Resistively-Detected NMR Studies of Quantum Hall Systems

Katsuyoshi Kodera, Hisashi Takado, Akira Endo, Yoshiaki Hashimoto, Shingo Katsumoto and Yasuhiro Iye

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581

Abstract. The resistively-detected NMR experiments have been carried out in the vicinity of filling ν=1 where skyrmion excitations play a crucial role. The NMR lineshape in this region exhibits a dip-peak structure (dispersive lineshape). The anomalous lineshape evolves to the usual dip structure either by moving further away from ν=1 or by raising temperature above ~150 mK. The nuclear spin relaxation rate $1/T_1$ shows a distinct ν-dependence at the dip and the peak. The temperature dependence of $1/T_1$ is anomalous in the region where the dispersive lineshape is observed. We compare our result with the conflicting experimental results recently reported.

Keywords: Quantum Hall effect, resistively-detected NMR, skyrmion solid
PACS: 73.43.-f, 73.20.-r, 73.63.Hs

Quantum Hall (QH) systems exhibit a wide variety of many body ground states depending on the Landau level (LL) filling factor ν, including integer and fractional quantum Hall liquids, Wigner solids, stripe and bubble phases, and composite fermion liquids. In recent years, phenomena associated with the spin degree of freedom have attracted much attention such as skyrmion excitations in spin transitions[1,2]. Resistively-detected NMR (RDNMR) which reflects the hyperfine interaction between electron and nuclear spins is expected to offer a powerful experimental tool to explore such intriguing states[3-7].

The mechanism of RDNMR in QH systems can be naively considered as follows. Conduction electrons in GaAs have a negative *g*-factor, so that the Overhauser shift due to (partially) polarized nuclear spins suppress the electronic spin gap. Scrambling of the nuclear polarization by a resonant rf magnetic field tends to increase the spin gap by reducing this suppression, leading to a corresponding change in resistivity. Thus the RDNMR signals around the odd fillings are expected to show a dip structure. While this is true, the experiments have found a few features that cannot be explained in such a simple picture. For example, the RDNMR signals around even fillings also have a dip structure, despite that the above picture predicts a peak there. Another anomaly is the so-called “dispersive” lineshape, *i.e.* a dip-peak structure, seen in the vicinity of ν=1, which is suspected to be related with the formation of skyrmion solid, but the exact mechanisms are yet to be elucidated[8].

In this work, we have focused on the behavior near the filling ν=1[9]. A Hall-bar sample with a front gate was fabricated from a GaAs/AlGaAs heterojunction 2DEG wafer with mobility μ~180 m^2/Vs. The sample was cooled in a mixing chamber of dilution refrigerator and magnetic fields up to 15 T and the front gate bias was used to change the filling factor. An rf magnetic field parallel to the 2DEG plane was applied by a single turn coil wound around the sample.

Figure 1(c) is the RDNMR signal typically observed in the vicinity of ν=1 (ν=0.84) at the lowest temperature which shows an anomalous “dispersive” lineshape. As one moves further away from ν=1, the dispersive lineshape evolves into an ordinary one as shown in Fig.1(b) (ν=0.81). Figure 1(a) shows a color-scale plot showing the evolution of the anomalous RDNMR lineshape with ν. A similar evolution of the lineshape occurs as a function of temperature. Figure 1(d) shows the RDNMR signal at ν=0.84 at 200 mK. The characteristic temperature for the disappearance of the dispersive lineshape is ~150 mK.

The nuclear spin relaxation time T_1 is generally on the order of 100 sec at the lowest temperature, except in the vicinity of ν=1 where enhancement of nuclear spin relaxation due to skyrmion excitations is observed. Figure 2(a) shows the filling dependence of the nuclear spin relaxation rate $1/T_1$. Two sets of data, $1/T_1^{dip}$ and $1/T_1^{peak,}$ each corresponding to the dip and the peak position of the dispersive lineshape are given. The measurement of T_1 was done in the following manner. Initially, the frequency of the rf magnetic field is set at an off-resonant position rf^{off}. It is brought to the resonant position (either the dip or the peak) for a certain duration (typically 100 sec) and then back to the off-resonant position. One can extract the relaxation time T_1 from relaxation of the resistivity thereafter. The data in Fig.2(a) show that $1/T_1^{dip}$ changes rapidly between ν~0.82 and 0.84, while $1/T_1^{peak}$ changes minimally. Thus the enhancement of the nuclear spin relaxation by the skyrmion excitations is reflected primarily in the dip region of the spectrum. (The apparent saturation of $1/T_1^{dip}$ for ν>0.84 may be due to the limited time resolution of the measuring system.)

The temperature dependence of $1/T_1^{dip}$ at ν=0.805 and 0.84 are given in Figs.2 (b) and (c), respectively. While the T-dependence of $1/T_1^{dip}$ is Korringa-like at ν=0.805, it exhibits an anomalous behavior at ν=0.84, i.e. $1/T_1^{dip}$ increases with decreasing temperature. It is interesting to compare the present result with two results that have been reported recently. Gervais *et al.*[10] reports an anomalous T-dependence and argue that it may reflect melting transition of skyrmion crystal. Their RDNMR lineshape is not a dispersive one at least under their low rf-power condition, and the values of T_1 are ~100sec even in the skyrmion regime which is very long in comparison to the results by other groups[6,8,11] including ourselves. Tracy *et al.*[11] observed Korringa-like behavior in the filling range where the dispersive lineshape is observed. Our result differs from either of these, in that anomalous T-dependence is observed for the $1/T_1^{dip}$ whose values are distinctively enhanced by the skyrmion excitations.

At the moment, the origin of the conflicting experimental results is not clear. Evidently, further experiments are needed to clarify the situation. We comment in passing that our search for RDNMR signal in 2D hole systems has yielded a negative result, as expected from very small coupling between holes and nuclear spins owing to the *p*-wave character of the valence band.

We thank Prof. M. Takigawa for help with the NMR experiments. The work is supported in part by Grant-in-Aid for Scientific Research from the MEXT, Japan. One of the authors (K.K.) acknowledges the support provided by the JSPS fellowship.

REFERENCES

1. H. A. Fertig *et al.*, Phys. Rev. B **50**, 11018 (1994).
2. S. E. Barrett *et al.*, Phys. Rev. Lett. **74**, 5112 (1995).
3. S. Kronmuller *et al.*, Phys. Rev. Lett. **82**, 4070 (1999).
4. J. H. Smet *et al.*, Phys. Rev. Lett., **86**, 2412 (2001).
5. J. H. Smet *et al.*,Nature **415**, 281 (2002).
6. K. Hashimoto *et al.*, Phys. Rev. Lett. **88**, 176601 (2002).
7. O. Stern *et al.*, Phys. Rev. B **70** 075318 (2004).
8. W. Desrat *et al.*, Phys. Rev Lett. **88**, 256807 (2002).
9. Since the resistivity vanishes in the close vicinity of ν=1, our method was limited to the filling range $|1-\nu|$>0.14 for the present sample.
10. G. Gervais *et al.*, Phys. Rev. Lett. **94**, 196803 (2005).
11. L. A. Tracy *et al.*, Phys. Rev. B**73**, 121306 (2006).

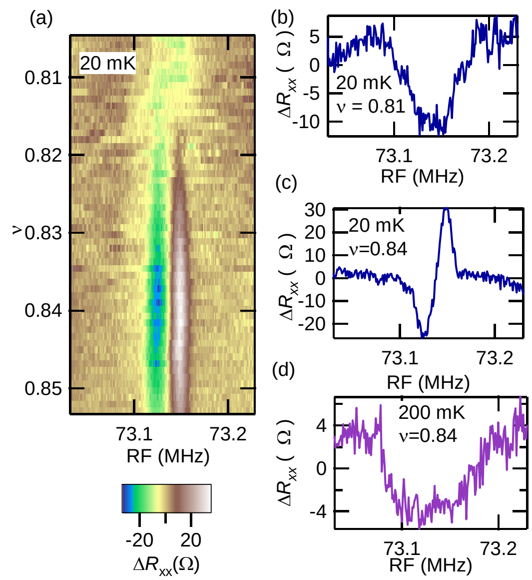

Fig.1. (a) Color-scale plot showing the evolution of the anomalous RDNMR lineshape as a function of ν. (b) RDNMR signal at the filling ν=0.81 and T=20 mK, (c) ν=0.84 and T=20 mK, and (d) ν=0.84 and T=200 mK. The dispersive lineshape evolves into a shallow dip either by moving further away from ν=1 or raising temperature to T>150mK.

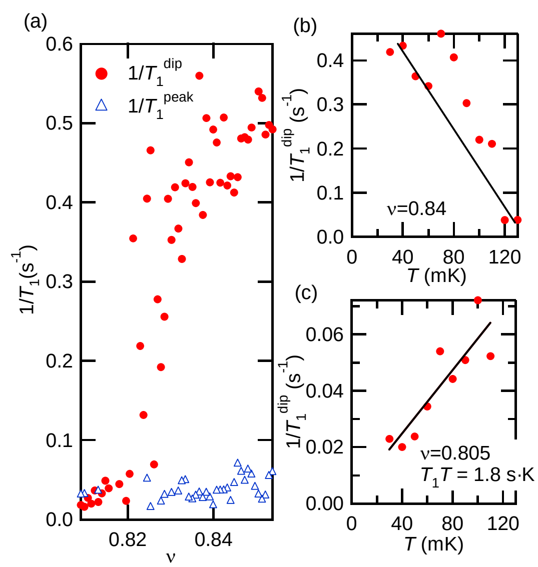

Fig.2 (a) Nuclear spin relaxation rate $1/T_1$ as a function of ν. Two sets of data correspond to those measured at the peak and the dip positions. (b) Temperature dependence of $1/T_1^{dip}$ at ν=0.805 (where the RDNMR line shape is shallow dip), and (c) at ν=0.84 (where dispersive lineshape is observed.)