Experimental Test of a New Technique to Overcome Spin-Depolarizing Resonances

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(Received 13 November 2008; published 16 June 2009)

We recently tested a new spin resonance crossing technique, Kondratenko Crossing (KC), by sweeping an rf-solenoid's frequency through an rf-induced spin resonance with both the KC and traditional fast crossing (FC) patterns. Using both rf bunched and unbunched 1.85 GeV/c polarized deuterons stored in COSY, we varied the parameters of both crossing patterns. Compared to FC with the same crossing speed, KC reduced the depolarization by measured factors of 4.7 ± 0.3 and 19^{+12}_{-5} for unbunched and bunched beams, respectively. This clearly showed the large potential benefit of Kondratenko Crossing over fast crossing.

DOI: 10.1103/PhysRevLett.102.244801 PACS numbers: 29.27.Bd, 29.27.Hj, 41.75.Ak

Polarized hadron and lepton beams are used to study the spin dependence of hadronic interactions in the multi-GeV/c region. These experiments [1–5] need high beam polarization for good precision. Thus, one must efficiently overcome spin-depolarizing resonances [6].

Siberian snakes [7] were first shown to work for protons and electrons near 1 GeV [8–11] and then above 100 GeV [12,13]. They are especially important at high energy. At lower energy one uses harmonic correction for imperfection spin resonances and fast crossing (FC) for intrinsic resonances [14–18]; recently, the AGS used two weak partial snakes [19]. These techniques are less effective than full snakes and often leave some polarization loss at many of the crossed resonances.

Kondratenko [20] proposed a new technique for overcoming medium strength depolarizing resonances. It involves crossing each resonance using the Kondratenko Crossing (KC) pattern; a typical pattern is shown in Fig. 1 and discussed below. This Letter describes a test of KC with 1.85 GeV/c deuterons at COSY; an earlier attempt [21] could not demonstrate KC's advantage over FC because the KC parameters were not yet optimized.

In flat circular rings, each beam particle'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 particle's energy: $\nu_s = G\gamma$, where $G = (g-2)/2$ is its gyromagnetic anomaly and γ is its Lorentz energy factor. The vertical polarization can be perturbed by any horizontal magnetic field [6,22–29]. RF magnetic fields can induce rf spin resonances. A deuteron's rf-induced spin resonance's frequency is

$$f_r = f_c(k \pm G_d\gamma), \tag{1}$$

where f_c is the deuteron's circulation frequency, k is an integer, and its G_d value is $-0.142\,987$.

Ramping an rf magnet's frequency f through a spin resonance with resonance strength $\boldsymbol{\epsilon}$, can change a stored beam's polarization. When f is ramped at a constant rate, during a ramp time Δt, by a range Δf, from far below to far above a resonance, the Froissart-Stora equation [22] can relate the beam's initial vector polarization P_i and its polarization P_f after crossing the resonance,

$$P_f = P_i\left\{2\exp\left[-\frac{(\pi\boldsymbol{\epsilon} f_c)^2}{\Delta f/\Delta t}\right] - 1\right\}. \tag{2}$$

We recently tested KC with the pattern shown in Fig. 1. We used the Chao matrix formalism [30–32] to calculate analytically the polarization for this pattern.

We ramped the frequency f of a new rf solenoid [30] through the Δf ranges in times Δt to produce the KC pattern shown in Fig. 1. The rf solenoid was a 25-turn air-core water-cooled copper coil, of length 57.5 cm and

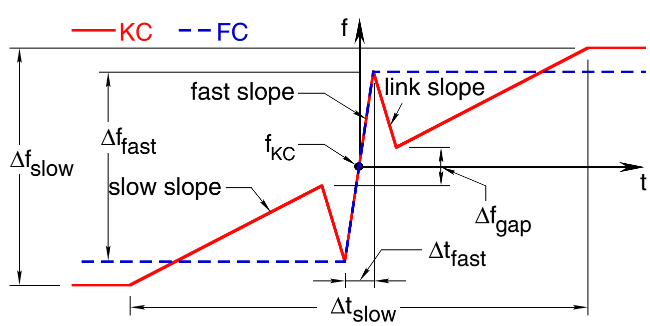

FIG. 1 (color online). KC (solid line) and FC (dashed line) patterns for rf-solenoid frequency f plotted vs time t. This figure defines the parameters Δf_{fast}, Δt_{fast}, Δf_{slow}, and Δt_{slow}. The KC and FC patterns are both centered at f_{KC}.

average diameter 21 cm. Its inductance was 41 ± 3 μH. It was part of an *RLC* resonant circuit, which operated near 917 kHz, typically at an rf voltage of 5.7 kV rms. Its longitudinal rf magnetic field at its center was about 1.17 mT rms, giving an rf $\int Bdl$ of 0.67 ± 0.03 T mm rms.

The other apparatus for this experiment, including the COSY storage ring [33–36], the EDDA polarimeter [37,38], the electron cooler [39], the low energy polarimeter [40], the injector cyclotron, and the polarized ion source [41–43] were shown in Fig. 4 of Ref. [32]. The beam from the polarized D^- ion source was accelerated by the cyclotron to 75.7 MeV and then strip-injected into COSY. The low energy polarimeter measured the D^- beam's polarization before injection into COSY to monitor the cyclotron's and ion source's stability.

In COSY, the deuterons' average circulation frequency f_c was 1.14743 MHz at 1.850 GeV/c, where their Lorentz energy factor was $\gamma = 1.4046$. For these parameters, the spin tune $\nu_s = G\gamma$ was -0.20084. Thus, Eq. (1) implies that the $(1 + G\gamma)$ spin resonance's central frequency should be at $f_r = (1 + G\gamma)f_c \simeq 917.0$ kHz.

To minimize the beam's momentum spread $\Delta p/p$, the 20.6 keV electron cooler was tuned carefully. It cooled the deuterons' emittances both longitudinally and transversely for 14 s. This reduced the spin resonance frequency spread δf to 23 Hz FWHM to better satisfy the KC conditions [44] with our rf solenoid. The deuterons were then accelerated to 1.85 GeV/c, where the rf acceleration cavity was either off during COSY's flat-top giving an "unbunched" beam, or on giving a "bunched" beam.

The EDDA polarimeter [37,38] 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:

$$(P_V, P_T) = (0,0),\ (+1,+1),\ \left(-\tfrac{1}{3}, -1\right),\ \left(-\tfrac{2}{3}, 0\right),\ (-1,+1).$$

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

We first obtained the rf-solenoid's resonance strength $\boldsymbol{\varepsilon}$ by measuring the polarization P_V after ramping the rf frequency through the resonance with various ramp times Δt, while the frequency range Δf and voltage were both fixed; these data are shown in Fig. 2. We fit these data to Eq. (2), the Froissart-Stora equation, to obtain the measured $\boldsymbol{\varepsilon}$ of $(1.067 \pm 0.003) \times 10^{-5}$.

We then used Kondratenko's procedure [44] to calculate the optimal values of the KC pattern's parameters (see Fig. 1), with the link and fast slopes equal, by using the above measured $\boldsymbol{\varepsilon}$ and the earlier measured [30] δf of 23 ± 1 Hz FWHM. We used these parameters and the Chao matrix formalism [30–32] to predict the polarization's behavior. The rf-solenoid's frequency was then programed to form the KC pattern using these parameters. Then we tested this predicted behavior experimentally by

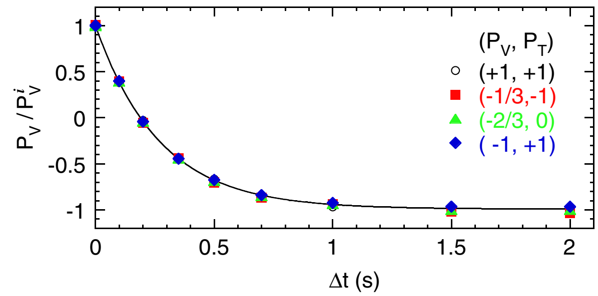

FIG. 2 (color online). Measured 1.85 GeV/c deuteron vector polarization ratio plotted vs frequency ramp time Δt for the four indicated spin states. P_V^i is the initial polarization. The rf-solenoid's voltage was 5.7 kV rms; Δf was 400 Hz centered at 917 kHz; the beam was unbunched.

varying each parameter around its predicted value; the resulting data are shown in Figs. 3–6.

To check that the KC pattern was centered at the rf resonance's center, we varied its central frequency f_{KC} and then measured, after the crossing, the deuterons' vector polarization in all five (P_V, P_T) states. The resulting vertical polarization data are plotted in Fig. 3 for both bunched and unbunched beams and for both KC and fast crossing (FC). For bunched KC, the rf cavity shifted the peak's central frequency by 5 Hz relative to unbunched KC; moreover, the bunched KC data have a broad flat-top. The unbunched beam's P_V/P_V^i ratio, measured at the KC

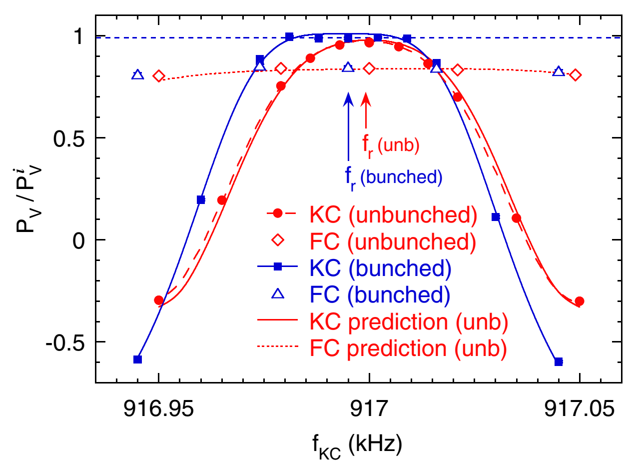

FIG. 3 (color online). Measured 1.85 GeV/c deuteron vector polarization ratios P_V/P_V^i averaged for all nonzero spin states, plotted vs the KC pattern's center frequency f_{KC}. The resonance strength $\boldsymbol{\varepsilon}$ was 1.067×10^{-5}; $\Delta f_{\rm fast}$ was 185 Hz; $\Delta t_{\rm fast}$ was 12 ms; $\Delta f_{\rm slow}$ was 400 Hz; and $\Delta t_{\rm slow}$ was 160 ms. The KC unbunched solid curve is the Chao formalism prediction for these parameters; 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; the horizontal dashed line fit to the five highest points gives the peak KC bunched value of 0.990 ± 0.002. The P_V/P_V^i errors in all figures are less than 1%. In all later figures, f_{KC} was set at 917 000 and 916 995 Hz for unbunched and bunched beams, respectively.

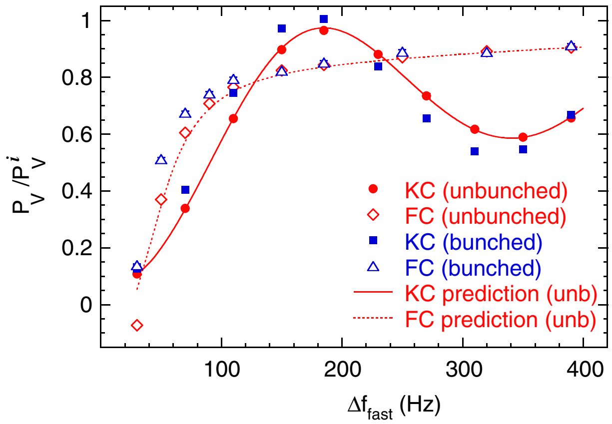

FIG. 4 (color online). Measured 1.85 GeV/c deuteron vector polarization ratios, averaged for all nonzero spin states, plotted vs fast frequency ramp range Δf_{fast}; Fig. 3 caption lists all other parameters.

peak, was 0.966 ± 0.004 for KC, and 0.839 ± 0.005 for FC. For the bunched beam, it was 0.990 ± 0.002 for KC, and 0.848 ± 0.003 for FC. By minimizing the KC unbunched data's χ^2, we obtained $f_r = 916\,999.1 \pm 0.1$ Hz and δf of 24.4 ± 0.2 Hz. Thus, Fig. 3 showed that beam bunching significantly decreased both KC's sensitivity to f_{KC} and its polarization loss.

Both the KC and FC data, when varying Δf_{fast}, Δt_{fast}, Δt_{slow}, and Δf_{slow}, are shown in Figs. 4, 5, 6(a), and 6(b), respectively. Their predictions used the more precise f_r and δf values from the fit to the Fig. 3 data. The KC and FC polarization ratios (P_V/P_V^i) at the KC peak in Figs. 3–6 are listed in Table I for both bunched and unbunched beams; the depolarizations ($1 - P_V/P_V^i$) are summarized in Fig. 7 and Table I. The unbunched KC data agree with the predictions. With the optimized KC crossing parameters, the average measured KC depolarizations were $3.3 \pm 0.2\%$ and $0.8 \pm 0.3\%$ for the unbunched and bunched beams, respectively; and the average measured FC depolarizations were $15.6 \pm 0.2\%$ and $15.0 \pm 0.3\%$, respectively. Thus, KC reduced the depolarization far more than FC, by factors of 4.7 ± 0.3 and 19^{+12}_{-5} for the unbunched and bunched beams, respectively.

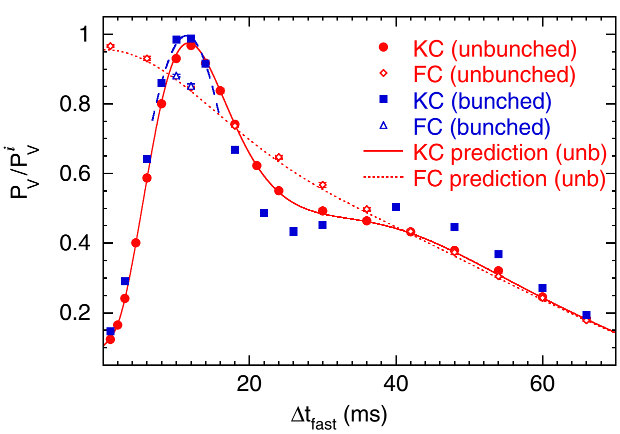

FIG. 5 (color online). Measured 1.85 GeV/c deuteron vector polarization ratios, averaged for all nonzero spin states, plotted vs fast frequency ramp time Δt_{fast}. The dashed line is an emperical 1st order Lorentzian fit to the four highest bunched KC points; Fig. 3 caption lists all other parameters.

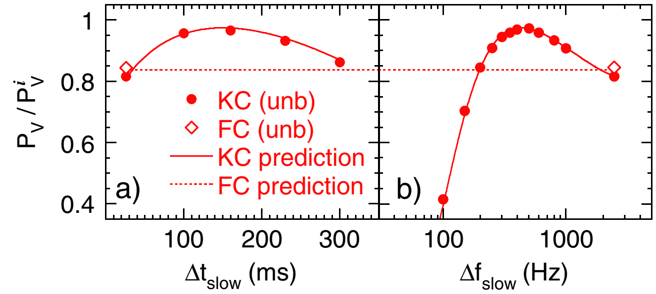

FIG. 6 (color online). (a) Measured 1.85 GeV/c deuteron vector polarization ratios plotted vs slow frequency ramp time Δt_{slow}. (b) Measured 1.85 GeV/c deuteron vector polarization ratios plotted vs slow frequency ramp range Δf_{slow}. The beam was unbunched; Fig. 3 caption lists all other parameters.

In summary, we tested Kondratenko's Crossing proposal to avoid most polarization loss when crossing a spin resonance. Using stored 1.85 GeV/c vertically polarized deuterons, we ramped an rf-solenoid's frequency through the KC pattern while crossing an rf depolarizing resonance. The unbunched beam data agree with the predicted KC behavior. With its optimal parameters, KC gave measured polarization losses of $3.3 \pm 0.2\%$ and $0.8 \pm 0.3\%$ with unbunched and bunched beams, respectively, while fast crossing, at the same crossing rate, gave measured losses of $15.6 \pm 0.2\%$ and $15.0 \pm 0.3\%$, respectively.

While the Chao formalism cannot yet calculate the KC behavior for bunched beams, the ~20-fold measured depolarization advantage of KC over FC, at the same crossing rate, shows that Kondratenko Crossing may be quite valuable for the bunched beams used in most accelerators and colliders.

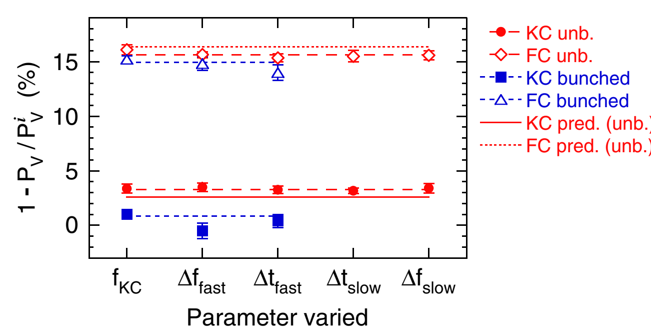

FIG. 7 (color online). Summary of depolarization at each KC peak for both KC and FC, with both the bunched and unbunched beam. The horizontal axis denotes the parameters varied to obtain the data listed in Table I. The solid and dotted lines are the Chao formalism predictions (only for unbunched beam). The dashed lines are fits to the measured data that give the average depolarization values and errors.

TABLE I. Summary of KC and FC polarization and depolarization ratios at KC peak in Figs. 3–6 for the indicated parameters.

Figure number	3	4	5	6a	6b	P_V/P_V^i	$(1 - P_V/P_V^i)$	
Parameter varied	f_{KC}	Δf_{fast}	Δt_{fast}	Δt_{slow}	Δf_{slow}	Average	Average	Prediction
KC (unbunched)	96.6 ± 0.4%	96.5 ± 0.4%	96.7 ± 0.4%	96.8 ± 0.3%	96.6 ± 0.4%	96.7 ± 0.2%	3.3 ± 0.2%	2.6%
FC (unbunched)	83.9 ± 0.5%	84.4 ± 0.3%	84.7 ± 0.4%	84.5 ± 0.5%	84.4 ± 0.4%	84.4 ± 0.2%	15.6 ± 0.2%	16.4%
KC (bunched)	99.0 ± 0.2%	100.5 ± 0.7%	99.6 ± 0.6%	N/A	N/A	99.2 ± 0.3%	0.8 ± 0.3%	N/A
FC (bunched)	84.8 ± 0.3%	85.2 ± 0.6%	86.0 ± 0.7%	N/A	N/A	85.0 ± 0.3%	15.0 ± 0.3%	N/A

We thank the COSY staff for the successful operation of COSY with its injector cyclotron and polarized ion source. We are grateful to E. D. Courant, Ya. S. Derbenev, D. Eversheim, G. Fidecaro, W. Haeberli, H. Huang, Yu. F. Orlov, H. Rohdjeß, T. Roser, H. Sato, W. Scobel, E. J. Stephenson, K. Ulbrich, K. Yonehara, and others for their help and advice. This research was supported by grants from the German BMBF Science Ministry, its FFE program at COSY, and the Helmholtz Association through funds provided to the virtual institute "Spin and strong QCD" (VH-VI-231).

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