Laser polarization of accelerated protons

A. N. Zelenskiĭ, S. A. Kokhanovskiĭ, V. M. Lobashev, and N. M. Sobolevskiĭ
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 16 February 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 10, 357–359 (20 November 1982)

A method is proposed for using laser beams to polarize protons in a beam of fast hydrogen atoms. An intense atomic beam with an energy in the range 160–3000 MeV can be produced by neutralizing accelerated negative hydrogen ions. The implementation of this method would make it possible to produce a pulsed proton current two orders of magnitude higher than that obtainable by other methods.

PACS numbers: 29.25.Cy, 07.77. + p, 29.25.Fb

The acceleration of protons which are polarized in their sources has made it possible to substantially increase the intensity of accelerated polarized beams and to increase their degree of polarization. The conventional methods used to produce polarized beams have recently been supplemented by a method which uses circularly polarized laser beams to optically orient beams of polarized nuclei of alkali metals, lithium and sodium. The high-power tunable dye lasers which have recently been developed have been used here and have made it possible to achieve a very efficient polarization process and to produce beams with record high properties. Figure 1 shows the arrangement for optical orientation of hydrogen atoms. Upon the absorption of a right-hand-polarized photon, the total angular momentum of the atom F increases by one: $\Delta m_F = 1$. Transitions with $\Delta m_F = 0, \pm 1$ are possible in the spontaneous emission. In the course of the orientation, the equilibrium population therefore changes in such a manner that the only sublevels left populated are those with $m_F = 2$ in the excited state and $m_F = 1$ in the ground state, in which both the electrons and the protons have a 100% polarization. The polarization direction can be changed by changing the circular polarization of the light. However, since we currently lack sufficiently intense sources of electromagnetic radiation at the wavelength (1216 Å) required to excite these transitions, this method cannot be implemented directly in sources of polarized protons.

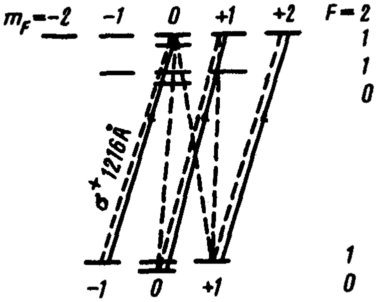

FIG. 1. Level diagram for optical orientation of hydrogen atoms. Solid lines—stimulated transitions; dashed lines—spontaneous transitions.

There is the possibility of using the Doppler shift of the wavelength into the region accessible to lasers by using a beam of fast atoms with $\beta = v/c \geqslant 0.5$. Fast neutrals can be obtained by stripping negative hydrogen ions in an electric field or, if necessary, singling out some short pulses of neutrals during a photoneutralization process. A unique possibility for producing intense beams of fast neutrals is being presented by the linear accelerator of the Institute of Nuclear Physics, for which there are plans to accelerate a beam of H^- ions with a pulsed current of 50 mA, a pulse length of 100 μs, a repetition frequency of 100 Hz, and an energy of 600 MeV (Ref. 1). The momentum spread at the exit will be $\Delta p/p = 10^{-3}$. When the Doppler shift of $\lambda_0 = 1216$ Å for the case in which the ion and laser beams are directed opposite each other is taken into account, we find the wavelength required for polarization: $\lambda = \lambda_0 \gamma (1 + \beta)$, where $\gamma = 1 + T/mc^2$, and m is the proton mass. As T is varied from 160 to 600 MeV, λ varies from 2160 to 3570 Å. The output frequencies of dye lasers can be doubled to achieve tuning in this wavelength range. The tuning interval, 4320–7140 Å, lies in the output range of efficient dyes. To polarize protons with energies in the range 600–2500 MeV will require wavelengths in the range 3570–9000 Å, which is the working range of dye lasers.

The Doppler broadening of the absorption line due to the longitudinal velocity spread of the accelerated particles is

$$\Delta \nu = \nu_0 \Delta p / \gamma m c = 2 \times 10^{12} \text{ Hz}, \quad \nu_0 = c/\lambda_0.$$

The fine splitting of the $2P_{1/2}$, $2P_{3/2}$ levels is 1.1×10^{10} Hz, so that transitions to all levels are excited, as shown in Fig. 1. The light intensity required to saturate these transitions, w_H, is about 20 kW/cm^2 over the entire velocity range of the atoms. In the case $w \geqslant w_H$, the number of photons absorbed over the time ($t = l/\beta c$) spent by an atom in the laser beam is $n = t/2\gamma\tau \simeq 10$, on the average, where $\tau = 1.6$ ns is the scale time of the spontaneous transition $2P \to 1S$, and $l = 10$ m. Figure 2 shows the results of a Monte Carlo calculation of the time dependence of the degree of polarization of the protons. We see that a high degree of polarization, ~90%, can be achieved over a reasonable illumination distance, $l = 10$ m. It is also possible to either make direct use of fast neutrals containing polarized protons in research on nuclear physics or to ionize the atoms through the removal of an electron in a charge-exchange target and then deflect and focus the resulting ions. As mentioned earlier, half of the atoms end up in the $m_F = 2$ excited state in the course of the optical orientation. If we use a laser beam

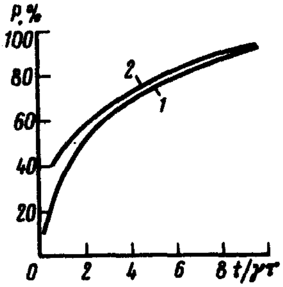

FIG. 2. Degree of polarization of the protons vs the time spent in the laser beam. 1—Summed over all sublevels; 2—polarization in excited states.

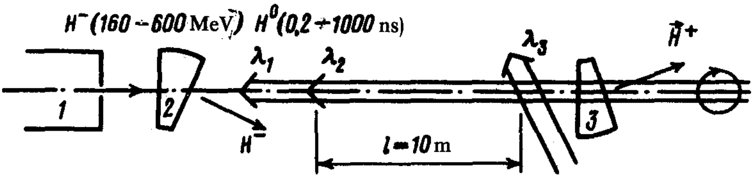

FIG. 3. Arrangement for laser polarization of accelerated protons. 1—Linear H^- accelerator; 2, 3—bending magnets; λ_1—laser used for photoneutralization; λ_2—polarizing laser; λ_3—laser used for photoionization.

which causes transitions from $n = 2$ to $n = 5$–10 to ionize the fast neutrals and then remove the electron in a strong electric field, we can achieve a degree of polarization for the resulting protons which is in fact higher than in ionization from the ground state (curve 2 in Fig. 2). The reason for this result is that the excited states are populated in a nonequilibrium manner from the very outset. Another possibility is to use the beam from a dye laser for 2→10 transitions. If the angle at which the particle and laser beams intersect is chosen correctly, electromagnetic radiation of the necessary length can be produced by using efficient dyes. Figure 3 shows one possible arrangement for achieving laser polarization of accelerated protons. The efficiency of the polarization process should approach 100%, and the intensity of the beam of polarized protons is equal to the intensity of the initial beam of H^- ions, about 50 mA. This method can therefore produce a pulsed intensity some two or three orders of magnitude higher than the highest reported to date. High-power lasers will be required to achieve a high average intensity. In practice, the intensity required could be achieved today by using flashlamp-pumped dye lasers (with a pulse energy of 1 J) and then doubling the frequency of the output beam. This approach could produce polarized protons in current pulses 1 μs long at a repetition frequency up to 100 Hz. The average current could be up to μA.

Laser ionization can be used to reduce the momentum spread of a beam of polarized protons to $\Delta p/p \sim 10^{-4}$–10^{-5}. For this purpose, the optical orientation and the subsequent excitation of the fast neutrals are carried out in a narrow interval of atomic velocities. This approach would reduce by one or two orders of magnitude the total radiation power required to saturate the transitions.

In the photoneutralization of H^- (Ref. 3) or in ionization one can separate and polarize separate bunches 0.2 ns long from the microstructure of the accelerated beam. The use of intense, short pulses of monoenergetic polarized protons in a time-of-flight approach might open up some new possibilities in nuclear spectroscopy.

We wish to thank M. I. Grachev and S. K. Esin for useful discussions of these questions.

---

[1] B. P. Murin, Trudy Pyatogo Vsesoyuznogo soveshchaniya po uskoritelyam zaryazhennykh chastits (Proceedings of the Fifth All-Union Conference on Charged-Particle Accelerators), Izd. Nauka, Vol. 1, 1977, p. 302.

[2] V. S. Letochov and V. G. Minogin, Phys. Rev. Lett. **41**, 775 (1978).

[3] I. Ya. Barit *et al.*, JINR Preprint P-0233, Moscow, 1982.

Translated by Dave Parsons
Edited by S. J. Amoretty