Unexpected reduction of rf spin resonance strength for stored deuteron beams

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Stored beams of polarized protons, electrons, or deuterons can be spin flipped by sweeping an rf dipole's or solenoid's frequency through an rf spin resonance. Fitting such data to the modified Froissart-Stora equation's spin resonance strength $\mathcal{E}_{\rm FS}$ gave very large deviations from the ${}^*\mathcal{E}_{Bdl}$ obtained from each rf magnet's $\int B_{rms}dl$. We recently varied an rf dipole's frequency sweep range Δf, and the momentum spread $\Delta p/p$ and betatron tune ν_y of stored 1.85 GeV/c polarized deuterons. We found a sharp constructive interference when ν_y was near an intrinsic spin resonance. Moreover, over large Δf and $\Delta p/p$ ranges, $\mathcal{E}_{\rm FS}$ was about 7 times smaller than the predicted ${}^*\mathcal{E}_{Bdl}$.

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A recent paper [1] analyzed all available data on spin-flipping stored beams of polarized protons, electrons, and deuterons. The polarization was typically manipulated by sweeping the frequency of an rf dipole or rf solenoid through an rf-induced spin resonance; spin-flip efficiencies of up to 99.9% were obtained. Fitting the modified [2,3] Froissart-Stora [4] equation to the measured polarization data after crossing an rf-induced spin resonance gave very large deviations from the widely used resonance strength equations. We recently measured the deuteron's resonance strength deviations by varying an rf dipole's frequency sweep range Δf, and the momentum spread $\Delta p/p$ and betatron tune ν_y of a 1.85 GeV/c polarized deuteron beam stored in COSY.

In any flat storage ring or circular accelerator with no horizontal magnetic fields, each beam particle's spin precesses around the vertical fields of the ring's dipole magnets. The spin tune ν_s, which is the number of spin precessions during one turn around the ring, is proportional to the particle's energy

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

where $G = (g-2)/2$ is the particle's gyromagnetic anomaly ($G_d = -0.142\,987$) and γ is its Lorentz energy factor. The vertical polarization can be perturbed by an rf magnet's horizontal rf magnetic field. This perturbation can induce an rf depolarizing resonance [4–6], which can flip the spin direction of stored polarized particles [1–3,7–18]; the resonance's frequency is

$$f_r = f_c(k \pm \nu_s), \tag{2}$$

where f_c is the circulation frequency and k is an integer.

Ramping an rf magnet's frequency through f_r can flip each particle's spin. The modified [2,3] Froissart-Stora (FS) equation [4] relates the beam's initial polarization P_i to its final polarization P_f after crossing the resonance,

$$P_f = P_i\left\{(1+\hat{\eta})\exp\left[\frac{-(\pi\mathcal{E}_{\rm FS}f_c)^2}{\Delta f/\Delta t}\right] - \hat{\eta}\right\}; \tag{3}$$

the parameter $\hat{\eta}$ is the limiting spin-flip efficiency and the ratio $\Delta f/\Delta t$ is the resonance crossing rate, where Δf is the ramp's frequency range during the ramp time Δt, and $\mathcal{E}_{FS}$ is the resonance strength obtained by fitting measured data to Eq. (3). Equation (3) should be valid if Δf is larger than the spin resonance's width.

For an ideal flat circular accelerator, with no horizontal B-fields, the resonance strength ${}^*\mathcal{E}_{Bdl}$ due to a short rf solenoid's longitudinal B-field or a short rf dipole's transverse B-field is thought to be given by [19–25]

$$\text{Solenoid}: {}^*\mathcal{E}_{Bdl} = \frac{1}{\pi 2\sqrt{2}}\frac{e(1+G)}{p}\int B_{rms}dl, \tag{4}$$

$$\text{Dipole}: {}^*\mathcal{E}_{Bdl} = \frac{1}{\pi 2\sqrt{2}}\frac{e(1+G\gamma)}{p}\int B_{rms}dl, \tag{5}$$

where e is the particle's charge, p is its momentum, and $\int B_{rms}dl$ is the rf magnet's rms magnetic field integral in its rest frame. There has been some theoretical disagreement about a factor of 2 in both Eqs. (4) and (5). While our experimental data cannot confirm either factor of 2, we now use the [24,25] factor of 2; thus, we changed the resonance strength symbol to ${}^*\mathcal{E}_{Bdl}$.

The recent compilation [1] of all available experimental data [1–3,7,10,11,13–18] allowed a simultaneous evaluation of the spin resonance strength ${}^*\mathcal{E}_{Bdl}$, obtained from Eqs. (4) and (5), and the spin resonance strength $\mathcal{E}_{\rm FS}$ obtained from Eq. (3). This compilation indicated that for many experiments the $\mathcal{E}_{FS}/{}^{*}\mathcal{E}_{Bdl}$ ratio disagrees with the predictions [19–25] by factors of 0.1, 10, or more. For protons $\mathcal{E}_{FS}/{}^{*}\mathcal{E}_{Bdl}$ was often much larger than 1; this was explained by a recent experiment [1], which demonstrated that much of this enhancement was due to constructive interference of the rf resonance with a strong intrinsic resonance. However for deuterons, $\mathcal{E}_{FS}$ was typically 7 times smaller than ${}^{*}\mathcal{E}_{Bdl}$. The proton experiment [1] was done with the same rf dipole at COSY; thus, these large strength deviations could not be due to an incorrect calibration of $\int Bdl$, which was known to $\pm 5\%$.

To better understand this unexpected deuteron behavior, we recently measured the dependence of a deuteron rf resonance's strength on various parameters, such as the proximity to a deuteron intrinsic resonance, the beam's momentum spread, and the rf dipole's frequency sweep range Δf. This experiment used a 1.85 GeV/c polarized deuteron beam stored in COSY.

The experimental apparatus (see Fig. 4 in [1]), included the COSY storage ring [26–29], the EDDA detector [30], the electron cooler [31], the low energy polarimeter, the injector cyclotron, and the polarized ion source [32–34]. The beam emerging from the polarized D^- ion source was accelerated by the cyclotron to COSY's injection energy of about 75.7 MeV. Then the low energy polarimeter measured the beam's polarization before injection into COSY to monitor the stable operation and polarization of the ion source.

The EDDA detector [30] measured the beam's polarization in COSY; we reduced its systematic errors by cycling the polarized source between the 4 different vector and tensor vertical polarization states:

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

The rf acceleration cavity was turned off and shorted during COSY's flattop. The measured $(+1, +1)$ vector polarization, before spin manipulation, was about 63%.

We first determined the resonance's position by measuring the polarization with the rf dipole set at different fixed frequencies. These data are shown in Fig. 1 with the electron cooling both on and off. Note that the deuteron resonance frequency changed slightly due to the slightly different accelerator parameters used when the electron cooling was on or off. The electron cooler reduced the beam's size and momentum spread at injection energy. A 20.6 keV electron beam cooled the deuteron beam to its equilibrium emittances in both the longitudinal and transverse dimensions. As shown in Fig. 1, the electron cooling decreased the resonance's total width w from 42 ± 2 to 23 ± 2 Hz FWHM. Since the resonance's natural width of $2\mathcal{E}_{FS}f_c$ is only 3 Hz, when it is unfolded from these measured w values, then the width values due to the beam's $\Delta p/p$ are essentially unchanged.

We manipulated the deuteron's polarization using a ferrite-yoke rf dipole, with an 8-turn copper coil, which

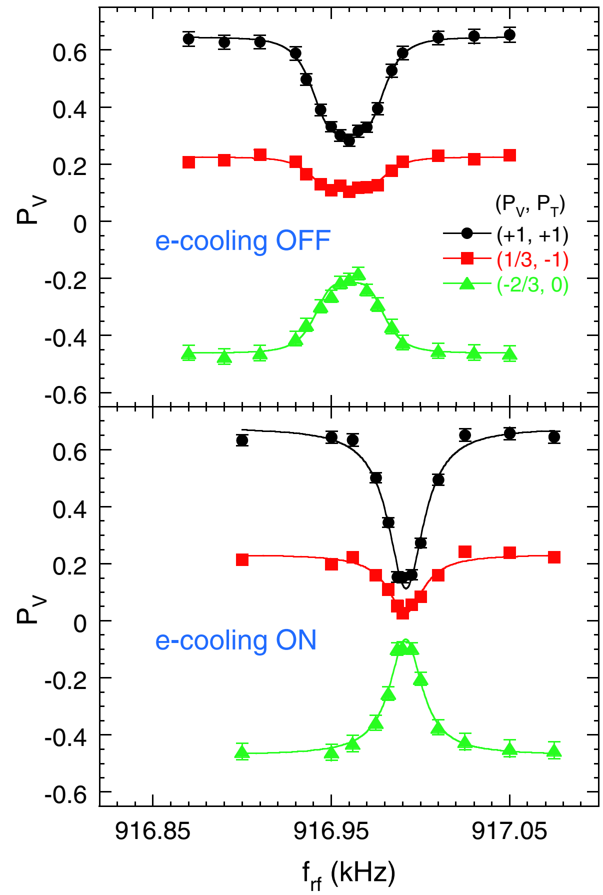

FIG. 1. (Color) Measured vector deuteron polarizations at 1.85 GeV/c are plotted vs rf-dipole frequency f_{rf}. Fits to a 2nd-order Lorentzian give a resonance frequency f_r of $916\,960 \pm 10$ Hz and a resonance width w of 42 ± 2 Hz for the uncooled beam. Fits to a 1st-order Lorentzian give f_r of $916\,992 \pm 10$ Hz and w of 23 ± 2 Hz with electron cooling.

produced a uniform radial magnetic field. The rf dipole was part of an LC resonant circuit, which operated near $f_r = 917$ kHz, typically at an rf voltage of 3.1 kV rms giving an rf $\int B_{rms}dl$ of 0.60 ± 0.03 T mm.

As shown in Fig. 2, the resonance strength $\mathcal{E}_{FS}$ was obtained by first measuring the final beam polarization P_f after ramping an rf magnet's frequency by a range Δf during a time Δt through a spin resonance. The measured dependence of P_f on Δt was then fit to Eq. (3). Thus, we obtained $\mathcal{E}_{FS}$ for two different frequency ranges, Δf of 100 and 300 Hz; and for two different momentum spreads by using electron cooling to reduce the beam's $\Delta p/p$.

The resonance strengths $\mathcal{E}_{FS}$ and their $\mathcal{E}_{FS}/{}^{*}\mathcal{E}_{Bdl}$ ratios were all obtained by fitting these data to Eq. (3) as explained in the Fig. 2 caption. The $\mathcal{E}_{FS}/{}^{*}\mathcal{E}_{Bdl}$ ratios at Δf of 100 and 300 Hz, for both the cooled and uncooled beams, are shown in Fig. 3 along with other data. Recall that Fig. 1 indicated that the cooling reduced $\Delta p/p$ by a factor of 2 while the $\mathcal{E}_{FS}/{}^{*}\mathcal{E}_{Bdl}$ ratios for the cooled and uncooled beams only differ by about 7%. Thus, any small $\Delta p/p$

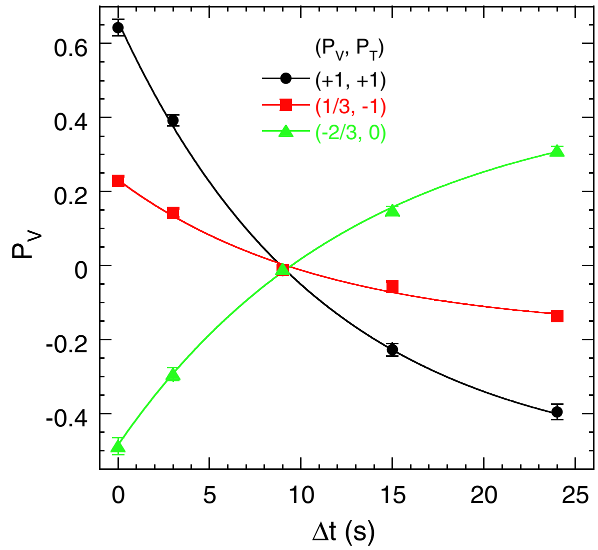

FIG. 2. (Color) Measured vector deuteron polarizations at 1.85 GeV/c are plotted vs rf-dipole ramp time Δt for 3 different spin states with electron cooling off. The rf dipole's frequency range Δf was 300 Hz; its $\int Bdl$ was 0.60 ± 0.03 T mm; thus, Eq. (5) gives $^*\mathcal{E}_{Bdl}$ of $(8.8 \pm 0.4) \times 10^{-6}$. The fit to Eq. (3) gives $\mathcal{E}_{\rm FS}$ of $(1.39 \pm 0.04) \times 10^{-6}$.

fluctuations cannot explain the observed sevenfold reduction of the resonance strength for experiments with both cooled and uncooled beams.

All earlier anomalous deuteron data [1] were at small Δf values of 100–200 Hz; thus, we increased Δf in four steps from 100 to 3000 Hz. The resulting $\mathcal{E}_{\rm FS}/^*\mathcal{E}_{Bdl}$ ratios at $\nu_y = 3.60$, along with all earlier deuteron data, are plotted vs Δf in Fig. 3, which shows no dependence of $\mathcal{E}_{\rm FS}/^*\mathcal{E}_{Bdl}$ on Δf. The fit to all rf-dipole points gives a resonance strength ratio of 0.15 ± 0.01 for deuterons, which certainly disagrees with Eq. (5). However, note that the Indiana University Cyclotron Facility (IUCF) cooler ring rf solenoid point [14] is quite near to 1.

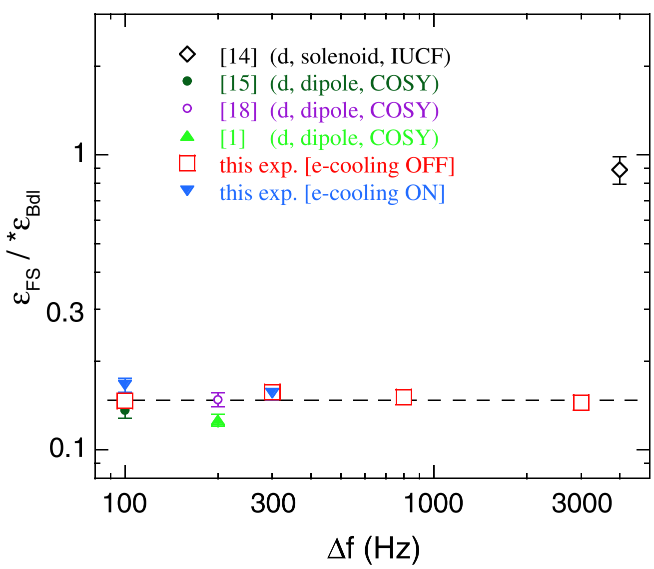

FIG. 3. (Color) Ratio of $\mathcal{E}_{\rm FS}$ to $^*\mathcal{E}_{Bdl}$ for deuterons is plotted vs rf dipole's frequency sweep range Δf. The ν_y values at COSY were all 3.60, and ν_y was 4.80 at IUCF. $\mathcal{E}_{\rm FS}$ is the resonance strength obtained by fitting the Δt curve for each data point to Eq. (3); $^*\mathcal{E}_{Bdl}$ was obtained using each data point's $\int Bdl$ in Eq. (4) or Eq. (5). The fit to all rf-dipole points gives a resonance strength ratio of 0.15 ± 0.01.

We next measured $\mathcal{E}_{\rm FS}$, as in Fig. 2, for different values of the vertical betatron tune ν_y; $^*\mathcal{E}_{Bdl}$ was again obtained using each data point's $\int Bdl$ in Eq. (5). The $\mathcal{E}_{\rm FS}/^*\mathcal{E}_{Bdl}$ ratios are plotted against ν_y in Fig. 4(a). Notice the nearby $\nu_s = \nu_y - 4$ first-order intrinsic spin resonance for deuterons [also see Fig. 4(b)]. We fit the observed asymmetric dependence of $\mathcal{E}_{\rm FS}/^*\mathcal{E}_{Bdl}$ on the distance between ν_y and the rf spin resonance's tune $\nu_r \equiv k \pm f_r/f_c$ (k is an integer) by empirically modifying the earlier-derived hyperbola [1,21] into an asymmetric hyperbola [35]

$$\mathcal{E}_{\rm FS}/^*\mathcal{E}_{Bdl} = \left| A + \frac{B}{\nu_r - \nu_y} \right|. \tag{6}$$

Fitting the deuteron data in Fig. 4(a) to Eq. (6) gave A of 0.06 ± 0.04, B of 0.010 ± 0.002, and ν_r of 3.798 ± 0.001. This ν_r value was near the ν_r value of $3.799\,23 \pm 0.000\,01$, calculated from

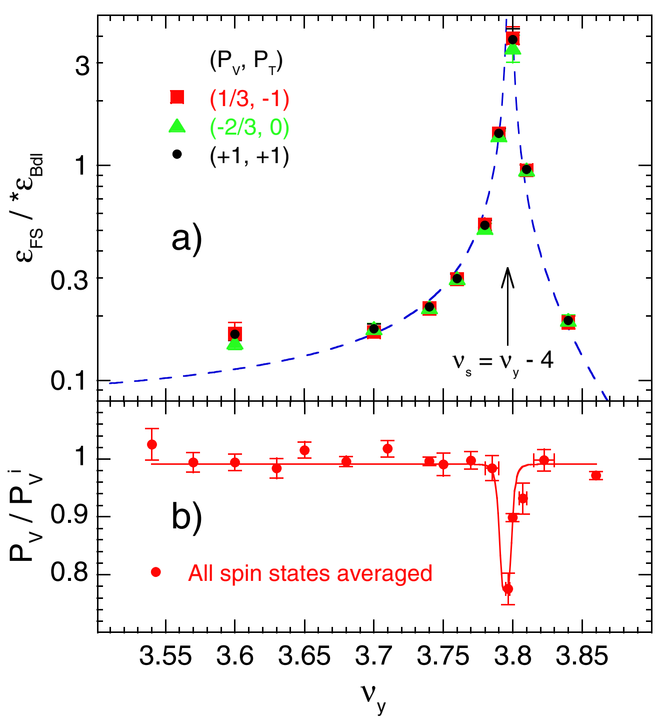

FIG. 4. (Color) (a) Ratio of $\mathcal{E}_{\rm FS}$ to $^*\mathcal{E}_{Bdl}$ is plotted vs the vertical betatron tune ν_y; Δf was 300 Hz; the cooling was off. The dashed blue curve is a fit to Eq. (6). (b) Measured deuteron vector polarization ratio at 1.85 GeV/c is plotted vs ν_y; the rf dipole was off; the cooling was on. The red curve is a fit to a 2nd-order Lorentzian.

$$\nu_r = 3 + f_r/f_c \tag{7}$$

using COSY's measured f_c of 1 147 306 Hz and the measured f_r of 916 960 $\pm$ 10 Hz from Fig. 1. The parameter B depends on many details of the ring. The parameter A should give the predicted [20–25] ratio $\mathcal{E}_{\rm FS}/{}^*\mathcal{E}_{Bdl}$ far from any intrinsic spin resonances.

Figure 4(b) shows the measured ratio of the final to initial vector polarization plotted against various values of ν_y with the rf dipole off. Fitting the sharp and narrow dip to a 2nd-order Lorentzian gave ν_r of 3.795 ± 0.002, exactly as in Fig. 4(a); and gave a width of $(10 \pm 3) \times 10^{-3}$ FWHM. Figures 4(a) and 4(b) may be the first detailed study of a deuteron intrinsic resonance.

Figure 3 demonstrated that the $\mathcal{E}_{\rm FS}/{}^*\mathcal{E}_{Bdl}$ reduction is not due to the earlier [1] small frequency ramp range, Δf. It also shows that, for deuterons, all ratios are far below 1 for an rf dipole, but near to 1 for the single rf solenoid point. Thus, perhaps the earlier unexpected behavior of spin-1 deuterons only occurs when they are spin-manipulated by an rf dipole. We hope to soon study this possibility using a new rf solenoid in COSY.

Recently there have been some theoretical efforts to understand what causes this large reduction in $\mathcal{E}_{\rm FS}/{}^*\mathcal{E}_{Bdl}$ for deuterons. Two independent approaches [36,37] now challenge the derivation of Eq. (5) [19–21,24,25]; they suggest that its factor $(1 + G\gamma)$ should instead be proportional to $G\gamma$. For high-energy protons, where it was studied earlier, the ratio of $G\gamma$ to $(1 + G\gamma)$ is very near 1. However, for our 1.85 GeV/c deuterons, the ratio's magnitude is $|-0.201/0.799| \approx 0.25$. Our measured $\mathcal{E}_{\rm FS}/{}^*\mathcal{E}_{Bdl}$ ratio of 0.15 ± 0.01 is certainly closer to 0.25 than to 1.

In summary, by compiling all available deuteron, electron, and proton data and fitting them to the Froissart-Stora equation, one found deviations of $\mathcal{E}_{\rm FS}/{}^*\mathcal{E}_{Bdl}$ in the range of about 0.12 to 170. A recent proton experiment at COSY [1] showed that much of the almost-ubiquitous enhancements for protons were due to the interference of the rf-dipole spin resonance with a nearby intrinsic proton spin resonance. The current deuteron experiment, using an rf dipole, shows that the sevenfold reductions for deuterons are not due to:

(i) the small Δf sweep used to flip the deuteron spin;
(ii) the beam's momentum spread;
(iii) interference with a deuteron intrinsic resonance;
(iv) a relativistic change in the deuteron's magnetic moment μ_d that was precisely measured in Figs. 1 and 4.

We plan to next study this intriguing problem experimentally by using a new rf solenoid to spin-manipulate polarized deuterons.

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