Method of obtaining polarized protons by laser radiation

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A method is proposed for obtaining a high-intensity beam of polarized protons, capable of 100% polarization in beams with angular aperture up to 10°. The method is based on optical quenching, selective in the projections of the total angular momentum, of the hydrogen atom from the metastable $2S$ state and subsequent photoionization of the atoms with definite projection of the angular momentum via the Rydberg state.

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1. We consider in this article the possibility of obtaining an intense beam of polarized protons, which is of extreme importance for physical experiments with high-energy proton accelerators. By now, two methods of selective action by optical radiation on atoms have been developed, and the joint application of these methods makes possible a new approach to the problem of obtaining intense beams of polarized ions. The first method is optical orientation of the atoms in circularly polarized light,[1] and the second is selective photoionization of the atoms by laser radiation (see the reviews[2]). A simple combination of these two methods still does not guarantee success if it is necessary, at the contemporary state of laser technology, to obtain beams of polarized protons with the parameters required for practice. In principle, by using the splitting of the components of the hyperfine structure, we can obtain polarized ions directly by multistep photoionization of atoms.[1)] To obtain intense beams of polarized protons, however, one cannot use any method that employs optical excitation that is selective with respect to the components of the hyperfine structure, since this excitation calls for a very small angular aperture of the beam. Nor is it possible to use direct photoionization into the continuum, for the low cross section necessitates the use of unattainable average laser-radiation powers in such methods.

The scheme proposed by us consists of quenching selectively (in terms of the projections of the total angular momentum) the hydrogen atoms from the state $2S_{1/2}$ in

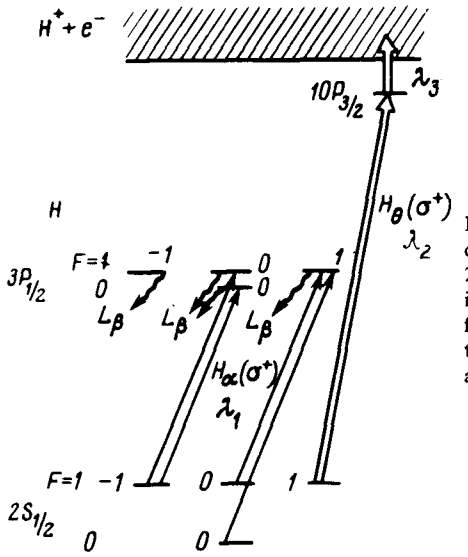

FIG. 1. Optical quantum transitions used for selective quenching of the sublevels $m_F=0, -1$ of the state $2S_{1/2}$, $F=1$ by the radiation λ_1 and for the photoionization of the oriented metastable hydrogen atoms from the state $2S_{1/2}$, $F=1$, $m_F=1$ with conservation of the orientation of the proton spin by the radiations λ_2 and λ_3.

the laser-induced optical transition $2S_{1/2}$–$3P_{1/2}$, followed by effective ionization of the atoms having a definite projection of the angular momentum through the Rydberg state. At the present state of the art of tunable lasers, this approach makes it possible to obtain $\approx 25\%$ polarized protons from the total number of atoms in the metastable $2S_{1/2}$ state, at a degree of nuclear polarization $\approx 100\%$ and at a beam angle aperture to 0.2 rad.

2. Consider a broad beam of hydrogen atoms brought to the metastable $2S_{1/2}$ state[2)] by one of the known method.[3] When the atoms are exposed in the $2S_{1/2} \rightarrow 3P_{1/2}$ transition to circularly polarized light $H_\alpha(\sigma^+)$ with wavelength $\lambda_1 = 6562$ Å, the only atoms that can remain in the $2S_{1/2}$ state are those on the level $F=1$, $m_F=1$ (Fig. 1). The atoms on the three remaining levels of the hyperfine structure experience, when excited to the $3P_{1/2}$ state, a rapid quenching to the ground state $1S_{1/2}$, owing to the large probability ratio of the spontaneous decays of the state $3P_{1/2}$ via the channels of the L_β and H_α lines ($\gamma_{1S}/\gamma_{2S} \approx 7.5$). At a laser intensity exceeding the intensity of the saturation on the $2S_{1/2}$–$3P_{1/2}$ transition, for a practically complete orientation of the state $2S_{1/2}$, several spontaneous decays to the transition $3P_{1/2} - 1S_{1/2}$ are sufficient.

We note that to conserve the IJ coupling in the $2S$ state under optical excitation it is necessary that the rate of the induced $2S \rightarrow 3P$ transitions satisfy the condition $dE/\hbar \ll \Delta\omega_{\text{hfs}}$, where d is the dipole moment of the $2S_{1/2} - 3P_{1/2}$ transition, E is the amplitude of the optical field, and $\Delta\omega_{\text{hfs}} = 170$ MHz is the hyperfine splitting of the $2S$ state. It is easy to verify that the condition that the $2S_{1/2}$ level become depleted during the time $t = d_1/v_0$ of the flight of the atoms through the light beam does not contradict the aforementioned condition.

Optical excitation of atoms on the $2S_{1/2}$–$3P_{1/2}$ transition must be effected in a

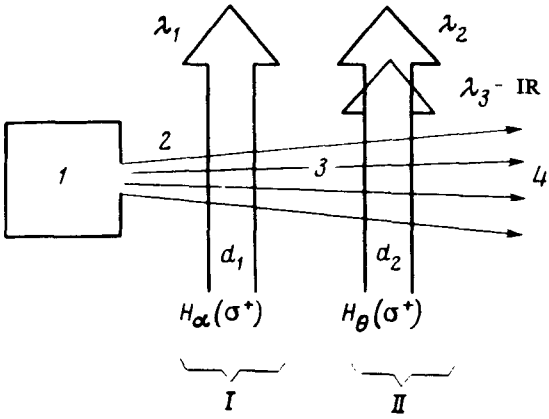

FIG. 2. Geometry of irradiation of a wide-aperture beam of metastable hydrogen atoms by selectively quenching (λ_1) and selectively ionizing (λ_2 and λ_3) laser beams.

direction perpendicular to the axis of the atom beam (Fig. 2). In this geometry, the absorption line width is minimal and is determined only by the angle divergence of the hydrogen-atom beam. The maximum beam divergence is determined from the condition that the overlap of the absorption lines on the transitions $2S_{1/2}$–$3P_{1/2}$ and $2S_{1/2}$–$3P_{3/2}$, which are separated by the amount of the fine splitting $\Delta = 0.12$ cm^{-1}, be small. Assuming that the allowed overlap is 1%, we obtain for the maximum angular aperture of the thermal ($u \approx 3 \times 10^5$ cm/sec) hydrogen atom a value $\approx 10°$. The corresponding total absorption width at half-height is $\Delta\nu = 5.5 \times 10^{-2}$ cm^{-1}. The $2S_{1/2}$–$3P_{1/2}$ transition saturation intensity corresponding to this width of the laser-emission spectrum is $I_S^{(1)} = 19.3$ W/cm^2. At a radiation intensity $I \gtrsim I_S^{(1)}$ the quenching of the states $2S_{1/2}(F=0,\ m_F=0;\ F=1,\ m_F=1.0)$ will be determined by the law $n(t) = n(0)\exp(-t/\tau)$, where $\tau = 6.1 \times 10^{-9}$ sec is the time of the spontaneous decay on the L_β transition $3P_{1/2} - 1S_{1/2}$ and t is the time of flight of atoms through the light beam. At a laser-beam diameter $d_1 = 1$ cm, for thermal atoms we have $t/\tau \approx 500$, and for atoms with energy 0.5 keV, which are used in Lamb's method, we have $t/\tau \approx 5.3$. Thus, to obtain deep quenching the required average laser power is much less than $P_{av}^{(1)} \approx d_1^2 I_S^{(1)} fT$, where T is the required duration of the proton pulse and f is their repetition frequency. For example, for a meson factory at $T = 10^{-4}$ sec and $f = 100$ Hz we obtain $P_{av}^{(1)} \approx 0.2$ W, which is perfectly attainable with a dye laser.

Illumination of the beam by a second circularly polarized radiation $H\theta(\sigma^+)$ of wavelength $\lambda_2 = 3798$ Å makes it possible to transfer the atoms from the state $2S_{1/2}(F=1,\ m_F=1)$ to the high-excited Rydberg state $10P_{3/2}(F=2,\ m_F=2)$. The saturation intensity of this transition is $I_S^{(2)} = 1.8 \times 10^2$ W/cm^2, and consequently the required average radiation power is equal to $P_{av}^{(2)} \approx d_2^2 I_S^{(2)} fT$, i.e., approximately 2 W at $d_2 = 1$ cm, which is also readily attainable with the aid of a dye laser.

The photoionization of the atoms from the state $10P_{3/2}(F=2,\ m_F=2)$ into the continuum makes it possible to obtain a beam of fully polarized protons. For the considered Rydberg state, the end-point photoabsorption frequency ($\nu_{ep} = 1082$ cm^{-1}) falls in the region of the CO_2-laser radiation. Time-synchronized photoexcitation into the Rydberg state and photoionization with IR radiation will make it possible to produce 100% ionization of atoms from the state $2S_{1/2}(F=1,\ m_F=1)$. The considered

photoionization scheme is optimal for the following reasons. An electric-field pulse cannot be used to ionize highly excited atoms because of the perturbation of the metastable atoms $2S_{1/2}(F=1, m_F=1)$. Direct photionization with shorter-wavelength radiation from the less excited states has a much smaller cross section and therefore requires a very high average radiation power at λ_3.

3. The proposed method has fundamental advantages over existing methods. The most important of them are: extremely high degree of polarization of the protons, an appreciable solid angle of the employed atom beam, reduction in the dimension of the polarization region to several centimeters, and the possibility of rapidly switching the polarization direction. We emphasize that the possibility of increasing, by three or four orders of magnitude, the solid angle of the employed atomic beam, compared with the existing methods, should lead to corresponding increase in the intensity of the beam of polarized protons. The small dimension of the polarizing and ionizing cells of the source greatly simplify the problem of installing the source in an accelerator.

All the foregoing features remain in force also when polarized ions of other elements are obtained, if the selection of the atoms by total (meaning also nuclear) angular momenta is effected by optical orientation of the atoms, while the oriented atoms are ionized through the Rydberg states.

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[1)]This possibility was noted by D.F. Zaretskiĭ in a discussion at an all-institute seminar on the prospects of the use of lasers in nuclear physics and nuclear chemistry.

[2)]Since no lasers with wavelengths 1215 and 2430 Å are presently available, we do not consider schemes for the orientation of nuclei in single- and two-photon excitation of the $2P$ or $2S$ levels.

[1]A. Kastler, 1967 Nobel Prize Lecture.

[2]V.S. Letokhov, V.I. Mishin, and A.A. Puretskiĭ, in: Khimiya plazmy (Plasma Chemistry), No. 4, B.M. Smirnov, ed. p. 3, Atomizdat 1977; V.S. Letokhov, V.I. Mishin, and A.A. Puretzky, Progress in Quantum Electronics, eds. J. Sanders and S. Stenholm, Vol. 5, part 3, p. 139, 1977.

[3]Yu.A. Plis and L.M. Soroko, Usp. Fiz. Nauk **107**, 218 (1972) [Sov. Phys. Usp. **15**, 318 (1972)].