New Type of Electron Nuclear-Spin Interaction from Resistively Detected NMR in the Fractional Quantum Hall Effect Regime

S. Kronmüller, W. Dietsche, and K. v. Klitzing
Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany

G. Denninger
2. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany

W. Wegscheider and M. Bichler
Walter Schottky Institut, Technische Universität München, München, Germany
(Received 24 November 1998)

Two-dimensional electron gases in narrow GaAs quantum wells show huge longitudinal resistance (HLR) values at certain fractional filling factors. Applying an rf field with frequencies corresponding to the nuclear spin splittings of ^{69}Ga, ^{71}Ga, and ^{75}As leads to a substantial decrease of the HLR establishing a novel type of resistively detected NMR. These resonances are split into four sublines each. Neither the number of sublines nor the size of the splitting can be explained by established interaction mechanisms. [S0031-9007(99)09173-5]

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

Two-dimensional electron gases (2DEGs) with very high mobilities of the electrons can be formed in quantum wells and heterostructures based on the GaAs/Al$_x$Ga$_{1-x}$As system. If such a 2DEG is subjected to an intense perpendicular magnetic field at very low temperatures, it shows the integer [1] and the fractional [2] quantum Hall effects at integer and fractional filling factors of one or more Landau levels. The signature of both types of quantum Hall effects is the quantization of the Hall resistance and the vanishing of the longitudinal resistance. Recently, however, huge longitudinal resistance maxima (HLR) have been observed at fractional filling factors between $\frac{1}{2}$ and 1 [3]. The HLR is found only in samples which have a reduced well thickness (15 nm [4]) as compared to the conventional ones. As an example, Fig. 1 shows longitudinal resistance measurements on a sample similar to the one used in [3] for two different carrier densities (dotted and dashed lines) at a temperature of 0.35 K. Here, the magnetic field is swept at a rate of 0.7 T/min and the applied source drain current is 100 nA. The width of the sample is 80 μm and the voltage probes are 80 μm apart. For both carrier densities a very regular behavior is seen. At integer filling factors the resistance vanishes completely and at filling factor $\nu = \frac{2}{3}$ one finds a clear minimum. However, if the sweep rate of the magnetic field is drastically reduced to 0.002 T/min, a huge maximum in the longitudinal resistance (solid lines) is observed at $\nu = \frac{2}{3}$ for both carrier densities. The size of the HLR is maximal at a current density of approximately 0.6 mA/m. The HLR vanishes in tilted magnetic fields, indicating that the electron spin polarization plays an important role for the HLR. Similar maxima are also reported at other fractional filling factors [3], but in this paper we want to concentrate on the HLR at $\nu = \frac{2}{3}$ at 0.35 K.

The HLR develops with a time constant of about 15 min. These very long times are typical for relaxation effects of the nuclear spin system [5,6]. The only direct way to demonstrate an involvement of the nuclear spins in the HLR is a nuclear magnetic resonance (NMR) [7–10] experiment, because it allows direct modification of the nuclear polarization. In this Letter we report on experiments where radio frequency is irradiated on a sample in the HLR state and a drastic reduction of the resistance values is observed whenever the nuclei are in resonance. This is to our knowledge the clearest form

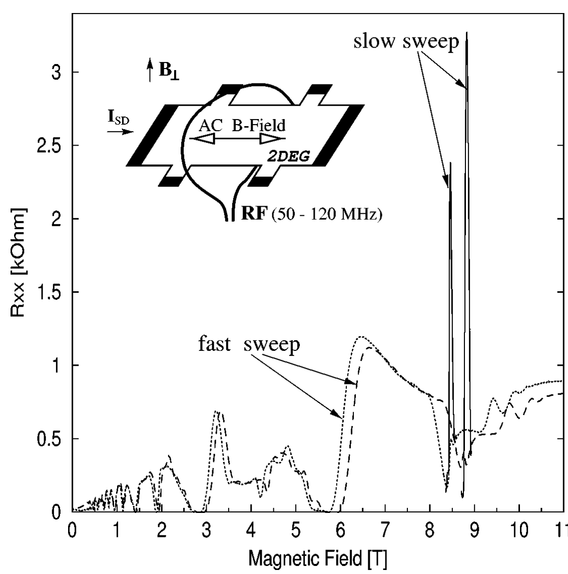

FIG. 1. Longitudinal resistance for two different carrier densities. The longitudinal resistance maximum (HLR) at filling factor 2/3 is clearly developed for the two carrier densities at the slow sweep rates (0.002 T/min) of the magnetic fields. The inset shows the experimental setup.

of a resistively detected NMR in a solid state system. Moreover we report that the NMR resonances are split into four sublines which can neither be explained by dipole-dipole interaction between neighboring nuclei nor by hyperfine interaction with the electrons. This indicates that the HLR is indeed a novel fractional state.

There have been only a few experiments where the interaction between electrons and nuclear spins in GaAs quantum wells has been probed. Effects of the nuclear polarization on the electron transport have been observed after a nonequilibrium electron spin distribution was first produced by ESR radiation [5,6] or by tunneling between different spin polarized Landau levels [11–13] which was then transferred into the nuclear system via the hyperfine interaction. Alternatively, it is possible to pump the nuclear polarization optically and observe the NMR either inductively [9] or optically [7,8,10,14]. The HLR seems to represent a completely different situation since the nuclear spin polarization occurs without special experimental preparation.

In our NMR experiment we measure the longitudinal resistance of a modulation doped 15 nm thick GaAs quantum well embedded in $Al_{0.3}Ga_{0.7}As$ barriers. The carrier density is about 1.3×10^{11} cm^{-2} and the mobility 1.8×10^6 $cm^2/V\,s$ after illumination with a light-emitting diode. The measurements are performed in a ^3He bath cryostat at 0.35 K using an ac lock-in technique with a modulation frequency of 23 Hz. To create a radio frequency (rf) magnetic field perpendicular to the static magnetic field we put a wire loop around our sample to which rf is applied (Fig. 1 inset). The loop is mounted so that its normal direction is perpendicular to the static magnetic field. We performed the NMR experiments on two different Hall bar samples which were 800 and 80 μm wide, using a source drain current of 400 and 50 nA, respectively. During the experiment the HLR maximum is allowed to develop at constant magnetic field until it reaches its peak value. Then the rf is applied and its frequency is swept over the range at which the nuclear resonances are expected while the resistance is monitored as a function of the rf frequency.

Results are shown in Fig. 2 where the longitudinal resistance is plotted as a function of the rf frequency for three different carrier densities. The applied rf amplitude is approximately 1 μT, which leads to the following transition rates: ^{69}Ga: 10 s^{-1}, ^{71}Ga: 12 s^{-1}, and ^{75}As: 7 s^{-1}. Minima are indeed found at frequencies corresponding to the nuclear resonance frequencies of ^{69}Ga [15]. The resonance frequencies shift because the HLR occurs at different magnetic fields for different densities. These traces are the first observation of NMR directly in the longitudinal resistance of a 2DEG.

Similar NMR resonances are also observed at the expected respective frequencies for the other ^{71}Ga isotope and for ^{75}As. At all resonances the HLR is approximately reduced by 5% to 10%. The amount of the decrease is

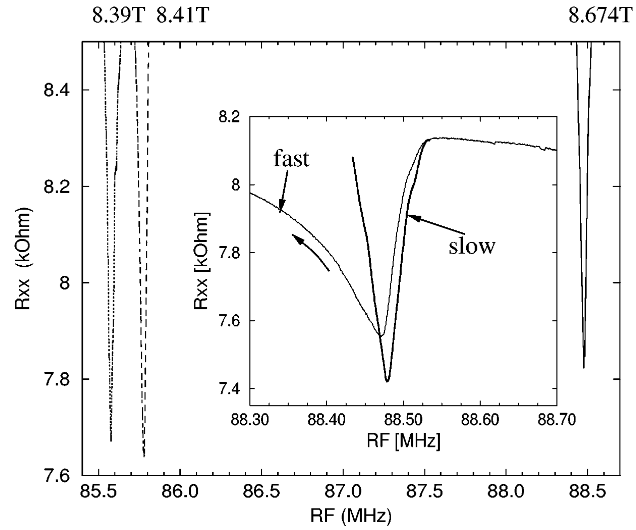

FIG. 2. The resistively detected NMR signal of ^{69}Ga. A current of 400 nA is passed through an 800 μm wide 2DEG sample and the HLR is at its peak value. A voltage drop of approximately 10% in the longitudinal voltage is observed when the rf is in resonance with the nuclei. The figure shows the resonance line for three different magnetic fields, which means three different carrier densities. The inset is the ^{69}Ga resonance for different sweep rates, 1 kHz/3 s and 1 kHz/60 s, of the rf frequency. The resonance is symmetric only if the frequency is swept slow enough.

slightly less at lower temperatures (100 mK) which indicates temperature dependent nuclear spin relaxation rates in this system. The HLR recovers fully after leaving the resonance region to the high or low frequency side. We take this as clear evidence that the HLR is connected with a polarization of the nuclei, because continuous irradiation of the nuclear system with a NMR resonance frequency saturates this transition leading to equal population of the respective spin levels. During this process the nuclear polarization is reduced. It is noteworthy that the NMR signals are most likely caused by a genuine reduction of the HLR maximum and not by a shift of the peak, because in measurements performed in the sides of the peak we find only reductions, but never increases of the resistance.

No resonance signal is observed for Al; therefore, one can conclude that the relevant nuclear spin polarization is indeed created in the quantum well only. The observed NMR minima cannot be due to resonant heating via the nuclei since the energy absorption is vanishingly small due to the long T_1 relaxation time. The line shape of the resonance depends on the sweep rate of the rf frequency (Fig. 2 inset). The slow sweep shows a very symmetric resonance so that one can assume the system is in equilibrium at all times, which is not the case for the fast sweeps. For the fast sweep rates a sharp drop of the HLR is observed when approaching the resonance. When leaving the resonance the HLR recovers on a time scale of several minutes, which is similar to the time scale needed for the HLR to develop in the first place.

Figure 3 shows the resistively detected NMR of the ^{75}As nuclei for two different carrier densities. Strikingly, one finds a clear fourfold splitting of the resonance. To clarify if a fine structure is contained in the Ga lines of Fig. 2 as well, we use a smaller sized sample to reduce the effect of the inhomogeneity of the magnetic field. Figure 4 shows the resonance lines of all three isotopes ^{75}As, ^{69}Ga, and ^{71}Ga for the 80 μm wide sample. With the smaller sample we indeed observe that the NMR resonances split into four sublines. The splitting is most pronounced for the As resonance lines. The separation between the respective four lines is nearly equidistant for all three isotopes and we find as average values of the splitting 30 kHz for ^{75}As, 14.5 kHz for ^{69}Ga, and 10 kHz for ^{71}Ga. For reduced rf powers the depths of the four resonance lines decrease monotonously but the exact power dependence could not yet be established.

The splitting into four sublines is very surprising. The three nuclei have a spin of $I = 3/2$ which corresponds to a fourfold degenerate nuclear spin ground state, which splits in a magnetic field by $E_Z = \gamma_n \hbar B_0 m_I$ [16], where γ_n is the gyromagnetic ratio, B_0 is the externally applied static magnetic field, and m_I is the z component of the nuclear spin. Three but not four different resonance frequencies would result if the electric quadrupole moment couples to an electric field gradient V_{zz}. Thus, the quadrupole moment cannot be responsible for the four resonance lines.

Another possibility to account for the splitting of nuclear resonance lines is direct dipolar coupling between two neighboring nuclear spins. The coupling to an isolated second spin $I = 3/2$ would indeed lead to a fourfold splitting. However, in a solid this leads only to a broadening because there are several different species of neighboring spins which have different distances from each other. Furthermore, the strength of the dipolar coupling is less than 1 kHz for the nuclear distances in GaAs, which is much too small. A similar argument applies to the effect of unknown impurities, which would be statistically distributed and therefore can lead to only a broadening of the NMR lines. Even though the dipolar interaction cannot account for the fourfold splitting of the lines, it is possibly responsible for the different line shapes one observes for the three nuclei. The ^{69}Ga and ^{71}Ga nuclei are surrounded by four identical ^{75}As nuclei having smaller γ values, while ^{75}As is surrounded by a mixture of ^{69}Ga and ^{71}Ga nuclei having larger ones. Therefore, it is conceivable that the line shapes of the As resonances are different from the Ga ones.

The nuclear moments can of course also interact with the electronic system. However, the standard treatment of the effect of quasimetallic electrons on NMR leads only to a shift, the so called Knight shift, but not to a splitting of the resonance lines.

Alternatively one could argue that the electrons possess an effective spin $S = 3/2$, which would lead to a fourfold split nuclear resonance via the hyperfine interaction. The hyperfine interaction for the coupling between an s electron with a nuclear spin is given by $H_{\mathrm{HF}} = \frac{2}{3}\mu_0 g_0 \mu_{\mathrm{B}} \hbar \gamma_n |\Psi(0)|^2 \vec{\mathrm{I}} \cdot \vec{\mathrm{S}}$ [16,17], where μ_{B} is the Bohr magneton, g_0 is the g factor of the free electron, $\vec{\mathrm{I}}$ is the nuclear spin, $\vec{\mathrm{S}}$ is the electron spin, and $|\Psi(0)|^2$ is the electron density at the nuclear site. Introducing the values from literature [15] leads to a hyperfine energy of 14 660 MHz per nucleus for ^{75}As, 12 210 MHz for ^{69}Ga and 15 514 MHz for ^{71}Ga. Scaling these values with the electron densities in the GaAs quantum well with respect to the density in a metal leads to hyperfine splittings of 27, 21, and 26 kHz for ^{75}As, ^{69}Ga, and ^{71}Ga, respectively. These splittings are of the experimentally observed order of magnitude. However, the theoretical ratio of the hyperfine splitting between the ^{69}Ga and the ^{71}Ga isotope is 0.79, which is just the quotient of the gyromagnetic ratios of the two Ga isotopes and does not depend on any other quantity. This would imply that the splitting of the ^{69}Ga nuclei should be smaller than the one of the ^{71}Ga nuclei by the same factor (0.79). Experimentally, however, the splitting of the ^{69}Ga is *larger*.

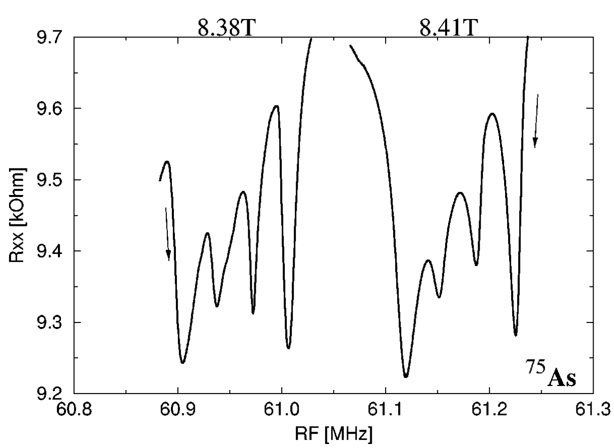

FIG. 3. The NMR resonance line of ^{75}As for two different carrier densities. A clear fourfold splitting of the resonance line is observed.

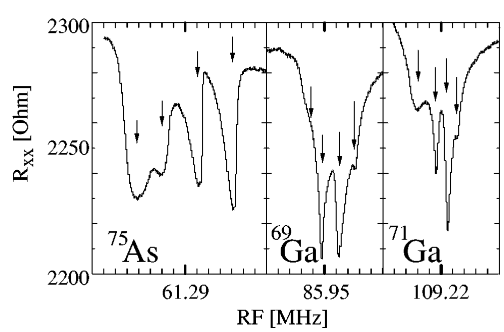

FIG. 4. The NMR resonance line for ^{75}As, ^{69}Ga, and ^{71}Ga measured on the 80 μm wide sample. The tick marks are in 10 kHz steps. A fourfold substructure is visible (arrows) for all three isotopes.

This clearly disagrees with the expected behavior even if only the positions of the two strong center lines of the Ga resonances are available with high precision. This rules out the hyperfine interaction with an effective electron spin of $3/2$ as the sole reason for the fourfold splitting of the resonances. Nevertheless, the order of magnitude of the observed splittings points towards the hyperfine interaction. It is noteworthy that the ratios between the experimentally observed values of the splittings can be quite well described by scaling the theoretical hyperfine interaction with the natural abundance of the isotopes, which is 0.61 for ^{69}Ga and 0.39 for ^{71}Ga. This would increase the theoretical ratio to 1.2, which is close to the experimental value of 1.4. This could suggest that the splitting is caused by the dipole interaction to other nuclei after all, but that the coupling strength is enhanced by the hyperfine interaction to the electrons. Since the other nuclei have $I = 3/2$, this coupling has the potential to lead to a fourfold splitting if the broadening from having many neighboring isotopes at different distances is not effective. Such a mechanism would, however, be completely novel and would amount to a new correlated phase between the electrons and the nuclei. At this time, however, the existence of such a phase is purely speculative.

The results of our investigation can be summarized as follows: First, the resistance value of the HLR maxima drops if rf with frequencies corresponding to the splitting of the nuclear spins is present. Since the rf irradiation leads to the saturation of the nuclear transitions and to a reduction of the nuclear polarization, we conclude that the HLR is caused or stabilized by a nuclear magnetic polarization. This polarization can build up only dynamically by the current flow, which indicates that the electronic transport is connected with spin flip processes.

Second, whatever the exact nature of the HLR maximum is, it must take place in the GaAs quantum well only, because otherwise we would also have observed nuclear magnetic resonances corresponding to the Al nuclei. The Al nuclei are absent in the well but are present in the surrounding AlGaAs barrier material.

Third, the splitting of the resonance lines into four lines is unexpected and not yet understood. At this time one can only say that the size of the splitting scales approximately with the product of the hyperfine interaction and the natural abundance of the respective isotope and that the size of the splitting is in the range of the expected splitting for the hyperfine interaction. To our knowledge, none of the commonly discussed interaction mechanisms can lead to the observed fourfold splitting.

In conclusion we have found that the electron transport in the HLR state must be related to a dynamic polarization of the nuclei. This fact gives the rare opportunity to detect NMR resistively in this state. One possible process that could cause a dynamic polarization would be electrons passing between domains of the unpolarized and polarized ground states [3,18] of the fractional quantum Hall effect, which would produce both the nuclear polarization and the longitudinal resistance. Such a domain picture alone can, however, not explain the unusual fourfold splitting of the NMR lines, which points to an unusual correlation between electrons and nuclei.

We acknowledge many discussions with T. Chakraborty, R. Gerhardts, and M. Mehring. We received important experimental help from J. Weis and U. Wilhelm.

[1] K. von Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
[2] D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[3] S. Kronmüller, W. Dietsche, J. Weis, K. von Klitzing, W. Wegscheider, and M. Bichler, Phys. Rev. Lett. **81**, 2526 (1998).
[4] We observe the same HLR phenomena also in 14 nm quantum wells.
[5] M. Dobers, K. v. Klitzing, J. Schneider, G. Weimann, and K. Ploog, Phys. Rev. Lett. **61**, 1650 (1988).
[6] A. Berg, M. Dobers, R. R. Gerhardts, and K. v. Klitzing, Phys. Rev. Lett. **64**, 2563 (1990).
[7] G. P. Flinn, R. T. Harley, M. J. Snelling, A. C. Tropper, and T. M. Kerr, Semicond. Sci. Technol. **5**, 533 (1990).
[8] M. Krapf, G. Denninger, H. Pascher, G. Weimann, and W. Schlapp, Solid State Commun. **78**, 459 (1991).
[9] S. E. Barrett, R. Tycko, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **72**, 1368 (1994).
[10] D. J. Guerrier and R. T. Harley, Appl. Phys. Lett. **70**, 1739 (1997).
[11] B. E. Kane, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **46**, 7264 (1992).
[12] K. R. Wald, L. P. Kouwenhoven, P. L. McEuen, N. C. van der Vaart, and C. T. Foxon, Phys. Rev. Lett. **73**, 1011 (1994).
[13] D. C. Dixon, K. R. Wald, P. L. McEuen, and M. R. Melloch, Phys. Rev. B **56**, 4743 (1997).
[14] I. V. Kukushkin, K. von Klitzing, and K. Eberl, Physica (Amsterdam) **1E**, 21 (1997); I. V. Kukushkin (to be published).
[15] Standard NMR tables, for instance, *Bruker Almanac* (Bruker GmbH, Karlsruhe, 1998).
[16] C. P. Slichter, *Principles of Magnetic Resonance* (Springer-Verlag, Berlin, 1990).
[17] D. Paget, G. Lampel, B. Sapoval, and V. I. Safarov, Phys. Rev. B **15**, 5780 (1977).
[18] T. Chakraborty and P. Pietiläinen, *The Quantum Hall Effects* (Springer, Berlin, 1995).