoms in excited states.

The anomalously rapid formation of Na^+ and Na_2^+ ions in a sodium cell illuminated with resonant light was studied in Ref. 9 under conditions similar to those of our own experiments. The contributions of various processes which result in ionization were examined there. The results found in the present study provide a new method for studying the effects which occur in a dense target illuminated with resonant light. The proton beam in this case is used to determine the composition of the charge-exchange target.

The particular features of charge exchange in an excited target found in the present study pose a serious obstacle to the implementation of the method of polarization through multiple charge exchange, since these effects reach a maximum (Fig. 3) at the target thickness $\sim 10^{16}$ atoms/cm^2 required for "collisional pumping" and at a laser-beam power of 300 W/cm^2 (Ref. 6).

A long target would evidently make it possible to reduce these effects considerably. A reduction of the density would also be useful for eliminating depolarization effects during the capture of unpolarized resonant light. At an acceptable density, 10^{13} atoms/cm^3, however, the target would have to be overly long, $\sim 10^3$ cm, so that intense beams could not be produced. There is the possibility that these difficulties could be overcome by using a mixture of potassium and sodium in the charge-exchange target; during the optical pumping of the sodium, the potassium would also be polarized in the course of an exchange of electrons. At a potassium density of 10^{14} atoms/cm^3 and a sodium density of 10^{13} atoms/cm^3 the degree of polarization could reach 70% (Ref. 10). Since the potassium does not interact with the laser light, ionization effects should be small.

We wish to thank V. M. Lobashev for interest in this study and for useful discussions.

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Translated by Dave Parsons