

Isotropic superconductivity in LaRu_2P_2 with the ThCr_2Si_2 -type structure

To cite this article: J J Ying *et al* 2010 *Supercond. Sci. Technol.* **23** 115009

View the [article online](#) for updates and enhancements.

You may also like

- [NMR and NQR studies on transition-metal arsenide superconductors \$\text{LaRu}_2\text{As}_2\$, \$\text{KCa}_2\text{Fe}_4\text{As}_4\text{F}_2\$, and \$\text{A}_2\text{Cr}_3\text{As}_3\$](#)
Jun Luo, , Chunguang Wang *et al.*
- [Observation of parabolic electron bands on superconductor \$\text{LaRu}_2\text{As}_2\$](#)
Xingtai Zhou, , Geng Li *et al.*
- [Large magnetoresistance in the iron-free pnictide superconductor \$\text{LaRu}_2\text{P}_2\$](#)
Marta Fernández-Lomana, Víctor Barrena, Beilun Wu *et al.*

Isotropic superconductivity in LaRu_2P_2 with the ThCr_2Si_2 -type structure

J J Ying, Y J Yan, R H Liu, X F Wang, A F Wang, M Zhang,
Z J Xiang and X H Chen¹

Hefei National Laboratory for Physical Science at Microscale and Department of Physics,
University of Science and Technology of China, Hefei, Anhui 230026,
People's Republic of China

E-mail: chenxh@ustc.edu.cn

Received 11 July 2010, in final form 14 September 2010

Published 5 October 2010

Online at stacks.iop.org/SUST/23/115009

Abstract

The anisotropic superconducting properties of the LaRu_2P_2 single crystal have been systematically investigated by magnetic and transport measurements. Both the upper critical field (H_{c2}) and the lower critical field (H_{c1}) show isotropic behavior, indicating the three-dimensional nature of its Fermi surface topology. This behavior is very much like that observed in iron-based superconductors. Weak vortex pinning was observed through magnetic measurement. The penetration depth and coherent length were estimated from upper and lower critical fields at zero temperature. The negative Hall coefficient indicates that the carrier is electron-type. The carrier density is about one order of magnitude larger than that of electron-doped iron-based superconductors.

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

The newly discovered iron-based high temperature superconductors provide a new family of materials to explore the mechanism of high- T_c superconductivity besides high- T_c cuprate superconductors [1–3]. Those with the ThCr_2Si_2 structure like hole-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ and electron-doped $\text{BaFe}_{2-x}\text{Co}_x\text{As}_2$ have been widely investigated [4–7]. Besides iron arsenide compounds, earlier works had already found other superconductors with the same crystal structure as BaFe_2As_2 . Ruthenium phosphide LaRu_2P_2 was found to be superconducting at about 4 K more than 20 years ago [8]. However, due to its low T_c , little work is focused on this material. Similar to the cuprates, both the iron-based superconductors and LaRu_2P_2 have a two-dimensional crystal structure. However, in contrast to the cuprates, the iron-based superconductors show a nearly isotropic superconducting property, which is probably attributed to the unique three-dimensional nature of its Fermi surface topology [9, 10]. This isotropic superconductivity is drastically different from the other layered superconductors. It is very meaningful to investigate the anisotropy of the isostructural superconductor LaRu_2P_2 and to find its correlation to the iron-based superconductors. Comparing the physical properties of LaRu_2P_2 with

iron-based superconductors may uncover the intrinsic high- T_c nature in iron-based superconductors.

LaRu_2P_2 is one of the members of ternary phosphides containing lanthanides and transition metals. This type of material has attracted much attention and showed a variety of interesting phenomena according to the composition of lanthanides and transition metals [11, 12]. The role of transition metal elements in the magnetism and the transport properties of this kind of material are attractive issues. Relatively high T_c for the other ruthenium phosphide superconductors were found in ZrRuP ($T_c = 13$ K) [13] and $\text{LaRu}_4\text{P}_{12}$ ($T_c = 7.2$ K) [14]. The origin of the superconductivity in these materials is an interesting problem.

In this brief paper, we systematically investigated the anisotropy of upper and lower critical fields in LaRu_2P_2 from the resistivity and magnetic measurements. Both the H_{c1} and H_{c2} show isotropic superconductivity in LaRu_2P_2 . The isotropic superconductivity is similar to the iron-based superconductors. We estimated the magnitude of some basic characteristic parameters in LaRu_2P_2 . The magnetic measurement indicates very weak vortex pinning in the superconducting state. The negative Hall coefficient indicates that the carrier type is electron. The carrier density is about

¹ Author to whom any correspondence should be addressed.

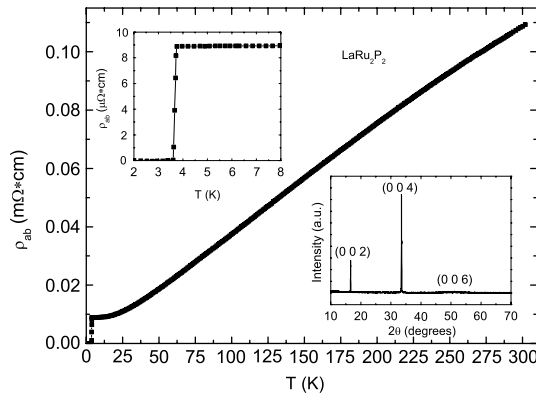


Figure 1. Temperature dependence of in-plane resistivity for the single crystals of LaRu_2P_2 . The lower inset shows the single-crystal x-ray diffraction pattern of LaRu_2P_2 . Only (00/) diffraction peaks show up indicating that the c axis is perpendicular to the plane of the plate. The upper inset shows the enlarged resistivity curve below 8 K.

one order of magnitude larger than that in the electron-doped $\text{BaFe}_{2-x}\text{Co}_x\text{As}_2$ system.

High quality single crystals of LaRu_2P_2 were grown by the Sn flux method. Raw materials of La (filings), Ru (powder) and P (powder) were mixed with Sn flux in a mol-ratio of 1:2:2:20. The mixture was loaded into an alumina crucible and then sealed under vacuum in a quartz tube. The quartz tube was slowly heated to 1473 K at a rate of 100 K h^{-1} and kept at 1473 K for 12 h, then the tube was cooled to 1173 K very slowly at a rate of 3 K h^{-1} . Finally the quartz tube was cooled in the furnace after shutting off the power. Plate-like single crystals can be obtained by dissolving the Sn flux in an aqueous solution of hydrochloric acid. Resistivity in magnetic fields and Hall coefficients were measured by a Quantum Design physical property measurement system (PPMS). Magnetic susceptibility was measured by a vibrating-sample magnetometer (VSM).

Single crystals of LaRu_2P_2 were characterized by x-ray diffraction (XRD) using $\text{Cu K}\alpha$ radiation. As shown in the lower inset of figure 1 only (00/) diffraction peaks were observed, suggesting that the crystallographic c axis is perpendicular to the plane of the single crystal. The lattice constant of the c axis was determined to be 1.067 nm. Figure 1 shows the temperature dependence of the resistivity for the current flowing in the ab plane of LaRu_2P_2 . At high temperature, the resistivity is metallic in nature with ρ_{ab} increasing almost linearly with increasing temperature. With temperature decreasing, the resistivity gradually deviates from T -linear behavior and the superconductivity emerges. The value of ρ_{ab} at 300 K is about $110 \mu\Omega \text{ cm}$ and the residual resistivity is about $8.9 \mu\Omega \text{ cm}$, which leads to the residual resistivity ratio ($\text{RRR} = \rho_{ab}(300 \text{ K})/\rho_{ab}(4 \text{ K})$) of approximately 12.4. The value of the residual resistivity is much smaller than that in 122 iron-based superconductors. The critical temperature determined from the midpoint of the resistive transition is 3.7 K. The 10–90% width in zero field is 0.1 K as shown in the upper inset of figure 1.

Figures 2(a) and (b) show the temperature dependence of in-plane resistivity at various fields applied perpendicular

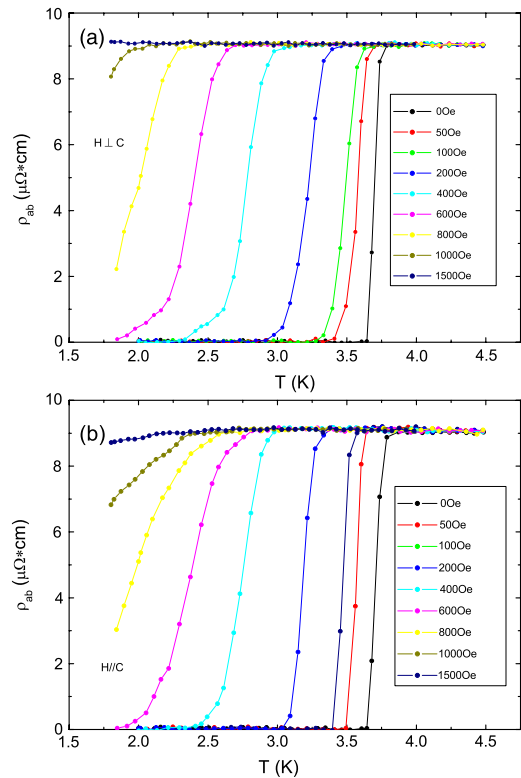


Figure 2. Temperature dependence of in-plane resistivity for the magnetic field (a) parallel and (b) perpendicular to the plane.

and parallel to the c axis, respectively. The broadening of the resistive transition with increasing magnetic field is not pronounced. The transition temperature of superconductivity is suppressed gradually with increasing magnetic field. We defined the midpoint of the resistive transition as $T_c(H)$. The transition temperature falls below 1.8 K after applying 1000 Oe magnetic field both along and perpendicular to the ab plane. Both the transition temperature and the upper critical field are much lower than that in 122 iron-based superconductors. No obvious difference was found for the magnetic field along different directions. The detailed analysis will be discussed later.

Figures 3(a) and (b) show the zero-field-cooled isotherms of the magnetization hysteresis curves for the magnetic field parallel and perpendicular to the plane, respectively. The discrepancies between the field-increasing and-decreasing processes are not pronounced, indicating a rather weak vortex pinning. The inset in figure 3(a) shows the ZFC and FC susceptibility for magnetic field parallel to the plane taken at 10 Oe. The FC and ZFC curves are almost superimposed, which also indicates a rather weak vortex pinning. The superconducting volume is about 80% which is enough for bulk superconductivity. We define H_0 as the applied magnetic field at which the M – H curve departs from linearity as the vertical arrows shown in the inset of figure 3(b). The lower critical field is significantly affected by demagnetizing effects. The effective lower critical field can be deduced by the formula $H_{c1} = H_0 - NM$, where N is the demagnetizing factor [15] and M is the magnetization of the sample. For a thin plate,

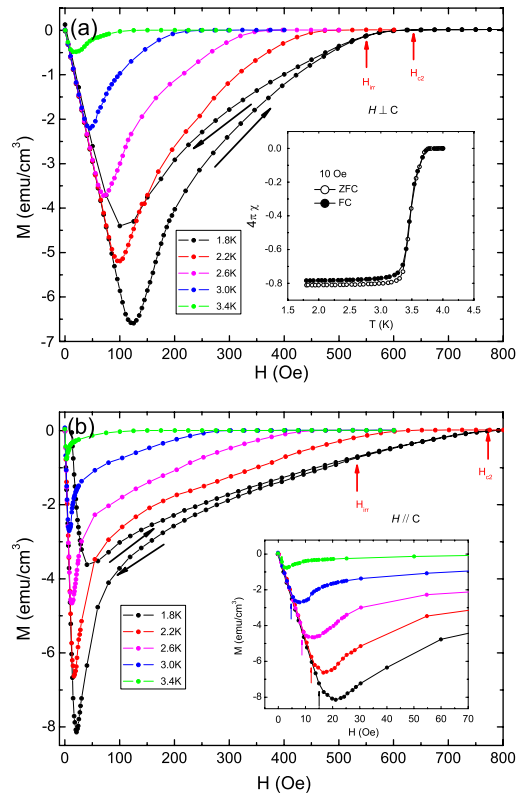


Figure 3. Zero-field-cooled isotherms for the magnetization hysteresis curves for the magnetic field parallel to the plane (a) and perpendicular to the plane (b). The inset of (a) shows the zero-field-cooled and field-cooled susceptibility taken at 10 Oe. The inset of (b) shows the enlarged M - H curve at low magnetic field perpendicular to the plane, while the arrows indicate the position where the M - H curve deviates from linearity.

N is close to zero when the applied field is parallel to the plate, while when the field is perpendicular to the plate the demagnetizing factor N becomes one. The dimension of the single crystal we used in the magnetic property measurement is $0.57 \times 0.55 \times 0.023 \text{ mm}^3$. We estimated the demagnetizing factors to be 0.04 and 0.92 for the magnetic field parallel and perpendicular to the plane, respectively. We ignored the effect of inhomogeneous field distribution around the sample to simplify the treatment. The value of H_{c1} is about 114 and 100 Oe at 1.8 K for H parallel and perpendicular to the plane, respectively. Though the H_0 is quite different for the magnetic field parallel and perpendicular to the plane, after the appropriate demagnetization correction, the value of H_{c1} is of the same order for the different field orientations. The correction of H_{c1}^c is quite necessary due to our thin plate sample. We defined the irreversibility field $H_{irr}(T)$ as the field below which there is an observable difference of the magnetization for increasing and decreasing magnetic field [16]. The value of H_{irr} at 1.8 K is 550 and 530 Oe (550 and 544 Oe considering the demagnetization correction) for the field parallel and perpendicular to the plane, respectively. The value of H_{irr} for different field orientations at 1.8 K are almost the same.

Figure 4 shows the anisotropy result of lower and upper critical fields. We used the field dependence of $T_c(H)$ as

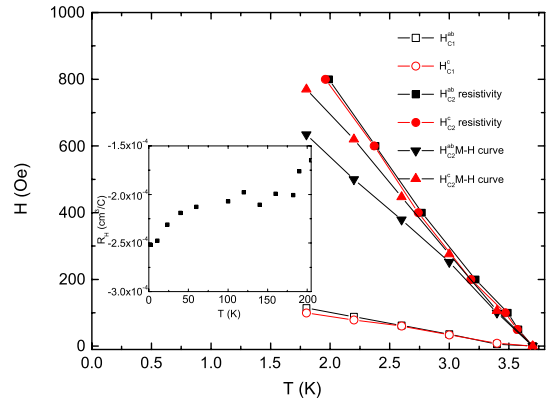


Figure 4. The anisotropy result of lower and upper critical field for magnetic field parallel (black) and perpendicular (red) to plane. The inset shows the temperature dependence of Hall coefficient of LaRu_2P_2 .

shown in figures 2(a) and (b) to determine the upper critical field H_{c2}^{ab} for the $H \parallel ab$ plane and H_{c2}^c for the $H \parallel c$ axis, respectively. The lower critical field H_{c1}^{ab} for the $H \parallel ab$ plane and H_{c1}^c for the $H \parallel c$ axis are determined from figures 3(a) and (b), respectively. From the result, we find both the H_{c1} and H_{c2} show isotropic behavior which indicates that the superconductivity in LaRu_2P_2 is rather isotropic. Thus we can use H_{c1} (H_{c2}) instead of H_{c1}^{ab} (H_{c2}^{ab}) and H_{c1}^c (H_{c2}^c), the anisotropy of coherence length and penetration depth discussed below were neglected. By linear fitting of $H_{c1}(T)$, we can estimate the $H_{c1}(0)$ is about 230 Oe. It is the same order of magnitude as the electron-doped iron-based superconductor $\text{BaFe}_{2-x}\text{Co}_x\text{As}_2$ [5]. Within the weak-coupling BCS theory, the upper critical field at $T = 0 \text{ K}$ can be determined by the Werthamer–Helfand–Hohenberg (WHH) equation [17] $H_{c2}(0) = 0.693[-(dH_{c2}/dT)]_T T_c$. The value of $H_{c2}(0)$ was estimated as about 1140 Oe, which is much smaller than that in iron-based superconductors. The coherence length ξ can be estimated using $H_{c2}(0) = \phi_0/(2\pi\xi^2)$, where ϕ_0 is the flux quantum $\phi_0 = 2.07 \times 10^{-7} \text{ G cm}^{-2}$. The value of coherence length is about 54 nm at zero temperature. We evaluated the penetration depth $\lambda(0)$ using the expression [18] $H_{c1} = (\phi_0/4\pi\lambda^2)(\ln\kappa + 0.5)$, where $\kappa = \lambda/\xi$ is the Ginzburg–Landau parameter. The value of $\lambda(0)$ is about 80 nm and $\kappa(0)$ is about 1.48. We can also deduce the upper critical field from the M - H curve at which the diamagnetic signal vanishes and the magnetization changes its slope as shown in figures 3(a) and (b). The values of H_{c2} determined from the M - H curve are shown in figure 4. These values are smaller than the H_{c2} determined from resistivity measurements, which is probably due to the small broadening of the resistive transition. Though the H_{c2}^c and H_{c2}^{ab} deduced from the M - H curve show some differences, the anisotropy is still very small compared to the other layered superconductors [19]. These results indicate that LaRu_2P_2 is a rather conventional type II superconductor. The inset of figure 4 shows the temperature dependence of the Hall coefficient for LaRu_2P_2 . The negative Hall coefficient for the whole temperature range indicates the carrier in LaRu_2P_2 is electron-type. The absolute value of the Hall coefficient that slightly increased with decreasing temperature indicates

the carrier number's decrease with the temperature decrease. The carrier density n was estimated to be of the magnitude of $3 \times 10^{22} \text{ cm}^{-3}$ from a relation where $R_H = -1/(en)$. The carrier density is about one order of magnitude larger than that of electron-doped iron-based superconductors [5].

As far as we are aware, no other layered superconductors exhibit isotropic upper critical fields except iron-based superconductors, which were reported before [9]. The rather isotropic H_{c1} and H_{c2} in the layered superconductor LaRu_2P_2 indicate the three-dimensional nature of its Fermi surface topology. The behavior of isotropic upper critical fields is very similar in $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$. The isotropic behavior in LaRu_2P_2 is very different to ternary phosphides BaNi_2P_2 , which have the same crystal structure as LaRu_2P_2 . For BaNi_2P_2 , the anisotropic ratio is about 2.2 and it is also proved to be a rather conventional type II superconductor [19]. However, the magnitude of T_c , H_{c1} and H_{c2} in BaNi_2P_2 are very close to LaRu_2P_2 . Thus, the dimensionality in this type of superconductor did not affect the superconductivity dramatically. A two-dimensional Fermi surface was found in LaORuP and LaOFeP through the de Haas–van Alphen (dHvA) effect measurement, while for LaFe_2P_2 it shows the three-dimensional Fermi surface [20]. For both iron- and ruthenium-based phosphides, all these results indicate that the two-dimensional Fermi surface evolves into three-dimensional Fermi surfaces when the crystal structure changes from ZrCuSiAs to ThCr_2Si_2 . The similarities of LaRu_2P_2 between the other ThCr_2Si_2 -type superconductors indicate that the LaRu_2P_2 has some connections with the conventional type II superconductor BaNi_2P_2 and the iron-based superconductors. It is very necessary to study the electronic structure of LaRu_2P_2 and to compare it with the iron-based superconductors.

In conclusion, we studied the properties of the normal and superconducting states of the LaRu_2P_2 single crystals prepared by the Sn flux method. Both the upper and lower critical fields show the isotropic superconductivity in LaRu_2P_2 . This behavior is very much like that for the iron-based superconductors. The isotropic superconductivity indicates the three-dimensional nature of its Fermi surface topology. The magnetic measurement indicates the very weak vortex pinning in the superconducting state. The magnitude of the upper and lower critical fields was estimated to be about 1140 and 230 Oe at zero temperature, which is of the same order of magnitude as the other conventional ThCr_2Si_2 -type superconductors.

The coherent length and penetration depth are about 54 nm and 80 nm, respectively. The negative Hall coefficient indicates the carrier is electron-type. The carrier density was estimated as about $3 \times 10^{22} \text{ cm}^{-3}$, which is about one order of magnitude larger than that in electron-doped iron-based superconductors.

Acknowledgments

This work is supported by the Nature Science Foundation of China and by the Chinese Academy of Sciences.

References

- [1] Kamihara Y, Watanabe T, Hirano M and Hosono H 2008 *J. Am. Chem. Soc.* **130** 3296
- [2] Chen X H, Wu T, Wu G, Liu R H, Chen H and Fang D F 2008 *Nature* **453** 761
- [3] Ren Z A *et al* 2008 *Europhys. Lett.* **83** 17002
- [4] Rotter M, Tegel M and Johrendt D 2008 *Phys. Rev. Lett.* **101** 107006
- [5] Sefat A S, Jin R, McGuire M A, Sales B C, Singh D J and Mandrus D 2008 *Phys. Rev. Lett.* **101** 117004
- [6] Wang X F, Wu T, Wu G, Chen H, Xie Y L, Ying J J, Yan Y J, Liu R H and Chen X H 2009 *Phys. Rev. Lett.* **102** 117005
- [7] Wang X F, Wu T, Wu G, Liu R H, Chen H, Xie Y L and Chen X H 2009 *New J. Phys.* **11** 045003
- [8] Jeitschko W, Glaum R and Boonk L 1987 *J. Solid State Chem.* **69** 93
- [9] Yuan H Q, Singleton J, Balakirev F F, Baily S A, Chen G F, Luo J L and Wang N L 2009 *Nature* **457** 565
- [10] Vilmercati P *et al* 2009 *Phys. Rev. B* **79** 220503
- [11] Mizusaki S, Adachi Y, Ohnishi T, Taniguchi T, Nagata Y, Ozawa T C, Noro Y and Samata H 2009 *J. Alloys Compounds* **468** 28–33
- [12] Jeitschko W and Reehuis M 1987 *J. Phys. Chem. Solids* **48** 667
- [13] Barz H, Ku H C, Meisner G P, Fisk Z and Matthias B T 1980 *Proc. Natl Acad. Sci.* **77** 3132–4
- [14] Meisner G P 1981 *Physica B* **108** 763–4
- [15] Osborn J A 1945 *Phys. Rev.* **67** 351
- [16] Andrzejewski B, Kowalczyk A, Jezierski A and Lees M R 2007 *Supercond. Sci. Technol.* **20** 728–35
- [17] Werthamer N R, Helfand E and Hohenberg P C 1966 *Phys. Rev.* **147** 295
- [18] Klemm R A and Clem J R 1980 *Phys. Rev. B* **21** 1868
- [19] Tomioka Y, Ishida S, Nakajima M, Ito T, Kito H, Iyo A, Eisaki H and Uchida S 2009 *Phys. Rev. B* **79** 132506
- [20] Muranaka H, Doi Y, Katayama K, Sugawara H, Settai R, Honda F, Matsuda T D, Haga Y, Yamagami H and Onuki Y 2009 *J. Phys. Soc. Japan* **78** 053705