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Local Field Distribution in YNi_2B_2C superconductor

YNi_2B_2C의 초전도 상태에서 국소자기장의 분포

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Local field distribution in the mixed state of type II superconductors has been numerically calculated and compared with ^{11}B NMR spectra for YNi_2B_2C single crystals. We find that only small distortion of vortex positions from the perfect lattice points is enough to smear out the low frequency shoulder. As the vortices are further distorted, the line shape changes from an asymmetric shape with a high frequency tail to a symmetric Gaussian line shape. It is found that the second moment of the field distribution has a major contribution from the high frequency tail. Consequently, a linewidth of the full width at half maximum calculated from the second moment assuming for a Gaussian line shape is overestimated.

1. Introduction

Numerous important research results have been reported on unusual vortex motions including vortex lattice melting in cuprate superconductors [1-7]. These features are attributed to the high transition temperature T_c, the short coherence length ξ, and the high anisotropy. Despite that T_c is low, ξ is relatively large, and superconducting properties are nealy isotropic, unique results, however, have been recently reported for RNi_2B_2C superconductors [8-12] showing exotic vortex structures as well as vortex motions. These include the vortex melting [8] and a transition from triangular to square vortex lattices [9]. Vortex dynamics for RNi_2B_2C are probed by transport measurements [8], STM [10], and small angle neutron scattering experiments [11-13].

Recently, NMR experiments have played a great role not only in clarifying the importance of anitferromagnetic fluctuation [14] but also in understanding vortex dynamics in cuprate cuperconductors [15-23]. NMR is sensitive to the local field distribution and fluctuation in the precession period of a nuclear spin. The static information is the peak position and the linewidth of NMR resonance signal, which reflect, respectively, the saddle-point field and the local field inhomogeneity in the mixed state.

In the mixed state of type II superconductors, vortices generate spatial field modulation. The vortex spacing for the square lattice is $d=\sqrt{\Phi_0/H_{ext}}$, where Φ_0 is the flux quantum and H_{ext} is the external field. Then NMR spectrum just reflects local field distribution at the probing nuclear sites. Since d is 333 Å at 1.8 T and the boron nuclei are 3.75 Å apart, the boron nuclei form a fine grid probing local magnetic field in the vortex state.

In this paper, we report numerical calculation of local field distribution in the mixed state of YNi_2B_2C superconductor and compare the results with ^{11}B NMR data.

2. Experiment

YNi_2B_2C single crystal was grown by the Ni_2B high-temperature flux growth method. The sample was roughly 11x7x2 mm^3. The pulsed ^{11}B NMR measurements were carried out at 1.8 and 3.0 T parallel to the c-axis. The phase-alternating pulse sequences were employed to significantly reduce the electromechanical vibration (ring-down) after pulses. The cryogenic measurements were performed in the Oxford continuous flow cryostat (CF1200N).

3. Results and Discussion

Figure 1 shows ^{11}B NMR spectrum at 1.8 T and 3.8 K. This line shape exhibits a typical asymmetric shape with a long tail in the high frequency side, which reminds us of the characteristic field distribution for Abrikosov vortex lattice, as calculated and shown in Fig. 2. However, a shoulder in the low frequency side is missing in Fig. 1. To understand absence of the shoulder, we have carried out numerical calculation of the local field distribution in the mixed state of YNi_2B_2C superconductor.

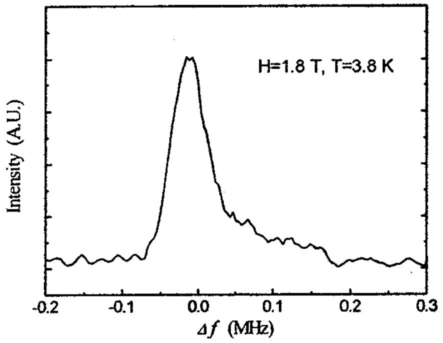

Fig. 1 ^{11}B NMR spectrum for YNi_2B_2C single crystal at 1.8 T and 3.8 K.

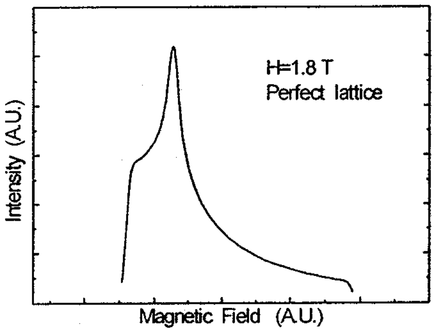

Fig. 2 Calculated ^{11}B NMR spectrum of YNi_2B_2C for the perfect square type of vortex lattice.

Assuming that the local magnetic field for a single vortex decreases as the modified Bessel function, $H(r)\approx\frac{\Phi_0}{2\pi\lambda^2}K_0[(r^2+2\xi^2)^{1/2}/\lambda]$ [2], we sum up the respective local fields of 300x300 vortices in a unit cell of 300x300

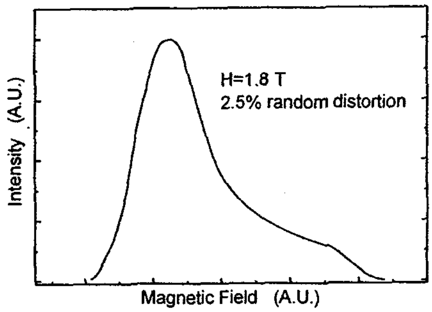

Fig. 3 Calculated ^{11}B NMR spectrum of YNi_2B_2C for the 2.5% randomly distorted vortex lattice of square type.

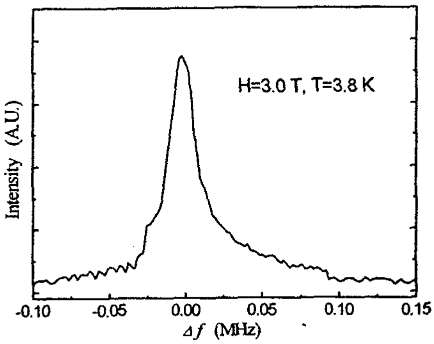

Fig. 4 ^{11}B NMR spectrum of YNi_2B_2C single crystal at 3.0 T and 3.8 K.

pixels. Since we think that the absence of the shoulder may originate from distortion of vortex lattice due to pinning centers, we calculate local field distribution accounting for random distortion of vortices from the regular lattice positions. Then, core finding from our numerical calculation is that a small amplitude (~2%) of random distortion is enough to wash out the left shoulder, as shown in Fig. 3. Furthermore, the line shape for larger distortion becomes much broader approaching a symmetric Gaussian shape. Indeed, at higher magnetic field of 3.0 T for a stronger NMR signal, we have finally observed a NMR line shape, which is very close to the calculated line shape, as shown in Fig. 4. From the line shape, we can unambiguously identify minimum field H_m, saddle-point field H_s, and maximum field H_M at the vortex core. This line shape confirms that vortices form a *vortex lattice*. The formation of vortex lattice at low temperature is due to dominance of the elastic energy. Defining $\beta \equiv (H_s - H_m)/(H_M - H_m)$, we can distinguish the triangular and the square lattices; $\beta=0.07$ for the triangular lattice and $\beta=0.29$ for the square lattice [24]. In YNi_2B_2C we obtain $\beta=0.26\pm0.05$, suggesting that the vortex lattice at 1.8 and 3.0 T parallel to the c-axis is a square type, consistent with the published reports [11-13]. It should be noted that this line shape has never been observed in the NMR measurements on the aligned powder samples of cuprate superconductors.

The field inhomogeneity of the perfect vortex lattice can be calculated by taking account of the spatial modulation of the local field in the mixed state. The second moment of the field variation is given as $\Delta H(T) \equiv \langle \Delta H^2(T)\rangle^{1/2} = k\frac{\Phi_o}{\lambda(T)^2}$ where $\lambda(T)$ is the penetration depth and k is a numerical factor. The formula for k has been calculated for $H_{c1} \ll H \ll H_{c2}$ and $0.5\,H_{c1} < H \leq H_{c2}$ [25]. However, for the intermediate field value as for our magnetic field of 1.8-4.0 T, k can be only numerically calculated. Using $\lambda(0)$=1207 Å [26] and the coherence $\xi(0)$=55 Å from $H_{c2}(0)$=10.5 T [27], we have carried out the numerical calculation and obtained k for several values of magnetic field, which is shown in Fig. 5. Numerical results are compared with the results of analytic calculation [25]. Two results are fairly close. We find that the second moment of local field distribution is dominated mostly by the long tail in the high frequency side.

To compare NMR data with calculation, we usually take a linewidth of NMR spectrum as a measure of field inhomogeneity for the local field distribution. Then, assuming a Gaussian line shape, the linewidth of full-width-at-half-maximum (FWHM) is given by $\Delta f = 2.36\, \gamma \Delta H/(2\pi)$ where γ is the nuclear gyromagnetic ratio of ^{11}B nucleus, $2\pi \times 13.67$ kHz/Oe. We find this kind of analysis is erroneous since contribution to the second moment of the line shape comes mostly from the long tail in the high frequency side and the line shape is not a Gaussian line shape unless the samples are dirty with many pinning centers.

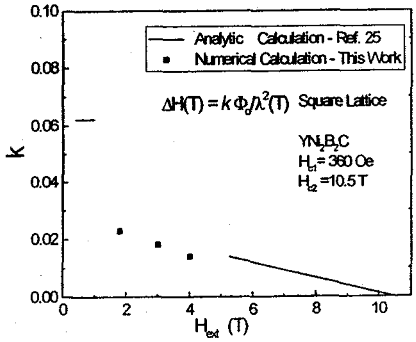

Fig. 5 The second moment calculation of ^{11}B NMR linewidth in the mixed state of YNi_2B_2C.

4. Conclusion

^{11}B nuclear magnetic resonance (NMR) measurements have been performed to probe vortex structure and distortion in YNi_2B_2C supercodncutor. Also, local field distribution in the mixed state of type II superconductors has been numerically calculated and compared with ^{11}B NMR spectra for YNi_2B_2C single crystals. We find that only small distortion of vortex positions from the perfect lattice points is enough to smear out the low frequency shoulder. As the vortices are further distorted, the line shape changes from an asymmetric shape with a high frequency tail to a symmetric Gaussian line shape. It is found that the second moment of the field distribution has a major contribution from the high frequency tail. Consequently, a linewidth of the full width at half maximum calculated from the second moment assuming for a Gaussian line shape is overestimated.

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