Penetration Depth Measurements in MgB$_2$: Evidence for Unconventional Superconductivity

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(October 30, 2018)

We have measured the magnetic penetration depth of the recently discovered binary superconductor MgB$_2$ using muon spin rotation and low field ac-susceptibility. From the damping of the muon precession signal we find the penetration depth at zero temperature is $\sim 85$nm. The low temperature penetration depth shows a quadratic temperature dependence, indicating the presence of nodes in the superconducting energy gap.

The discovery of superconductivity in the simple binary compound MgB$_2$ with a remarkably high transition temperature $T_c \sim 30$K has attracted great interest [1]. MgB$_2$ is a hexagonal AlB$_2$-type compound, consisting of alternating hexagonal Mg layers and graphite-like B layers. To explore the mechanism of superconductivity in this material it is important to determine the symmetry of the superconducting order parameter which governs the behavior of quasiparticle excitations below $T_c$. Experimentally this can be done by measuring thermodynamic responses of superconducting quasiparticles at low temperatures. In conventional $s$-wave superconductors, there are no quasiparticle excitations at low energies and the thermodynamic and transport coefficients decay exponentially at low temperatures. However, in unconventional superconductors with gap nodes, such as in high-$T_c$ oxides, power law behaviors are expected in thermodynamic coefficients at low temperatures.

Recently, the scanning tunneling conductance [2,3], the nuclear spin-lattice relaxation rate [4] of MgB$_2$, and the specific heat [5] have been measured. Although it was claimed that the experimental data are consistent with a conventional $s$-wave pairing gap, the data reported are rather controversial and no consensus can really be reached regarding the pairing symmetry. The gap values obtained from the scanning tunneling measurements vary from 2meV to 7meV. The low temperature dependences of tunneling spectra reported by different experimental groups also behave differently. The difference in both the value of the energy gap and the low temperature dependence of the tunneling spectrum is probably due to the state of the surface, as well as the inhomogeneity of the samples measured. The spin-lattice relaxation rate measured by Kotegawa et al. [6] shows a very small coherence peak just below $T_c$, followed by an exponential decay in a broad temperature range. However, their measurement was done at relatively high temperatures (above 15K), and it is not known whether this exponential behavior extends to lower temperatures.

In this paper, we report our experimental data of the magnetic penetration depth $\lambda$ of MgB$_2$ in the superconducting state. We have measured $\lambda$ using the transverse-field muon spin rotation (TF-$\mu$SR) and low field ac-susceptibility. From both measurements, we find that at low temperatures $\lambda$ varies quadratically with temperature and does not show the activated exponential behavior expected for a conventional $s$-wave superconductor. This quadratic behavior of $\lambda$ indicates the existence of nodes in the superconducting energy gap of MgB$_2$.

The penetration depth is inversely proportional to the square root of the superfluid density. Its temperature dependence is a measure of the low-lying superconducting quasiparticle excitations and no phonon contribution is directly involved. This makes the analysis of penetration depth data simple. Another advantage of the penetration depth measurement is that it allows us to determine whether there are nodes in the superconducting energy gap even with slightly impure samples [8,9].

The sample measured was commercially available MgB$_2$ powder (Alfa Aesar). The superconducting transition temperature, as determined by both ac-susceptibility and dc-SQUID (at 20G) measurements, is 37.5K. High field dc-SQUID and electron microscopy investigations showed less than 1% of impurities present. The $ac$-susceptibility measurements were performed at an applied field $H_{ac}=1G$ RMS and frequency $f=333$Hz on fine powder. The absence of weak links was confirmed by checking the linearity of the pick-up voltage at 4.2K for $H_{ac}$ from 1 to 10G RMS and $f$ from 16 to 667Hz.

TF-$\mu$SR is a sensitive technique for measuring $\lambda$. In this technique, the field distribution of a flux-line lattice of a type-II superconductor produced by an applied magnetic field is probed by fully polarised positive muons implanted into a specimen. The muon decays with a life time 2.2$\mu$s, emitting a positron preferentially in the direction of the muon spin at the time of decay. By accumu-
tailing time histograms of the decay positrons the muon polarisation can be followed as a function of time. In type-II superconductors, the muon spin precesses about the local field which is modulated by flux vortices. The time resolved polarisation signal is oscillatory with a decreasing amplitude. The damping of the muon precession signal provides a measure of the inhomogeneity of the magnetic field ∆B in the vortex state, hence the magnetic penetration depth λ [4][22]. For polycrystalline samples the envelope of the muon precession signal has approximately a Gaussian form exp(−σ^2r^2/2) and the depolarisation rate σ can be shown to be proportional to the superfluid density 1/λ^2 [10][14]. For isotropic type II superconductors, λ is given by

\[ \lambda = \frac{\sqrt{\chi}}{g} \]

whereas for anisotropic superconductors such as the high-Tc cuprates, the in-plane penetration depth can be determined from Eq. [1]

\[ \sigma = 7.086 \times 10^4 \times \lambda^{-2}(\text{nm}) \]  

(2)

Evidence about the anisotropy of the superconductivity may be obtained from the form of the distribution of internal fields P(B), which can be derived by Fourier transforming the muon precession signal. Detailed information requires data from single crystals. However in powder samples of anisotropic superconductors it is found that the distribution P(B) has a characteristic shoulder on the low field side of the central frequency [13]. We used the maximum entropy method to extract P(B) from the TF-μSR data for MgB2. For temperatures just below Tc the low field shoulder is clearly evident, so we conclude that MgB2 is anisotropic.

Our TF-cooled μSR measurements were performed at the ISIS Facility, Rutherford Appleton Laboratory. The sample measured by TF-μSR was a pellet of MgB2, with 4cm in diameter and 2mm thick, prepared by cold pressing the powder. The pellet was mounted in a transverse magnetic field H_app which was above the lower critical field but below the upper critical field. Hc1 < H_app < Hc2. Hc1 and Hc2 of MgB2 are about 300G and 18T, respectively [4]. We used a field of 450G. (Measurements at not too high fields compared to Hc2 can minimise possible effects of dissipation due to flux motion and allow us to obtain reliable data for the temperature dependence of the relaxation rate σ [13].) A set of measurements at different fields (up to 600G) was also done to ensure that the values of σ obtained were independent of the applied field.

The low-field ac-susceptibility is also a commonly used technique for measuring λ. It has been successfully applied to high-Tc materials [13] and is particularly suitable for powder samples. The accuracy in the temperature dependence of λ determined from the ac-susceptibility technique is significantly higher than that of TF-μSR [13]. In the superconducting state, the effective ac-susceptibility χ of a powder sample is related to λ by the equation

\[ \chi(T) = \chi_0 \left(1 - \frac{3\lambda}{R} \coth \frac{R}{\lambda} + \frac{3\lambda^2}{R^2}\right), \]

(3)

where \(\chi_0\) is the susceptibility in an ideal diamagnetic system, R is the radius of a grain, and \(\langle \cdots \rangle\) denotes a grain average defined by \(\langle x \rangle \equiv \int dR x R^k g(R)/\int dR R^k g(R)\) with g(R) the grain size distribution function. At low temperatures, \(\chi(T)\) can be expanded with \(\delta \lambda(T) = \lambda(T) - \lambda_0\), where \(\lambda_0 = \lambda(0K)\). To the leading order in \(\delta \lambda\), we find

\[ \chi(T) \approx \chi(0) + \alpha \delta \lambda(T), \]

(4)

where

\[ \chi(0) = \chi_0 \left(1 - \frac{3\lambda_0}{R} \coth \frac{R}{\lambda_0} + \frac{3\lambda_0^2}{R^2}\right), \]

(5)

\[ \alpha = \chi_0 \left(\frac{6\lambda_0}{R} - 3 \coth \frac{R}{\lambda_0} - \frac{3R}{\lambda_0 \sinh^2[R/\lambda_0]}\right) < 0. \]

(6)

At low temperatures, the change in λ is proportional to the change in χ. Thus from the temperature dependence of \(\chi(T)\) (exponential or power law), one can readily determine the temperature dependence of \(\lambda(T)\) in the low temperature regime. However, to determine the absolute value of λ, we need to know accurately the grain distribution function g(R) which is beyond the scope of the present work.

![FIG. 1. The muon depolarisation rate σ for MgB2 and the corresponding penetration depth λ as determined from Eq. (6) versus temperature.](image)

Fig. 1 shows the temperature dependence of the muon depolarisation rate σ. At zero temperature we find that σ(0K) ∼ 10μs⁻¹. The corresponding in-plane penetration depth at 0K is λ0 ∼ 85nm. The temperature dependence of λ at low temperature is clearly stronger than...
the exponentially activated temperature dependence expected for an $s$-wave superconductor. In fact, we find that $\sigma$ varies approximately quadratically with $T$ in the whole temperature range below $T_c$ (Fig. 2). This is supported by our low temperature $ac$-susceptibility data shown in Fig. 3, which is related to the penetration depth by Eq. (4). This $T^2$ behavior of $\lambda$ at low temperatures shows unambiguously that there are nodes in the superconducting energy gap of MgB$_2$.

FIG. 2. The muon depolarisation rate $\sigma$ versus $T^2$.

The $\lambda$ values shown in Fig. 1 have been estimated using Eq. (2). If the electromagnetic response of MgB$_2$ is more isotropic, the values of $\lambda$ reported here need to be multiplied by a constant factor $c$ of order 1. In the extremely isotropic case $c = 1.06$. However, the $T^2$ dependence of $\lambda$ is unchanged.

The $T^2$ behavior of $\lambda$ at low temperatures is a typical feature of disordered superconductors with line nodes, such as the Zn-doped high-$T_c$ superconductor YBa$_2$Cu$_3$O$_7$ [13]. In fact as little as 0.31 percent Zn substitution can cause a crossover from a linear temperature dependence to $T^2$ without affecting $T_c$ [13]. In MgB$_2$ it has also been found that this $T^2$ behavior of $\lambda$ is robust against non-magnetic (Zn and Ca) doping [20].

In conclusion, we have measured the magnetic penetration depth of the newly discovered superconductor MgB$_2$ using the transverse-field muSR and low-field $ac$-susceptibility techniques. The value of $\lambda$ at 0K is about 85nm. $\lambda$ shows a $T^2$ dependence at low temperatures. This is strong evidence for unconventional superconducting pairing in MgB$_2$.

We are grateful to A.D. Taylor of the ISIS Facility, Rutherford Appleton Laboratory for the allocation of muon beam time. We thank J.R. Cooper for useful discussions and Y. Shi for help in the characterisation measurements. C.P. thanks the Royal Society for financial support. T.X. acknowledges the hospitality of the Interdisciplinary Research Center in Superconductivity of the University of Cambridge, where this work was done, and the financial support from the National Natural Science Foundation of China.

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