Aspects of Superconductivity in the Non-Centrosymmetric Superconductor CePt$_3$Si

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In all superconductors, the gauge symmetry is broken. In the heavy-fermion superconductor CePt$_3$Si, 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$_3$Si revealing some of these unusual properties.

Antiferromagnetic order in CePt$_3$Si 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$_3$Si**

Our investigation carried out on a high-quality single crystal of CePt$_3$Si with $T_c = 0.45$ K reveals extremely slow flux dynamics with creep rates even lower than those in Sr$_2$RuO$_4$, PrOs$_4$Sb$_{12}$, and UPt$_3$ (see references in [3]). Interestingly, the critical current in CePt$_3$Si is also low, in spite of the very strong pinning.

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 $S = \frac{\partial \ln (M_{rem})}{\partial \ln (t)}$ for CePt$_3$Si is depicted in Figure 2 together with the rates obtained for the heavy-fermion superconductor.

![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 $2.25 \times 10^4$ s the sample is warmed up above $T_c$ and all the trapped magnetic flux is expelled.](image1)

![Fig. 2: Comparison of the normalized relaxation rates $S = \frac{\partial \ln (M_{rem})}{\partial \ln (t)}$ a function of temperature for different compounds in a log-log representation.](image2)
UBE$_13$ which only breaks gauge symmetry, PrOs$_8$Sb$_{12}$ which, in addition, violates time-reversal symmetry and the non-centrosymmetric superconductor Li$_2$Pt$_3$B (Ref. [3] and references therein). Remarkably, CePt$_3$Si has anomalously small decay rates comparable only with Li$_2$Pt$_3$B and lower by a factor of five than the very low creep rates observed in PrOs$_8$Sb$_{12}$: Li$_2$Pt$_3$B 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$_3$Si 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$_3$Si. 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$_3$Si 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$_3$Si**

To study the effect of non-magnetic impurities on the physical properties of the non-centrosymmetric superconductor CePt$_3$Si, 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$_3$Si [3].

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$_3$Si (inset of Fig. 3), the superconducting state in CePt$_3$Si$_{0.94}$Ge$_{0.06}$ responds more sensitively to external pressure. At 0.24 GPa, no zero resistivity state is observed any more, 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 observed in a $T$-$p$ phase diagram in heavy-fermion superconductors, CePt$_3$Si 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 4f-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\(_3\)Si\(_{0.94}\)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, 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\(_3\)Si.

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\(_3\)Si which is destroyed by non-magnetic impurities (see Fig. 4). In addition, we find that the strength of the potential scattering off the Ge dopants, 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\(_3\)Si 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\(_3\)Si. In addition, we have shown that the superconducting state in the Ge-substituted sample is much more sensitive to pressure than in CePt\(_3\)Si.

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Fig. 4: Phase diagram of CePt\(_3\)Si\(_{1-x}\)Ge\(_x\) as a function of the reduced unit-cell volume \( V/V_0 \) with \( V_0 \) the unit-cell volume of CePt\(_3\)Si. Triangles correspond to \( T_c \) of Ge-substituted samples while circles present \( T_c \) of CePt\(_3\)Si. 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\(_3\)Si and CePt\(_3\)Si\(_{1-x}\)Ge\(_x\), respectively, assuming that the superconducting behavior were only governed by volume effects.

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