Optically Pumped NMR Evidence for Finite-Size Skyrmions in GaAs Quantum Wells near Landau Level Filling $\nu = 1$

S. E. Barrett,* G. Dabbagh, L. N. Pfeiffer, K. W. West, and R. Tycko[†]
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 19 December 1994)

The Knight shift $[K_s(\nu,T)]$ and spin-lattice relaxation time $[T_1(\nu,T)]$ of the ^{71}Ga nuclei located in n-doped GaAs quantum wells are measured using optically pumped NMR, for Landau level filling $0.66 < \nu < 1.76$ and temperature $1.55 < T < 20$ K. $K_s(\nu)$ [proportional to the electron spin polarization $\langle S_z(\nu)\rangle$] drops precipitously on either side of $\nu = 1$, which is evidence that the charged excitations of the $\nu = 1$ ground state are finite-size Skyrmions. For $\nu < 1$, the data are consistent with a many-body ground state which is not fully spin polarized, with a very small spin excitation gap that increases as $\nu \rightarrow \frac{2}{3}$.

PACS numbers: 73.20.Dx, 73.20.Mf, 73.40.Hm, 76.60.–k

Electron-electron Coulomb interactions significantly affect the physics of two-dimensional electron systems (2DES) in strong magnetic fields, producing a wide variety of unexpected phenomena. The most spectacular consequence of these correlations is the fractional quantum Hall effect (FQHE) [1]. One vestige of the independent electron picture in the standard model of the FQHE [2] is the assumption of a spin-polarized ground state for the Landau level filling factor $\nu < 1$ ($\nu \equiv n/n_B$, where n is the number of electrons per unit area, and $n_B = eB/hc \equiv 1/2\pi l_c^2$ is the number of states per unit area in each Landau level) [3,4]. However, even in a strong field (e.g., $B = 10$ T), the Zeeman splitting ($E_z = g^*\mu B = 0.3$ meV, with $g^* = -0.44$) [5] for electrons in GaAs is typically much less than both the Coulomb energy ($E_C = e^2/\kappa l_c = 13.7$ meV, with $\kappa = 13$) and the cyclotron energy ($\hbar\omega_c = \hbar eB/m^*c = 16.8$ meV, with $m^* = 0.07 m_e$), as first pointed out by Halperin [6]. Numerical calculations [3,4] and transport measurements [7–9] have provided mounting evidence that correlations can lead to spin reversal in particular low-lying many-body states.

In this Letter, we present optically pumped nuclear magnetic resonance (OPNMR) [10] measurements of the Knight shift K_s and spin-lattice relaxation time T_1 of ^{71}Ga nuclei in an electron-doped multiple quantum well (MQW) structure. The K_s data are the first direct measurement of the electron spin polarization $\langle S_z(\nu,T)\rangle$ of a 2DES as a function of ν and temperature. These measurements provide the first experimental support for the recent predictions that the ground state at $\nu = 1 \pm \varepsilon$ contains finite-size Skyrmions (or charged spin-texture excitations) [11,12], with an effective spin which reflects the competition between the Coulomb energy and the Zeeman energy.

The MQW sample contains forty 300 Å wide GaAs wells separated by 1800 Å $Al_{0.1}Ga_{0.9}As$ barriers, grown by molecular beam epitaxy on a semi-insulating GaAs(001) substrate. Electrons (which arise from Si delta-doping spikes located in the center of the barriers) are confined in the wells at low temperatures. Characterization of this wafer by low-field transport measurements at 4.2 K yielded the carrier density $n = (1.41 \pm 0.14) \times 10^{11}$ cm^{-2} in each well, with mobility $\mu = 1.44 \times 10^6$ cm^2/V s. Using home-built NMR probes, the growth axis of the MQW sample was tilted by an angle θ ($0° < \theta < 60°$, $\pm 0.5°$) away from the constant field B, thereby varying the filling factor $[\nu = nhc/eB\cos(\theta)]$ *in situ.* Low sample temperatures ($1.5 < T < 20$ K) were obtained using liquid ^{4}He in a bucket dewar and a cold finger dewar.

The OPNMR measurements described below utilized the timing sequence SAT-τ_L-τ_D-DET, where SAT represents an rf pulse train that saturates (destroys) the nuclear polarization, τ_L is a period of illumination by the laser (σ^+ light, $\lambda = 806$ nm, 10–300 mW/cm^2), τ_D is a period of no illumination ($\tau_D \geq 1$ sec), and DET represents the direct detection of the NMR free induction decay (FID) signals following a single $\pi/2$ pulse [10]. During τ_L, optical pumping of interband transitions generates electrons and holes in the GaAs wells with nonequilibrium spin polarizations, which then polarize the nuclei in the well through the contact hyperfine coupling. The electronic system quickly equilibrates at the beginning of τ_D, but the enhanced nuclear polarization persists until the DET period, since $T_1 \gg 1$ sec.

Figure 1 shows the ^{71}Ga NMR spectra acquired as a function of τ_L ($\tau_D = 1$ sec) in a 7.05 T field at $T = 1.55$ K with $\theta = 0°$. The broad, asymmetric resonance observed for $\tau_L = 5$ sec is due to the ^{71}Ga nuclei in the GaAs wells, where the nonequilibrium nuclear spin polarization is photogenerated. As τ_L is increased, polarization diffuses into the barriers via the nuclear spin-spin coupling [10]. The narrow, symmetric resonance which dominates the spectrum for $\tau_L = 480$ sec is due to the ^{71}Ga nuclei in the $Al_{0.1}Ga_{0.9}As$ barriers. The electrons confined in the wells produce an extra hyperfine field which shifts the well resonance below the barrier resonance, as expected for the Fermi contact interaction

0031-9007/95/74(25)/5112(4)$06.00

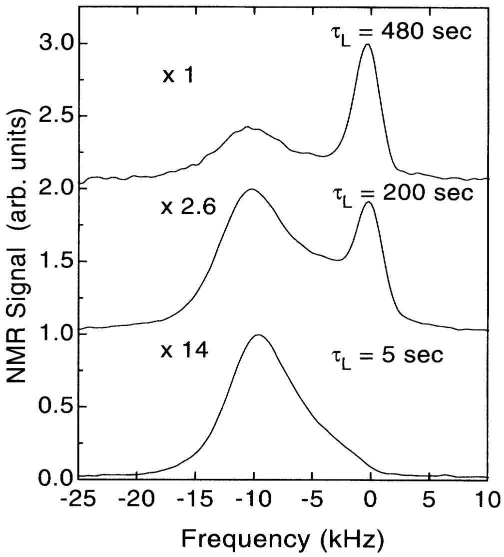

FIG. 1. ^{71}Ga NMR spectra of the GaAs/AlGaAs MQW acquired in the dark ($\tau_D = 1$ sec) for various optical pumping times τ_L, with $B = 7.05$ T, $\theta = 0°$, and $T = 1.55$ K. For ease of comparison, the signals are scaled by the indicated factors, and are offset for clarity.

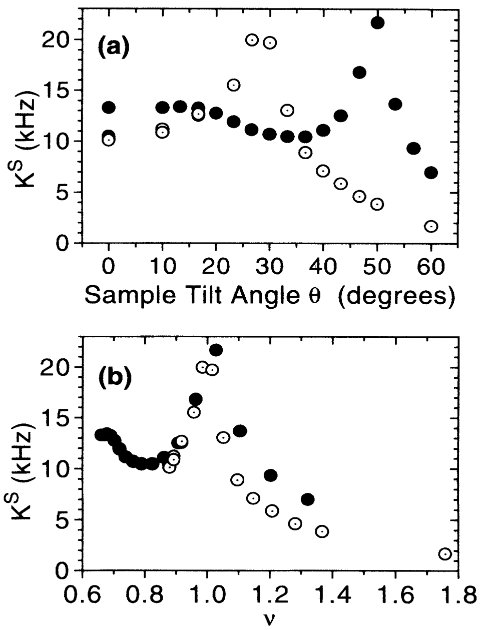

FIG. 2. (a) Dependence of ^{71}Ga Knight shift K_s on the sample's tilt angle θ for $B = 7.05$ (open circles) and 9.39 T (filled circles) at 1.55 K. (b) Dependence of K_s on filling factor ν for $B = 7.05$ (open circles) and 9.39 T (filled circles) at 1.55 K. There conversion from θ to ν used $n = 1.50 \times 10^{11}$ cm^{-2}.

with $g^* < 0$ [13]. The variation of the lowest subband electron wave function along the growth direction leads to the asymmetry of the well resonance [14]. We define the Knight shift to be the peak-to-peak frequency splitting between the well and barrier resonance lines. The Knight shift is $K_s(\nu, T) = A_{zz}\langle S_z(\nu, T)\rangle$ for $\mathbf{B}\|\mathbf{z}$, where A_{zz} is the hyperfine coupling constant for nuclei in the center of the well, and the hyperfine Hamiltonian is $\hat{H} = \sum_{(\alpha,\alpha'=x,y,z)} hA_{\alpha\alpha'}I_\alpha S_{\alpha'}$ [15].

Figure 2(a) shows the dependence of the ^{71}Ga Knight shift K_s on the tilt angle θ for $B = 7.05$ and 9.39 T, at $T = 1.55$ K. Assuming that the maximum K_s observed at $\theta = 28.5°$ for $B = 7.05$ T corresponds to $\nu = 1$, we infer an electron density $n = 1.50 \times 10^{11}$ cm^{-2}. This density is used to convert the sample tilt angle θ to the Landau level filling factor ν. Figure 2(b) is a plot of K_s vs ν for $B = 7.05$ and 9.39 T. The striking similarity between the two data sets in Fig. 2(b) demonstrates the isotropy of the hyperfine coupling constant (i.e., $A_{\alpha\alpha} = A$), which implies that the Knight shift directly reflects the electron spin polarization, i.e., $K_s(\nu(\theta)) = A\langle S_z(\nu(\theta))\rangle$. The small discrepancies between the two data sets may be due to the effects discussed below.

In Fig. 3, two fits to the $K_s(\nu)$ data for $B = 7.05$ T at $T = 1.55$ K are shown. The functional form of these fits is obtained by "generalizing" the $T \approx 0$ independent electron model for the spin polarization, which parametrizes the effect of interactions near $\nu = 1$. In this picture, the lowest spin-split Landau level is completely filled at $\nu = 1$, so the electrons are completely polarized. Reducing the magnetic field so that $\nu = 1 + \varepsilon$ removes a single state from each Landau level, forcing S electrons into the upper spin-split Landau level, and hence reducing the electron polarization. Alternatively, increasing the field so that $\nu = 1 - \varepsilon$ adds a single empty state to each Landau level, forcing $\mathcal{A}$ holes into the lower spin-split Landau level, which also reduces the polarization if $\mathcal{A} > 1$. If there is electron-hole symmetry, then $\mathcal{A} = S$. This

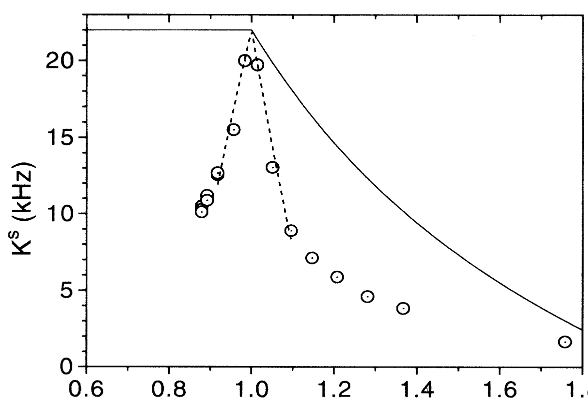

FIG. 3. Dependence of K_s on filling factor ν for $B = 7.05$ T (open circles) at 1.55 K. As explained in the text, both fits are given by Eq. (1), but the solid line has $\mathcal{A} = S = 1$ (noninteracting electrons), while the dashed line has $\mathcal{A} = S = 3.6$ (finite-size Skyrmions).

simple model leads to the prediction

$$K_s(\nu) = \frac{A}{2}\left(\Theta(1-\nu)\left[\frac{2}{\nu}(1-\mathcal{A}) - (1-2\mathcal{A})\right] + \Theta(\nu-1)\left[\frac{2S}{\nu} + (1-2S)\right]\right), \quad (1)$$

where $\Theta(x) = 1$ for $x > 0$, and $\Theta(x) = 0$ for $x < 0$. Equation (1) is valid near $\nu = 1$, where $\mathcal{A}$ and S are independent of ν. Earlier estimates for the hyperfine coupling imply $A \sim 27$ kHz for three-dimensional electrons [13], or $A \sim 54$ kHz for nuclei in the center of the 300 Å GaAs well. $A = 44$ kHz is used for the fits in Fig. 3, a value consistent with the largest shift measured in either field at $T = 1.55$ K.

The solid line in Fig. 3, which assumes $\mathcal{A} = S = 1$ (i.e., noninteracting electrons), fails to fit the data. The dashed line is an excellent fit to the data for $0.9 < \nu < 1.1$, with $\mathcal{A} = S = 3.6 \pm 0.3$. Apparently, the charged excitations of the $\nu = 1$ ground state have an effective spin of $(3.6 \pm 0.3)/2$.

These results are in good agreement with the recent predictions that the lowest energy charged excitations of the $\nu = 1$ ground state are charged spin-texture excitations (CSTE's or finite-size Skyrmions) with an effective spin of ~ 3.5 for $E_Z/E_C \sim 0.02$ [11,12]. Qualitatively, at $\nu = 1 + \varepsilon$, the CSTE is cylindrically symmetric with the boundary conditions of a down spin at $r = 0$ and an up spin at $r = D$, with a particular radial transition between those two states that maximizes the alignment of nearest neighbor spins, leaving up spins for $D < r < \infty$. The length scale D is set by the competition between the Coulomb and Zeeman energy, which increase and decrease D, respectively. The effective spin is $> \frac{1}{2}$, since all electrons within $0 < r < D$ are distorted. For brevity, we will refer to a charged spin-texture excitation as a Skyrmion [16]. By analogy, the $\nu = 1 - \varepsilon$ ground state is an anti-Skyrmion, and Skyrmion–anti-Skyrmion pairs are neutral excitations of the $\nu = 1$ ground state. Similar charged spin-texture excitations may occur around other filling factors with incompressible many-body ground states (e.g., $\nu = \frac{1}{3}$) [11,17].

The temperature dependence of the Knight shift probes low-lying excited states, since $K_s(T) \propto \langle S_z(T)\rangle$, and

$$\langle S_z(T)\rangle \equiv \frac{1}{Z}\langle 0|S_z|0\rangle + \sum \frac{1}{Z} e^{-\Delta_i/kT}\langle i|S_z|i\rangle,$$

where $|0\rangle$ is the many-body ground state, Z is the partition function, and the summation is over all excited states $|i\rangle$ with energy Δ_i. Figure 4 (main figure) shows the dependence of K_s on the temperature for $\nu = 0.98$ in the 7.05 T field. The shift saturates at ~ 20 kHz for T below ~ 2 K, which validates our comparison in Fig. 3 of the $T = 1.55$ K shift data near $\nu = 1$ with the $T \approx 0$ Skyrmion model.

A simple model for $\langle S_z(T)\rangle$ at $\nu = 1$ assumes noninteracting electrons which obey Fermi-Dirac statistics, with the chemical potential in the middle of the Zeeman gap. This leads to the dashed line in Fig. 4 [$K_s(T) = K(0)\tanh(E_z/4kT)$, with $K(0) = 20$ kHz and $E_z/k = 2.08$ K], which clearly does not fit the data. Treating E_z as an adjustable parameter in order to fit the saturated region implies an "exchange enhancement" of the Zeeman splitting by a factor of ~ 10, a result consistent with other measurements [18]. A more realistic model for $\langle S_z(T)\rangle$ at $\nu = 1$ includes interactions, so that spin-wave modes (corresponding to reversed spins) are the low-lying excited states, with the Bose-Eistein distribution function determining the occupancy of each mode [19]. The dash-double-dotted line shown in Fig. 4 is a calculation [17] of $K_s(T)$ using the $T \approx 0$ two-dimensional spin-wave dispersion spectrum [20], and it is obvious that this model does not fit the data either. For T above ~ 2 K, $K_s(T)$ drops off more rapidly than the spin-wave fit, which qualitatively suggests a collapse

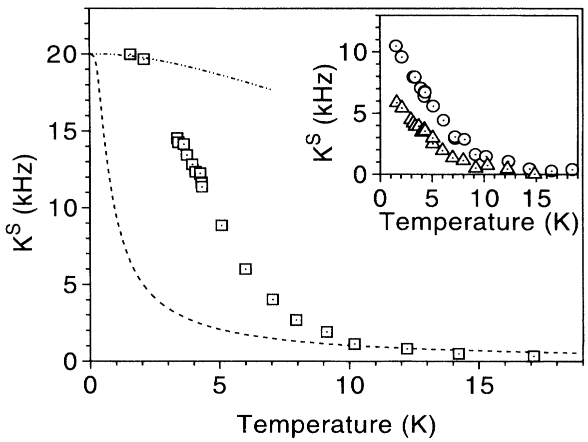

FIG. 4. Dependence of K_s on temperature, for $\nu = 0.98$ and $B = 7.05$ T (open squares). As explained in the text, the dashed line is a calculation of $K_s(T)$ assuming noninteracting electrons, and the dash-double-dotted line is a calculation of $K_s(T)$ assuming that the low-lying excitations are spin waves. Inset: Dependence of K_s on temperature, for $\nu = 0.88$ (open circles) and $\nu = 1.2$ (open triangles), at $B = 7.05$ T.

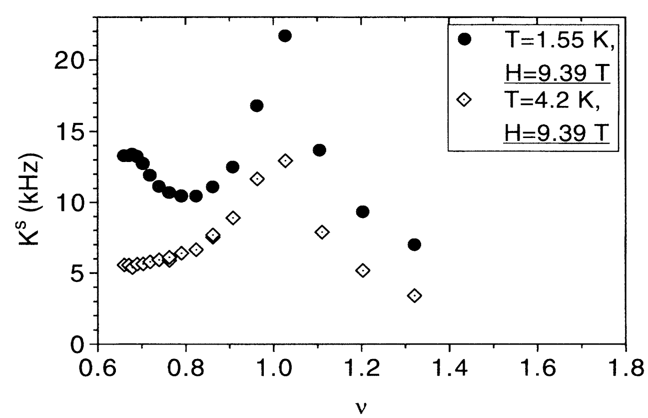

FIG. 5. Dependence of K_s on filling factor ν for $B = 9.39$ T, at $T = 4.2$ (open diamonds) and 1.55 K (filled circles).

TABLE I. ^{71}Ga nuclear spin-lattice relaxation time T_1 as a function of temperature and Landau level filling factor ν.

	$\nu = 1.01$	$\nu = 0.88$	$\nu = 0.66$
$T_1(T = 4.2\ \text{K})$ (sec)	122	24	43
$T_1(T = 2.1\ \text{K})$ (sec)	1280	20	68

of the exchange energy as the polarization is reduced. Apparently, even at $\nu = 1$, existing models for $\langle S_z(T)\rangle$ are inadequate. $K_s(T)$ may also be measured at arbitrary ν using OPNMR. The inset of Fig. 4 shows the data for $\nu = 0.88$ and $\nu = 1.2$, which do not saturate by $T \sim 2$ K, demonstrating the dependence of the many-body states and energy spectrum on the filling factor.

Clear signatures of the fractional quantum Hall regime [3,4,7] are also evident in the OPNMR data. Figure 5 shows $K_s(\nu)$ at $T = 4.2$ and 1.55 K, for $B = 9.39$ T. At $T = 1.55$ K, a local maximum appears in $K_s(\nu)$ near $\nu = \frac{2}{3}$, one of the fundamental FQHE states. The fact that $K_s(1.55\ \text{K}, \nu = \frac{2}{3}) \ll K_s(1.55\ \text{K}, \nu = 1)$ suggests that the $\nu = \frac{2}{3}$ FQHE ground state may not be fully polarized [3,7] for $B = 9.39$ T, but these measurements need to be repeated at lower temperatures to ensure that $\langle S_z(T, \nu = \frac{2}{3})\rangle \cong \langle S_z(0, \nu = \frac{2}{3})\rangle$. Qualitatively, the temperature dependence of $K_s(\nu)$ suggests that the energy gap to spin-flip excitations is large, medium, and small for $\nu = 1$, $\frac{2}{3}$, and $\sim$0.9, respectively. This assignment is consistent with our measurements of the ^{71}Ga nuclear spin-lattice relaxation time T_1, which probes electron spin dynamics [21,22], since the temperature dependence of T_1 is a strong function of ν, as is seen in Table I. Although the long T_1 at $\nu = 1$ is consistent with either interacting or independent electrons, the short T_1 at $\nu = 0.88$ can only be explained if interactions induce nearly gapless low-lying spin-flip excitations. Further details of these T_1 measurements will appear in a subsequent publication [14].

We have shown that OPNMR is a powerful local probe of 2DES. Many interesting features of the above results remain to be understood theoretically. In future work, we will extend these measurements to other filling factors, lower temperatures, and higher fields.

We thank J. P. Eisenstein, N. Read, and A. H. MacDonald for helpful discussions, and B. I. Greene and T. D. Harris for experimental assistance.

*Present address: Department of Physics, Yale University, P.O. Box 208120, New Haven, CT 06520-8120.

†Present address: National Institutes of Health, Bldg. 5, Rm. 112, Bethesda, MD 20892.

[1] D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[2] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).
[3] T. Chakraborty and P. Pietiläinen, *The Fractional Quantum Hall Effect* (Springer-Verlag, Berlin, 1988).
[4] *The Quantum Hall Effect*, edited by R. E. Prange and S. M. Girvin (Springer, New York, 1990).
[5] C. Weisbuch and C. Hermann, Phys. Rev. B **15**, 816 (1977).
[6] B. I. Halperin, Helv. Phys. Acta **56**, 75 (1983).
[7] J. P. Eisenstein and H. L. Störmer, Science **248**, 1510 (1990).
[8] R. L. Willett *et al.*, Phys. Rev. Lett. **59**, 1776 (1987).
[9] R. G. Clark *et al.*, Phys. Rev. Lett. **62**, 1536 (1989); J. P. Eisenstein *et al.*, *ibid.* **62**, 1540 (1989); J. E. Furneaux, D. A. Syphers, and A. G. Swanson, *ibid.* **63**, 1098 (1989).
[10] S. E. Barrett, R. Tycko, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **72**, 1368 (1994).
[11] S. L. Sondhi, A. Karlhede, S. A. Kivelson, and E. H. Rezayi, Phys. Rev. B **47**, 16 419 (1993).
[12] H. A. Fertig, L. Brey, R. Côté, and A. H. MacDonald, Phys. Rev. B **50**, 11 018 (1994).
[13] D. Paget, G. Lampel, B. Sapoval, and V. I. Safarov, Phys. Rev. B **15**, 5780 (1977).
[14] R. Tycko, S. E. Barrett, G. Dabbagh, L. N. Pfeiffer, and K. W. West, Science **268**, 1460 (1995).
[15] C. P. Slichter, *Principles of Magnetic Resonance* (Springer, New York, 1990), 3rd ed..
[16] R. Rajaraman, *Solitons and Instantons* (North-Holland, Amsterdam, 1989).
[17] A. H. MacDonald (private communication).
[18] A. Usher, R. J. Nicholas, J. J. Harris, and C. T. Foxon, Phys. Rev. B **41**, 1129 (1990).
[19] A. Narath, in *Hyperfine Interactions*, edited by A. J. Freeman and R. B. Frankel (Academic, New York, 1967), Chap. 7.
[20] Y. A. Bychkov, S. V. Iodanskii, and G. M. Eliashberg, JETP Lett. **33**, 143 (1981); C. Kallin and B. I. Halperin, Phys. Rev. B **30**, 5655 (1984).
[21] A. Berg, M. Dobers, R. R. Gerhardts, and K. v. Klitzing, Phys. Rev. Lett. **64**, 2563 (1990).
[22] I. D. Vagner and T. Maniv, Phys. Rev. Lett. **61**, 1400 (1988).