EFFECT OF ANISOTROPIC STRAIN ON THE ELECTRONIC PROPERTIES OF THE PRESSURE INDUCED SUPERCONDUCTOR $CePd_2Si_2$*

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Taking advantage of the additional uniaxial stress present in the non-ideal pressure conditions of a Bridgman anvil cell, we demonstrate the high sensitivity of the physical properties in $CePd_2Si_2$ to anisotropic strain. Stress applied along the c-axis extends the phase diagram to higher pressures and enhances the superconducting phase emerging around the magnetic instability, with a 40% increase in the maximum superconducting temperature and a doubled pressure range. We discuss first the possible effect of anisotropic strain on the physics described only by spin fluctuations. However, the pressure dependence of the resistivity suggests a more complex ground state around the quantum critical point, where the Kondo and excited crystal field energies interact.

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1. Introduction

Among the heavy fermion superconductors, the case of $CePd_2Si_2$ has attracted much interest because superconductivity is induced by pressure in a narrow window of about 1 GPa around its magnetic instability at a critical pressure $P_c \simeq 2.8$ GPa, where the antiferromagnetic ordering temperature collapses to zero. In addition, a strikingly temperature rigid non-Fermi liquid behaviour in resistivity, consisting of a power law $\rho - \rho_0 \propto T^{1.2-1.3}$ extending up to 40 K was found at P_c, generating interest in the nature of the ground state [1]. Another investigation, performed in our group, found a phase diagram expanded to higher pressures, with superconductivity present in a pressure window of 5 GPa and a higher maximum T_c [2]. As the two investigations were performed with different pressure techniques, using either a "liquid" or a solid as the pressure transmitting medium, we wondered whether these differences were due to the samples or the pressure quality.

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2. Experimental

This experiment was carried out in a Bridgman anvil cell, using a soft solid (steatite) as a pressure transmitting medium in which we suspect an additional uniaxial stress along the force load direction. The samples were extracted from a tiny single crystalline platelet. A parallelepiped sample ($510\times75\times60\,\mu$m) was cut into two pieces of length $250\,\mu$m. After polishing to small cross-sections ($\sim70\times20\,\mu\text{m}^2$) and spot-welding with $5\,\mu$m diameter gold wires, the samples had high residual resistivity ratio RRR values of 48 and 103. The samples were mounted in the pressure cell with the force load direction (and that of the additive stress) perpendicular and parallel to the c-axis and will be referred to as //(lower RRR) and $\perp$ (higher RRR) respectively. Both samples were connected for four-point DC resistivity measurements, with sample $\perp$ having additional connections for a constantan resistive heater and a thermocouple Au/Au-0.07 at.% Fe suitable for AC calorimetric measurements.

3. Results and discussion

Sample $\perp$ gave rise to a phase diagram similar to that obtained in hydrostatic conditions (Fig. 1(a)). The superconductivity was limited to the range 2.14–3.25GPa around $P_{c\perp} \simeq 2.7$GPa, with $T_{c\perp}$ having a maximum of 375mK (mid-point criterion). In contrast, the phase diagram of sample // seems to be stretched towards higher pressures. T_N collapses at $P_{c//} = 3.9$ GPa with a critical behaviour $(P - P_{c\perp})^{\alpha}$, $\alpha = 0.60 \pm 0.05$, as distinct from the quasi-linear dependence in the hydrostatic case. Superconductivity occurred between 2.14 and 5.0GPa (using a mid-point criterion) and T_c reached a higher value, 520 mK. This value of T_c is obtained in the sample with the larger residual resistivity, showing that the superconductivity enhancement is not simply due to an increase in the electronic mean free path. This maximum of T_c coincides with P_c, suggesting that this extended superconductivity is still related to the instability.

Subtracting from $\rho(T)$ curves a linear term of $0.1T$ assumed for the phonon contribution, it is possible to define a maximum at a temperature $T_{\max}$, thought to be related to the Kondo temperature T_K. In addition, a shoulder ascribed to the excited crystal field CF levels is visible at low pressures $P < P_c$. This quasi pressure-independent anomaly at about 100 K seems to merge with the Kondo peak for pressures close to P_c and to collapse in amplitude, the CF excitations not being well-defined. $T_{\max}(P)$ shows no anomaly at P_c and identical values $T_{\max}(P_c)$ in both samples (Fig. 2(a)).

The resistivity was analysed at low temperature in terms of a power law $\rho(T) = \rho_0 + AT^n$ limited to a window of 0.5–2 K, in order to compare data over the entire pressure range. As expected, the coefficient A and the

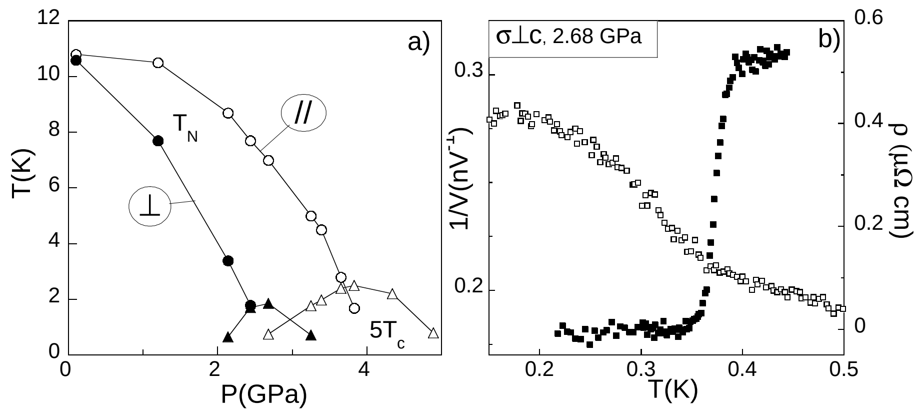

Fig. 1. (a) Phase diagram of the two samples (filled and open symbols for samples ⊥ and // respectively) pressurised as described in the text.(b) Superconducting transition in resistive and calorimetric measurement for sample ⊥ close to P_c.

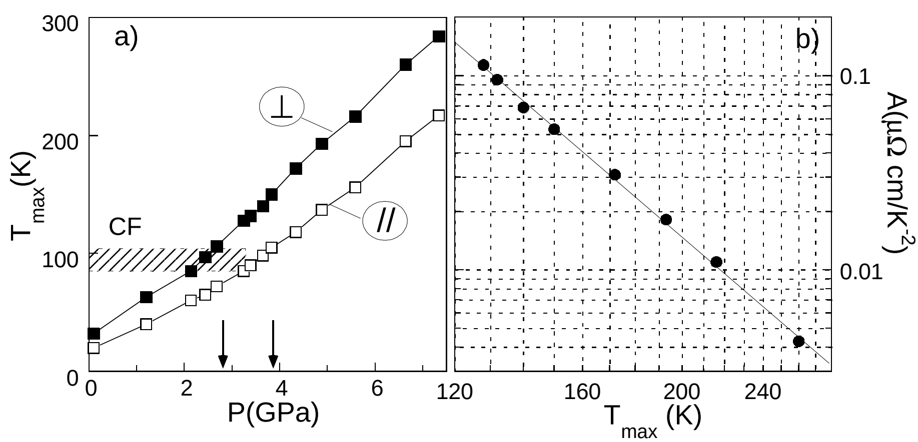

Fig. 2. (a) Pressure dependence of T_{max}, the temperature of the maximum in the magnetic part of $\rho(T)$. The dashed line, which qualitatively indicates the position of the crystal-field (CF) contribution, crosses T_{max} close to P_c for both samples. (b) Decrease of the resistive coefficient A *vs* T_{max}.

exponent n present a sharp maximum and minimum respectively at P_c in both samples. The maximum value of A is similar in both samples with $A(P_c) \simeq 0.2\,\mu\Omega$ cmK^{-n}. At 7.4 GPa, the A coefficient of sample ⊥ has fallen by a factor of 100 compared to its value at P_c. The minimum values of n were 1.32 and 1.42 (± 0.03) for samples ⊥ and // respectively, in good agreement with previous non-Fermi liquid behaviour previously reported.

The existence of bulk superconductivity is demonstrated in the sample $\perp$ by an anomaly in the calorimetric signal (Fig. 1(b)). However, this anomaly is visible only at 2.68 GPa, the closest pressure to P_c, and collapses rapidly in amplitude with increasing field, being undetectable above 0.5 T. This suggests a non-homogeneous situation in the sample, as suggested by the large transition widths in $\rho(T)$ for pressures away from P_c. The large initial slopes of the upper critical magnetic field at P_c give -6 and -11 T/K for sample $\perp$ ($H \perp c$) and // ($H//c$) respectively, indicating the anisotropy of the Fermi velocity and that heavy quasi-particles are involved in superconductivity.

As suggested earlier, the temperature $T_{\max}$ of the maximum in the magnetic contribution to the resistivity is related to the Kondo temperature, T_K. The same value of $T_{\max}$ for both samples at their respective P_c supports the idea that $T_{\max}$ is a reliable characteristic energy for the instability. The absence of anomaly in $T_{\max}(P)$ at P_c indicates that quasi-particles bands are still formed at the instability which should be treated in terms of fluctuations at a quantum critical point (QCP). Considering only spin fluctuations, the usual model predicts, in the vicinity of the QCP, $T_N(P) \propto (P_c - P)^{2/d}$ and $\rho(T, P_c) \propto T^{d/2}$ where d is the dimensionality of spin fluctuations. The T_N exponent 0.60 ± 0.05 obtained for sample // and the slight difference in the minimum of resistivity exponent obtained between the two samples suggests that applying σ along the c-axis restores a 3D spin-fluctuation spectrum. If these fluctuations are at the origin of superconductivity, we may wonder if 3D fluctuations are more favourable. However, there are signs that spin fluctuations are not enough to properly describe the physics at this instability. In both of our samples, the QCP occurred in a pressure domain where the characteristic Kondo energy $k_B T_K$ ($T_K \propto T_{\max}$) typically reaches the crystal-field splitting energy (see Fig. 2(a)). Furthermore, for $P > P_c$, $\ln A$ is found to behave as $-\alpha \ln T_{\max}$ with a slope $\alpha \simeq 4$ (Fig. 2(b)), instead of the value of 2 expected for a normal heavy-fermion regime. This indicates the entrance into an intermediate valence regime. In some compounds such as $CeCu_2Ge_2$, this regime occurs for pressures higher than P_c and seems to induces large effects on superconductivity. In $CePd_2Si_2$, the existence of this valence regime at P_c requires to consider the influence of charge fluctuations.

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