Evidence for Strong-coupling $s$-wave Superconductivity in MgB$_2$ :$^{11}$B NMR Study

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We have investigated a gap structure in a newly-discovered superconductor, MgB$_2$ through the measurement of $^{11}$B nuclear spin-lattice relaxation rate, $^{11}(1/T_1)$. $^{11}(1/T_1)$ is proportional to the temperature ($T$) in the normal state, and decreases exponentially in the superconducting (SC) state, revealing a tiny coherence peak just below $T_c$. The $T$ dependence of $1/T_1$ in the SC state can be accounted for by an $s$-wave SC model with a large gap size of $2\Delta/k_BT_c \sim 5$ which suggests to be in a strong-coupling regime.

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Quite recently, Akimitsu and co-workers have discovered a new superconducting (SC) material MgB$_2$ that reveals a remarkably high SC transition temperature of $T_c \sim 40$ K. MgB$_2$ crystallizes in the hexagonal AlB$_2$-type structure, consisting of alternating hexagonal layers of Mg atoms and graphite-like layers of B atoms. The discovery of superconductivity with a relatively high value of $T_c$ in this compound gives a new impact in the solid state physics, since it may give other possibility for finding high-$T_c$ superconductivity in some binary intermetallic compounds besides cuprates and C$_60$-based compounds. It may be promising to discover new compounds with a high-$T_c$ value exceeding the liq.-N$_2$ temperature other than cuprates. Soon after the discovery, Bud’ko and co-workers reported that $T_c$ increases from 39.2 K for Mg$^{11}$B$_2$ to 40.2 K for Mg$^{10}$B$_2$, giving a clear indication that electron-phonon interactions are playing an important role. However, the observed high $T_c$ value of this compound seems to be either beyond or at a limitation for the phonon-mediated superconductivity that was predicted theoretically several decade ago. Therefore we speculate on that a new exotic mechanism might be possible for the occurrence of the high-$T_c$ superconductivity in MgB$_2$. In order to gain an insight into a possible mechanism, it is quite important to understand its pairing symmetry and a SC-gap structure.

In this letter, we report $^{11}$B-NMR study that has shed light on the above issues. Spin-lattice relaxation rate $(1/T_1)$ of $^{11}$B has been measured in a temperature ($T$) range of 15 - 260 K. We have found a $T_1T$=constant behavior in the normal state, and an exponential decrease of $1/T_1$ that was accompanied with a tiny coherence peak in the SC state. From the $T$ dependence of $1/T_1$ in the SC state that is consistent with an $s$-wave model with a larger isotropic gap of $2\Delta/k_BT_c \sim 5$ than the BCS value of 3.5, the superconductivity in MgB$_2$ is concluded to be in a strong coupling regime and suggested to be mediated by strong-electron phonon interactions.

A polycrystalline sample of MgB$_2$ was prepared as in reference. Electric resistivity and DC magnetization show the SC transition at 39 K. The bulk sample without powdering has been used for NMR measurements to avoid some crystal defects if any. $T_1$ was measured by monitoring the nuclear magnetization after a saturation rf-pulse under an external field $H =13.5$ kOe at a frequency $f=18.5$ MHz in the normal state and $H=44.2$ kOe at $f=60.4$ MHz in the SC state. $T_c$=29 K under $H=44.2$ kOe was determined from an ac-susceptibility that was measured using an “in-situ” NMR coil, as shown in an inset of Fig.1. The result is in good agreement with the references reported recently.

$^{11}$B-NMR spectrum has a simple shape with a full width at the half maximum of $\sim 10$ Oe. Its resonance peak does not show any $T$ dependence in the normal state within an experimental error of 2 Oe. $T_1$ measured at the peak in spectrum was determined by fitting the relaxation function of the nuclear magnetization $m(t)$ to the following theoretical two-exponential form.

$$m(t) = \frac{M(\infty)-M(t)}{M(\infty)} + \frac{M(t)}{M(\infty)} \exp \left(-\frac{t}{\tau_1}\right) + \frac{M(t)}{M(\infty)} \exp \left(-\frac{t}{\tau_2}\right).$$

Here $M(t)$ is the nuclear magnetization at time $t$ after saturation pulses. From good fits to this formula, $T_1$ was precisely determined over a measured $T$ range, although a short component of $T_1$ appears at low temperatures below 20 K, associated with the presence of vortex cores in the mixed state.

Figure 1 shows the $T$ dependence of $1/T_1$ in the $T$ range of 15 - 260 K. In the normal state, $1/T_1$ obeys a $T_1T$=constant relation with $T_1T = 1.8 \times 10^2$ (s·K) down to $T_c$. In the SC state, we have found a tiny coherence peak in $1/T_1$ just below $T_c$, followed by an exponential decrease of $1/T_1$.

In general, $1/T_1$ in the SC state is related to the density of states (DOS) in the SC state, $N_s(E)$ as follow,

$$\frac{1}{T_1} \propto \int_0^\infty (N_s(E)^2 + M(E)^2)f(E)(1-f(E))dE$$

where $M(E)$ and $f(E)$ are the so-called ”anomalous” DOS arising from the coherence effect of scattering inherent to a spin-singlet SC state and the Fermi-distribution.
function, respectively \[\delta.\] Note \(M(E) = 0\) in the case of spin-triplet pairing state. The \(T\) dependence of \(1/T_1\) is calculated by using a typical \(s\)-wave model where a phenomenological energy broadening function in \(N_s(E)\) is assumed to be of a rectangle type with a width \(2\delta\) and a height \(1/2\delta\) as presented by Hebel \[4\]. A calculation is shown by a solid curve in Fig.1. The \(T\) dependence of \(1/T_1\) except just below \(T_c\) can be well reproduced by the calculation that assumes the SC gap size of \(2\Delta/k_BT_c \sim 5\) and \(\delta/\Delta(0) \sim 1/3\). It should be noted that the \(T\) dependence of \(1/T_1\) cannot be reproduced by a model of the spin-triplet Balian-Werthamer (BW) state with an isotropic gap \[7\], therefore the spin-triplet state should be ruled out. Remarkable findings are in cuprates such as La\(_{2-x}\)Sr\(_x\)CuO\(_4\) that reveal a comparable \(T\) dependence of \(1/T_1\) with that in Chevrel-phase compound TlMo\(_6\)Se\(_{7.5}\) with \(T_c = 12.2\) \(K\) \[1\]. Therefore we conclude that the superconductivity in MgB\(_2\) is of a strong coupling regime. The SC-gap value larger than the weak-coupling BCS value suggests that the superconductivity is quite different from in cuprates. Rather the electron-phonon interactions may play an important role. We suggest that the high value of \(T_c\) in MgB\(_2\) may be due to the strong electron-phonon coupling via some phonon modes inherent to a light element of boron.

In conclusion, we report that the \(1/T_1\) of \(^{11}\)B decreases exponentially in the SC state, revealing a tiny coherence peak just below \(T_c\). The \(T\) dependence of \(1/T_1\) in the SC state can be accounted for by a spin-singlet \(s\)-wave model where \(2\Delta/k_BT_c \sim 5\) is substantially larger than the weak coupling BCS value of 3.5. It is suggested that the strong electron-phonon interaction may play an important role for the high temperature superconductivity in MgB\(_2\).

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FIG. 1: $T$ dependence of $^{11}(1/T_1)$ in MgB$_2$. Closed and open circles correspond to $1/T_1$ measured in the external field of 44.2 kOe and 18.5 kOe, respectively. A solid curve in the SC state shows the calculation using the typical $s$-wave model (see text). The inset shows $T$ dependence of ac-susceptibility in 44.2 kOe measured by an in-situ NMR coil. The arrows show an onset of the superconductivity under 44.2 kOe.
Fig. 1: Kotegawa et al.

Fig. 1: $T_c(H) \sim 29$ K

$H = 44.2$ kOe

$\sim T^3$

$\sim T$

$1/T_1$ (sec$^{-1}$)

$T$ (K)

MgB$_2$

$^{11}$B NMR

- $44.2$ kOe
- $13.5$ kOe

$T_c(H)$