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SPIN-MANIPULATING POLARIZED DEUTERONS*

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Abstract

Spin dynamics of polarized deuteron beams near depolarization resonances, including a new polarization preservation concept based on specially-designed multiple resonance crossings, has been tested in a series of experiments in the COSY synchrotron. Intricate spin dynamics with sophisticated pre-programmed patterns as well as effects of multiple crossings of a resonance were studied both theoretically and experimentally with excellent agreement. Possible applications of these results to preserve, manipulate and spin-flip polarized beams in synchrotrons and storage rings are discussed.

INTRODUCTION

Polarized hadron and lepton beams are used to study the spin dependence of hadronic interactions in the multi-GeV/c region. Precise polarized scattering experiments require frequent spin-direction reversals to reduce systematic errors. Moreover, one must efficiently overcome spin resonances to maintain the polarization.

The spin state of a spin-1 particle beam is described by vector and tensor polarizations [1]:

$$P_V \equiv (N_+ - N_-)/N, \quad P_T \equiv 1 - 3(N_0/N), \qquad (1)$$

where N_+, N_0, and N_- are the number of particles in $m=+1$, 0, and -1 states and $N = N_+ + N_0 + N_-$ is the total number of particles.

In flat circular rings, each deuteron's spin precesses around the vertical fields of the ring's dipole magnets, except near a spin resonance. The spin tune ν_s (the number of spin precessions during one turn around the ring) is proportional to the deuteron's energy $\nu_s = G\gamma$, where $G \equiv (g-2)/2 = -0.142987$ is the deuteron's gyromagnetic anomaly and γ is its Lorentz energy factor.

The deuteron's polarization can be perturbed by the horizontal rf magnetic field from either an rf solenoid or an rf dipole. At a resonant frequency the perturbations can add coherently to induce an rf spin resonance. The rf-induced spin resonance's frequency is

$$f_r = f_c(k \pm \nu_s), \qquad (2)$$

where f_c is the deuterons' circulation frequency and k is an integer. A stored beam's polarization can be manipulated in a well-controlled way by ramping an rf magnet's frequency through an rf-induced spin resonance [2-10].

EXPERIMENTAL RESULTS

The apparatus used in our experiments included the COSY storage ring, the EDDA detector, the low energy polarimeter, the injector cyclotron, the polarized ion source, and the rf dipole or rf solenoid [4-10]. The beam from the polarized D^- ion source was accelerated by the cyclotron to 75.7 MeV and then strip-injected into COSY. When needed, the beam was electron-cooled in COSY for up to 25 s at the injection energy. The deuterons were then accelerated to 1.85 GeV/c, where their average circulation frequency f_c was 1.14743 MHz and their Lorentz energy factor was $\gamma = 1.4046$. With these parameters, the spin tune $\nu_s = G\gamma$ was -0.20084.

The rf dipole consisted of an 8-turn ferrite-core water-cooled copper coil with the spacing between its turns optimized to produce a uniform radial magnetic field; it ran as a part of an LC resonant circuit giving an $\int B \cdot dl$ of 0.54 ± 0.03 T·mm rms at 917 kHz. It was later replaced with a 25-turn air-core water-cooled rf solenoid, which produced an rf $\int B \cdot dl$ of 0.67 ± 0.03 T·mm rms at the same frequency.

The EDDA polarimeter measured the beam's polarization in COSY. We reduced its systematic errors by repeatedly cycling the polarized deuteron ion source beam through five spin states with nominal vector P_V and tensor P_T vertical polarizations:

$$(P_V, P_T) = (0,0), (+1,+1), (-1/3,-1), (-2/3,0), (-1,+1).$$

The measured $(0,0)$ state polarization was subtracted from each of the other measured polarizations to correct for detector efficiencies and beam motion asymmetries.

Spin Flipping

Ramping an rf magnet's frequency through the spin resonance frequency f_r can rotate the deuteron beam's polarization. The modified [2] Froissart-Stora formula [11] gives the beam's final vector P_V and tensor P_T polarizations [3] after such a ramp in terms of the beam's initial vector P_V^i and tensor P_T^i polarizations, the spin resonance strength ε, the ramp's frequency range Δf and its ramp time Δt:

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$$\frac{P_V}{P_V^i} = (1+\hat{\eta})\exp\left[-\frac{(\pi\varepsilon f_c)^2}{\Delta f/\Delta t}\right] - \hat{\eta}, \tag{3}$$

$$\frac{P_T}{P_T^i} = \frac{3}{2}\left\{(1+\hat{\eta})\exp\left[-\frac{(\pi\varepsilon f_c)^2}{\Delta f/\Delta t}\right] - \hat{\eta}\right\}^2 - \frac{1}{2}, \tag{4}$$

the parameter $\hat{\eta}$ is the limiting spin-flip efficiency.

In our spin-flipping studies, we first used Eq. (2) to determine the approximate frequency of this spin depolarizing resonance $f_r = f_c(1+G\gamma) = 917.0$ kHz. We then experimentally determined f_r with high precision by running the rf dipole at different fixed frequencies near 917 kHz.

We next flipped the deuteron beam by linearly ramping the rf dipole's frequency from $f_r - 0.1$ to $f_r + 0.1$ kHz, with various ramp times Δt, and measured the deuteron polarizations after each frequency ramp as shown in Fig. 1. The curves in Fig. 1 are fits of the vector and tensor data to Eqs. (3) and (4), respectively. Note the interesting behavior of the tensor polarization, which is well-described by Eq. (4).

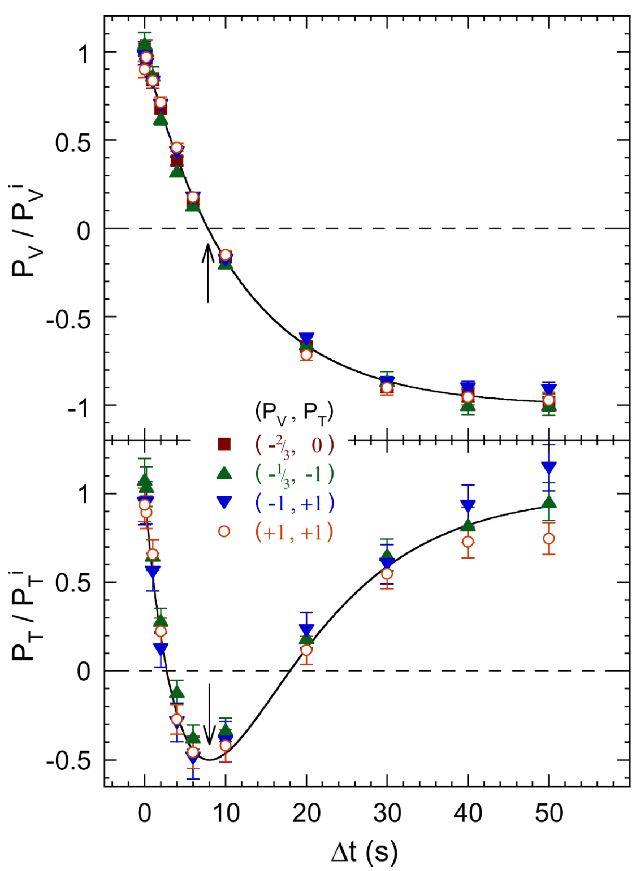

Figure 1: The measured vector and tensor deuteron polarization ratios at 1.85 GeV/c are plotted against the rf dipole ramp time Δt. The rf dipole's frequency half-range $\Delta f/2$ was 100 Hz, and its $\int B \cdot dl$ was 0.54 T·mm rms. The curves are fits of the vector and tensor data using Eqs. (3) and (4), respectively.

After optimizing Δt and Δf for the maximum spin-flip efficiency at our maximum $\int B \cdot dl$, we more precisely determined the spin-flip efficiencies by simultaneously measuring, after n frequency sweeps, the vector P_V^n and tensor P_T^n polarizations. We fit these data using [3]

$$P_V^n / P_V^i = (-\eta_V)^n, \quad P_T^n / P_T^i = \left[\frac{3}{2}(-\eta_T)^2 - \frac{1}{2}\right]^n, \tag{5}$$

to obtain vector and tensor spin-flip efficiencies of $\eta_V = 96.5 \pm 0.6\%$ and $\eta_T = 98.3 \pm 1.0\%$, respectively. In a later run, we were able to flip the spin 5 times with rather high spin-flip efficiency. The vector polarization data from that experiment are shown in Fig. 2. Fitting them to Eq. (5) gave $\eta_V = 98.5 \pm 0.3\%$.

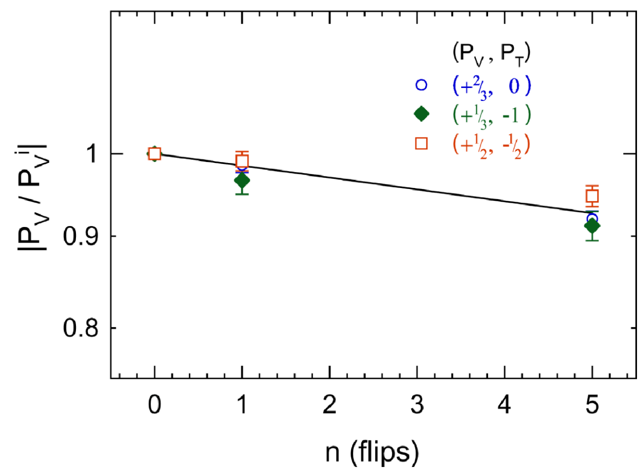

Figure 2: The measured vector deuteron polarization ratios at 1.85 GeV/c are plotted against the number of frequency sweeps. The rf dipole's frequency ramp time Δt was 60 s; its frequency half-range $\Delta f/2$ was 75 Hz, and its $\int B \cdot dl$ was 0.60 T·mm rms. The line is a fit using Eq. (5).

Chao Matrix Formalism

The Froissart-Stora (F-S) formula [11] has been widely used to calculate a beam's polarization after crossing a spin resonance. However, it is valid only for a constant-rate linear crossing from far below to far above the resonance. Chao's matrix formalism was proposed [12] to deal with conditions where the F-S formula is not valid. The Chao formalism can be used to calculate the spin dynamics anywhere inside a piecewise linear resonance crossing. It allows one to analytically solve the spin equation of motion near an isolated spin resonance, if its crossing can be expressed as a series of linear segments. Each segment must have a fixed or linearly changing distance between the spin tune $\nu_s = G\gamma$ and the resonance tune $\nu_r \equiv k \pm f_r/f_c$. After obtaining, for each segment, the time-dependent matrix describing a spinor's evolution in the segment, one multiplies these matrices sequentially to obtain the final polarization P_f.

To experimentally verify the validity of the Chao formalism, we first obtained the rf solenoid's strength ε by measuring the polarization after ramping its frequency trough the resonance with various ramp times Δt with its frequency range Δf and voltage fixed. We then fit these data to the Froissart-Stora formula [11] Eq. (3) to obtain the measured value of $\varepsilon = (1.060 \pm 0.005) \times 10^{-5}$.

To study the Chao formalism's predicted dependence on the beam's momentum spread $\Delta p/p$, we varied the COSY electron cooler's on-time at injection. It cooled the deuterons' emittances both longitudinally and transversely for 15 or 25 s. The deuterons were then accelerated to 1.85 GeV/c. The rf acceleration cavity was off and shorted during COSY's flat top; thus, there were no synchrotron oscillations.

We tested the Chao formalism by ramping the rf solenoid's frequency over a range Δf, which started at a frequency f_{start} (well outside the rf spin resonance centered at f_r) and ended at a frequency f_{end} near or inside the resonance, as illustrated in Fig. 3. Both Δf and the ramp time Δt were held fixed at 400 Hz and 100 ms, respectively, while f_{end} was set to different values. After f_{rf} reached f_{end}, the rf solenoid was turned off abruptly (in a few μs) to preserve the vertical polarization at that instant. We then measured the deuterons' vector polarization in all polarization states. The resulting final vector polarization P_V for each nonzero spin state is plotted vs f_{end} in Figs. 4 and 5 for electron cooling times of 15 and 25 s, respectively.

We first calculated [8-10,12] the Chao formalism's prediction for $\Delta p/p = 0$ using Δf of 400 Hz, Δt of 100 ms, and our measured ε of 1.06×10^{-5}. To take into account the beam's momentum spread $\Delta p/p$, we next folded this result together with Gaussians representing different values of the beam's f_r spread $\delta f_{\Delta p}$ due to $\Delta p/p$. We then fit the data in Figs. 4 and 5 with f_r and $\delta f_{\Delta p}$ as the two free parameters. The Chao formalism fits are shown as solid lines for each nonzero spin state in each figure.

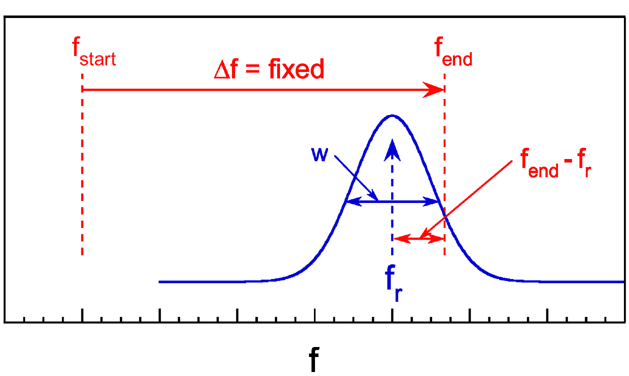

Figure 3: Schematic of the Chao formalism test. The rf solenoid's frequency f_{rf} was ramped, by a fixed range Δf, for different distances between the ramp's end frequency f_{end} and the resonance's center f_r. The curve shows the resonance with a total (FWHM) width w.

We calculated $\chi^2/(N-2)$ for each fit to compare its agreement with the data for each of the four nonzero spin states. Each χ^2 analysis included only the data's statistical errors and ignored systematic errors; nevertheless, all $\chi^2/(N-2)$ were near 1 despite the curves' complex shapes. The oscillations' positions and magnitudes are very sensitive to the values of f_r and $\delta f_{\Delta p}$, respectively. As predicted, the oscillation amplitude increased as $\delta f_{\Delta p}$ decreased. An excellent agreement of the data with the calculations in both Figs. 4 and 5 confirms the validity the Chao formalism [8-10,12].

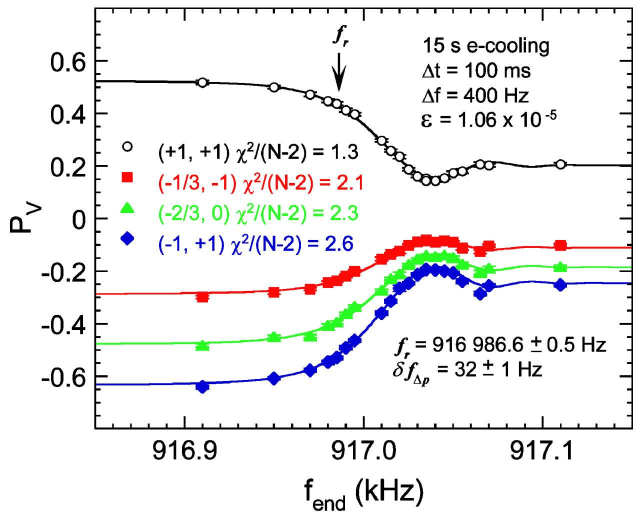

Figure 4: Measured 1.85 GeV/*c* deuteron vector polarizations plotted vs rf-solenoid end frequency f_{end}. Its ramp time Δt was 100 ms; its frequency range Δf was 400 Hz, and its ε was 1.06×10^{-5}. Electron cooling was on for 15 s. The curves are the Chao formalism fits giving the values of the resonance frequency f_r and of the Gaussian $\delta f_{\Delta p}$ indicated in the plot.

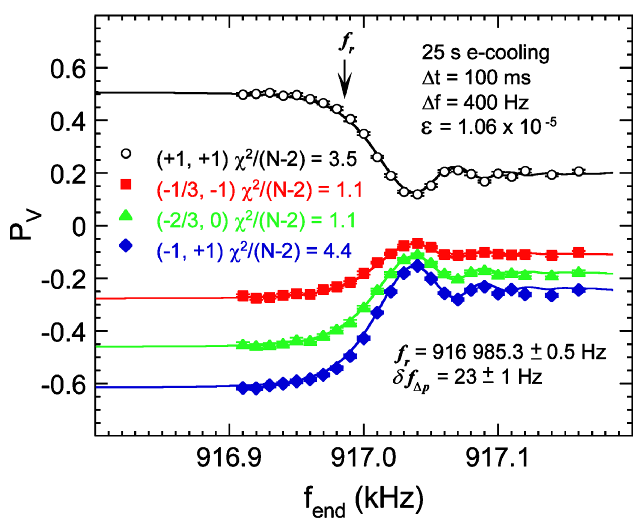

Figure 5: Measured deuteron vector polarizations plotted vs f_{end} as in Fig. 4. Electron cooling was on for 25 s. The corresponding Chao formalism fit results are indicated in the plot.

Kondratenko Crossing

Kondratenko [13] proposed a technique for overcoming medium-strength depolarizing resonances, as an alternative to simple Fast Crossing (FC). This method, Kondratenko Crossing (KC), uses a more complicated crossing pattern, illustrated in Fig. 6, in which depolarizing phases before the resonance point are canceled by phases after the resonance. For a given maximum crossing rate, this pattern should result in less depolarization than FC. Our tests of this method used an rf solenoid to produce the resonance; thus, Fig. 6 is presented as frequency vs time; in other uses of KC the vertical axis might be the betatron tune or spin tune.

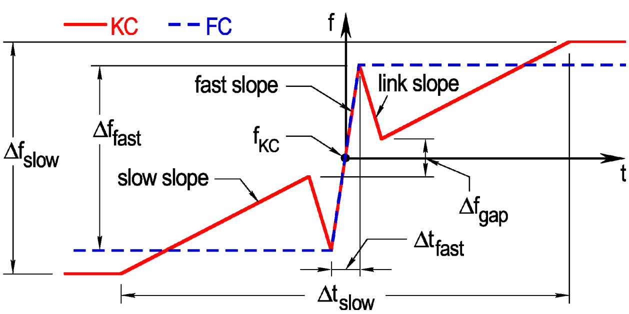

Figure 6: Kondratenko Crossing (KC) [solid line] and Fast Crossing (FC) [dashed line] patterns defining the parameters Δf_{fast}, Δt_{fast}, Δf_{slow}, and Δt_{slow}. The KC and FC patterns are both centered at f_{KC}.

We experimentally tested KC using a 1.85 GeV/c stored polarized deuteron beam at COSY by ramping an rf solenoid's frequency with the patterns shown in Fig. 6. We used Kondratenko's optimization procedure [14] along with the measured resonance strength ε of $(1.067 \pm 0.003) \times 10^{-5}$ and the previously-measured [9] resonance frequency spread δf of 23 ± 1 Hz to calculate the optimal values of the KC pattern's parameters defined in Fig. 6. The parameters chosen were Δf_{fast} = 185 Hz, Δt_{fast} = 12 ms, Δf_{slow} = 400 Hz, and Δt_{slow} = 160 ms. We used Chao's matrix formalism [8-10,12] with these parameters to predict the polarization's behavior for unbunched beam. The rf solenoid's frequency was then programmed to form the KC pattern. To test the predicted behavior experimentally, we varied each parameter around its predicted optimal value.

We first checked that the KC pattern's central frequency f_{KC} was centered on the resonance frequency f_r by varying f_{KC}. The resulting data are plotted in Fig. 7 for both bunched and unbunched beam and for both KC and Fast Crossing (FC). For KC, bunching shifted the peak's central frequency by 5 Hz relative to unbunched KC; moreover, the bunched KC data had a broader flat-top. We fit the KC unbunched data to obtain f_r of 916 999.1 ± 0.1 Hz and δf of 24.4 ± 0.2 Hz. These values were used to predict the unbunched behavior as the parameters Δf_{fast}, Δt_{fast}, Δf_{slow}, and Δt_{slow} were individually varied; the resulting predictions and data are shown in Figs. 8-10.

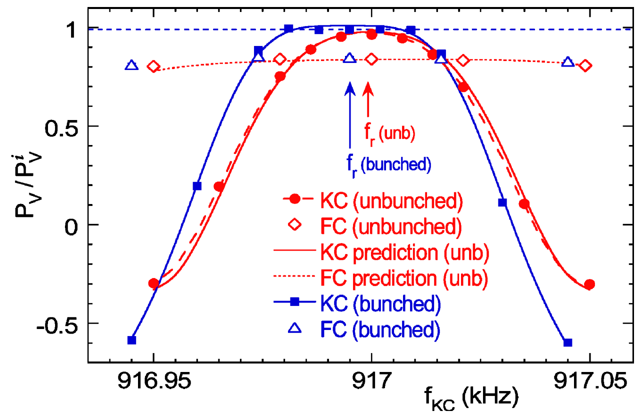

Figure 7: Measured 1.85 GeV/c deuteron P_V/P_V^i, averaged for all nonzero spin states, plotted vs the KC pattern's center frequency f_{KC}. The KC unbunched solid curve is the Chao formalism prediction while the long-dashed line through these unbunched points is a Chao formalism fit with parameters f_r and δf. The KC bunched solid curve is an empirical 2nd-order Lorentzian fit. In later studies, f_{KC} for unbunched and bunched beams was set at 917 000 and 916 995 Hz, respectively.

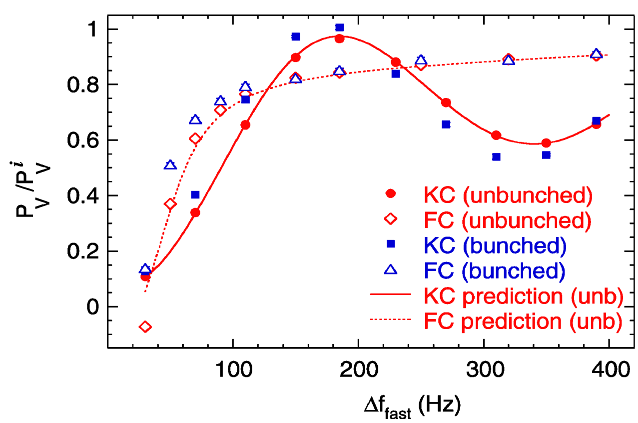

Figure 8: Measured 1.85 GeV/c deuteron P_V/P_V^i, averaged for all nonzero spin states, plotted vs fast frequency ramp range Δf_{fast}.

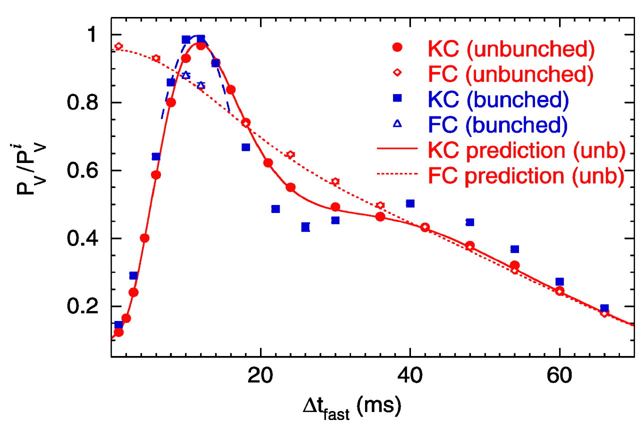

Figure 9: Measured 1.85 GeV/c deuteron P_V/P_V^i, averaged for all nonzero spin states, plotted vs fast frequency ramp time Δt_{fast}.

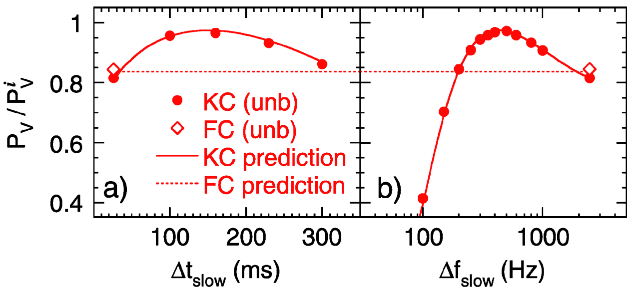

Figure 10: (a) Measured 1.85 GeV/c deuteron P_V/P_V^i plotted vs slow frequency ramp time Δt_{slow}. (b) Measured 1.85 GeV/c deuteron P_V/P_V^i plotted vs slow frequency ramp range Δf_{slow}.

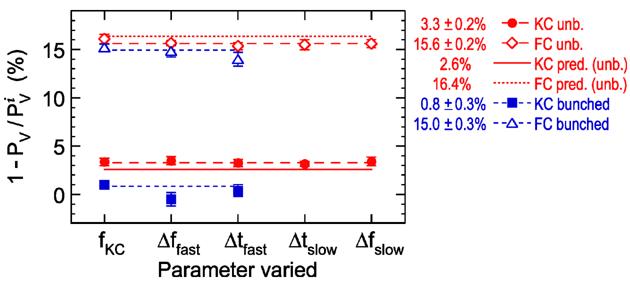

Figure 11: Summary of depolarization at each KC peak in Figs. 7-10 for both KC and FC, with both bunched and unbunched beam.

The depolarization values $(1 - P_V/P_V^i)$ at the KC peaks in Figs. 7-10 are summarized in Fig. 11. With the optimized KC parameters, the average measured depolarizations were 3.3 ± 0.3% and 0.8 ± 0.3% for unbunched and bunched beams, respectively; the average measured FC depolarizations were 15.6 ± 0.2% and 15.0 ± 0.3%, respectively. Thus, KC reduced the depolarization far more than FC: by factors of 4.7 ± 0.3 and $19\pm_5^{12}$ for unbunched and bunched beams, respectively.

While the Chao formalism cannot yet calculate the KC behavior for bunched beams, the measured 19-fold reduction in depolarization for KC over FC at the same crossing rate shows that Kondratenko Crossing may be quite valuable for the bunched beams used in accelerators. Kondratenko later proposed [15] an improved version of the crossing pattern, which involves crossing a spin resonance three times. The new pattern should be less demanding to the required crossing rates and should be less sensitive to the beam's momentum spread. By choosing appropriate crossing parameters, the multiple crossing pattern can be used to preserve the polarization during a spin resonance crossing as well as for highly efficient spin flipping. Therefore, it possesses a high potential for application in the existing and future accelerators, storage rings and colliders.

SUMMARY

By adiabatically sweeping an rf dipole's frequency through an rf-induced spin resonance, we reached a measured spin-flip efficiency of 97 ± 1% and 98.5 ± 0.3% for two separate runs with 1.85 GeV/c vertically polarized spin-1 deuterons stored in the COSY ring [5]. We demonstrated that the observed behavior of the vector and tensor polarizations can be understood in terms of the quantum mechanics of spin-1 rotations and the Froissart-Stora equation. We tested the Chao formalism's [12] prediction of polarization oscillations when crossing an isolated spin resonance, in a region where the Froissart-Stora formula is not valid. An excellent agreement of the data with the calculations confirmed the validity the Chao formalism [8-10]. We tested Kondratenko's Crossing proposal to avoid most polarization loss when crossing a spin resonance. In comparison with fast crossing at the same crossing rate, KC reduced the depolarization by factors of 4.7 ± 0.3 and $19\pm_5^{12}$ for unbunched and bunched beams, respectively.

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