Energy change of a depolarizing resonance due to a type-3 Siberian snake

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Abstract

We measured the proton beam polarization in the IUCF Cooler Ring at five energies. We found that the $G\gamma = 2$ imperfection depolarizing resonance occurred about 1.9 MeV below the expected resonance energy of 108.4 MeV. This energy shift could be due to a shift of about + 0.0036 in the spin tune, ν_s, which is the number of spin rotations in each turn around the ring. We then demonstrated that this spin tune shift is consistent with the Cooler Ring containing a partial type-3 Siberian snake, which is apparently caused by the magnets that confine the electron and proton beams in the cooling region.

I. Introduction

To confirm the Siberian snake concept, we have been studying various properties of Siberian snakes and depolarizing resonances[1,2]. The various types of depolarizing resonances can be described in terms of the spin tune, ν_s, which is the number of spin precessions in each turn around a circular accelerator. An *imperfection* depolarizing resonance[1] occurs whenever the spin tune, which is normally equal to $G\gamma$, becomes equal to an integer n

$$\nu_s = G\gamma = n, \tag{1}$$

where $G = (g-2)/2 = 1.7928$ is the anomalous part of the proton magnetic moment and γ is the relativistic energy factor. An *intrinsic* depolarizing resonance[2] occurs whenever $\nu_s = G\gamma = m\,P \pm \nu_y$, where m is an integer, P is the ring's periodicity, and ν_y is the vertical betatron tune. More generally a depolarizing resonance occurs whenever the spin tune satisfies $\nu_s = n + m\,P \pm q\,\nu_x \pm r\,\nu_y \pm s\,\nu_{syn}$, where m, n, q, r, and s are integers, ν_{syn} is the synchrotron tune, and ν_x is the horizontal betatron tune. A *synchrotron* depolarizing resonance[2] occurs when s is non-zero.

Polarized proton beams were accelerated at the ZGS, Saturne, the AGS, and KEK to GeV energies[3]. However, the process of individually overcoming each of the many depolarizing resonances was difficult, expensive, and time consuming. A Siberian snake is a device proposed by Derbenev and Kondratenko[4] to simultaneously overcome all depolarizing resonances. A snake generally rotates the proton's spin by 180°, which forces the spin tune to be exactly 1/2; this should eliminate the effects of all depolarizing resonances. Moreover, this 180° spin rotation should not perturb the particle orbit except inside the snake.

Recent experiments[1,2] at the IUCF Cooler Ring have shown that Siberian snakes can overcome depolarizing resonances and thus preserve the proton spin polarization during acceleration. However, we found that the $G\gamma = 2$ imperfection depolarizing resonance appeared to occur about 1.9 MeV below the expected beam energy of 108.4 MeV. Since the energy calibration of the Cooler Ring was believed to be accurate to better than 10^{-3}, this apparent 1.9 MeV miscalibration caused some concern.

An alternate explanation for the observed discrepancy was that the spin tune, ν_s, was somehow shifted upward by about 0.0036. This shift would make $\nu_s = 2.0036$ at 108.4 MeV and thus move the $G\gamma = 2$ resonance to about 106.5 MeV. Recently, Pollock[5] suggested that the magnets in the electron cooling system of the IUCF Cooler Ring could act as a partial type-3 Siberian snake[6] which might cause such a spin tune shift. A type-3 snake is a device which rotates the spin around the direction perpendicular to the ring plane. A type-1 Siberian snake rotates the spin around the longitudinal direction, while a type-2 snake rotates the spin around the radial direction. Earlier Shatunov and Skrinsky[7] had indicated that energy calibrations based on depolarizing resonances were only reliable in the absence of longitudinal magnetic fields; note that interleaved longitudinal and radial fields can cause a type-3 Siberian snake.

In the electron cooling system of the Cooler Ring, each proton's spin is rotated by several magnets including: the main cooling solenoid, two toroids, two compensating solenoids, four vertical steerers, and four weaker horizontal steerers. These magnets confine the protons together with the electrons which cool them; the magnets are designed to fully compensate all orbital distortions outside the cooling system. However, since spin rotations *do not commute*, these magnets can rotate a proton's spin and thus shift the spin tune, ν_s. At a fixed energy, a shift in ν_s would change the proximity to any nearby depolarizing resonance. This proximity can be measured by studying how sharply the radial and vertical polarization components depend on the net longitudinal $\int \mathbf{B} \cdot d\mathbf{l}$ of the cooling magnets.

II. Snake Experiments

We recently stored and cooled vertically polarized proton beams at nominal energies of 104.6, 105.9, 106.9, 107.8, and 110.5 MeV. The stored beam intensity was 15 to 50 nA and the cycle period ranged from 4 to 20 seconds. The vertical and radial components of the polariza-

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tion were measured simultaneously using a 4.5 mm thick Carbon skimmer target and the cylindrically symmetric CE01 detector[8]. The beam polarization was measured before injection into the Cooler Ring using a beam line polarimeter[9]; it was found to be 77 ± 2% at all incident beam energies.

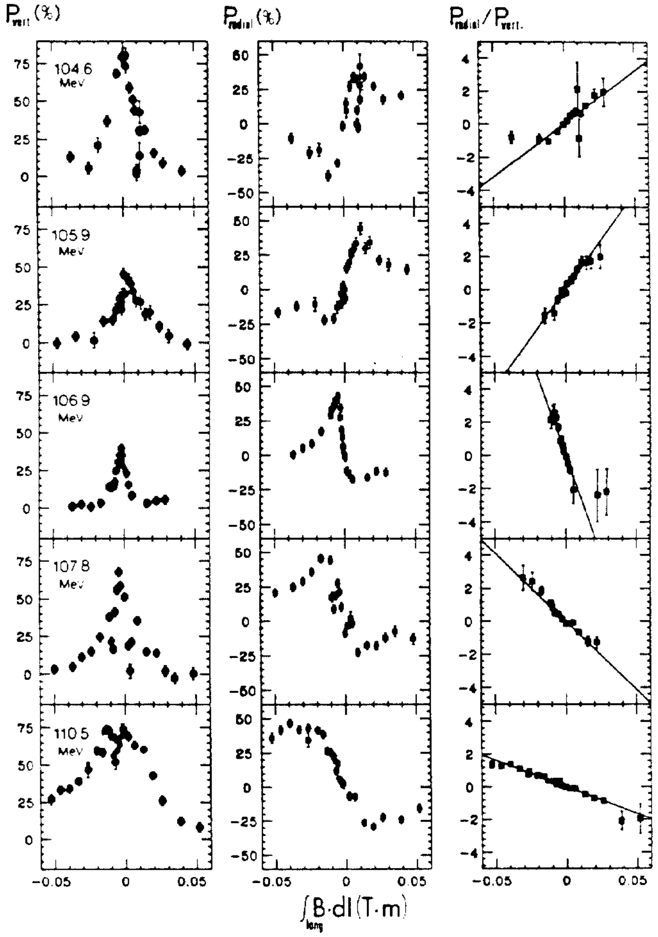

Figure 1. Measured vertical (left) and radial (center) polarization at 104.6, 105.9, 106.9, 107.8, and 110.5 MeV are plotted against the net longitudinal magnetic field integral in the Cooler Ring solenoids. Vertically polarized protons were injected into the ring. The narrow dips in the radial and vertical polarizations are probably due to synchrotron depolarizing resonances. The ratio $P_{radial}/P_{vertical}$ is plotted on the right; the curves are straight line fits to the data at each energy.

At each beam energy we measured both the vertical and radial components of the beam polarization in the Ring, while varying the net longitudinal $\int \mathbf{B} \cdot d\mathbf{l}$ by changing the currents in the main cooling solenoid and the two compensating solenoids, and holding fixed the steerer and toroid magnet currents. At each energy, the width of the resulting vertical polarization curve[1] was a measure of the actual proximity to the $G\gamma = 2$ imperfection resonance, which should occur at 108.4 MeV. These curves are shown in Fig. 1.

One can better parameterize this proximity by plotting the ratio $P_{radial}/P_{vertical}$ against $\int \mathbf{B} \cdot d\mathbf{l}$. At each energy $P_{radial}/P_{vertical}$ is proportional to the tangent of the angle ϕ between the vertical and the stable spin direction. Since $\int \mathbf{B} \cdot d\mathbf{l}$ is small one can also show that $P_{radial}/P_{vertical}$ is proportional to $\int \mathbf{B} \cdot d\mathbf{l}$ by using equations 2, 3, and 5 of reference 1,

$$\frac{P_{radial}}{P_{vertical}} = -\tan\phi \cdot \sin\left(\frac{2\pi G\gamma}{3}\right) = S \int \mathbf{B} \cdot d\mathrm{l}. \quad (2)$$

The $\sin\left(\frac{2\pi G\gamma}{3}\right)$ term occurs because the polarimeter was 120° downstream of the Snake.[1] The quantity, S, is given by

$$S = \frac{e(1+G)\sin\left(\frac{2\pi G\gamma}{3}\right)}{2cp\sin(\pi\nu_s)}. \quad (3)$$

The quantities e and p are the proton's electric charge and momentum, while c is the speed of light.

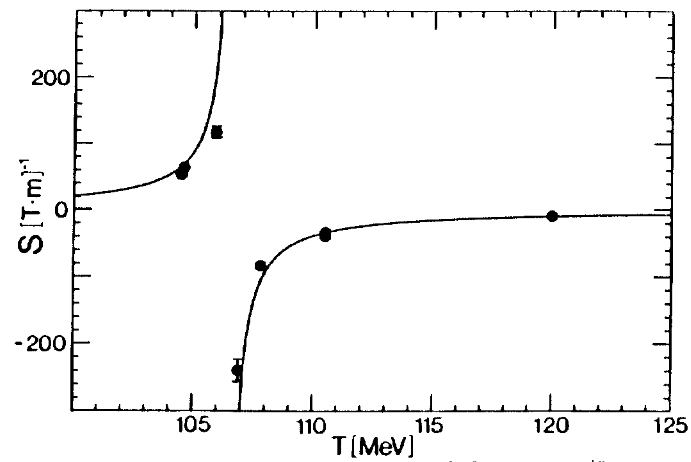

Figure 2. The experimental slopes of the $P_{radial}/P_{vertical}$ curves are plotted against the energy. The curve is given by equation 3.

The new experimental data at 104.6, 105.9, 106.9, 107.8, and 110.5 MeV are plotted against $\int \mathbf{B} \cdot d\mathbf{l}$ in Fig. 1. The measured values of the vertical polarization are plotted on the left, while the measured radial polarization values are plotted in the center. The ratio of P_{radial} to $P_{vertical}$ is plotted on the right. The solid lines in Fig. 1 are straight line fits to the ratio $P_{radial}/P_{vertical}$; the slope of this fit is the quantity, S, defined in equations 2 and 3. The measured slopes at each energy are plotted in Fig. 2 along with previously published 104.5 and 120.0 MeV data[1,2] and a less detailed new data set at 110.5 MeV. The curve in Fig. 2 is obtained from equation 3 with the best fit value of

$$\nu_s = G\gamma + 0.0036 \pm 0.0003$$

Figures 1 and 2 show that the $G\gamma = 2$ imperfection depolarizing resonance energy certainly lies between 105.9 and 106.9 MeV, since the slope, S, changes sign between these two energies. This result seemed to contradict the prediction that the $G\gamma = 2$ resonance should occur at 108.4 MeV; our data instead suggest that this resonance is located near 106.5 MeV. This apparent energy shift of about -1.9 MeV implies that the spin tune could be shifted upward by about 0.0036. This shift can be explained by the presence of a partial type-3 Siberian snake in the electron cooling system[5].

We directly tested for the existence of a partial type-3 Siberian snake by measuring the beam polarization after turning off all the magnetic fields in the cooling system. Turning off these magnets should eliminate any possibility of a type-3 snake and thus give an absolute energy calibration[7]. The ratio $P_{radial}/P_{vertical}$ is plotted against $\int \mathbf{B} \cdot dl$ in Fig. 3 at 105.9 MeV. The dependence of the ratio on $\int \mathbf{B} \cdot dl$ was clearly much flatter with the cooling magnets off; the data then had somewhat poorer statistics because of the shorter beam lifetime. Nevertheless, the precision was certainly adequate to show a definite change. This change clearly demonstrates that the spin tune, ν_s, and thus the resonance energy were significantly shifted by the cooling magnets. The best fit to the data in Fig. 3 with the cooling magnets off was $\nu_s = 1.9949 \pm 0.0005$; this agrees well with the calculated value of $G\gamma = 1.9951$ at 105.9 MeV. This agreement directly supports the hypothesis[5] that the apparent 1.9 MeV energy miscalibration was caused by a partial type-3 Siberian snake[6] due to the cooling magnets in the Cooler Ring. We plan to later make more precise calibrations of the energy and the spin tune by using rf magnets to induce depolarizing resonances at various rf frequencies[7,10].

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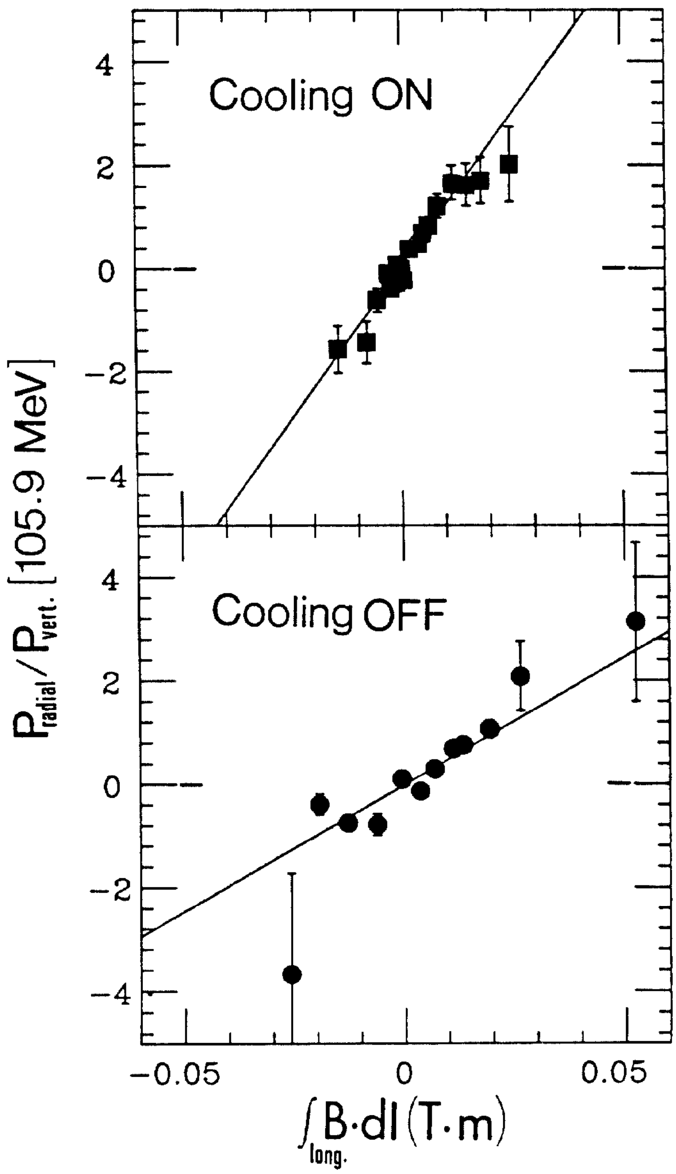

Figure 3. The measured ratio $P_{radial}/P_{vertical}$ is plotted against the net longitudinal $\int \mathbf{B} \cdot dl$. Vertically polarized 105.9 MeV protons were injected into the ring. The data shown as squares at the top were taken with the cooling magnets turned on. The data shown as circles at the bottom were taken with the cooling magnets set near zero.