Aspects of Superconductivity in the Non-Centrosymmetric Superconductor $CePt_3Si$

Michael Nicklas, Corneliu Florin Miclea[1], Ernst Bauer[2], Raul Cardoso, Ilya Eremin[3], Anna Celia Mota[4], Andrey Prokofiev[2], Manfred Sigrist[5], and Frank Steglich

In all superconductors, the gauge symmetry is broken. In the heavy-fermion superconductor $CePt_3Si$, the inversion symmetry is broken in addition to the gauge symmetry. This leads to new unconventional behavior in the superconducting phase. In this report, we present two studies on $CePt_3Si$ revealing some of these unusual properties.

Antiferromagnetic order in $CePt_3Si$ sets in at T_N = 2.2 K while the system adopts a superconducting ground state below T_c = 0.75 K for polycrystalline samples [1]. For single crystals, lower superconducting transition temperatures have been reported [2]. Furthermore, the upper critical field H_{c2} = 3 T – 5 T exceeds the Pauli-Clogston limit hinting at spin-triplet pairing.

Extreme vortex pinning in $CePt_3Si$

Our investigation carried out on a high-quality single crystal of $CePt_3Si$ with T_c = 0.45 K reveals extremely slow flux dynamics with creep rates even lower than those in Sr_2RuO_4, $PrOs_4Sb_{12}$, and UPt_3 (see references in [3]). Interestingly, the critical current in $CePt_3Si$ is also low, in spite of the very strong pinning.

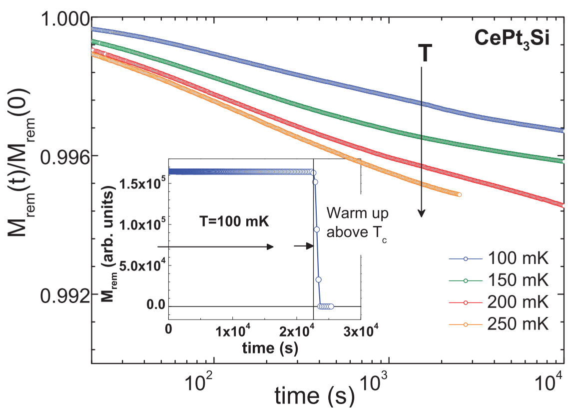

Fig. 1: Normalized remnant magnetization as a function of time at different constant temperatures. Inset: remnant magnetization as a function of time at T = 0.1 K. After 2.25 × 10^4 s the sample is warmed up above T_c and all the trapped magnetic flux is expelled.

Isothermal decays of the remnant magnetization at different temperatures are depicted in Figure 1. At constant temperature, the flux escaping the sample is typically recorded for more than 10^4 s. Then the sample is heated up above T_c all the trapped field to expell out of the sample (inset of Fig. 1). In this way, we obtain the value of the total remnant magnetization as the sum of the amount of flux expelled in the first 10^4 s plus the flux removed while crossing T_c. This value of M_{rem} is then used to normalize the creep rate. At all temperatures, the decays show logarithmic time dependence as predicted by the Kim-Anderson theory. The creep rate becomes faster upon increasing the temperature as expected for thermally activated flux motion. The temperature dependence of the normalized relaxation rates $S = \partial \ln(M)/(\partial \ln(t))$ for $CePt_3Si$ is depicted in Figure 2 together with the rates obtained for the heavy-fermion superconductor

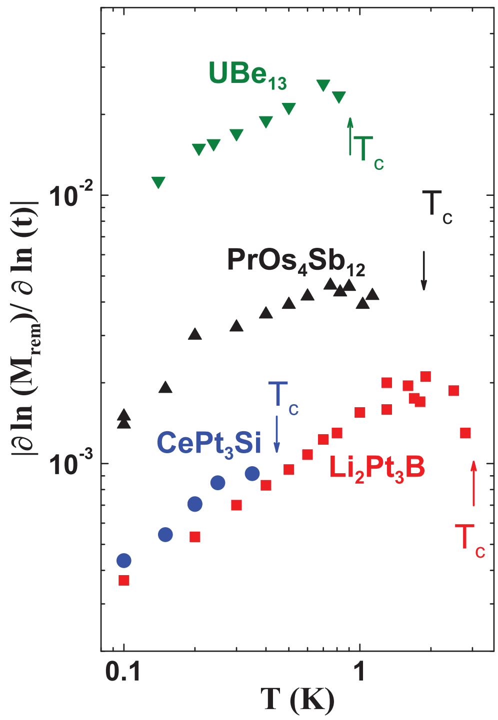

Fig. 2: Comparison of the normalized relaxation rates $S = \partial \ln(M)/(\partial \ln(t))$ a function of temperature for different compounds in a log-log representation.

UBe_{13} which only breaks gauge symmetry, $PrOs_4Sb_{12}$ which, in addition, violates time-reversal symmetry and the non-centrosymmetric superconductor Li_2Pt_3B (Ref. [3] and references therein). Remarkably, $CePt_3Si$ has anomalously small decay rates comparable only with Li_2Pt_3B and lower by a factor of five than the very low creep rates observed in $PrOs_4Sb_{12}$. Li_2Pt_3B breaks the inversion symmetry and displays extremely small creep rates as well. For the latter compound, however, in a certain temperature interval, the weak initial logarithmic creep is followed after several thousand seconds by a much faster, avalanche-like, also logarithmic, decay [4].

In general, in superconductors with strong vortex pinning the critical current j_c is high. However, this is not the case in $CePt_3Si$ which has the lowest critical current among the compared superconductors. We conclude that the critical current is not the relevant parameter for the pinning mechanism in $CePt_3Si$. The extremely slow vortex dynamics in combination with the comparatively small critical current suggests that an unconventional and very effective pinning mechanism is at work. A possible explanation of this pinning mechanism could be based on the existence of fractionalized vortices localized at interfaces between crystal twins where time reversal symmetry is not conserved. In order to move into the bulk of the sample, a fractionalized vortex would have to find the right partner and recombine into an integer flux quanta. Twin boundaries would then act as planar barriers for flux flow without affecting the critical current. A refinement of the crystal structure of $CePt_3Si$ from X-ray intensity data shows a contribution of 87% of the main inversion twin component. However, there has been no direct observation of such flux-line pinning on twin boundaries so far.

Pair breaking by non-magnetic impurities in the non-centrosymmetric superconductor $CePt_3Si$

To study the effect of non-magnetic impurities on the physical properties of the non-centrosymmetric superconductor $CePt_3Si$, we carried out combined Ge-doping and hydrostatic pressure experiments on polycrystalline samples. This allowed us to disentangle the effect on volume effects and introduction of additional disorder by isoelectronic Ge-doping. Our results show exemplarily the peculiar effect of nonmagnetic disorder on non-centrosymmetric superconductors and provide an additional proof for the unconventional character of the superconductivity in $CePt_3Si$ [3].

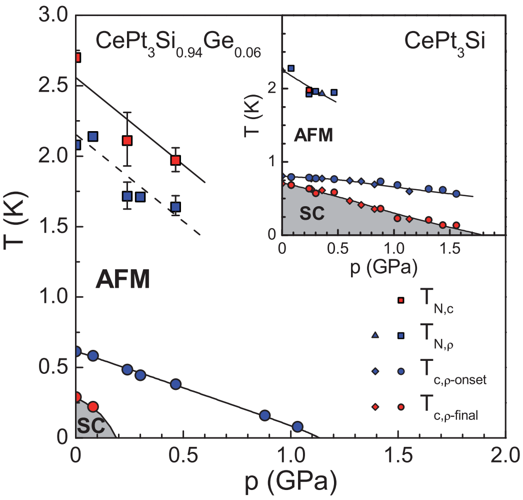

Fig. 3: *T-p* phase diagram of $CePt_3Si_{0.94}Ge_{0.06}$ (main panel) and $CePt_3Si$ (inset). In the case of $CePt_3Si$, additional data from Ref. [8] (triangles and diamonds) have been included.

The results of our heat-capacity and electrical resistivity experiments under hydrostatic pressure are summarized in the phase diagram displayed in Figure 3. Compared with $CePt_3Si$ (inset of Fig. 3), the superconducting state in $CePt_3Si_{0.94}Ge_{0.06}$ responds more sensitively to external pressure. At 0.24 GPa, no zero resistivity state is observed anymore, but the onset of the superconducting transition in resistivity is still visible up to 1.03 GPa. Not surprisingly, the resistive transition for the alloy at ambient pressure is found to be already rather broad compared with the stoichiometric compound.

Considering the dome-like shape of the superconducting phase often observed in a *T-p* phase diagram in heavy-fermion superconductors, $CePt_3Si$ seems to be situated close to the T_c maximum which occurs at a hypothetical minor negative pressure [5]. The small initial slope of $T_c(p)$ suggests that the maximum T_c only slightly exceeds T_c at ambient pressure. It is important to note that substituting Si by isoelectronic Ge expands the unit-cell volume without changing the electronic structure significantly [5]. Doping with 6% Ge leads to an increase in the unit-cell volume, V, of approximately 0.38% compared to the stoichiometric compound. Using the bulk modulus B = 162 GPa, this corresponds to the application of a hypothetical negative pressure of $\Delta p = -0.6$ GPa, resulting in a reduction of T_c and an increase of T_N [3]. Since the volume expansion reduces the 4*f*-conduction electron hybridization and, thus, strengthens the RKKY interaction (while weakening the Kondo effect), the observed dependence of T_N on the unit-cell volume can be easily explained. It can be expected that disorder has only a minor influence on the magnetic properties in this material.

The consequence of adding a non-magnetic impurity in a non-centrosymmetric superconductor, which is the case for $CePt_3Si_{0.94}Ge_{0.06}$, is far from being obvious. Theoretical analysis shows that adding non-magnetic impurities results, for weak disorder, in the suppression of T_c for both conventional as well as unconventional Cooper-pairing (see references in [6]). Moreover, for the conventional Cooper-pairing, non-magnetic impurities yield a decrease of T_c; superconductivity, however, will not be destroyed completely. This is the origin of the suppression of T_c due to being interband impurity scattering which tends to reduce the difference between the gap magnitudes in the two bands. Once both gaps have become equal,

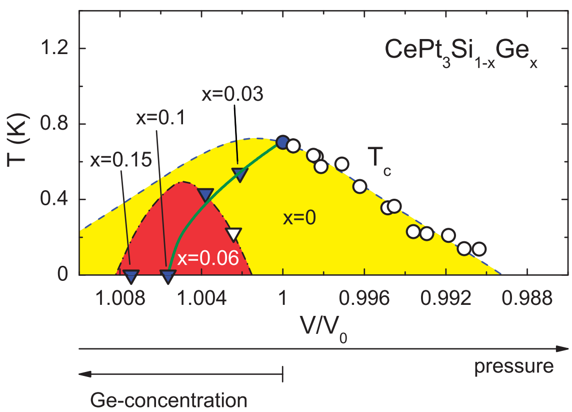

Fig. 4: Phase diagram of $CePt_3Si_{1-x}Ge_x$ as a function of the reduced unit-cell volume V/V_0 with V_0 the unit-cell volume of $CePt_3Si$. Triangles correspond to T_c of Ge-substituted samples while circles present T_c of $CePt_3Si$. Ambient pressure data is indicated by filled symbols and data under applied pressure by open symbols. T_c of the Ge-substituted samples at $p = 0$ is taken from Ref. [5]. The solid line represents a fit to the data according to the AG function. The dashed and dashed-dotted lines are suggesting the shape of the superconducting dome for $CePt_3Si$ and $CePt_3Si_{1-x}Ge_x$, respectively, assuming that the superconducting behavior were only governed by volume effects.

adding further impurities should be harmless for superconductivity, which is in striking contrast to our observation that superconductivity is completely suppressed for a doped sample of 10% Ge. Thus, the latter observation points toward an *unconventional* symmetry of the Cooper-pairing in $CePt_3Si$.

The agreement between our experimental data and the Abrikosov-Gor'kov (AG) theory clearly points toward the unconventional symmetry of the SC order parameter in $CePt_3Si$ which is destroyed by non-magnetic impurities (see Fig. 4). In addition, we find that the strength of the potential scattering off the Ge dopands, rather than the Ge-induced expansion of the average unit-cell volume, more strongly affects the SC transition temperature, quite opposite to the response of T_N temperature to these parameters.

In conclusion, our results show that the suppression of T_c on Ge substitution in $CePt_3Si$ is basically not due to a volume effect but is caused by scattering processes on non-magnetic impurities introduced by the Ge substitution. We have argued that the peculiar effect of non-magnetic impurities in non-centrosymmetric superconductors plays an important role in destroying superconductivity in $CePt_3Si$. In addition, we have shown that the superconducting state in the Ge-substituted sample is much more sensitive to pressure than in $CePt_3Si$.

References

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[1] Present address: Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[2] Institut für Festkörperphysik, Technische Universität Wien, A-1040 Wien, Austria
[3] Institut für Theoretische Physik III, Ruhr-Universität Bochum, 44801 Bochum, Germany
[4] Solid State Laboratory, ETH Zurich, CH-8093 Zurich, Switzerland
[5] Institute for Theoretical Physics, ETH Zurich, CH-8093 Zurich, Switzerland