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^{11}B NMR study of MgB_2 superconductor

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Abstract : ^{11}B nuclear magnetic resonance (NMR) measurements have been performed to investigate electronic structures and vortex states of MgB_2 superconductor. The central transition shows a narrow peak down to 25 K at 3.15 T. Below 25 K, an extra line starts to show up and dominates. The extra line is broad and asymmetric with a long tail in the high frequency side, which confirms that this originates from vortex pinning below the irreversibility temperature. From temperature evolution of the fraction and linewidth of the broad portion, temperature dependence of coherence length and penetration depth are extracted.
Keywords : MgB_2 superconductor, ^{11}B NMR spectrum, Shift, linewidth, penetration depth

INTRODUCTION

Recent discovery of MgB_2 superconductor has generated reconsideration and extension of BCS theory because of the highest transition temperature among bimetallic compounds.[1] To date a number of papers have reported that superconductivity is of a phonon-mediated BCS type. The key measurement is isotopic effect on the transition temperature.[2] However, the pairing mechanism in MgB_2 is not settled down by microscopic probes such as NMR.

Nuclear magnetic resonance techniques play a crucial role in understanding of electronic structures as well as vortex dynamics for high temperature cuprate oxides.[3] Although a few NMR papers were reported regarding electronic structures of MgB_2,[4-7] the pairing state is controversial and not clearly unveiled since presence of a coherence peak and temperature dependence of Knight shift and spin-lattice relaxation rate in the superconducting state are discrepancy. This complexity comes from inhomogeneous field distribution in the vortex state.[4, 5]

In this paper, we report ^{11}B NMR measurements on a MgB_2 powder sample. Our ^{11}B NMR spectrum shows an extra peak below 25 K at 3.15 T. The extra peak is broad and

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asymmetric with a long tail in the high frequency side, similar to the Abrikosov field distribution in the mixed state. The broad peak is interpreted to come from vortex pinning. The onset temperature of the broad peak associated with the vortex pinning roughly agrees with an irreversibility line reported from magnetization measurements.[8]

EXPERIMENT

Polycrystalline MgB_2 was prepared by solid state reaction techniques using a mixture of magnesium and boron powders. The superconducting transition temperature was measured to be 39K for zero resistance and 39.5K for onset of diamagnetism by magnetization at 10 Oe. 0.2 gram of MgB_2 powder was loaded into a teflon container. NMR measurements were carried with a home-made pulsed spectrometer in the range of 5-300 K at 3.15 T. The broad spectra were scanned by the Fourier transform of echo signals with different carrier frequencies.

RESULTS AND DISCUSSION

Fig. 1 shows ^{11}B NMR spectrum at 5 K and 3.15 T. The figure shows a powder pattern for the quadrupolar broadened spectra for the nuclear spin of I=3/2 for ^{11}B nucleus. However, the spectrum clearly shows a composite line for the central (1/2↔-1/2) and the satellite transitions. The composite feature of the spectrum is more clear from the central transition shown in Fig. 1(b). The central transition consists of a narrow peak and a broad peak. The composite line shape confirms that local magnetic field seen by the boron nuclei is inhomogeneously distributed. It should be mentioned that the spectrum in the normal state shows only a single narrow component consistent with previous reports.[5, 6]

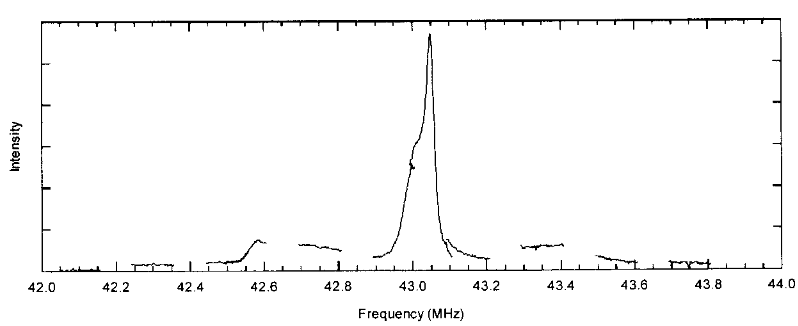

Fig. 1(a). ^{11}B NMR spectrum at 5 K and 3.15 T

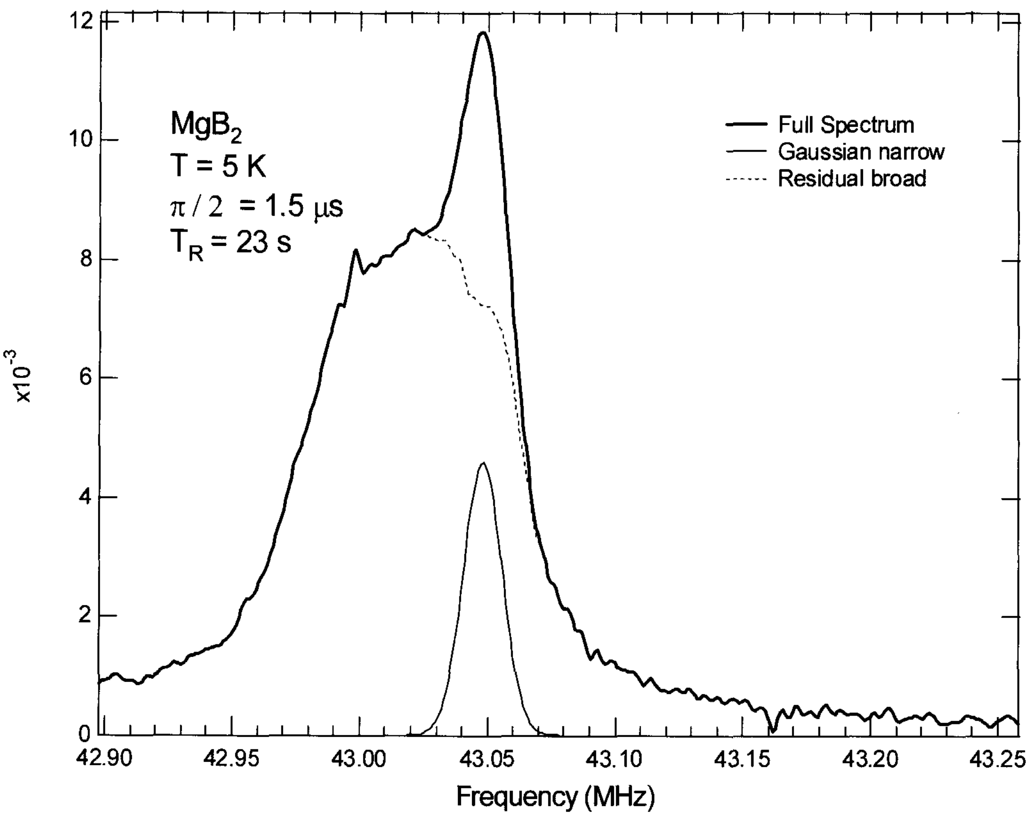

Fig. 1(b). The central transition of ^{11}B NMR spectrum at 5 K and 3.15 T.

The broad peak shows an asymmetric line shape with a long tail in the high frequency side. Since this is similar to a field distribution in the Abrikosov vortex state, we identify that the broad portion originates from the field distribution in the vortex state. Indeed, the broad peak shifts to a low frequency side at low temperature due to incomplete field penetration. We also notice that the broad peak emerges much stronger at lower temperature. The long tail in the high frequency side of the broad portion is also evident from the different shape of the satellite transitions; the -1/2↔-3/2 transition near 42.5MHz shows fast decrease in the low frequency side whereas the 3/2 ↔1/2 transitions near 43.5MHz shows slow decrease in the high frequency side.

Fig. 2 shows temperature evolution of the central transition. From the figure, it is obvious that as temperature decreases, the narrow portion of the total spectrum decreases whereas the broad portion increases. Also, the broad peak shifts to the low frequency side and the narrow peak stays almost at the same position.

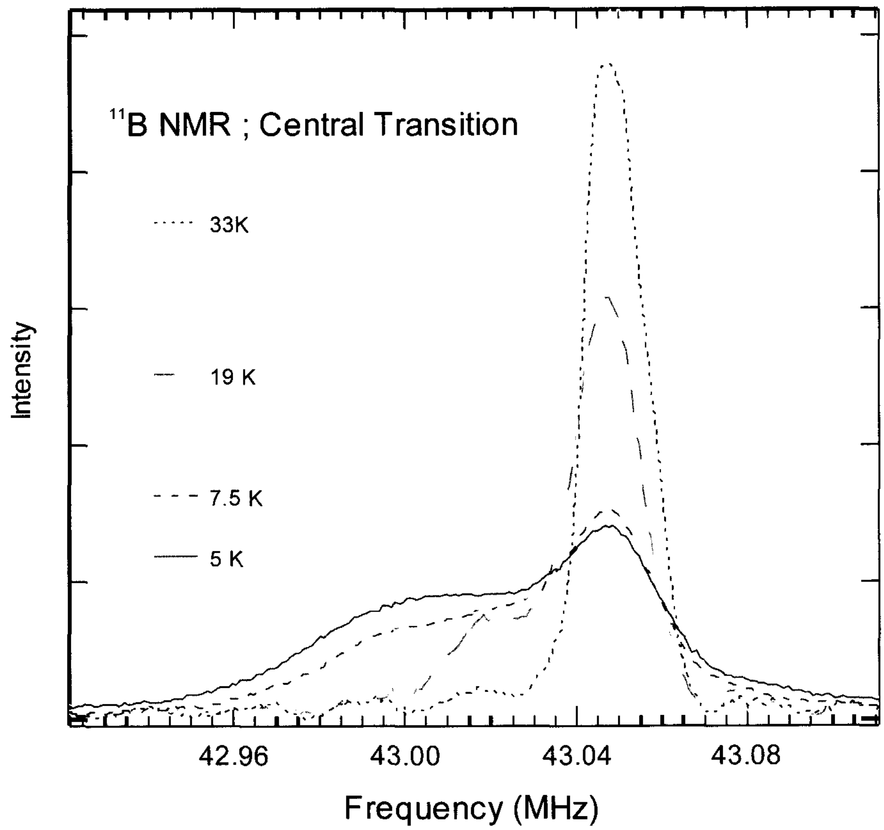

Fig. 2. Temperature evolution of the central transition for ^{11}B NMR at 3.15 T. Areas of all spectra are normalized.

Since the spin-lattice relaxation time was measured to be very long in the superconducting state,[4, 5] we paid special attention to record the full intensity of NMR signal throughout the entire spectrum. Then we find that the broad peak shows up stronger with a slow repetition rate proving that the ^{11}B nuclei in the broad portion relax slowly. This suggests that the relaxation rates are also inhomogeneous across the spectrum and that the boron nuclei see a different concentration of thermally broken pairs.

We deconvolute the composite spectrum for the central line to extract the relative fraction of the broad portion as shown in Fig. 3(a). Then the fraction of the broad portion dominates at lower temperature whereas the fraction of the narrow peak is reduced. The broad portion starts to appear around 25 K. We notice that this is very close to the irreversibility line observed from magneto-resistance measurements.[8] This strongly

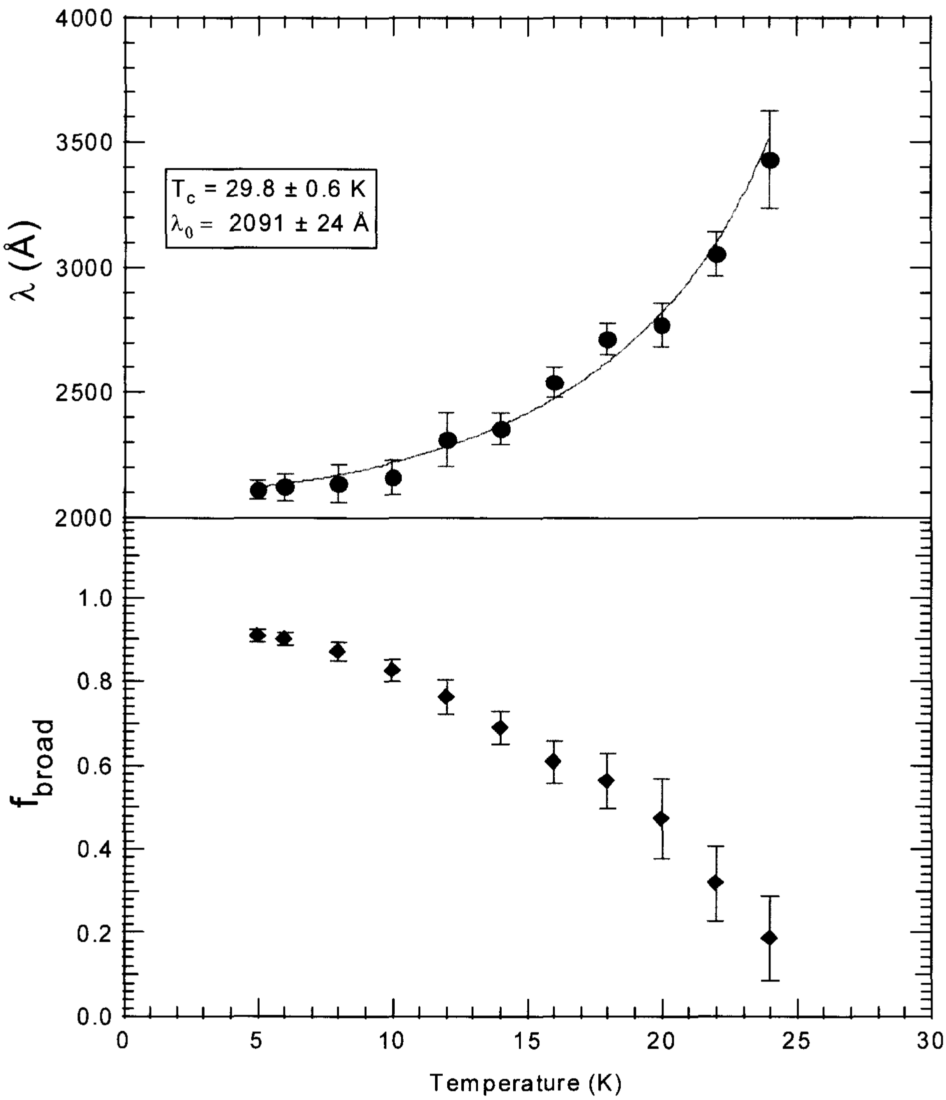

Fig. 3. Temperature dependence of a fraction and a linewidth for the broad portion.

indicates that the broad portion really originates from the vortex state and its onset is due to pinning of the vortices.

Since it is clear that the broad portion originates from the vortex state, the linewidth of the broad portion reflects the field distribution. Therefore, the second moment of the broad portion is a measure of field inhomogeneity, which is related to the penetration depth;

If we assume that the shape of the broad portion is Gaussian, the linewidth (full-width-at-half-maximum) is given as $2\Delta f\,[2ln2]^{1/2} = 2.35\Delta f = 2.35\ \gamma\,\Delta H$, where Δf and ΔH are respectively second moments in frequency and magnetic field distributions and γ is the gyromagnetic ratio of the ^{11}B nucleus, 13.66 MHz/T. Since the second moment of field distribution is given by $\Delta H \approx 0.0609\phi_o/\lambda^2$ for the triangular lattice,[9] where ϕ_o is the flux quantum, the penetration depth λ can be determined from the NMR linewidth as a function of temperature.

Fig. 3(b) shows the temperature dependence of penetration depth extracted from the second moment of the broad portion. The penetration depth at low temperature is measured to be $\lambda(0) \approx 2100$ Å, which is compatible with other measurements.[8]

In Fig.3(a), the fraction of the broad portion increases and is saturated around 90% at 5 K. This means that the narrow portion still persists even at the lowest temperature. The vortex spacing is given by $d = [2\phi_o/(H_{av}\sqrt{3})]^{1/2}$ for a triangular lattice, where H_{av} is the average field. Since it is ~2100 Å at 3.15 T, the area fraction of vortex core is $f = 2\pi\xi^2/(\sqrt{3}d^2) = 12.3\%$, if the radius of vortex core is assumed to be one coherence length ξ. This value is quite close to the persistent fraction of the narrow portion at 5 K. This indicates that the narrow portion may originate from the vortex core region. Furthermore, the spin-lattice relaxation rate for the narrow portion is found to be similar to the Korringa value in the normal state.[4-6] Therefore we identify that the narrow portion comes from the boron nuclei positioned in the vortex core.

Then the part of the broad line extending beyond the narrow line means that local magnetic field is larger than an external magnetic field. This part may come from a region of packed vortices, which is generated by vortex distortion due to pinning centers. In this interpretation, the fraction of the broad line is determined by temperature dependence of the coherence length.

Fig. 4 shows temperature dependence of the first moments for the narrow and the broad portions. The first moment of the narrow peak shows a slight change from that in the normal state. This small change may be due to the field distribution in the vortex state or due to the spin susceptibility. On the other hand, the first moment of the broad portion decreases significantly at low temperature as expected for a diamagnetic signal. Since this is an average of local magnetic field, the difference in the first moments for the narrow and the broad portions reflects incomplete field penetration and should be related to a diamagnetic moment from magnetization measurements.

In summary, we have performed ^{11}B NMR measurements on MgB_2 superconductor. The spectrum shows an extra peak below 25 K at 3.15 T, which becomes dominating. The extra peak is broad and asymmetric with a long tail in the high frequency side, which suggests that it originates from vortex pinning. The onset temperature of the broad peak is found to be consistent with the irreversibility temperature. This indicates that there is a significant vortex dynamics in MgB_2 superconductors.

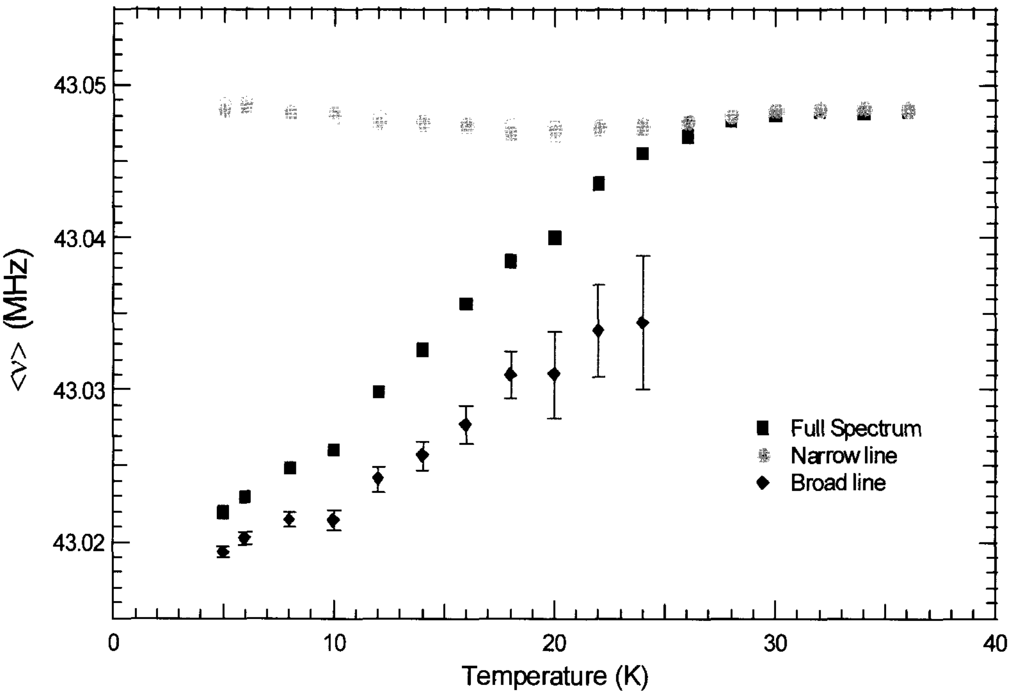

Fig. 4. Temperature evolution of the first moments for the narrow and the broad portions.

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