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Isotropic s-wave pairing symmetry in non-centrosymmetric Re_3W revealed by point-contact spectroscopy

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Abstract

We use point-contact spectroscopy to study the temperature and magnetic field dependence of the superconducting gap of a non-centrosymmetric superconductor Re_3W for the first time. The spectra can be fitted very well to the isotropic s-wave BTK theory. The superconducting gap determined depends on the temperature and magnetic field in the same way as expected for the weak-coupling s-wave BCS superconductors. These results suggest that the contribution of the spin-triplet pairing channel can be negligible in the Re_3W system.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Non-centrosymmetric material has attracted more and more attention recently [1–16]. For most superconductors, due to Pauli's exclusion rule and parity conservation, the Cooper pair with orbital even parity should have an anti-parallel spin state, namely a spin singlet, while those having orbital odd parity should have a parallel spin state, i.e. a spin triplet. In a non-centrosymmetric system, however, the parity is not a good quantum number since the inversion symmetry is broken (due to the anti-symmetric spin–orbit interaction). Hence a pairing state with a mixed singlet–triplet character is expected. Most recently, the line nodes have indeed been observed in some non-centrosymmetric superconductors, such as $\text{Li}_2\text{Pt}_2\text{B}$ [2, 3] and CePt_3Si [4–8], indicating the significant contribution of the spin-triplet channel. On the other hand, in a non-centrosymmetric superconductor $\text{Li}_2\text{Pd}_2\text{B}$ which has the same structure as that of $\text{Li}_2\text{Pt}_2\text{B}$, a spin-singlet-dominated pairing was revealed by both NMR [9] and penetration depth measurement [2]. The striking difference between the isostructural $\text{Li}_2\text{Pt}_2\text{B}$ and $\text{Li}_2\text{Pd}_2\text{B}$ was ascribed to the larger atomic number of Pt than that of Pd, which enhances the spin–orbit coupling. Recently, a new non-centrosymmetric superconductor $\text{Mg}_{12-\delta}\text{Ir}_{19}\text{B}_{16}$ was discovered [10] and the specific heat measurements on

this sample revealed evidence supporting a possible nodeless superconductivity [11]. In order to get further insight into the correlation of the broken inversion symmetry and the pairing symmetry, more heavily non-centrosymmetric systems containing heavy atoms need to be studied extensively. Besides the samples mentioned above, Re_3W is another good choice for this purpose since it is a heavily non-centrosymmetric system [12, 17, 18] and the atomic numbers of Re and W are 75 and 74, respectively, being close to that of Ir and Pt. Surprisingly, recent penetration depth measurements suggested that Re_3W is a weak-coupling, dirty-limit, s-wave BCS superconductor [12]. It is also noted that most of the experiments on non-centrosymmetric superconductors (including specific heat and penetration depth) are phase-irrelevant.

In this paper, we report the Andreev reflection spectra of the Au-tip/ Re_3W point-contact junctions, which is a phase-relevant experiment. By comparing the spectra measured at various temperatures and magnetic fields with the generalized Blonder–Tinkham–Klapwijk theory [19, 20], we demonstrate that the superconducting gap of Re_3W is almost perfectly isotropic without any sign change in the momentum space. The temperature and field dependence of the gap value is in good agreement with that of the conventional s-wave BCS superconductors. Thus the spin-triplet pairing channel can be

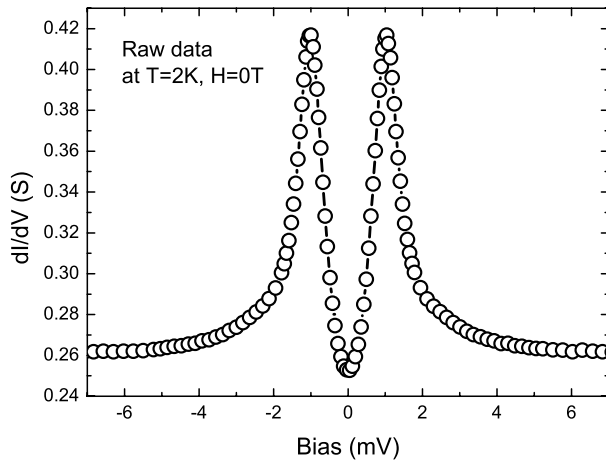


Figure 1. Raw data of the point-contact spectra of Re_3W measured at $T = 2 \text{ K}$ and $H = 0 \text{ T}$.

negligible in this system, which is consistent with recent results of penetration depth measurements [12].

2. Experiment

The Re_3W alloy studied in this work was prepared by arc melting pure Re and W in a Ti-gettered argon atmosphere [21]. The synthesized sample is a firm drop with a shiny surface. The major phase in the sample has a critical temperature of $T_c = 7.4 \text{ K}$. A minor phase with $T_c = 9.0 \text{ K}$ is also detected by ac susceptibility measurement. Both phases are proved to be non-centrosymmetric with a so-called α -Mn or A12 structure [12]. In our spectrum measurement, only the major phase was detected and can be readily compared with the results reported in [12]. The point-contact junctions were prepared by driving a mechanically sharpened Au tip (made of a ϕ 0.25 mm gold wire) towards the shiny surface of the Re_3W with a fine differential screw. The experimental environment of low temperature down to 2 K and high magnetic field up to 12 T was provided by an Oxford cryogenic system (Maglab-Exa12).

3. Results and discussions

Figure 1 shows the Andreev reflection spectrum measured at $T = 2 \text{ K}$ and $H = 0 \text{ T}$. These two sharp Andreev reflection peaks at about $\pm 1.05 \text{ mV}$ and the dip around zero energy indicate that the interfacial barrier of the junction is far from the quasiparticle tunneling regime and hence the contribution from the superfluid (and/or Cooper pairs) is significant. The spectrum is symmetric by zero energy and the high bias normal conductance is a constant, which is consistent with the situation of a conventional metallic superconductor. Therefore, the raw data can be easily normalized by dividing it by the constant high bias normal conductance in order to be compared with theoretical calculation.

We use the extended BTK model [19, 20] to simulate the Andreev reflection spectra, in which the anisotropy of the gap function can be taken into account. It is well known that, if

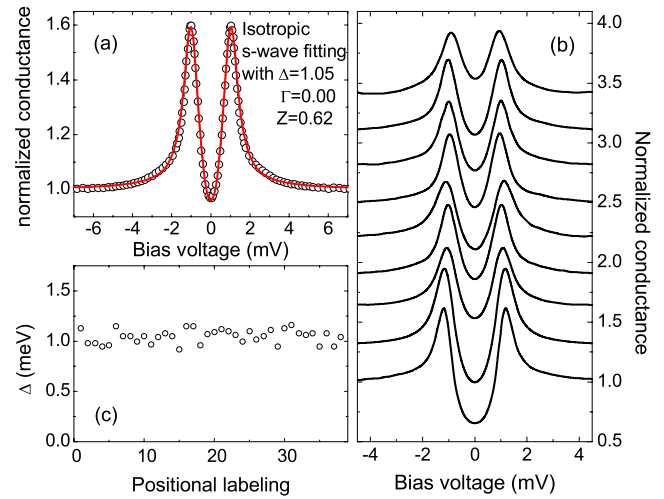


Figure 2. (a) Comparison of the experimental data with the calculation according to the isotropic s-wave BTK model with $Z = 0.618$, $\Delta = 1.05$ and $\Gamma = 0.00$. (b) The spectra measured at various locations on the sample surface. (c) The statistics of the gap values determined from many measurements.

there exists a node (either a line node or point node) in the gap function, a zero-bias conductance peak (ZBCP) is formed for all directions (under a finite interfacial barrier) except when current is injected into the anti-nodal directions [20]. Therefore, a ZBCP should be frequently observed in the spectra of a non-centrosymmetric superconductor if the spin-triplet pairing is dominated, which is similar to the case of high-temperature cuprate superconductors with a d-wave pairing symmetry. On the other hand, as long as the singlet channel is mixed with the triplet channel, the observable gap function should be anisotropic to a certain extent determined by the significance of the triplet channel. However, there is an obstruction to accurately distinguishing the anisotropy or nodal character from the point-contact spectra. As pointed out by Plecenik *et al* [22], if the interface of the point-contact junction is not clean enough, various scattering effects will smear the measured spectrum. In this case, in order to fit the experimental data, the quasiparticle energy E should be replaced by $E + i\Gamma$ in the extended BTK model, where Γ is the broadening parameter characterizing the finite lifetime of the quasiparticles due to inelastic scattering near the N/S micro-constriction. Such a Γ factor will also be introduced by the interior inelastic scattering of a superconductor itself [23]. Consequently, if the Γ value is very large, we could not obtain any detailed information about the gap function, while this is important to judge the existence of the singlet–triplet mixture. As elaborated below, we have successfully prepared high-quality point-contact junctions with $\Gamma \approx 0$ and hence ruled out the possible confusion caused by interface scattering.

As a first approximation, we consider the case of an s-wave gap without any anisotropy. Figure 2(a) shows the theoretical simulation with an isotropic s-wave gap function. The parameters used of Δ , Γ and Z are superconducting gap, broadening factor and effective barrier height, respectively. As mentioned above, the Γ value is very close to zero, providing a good chance to detect the intrinsic property of

the sample. The determined superconducting gap $\Delta = 1.05$ is in good agreement with the value probed by penetration depth [12]. We have measured many spectra by randomly selecting the positions on the sample surface to make point-contact junctions. Figure 2(b) shows some of the spectra measured at various locations on the sample surface. It is obvious that all the data have a similar shape with two clear Andreev reflection peaks. The energy scales of the peaks vary slightly, suggesting that the superconducting gap is insensitive to the studied position and the direction of the injected current. By fitting the experimental data to the isotropic s-wave BTK model, we find that the difference of the various measurements is the barrier height at the interface (varying from 0.52 to 0.80), while the determined superconducting gap has an almost identical value of 1.05 meV with a small distribution between $\pm 10\%$, as presented in figure 2(c).

BTK theory deals with the ballistic or Sharvin regime in which the lateral dimension of a contact is smaller than the mean free path of the electrons. In order to check the validity of BTK theory for explaining our data, we have estimated the size of the point contacts using the formulas of $R = R_0(1+Z^2)$ and $R_0 = l\rho/4a^2$. Here the resistivity of Re_3W is about $44 \mu\Omega \text{ cm}$, where the mean free path of an electron l is about $15 \text{ \AA}$ obtained from the resistivity measurement, $Z \approx 0.62$, and the junction resistance $R \approx 20 \Omega$ was obtained from the experiments. Thus the size of the contact was found to be $a \approx 34 \text{ \AA}$, which is close to $l = 15 \text{ \AA}$, indicating that our point-contact junctions are between the diffusive limit and the ballistic limit. Although these two limits have different formulas to fit the experimental data, the determined superconducting gap values from them are very close to each other. The major difference between these two limits is the different Z values determined from them [24, 25]. On the other hand, a point-contact junction usually contains a large number of randomly distributed individual contacts [26, 27]. Each individual contact has bigger resistance and smaller size and hence is still possible to locate in the ballistic limit.

It is noted that no ZBCP was observed among all the measurements. As mentioned above, since our sample is a polycrystalline alloy, if some nodes exist in the gap function, a ZBCP should be observed frequently with a magnitude depending on the practical direction of the injecting current. In figure 3(a), we present a demonstration of a ZBCP showing up in a nodal superconductor. In the calculation, we only consider a two-dimensional nodal gap function for simplicity. As shown in figure 3(b), the selected gap function is consistent with cubic symmetry and qualitatively similar to the assumption of [2] in its physics. The fourfold symmetric petal-shaped pieces and the dark spiny pieces have two opposite signs. The nodes in this gap function are due to the spin-triplet-dominated pairing symmetry. In order to calculate the spectra for such an anisotropic gap, we use the extended BTK model in which another parameter of α has to be introduced to take into account the current-injecting direction compared to the crystalline axis. Figure 3(a) shows the calculated spectra for different current-injecting directions. When the injecting direction varies from 0° to 45° , the shape of the spectrum is modified remarkably. Most importantly, if the injecting direction deviates from the

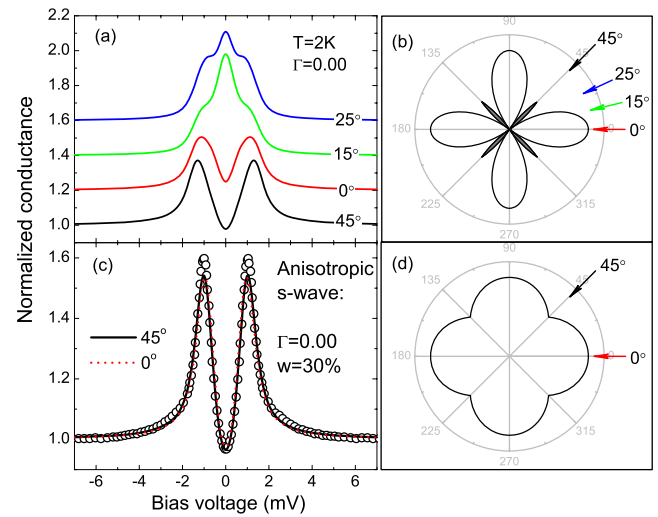


Figure 3. (a) The dependence of the spectra on the current-injecting direction, which is calculated according to the extended BTK model with a nodal gap function as shown in (b). (b) The simplified two-dimensional gap function with some nodes used in (a). The fourfold petal-shaped pieces and the spiny pieces have two opposite signs. (c) Comparison of the experimental data and the calculations according to the extended BTK model with a slightly anisotropic gap function with an anisotropy ratio of $w = 30\%$. (d) The anisotropic gap function used in (c). The arrows in (b) and (d) indicate the current-injecting directions.

symmetry axes (such as 0° and 45°), a ZBCP appears on the spectrum due to the anti-symmetry of the sign of the gap function. In other words, the non-existence of ZBCP on the measured spectra for random injecting directions indicates that Re_3W is most probably a nodeless superconductor. As another proof of this judgment, the experimental data have much higher Andreev reflection peaks than the theoretical expectations for the strongly anisotropic gap function with nodes since the spectra are remarkably dispersed in this case. There is still another possibility for the indistinguishability of the nodes in this system. It has been noted that our Re_3W sample is in the dirty limit with $l_{\text{mf}} \ll \xi_{\text{BCS}}$, where ξ_{BCS} is the BCS coherence length and l_{mf} is the mean free path of the quasiparticle, which is similar to the case of [12]. Therefore, the disorder-induced scattering may smear the nodes in the gap function. However, this will also induce a finite quasiparticle density of states around the nodes and hence enhances the Γ value by fitting to the BTK model, which is obviously not the case in our investigation. Therefore, it can be safely concluded that the spin-triplet pairing is not dominated in the heavily non-centrosymmetric superconductor Re_3W .

As presented in [2], if the spin singlet and spin triplet is mixed while the former is dominated, the gap function should be anisotropic s-wave-like. Hereafter, we try to estimate the anisotropy by fitting our data to the anisotropic s-wave BTK model with a gap function illustrated in figure 3(d). As shown in figure 3(c), when the anisotropy ratio (defined as $w = (\Delta_{\text{max}} - \Delta_{\text{min}})/\Delta_{\text{max}}$) reaches 30%, the theoretical calculation substantially deviates from the experimental data. Therefore, the anisotropy ratio of the gap function of Re_3W should be lower than 30%. Although this estimation is simplified,

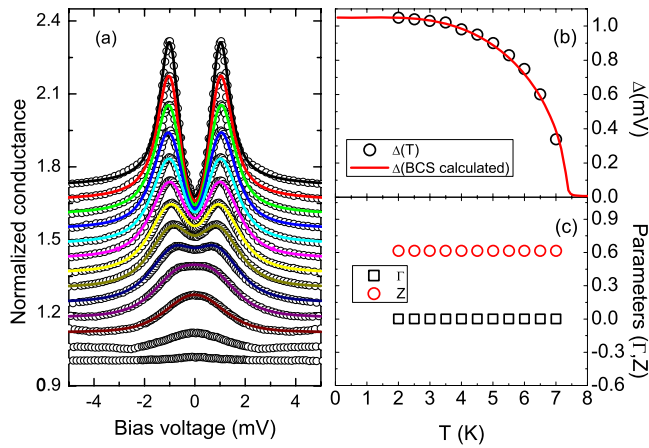


Figure 4. (a) Normalized spectra (open circles) for various temperatures measured in zero field. All the curves except the lowest one are offset vertically for clarity. The corresponding temperatures from top to bottom are from 2 to 8 K in steps of 0.5 K. The isotropic s-wave BTK fitting curves are shown by the solid lines superimposed on the experimental data. (b) The obtained temperature dependence of the superconducting gap: the solid line indicates the prediction of BCS theory. (c) The other two parameters used in the fitting process, i.e. the broadening parameters Γ and the effective barrier height Z .

it presents qualitative evidence that the spin-singlet pairing should be dominated in this system, which is similar to the case of $\text{Li}_2\text{Pd}_2\text{B}$, although Re and W atoms are heavier than the Pd atoms. If this viewpoint is correct, the conventional behaviors of the superconductivity of Re_3W should be expected, such as its temperature and field dependences, as elaborated below.

Figure 4(a) shows the spectra measured at various temperatures from 2 to 8 K. The normalized spectra evolve continuously with increasing temperature and finally into a featureless normal conductance at $T = 8$ K. We can roughly estimate the low-temperature superconducting gap as $\Delta \approx 1.05$ directly from the position of the Andreev reflection peaks. The more accurate result of the Δ versus T relation can be obtained by fitting the data to the isotropic s-wave BTK model in the same way we used in figure 2(a). The temperature dependence of all the determined parameters of Δ , Γ and Z are shown in figures 4(b) and (c). The effective barrier height ($Z = 0.62$ in this figure) remains constant at various temperatures, demonstrating the high stability of the point-contact junctions. The Γ value is very close to zero, indicating an ideal interface of the junction. Furthermore, the temperature independence of the broadening factor Γ is similar to the case of the conventional superconductors such as Zn [28] and Nb [27]. Thus no obvious inelastic scattering process was involved in our measurements. As shown in figure 4(b), the temperature dependence of the superconducting gap determined here is in good agreement with BCS theory, presenting strong evidence of the conventional pairing mechanism of Re_3W . The local $T_c \approx 7.4$ is then obtained by extrapolating $\Delta(T)$ to zero, and the gap ratio is determined as $\Delta(0)/k_B T_c \approx 1.65$, which is very close to the value of 1.76 expected by the weak-coupling BCS theory. The somewhat lower value here may be due to the slight anisotropy discussed above. $T_c \approx 7.4$ K is in good

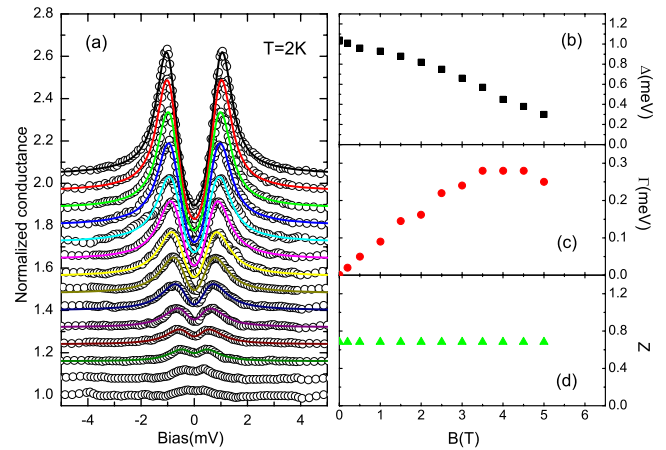


Figure 5. (a) Normalized spectra (open circles) for various magnetic fields measured at 2 K. All the curves except the lowest one are offset vertically for clarity. The corresponding fields from top to bottom are 0 T, 0.2 T, 0.5 T, 1 T, 1.5 T, 2 T, 2.5 T, 3 T, 3.5 T, 4 T, 4.5 T, 5 T, 5.5 T and 6 T, respectively. The solid lines superimposed on the measured spectra are the fitting results according to the isotropic s-wave BTK model. The fitting parameters are shown in (b) Δ , (c) Γ and (d) Z .

agreement with that reported in [12], indicating the same phase was measured in these two works.

Figure 5 shows the spectra measured in various applied fields at a very low temperature of 2 K. The distance between the two Andreev reflection peaks shrinks continuously with increasing field, showing the field-induced suppression of the superconducting gap (or pairing strength). At the upper critical field around 6 T, a constant normal conductance is recovered. We have done the same fitting process as discussed above. The parameters determined are shown in figures 5(b)–(d). Again, the barrier height Z remains constant for all fields, indicating the high stability of the junctions. The monotonic increase of Γ indicates the field-induced de-pairing effect and/or the dispersion of the pairing strength. As presented in figure 5(b), the averaged gap value decreases continuously with increasing field until the upper critical field. Combining the temperature and field dependences of the superconductivity in Re_3W , no unconventional behaviors related to novel pairing symmetry or a multi-band effect can be observed. All the results presented here are very similar to that of a conventional single-band superconductor.

4. Conclusion

In summary, we have successfully prepared high-quality point-contact junctions on the non-centrosymmetric superconductor Re_3W . The Andreev reflection spectra (phase related) were then studied in detail and a nodeless gap function was undoubtedly demonstrated in this system. Both the temperature and the field-dependent data presented strong evidence that Re_3W is a weak-coupling s-wave BCS superconductor. The negligible contribution of spin-triplet pairing in this heavily non-centrosymmetric system is thus worth considering further in order to shed light on the relationship between the pairing symmetry and the inversion-symmetry breaking.

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