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AN 800-MeV SPIN PRECESSOR FOR POLARIZED H^- BEAMS USING H^- TO H^0 STRIPPING*

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ABSTRACT

A new method is described for precessing the proton polarization axis of the incident H^- polarized beam at LAMPF. The method uses a thin stripper to convert H^- to H^0 with ~50% efficiency at 800 MeV, and uses relatively small magnets to precess the H^0 spin. The large magnetic moment of the H^0 relative to the charged ion (either H^+ or H^-) allows small magnets to produce any required spin orientation (with zero deflection of the neutral beam in the precession apparatus). Either H^0 or H^+ beam is delivered; for H^0, the magnitude of the proton polarization oscillates in proper time at the hyperfine frequency. The theory and test results will be summarized. Areas of possible application will be mentioned, including use for experiments and spin axis control where neutral beams can be used for injection of accelerated H^- beams into storage rings or synchrotrons.

I. INTRODUCTION

A spin precessor using H^- to H^0 stripping, followed by small precession magnets, has been developed for the LAMPF 800-MeV polarized H^- beam. The system is shown schematically in Fig. 1. The H^- beam is incident on a thin foil stripper ST1, which converts approximately half the beam to H^0. The neutral beam and residual charged beams pass through dipole magnets B1 and B2 with fields on the order of 50 gauss-meters (G·m). These small fields are sufficient to precess the H^0 spin because of the large magnetic moment of the unpaired electron. The field region also separates the charged and neutral beams. After the first stripper, the proton in the H^0 depolarizes and repolarizes at the H^0 hyperfine frequency. The precessed beam may be stripped by ST2 to H^+ at a maximum of polarization.

II. MOTIVATION

The polarized H^- beam at LAMPF may be distributed among three beam lines by sequential stripping and magnetic separation. A particular requirement foreseen was to enable the External Proton beam line to control the beam polarization axis independently of the High-Resolution Spectrometer beam line. Because the charged-beam precessor requires such large magnets,[1] we decided to investigate the H^0 Spin Rotator System (H0SR) although half the beam is lost in conversion to H^0.

III. H^0 STRIPPER

A beam of H^- passing through a thin layer of material is partially stripped to H^0 and to H^+; the H^0 component as it is created in the material is also depleted by further stripping to H^+. Thus there is a definite maximum of H^0 production at a certain stripper thickness. The maximum yield of H^0 depends upon the ratios among the fundamental stripping cross sections. The H^0 yield was measured with three thicknesses of Formvar strippers ($C_6H_7O_2$); the maximum yield obtained was 55% with a 36-μg/cm² stripper.

IV. MAGNETIC FIELD REGION

A particle of magnetic moment **M** and intrinsic angular momentum s precesses at a rate $\boldsymbol{\omega} = \mathbf{B} \times \mathbf{M}/s$ in an external magnetic field **B**. The H^0 has essentially the same magnetic moment as the electron, since $M_e/M_p \sim 660$, and for the moment we will consider the H^0 to be in spin-1 state. Then the precession angle θ of the H^0 spin axis travelling at velocity βc through a magnet of length L and field **B** perpendicular to **M** is

$$\theta = \mu_e BL/\beta c \quad ,$$

$$\mu_e = e/2m_e c = \text{Bohr magneton} \quad .$$

For an 800-MeV beam, 45 G·m of field gives $\theta = 90°$. Note that $B_t L$ is Lorentz invariant, where B_t is the field transverse to the velocity.

The field required to precess the H^0 spin by some angle is smaller than the field required to precess the $H^{\pm}$ spin by the factor $\mu_e/2\mu_p \sim 330$.

The transverse field also serves the purpose of separating the charged and neutral beams. A precession field of 45 G·m deflects the $H^{\pm}$ by 1 milliradian (mrad). If it is necessary to absorb the charged beams in a collimator, as shown in Fig. 1, fields several times larger would probably be used; however, entering the H^0 "strong-field region" brings on a complication to be discussed later.

If the magnetic field region consists of two compound dipoles with separate horizontal and vertical field excitation, any input spin direction can be processed to any required output direction.

V. HYPERFINE INTERACTION

It is suggested in the discussion above that the H^0 system precesses as a unit with the effect of the external fields greatly amplified by the large magnetic moment of

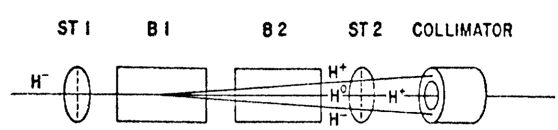

Fig. 1. H^0 Spin Rotator System. Microstripper ST1 strips half of polarized incident H^- beam to H^0; small magnets B1, B2 precess H^0 spin and deflect residual $H^{\pm}$.

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the single electron. We must analyze the effect of the initial spin orientation of the electron and the conditions under which the proton spin is able to follow the electron spin. In the analysis, 100% proton polarization of the incident H^- beam is assumed.

0-Field Analysis

The polarized H^- ion has a spin-aligned proton and two s-state electrons with paired spins (total spin 0). The stripping process to H^0 presumably is nonselective for electron spin; therefore, the electron remaining with the H^0 is randomly oriented. Choosing the proton spin axis as the quantization direction, the H^0 beam at the instant of stripping may be specified as consisting of half spin-parallel and half spin-antiparallel atoms. The latter half of the beam has a spin wave function at time 0

$$\chi(0) = \bar{e}p \quad ,$$

where $\bar{e}$ represents a spin-down electron, and p a spin-up proton. To obtain the energy eigenstates of the hyperfine interaction $\mathbf{M}_e \cdot \mathbf{M}_p$, we project out the spin-0 and spin-1 components:

$$\chi(0) = \bar{e}p = (\bar{e}p - e\bar{p})/2 + (\bar{e}p + e\bar{p})/2 \quad .$$

The quantum phase of the two components changes in time as $e^{i\omega t}$, $\omega = 2\pi f$; f = hyperfine frequency = 1.4 GHz.

$$\chi(t) = e^{i\omega t}(\bar{e}p - e\bar{p})/2 + (\bar{e}p + e\bar{p})/2 \quad .$$

This wave function gives a density for spin-up protons of

$$N_+ = (1 + \cos \omega t)/2 \quad .$$

For $\cos \omega t = -1$, $N_+ = 0$ and $N_- = 1$. Therefore, for that half of the H^0 beam starting out as $\bar{e}p$, the polarization completely reverses at the hyperfine frequency. The other half of the beam, starting out in the spin state ep, has a constant 100% polarization. The total beam polarization is the average in the two components, and is

$$P = (1 + \cos \omega t)/2 \quad .$$

When the proton polarization is 0, the electron is 100% polarized. Every half-cycle of $\cos \omega t$, the polarization transfers between electron and proton. The period of hyperfine oscillation in the laboratory frame is Lorentz-dilated by the factor $\gamma = E/m$; the polarization oscillation wavelength at 800 MeV is

$$\lambda = \beta\gamma c/f = 33 \text{ cm} \quad .$$

Past the H^0 stripper there is in effect a "standing wave" of proton polarization with a 33-cm wavelength. If the beam is stripped from H^0 to H^+, or used as H^0 on target, where the proton polarization oscillation is at a maximum, the incident H^- beam polarization is completely preserved, except for other effects discussed below.

It is interesting to note that although the spin wave function has a spin-0 component, it is not correct to think of a stationary spin-0 component to the beam. If this were present, there would be a component ($^1/_4$) of the beam which would not precess.

Low-Field Analysis

For external magnetic fields small with respect to the field exerted on the electron by the proton, $B_0 = \omega/g\mu_e$ = 506 G, the H^0 system precesses as a unit. It is possible to show this analytically with a more lengthy calculation than appropriate here.

High-Field Effects

For external magnetic fields not small with respect to B_0 = 506 G, the analysis changes in two regards. First, the hyperfine frequency ω shifts, as shown on the Breit-Rabi diagram, and second, the energy eigenstates depart from the simple symmetrized spinor combinations. It has been shown in the context of muon spin rotation[2,3] that the observable effect is to give two-frequency precession.

The departure from adiabatic single frequency precession initially occurs quadratically, as $(B/B_0)^2$. Note that transverse magnetic fields are increased by the factor $\gamma = E/m$ in the H^0 rest frame; at 800 MeV, $\gamma = 1.85$.

To analyze H0SR performance under any combination of magnetic fields, a computer program was written,[4] using as a reference[5] the fundamental equations for the H^0 spin dynamics developed for work on the LASL Lamb-shift polarized beam injectors. The program shows it is possible to retain essentially all of the incident H^- polarization by using proper combinations of high magnetic fields. In the two-compound-dipole precessor shown in Fig. 1, there is a degree of freedom remaining after the constraints of precession angle and axis have been imposed. This degree of freedom can be used to tune to a maximum in "two-frequency precession." The location of the maximum polarization shifts along the beam axis; therefore the position of the second stripper, which converts to H^0 to H^+, is made variable to permit stripping at a maximum of polarization.

The computer calculation for the H0SR test configuration is shown in Fig. 2. Incident polarization P_y is precessed 90° by field B_x 1-m long to become P_z, then precessed 90° by field B_y 30-cm long to become P_x. The maximum of the polarization is 98%, i.e., there is 2% depolarization. If the first field B_x is increased to obtain 3 × 90° precession, 38% of the incident polarization is lost.

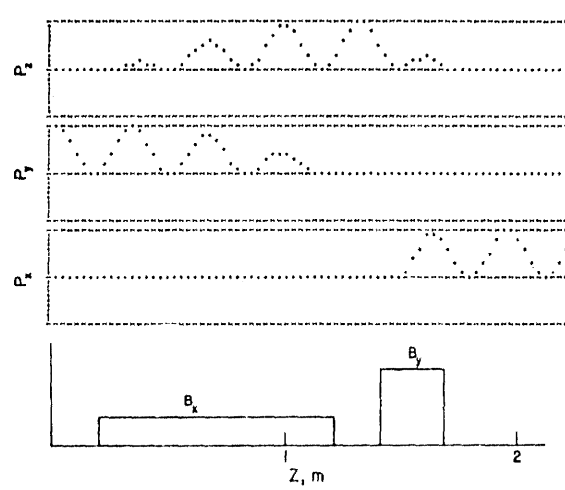

Fig. 2. Computed proton polarization components vs position along z-axis in H0SR, showing precession $B_x \times P_y = P_z$, $B_y \times P_z = P_x$. Hyperfine oscillation of polarization is seen independently from precession.

Depolarization from Excited State Production

A depolarizing mechanism at the few percent level is creation of excited states H^{0*} in the stripping process. The metastable state H^{2S} should be the principal excited component. The first precession field, or even a stray magnetic field, will transform to a sufficiently large electric field in the H^0 rest frame to rapidly quench the 2S state to 2P. The 2P state will decay to the 1S state with a 1.6-ns lifetime, equivalent to 0.9-m decay length for an 800-MeV beam. This will add a well-depolarized component to the final beam.

VI. TEST RESULTS

A trial installation of H0SR used a horizontal field B_x, L = 1 m, followed by a vertical field B_y, L = 0.3 m. The incident H^- beam had vertical polarization P_y which was precessed in B_x to P_z (longitudinal), then precessed in the horizontal plane by B_y. The horizontal-transverse component P_x was measured in a beam-line polarimeter using conjugate-arm detectors, as the field B_y was swept over ~ ±60 G·m. The results are shown in Fig. 3. Data were taken with the H^- source operating under automatic spin reversal to permit averaging over instrumental asymmetries; the large "normal-reverse" differences shown in Fig. 3 indicate systematic instrumental errors of ~10% in measuring polarization, possibly from a missteered beam (the magnet usually available to steer the beam was used as the second precession magnet). These effects make it difficult to say more than that the test demonstrated precession of polarization with ~90 ± 5% retention of input polarization. An additional test is planned.

VII. POTENTIAL APPLICATIONS

H0SR would be useful as a spin precessor for experimental area beams where the loss of half the beam in the conversion to H^0 could be tolerated. In a new design of a beam switchyard, triple splitting of an H^- beam into H^-, H^0, and H^+ could be used to form beams for three beam lines, and the H0SR system would fit in naturally. Alternatively, advanced laser technology may eventually permit more efficient conversion to H^0 by photodetachment so that the $H^{\pm}$ components would be very small.

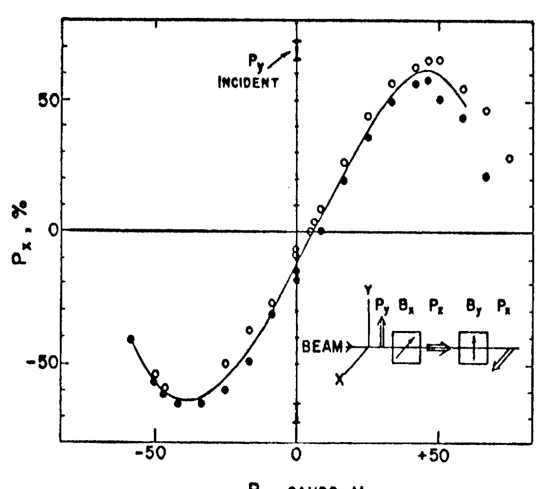

Fig. 3. Measured precession in H0SR test.

It would be relatively easy to make a fast-spin-flip system with H0SR, since the magnetic fields required are small.

Suppose one wished to inject an energetic polarized beam into a storage ring or circular accelerator, and wanted to have the spin in the orbital plane. Multiturn injection with stripping would give a depolarized beam except at synchronous energies because of the "g-2" advance of proton polarization angle (g-2 = anomalous fraction of proton magnetic moment). Using H^0 in the injection line with a fast-slewing H0SR system would permit synchronous spin injection at any energy. Depending upon the facility, this might also be accomplished by the usual precessor system at the injector, but the ability to perform this operation in one beam line could be useful in a multi-user environment. A colliding beam experiment with polarization in the orbital plane might thus be made feasible. Also, a g-2 type of measurement of the rate of advance of the polarization axis of a circulating proton beam would provide a precise measure of beam energy.[6]

The use of a polarized beam may be a useful probe into the physics of the H^- system.[7] For example, definitive measurements of the amount of H^{0*} produced in H^- stripping should be possible in the H0SR system since the H^{0*} appears as a depolarized component.

There is a class of experiments on the fundamental symmetries P, C, and T — for example, the search for parity violation using polarized beams. Unusual combinations of terms, difficult to probe any other way, may be possible with an energetic polarized H^0 beam. For example, the P-, C-, and T-violating term $\boldsymbol{\sigma}\cdot E$ can be probed with fields $>10^7$ V/cm produced by the Lorentz-transform of realizable magnetic fields in the laboratory.

VIII. ACKNOWLEDGMENTS

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