First Spin Flipping of a Stored Spin-1 Polarized Beam

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We recently studied spin flipping of a 270 MeV vertically polarized deuteron beam stored in the Indiana University Cyclotron Facility Cooler Ring. We adiabatically swept an rf solenoid's frequency through an rf-induced spin resonance and observed its effect on the deuterons' vector and tensor polarizations. After optimizing the resonance crossing rate and maximizing the solenoid's voltage, we measured a vector spin-flip efficiency of 94.2% ± 0.3%. We also found striking behavior of the spin-1 tensor polarization.

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Polarized beam experiments are now quite important in storage rings such as the Indiana University Cyclotron Facility (IUCF) Cooler Ring [1], the MIT-Bates Storage Ring [2], Cooler Synchrotron (COSY) [3], Relativistic Heavy Ion Collider (RHIC) at Brookhaven [4], and HERA at DESY [5,6]. Frequent reversals of the beam polarization direction can significantly reduce the systematic errors in spin asymmetry measurements. We have successfully spin-flipped beams of spin-$\frac{1}{2}$ particles: horizontally polarized electrons at the MIT-Bates Storage Ring [7], and horizontally and vertically polarized protons at the IUCF Cooler Ring [8–14].

The polarization of a beam of spin-1 particles is more complex; the component m_z of their spin along the vertical axis can have three values: $m_z = +1, 0, -1$. Describing the polarization of a spin-1 particle requires three ordinary vector polarization components and five independent components of a second-rank tensor [15]. For our experiment the degree of tensor alignment can be described by a quantity called the tensor polarization [15]

$$P_{zz} \equiv 1 - 3(N_0/N_T), \tag{1}$$

where N_0 is the number of particles in the $m_z = 0$ state and N_T is the total number of particles. We recently studied the spin flipping of a vector and tensor polarized deuteron beam stored at the IUCF Cooler Ring.

In any flat circular accelerator or storage ring, each deuteron's spin precesses around the stable spin direction, which is defined by the ring's magnetic structure. With no horizontal magnetic fields present in the ring, the stable spin direction points along the vertical fields of the ring's bending magnets. The spin tune ν_s, which is the number of spin precessions during one turn around the ring, is proportional to the deuteron's energy

$$\nu_s = G\gamma, \tag{2}$$

where $G = (g-2)/2 = -0.142\,987$ is the deuteron's gyromagnetic anomaly and γ is its Lorentz energy factor.

The polarization can be perturbed by the horizontal rf magnetic field from either an rf solenoid or an rf dipole. This perturbation can induce an rf depolarizing resonance, which can flip the spin of the Cooler Ring's stored polarized deuterons [8–14,16]; the rf-induced depolarizing resonance's frequency is

$$f_r = f_c(k \pm \nu_s), \tag{3}$$

where f_c is the deuterons' circulation frequency and k is an integer. Adiabatically sweeping the rf magnet's frequency through f_r can rotate the deuterons' polarization direction by an angle θ around a horizontal axis. Under this rotation, the spin-1 vector and tensor polarizations, P_z and P_{zz}, respectively, transform as

$$P_z(\theta) = P_z^i \cos\theta, \qquad P_{zz}(\theta) = P_{zz}^i[\tfrac{3}{2}\cos^2\theta - \tfrac{1}{2}], \tag{4}$$

where P_z^i and P_{zz}^i are, respectively, the initial vector and tensor polarizations. When $\theta = \pi$ this causes a spin flip: $P_z(\pi) = -P_z^i$, while $P_{zz}(\pi) = P_{zz}^i$. Note that when $\theta = \frac{\pi}{2}$ (mid-spin-flip), then $P_z(\frac{\pi}{2}) = 0$ while $P_{zz}(\frac{\pi}{2}) = -\frac{1}{2}P_{zz}^i$.

The Froissart-Stora equation [17] relates the beam's vector polarization P_z, while crossing a resonance, to its initial vector polarization P_z^i as functions of the ramp's frequency range Δf and ramp time Δt:

$$P_z = P_z^i\left\{2\exp\left[\frac{-(\pi\epsilon f_c)^2}{\Delta f/\Delta t}\right] - 1\right\}, \tag{5}$$

where ϵ is the resonance strength, and $\Delta f/\Delta t$ is the resonance crossing rate.

The apparatus used for this experiment, including the rf solenoid, the IUCF Cooler Ring, and the polarimeter, were discussed earlier [8–14,18–29] and are shown in Fig. 1. For this experiment, the polarimeter used an unpolarized hydrogen gas cell target [30]; its thickness was optimized to about 5×10^{13} atoms cm^{-2} to maximize the statistics while minimizing the background due to both the cell walls and deuteron breakup.

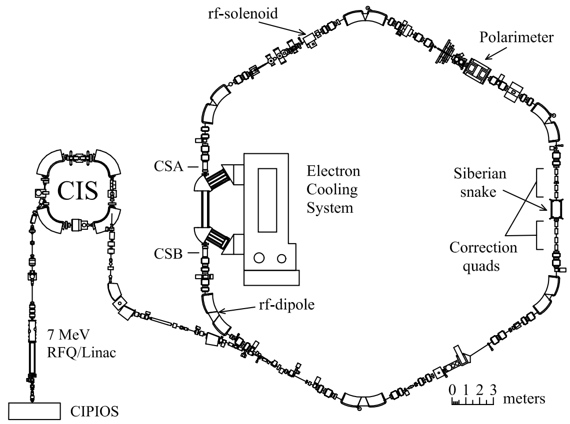

FIG. 1. Layout of the IUCF Cooler Ring with its CIS injector synchrotron and its CIPIOS polarized ion source. Also shown in the Cooler Ring are the rf dipole, the rf solenoid, the polarimeter, and the Siberian snake.

The 270 MeV polarized deuteron beam in the Cooler Ring was produced by the CIPIOS polarized ion source [31] and the CIS injector synchrotron [32]. CIPIOS can produce different states of deuteron polarization [33]. To reduce the systematic errors in our polarization measurements, CIPIOS was cycled through four vertical polarization states:

$$|p_z p_{zz}\rangle = |1\ 1\rangle, |-1\ 1\rangle, |0\ 1\rangle, \text{ and } |0\ -2\rangle.$$

The beam's injected vector polarization magnitude was about 0.6 for the p_z: ± 1 states; the tensor polarization magnitudes for the p_{zz}: $+1$ and p_{zz}: -2 states were about 0.8 and -1.6, respectively. Each data point required about an hour for statistical errors of about $\pm 2\%$ and $\pm 5\%$ for the vector and tensor polarizations, respectively.

The deuteron circulation frequency in the Cooler Ring was $f_c = 1.677\,55$ MHz at 270 MeV where its Lorentz energy factor was $\gamma = 1.1440$. With these parameters, Eq. (2) gave a spin tune $\nu_s = G\gamma$ of $-0.163\,58$. Thus, at 270 MeV, Eq. (3) implies that the $k = 1$ depolarizing resonance's central frequency occurs at

$$f_r = (1 + G\gamma)f_c = 1.4031 \text{ MHz}. \quad (6)$$

We found the approximate position of this spin depolarizing resonance by sweeping the rf solenoid's frequency first by ± 32 kHz around this f_r and then continually narrowing the frequency sweeping range into those half ranges, which caused spin flip. This technique was similar to that described earlier [7,13,14]. The resulting data indicated that the resonance was located near 1.4025 MHz.

We then more precisely determined f_r by measuring the polarization, after running the rf solenoid at different fixed frequencies near 1.4025 MHz. At each frequency, we linearly ramped the solenoid's rf amplitude from about 0 to 4.5 kV peak to peak, during 50 ms, producing $\int Bdl = 0.7$ T mm rms. We next held this voltage constant for about 1 s and then ramped it back to 0 V during 50 ms; then we measured the beam's vector and tensor polarizations. The average measured vector polarization for the states $|1\ 1\rangle$ and $|-1\ 1\rangle$ is plotted against the rf solenoid's frequency in Fig. 2. The curve is a first-order Lorentzian fit with a central resonance frequency of $f_r = 1\,403\,002 \pm 14$ Hz and a width w of about 75 Hz. Figure 2 also shows similar tensor polarization data.

The lower curves are second-order Lorentzian fits to both tensor polarizations; the resonance's averaged central frequency is $f_r = 1\,402\,999 \pm 17$ Hz, while its averaged width w is about 100 Hz. Note that f_r for the vector and tensor polarizations agree within 3 ± 22 Hz; however, their widths seem to agree less well.

We next varied the rf solenoid frequency's ramp time Δt to maximize the vector polarization's spin-flip efficiency. We spin-flipped the deuterons by linearly ramping the rf frequency from $f_r - 2$ kHz to $f_r + 2$ kHz, with various ramp times Δt, while measuring the polarizations after each frequency ramp. The measured vector and

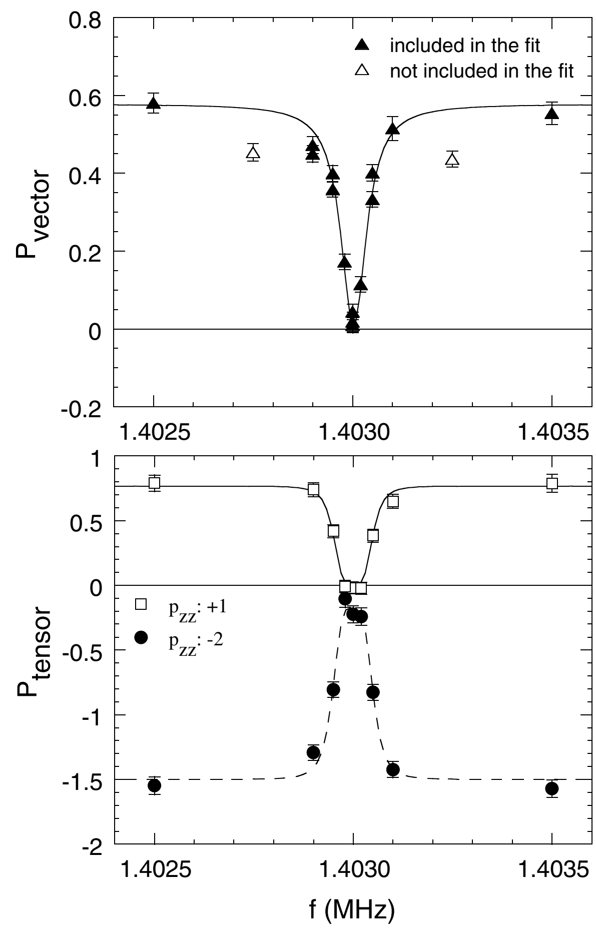

FIG. 2. The measured vector and two tensor deuteron polarizations at 270 MeV are plotted against the rf solenoid's fixed frequency. The rf solenoid's $\int Bdl$ was 0.7 T mm rms. The black triangles in the top graph were used in the first-order Lorentzian fit; the white triangles were not used and could be due to sideband resonances. The curves in the bottom graph are second-order Lorentzian fits.

tensor polarizations are plotted against the ramp time in Fig. 3. The vector polarization data are fit to a modified [7,12] Froissart-Stora formula [17]

$$\frac{P_z}{P_z^i} = (1 + \eta_v)\exp\left[\frac{-(\pi\epsilon_v f_c)^2}{\Delta f/\Delta t}\right] - \eta_v, \qquad (7)$$

where η_v is the vector spin-flip efficiency and ϵ_v is the vector resonance strength. Ignoring the $\Delta t = 0.5$ s point, which was probably due to an operator error, this fit gave $\eta_v = 91\% \pm 5\%$ and $\epsilon_v = (17.3 \pm 0.6) \times 10^{-6}$.

To fit the tensor data in Fig. 3, we relate P_{zz} to P_z using Eq. (4), and we use Eq. (7) for P_z/P_z^i to obtain

$$P_{zz}/P_{zz}^i = \frac{3}{2}(P_z/P_z^i)^2 - \frac{1}{2}$$

$$= \frac{3}{2}\left\{(1 + \eta_t)\exp\left[\frac{-(\pi\epsilon_t f_c)^2}{\Delta f/\Delta t}\right] - \eta_t\right\}^2 - \frac{1}{2}, \qquad (8)$$

where η_t is the tensor spin-flip efficiency and ϵ_t is the tensor resonance strength. Fitting the tensor polarization data in Fig. 3 then gives

$$\eta_t = 87\% \pm 3\%, \epsilon_t = (17.7 \pm 0.5) \times 10^{-6} \quad \text{for } p_{zz}: +1;$$

$$\eta_t = 99\% \pm 2\%, \epsilon_t = (16.3 \pm 0.3) \times 10^{-6} \quad \text{for } p_{zz}: -2.$$

Near the Δt value in Fig. 3 where $P_z = 0$, the tensor ratio P_{zz}/P_{zz}^i is $-49.6\% \pm 3.4\%$. This agrees very well with the prediction of Eqs. (4) and (8) that P_{zz}/P_{zz}^i is $-\frac{1}{2}$ when $P_z = 0$; this provides evidence that we were indeed spin flipping spin-1 particles. Moreover, the average $\eta_t = 95\% \pm 6\%$ and $\epsilon_t = (16.7 \pm 0.6) \times 10^{-6}$; both seem consistent with the measured vector $\eta_v = 91\% \pm 5\%$ and $\epsilon_v = (17.3 \pm 0.6) \times 10^{-6}$. This suggests that one η and one ϵ describe both the vector and tensor polarizations during a resonance crossing.

We next spin-flipped the deuterons 11 times while varying the rf solenoid's frequency range Δf, with its Δt at 2 s and its rms $\int Bdl$ at 0.7 T mm. The unshown data indicated a broad maximum in the spin-flip efficiency

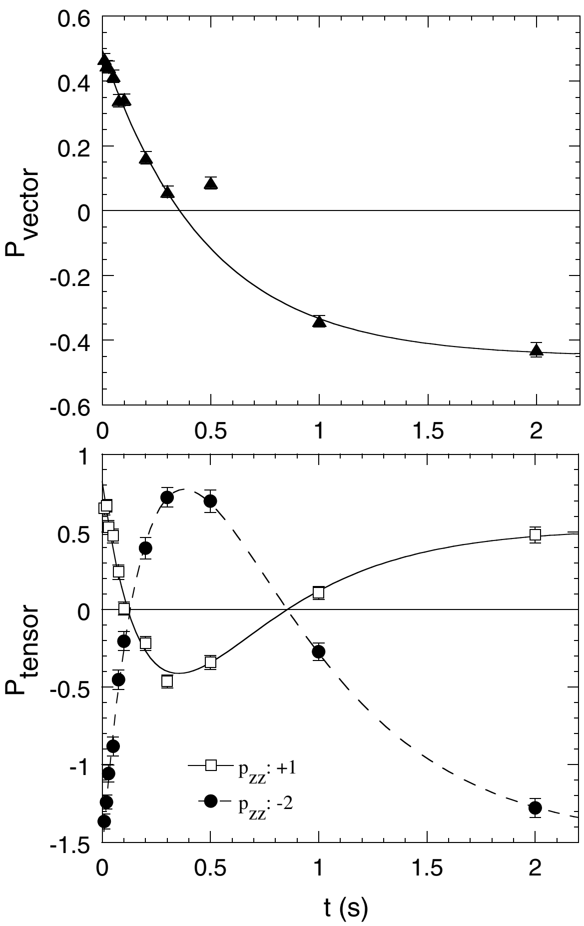

FIG. 3. The measured vector and two tensor deuteron polarizations at 270 MeV are plotted against the rf solenoid ramp time Δt. The rf solenoid's frequency range Δf was ± 2 kHz, and its $\int Bdl$ was 0.7 T mm rms. The curve in the top part is a fit using Eq. (7). The solid and dashed lines in the bottom part are fits using Eq. (8).

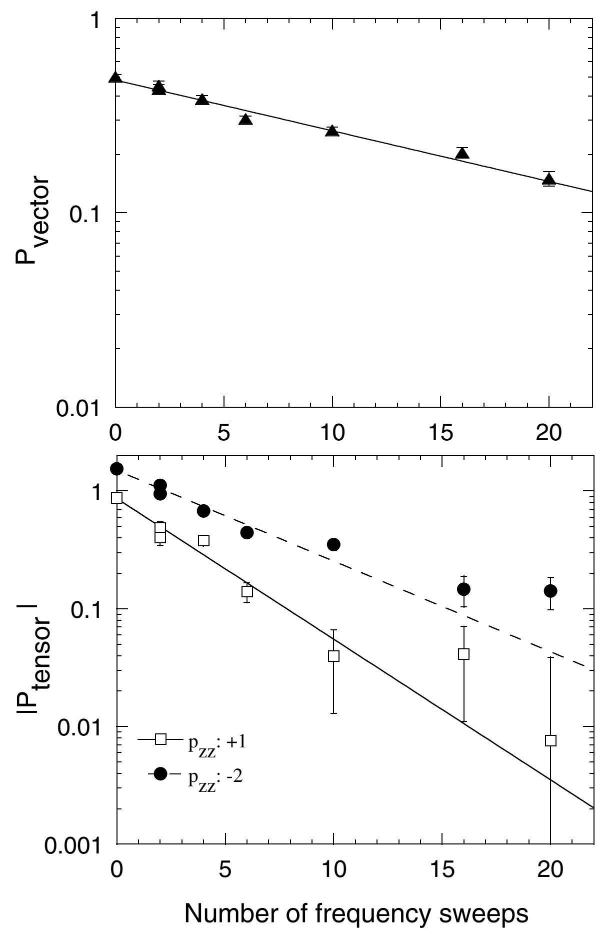

FIG. 4. The measured vector and two tensor deuteron polarizations at 270 MeV are plotted against the number of frequency sweeps. The rf solenoid's frequency ramp time Δt was 1.5 s; its frequency range Δf was ± 0.75 kHz, and its $\int Bdl$ was 0.7 T mm rms. The lines are fits using Eq. (9).

near $\Delta f = \pm 0.75$ kHz. We then similarly varied the frequency ramp time to optimize Δt at 1.5 s.

After optimizing Δt, Δf, and $\int B dl$, we more precisely determined the spin-flip efficiencies by simultaneously measuring the vector and tensor polarizations after n frequency sweeps, P_z^n and P_{zz}^n. These data are plotted against n in Fig. 4. To fit these vector and tensor polarization data, we defined the *measured* spin-flip efficiencies $\hat{\eta}_v$ and $\hat{\eta}_t$ in terms of the measured P_z^n and P_{zz}^n by taking the nth power of Eqs. (7) and (8), in the limit where their exponents go to $-\infty$:

$$P_z^n/P_z^i = (-\hat{\eta}_v)^n; \qquad P_{zz}^n/P_{zz}^i = [\tfrac{3}{2}(-\hat{\eta}_t)^2 - \tfrac{1}{2}]^n. \quad (9)$$

The best fits gave spin-flip efficiencies $\hat{\eta}_v = 94.2\% \pm 0.3\%$ and $\hat{\eta}_t = 93.9\% \pm 1.1\%$. These two values of $\hat{\eta}$ agree very well, confirming that a single $\hat{\eta}$ (and thus η) indeed describes both the vector and tensor polarizations.

In summary, by adiabatically sweeping an rf solenoid's frequency through an rf-induced spin resonance, we spin-flipped the polarization of a stored spin-1 polarized beam for the first time. By optimizing the spin-resonance crossing parameters, we reached a spin-flip efficiency of $94.2\% \pm 0.3\%$ for 270 MeV polarized deuterons stored in the IUCF Cooler Ring. We also found striking behavior of the spin-1 tensor polarization, while crossing an rf-induced resonance, as described by Eqs. (4) and (8).

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[1] B. von Przewoski *et al.*, Phys. Rev. C **58**, 1897 (1998).
[2] BLAST Collaboration, R. Alarcon *et al.*, in MIT Bates Report No. 2-39, 1999.
[3] H. Rohdjess *et al.*, in *SPIN 2002: 15th International Spin Physics Symposium, Upton, NY, 2002*, edited by Y. I. Makdisi *et al.*, AIP Conf. Proc. No. 675 (AIP, Melville, NY, 2003), p. 523.
[4] Y. Makdisi, in *High Energy Spin Physics: 11th International Symposium, Bloomington, IN, 1994*, edited by Kenneth J. Heller and Sandra L. Smith, AIP Conf. Proc. No. 343 (AIP, Woodbury, NY, 1995), p. 75.
[5] SPIN Collaboration, A. D. Krisch *et al.*, "Acceleration of Polarized Protons to 820 (and 920) GeV in HERA," University of Michigan Report No. UM-HE 96-20, 1996; University of Michigan Report No. UM-HE 99-05, 1999.
[6] HERMES Collaboration, A. Airapetian *et al.*, "The HERMES Physics Program & Plans for 2001–2006," DESY-PRC Report No. 99-08, 1999.
[7] V. S. Morozov *et al.* Phys. Rev. ST Accel. Beams **4**, 104002 (2001).
[8] D. D. Caussyn *et al.*, Phys. Rev. Lett. **73**, 2857 (1994).
[9] D. A. Crandell *et al.*, Phys. Rev. Lett. **77**, 1763 (1996).
[10] B. B. Blinov *et al.*, Phys. Rev. Lett. **81**, 2906 (1998).
[11] V. A. Anferov *et al.* Phys. Rev. ST Accel. Beams **3**, 041001 (2000).
[12] B. B. Blinov *et al.*, Phys. Rev. ST Accel. Beams **3**, 104001 (2000).
[13] A. M.T. Lin *et al.*, *SPIN 2000: 14th International Spin Physics Symposium, Osaka, 2000*, edited by K. Hatanaka, AIP Conf. Proc. No. 570 (AIP, Melville, NY, 2001), p. 736.
[14] B. B. Blinov *et al.*, Phys. Rev. Lett. **88**, 014801 (2002).
[15] *Madison Convention, Proceedings of the 3rd International Symposium on Polarization Phenomena in Nuclear Physics, Madison, 1970*, edited by H. H. Barschall and W. Haeberli (University of Wisconsin Press, Madison, WS, 1971), p. xxv.
[16] B.W. Montague, Phys. Rep. **113**, 35 (1984).
[17] M. Froissart and R. Stora, Nucl. Instrum. Methods **7**, 297 (1960).
[18] A. D. Krisch *et al.*, Phys. Rev. Lett. **63**, 1137 (1989).
[19] J. E. Goodwin *et al.*, Phys. Rev. Lett. **64**, 2779 (1990).
[20] M. G. Minty *et al.*, Phys. Rev. D **44**, 1361(R) (1991).
[21] V. A. Anferov *et al.*, Phys. Rev. A **46**, 7383(R) (1992).
[22] R. Baiod *et al.*, Phys. Rev. Lett. **70**, 2557 (1993).
[23] R. A. Phelps *et al.*, Phys. Rev. Lett. **72**, 1479 (1994).
[24] B. B. Blinov *et al.*, Phys. Rev. Lett. **73**, 1621 (1994).
[25] C. Ohmori *et al.*, Phys. Rev. Lett. **75**, 1931 (1995).
[26] L.V. Alexeeva *et al.* Phys. Rev. Lett. **76**, 2714 (1996).
[27] R. A. Phelps *et al.*, Phys. Rev. Lett. **78**, 2772 (1997).
[28] C. M. Chu *et al.*, Phys. Rev. E **58**, 4973 (1998).
[29] B. B. Blinov *et al.*, Phys. Rev. ST Accel. Beams **2**, 064001 (1999).
[30] E. J. Stephenson *et al.*, in *Proceedings of the 9th International Workshop on Polarized Sources and Targets, Nashville, IN, 2001*, edited by V. P. Derenchuk and B. von Przewoski (World Scientific, Singapore, 2002), p. 304.
[31] V. P. Derenchuk and A. S. Belov, in *Polarized Gas Targets and Polarized Beams*, edited by R. J. Holt and M. A. Miller, AIP Conf. Proc. No. 421 (AIP, Melville, NY, 1998), p. 422.
[32] D. L. Friesel and S.Y. Lee, in *Proceedings of the 1997 Particle Accelerator Conference, Vancouver, 1997*, edited by Martin Comyn (IEEE, Piscataway, NJ, 1998), p. 935.
[33] B. von Przewoski *et al.*, Phys. Rev. E **68**, 046501 (2003).