Unexpected reduction of rf spin resonance strength for stored deuteron beams

A. D. Krisch, M. A. Leonova, V. S. Morozov, R. S. Raymond, D. W. Sivers, and V. K. Wong
Spin Physics Center, University of Michigan, Ann Arbor, Michigan 48109-1120, USA

R. Gebel, A. Lehrach, B. Lorentz, R. Maier, D. Prasuhn, A. Schnase, and H. Stockhorst
Forschungszentrum Jülich, Institut für Kernphysik, Postfach 1913, D-52425 Jülich, Germany

F. Hinterberger and K. Ulbrich
Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany

(Received 8 December 2006; published 3 July 2007)

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 \(E_{\text{FS}}\) gave very large deviations from the \(E_{\text{FS}}\) obtained from each rf magnet’s \(\int B_{\text{rms}}dl\). We recently varied an rf dipole’s frequency sweep range \(\Delta f\), and the momentum spread \(\Delta p/p\) and betatron tune \(\nu_s\) of stored 1.85 GeV/c polarized deuterons. We found a sharp constructive interference when \(\nu_s\) was near an intrinsic spin resonance. Moreover, over large \(\Delta f\) and \(\Delta p/p\) ranges, \(E_{\text{FS}}\) was about 7 times smaller than the predicted \(E_{\text{Bdl}}\).

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 \(E_{\text{Bdl}}\), obtained from Eqs. (4) and (5), and the spin resonance strength \(E_{\text{FS}}\) 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 $f_{Bdl}$, which was known to ±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 $\Delta f$. 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 $^\text{3}^\text{He}$ 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:

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

The rf acceleration cavity was turned off and shorted during COSY’s flappert. 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 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 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 $\Delta f$ during a time $\Delta t$ through a spin resonance. The measured dependence of $P_f$ on $\Delta t$ was then fit to Eq. (3). Thus, we obtained $\mathcal{E}_{FS}$ for two different frequency ranges, $\Delta f$ 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 $\Delta f$ 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 $\Delta p/p$
steps from 100 to 3000 Hz. The resulting $\mathcal{E}_{FS}/\mathcal{E}_{Bdl}$ ratios at $\nu_y = 3.60$, along with all earlier deuteron data, are plotted vs $\Delta f$ in Fig. 3, which shows no dependence of $\mathcal{E}_{FS}/\mathcal{E}_{Bdl}$ on $\Delta f$. 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.

We next measured $\mathcal{E}_{FS}$, as in Fig. 2, for different values of the vertical betatron tune $\nu_y$; $\mathcal{E}_{Bdl}$ was again obtained using each data point’s $\int Bdl$ in Eq. (5). The $\mathcal{E}_{FS}/\mathcal{E}_{Bdl}$ ratios are plotted against $\nu_y$ 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 $\mathcal{E}_{FS}/\mathcal{E}_{Bdl}$ on the distance between $\nu_y$ and the $r_f$ spin resonance’s tune $\nu_r = k \pm f_c/f_r$ ($k$ is an integer) by empirically modifying the earlier-derived hyperbola [1, 21] into an asymmetric hyperbola [35]

$$\mathcal{E}_{FS}/\mathcal{E}_{Bdl} = \left| A + \frac{B}{\nu_r - \nu_y} \right|.$$  \hspace{1cm} (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 $\nu_r$ of 3.798 ± 0.001. This $\nu_r$ value was near the $\nu_r$ value of 3.79923 ± 0.00001, calculated from

![FIG. 2. (Color) Measured vector deuteron polarizations at 1.85 GeV/c are plotted vs rf-dipole ramp time $\Delta t$ for 3 different spin states with electron cooling off. The rf dipole’s frequency range $\Delta f$ 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 $\mathcal{E}_{FS}$ 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.

![FIG. 3. (Color) Ratio of $\mathcal{E}_{FS}$ to $\mathcal{E}_{Bdl}$ for deuterons is plotted vs rf dipole’s frequency sweep range $\Delta f$. The $\nu_y$ values at COSY were all 3.60, and $\nu_y$ was 4.80 at IUCF. $\mathcal{E}_{FS}$ is the resonance strength obtained by fitting the $\Delta f$ 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.

![FIG. 4. (Color) (a) Ratio of $\mathcal{E}_{FS}$ to $\mathcal{E}_{Bdl}$ is plotted vs the vertical betatron tune $\nu_y$; $\Delta f$ 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 $\nu_y$; the rf dipole was off; the cooling was on. The red curve is a fit to a 2nd-order Lorentzian.

071001-3
\[ \nu_r = 3 + f_r/f_c \] (7)

using COSY's measured \( f_c \) of 1147306 Hz and the measured \( f_r \) of 916960 \( \pm \) 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 \( \varepsilon_{FS}/\varepsilon_{Bdl} \) 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 \( \nu_r \) with the rf dipole off. Fitting the sharp and narrow dip to a 2nd-order Lorentzian gave \( \nu_r \) of \( 3.795 \pm 0.002 \), 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 \( \varepsilon_{FS}/\varepsilon_{Bdl} \) reduction is not due to the earlier [1] small frequency ramp range, \( \Delta f \). 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 \( \varepsilon_{FS}/\varepsilon_{Bdl} \) for deuterons. Two independent approaches [36,37] now challenge the derivation of Eq. (5) [19–21,24,25]; they suggest that its factor \( (1+Gy) \) should instead be proportion to \( Gy \). For high-energy protons, where it was studied earlier, the ratio of \( Gy \) to \( (1+Gy) \) is very near 1. However, for our 1.85 GeV/c deuterons, the ratio's magnitude is \( | -0.201/0.799 | = 0.25 \). Our measured \( \varepsilon_{FS}/\varepsilon_{Bdl} \) ratio of 0.15 \( \pm \) 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 \( \varepsilon_{FS}/\varepsilon_{Bdl} \) 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 \( \Delta f \) 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 \( \mu_d \) 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.

**ACKNOWLEDGMENTS**

We thank the COSY staff for the successful operation of COSY. We also thank B.B. Blinov, A.W. Chao, E.D. Courant, Ya.S. Derbenev, D. Eversheim, A.M. Kondratenko, H. Rohdjéß, T. Roser, H. Sato, W. Scobel, K. Yonehara, and others for help and advice. This research was supported by grants from the German BMBF Science Ministry.

Above the $\nu_{ij} \approx 3.80$ intrinsic resonance, one had to first sweep $\nu_{ij}$ through it, since the beam was accelerated at $\nu_{ij} = 3.60$; then $f_{rf}$ was swept through the interfering rf/intrinsic resonance. Perhaps this contributed to an asymmetry.


D. W. Sivers et al., SPIN@COSY Internal Report, 2007.