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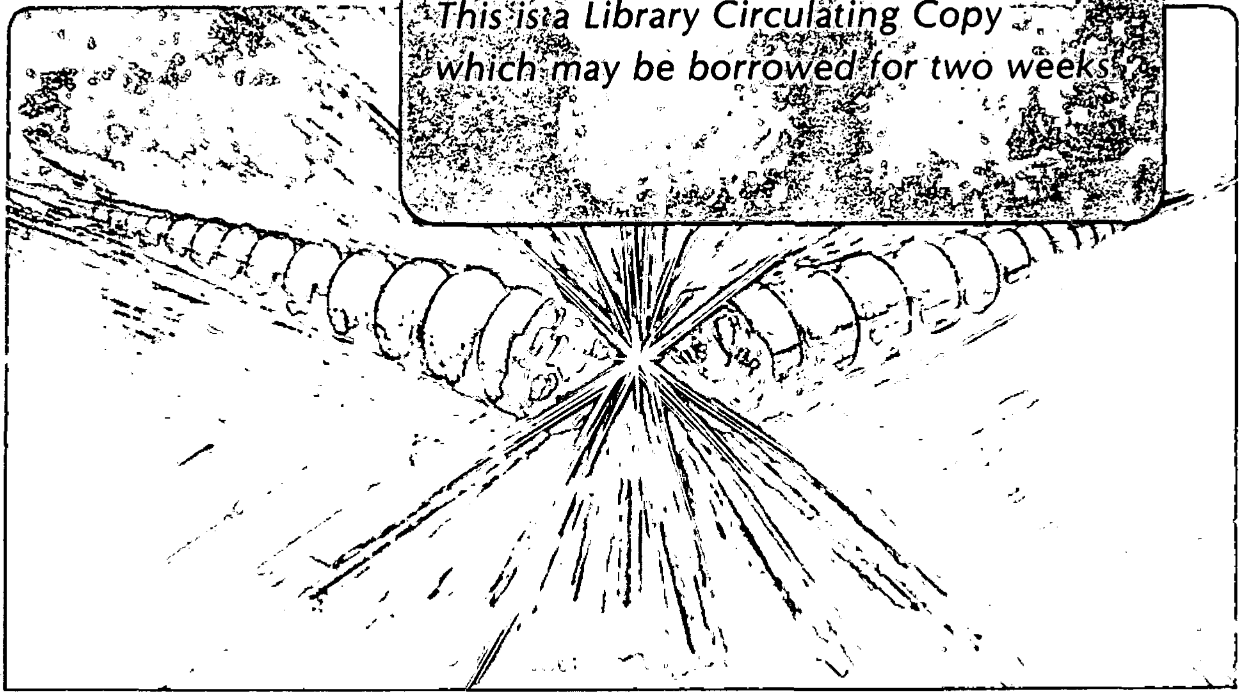

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COLLISIONAL PUMPING FOR THE PRODUCTION OF INTENSE SPIN-POLARIZED NEUTRAL BEAMS: TARGET CONSIDERATIONS*

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INTRODUCTION

The production of intense polarized beams has potentially important applications in fusion-reactor technology. If the reactants in a fusion reactor are polarized, the nature of the fusion reactions is affected in several ways. For the d,t reaction, fusion results almost entirely from the 3/2+ state of the ^{5}He compound nucleus. By enhancing the 3/2+ state, an effective increase in the cross section of up to 50% can be achieved. Such enhancement is achieved if both triton and deuteron spins are aligned in a parallel fashion (ortho-d-t.) At least two recent studies[1] have pointed out other characteristics of fusion reactions with polarized reactants. Most important, it appears that depolarizing mechanisms do not operate effectively in the 30 seconds or so which constitute the reaction time in projected fusion-reactor designs. As a consequence of the enhanced fusion cross section, the minimum requirements for both thermalized breakeven and for plasma ignition are significantly reduced. These requirements involve the values for the average ion temperature and for the product of the ion density and the reaction time. The directionality of the reaction products from reactions with polarized reactants is also affected. Rather than an isotropic distribution, the ortho-d-t condition produces a $\sin^2\theta$ distribution. This distribution is beneficial for directing neutrons towards the breeding blanket of a tandem-mirror machine. Analysis of the d,d interactions is more complicated, and is not completely understood. However, it has also been proposed that significant benefits may be derived from polarized deuterons in the d-d reaction.[1]

Neutral-beam heating and/or fueling offers the possibility of establishing deuteron and triton spins oriented parallel to the magnetic field (or antiparallel to the field). It is believed that the polarizations can be maintained by guide fields until the particles are within the reactor. A beam suitable for this magnetic fusion-energy application would require five to six orders of magnitude increase in polarized beam intensity from the limits imposed by present technology, which is on the order of 10-100 μA.

We have recently proposed[2,3] that ampere-sized beams of nuclear-spin-polarized ions and atoms can be produced by multiple atomic collisions in an electron-spin-polarized medium. By analogy to optical pumping, we have called the process "collisional pumping." Such pumping will occur when an ion beam passes through a thick electron-spin-polarized target in a low magnetic field. As an ion in the beam undergoes a succession of electron-capture and -loss collisions, polarization is transferred from the electron to the nucleus through the hyperfine interaction. After a sufficient number of charge-changing collisions, both the electron and nuclear polarization of the beam will be pumped to the electron polarization of the target.

We have analyzed and theoretically demonstrated several examples of collisional pumping[2,3]; the case that lends itself to earliest testing is that of a low-energy (0.1 - 10 keV/u) hydrogen or deuterium beam passing through a thick electron-spin-polarized alkali-vapor target in a low magnetic field.

A sample calculation[2] for collisional pumping is shown in Fig.1, which shows neutral

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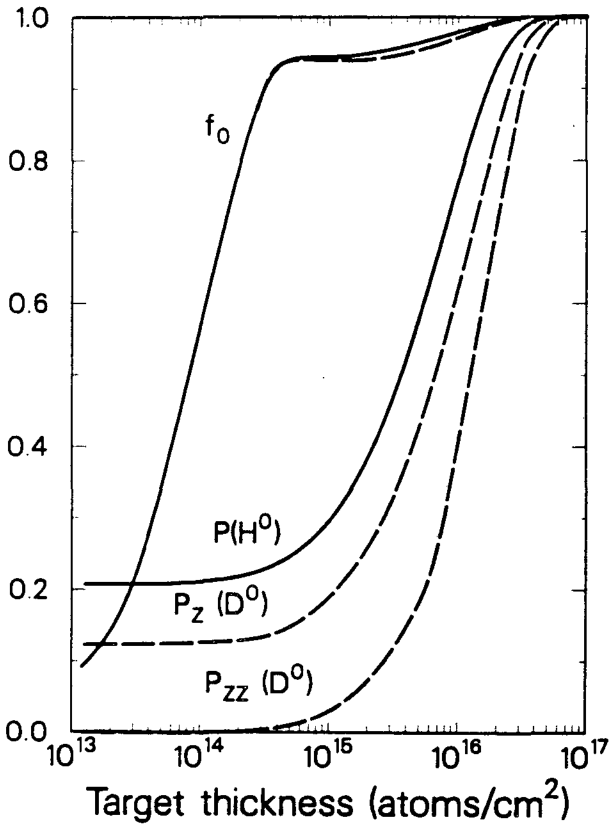

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Fig. 1.Polarization P and neutral fraction f_0 for 2.5 keV/u H(solid) and D(dashed) in Na vapor. P_z and P_{zz} are vector and tensor polarizations for D.

fraction and polarization for 2.5-keV/u H$^+$ or D$^+$ incident on an electron-spin-polarized sodium-vapor target. Two remarkable features should be noted: the beam emerging from the target is entirely neutral, and it is entirely electron-spin and nuclear-spin polarized. This conversion of an entire beam to a nuclear-spin-polarized beam is the essential feature of collisional pumping. The beam can subsequently be ionized to produce either polarized H$^+$ (D$^+$) or H$^-$ (D$^-$). The conversion of polarized H^0 (D^0) to polarized H (D$^-$) can be highly efficient because of spin-dependent atomic processes.

Experimental demonstration of collisional pumping will require production of a target of electron-spin-polarized sodium vapor at a line density of approximately 10^{17} atoms/cm^2, which is a factor of a thousand greater than targets presently produced.

PRESENT STATUS OF POLARIZED BEAMS

Nuclear-spin-polarized ion beams have important applications in physics, and considerable effort has been devoted to developing such beams for particle accelerators.

Current state-of-the-art polarized hydrogen-ion sources produce beams of up to approximately 100μA (H$^+$, D$^+$) or 25μA (H$^-$, D$^-$). Methods of production have recently been reviewed.[4-6] The most promising method for polarized H$^-$ beam production employes optically-pumped alkali-vapor targets.[7,8] These optically pumped ion sources use capture of a spin-polarized electron by a fast proton in a thin electron-spin-polarized sodium-vapor target in a high magnetic field. Electronic polarization is converted to nuclear polarization by a Sona transition and the beam is ionized for further acceleration. This technique can produce polarizations approaching 100% only for spin-1/2 nuclei. As a result of interest for accelerator applications, optically pumped sources are undergoing rapid development, especially by Mori et al.[7] at KEK in Japan and by Levy et al.[8] at TRIUMF in Vancouver, Canada.

In recent years, several groups have produced highly-polarized targets of sodium vapor in a high magnetic field. Cornelius et al[9] used a field of 0.35 T and a single-frequency 300 mW pumping laser. A broadband probe laser was tuned to a frequency midway between the two D lines of sodium, and a measurement was made of the optical rotation induced in the probe laser light by the polarized medium. The optical rotation was then related theoretically to the polarization. Mori et al[7] used two 1-W pumping lasers in sodium vapor and employed the optical-rotation method to measure the polarization. The magnetic field was 0.3 T, and the polarization was reported to be about 0.90 at 1 x 10^{13} atoms/cm^2. The TRIUMF group has also made recent advances.[8]

The major depolarization mechanism for the target which has been considered by experimenters to date is that resulting from wall collisions. Anderson[10] has been successful in using an organic wall coating to mitigate the effect of such collisions. This has been applied by Levy et al,[11] who find a large increase in polarization.

APPLICATION TO COLLISIONAL PUMPING

Production of polarized ions by collisional pumping differs in several important respects from the method presently used in optically pumped sources; although the apparatus appears to be very similar, the physics is, in fact, different. An optically pumped source uses direct capture of a polarized electron in a relatively thin polarized target (10^{14} atoms/cm^2) in a high magnetic field, i.e., capture in a single collision. Nuclear polarization is not directly produced, but results from a subsequent Sona transition. Collisional pumping will utilize multiple charge-changing collisions in a thick polarized target (up to 10^{17} atoms/cm^2) in a low magnetic field, directly producing a nuclear-spin-polarized beam.

The nuclear polarization is achieved by the hyperfine interaction transferring electron spin to nuclear spin in the time between collisions. As the entire ion beam can be converted to polarized beam, very large increases in intensity should be possible by use of collisional pumping. However, collisional pumping requires a polarized target approximately three orders of magnitude thicker than has been produced to date. This is not presently possible with cw lasers, nor is all the physics of depolarization mechanisms for thick targets understood.

POLARIZED TARGET

Experimental confirmation and study of collisional pumping requires an electron-spin-polarized alkali-vapor target that is thick enough for an incident beam ion to undergo multiple charge-changing collisions during passage through the target. For sodium vapor, in which charge-changing cross sections are large, and for which suitable optical-pumping lasers exist, the vapor target should have a thickness of about 10^{17} atoms/cm^2, about 1000 times thicker than those now used to produce polarized hydrogen beams by direct capture of a polarized electron in a high magnetic field. Unpolarized alkali-vapor targets of such thicknesses have been used for studying charge equilibration of hydrogen-ion beams.

The minimum laser power required for optical pumping is determined by the relaxation times of the depolarization mechanisms and by the efficiency of the optical pumping. The principal depolarization process is believed to occur through angular-momentum transfer during wall collisions. Atomic-collision processes are a lesser contributor. In an optically thin target the production of each polarized atom requires the absorption of 3 laser photons. Therefore a laser photon flux greater than 3 times the target line density divided by the depolarization relaxation time is required. For a sufficiently intense laser beam the rate of optical pumping is limited by the radiative decay rate of the intermediate excited state. While the radiative lifetime of the excited state is relatively short, the effective lifetime can be greatly increased by a process called radiation trapping, whereby each photon undergoes a succession of absorptions and reemissions. Radiation trapping is of particular concern in thick targets. In order to achieve a high degree of polarization, the laser-beam duration must be long compared to the effective excited-state lifetime, and the laser power must be sufficient to optically pump the target in a time period which is less than the polarization relaxation time.

We propose, as the first step, to study the processes contributing to both of these time constants by employing some of the technology, and building on the experience, of several accelerator research groups that have made significant recent advances in understanding and producing polarized alkali vapors.[7-9] Collisional pumping requires a thick target in a low magnetic field. Radiation trapping is expected to be both more severe and more amenable to study than in a thin target. Furthermore, in a weak magnetic field, the pumping mechanism is complicated by the hyperfine interaction between the nucleus of the alkali atom and the valence electron.

The planned work will utilize two lasers: a high-powered optical-pumping laser that can produce about 10 kW of circularly polarized light over a time interval that is long compared to effective excited level lifetimes, and a second, low-power, narrow-band dye laser for diagnostics, to measure target polarization. Low-powered cw diagnostic lasers are readily available, whereas a laser almost ideally suited for the optical-pumping has only recently become commercially available. It is a pulsed dye laser, manufactured by Candella Corporation, that produces a 10-kW pulse with a time duration of 500 µs. The spectral range of this laser is suitable for optically pumping sodium vapor, which will therefore be the first medium investigated.

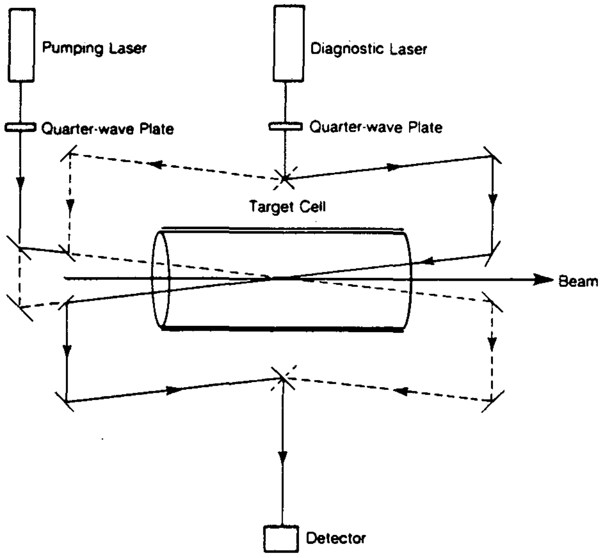

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Fig. 2. The experimental arrangement.

The experiment is shown schematically in Fig. 2. Light from the long-pulse flash-lamp-pumped laser enters a heated tube containing sodium vapor. The atomic line density in the tube is changed by changing the temperature. Measurements will include polarization versus line density, polarization versus pump-laser power, and relaxation processes and time constants for the medium.

Two methods are commonly used to measure the degree of polarization of an alkali-vapor target: transmission, and Faraday rotation. Either of these methods, with some modifications because of the thick targets, can be applied to measurement of the degree of polarization of a target for collisional pumping. We intend to pursue both of these methods, and will acquire a laser appropriate for either diagnostic.

The transmission method[8] uses a beam of left- or right-circularly polarized light from a diagnostics laser to probe the target; target polarization is determined from attenuation of the polarized light. For a thick target, we expect that the optical transmission at the fundamental-resonance wavelength will be very low. We will therefore use one or both of two possible variants for thick-target measurements, both of which use diagnostic-laser frequencies other than the fundamental absorption resonance. If the laser frequency is tuned off of the resonance frequency until transmission is observed, the vapor polarization can be inferred.[12] Alternately, we can employ absorption resonances corresponding to higher atomic levels, which are characterized by lower absorption coefficients. For example, in sodium, instead of 3S → 3P, a 3S → 4P or 3S → 5P could be probed; many such transitions are within the reach of tunable dye lasers.

Faraday rotation, a more precise method currently employed for polarization measurements, makes use of the birefrigence of alkali vapors.[7-9] A beam of linearly polarized light incident along the magnetic axis will undergo optical rotation; the angle of this rotation is directly related both to the vapor thickness and to its polarization. The relationship between the optical rotation and the vapor polarization is known for the case of a magnetic field which is large compared to the critical field of the vapor; experiments have been done only at high magnetic fields (0.2-0.4 T). However, we have recently verified that a measurable rotational shift is produced in a low magnetic field, with the generous cooperation of P. W. Schmor, C. D. P. Levy, and Y. Mori, who made this measurement at TRIUMF, and we and others[13] have made progress in working out the theory for this case. Furthermore, while collisional pumping requires a low magnetic field – a field which is smaller than the critical field for the beam atoms – there are cases where a magnetic field can be chosen which is smaller than the critical field for the beam, but which is larger than the critical field for the alkali-vapor target. Potassium and hydrogen constitute a pair of materials where this could be achieved. For such a target-beam combination, we can choose a magnetic field which is high for the potassium target and low for the hydrogen atoms, and thus benefit from the already developed high-field Faraday-rotation technique.

POLARIZED BEAM

A polarized beam will be produced by hydrogen ions passing through the electron-spin polarized vapor. The collisional-pumping mechanism itself provides a means for measuring both the target polarization and the fast-atom-beam polarization. For polarized sodium-vapor target thickness of $\geq 10^{17}$ cm^{-2}, the positive-ion fraction of a 2.5-keV/u H^+ or D^+ beam leaving the target is negligibly small, and the polarization of the beam and of the target can be inferred from the negative-ion current (H^- or D^-) leaving the target. The target and beam polarization is

$$P = 1 - I^-(p)/I^-(u),$$

where $I^-(p)$ and $I^-(u)$ are the H^- or D^- currents emerging from the target for the polarized and unpolarized target respectively. This measurement can be made simply by measuring the negative-ion current emerging from the target with the pumping laser turned on and then off, while the other parameters remain constant. This simple method for measuring beam and target polarization is a special characteristic of collisional pumping.

A beam of 2.5-keV/u H^+ or D^+ was selected because charge-transfer cross sections are large, leading to a minimal target-thickness requirement for collisional pumping, and because the equilibrium positive ion charge fraction in sodium is small (Fig. 3). Scattering should be minimal at this energy. Another energy in the range 1-10 keV/u might be found optimal.

The usual method for measuring beam polarization involves scattering from a spin-zero nucleus. However, below energies of a few MeV, the analyzing power of such reactions is not appreciable. Since such energies will not be conveniently available we will employ nuclear reactions as a means of measuring the beam polarization. Such reactions are useful at low beam energies, and the reaction-product asymmetries can be

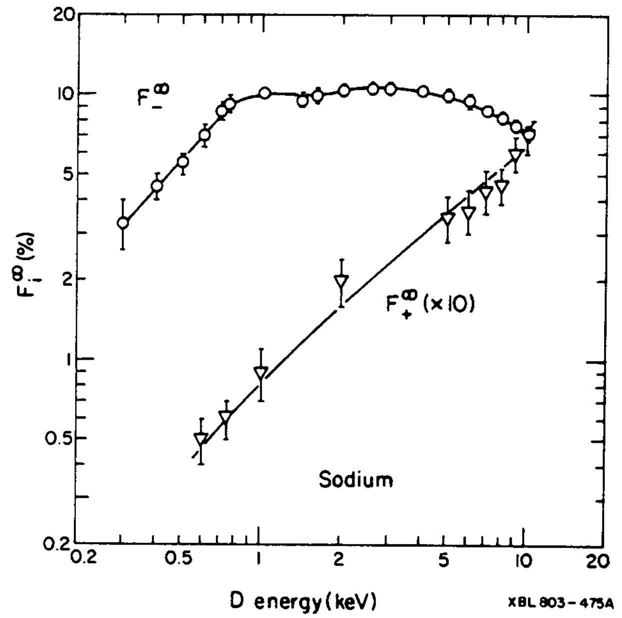

Fig. 3. Equilibrium charge fractions[15] vs E for D in Na. D at 5 keV = 2.5 keV/u.

related to the polarization. Mori et al.[7] used the reaction: H + ^{6}Li → ^{3}He + ^{4}He + 4.02 MeV, to study the polarization of a 355-keV proton beam. Left-right asymmetries were measured at two separate angles, using solid-state detectors, and the polarization was calculated from the available analysing power of the reaction. A Wien filter was used to rotate the plane of polarization by 90° before the beam struck the Li target (50-100 μg/cm^2).

Polarization for a beam of deuterons is difficult to measure by reaction asymmetries, even in the case of the reaction: ^{2}H + ^{3}H → ^{4}He + n + 17.6 MeV, because of the complexity introduced by the unit spin of the deuteron. However, Ohlsen et al[14] have developed a method which provides the tensor polarization from a simple ratio of the reaction-product intensities at a fixed angle. The tensor polarization (p_{zz}) is defined as (n_+ + n_- - $2n_0$), and, assuming a pure s-wave interaction, p_{zz} is related to the differential cross sections for the polarized and unpolarized beams by the expression

$$d\sigma/d\Omega = (d\sigma/d\Omega_0)\ [1 + 0\ .5(P_{zz})\ P^0_{zz}]$$

$$\text{for } P^0_{zz} = -\ 0.5g\ (3\ \cos\theta_s\ -\ 1)$$

where g is a factor which measures the probability of attaining the 3/2+ state of helium-5, and θ_s is the angle of the emitted particle with respect to the quantization axis. Ohlsen et al. have determined that, at low energies, g is independent of energy and has the value 0.95. Thus, the relative difference between the intensities of reaction products from the polarized and unpolarized beams, gives (P_{zz}).

A polarization analyzer will be used on the beam-output side of the target chamber in order to confirm the beam polarization by the nuclear reactions discussed above. The apparatus is shown in schematic form in Fig. 4.

Ionization of the 2.5-keV/u polarized H^0 atoms produced by collisional pumping can readily be achieved by electron attachment in a second alkali-vapor target ("electron-attachment ionizer" in Fig. 4). The H$^-$ equilibrium yield is about 10% for 2.5-keV/u H atoms in a sodium-vapor target.[15] An H$^-$ yield greater than equilibrium can be achieved[2] by use of a second polarized sodium-vapor target, thinner than that used to produce the polarized H^0, and with the polarization oppositely directed relative to the first target. This enhancement of the H$^-$ formation is due to spin-dependent atomic processes in the electron attachment.

In the case of a 2.5-keV/u H$^+$ or D$^+$ beam, each ion will undergo up to 20 electron-capture and electron-loss collisions while passing through a 10^{17} cm^{-2} sodium-vapor target. Therefore some consideration must be given to the increase in beam divergence due to scattering of the ion beam as it passes through the vapor target. Measurements, mostly with 1-2 keV D incident on Na or Cs vapors with thickness $\leq 10^{15}$ cm^{-2}, have been analyzed by Hooper, Poulsen, and Pincosy.[16] We expect that a 2.5-keV/u H$^-$ or D$^-$ ion would scatter by an average angle of approximately one degree. This is suitable for fueling fusion experiments and for injection into accelerators, depending upon the acceptance requirements of the accelerator.

CONCLUSION

Polarized beams at intensity levels heretofore not considered feasible have recently been proposed for heating and fueling fusion plasmas. Polarized-beam fueling could increase fusion rates by 50% as well as allow control of the directionality of the fusion products. A process which we have recently described, and called collisional pumping, promises to produce beams of polarized ions vastly more intense than producible by current methods.

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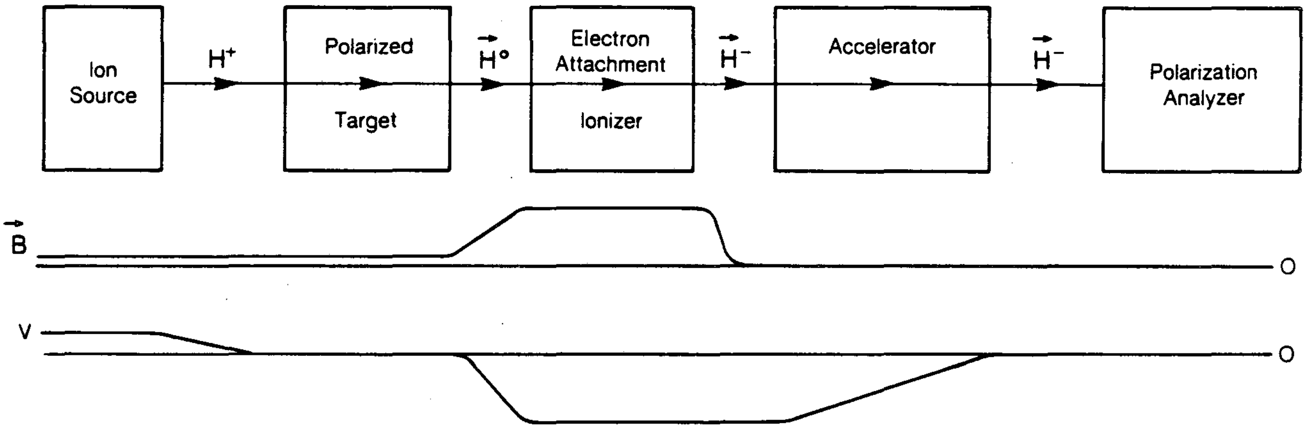

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Fig. 4. Scheme for high-energy analysis of H^- beam polarization.

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