Resistively detected NMR of the $\nu=1$ quantum Hall state: A tilted magnetic field study

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Previous resistively detected NMR (RDNMR) studies on the $\nu\approx1$ quantum Hall state have reported a "dispersionlike" line shape and extremely short nuclear-spin-lattice relaxation times, observations which have been attributed to the formation of a skyrme lattice. Here we examine the evolution of the RDNMR line shape and nuclear-spin relaxation for Zeeman:Coulomb energy ratios ranging from 0.012 to 0.036. According to theory, suppression of the skyrme crystal, along with the associated Goldstone mode nuclear-spin-relaxation mechanism, is expected at the upper end of this range. However, we find that the anomalous line shape persists at high Zeeman energy, and only a modest decrease in the RDNMR-detected nuclear-spin-relaxation rate is observed.

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The interplay between Zeeman and Coulomb interactions in a two-dimensional electron system (2DES) is a theme common to many recent studies of the quantum Hall (QH) effect. Filling factors close to $\nu=1$ have been of particular interest, where according to theory,[1] charged spin-texture excitations known as skyrmions can occur. The spin and size of skyrmions are governed by the ratio of the electron Zeeman and electron-electron Coulomb energies, $\eta=|g^*|\mu_B B/(e^2/\varepsilon l_c)$, where $l_c=\sqrt{\hbar c/eB_\perp}$. For $\eta>\eta_c$, theory predicts skyrmions to disappear, and it follows that noninteracting electron properties should emerge. Near $\nu=1$ of a 2DES in GaAs, Fertig *et al.* predicted $\eta_c=0.022$ (Ref. 1) while Cooper estimates $\eta_c=0.05$.[2] Although evidence for skyrmion formation near $\nu=1$ has been provided by NMR (Refs. 3–5) and other methods, only a few experiments demonstrating a clear evolution from the strongly coupled to weakly coupled many-body states have been reported.[6–10]

The advent of resistively detected NMR (RDNMR) in QH systems, in which nuclear-spin transitions are registered directly in the longitudinal resistance, R_{xx}, offers a completely new way to probe the electron-spin degrees of freedom of the 2DES. RDNMR has the requisite sensitivity to detect the relatively small number of GaAs quantum-well nuclei with a hyperfine coupling to the 2DES, and it is well suited for probing the QH states at thermal equilibrium in a dilution refrigerator environment. RDNMR has been applied previously in the vicinity of $\nu=1,2/3,1/2,1/3$, and other fractions.[11–19] Most of the RDNMR experiments at $\nu=1$ focused on probing the 2DES in the $\eta<\eta_c$ regime where skyrmion formation should be favorable. RDNMR spectra acquired on the flanks of $\nu=1$ in fields of 5.5–10.0 T consistently exhibit a so-called "dispersionlike" line shape.[12,14,15,17–19] However, despite intensive study, the origin of this line shape is still unclear. In Ref. 15, it was reported that the RDNMR signal amplitude, $\Delta R_{xx}^{\mathrm{NMR}}$, was reduced by a factor of 5 when the field was increased from 5.5 to 14.1 T at filling factor $\nu=1.2$, and that the line transitioned to a more absorptionlike shape. This led to the suggestion that the dispersionlike shape is a hallmark of skyrmion formation.[15] This assertion was scrutinized in Ref. 18 which compared the RDNMR line shapes recorded near $\nu=1$, 2/3, and 1/3. At $\nu=1/3$, skyrmions of composite fermions are predicted only in the limit of very low Zeeman energy due to the relatively low-spin stiffness at this filling factor. In Ref. 18, the RDNMR line shape collected at $\nu=0.355$ in the $\eta\gg\eta_c$ regime was characterized as dispersionlike, which would seem to rule out its correlation to skyrmions. In our opinion, that result is inconclusive (see Fig. 9e of Ref. 18). The spectrum consists of a minute negative dip flanked by much larger peaks of positive resistance change. At $\nu=0.69$, where the ground state is unpolarized and cannot support skyrmions, the RDNMR spectrum does clearly exhibit the distinct dispersionlike line shape. Yet, this result still does not rule out the possibility that at different filling factors, different mechanisms produce similar dispersionlike line shapes. For instance, the polarized-unpolarized phase transition near $\nu=2/3$ is associated with a mechanism for dynamic nuclear polarization. A more stringent test, as is applied in the current work, is to compare the line shapes and spin-relaxation times at values of η above and well below η_c at precisely the same filling factor (near $\nu=1$).

Recent RDNMR studies have invoked a mechanism involving the low-frequency Goldstone mode of the skyrme crystal to explain the efficient nuclear-spin-lattice relaxation observed around $\nu=1$,[16] consistent with the data of Smet *et al.*[10] Interestingly, the ^{75}As spin-relaxation temperature dependences measured by RDNMR by different groups in samples with similar density and electron mobility are inconsistent. In Ref. 16, T_1 (the longitudinal nuclear-spin-relaxation time) increases monotonically with T, with $T_1>30$ s under all conditions. In contrast, Ref. 19 reports a Korringa-law dependence with $T_1T=0.28$ K s down to about 40 mK, where $T_1=7$ s. In Ref. 17, different temperature dependences were found on the dip and peak of the dispersionlike RDNMR line shape.

In this report, the η dependence of the dispersionlike line shape at constant filling factor near $\nu=1$, spanning the transition from the skyrmion to single-electron excitation regimes, is presented under conditions of high signal to noise. The data provide compelling evidence that there is no correlation between this anomalous dispersionlike line shape and skyrmion formation near $\nu=1$. Furthermore, we present the RDNMR-detected nuclear-spin-relaxation measurements in the $\eta > \eta_c$ regime, where a quenching of the Goldstone mode mediated relaxation channel is to be expected.

RDNMR experiments were performed at fields in the $5.1 \rightarrow 16$ T range, focusing on filling factors in the $\nu=0.84 \rightarrow 0.90$ range, where both dR_{xx}/dB and $\Delta R_{xx}^{\mathrm{NMR}}/R_{xx}$ are maximal. Variation in η (at constant ν) was achieved by the well-established tilted field method,[20] whereby the sample is rotated by an angle θ (see Fig. 2(c), inset) while simultaneously increasing B such that $B_{\perp}=B\cos\theta$ remains constant. Thus, l_c remains constant while $g^{*}\mu_B B$ is increased. In GaAs, $\eta(B,\theta)=0.0055\sqrt{B\sec\theta}$ (assuming $|g^{*}|=0.41$).[9,21] RDNMR experiments were performed at a series of angles between $\theta=0°$ and 68°, corresponding to $\eta=0.013 \rightarrow 0.036$. Theory predicts that for $\eta > 0.022$, there is only a single-spin flip per excitation,[1] i.e., skyrmions desist. If the T_1 and line shape observed by RDNMR are in fact significantly affected by the coupling to the skyrmionic states of the 2DES, then these observables should change significantly over this range of η.

The specific sample studied here is a single 30-nm-wide GaAs quantum well with $Al_{0.3}Ga_{0.7}As$ barriers, grown at Sandia National Laboratory. Electrons were introduced by silicon δ doping, yielding a 2DES density and mobility of $1.3\times10^{11}/\mathrm{cm}^2$ and $\sim1\times10^{6}$ $\mathrm{cm}^2/\mathrm{V\,s}$, respectively. The sampled was patterned into the form of a standard Hall bar with a channel width of 200 μm and a probe separation of 1.4 mm. The density varied slightly from one cool down to the next. The RDNMR data was found to be consistently the same and reproducible in this sample, aside from slight variations in the electron density, over the course of three separate cool downs from ambient temperature. The sample was mounted onto a standard eight-pin header with GE varnish, and the header was inserted into the 16-pin socket of the rotation stage. Measurements were performed in an Oxford Instruments top loading dilution refrigerator/superconducting magnet (NHMFL SCM-1) in which the sample is immersed in liquid ^{3}He. The reported bath temperatures correspond to the temperature of the mixing chamber, although as is discussed below, the data indicate that the electron temperature was generally higher than the bath temperature, depending on the radio frequency (rf) power and injection current. The four-turn rf solenoid coil (not impedance matched or tuned) was wound around the entire rotation stage so that the rf field would be parallel to the sample rotation axis (i.e., y axis). RDNMR signals were acquired using a Signal Recovery model 7265 lock-in amplifier. The longitudinal magnetoresistance traces, R_{xx}(B), recorded at two different tilt angles, $\theta=0°$ and $\theta=68°$, are presented in Fig. 1. Comparison of the data obtained with excitation currents of 10 and 100 nA shows that some Joule heating occurs in the sample at the higher current. Therefore, the temperature of the electron system is certainly higher than the bath temperature of $\sim$20 mK. RDNMR spectra were acquired at

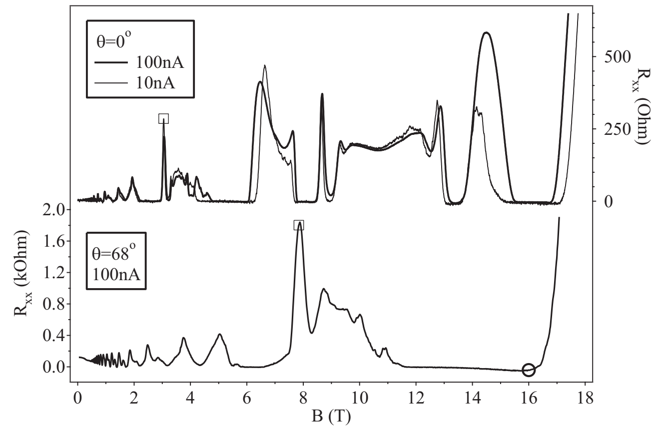

FIG. 1. Longitudinal magnetoresistance traces acquired at $\theta=0°$ (top), where $\nu=1$ occurs at 5.25 T and in the tilted field with $\theta=68°$, where $\nu=1$ occurs at 13.9 T. In the $\theta=0°$ orientation, R_{xx} was measured using two different excitation currents: 10 and 100 nA. The bath temperature was maintained at or below $\sim$20 mK. The circle on the lower trace indicates the location at which the spectrum in Fig. 2(c) was recorded.

fixed B by sweeping the frequency of the PTS™ rf synthesizer. The 1 dBm output of the synthesizer was typically attenuated by >35 dB. The frequency jump technique of Gervais[16] was employed in the NMR saturation-recovery spin-lattice relaxation experiments.

Figure 2(a) presents the RDNMR spectra recorded at a series of bath temperatures ranging from 31 to 173 mK at 5.1 T ($\eta=0.012$, $\nu=0.91$, and $\theta=0°$). For this temperature range, the thermal equilibrium ^{75}As nuclear-spin polarization varies from 5.4% to 0.96%. Spectra recorded at lower bath temperatures were essentially the same as the spectrum at 31 mK, indicating that the base temperature of the electron system is not lower than 31 mK. The spectra at both low and high η fit nicely to a superposition of low-frequency (LF) and high-frequency (HF) Gaussian functions, with $\Delta R_{xx}^{\mathrm{NMR}}(\mathrm{LF})<0$ and $\Delta R_{xx}^{\mathrm{NMR}}(\mathrm{HF})>0$. The LF-HF frequency splitting increased according to $\Delta f_{\mathrm{HF\text{-}LF}}=7.9$ kHz$+0.9B$ over the $B=5.1-16$ T range. As is evident in Fig. 2(a), the splitting is temperature independent up to 173 mK.

The ^{75}As RDNMR spectrum acquired at the filling factor $\nu=1.125$ is shown in Fig. 2(b). Clearly, the dispersionlike line shape is not observed in the range where antiskyrmions (quasihole excitations) should prevail. Furthermore, much longer nuclear-spin-relaxation decay times were observed on the high-frequency side of the RDNMR line at this filling factor, as evidenced by a strong rf sweep-rate dependence of the line shape.

Representative saturation-recovery traces following switching of the rf frequency away from resonance are shown in Fig. 2(a). The decay is clearly biexponential. The fast decay is attributed to electron-nuclear hyperfine relaxation between quantum-well nuclei and the 2DES while the slower decay is attributed to a process involving nuclear-spin diffusion to the much more slowly relaxing nuclei in the barrier regions.[19] It should be noted that the extraction of nuclear-spin-relaxation times directly from the decay of the

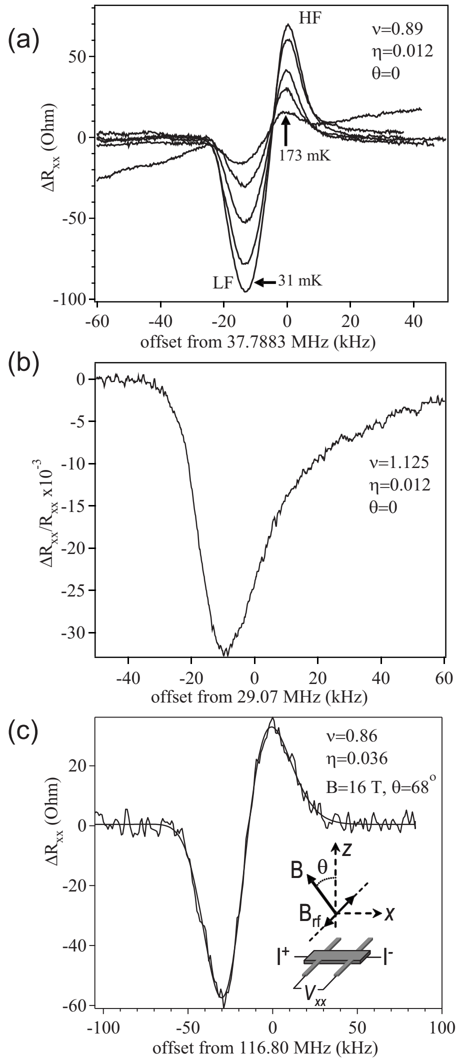

FIG. 2. (a) ^{75}As RDNMR spectra acquired at bath temperatures of 31, 58, 85, 116, and 173 mK at 5.185 T and 100 nA ($\theta=0°$, $\nu=0.89$, and $\eta=0.012$). Off-resonance resistances at these temperatures were 200, 250, 545, 1250, and 2870 Ω, respectively. (b) ^{75}As RDNMR spectrum acquired at 4.0 T ($\theta=0°$ and $\nu=1.125$), showing a single peak with negative resistance change. The spectrum was recorded at a sweep rate of 166 Hz/s. (c) RDNMR spectrum of ^{75}As at 16 T ($\nu=0.86$, $\theta=68°$, and $\eta=0.036$). The solid curve represents the fit to a superposition of Gaussian line-shape functions.

resistance assumes that the resistance depends linearly on the nuclear-spin polarization. In the thermal activation mechanism of RDNMR, a resistance response occurs when NMR perturbs the local nuclear hyperfine field contribution to the activation energy, ΔB_n.[22,23] A linear relationship between ΔR_{xx} and ΔB_n is obtained provided that $\Delta B_n \ll k_B T$. However, the resistance at the flanks of $\nu=1$ usually has a nonlinear dependence on the Zeeman energy. Nevertheless, for small changes, a linear relationship will be recovered, and exponential nuclear-spin relaxation will produce an exponential resistance time dependence. Indeed, the $\ln \Delta R_{xx}$ versus t plots presented in Fig. 3 exhibit excellent fits to a line for $t \lesssim 5$ s.

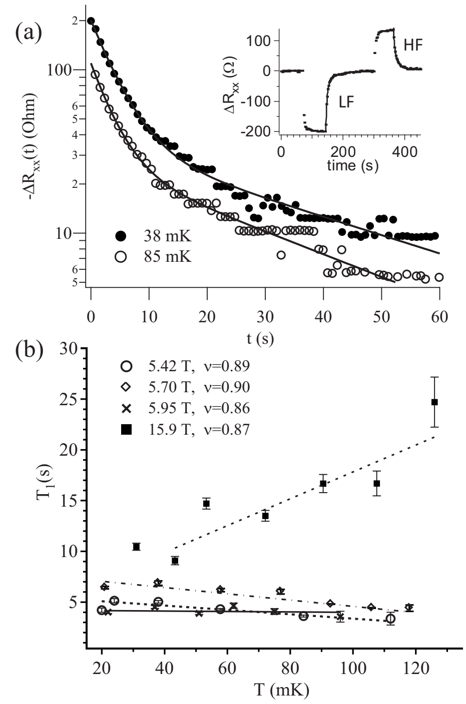

FIG. 3. (a) Representative saturation-recovery traces at 5.42 T at 38 and 85 mK. Inset: raw $R_{xx}(t)$ traces obtained on the LF and HF components. (b) Temperature dependences of the ^{75}As T_1 at the magnetic fields and filling factors indicated. The 5.42 T data were collected at slightly lower density during a separate cool down.

Figure 2(b) presents the temperature dependence of the ^{75}As T_1 (the fast relaxation component) in the perpendicular and tilted magnetic fields. At $\eta \approx 0.012$, T_1 was only weakly temperature dependent, and the T_1 times are comparable to those reported in Ref. 19. Consistent with Ref. 19, T_1 *decreases* with temperature, though the temperature dependence deviates substantially from the Korringa Law ($T_1 T$ =constant). At 15.9 T ($\eta=0.036$), T_1 *increases* slightly with temperature. At the base temperature, T_1 is only a factor of 2–3 longer than the relaxation time at $\eta=0.012$.

In summary, we have presented the RDNMR spectra and RDNMR-measured nuclear-spin-relaxation times at filling factors near $\nu=1$ over an unprecedented range of Zeeman-:Coulomb energy ratios, spanning the transition from skyrmion to single-spin flips. The anomalous dispersionlike RDNMR line shape, which was attributed to skyrmion formation in earlier literature reports, prevails at Zeeman energies that should effectively suppress skyrmion formation. This shows decisively that there is no correlation between this line shape and skyrmion formation. Furthermore, the nuclear-spin-relaxation time, as measured by RDNMR, was found to be on the order of a few seconds at relatively low Zeeman energies, well within the skyrmion regime. Such highly efficient spin relaxation is consistent with a mechanism involving the Goldstone mode of the skyrme crystal. This mechanism should be completely quenched at high Zeeman energies, resulting in an increase in the relaxation time by several orders of magnitude.[24] To the contrary, we found that the spin-relaxation time depends only weakly on magnetic field. It changed by only a factor of ~2 upon increasing the field from 5.1 to 16 T. These results suggest that other relaxation mechanisms, not involving the Goldstone mode, are important. A modest decrease in relaxation rate with magnetic field can be explained simply as a reduction in the spectral density of fluctuations in the hyperfine interaction at the electron-nuclear Larmor frequency difference, as observed in bulk GaAs.[25] In conclusion, the evolution of the spin-relaxation time with magnetic field, as detected by RDNMR, was found to be insensitive to the transition from skyrmion to single-spin-flip excitations. Clearly, an understanding of the active T_1 processes in the context of RNDMR measurements is far from complete.

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