Two-band superconductivity in electron-irradiated $CeCu_2Si_2$ and $PrOs_4Sb_{12}$ studied by local magnetization measurements

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Phases of matter are usually identified through spontaneous symmetry breaking, which sets in at a critical temperature T_c. This particular transition from the normal state into the ordered state builds up continuously and may be expressed quantitatively by introducing an order parameter that is finite for $T < T_c$ and zero for $T \geq T_c$. This concept also applies to superconductors (SCs), where a superconducting energy gap is an order parameter. In the case of conventional SCs, such as the elemental metals, the most symmetric *s*-wave spin-singlet state with zero angular momentum is constant in momentum space, and hence is insensitive to the presence of non-magnetic scattering. In unconventional SCs, however, both the phase and amplitude of the order parameter are expected to have a strong momentum dependence that gives rise to a sign-change of the superconducting gap function. Therefore, their superconducting properties are sensitive to the presence of disorder, in particular to the electron irradiation. Specifically, by measuring the temperature dependence of lower critical field $H_{c1}(T)$ for samples with different electron irradiation doses, we were able to distinguish between possible gap structures in the canonical heavy-fermion compounds $CeCu_2Si_2$ and $PrOs_4Sb_{12}$.

The discovery of the first heavy-fermion superconductor $CeCu_2Si_2$ was a turning point in the history of superconductivity because it led to the birth of research on non-phonon-mediated Cooper pairing [1]. After four decades of research, the unexpected observations of the multiband superconductivity with absence of nodal quasiparticles have challenged the long-held dichotomy between simple *s*- and *d*-wave spin-singlet pairing states [2,3]. Utilizing a new innovative Hall micromagnetometry with a high spatial resolution, we measured the temperature dependence of the lower critical field of tetragonal $CeCu_2Si_2$ ($T_c \simeq 0.58$ K). For the main crystallographic directions, we found a sharp anomaly at $\simeq 0.41T_c$ followed by a moderate enhancement, indicative of two nearly decoupled bands. Moreover, the $H_{c1}(T)$ curves saturate in the limit $T = 0$ K, providing a further support for the absence of nodal quasiparticles. In addition, we studied the effect of electron irradiation on $H_{c1}(T)$. We observe irradiation to strongly suppress the enhancement of H_{c1} connected with the small gap and this enhancement is hardly visible for a dose as small as 0.8 C/cm^2. In striking contrast, the $H_{c1}(T)$ dependence above $\simeq 0.4T_c$, which is well described by a single-band BCS-like relation, is robust against disorder. All these findings turn out to be more consistent with an $s_\pm$-wave scenario with weak interband coupling than a $d_{xy} + d_{x^2-y^2}$ model [4].

The heavy-fermion and multiband superconductor $PrOs_4Sb_{12}$ ($T_c \simeq 1.85$ K) is a leading candidate to display chiral superconductivity, and hence to host Majorana fermions – exotic particles that could be used for quantum computing [5]. Based on measurements of $H_{c1}(T)$, we have proposed a multiband and multisymmetric scenario, in which a superconducting condensate is composed of a sign-changing smaller gap and a large isotropic *s*- wave gap [6]. To develop a detailed understanding of multicomponent superconductivity in cubic $PrOs_4Sb_{12}$, we have extended measurements of $H_{c1}(T)$ down to temperatures as low as 7 mK. We observed a sudden increase in $H_{c1}(T)$ deep in a superconducting state that is followed by a non-saturating and concave behavior of $H_{c1}(T)$ below about 0.45 K. These findings clearly point at a sign-changing symmetry of the smaller gap. Equally remarkable is a high sensitivity of this characteristic to electron irradiation. Indeed, even small concentration of artificial atomic defects (0.5 C/cm^2) destroys a sign-changing order parameter, as evidenced from both a saturated dependence of $H_{c1}(T)$ and a strong suppression of its enhancement [7].

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