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^{11}B NMR study of vortex dynamics in $LuNi_2B_2C$

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Abstract

^{11}B NMR measurements have been performed on single crystals of $LuNi_2B_2C$ superconductor to investigate vortex lattice structures and dynamical behavior. The spectrum in the superconducting state is significantly broadened by local field inhomogeneity due to the vortex lattice and the peak point of the spectrum shifts toward low magnetic field due to the imperfect field penetration. The linewidth of the spectrum reflecting local field variation is much smaller than expected for conventional vortex lattices and shows peculiar increase at low temperature. Furthermore, the transverse relaxation rate, $1/T_2$, probing the slow motion of vortices, exhibits a single peak as temperature decreases. These prominent results highlight significant fluctuation of vortices even for this low T_c and nearly isotropic 3D superconductor.

Keywords : $LuNi_2B_2C$, vortex dynamics, ^{11}B NMR, shift and transverse relaxation rate

I. Introduction

RNi_2B_2C (R; rare-earth elements) superconductors [1] exhibit a variety of interesting phenomena due to interplay between magnetism and superconductivity [2, 3]. Furthermore, RNi_2B_2C systems draw even more attention recently since the exotic vortex structures and dynamics are reported [4, 5]. In particular, YNi_2B_2C is important since the vortex melting [6] reported in this system is controversial [7]. However, vortex lattice fluctuation is observed even at low temperatures in these nearly isotropic superconductors [7, 8].

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Nuclear magnetic resonance (NMR) techniques have played an important role in understanding of superconductivity since NMR can sensitively probe local electronic structures and dynamics. In RNi_2B_2C, ^{11}B NMR is often employed to investigate electronic structures in the normal and the superconducting states [9, 10]. On the other hand, NMR can also detect magnetic structures microscopically since the resonance frequency of each nucleus just reflects the local magnetic field. In this regard, NMR has played a great role in unveiling the vortex dynamics including vortex melting and vortex fluctuation in YBCO systems [11-13].

In this paper, we report vortex lattice dynamics in $LuNi_2B_2C$ single crystals measured by ^{11}B NMR techniques. Since this system is similar to YNi_2B_2C in various properties, this measurement is going to provide complementary information regarding vortex dynamics in RNi_2B_2C systems.

II. Experiments

$LuNi_2B_2C$ single crystals were grown by the Ni_2B high-temperature flux growth method. The sample size was roughly 8x8x2 mm^3. ^{11}B NMR measurements were carried out at 1.8 T for field parallel and perpendicular to the c-axis at various temperatures. The phase-alternating pulse sequences were employed to significantly reduce the electromechanical vibration (ring-down) after pulses [14]. The transverse relaxation time, T_2, was measured by the solid-echo pulse sequence. The cryogenic measurements were performed in the Oxford continuous flow cryostat (CF1200N).

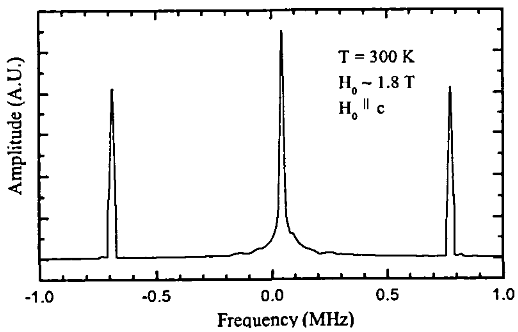
III. Results and Discussion

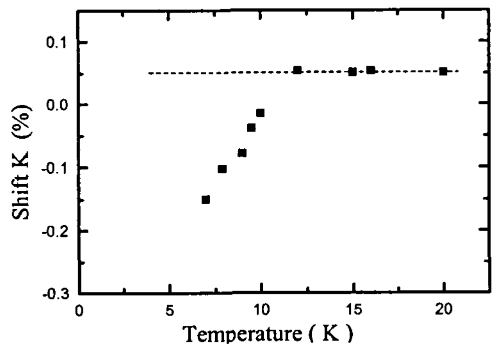
^{11}B NMR spectrum in Figure 1 shows three resonance lines due to the nuclear Zeeman interaction for I=3/2 nuclear spin of ^{11}B with the quadrupolar perturbation. From measurements for field parallel and perpendicular to the c-axis, the electric field gradient (EFG) tensor at the boron site is found to have the c-axis as its principal axis with the asymmetry factor of $\eta \sim 0$. The quadrupolar frequency ν_Q is measured to be 700 kHz. The linewidth in the normal state is narrow, roughly 8 kHz, which accounts for high quality of crystals.

In the superconducting state, the spectrum becomes progressively broader as the spatial field modulation due to the vortex lattice sets in. Then the spectrum just reflects local field variation at the boron nuclear sites. Since the vortex spacing is roughly 10 nm at 1.8 T and the boron nuclei are 0.35 nm apart, the boron nuclei form a fine grid probing the local magnetic field. The spectrum in the mixed state exhibits a typical field distribution of the vortex lattice; minimum field H_m, saddle point field H_s, and maximum field at the vortex core H_M. Defining $\beta=(H_s - H_m)/(H_M - H_m)$ as an aspect of the field distribution, we can distinguish triangular and square lattices; $\beta=0.07$ for the triangular lattice and $\beta=0.29$ for the square lattice [15].

^{11}B NMR shift is shown in Figure 2. The shift in the superconducting state consists of three parts; $K_{tot} = K_{spin} + K_{orb} + K_{dia}$ where K_{spin} is the spin part due to the spin susceptibility of cooper pairs, K_{orb} is the orbital part due to the orbital paramagnetism, and K_{dia} is the diamagnetic shift due to the incomplete field penetration. For the spin singlet (S=0) pairing, K_{spin} is reduced to zero at low temperature following Yoshida function. K_{orb} is usually positive and temperature-independent. K_{dia} depends on field and temperature. Therefore, the temperature dependence of total shift comes from K_{spin} and K_{dia}. These may have different temperature and field dependence and, in principle, can be separated.

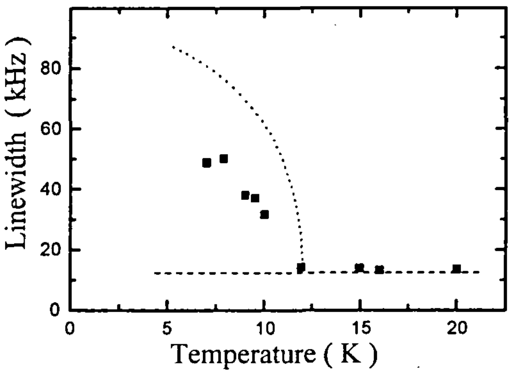
The temperature dependence of shift shown in Figure 2 is far different from the temperature dependence of spin shift and penetration depth; that is, it shows a linear decrease in the superconducting state. This peculiar change is most likely to originate





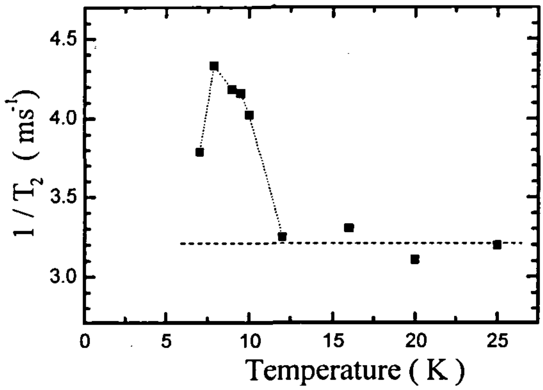
from the diamagnetic shift since the spin part is reduced rapidly below T_c and quickly converges to the low temperature value. This indicates that there is significant contribution to the total shift from incomplete field penetration in the mixed state of type II superconductors.

The linewidth shown in Figure 3 is almost temperature-independent in the normal state [16]. This linewidth is governed by the nuclear dipole-dipole interaction. On the other hand, the linewidth in



the superconducting state is roughly constant down to T_c, where it becomes much broader by the vortex lattice. However, the linewidth is much smaller than the expected value (the dotted curve in the figure) for triangular or square lattices of *rigid* vortices. This deviation is also observed for YNi_2B_2C and comes from fast vortex motion [17]. The large inhomogeneity of field for the *rigid* vortex lattice [18] is averaged and the linewidth is reduced by rapid vortex fluctuation. Then, the amplitude of vortex fluctuation can be estimated from the reduction ratio of linewidth from the theoretical value for the vortex lattices.

The transverse relaxation rate $1/T_2$ is shown in Figure 4. $1/T_2$ is temperature-independent in the normal state, which is determined by the homonuclear dipole-dipole interaction between boron nuclei. In the superconducting state, on the other hand, $1/T_2$ usually decreases since the local field inhomogeneity blocks the nuclear dipole-dipole interaction between neighboring nuclei and consequently $1/T_2$ is suppressed *if vortices are*



stationary. This reduction is commonly observed for most conventional superconductors, where vortex motion is negligible due to low transition temperature, small penetration depth, and large coherence length.

On the contrary, Figure 4 highlights the single peak behavior of $1/T_2$ due to the significant vortex motion. Since $1/T_2$ is sensitive to the local field fluctuation in the time scale of echo formation interval, this peak proves that vortices fluctuate in the time scale of ~10 μs. The peak of $1/T_2$ and the reduction of linewidth confirm that significant vortex motion and fluctuation exists even for this low T_c and isotropic 3D superconductor.

IV. Summary

We have performed ^{11}B NMR measurements on $LuNi_2B_2C$ single crystal to investigate the vortex lattice dynamics. ^{11}B NMR shift shows a peculiar decrease at low temperature and the linewidth is significantly reduced from the expected value for the rigid vortices. Furthermore, the transverse relaxation rate clearly shows a single peak. The temperature dependence of shift, linewidth, and transverse relaxation rate confirm that flux lines fluctuate significantly in this low T_c and isotropic superconductor.

Acknowledgments

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