H^- charge-exchange injection without hazardous stripping foils

Isao Yamane

KEK, High Energy Accelerator Research Organization, Oho 1-1, Tsukuba, Ibaraki, 305 Japan

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A new scheme of H^- charge-exchange injection without stripping foils is proposed. It is composed of a neutralizer of the H^- beam using Lorentz stripping, the colliding system of a high power laser and the H^0 beam to excite H^0 atoms to the $3P$ state using the Rabi oscillation, and a magnet to strip the $H^0(3P)$ to a proton beam by Lorentz stripping. The necessary laser wavelength, laser power, magnetic-field gradient, and maximum magnetic field are estimated for a beam energy from 1.0 to 3.0 GeV. The result shows that such a scheme is sufficiently feasible for H^- beams with an energy discussed here. [S1098-4402(98)00015-9]

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I. INTRODUCTION

Thin foils of a solid material have been used as convenient strippers since the invention of the H^- charge-exchange injection method. Since H^- charge-exchange injection is very effective, it seems that it will continue to be a very useful method in the future to stack a very high-intensity proton beam in a proton synchrotron or a storage ring. However, the stripping foil must be reviewed from the viewpoint of a radiation hazard introduced by an uncontrollable beam loss due to scattering by the foil atoms. This kind of uncontrollable beam loss inevitably produces radioactivity around an accelerator. As long as the H^- energy is no higher than 100 MeV or the average power of the injected H^- beam is not very high, the induced residual radioactivity may be tolerable and does not introduce very serious problems. However, the situation is far more serious and the residual radioactivity may prevent daily maintenance services when the energy of the injected H^- beam is high and the average beam power becomes on the order of MW, as in the proposed ring for the neutron source driver of the Japan Atomic Energy Research Institute (JAERI) (1.5 GeV, 5 MW), the U.S. Spallation Neutron Source Project (SNS) (1 GeV, 1 MW), or the European Spallation Source (ESS) (1.334 GeV, 5 MW).

The JAERI neutron source driver, for instance, is planned to be a 5 MW proton compressor ring. Beam pulses of a 1.5 GeV H^- beam with a 30 mA peak intensity are injected into the compressor ring at a 50 Hz repetition rate. The number of protons stacked in the ring is 4×10^{14} . In order to strip a 1.5 GeV H^- beam sufficiently to a proton beam by a carbon foil, the necessary foil thickness is about $400 \mu\text{g}/\text{cm}^2$. At a beam energy of 1.5 GeV, the major elementary scattering processes that induce uncontrollable beam losses are large-angle Coulomb scattering, nuclear scattering, and scattering by electrons in the foil with a large momentum transfer. The total loss rate due to these scattering processes amounts to about 10^{-5} per every foil passage. Although accurate numbers depend upon the details of the ring design, the typical number of turns during injection is a few thousand

and the foil hitting probability is typically several parts of a thousand. Thus the average number of foil hitting may be about 10. As a result, the average beam loss rate due to uncontrollable scattering by the foil amounts, in order of magnitude, to 10^{-4} of the injected beam. Thus for a MW-class proton ring, the uncontrollable beam loss due to scattering by foil atoms may amount to several hundred watts, which is comparable to or more than the tolerance limit in the hands-on maintenance.

A charge-exchange method without a stripping foil was proposed by Zelenskiy *et al.* [1] as a new method to obtain a high-intensity polarized proton beam. First, a high energy H^- beam is converted to a H^0 beam by a photodetachment or a field-dissociation process. Then, the H^0 beam is polarized by an optical-pumping process to one of the $2P$ states. Last, the polarized H^0 beam is again converted to a proton beam by some stripping process without a foil, such as photoionization. If this method works well, it should be applicable to an injection method to form a high-intensity polarized proton beam in a ring. However, the method does not seem to be feasible because H^- photodetachment or H^0 photoionization also requires an impractically high-power laser beam due to the small cross sections of these reactions, as is mentioned in the following section.

Therefore, it is meaningful to try a new scheme of stripping with neither a stripping foil nor photostripping reactions. This paper proposes such a new charge-exchange injection scheme of the H^- beam, where H^- beams are converted to H^0 beams by field-detachment at first; then, H^0 atoms are excited to the $3P$ state by a high-power laser beam using the optical-nutation process; at last, $3P$ state H^0 atoms are stripped again by field dissociation.

II. LORENTZ STRIPPING OF H^- IONS AND H^0 ATOM EXCITED STATES

Since the binding energy of the second electron is as small as 0.755 eV, an H^- ion with an energy higher than several hundred million electron volts is easily stripped to a H^0 atom in a magnetic field higher than several

kilogauss by the Lorentz force. The equivalent electric field E (V/m) in the rest frame of the H^- ion is given by

$$E = \beta \gamma c B, \quad (1)$$

where $\beta = v/c$ and $\gamma = (1 - \beta^2)^{-1/2}$; v and c are the velocity of the H^- ion and light, respectively. B is the magnetic field in Tesler.

Electron stripping by the electric field of the Lorentz force is hereafter called Lorentz stripping. Thus Lorentz stripping includes field detachment of the H^- ion as well as field dissociation of the H^0 atom.

Studies on Lorentz stripping of the H^- ion have been reported in several papers [2–4]. The rest-frame lifetime (τ) of the H^- ion in a magnetic field is given by Scherk [3] and Jason *et al.* [4] as follows:

$$\tau = \left(\frac{A_1}{E} \right) \exp \left(\frac{A_2}{E} \right), \quad (2)$$

where $E = \beta \gamma c B$, $A_1 = 2.47 \times 10^{-6}$ Vs/m ($\pm 4\%$), and $A_2 = 4.49 \times 10^9$ V/m ($\pm 0.25\%$). The probability (τ^{-1}) of Lorentz stripping, calculated using this empirical formula, is indicated as the dotted line in Fig. 1.

At the Los Alamos proton storage ring (PSR), 800 MeV H^- beams from a linac are injected by a two-step H^0 injection scheme, where at first H^- beams are converted to H^0 beams by Lorentz stripping just before injection into the ring, then, formed H^0 beams drift into the ring through a dipole magnet and are at last stripped to proton beams by a thin foil. Conversion from a H^- beam to a H^0 beam is successfully carried out by Lorentz stripping half way along a steep rising magnetic field of a properly designed dipole magnet. Although a small emittance growth accompanies the stripping process, it is ignorable compared with the large emittance of the ring proton beam to be formed.

When an H^0 atom has a velocity v , the proton and the electron comprising the H^0 atom are also subject to an

electric field of E , given by Eq. (1), in a magnetic field B . The probability for the field dissociation of an H^0 atom in an electric field has been studied from the early days of quantum mechanics [5,6]. A convenient chart of the probability for the field dissociation of H^0 excited states with various principal quantum numbers has been given by Riviere [7]; see Fig. 1. The solid lines with a number show the electric-field dependence of the probability for the central component of the Stark states [8]. Because each state is split into plural states by the Stark effect, each line represents a group of lines slightly separated from each other; “ n ” indicates the principal quantum number of the state.

The most remarkable point indicated in Fig. 1 is that the probability line for the Lorentz stripping of H^- ions is very closely located to that for the $n = 3$ excited state of the H^0 atom. This fact suggests that the H^0 atom in the $n = 3$ excited state may be effectively stripped similarly to the H^- ion by the Lorentz stripping process. Thus if H^0 atoms with a GeV-order energy could be excited to the $n = 3$ excited state, an H^0 beam is successfully charge exchanged to a proton beam.

It should be mentioned that this is not true for the $n = 2$ state of the H^0 atom. As shown in Fig. 1, the $n = 2$ state requires a much higher magnetic field to be sufficiently stripped by Lorentz stripping. The following section gives a preliminary discussion of the possibility to excite the ground state H^0 atom with a GeV-order energy to the $n = 3$ state by a high-power laser.

III. EXCITATION OF 3P STATE USING HIGH-POWER LASER BEAM

In order to discuss the excitation of an H^0 atom from the ground state to a $n = 3$ state, we consider a colliding system of an H^0 beam and a high-power laser beam, as

FIG. 1. Probability of Lorentz stripping for an H^- ion and excited states of an H^0 atom. “ n ” is the principal quantum number of an H^0 atom. “A” indicates the probability of field dissociation for an H^- ion.

FIG. 2. Colliding system of an H^0 atom beam and a laser beam. Variables in the H^0 rest frame are shown in the upper right and those in the laboratory frame are shown in the upper left.

shown in Fig. 2. Since the H^0 atom has a very high velocity, near that of light, the relativistic transformation between the H^0 atom rest frame and the laboratory frame is very important. We assume $\beta = v/c$ and $\gamma = (1 - \beta^2)^{-1/2}$, where v and c are the velocity (m/s) of the H^0 atom and light, respectively, and α is the angle between the H^0 and the laser beam in the laboratory frame. The subscript “0” indicates a quantity in the H^0 atom rest frame. We then have

$$\nu_0 = \nu \gamma (1 + \beta \cos \alpha) \quad (3)$$

for the laser frequency,

$$W_0 = W \gamma^2 (1 + \beta \cos \alpha)^2 \quad (4)$$

for the energy density of the laser, and

$$\tan \alpha_0 = \frac{\sin \alpha}{\gamma (\cos \alpha + \beta)} \quad (5)$$

for the angle. The Doppler shift of the laser frequency for a particle with a momentum deviation ($\Delta p/p$) is

$$\Delta \nu_0^D = \nu_0 \beta \left(\frac{\Delta p}{p} \right). \quad (6)$$

Since the excitation energy of the $n = 3$ state of an H^0 atom is 12.10 eV, photons of the laser beam with a wavelength of $\lambda_0 = c/\nu_0 = 102.6$ nm induce a transition of H^0 atoms between the ground and $3P$ states. The $3P$ state is allowed to make a transition to the $1S$ and $2S$ states with spontaneous transition rates of 160 and $22 \times 10^6 \text{ sec}^{-1}$ [9], respectively. The lifetime (τ) of the state is $5.3 \times 10^{-9} \text{ sec}$.

For the purpose of a charge exchange of the beam, almost all H^0 atoms of the beam should be excited to

the $3P$ states. One possibility to be investigated is the optical Rabi oscillation. When the damping of the Rabi oscillation is sufficiently suppressed, the population of the $3P$ state becomes nearly 100% at the π -phase advance of the oscillation. Because H^0 atoms are well isolated from each other in the beam, damping of the Rabi oscillation by transverse relaxation is expected to be sufficiently suppressed. Therefore, we try to check the necessary condition to realize the π pulse in a reasonable time for a laser beam that has a wavelength of 102.6 nm and collides with an H^0 beam, as in Fig. 2.

The Rabi frequency (V_R) for the present two state system is given as

$$V_R = \frac{3^3 e a_0}{2^{13/2} \hbar} \sqrt{\frac{2 Q_0}{c \epsilon_0}}, \quad (7)$$

where e is the electric charge of an electron, a_0 is the Bohr radius ($0.53 \times 10^{-10} \text{ m}$), $\hbar$ is the reduced Planck's constant ($1.055 \times 10^{-34} \text{ Js}$), ϵ_0 is the permittivity of free space ($8.854 \times 10^{-12} \text{ Fm}^{-1}$), and Q_0 is the laser power density $Q_0 = c W_0$. Provided that $t_{\pi 0}$ is the time during which the phase of Rabi oscillation advances by π , $V_R t_{\pi 0} = \pi$. Figure 3 shows the dependence of V_R on Q_0 .

In the situation depicted in Fig. 2, H^0 atoms see the laser as a pulsed laser, even if the laser is continuous. In order to obtain the highest population of the $3P$ state after a collision, the time while H^0 atoms interact with the laser should be equalized to $t_{\pi 0}$ in the H^0 atom rest frame. Furthermore, $t_{\pi 0}$ should be taken to be less than the lifetime (τ) in order to sufficiently suppress any damping of the Rabi oscillation and to get almost all of the H^0

FIG. 3. (Color) Q_0 dependence of Rabi frequency V_R .

atoms into the $3P$ state. When L is the length over which H^0 atoms interact with the laser beam,

$$t_{\pi 0} = \frac{L}{\beta \gamma c} < \tau. \quad (8)$$

This means that $L < 3.8$ m for a 1.5 GeV H^0 beam.

The most serious problem is the Doppler broadening of the absorption line width due to the momentum spread of the H^0 beam, given by Eq. (6). Since the momentum spread ($\Delta p/p$) is usually on the order of 0.001, $\Delta \nu_0^D$ amounts to as much as $2.7 \times 10^{12} \text{ sec}^{-1}$. On the other hand, the frequency range which contributes to the Rabi oscillation is on the order of $V_R \sim 10^9 \text{ sec}^{-1}$. Therefore, we must consider two things: one is that the frequency spread of the incident laser should be broad enough to cover the Doppler broadening ($\Delta \nu_0^D$); the other is that the total laser power density should be as intense as a factor of $(\Delta \nu_0^D / V_R)$ times Q_0 , derived from Eq. (7). Figure 4 shows the dependence of the necessary laser wavelength (ν) and its power (Q_{lab}) on the H^0 beam energy in the laboratory frame

$$Q_{\text{lab}} = Q_0 \left(\frac{\Delta \nu_0^D}{V_R} \right) d, \quad (9)$$

where d is the duty factor of a pulsed laser beam, which may be equal to that of the H^0 beam. As the beam energy becomes higher from 1.0 to 3.0 GeV, the necessary laser wavelength gradually increases from the violet region to the red region and, conversely, the necessary laser power gradually decreases. Thus as long as the laser excitation of the H^0 atom to the $3P$ state is concerned, a higher energy is more advantageous.

Since the emittance of a GeV-energy H^- beam accelerated by a linac is usually small, that of an H^0 beam may be expected to be a few $\pi \mu\text{m rad}$ or less, even if an emittance growth due to Lorentz stripping is taken into account. Thus although the actual value depends on the detailed design of the ring and the injection system, the size of the H^0 beam may be expected to be several mil-

FIG. 4. (Color) Dependence of necessary laser wavelength and its power (Q_{lab}) on H^0 energy (T).

limeters or less in diameter. Therefore, the necessary size of the laser beam is considered to be about 10 mm in diameter, and the cross sectional area may be about 1 cm^2 . Then the necessary laser power is estimated to be several kilowatts for the beam energy discussed here, provided that the interaction length is taken as long as 2 m or more. Such a power of the pulsed laser is not extremely high these days. However, the momentum spread of the H^0 beam requires the laser to have a considerably broad and uniform frequency distribution. This is a subject of future development to be overcome by the rapidly progressing laser technology.

Of course, some part of the H^0 atoms remains in the ground state and a small fraction of the H^0 atoms excited to the $3P$ state decays to $2S$ or the ground state. However, these atoms are stable in the usual magnetic field in a synchrotron and can be safely guided to a beam dump. Thus they do not produce such a beam loss as was found downstream of a stripping foil [10].

IV. LORENTZ STRIPPING OF THE $H^0(3P)$ STATE IN A MAGNETIC-FIELD GRADIENT

As suggested in Fig. 1, the $3P$ state of a high-energy H^0 atom seems to be stripped by a magnetic-field gradient in the same way as adopted for the high-energy H^- ion beam. However, there are some remarkable differences and the following two points should be mentioned. The first is that the electric-field dependence of the stripping probability is much steeper for $H^0(3P)$ than for H^- . The second is that the $H^0(3P)$ state is split into several Stark states that have slightly different electric-field dependences of the ionization probability on the magnetic field.

The first means that when beams of these particles with a GeV-order energy pass through a magnetic field gradient, Lorentz stripping of $H^0(3P)$ atoms occurs more suddenly and within a much shorter range of flight pass than that

of H^- ions. Thus the angular divergence of the beam due to Lorentz stripping in the same field gradient is expected to be much smaller for $H^0(3P)$ beams. Therefore, if the same angular divergence is allowed for $H^0(3P)$ and H^- ion beams, the necessary field gradient for the former is much smaller than that for the latter. We estimated the angular divergence of an H^0 pencil beam during passage through a magnetic-field gradient, shown in Fig. 5, following the same method described in Ref. [11], using data of the ionization probability in Fig. 1. The results for five energies of the $H^0(3P)$ beam are shown in Figs. 6(a)–6(e). It shows that the angular distribution rapidly varies along with the magnetic field gradient and the beam energy. Since the beam loss should be less than 10^{-4} of the beam, the angular spread of the stripped beam that includes 99.999% of the beam particles should be narrower than the tolerance limit. Although the tolerance limit is determined by the design criterion of the ring, it may be reasonably presumed to be 3 mrad, or something like that. In order to obtain a sufficiently narrow angular spread, a field gradient higher than 20 T/m is necessary when the beam energy is 1.0 GeV. However, for a beam energy higher than 2.0 GeV, a field gradient of 10 T/m, or slightly less, may be adequate.

The second issue also introduces a broadening of the angular spread of the stripped beam. The electric-field dependence of the ionization probability was extensively studied by Bailey *et al.* [8] for various excited states of the hydrogen atom. The excited state with the principal quantum number $n = 3$ splits into six states in an electric field due to the Stark effect. The angular distribution of a stripped beam through each Stark state can be calculated using the data of the electric-field dependence of the ionization probability for these states. Figure 7 shows one of the results. All of the lines of this figure show the angular distribution normalized to an equal total

amount. Actually, the $3P$ state of the H^0 atom does not split to all of these states, and the fractional amount of splitting to each Stark state differs from state to state. Therefore, the angular distribution of the proton beam actually formed from the $H^0(3P)$ beam by the Lorentz stripping is a weighted sum of these angular distributions, and the resultant angular spread is the overall spread including all of these angular distributions. However, as shown in Fig. 7, the resultant angular spread can be made sufficiently narrow for a magnetic field of 10 T/m when the beam energy is as high as 2.5 GeV. Of course, this angular spread becomes narrower as the beam energy or the magnetic field gradient becomes higher.

V. POSSIBLE TWO-STEP STRIPPING SCHEME FOR A MW PROTON RING

Based on the discussion given in the preceding sections, such an injection scheme as shown in Fig. 8 may be practical. It is composed of three components: a neutralizer of the H^- beam just before injection into the ring, a colliding system of the injected H^0 beam and a laser beam to excite H^0 atoms to the $3P$ state, and a device to produce a magnetic-field gradient to strip the $H^0(3P)$ beam to a proton beam.

With respect to the neutralization of the H^- ion beam, there are many experiences of a stripping magnet used for 800 MeV H^- beams at the Los Alamos PSR [4]. The performance of the magnet is sufficiently satisfactory. As the H^- beam energy increases, not only the highest field, but also the field gradient required for the stripping magnet, becomes lower. In addition, the angular divergence due to Lorentz stripping becomes smaller. Therefore, a Los Alamos-type stripping magnet is expected to be sufficiently applicable at the energy region from 1.0 GeV to a few GeV.

As for excitation of a high-energy H^0 atom to the $3P$ state by collisions with a laser beam, necessary laser wavelength comes to the color region for the H^0 beam energy from 1.0 GeV to a few GeV. The necessary laser power becomes lower as the H^0 beam energy increases, and the laser power necessary for an interaction length of 2 or 3 m is sufficiently obtainable using present technology. In the situation shown in Fig. 2, the interaction length over which an H^0 particle interacts with a laser beam is about half of the length of the interaction region. Therefore, the interaction length cannot be longer than a few meters, and shorter may be better. A part of the $H^0(3P)$ atoms must drift through a space without a laser beam, and a small fraction of them decay to the $2S$ and $1S$ states. These atoms cannot be stripped in a following magnetic field of the ring and can be safely guided to a beam dump outside of the ring. The fraction that makes a transition from $3P$ to $2S$ and $1S$ becomes smaller as the drift length of $H^0(2S)$ becomes shorter. These facts mean that a higher energy of the H^0 atom is more advantageous.

FIG. 5. Stripping of an $H^0(3P)$ pencil beam in a magnetic-field gradient and angular divergence of the resultant proton beam.

FIG. 6. (Color) Angular distribution of proton beam formed from $H^0(3P)$ pencil beam by Lorentz stripping in a magnetic-field gradient. (a) $T = 1.0$ GeV, (b) $T = 1.5$ GeV, (c) $T = 2.0$ GeV, (d) $T = 2.5$ GeV, and (e) $T = 3.0$ GeV.

In order to apply the Lorentz stripping for the charge exchange of the $H^0(3P)$ to a proton beam in high-intensity proton rings, two requirements must be fulfilled. One is that the angular divergence due to Lorentz stripping must be sufficiently small; the other is that the necessary magnetic-field gradient and the maximum field must

be available in those rings. Because the electric-field dependence of the ionization probability is much steeper, the necessary magnetic-field gradient for Lorentz stripping of the $H^0(3P)$ beam is not as high as for the H^- beam. However, the $H^0(3P)$ state splits into several Stark states, and the resultant angular spread of the whole stripped

FIG. 7. (Color) Angular distribution of proton beams formed by Lorentz stripping in a magnetic-field gradient through H^0 ($n = 3$) Stark states. $T = 2.5$ GeV.

beam is about one-and-a-half times larger than that of the central component. As can be seen from Fig. 6, when the energy of the $H^0(3P)$ beam is 1.0 GeV, a magnetic-field gradient higher than 40 T/m and a maximum field higher than 1.4 T are necessary to suppress the angular divergence of the part including 99.999% of the stripped protons to less than 3 mrad. However, when the energy is increased to 2.5 GeV, a field gradient higher than 6 T/m and a maximum field as high as 0.73 T are enough. Thus a higher beam energy is more advantageous. Actually, the aperture of a component magnet is usually considerably large in a high-intensity proton ring, and it does not seem easy to obtain a magnetic-field gradient higher than 10 T/m or a field higher than 1 T. Therefore, in order to apply Lorentz stripping of the $H^0(3P)$ beam, it is desirable to adopt a beam energy as high as 2.5 GeV. It seems sufficiently feasible to install a magnetic field with a gradient of several T/m and a maximum field of about 1 T as a wiggler magnet or a fringe field of a dipole or quadrupole magnet in a high-intensity proton ring.

VI. PHOTODETACHMENT OF H^- AND PHOTOIONIZATION OF H^0 EXCITED STATES

A theoretical calculation [12] suggested that the photodetachment cross section of a H^- ion has a resonance at 112.95 nm and that the peak value reaches $2.7 \times 10^{-17} \text{ cm}^2$. The resonance is very narrow, and off the resonance the cross section decays rapidly to under 10^{-17} cm^2 . Thus a MW/cm² laser beam with a several hundred nanometer wavelength in the laboratory frame is necessary in order to sufficiently neutralize a H^- beam by photodetachment. Such a neutralization method seems to be very hard in comparison to Lorentz stripping, which is well known as being sufficiently applicable based on the experience at the Los Alamos PSR.

Concerning the photoionization of H^0 atoms, there have been many studies, not only theoretical but also experimental [13]. It is said that for many practical purposes Kramers' formula is sufficiently accurate to calculate the cross section of the photoionization of hydrogenlike systems. Kramers' formula is given as

$$\sigma(n, \lambda) = 1.045 \times 10^{-14} z^4 \lambda^3 n^{-5}, \quad (10)$$

where $\sigma(n, \lambda)$ is the cross section in cm², z is the charge number of the nucleus, λ is the wavelength of the photon in micrometers, and n is the principal quantum number of the electron state. Although the cross section increases with the wavelength as λ^3 , the wavelength is limited by that of the ionization energy. Thus the cross section of the photoionization is on the order of 10^{-17} cm^2 for states of the H^0 atom. Therefore, it also seems to be impractical to apply photoionization to the ionization of a two-step charge-exchange scheme using present technology.

VI. SUMMARY

The thin foils of solid material used for the stripper in the H^- charge-exchange injection are hazardous, especially in a MW-class proton accelerator, because they

FIG. 8. New scheme of H^- charge-exchange injection using Lorentz stripping and laser excitation of an H^0 atom instead of a stripping foil.

produce uncontrollable beam losses by scattering high-energy protons, and thus radioactivity, around the accelerator. Therefore, a new type of charge-exchange injection scheme without a stripping foil is proposed. It is composed of three components: a magnetic neutralizer of the H^- beam, a colliding system of the H^0 beam and a high-power laser beam to excite the H^0 atom to the $3P$ state, and a magnetic stripper which converts the $H^0(3P)$ to a proton beam by Lorentz stripping.

The excitation of H^0 atoms is carried out by the optical Rabi oscillation under the π -pulse condition. Because the energy of the H^0 beam is as high as 1.0 GeV, or something like that, the necessary wavelength of the laser comes to the color region in the laboratory frame. The necessary laser power becomes lower as the H^0 beam energy becomes higher and as the interaction length becomes longer. Although the interaction length available in the usual high-intensity proton ring is probably no longer than about 3 m, the necessary laser power seems to be feasible using a pulsed laser.

Since we have much experience at the Los Alamos PSR, there seems to be no problem with Lorentz stripping of the H^- beam with a GeV-order energy. As for Lorentz stripping of a $H^0(3P)$ beam, there is an advantage and a disadvantage as well. Since the electric-field dependence of the ionization probability is much steeper for the $H^0(3P)$ atom than for the H^- ion, the resultant angular divergence of the stripped beam is much narrower for the former. Therefore, the necessary magnetic-field gradient and the maximum field become much lower for the $H^0(3P)$ beam. However, the $3P$ state of the H^0 atom splits into several Stark states with a slightly different electric-field dependence of the ionization probability. Thus the proton beam formed from the $H^0(3P)$ beam by Lorentz stripping has several components from different Stark states and its angular divergence is that which covers all of these component beams. The angular divergence depends upon the beam energy and the gradient of the magnetic field. When the beam energy is 1.0 GeV, the field gradient should be higher than 40 T/m in order to suppress the angular divergence of the resultant proton beam, including 99.999% particles no larger than 3 mrad. However, as the beam energy increases, the necessary field gradient and the maximum field rapidly decrease. When the $H^0(3P)$ energy is 2.5 GeV, a magnetic field with a gradient of 6 T/m and a maximum field

of 1 T seems to be adequate. Such a magnetic field is sufficiently feasible as a form of a wiggler magnet or a fringe field of a dipole or quadrupole magnet in a usually high-intensity proton ring.

Thus a charge-exchange injection scheme without stripping foils is feasible by a system using excitation of the H^0 atom to the $3P$ state by collisions with a laser beam and Lorentz stripping of the H^- and the $H^0(3P)$ beam.

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