HIGHER ORDER SPIN RESONANCES IN 2.1 GeV/c POLARIZED PROTON BEAM*

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Abstract

Spin resonances can depolarize or spin-flip a polarized beam. We studied 1st and higher order spin resonances with stored 2.1 GeV/c vertically polarized protons. The 1st order vertical (ν_y) resonance caused almost full spin-flip, while some higher-order ν_y resonances caused partial depolarization. The 1st order horizontal (ν_x) resonance caused almost full depolarization, while some higher order ν_x resonances again caused partial depolarization. Moreover, a 2nd order ν_x resonance is about as strong as some 3rd order ν_x resonances, while some 3rd order ν_y resonances are much stronger than a 2nd order ν_y resonance. One thought that ν_y spin resonances are far stronger than ν_x, and that lower order resonances are stronger than higher order; the data does not support this.

INTRODUCTION

To study the strong interaction's spin dependence with polarized proton beams, one must preserve and control the polarization during acceleration and storage [1, 2, 3]. This can be difficult due to many 1st and higher order depolarizing (spin) resonances. For vertically polarized beams in flat accelerators, it was thought that vertical spin resonances should be stronger than horizontal, and lower-order resonances should be stronger than higher-order ones [4]. There were several theoretical attempts to calculate the strengths of higher order spin resonances [5]. Some 2nd order and synchrotron-sideband resonances were seen in electron rings [6] and proton rings [7]. Moreover, a 2nd order proton resonance was studied in detail at IUCF [8].

We used 2.1 GeV/c polarized protons stored in the COSY synchrotron for a detailed experimental study of higher-order spin resonances. Our preliminary ν_y data was presented at SPIN 2004 [9], but both the ν_y data and the never-presented ν_x data needed significant reanalysis. The reanalyzed data presented here suggest that many higher-order spin resonances, both ν_y and ν_x, must be overcome to accelerate polarized protons to high energies.

In flat circular rings, a beam proton's spin precesses around the vertical fields of the ring's dipole magnets. The spin tune $\nu_s = G\,\gamma$ is the number of spin precessions during one turn around the ring, where $G = (g-2)/2$ is the proton's gyromagnetic anomaly and γ is its Lorentz energy factor. Horizontal magnetic fields can perturb the proton's stable vertical polarization creating a spin resonance [10, 11]. Spin resonances occur when

$$\nu_s = k\nu_x + l\nu_y + m, \tag{1}$$

where k, l and m are integers; ν_x and ν_y are the horizontal and vertical betatron tunes, respectively. Imperfection spin resonances occur when $k = l = 0$. Intrinsic spin resonances occur when either $k \neq 0$ or $l \neq 0$, or both; the sum $|k| + |l|$ defines each resonance's order.

EXPERIMENTAL PROCEDURE AND RESULTS

The experiment's apparatus, including the COSY storage ring [12], the EDDA detector [13], the electron cooler [14], the low energy polarimeter (LEP) [15], the injector cyclotron, and the polarized ion source [16], were shown in Fig. 1 of Ref. [17]. The beam from the polarized H^- ion source was accelerated by the cyclotron to 45 MeV and then strip-injected into COSY.

Before the injection, the LEP measured the H^- beam's polarization to monitor its stability. The cylindrical EDDA detector measured the beam's polarization in COSY after crossing the resonances. We reduced its systematic errors by cycling the polarized source between the up and down vertical polarization states. The measured initial flat-top polarization was typically about 75%.

In the COSY ring, the protons' average circulation frequency f_c was 1.491 85 MHz at 2.1 GeV/c, where their Lorentz energy factor was $\gamma = 2.4514$. For these parameters, the spin tune $\nu_s = G\gamma$ was 4.395. During injection, acceleration and at the beginning of the flat-top the betatron tunes ν_x and ν_y were kept fixed at 3.575 and 3.525, respectively. This kept both betatron tunes away from any 1st, 2nd, or 3rd order spin resonances on flat-top. After reaching the flat-top, we varied the ring quadrupoles' currents to vary either ν_y or ν_x, while keeping the other tune fixed; then we measured the polarization.

Figure 1 shows the betatron tunes' behavior in a typical COSY cycle, during the higher order vertical (ν_y) spin resonance study. We first ramped ν_y rapidly from 3.525 to some value between $3.51 - 3.71$ during 0.5 s, next we slowly ramped ν_y through a very small tune range of about

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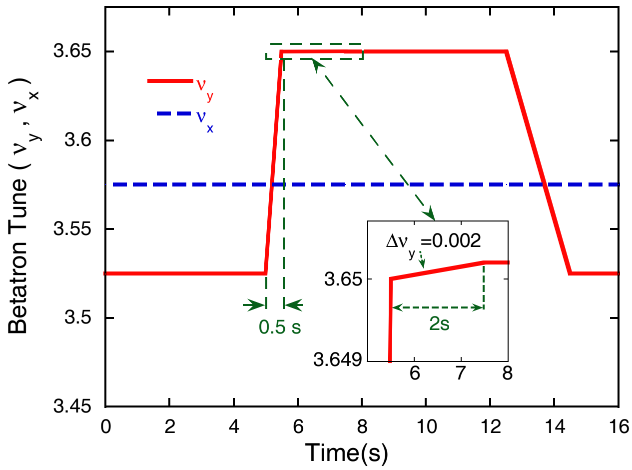

Figure 1: Typical ν_y betatron tune ramp during COSY cycle.

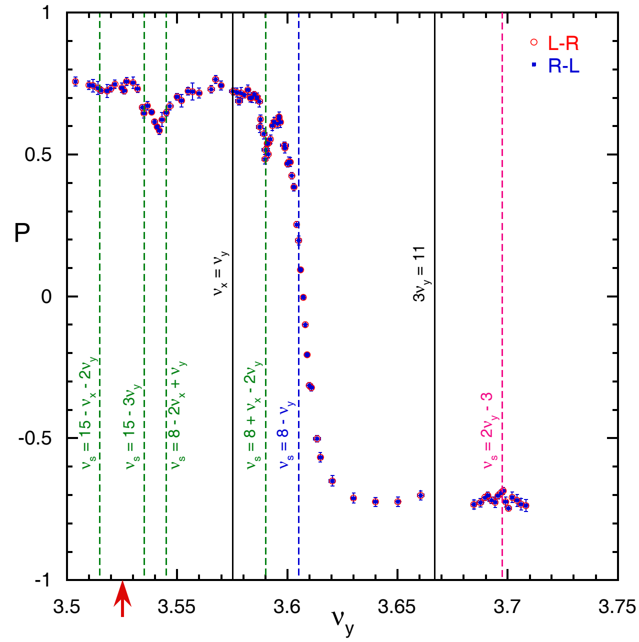

Figure 2: Polarization normalized to the LEP asymmetry plotted vs. ν_y. The horizontal bars show the combined slow ν_y ramps. The calculated positions are indicated by dashed lines for each spin resonance, and by solid lines for each beam-blow-up resonance. Arrow shows ν_y at injection.

0.002 during 2 s, with ν_x fixed at 3.575; then we measured the polarization. The rapid ramp reduced the effects of the resonances between the injection tune of 3.525 and the start of the slow ramp, while each slow ν_y ramp enhanced the effect of any spin resonance in that small ν_y range. We used Eq. (1) to calculate the positions of 1^{st}, 2^{nd} and 3^{rd} order resonances that could be studied between the half-integer 3.5 and quarter-integer 3.75 beam blow-up resonances.

The measured LEP asymmetries indicated that the initial polarization changed by about 10% during the experiment. Thus, we normalized each final COSY polarization measured by EDDA to the measured LEP asymmetry for that data-run. Each EDDA data-run was typically 25 min long; thus, the LEP data bin sizes were typically ± 30 min centered on EDDA runs.

To test the data's reproducibility, we tried to measure polarizations for the same settings several times. However, when we precisely measured ν_y after each setting, we found that they varied at the ± 0.0002 level. Thus, there were many partly-overlapping points that obscured the polarization's behavior near each resonance. We tried to clarify it by combining points with nearby ν_y values, except in the region where the polarization changed very rapidly (between ν_y values of 3.586 to 3.620). We first combined all pairs of points that had ν_y values within $\delta\nu_y = 0.1 \times 10^{-4}$. To ensure that this did not bias the results, we combined the data in both the increasing (L-R) and decreasing (R-L) orders in ν_y; the two results were identical. We then increased the $\delta\nu_y$ intervals in steps of 0.1×10^{-4}; the input data for each step were the output data from the previous step. The error and position of each newly combined point after each step were the properly weighted averages of the errors and positions of the two combined points; each new horizontal bar encompassed the slow ramps of both combined points.

Figure 2 plots polarization vs. ν_y for the combination interval of $\delta\nu_y = 7.6 \times 10^{-4}$, where 36 points were incorporated. The plot shows clear resonance behavior around several 3^{rd} order resonances, but the behavior around the 2^{nd} order resonance is still unclear. When we further increased the combination interval size, the polarization's behavior around the narrow resonances was broadened excessively, as expected.

We observed full spin-flip when the 1^{st} order vertical (ν_y) spin resonance was crossed and partial depolarization near several 3^{rd} order resonances and possibly near a 2^{nd} order resonance. The 3^{rd} order $8 + \nu_x - 2\nu_y$ resonance and the partly overlapping $15 - 3\nu_y$ and $8 - 2\nu_x + \nu_y$ resonances appear much stronger than the 2^{nd} order $2\nu_y - 3$ resonance. This suggests that many significant 3^{rd} and possibly higher order spin resonances must be overcome to accelerate and store polarized protons above 100 GeV.

We also studied the higher-order horizontal (ν_x) spin resonances by using ν_x ramps similar to the ν_y ramps shown in Fig. 1, with ν_y fixed at 3.525. The polarizations are plotted in Fig. 3 against ν_x. Only 5 pairs of overlapping points were combined, as earlier described for Fig. 2, at the combination interval of $\delta\nu_x = 20 \times 10^{-4}$.

Figure 3 shows almost full depolarization at the 1^{st} order spin resonance. Above this resonance, the polarization increased steadily because this fairly strong resonance was crossed at increasing $\Delta\nu_x/\Delta t$ rates, which decreased the depolarization [10]; $\Delta\nu_x/\Delta t$ increased because the ramp time Δt was fixed at 0.5 s, while the ramp range $\Delta\nu_x$ was increased. We found partial depolarization near a 2^{nd} order ν_x resonance and near several 3^{rd} order ν_x resonances; these ν_x resonances all appear about equally strong.

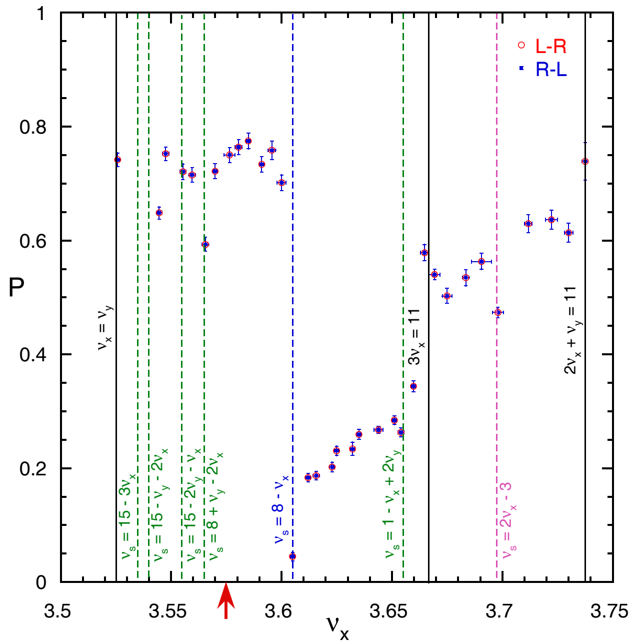

Figure 3: Polarization normalized to the LEP asymmetry plotted vs. ν_x. The horizontal bars show the combined slow ν_x ramps. The calculated positions are indicated by dashed lines for each spin resonance, and by solid lines for each beam-blow-up resonance. Arrow shows ν_x at injection.

Note that the polarization increased significantly at the two ν_x beam blow-up resonances probably because they removed mostly those beam particles with larger betatron amplitudes, as supported by the sharp decrease in the measured count rates in EDDA at each blow-up resonance. These outside particles were probably more depolarized [18] when crossing the strong 1st order resonance; thus, removing them increased the beam's polarization while decreasing its intensity.

There have been several theoretical attempts to calculate the strengths of higher order spin resonances [5]; some calculations suggest that odd order resonances may be stronger than even-order resonances for rings with Siberian snakes. It is not yet clear if these theoretical approaches allow one to explain our experimental results. We plan to soon obtain numerical values of the strengths ε.

SUMMARY

We used 2.1 GeV/c polarized protons stored in COSY to study 1st and higher order spin resonances. We observed almost full spin-flip when the 1st order ν_y spin resonance was crossed and partial depolarization near the 2nd and 3rd order spin resonances. We also observed almost full depolarization near the 1st order ν_x spin resonance and partial depolarization near the 2nd and 3rd order spin resonances. The observed 2nd order ν_x and several 3rd order ν_x resonances all appear about equally strong; while some 3rd order ν_y resonances appear much stronger than the 2nd order ν_y resonance. It was thought that, for vertically polarized protons in flat accelerators, vertical spin resonances are stronger than horizontal, and lower order resonances are stronger than higher order ones. The data suggest that many higher order spin resonances, both horizontal and vertical, must be overcome to accelerate polarized protons to high energies; these data may help RHIC to better overcome its snake resonances between 100 and 250 GeV/c.

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REFERENCES

[1] D.G. Crabb *et al.*, Phys. Rev. Lett. **41**, 1257 (1978).

[2] *Proc. SPIN 2002*, AIP Conf. Proc. **675** (AIP, NY, 2003).

[3] *Proc. SPIN 2004*, eds. K. Aulenbacher *et al.* (World Scientific, Singapore, 2005).

[4] R.D. Ruth *et al.*, AIP Conf. Proc. **145** (AIP, NY, 1986), p62; V.A. Anferov *et al.*, *Acceleration of Polarized Protons to 120 GeV and 1 TeV at Fermilab*, Univ. of Michigan Report UM HE 95-09 (July 24, 1995), p 127.

[5] S. Tepikian, AIP Conf. Proc. **187** (AIP, NY, 1989), p 1450; S.R. Mane, *ibid*, p 959; G.H. Hoffstaetter and M. Vogt, Phys. Rev. **E 70**, 056501 (2004).

[6] J.R. Johnson *et al.*, NIM **204**, 261 (1983).

[7] J.E. Goodwin *et al.*, Phys. Rev. Lett. **64**, 2779 (1990).

[8] C. Ohmori *et al.*, Phys. Rev. Lett. **75**, 1931 (1995).

[9] A.D. Krisch *et al.*, Ref. 3, p 691.

[10] M. Froissart and R. Stora, NIM **7**, 297 (1960).

[11] E.D. Courant, Bull. Am. Phys. Soc. **7**, 33 (1962) and Rpt. BNL-EDC-45 (1962); B.W. Montague, Phys. Rep. **113**, 24 (1984); S.Y. Lee, *Spin Dynamics and Snakes in Synchrotrons* (World Scientific, Singapore, 1997), p 26.

[12] R. Maier, NIM A **390**, 1 (1997); A. Lehrach *et al.*, Ref. 2, p 153.

[13] V. Schwarz *et al.*, *Proc. SPIN 1998*, eds. N.E. Tyurin *et al.*, (World Scientific, Singapore, 1999), p 560; M. Altmeier *et al.*, Phys. Rev. Lett. **85**, 1819 (2000).

[14] H. Stein *et al.*, At. Energ. **94**, 24 (2003).

[15] D. Chiladze *et al.*, Phys. Rev. ST-AB **9**, 050101 (2006).

[16] P.D. Eversheim *et al.*, AIP Conf. Proc. **339** (AIP, NY, 1995), p 668; R. Weidmann *et al.*, Rev. Sci. Instrum. **67**, 1357 (1996); O. Felden *et al.*, *Proc. 9th Int. WS Polar. Sources, Targets, 2001*, eds. V.P. Derenchuk and B. von Przewoski (World Scientific, Singapore, 2002), p. 200.

[17] M.A. Leonova *et al.*, Phys. Rev. Lett. **93**, 224801 (2004).

[18] S.Y. Lee, *Spin Dynamics and Snakes in Synchrotrons* (World Scientific, Singapore, 1997), p 58.