



Single gap s-wave superconductivity in Nb₂PdS₅



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ABSTRACT

Superconducting order parameter and its symmetry are important parameters towards deciphering the pairing mechanism in newly discovered superconducting systems. We report a study on penetration depth measurement on Nb₂PdS₅ that has recently been reported with extremely high upper critical field with possible triplet pairing mechanism. Our data show that at low temperatures the change in penetration depth $\Delta\lambda$ is best fitted with BCS s-wave model for single gap with zero-temperature value of the superconducting energy gap $\Delta_0 = 1.05$ meV, corresponding to the ratio $2\Delta_0/k_B T_c = 3.9 \pm 0.18$. The superfluid density in the entire temperature range is well described by single gap with gap ratio $2\Delta_0/k_B T_c = 4.1 \pm 0.13$ for $\lambda(0) = 225$ nm.

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1. Introduction

Recently superconductivity was reported in a quasi one-dimensional compound Nb₂PdS₅ with superconducting transition temperature (T_c) of ~ 6 K and extremely high upper critical field $H_{c2} \sim 35$ T [1]. This value exceeds the Pauli paramagnetic limit $H_{c2}(0) = 1.84T_c$ by over 3 times [1–4]. The highly anisotropic upper critical field ($\Gamma \sim 6$) along with temperature dependent anisotropy was indicative of possible multiband superconductivity [1,5]. Concepts related to strong spin-orbit scattering (due to the presence of Pd) and spin triplet pairing mechanism were invoked to explain the highest ever reported $H_{c2}(0)/T_c$ value. The high H_{c2} value and the presence of chalcogen in the layered structure are reminiscent of Chevrel phase compounds such as PbMo₆S₈ [6,7] and SnMo₆S₈ [8] but still there is no clarity on the macroscopic origin of superconductivity in Nb₂PdS₅.

The band structure calculations show that the Fermi surface is composed of multiple sheets with both quasi-two-dimensional (Q2D) of hole character and quasi-one-dimensional (Q1D) sheets of both hole and electron character that may give rise to multiband superconductivity in this compound [1,5]. Multiband superconductivity is also predicted for similar quasi one-dimensional isomorphous Nb₂Pd_xSe₅ and Ta₂Pd_xS₅ compounds [9,10] and the analysis on Nb₂PdS₅ would also shed light on such high H_{c2} anisotropic compounds. As evidenced in many superconducting systems, radio frequency (RF) penetration depth study has been proved extremely

useful in establishing d wave superconductivity in cuprate [11,12], s± wave symmetry in iron pnictide [13] and two gap superconductivity in MgB₂ superconductors [14]. In this paper we report a similar study on the symmetry of the superconducting order parameter and superconducting gap by penetration depth measurement of Nb₂PdS₅ using tunnel diode oscillator technique. Results from our study show that the data are best described by s-wave model with superconducting gap $2\Delta_0/k_B T_c = 3.9$ which is higher than the weak coupling BCS value suggesting Nb₂PdS₅ to be an intermediate-strong coupling superconductor.

2. Experimental

Polycrystalline sample of Nb₂PdS₅ were prepared by solid state reaction method as described elsewhere [4]. Resistivity measurement was done using four probe method in Cryogenic low temperature and high magnetic field Cryogen Free system in conjunction with variable temperature insert. Tunnel diode oscillator technique was used to study London penetration depth in Nb₂PdS₅ superconductor. This technique gives change in penetration depth with temperature [15]. It consists of an LC circuit made up of copper coil inductor and a capacitor connected in parallel and is driven to resonance using a tunnel diode oscillator. The sample is kept inside this copper coil and cooled below its transition temperature. The frequency of the LC circuit is given by, $2\pi f = 1/(LC)^{1/2}$ which is 2.3 MHz for our apparatus. The inductance L of the coil is directly proportional to the cross sectional area occupied by the magnetic flux passing through the coil. Thus as sample temperature decreases below T_c , the amount of magnetic flux passing through the coil also decreases and hence results in a change

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in frequency of the LC circuit. This change in frequency is proportional to the magnetic susceptibility of the sample. If f_0 is the frequency of empty coil and f_s is the frequency of coil with sample then the shift in resonant frequency $\Delta f = f_s - f_0 = -4\pi\chi G$ where χ is the total magnetic susceptibility and G is the geometric calibration defined by the geometry of coil and sample. For our apparatus we have calculated the G by taking pure niobium sample of similar dimensions as of our sample and fitting its low temperature penetration data with isotropic BCS s-wave equation. The value of G thus comes out to be $2.27 \text{ \AA/Hz}$. The susceptibility in the Meissner state is related to the penetration depth with the formula as $-4\pi\chi = \frac{1}{(1-N)}[1 - \frac{\lambda}{R} \tanh(\frac{R}{\lambda})]$ where R is the effective dimension of the sample [16].

An oven stabilized frequency counter (Agilent 53131A) was used for measurements of frequency, whereas, the sample temperature was measured using Lakeshore Temperature Regulator 340. The ac field of the coil is $\sim 1 \mu\text{T}$ which is much less than the lower critical field for the sample $\sim 150 \text{ G}$ thus the sample remains in Meissner state below its transition temperature.

3. Result and discussions

Fig. 1 depicts the room temperature observed and fitted X-Ray diffraction (XRD) patterns for as synthesised Nb_2PdS_5 . The studied sample is crystallized in Centro-symmetric structure with C2/m space group. The lattice parameters are $a = 12.132(2) \text{ \AA}$, $b = 3.2774(3) \text{ \AA}$, and $c = 15.024(1) \text{ \AA}$. These are in agreement with earlier reports [1–4]. The inset of Fig. 1, shows the DC magnetic susceptibility of the studied Nb_2PdS_5 compound with superconducting transition temperature (T_c) at below around 6 K. The shielding fraction (ZCF) is close to 90%. It is clear that the studied Nb_2PdS_5 is bulk superconducting below say 6 K. This is in agreement with earlier reports on this compound [1–4].

Fig. 2 confirms the superconductivity in Nb_2PdS_5 sample. Left axis of Fig. 2 shows the temperature dependence of sample frequency. Sample frequency shows a sharp decrease at 6.25 K which is indicative of superconducting transition. The sudden decrease in frequency occurs when sample goes from superconducting to normal state thereby allowing magnetic flux to pass through it. The right axis shows electrical resistivity as a function of temperature. The resistivity shows superconducting transition with $T_{c\text{-onset}}$ at 6.4 K and $T_{c\text{-zero}}$ at 6.0 K.

Fig. 3 shows change in penetration depth as a function of temperature normalized with the total change in penetration depth down to lowest measured temperature. The Fig clearly shows the superconducting transition at 6.25 K.

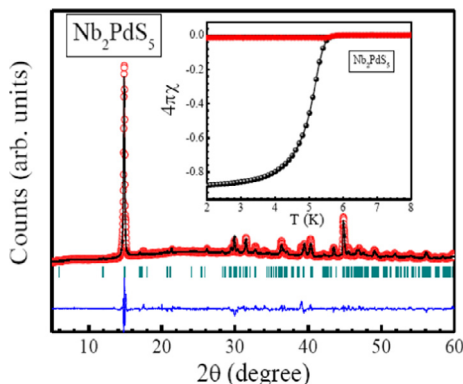


Fig. 1. Room temperature XRD pattern of studied Nb_2PdS_5 , inset shows both zero-field cooled (ZFC) and field cooled (FC) magnetic susceptibility of the sample.

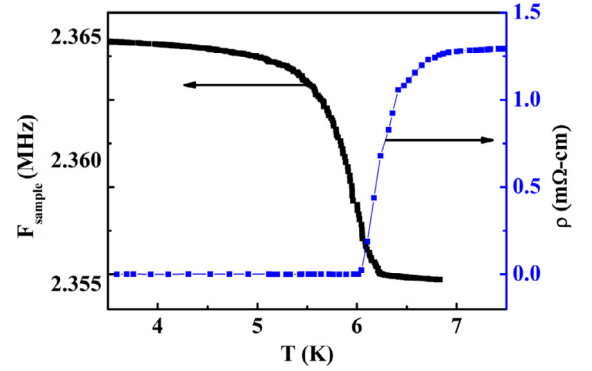


Fig. 2. Left axis shows the temperature dependence of sample frequency with superconducting transition at 6.25 K. Right axis shows the temperature dependence of resistivity with $T_{c\text{-onset}}$ at 6.4 K and $T_{c\text{-zero}}$ at 6.0 K.

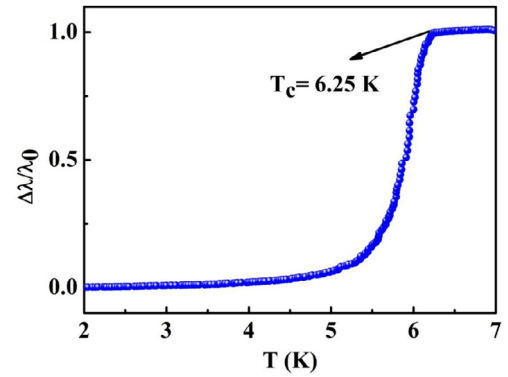


Fig. 3. Change of the penetration depth $\Delta\lambda$ normalized to total shift down to 1.68 K, which reveals a sharp superconducting transition at $T_c \sim 6.25 \text{ K}$.

For an isotropic one-gap BCS model the $\Delta\lambda$ at $T \ll T_c$ follows as;

$$\Delta\lambda(T) = \lambda(0) \sqrt{\frac{\pi \Delta_0}{2k_B T}} \exp\left(-\frac{\Delta_0}{k_B T}\right) \quad (1)$$

where, $\lambda(0)$ and Δ_0 are the values of penetration depth λ and the superconducting energy gap Δ at $T = 0 \text{ K}$ [17,18]. The same exponential temperature dependence of $\Delta\lambda$ is valid for superconductor with a nodeless anisotropic energy gap or distinct gaps on different Fermi-surface sheets but in that case, $\lambda(0)$ gives effective value that depends on the details of the gap anisotropy and Δ_0 approximately equals to the minimum energy gap in the system [17]. Whereas for d-wave pairing in the clean limit,

$$\Delta\lambda(T) \approx \lambda(0) \frac{2\ln 2}{\alpha \Delta_0} T \quad (2)$$

where $\alpha = \Delta_0^{-1} [d\Delta(\phi)/d\phi]_{\phi \rightarrow \phi_{\text{node}}}$ and $\Delta(\phi)$ is the angle dependent gap function [19]. In case of dirty limit, d-wave gap is suppressed and the temperature dependence changes from linear behavior to power law [19]; $\Delta\lambda \sim T^2$

Fig. 4 shows low temperature dependence of change in penetration depth $\Delta\lambda$ of Nb_2PdS_5 along with the fittings of a conventional BCS model (solid black line) and quadratic temperature dependence (red line). Clearly the s-wave BCS model proves to be a better fit for the data as compared to quadratic temperature dependence for d-wave pairing. This rules out the possibility of d-wave pairing in this compound. At low temperature $T/T_c < 0.5$, fitting parameters obtained from s-wave BCS model are gap ratio $2\Delta_0/k_B T_c = 3.9 \pm 0.18$ and the corresponding value of energy gap $\Delta_0 \sim 1.05 \text{ meV}$. This value of gap ratio is slightly higher than the

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