On the Possibility of Obtaining the Polarised Protons by the Method of Direct Optic Pumping of a Fast Atomic Beam

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ABSTRACT

The direct optic pumping of accelerated hydrogen atoms is shown to be really possible. The method allows us to obtain a spin polarized H ion beam with the polarization degree ~ 1 and the real intensity which is close to the currently attained intensity of nonpolarized ion beams.

The use of polarized protons and light nuclei in the experiments on elementary particle physics and researches in the field of nuclear physics is rather promising at present and enable the obtaining of the valuable information about the mechanism and peculiarities of these processes [1], which are often impossible to distinguish in the experiments with nonpolarized beams.

In the last decade, due to the use of the method of charge-exchange of high-speed ions on polarized alkali metal targets [2] $\div$ [5], the progress has been gained in obtaining intense ion beams with high degree of nuclear polarization [6, 7]. Nevertheless, the problem of an increase in intensity of the polarized beams remains urgent.

We would like to call the attention of researchers to one of the possibilities of increasing the intensity of the polarized ion beams which appears as a results of achievements in the field of modern laser physics.

The polarized charge-exchange target method of generation of polarized ions has, in addition to all its advantages, the following shortcomings:

1. The substantial difficulties in creating a sufficiently dense polarized alkali metal atom target. In the best constructions this gives the efficiency of charge-exchange of high-speed ions to neutral atoms ~ 0.2.
2. The necessity of charge-exchange in a high magnetic field (1–1.5 T for hydrogen). This substantially complicates the construction of the ion source, creates the problems in formation and transportation of the polarized beam, and finally results in considerable deterioration of its ion-optic characteristics and decrease in real intensity.
3. The necessity of using the high frequency or Sona-transition to transform the electron polarization of an atomic beam to nuclear one.

The current progress in laser physics and technique has been gained both in increasing the power of generated light fluxes and in extension of the range of wave lengths available for use. This practically opens the possibility the optic pumping of the high-speed atom beam. Thus, the above-mentioned shortcomings of the charge-exchange method can be overcome and the efficiency of polarized ion generation can be close to 1. In this case, the problem is aimed to formation of sufficiently powerful pulses of circularly polarized light with the necessary wave length.

Fig. 1 presents the scheme for obtaining the polarized ion beam, which is based on direct optic pumping of a high-speed atomic beam.

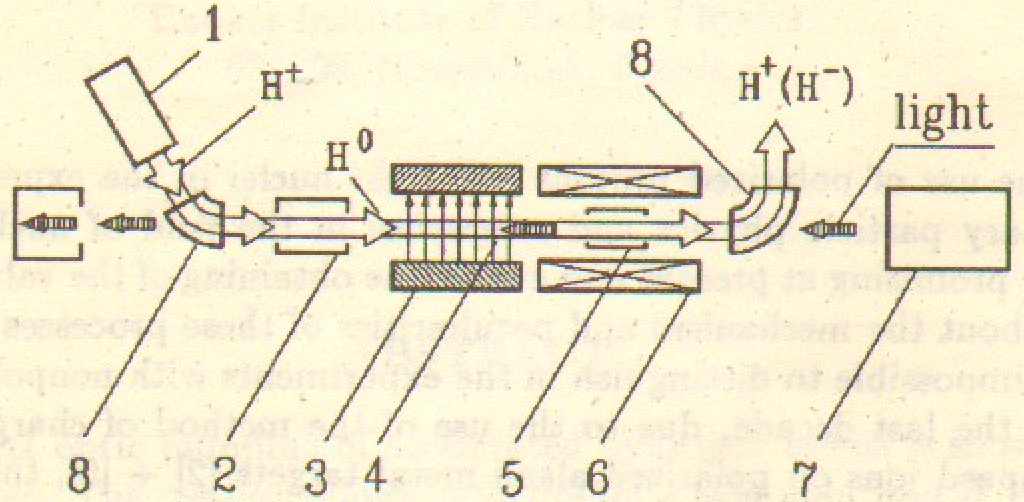

Fig. 1. 1) — ion source, 2) — first charge-exchange target, 3) — magnet generating the weak magnetic field, 4) — optical pumping region, 5) — second charge-exchange target, 6) — solenoid, 7) — laser, 8) — analyzing magnets.

A high-speed ion beam from the ion source (1) is transformed into a high-speed atom beam in the first charge-exchange target (2) (with the charge-exchange coefficient ~ 1) and pumped optically in a weak transversal magnetic field in region (4) by circularly polarized light. Thus-obtained beam of the high-speed atoms polarized by both the nuclear and electron spins in a powerful longitudinal magnetic field is transformed into the beam of either positive (with the charge-exchange coefficient ~ 1 or negative (with the charge-exchange coefficient ~ 0.1 ions in the second charge-exchange target (5).

Let us now estimate the circularly polarized light flux power which is necessary for efficient optic pumping.

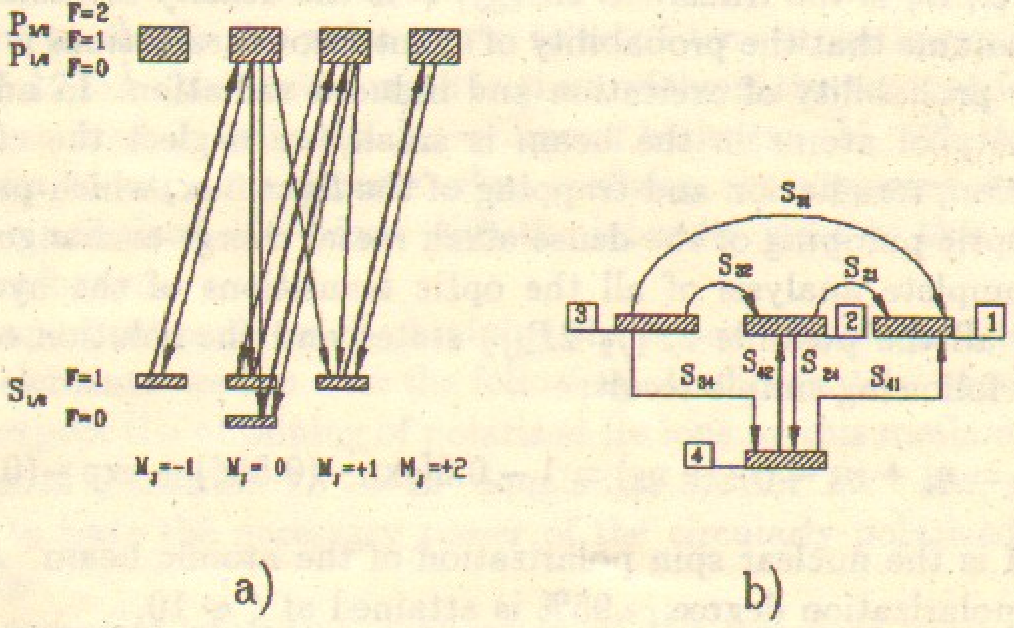

Fig. 2

Fig. 2,*a* demonstrates the known diagram of transitions between sublevels of hyperfine structure of hydrogen-like atom inter the action of the circulary polarized light. For the sake of simplicity, all the levels $P_{1/2}$, $P_{3/2}$, $F = 0$, $F = 1$ and $F = 2$ graphically united. In this case, for σ transitions holds the selection ruls $F = 0, \pm 1$, $M = +1$

The optic pumping of the atomic beam via the excited P-state results in the change of population of the S-state sublevels with the efficient probability of the transitions (S_{ij}) presented schematically in Fig. 2,*b*.

The dependence of the population of sublevels of the ground state on the distance along the beam is described by a linear system of equations

$$\begin{cases} \frac{d}{d\zeta}\eta_1 = \sigma_{21}\eta_2 + \sigma_{31}\eta_3 + \sigma_{41}\eta_4 \\ \frac{d}{d\zeta}\eta_2 = \sigma_{32}\eta_3 + \sigma_{42}\eta_4 - (\sigma_{21} + \sigma_{24})\eta_2 \\ \frac{d}{d\zeta}\eta_3 = -(\sigma_{31} + \sigma_{32} + \sigma_{34})\eta_3 \\ \eta_1 + \eta_2 + \eta_3 + \eta_4 = 1 \end{cases} \tag{1}$$

with the initial condition $\eta_1 = \eta_2 = \eta_3 = \eta_4 = 1/4$. Here, $\eta_i = n_i/n_0$ is the population of the levels of hyperfine structure at the ground S-state, n_0 is the density of atoms in the beam, $\sigma_{ij} = S_{ij}/W_0$, W_0 is the probability of the spontaneous transition $2P \rightarrow 1S$ ($6.25 \cdot 10^{-8}$ s^{-1} for hydrogen) and $\zeta = \beta_0 Ct/L_0 = X/L_0$

$$L_0 = \frac{\beta_0 C^2}{\lambda^3}\frac{E_\gamma}{P}\frac{(\Delta\lambda/\lambda)}{W_0}, \tag{2}$$

$\beta_0 = V/C$, E_γ is the transition energy, P is the density of radiation power.

We assume that the probability of spontaneous transitions is much higher that the probability of excitation and induced radiation. In addition, since the density of atoms in the beam is small, we neglect the effects due to attenuation, reradiation and trapping of the light flux, which play a decisive role in optic pumping of the dense alkali metal charge-exchange target.

A complete analysis of all the optic transitions of the hydrogen atom through all the possible $2P_{1/2}$ $2P_{3/2}$ states and the solution of system (1) give the following simple result:

$$\Pi = \eta_1 + \eta_4 - (\eta_2 + \eta_3) = 1 - 0.5[\exp -(0.50\zeta) + \exp -(0.29\zeta)], \qquad (3)$$

where Π is the nuclear spin polarization of the atomic beam. As seen from (3) the polarization degree $\sim 95\%$ is attained at $\zeta \sim 10$.

It is natural that in such problems the necessary radiation power depends on the line width $\Delta\lambda/\lambda$. In our case, the latter is mainly determined by the velocity spread and angular spread in the high-speed atom beam.

In the case where the beam propagates parallel or antiparallel to the direction of light propagation, the line width determined by the Doppler effect is as follows:

$$\frac{\Delta\lambda}{\lambda} = \beta_0 \left(\frac{\delta\beta}{\beta_0}\right) + 0.5\beta_0(\delta\varphi)^2 \qquad (4)$$

Here, $\delta\beta$ and $\delta\varphi$ denote the velocity spread and the angular spread in the atomic beam, respectively.

If for the the sake of definiteness we take the proton source [8, 9] with the parameters $I_p^+ = 1 \div 2$ A, $\beta_0 = 3.2 \cdot 10^{-3}$, $\delta\beta/\beta_0 = 0.25 \cdot 10^{-4}$ and $\delta\varphi = 2 \cdot 10^{-2}$, which seems to be appropriate for this purpose, then $\Delta\lambda/\lambda = 1 \cdot 10^{-6}$. This in the order of magnitude is close to the value of the hyperfine splitting of the sublevels in the hydrogen atom. In addition, it is worth of noting that in the case of optic pumping of the high-speed atom beam, the Doppler spread of frequencies turns out to be substantially less than that obtained at the optic pumping of the gas at the same temperature. The analogous effect is well-known in the theory of electron cooling.

Taking that the reasonable length of the optic pumping region is $X_{pump} \sim 10$ cm, we can obtain from (2) the necessary laser power.

$$P = 10\frac{\beta_0 C^2 E_\gamma (\Delta\lambda/\lambda)}{\lambda^3 W_0 X_{pump}} \sim 4\,\mathrm{W/cm^2} \qquad (5)$$

The use of the nonlinear laser radiation frequency transformation method for nonlinear gas media [10] allows us to obtain the coefficient of the conversion of the visible light into vacuum ultraviolet $\sim 10^{-4} - 10^{-5}$ in short pulses. This is sufficient to obtain the pulse power to some tens of watts even with the wave length 1215Å (the wave length is given without the account for the Doppler shift) required to exite the L_α — line of hydrogen [11, 12], thereby giving the reason to expect a success when realizing the proposed method of obtaining the polarized H — ions with the intensity close to that of the nonpolarized ion beams.

As to the important problem of obtaining the beams of polarized ions of the other light elements, we can note the following. Unfortunately, at present we can hardly expect the obtaining of polarized He ions by this method since the wave length of transition $1S \to 2P$ equals 308.8Å for He^+ ion, and it is problematic to have the necessary power of the circularly polarized light within this range.

From the viewpoint of optics, realization of the proposed method for obtaining the polarized nuclei of the other elements of the I and II groups is less problematic than in the case of hydrogen atom polarization. First, all the $nS - nP$ transitions used in optic pumping of atoms (ions) of this group are within the visible range from 3331Å for Be^+ to 6708Å for Li. Second, for the atomic (ion) group under consideration the oscillator forces of for $nS \to nP$ transitions differ from those of the $1S - 2P$ transition for hydrogen by no more than an order [13], and it is obvious, with taking into account the factor $E_\gamma/\lambda^3 \sim 1/\lambda^4$ in (2), that the laser power required for the efficient optic pumping should be substantially less than that required for the hydrogen atom polarization.

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