Toward Understanding the Non-Centrosymmetric Superconductors

New MPI partner group established in Zhejiang University

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In May 19, 2010, a new Partner Group of the MPI-CPfS was established at Zhejiang University (ZJU), China, which will further strengthen the project-oriented cooperation and promote student exchanges between these two institutions. This is the third Partner Group of the MPI CPfS established abroad and the second one in China. Prof. Huiqiu Yuan, an alumnus of the MPI CPfS and currently working as a Changjiang Scholar Professor in the Department of Physics, Zhejiang University, was appointed the leader of the new Partner Group.

The opening inauguration of the Partner Group was followed by the 2010 Hangzhou Workshop on Quantum Matter. The main subject of this workshop was on unconventional superconductivity, quantum phase transitions and topological states. About 90 participants attended the workshop, among which there were 35 invited speakers from more than 10 countries. The establishment of the Partner Group was highly evaluated by the participants and also by the Chinese condensed-matter-physics community.

Scientific objectives of the Partner Group

The main research topic of the Partner Group are the non-centrosymmetric superconductors. The research efforts will be devoted to revealing the unique pairing states, the vortex dynamics and the possible exotic magnetic states arising from an antisymmetric spin-orbit coupling (ASOC) due to the lack of inversion symmetry.

When parity symmetry is violated, the ASOC that breaks the spin degeneracy of each band may take the form of $\alpha\mathbf{g}(\mathbf{k})\cdot\mathbf{S}(\mathbf{k})/\hbar$, where α denotes the spin-orbit coupling strength, $\mathbf{S}(\mathbf{k})$ is the spin of an electron with momentum $\hbar\mathbf{k}$, and $\mathbf{g}(\mathbf{k})$ is a dimensionless vector ($\mathbf{g}(-\mathbf{k}) = -\mathbf{g}(\mathbf{k})$ to preserve time-reversal symmetry). The ASOC leads to an energy splitting of the originally degenerate spin states and results in spin eigenstates that are polarized parallel or antiparallel to $\mathbf{g}(\mathbf{k})$, allowing the admixture of spin-singlet and spin-triplet pairing states [1,2]. The ASOC plays a crucial role on the pairing state of non-centrosymmetric superconductors. A key point is that a spin-triplet state may significantly contribute to the superconducting gap function provided that the ASOC strength is sufficiently large; its characteristic vector $\mathbf{d}(\mathbf{k})$ must be parallel to $\mathbf{g}(\mathbf{k})$ [3]. Theoretically the two gap functions can be written as: $\Delta_{\pm}(\mathbf{k}) = \psi \pm t|\mathbf{g}(\mathbf{k})|$, where each gap is defined on one of the two bands formed by the degeneracy lifting of the ASOC; ψ and t are the spin-singlet and spin-triplet order parameters, respectively. Unconventional behavior, including zeroes in the superconducting gap function, is then possible, even if the pair wave function exhibits the full spatial symmetry of the crystal.

Non-centrosymmetric superconductivity was discovered for the heavy-fermion compound $CePt_3Si$ [4] and discussed in quite a few heavy-fermion compounds, e.g., $CeIrSi_3$ and $CeCoSi_3$ [5,6]. In these compounds, the observation of a pronounced coherence peak in $1/T_1T$ vs. T just below T_c, together with a power-law temperature dependence of both the penetration depth and $1/T_1T$ were regarded as a consequence of the admixture of spin-singlet and spin-triplet pairing states [4,7,8]. Furthermore, the huge upper critical field observed in $CeIrSi_3$ [7] and $CeCoSi_3$ [8] was also attributed to the contribution of a spin-triplet component in their pairing states. The unconventional nature of the superconducting state in $CePt_3Si$ has also direct consequences for the effect of non-magnetic disorder, i.e. Ge doping, on the superconducting state [9]. Unfortunately, in these correlated-electron systems the nature of superconductivity is complicated by its coexistence with magnetism, and, therefore, the study of parity-broken superconductivity is severely restricted. In order to reveal the pure effect of ASOC on the superconducting pairing state, the Partner Group is going to concentrate on weakly coupled superconductors with tunable ASOC strength. We aim at revealing a novel superconducting pairing state arising from the ASOC as a result of broken inversion symmetry. On the other hand, non-centrosymmetric superconductors have been theoretically proposed as important candidates for studying topologic superconductivity [10,11]. Along this route, we will try to search for new materials which might provide an opportunity to investigate this new topological state.

Nodal gap structure in weakly coupled non-centrosymmetric superconductors

The systems $Li_2(Pd_{1-x}Pt_x)_3B$ (cubic $P4_332$) were the first weak-coupling superconductors showing evidence of a spin-triplet state driven purely by the ASOC effect as a result of broken inversion symmetry. In contrast to the heavy-fermion systems, these compounds neither form any magnetic order nor bear strong electronic correlations, and, therefore, are suitable for studying the effect of ASOC on superconductivity.

Penetration-depth (λ) measurements using a tunnel diode (TDO)-based resonant oscillator are powerful to look into the superconducting order parameter because this yields an accurate temperature dependence of $\lambda(T)$. Very surprisingly, it was found that the penetration depths of Li_2Pd_3B and Li_2Pt_3B exhibit sharply distinct behaviors at low temperature [12]: in the former case $\lambda(T)$ at low temperatures shows BCS-like exponential behavior, while in Li_2Pt_3B it follows a linear temperature dependence, indicating the existence of line nodes in the energy gap. It was proposed that the broken inversion symmetry and the accompanying ASOC are responsible for this behavior. The spin-triplet contribution is weak in Li_2Pd_3B, leading to a full, but anisotropic gap. On the other hand, the spin-triplet state may become dominant in Li_2Pt_3B attributed to its much larger ASOC strength, giving rise to the existence of line nodes in the energy gap. The experimental data are in quantitative agreement with theoretical calculations for mixed singlet and triplet states based on ASOC, which was further supported by subsequent NMR experiments.

Recently, similar experiments on the non-oxide transition-metal sesquicarbides M_2C_3 (M = La, Y) have been performed by the Partner Group [12,13]. These materials crystallize in the cubic Pu_2C_3-type structure (space group), presenting another family of non-centrosymmetric superconductors with a

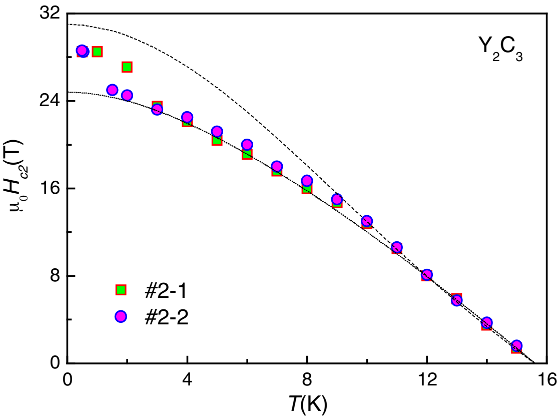

Fig. 1: The upper critical field versus temperature for two samples of Y_2C_3: #2-1 and #2-2. The dotted and the dashed lines are fits to the weak-coupling Werthamer-Helfand-Hohenberg (WHH) method and the Ginzburg-Landau (GL) theory, respectively [14].

relatively high T_c ($T_c \approx 18$K). Resembling the $Li_2(Pd_{1-x}Pt_x)_3B$ system, M_2C_3 shows no evidence of strong electronic correlations and/or magnetic fluctuations that could cause unconventional superconducting behavior.

The upper critical field $\mu_0 H_{c2}(T)$ and the penetration depth $\lambda(T)$ of Y_2C_3 were obtained using a TDO-based resonant oscillator [13,14]. It was found that $\mu_0 H_{c2}(T)$ shows a very unusual temperature dependence: $\mu_0 H_{c2}(T)$ increases linearly with decreasing temperature near T_c, and reveals an upturn curvature at low temperatures (Fig. 1). Such behavior of $\mu_0 H_{c2}(T)$ cannot be described by either the weak-coupling WHH method or the GL theory. Furthermore, Y_2C_3 possesses a large upper critical field of $\mu_0 H_{c2}(0) \approx 29$T (Fig. 1), being slightly above the paramagnetic limit derived in terms of the weak coupling BCS theory. These unusual features of $\mu_0 H_{c2}(T)$ suggest that the spin-triplet component might be important in Y_2C_3 as discussed in some heavy-fermion non-centrosymmetric super-conductors [7,8].

On the other hand, it was found that the low temperature penetration depth $\lambda(T)$ follows a weak linear T-dependence in Y_2C_3, indicating the existence of line nodes in its superconducting energy gap. Moreover, it was shown that a two-gap model can indeed describe the superfluid density $\rho_s(T)$ of Y_2C_3 at temperatures near T_c, but it is clearly violated at low temperatures (see Fig. 2). Reanalysing the NMR data [15] one finds $1/T_1 \sim T^3$ at $T < 3$K, further supporting the existence of line nodes in

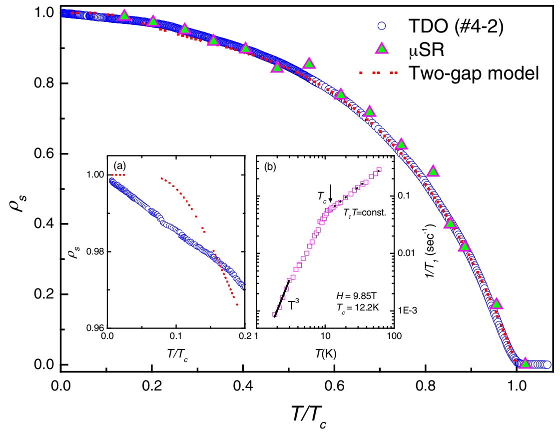

Fig. 2: The normalized superfluid density $\rho_s(T)$ versus temperature for Y_2C_3 (from Ref.[13]). Inset (a) shows $\rho_s(T)$ and the fittings in the low-temperature region and (b) shows the temperature dependence of $1/T_1$ for Y_2C_3, respectively.

Y_2C_3 (inset (b) in Fig. 2). It is argued that these nontrivial superconducting properties might be attributed to the broken inversion symmetry in Y_2C_3, in which the ASOC splits the electronic bands, mixing the spin-singlet and spin-triplet pairing states and, therefore, leading to the existence of line nodes in the superconducting energy gap rather than a full gap. These new findings of the Partner Group indicated that Y_2C_3 might present another important example to study the pure effect of ASOC on superconductivity.

In practice, $Li_2(Pd_{1-x}Pt_x)_3B$ and Y_2C_3 are extremely air sensitive and it is rather difficult to grow single crystals, which have largely restricted further measurements on these compounds. Searching for new material candidates with a tunable ASOC is highly desirable in order to further reveal these non-trivial superconducting states. Our continuous research efforts include synthesizing new non-centrosymmetric super-conductors, e.g., LaRhSi, $LaNiC_2$ and $(Mo_{1-x}W_x)_3P$, characterizations of their superconducting pairing states by carrying out magnetic penetration-depth, thermodynamic, and thermal- as well as electrical transport experimants, to be conducted at both institutions, Zhejiang University and MPI CPfS, respectively. Doctoral students from Zhejiang University will be directly involved in the experiments at the MPI CPfS.

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