Research Group for Materials Physics for Heavy Element systems

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In heavy element systems, valence fluctuations, the Kondo effect, and the RKKY interaction compete with one another. Because of this, exotic behaviors such as quantum critical points, heavy fermions, non-Fermi liquids, anisotropic superconductivity and multipolar ordering appear when such competition is strong. Recently, it has become clear that these exotic behaviors for 5*f*-electron systems are different from those for 4*f*-electrons. This is because electrons with different spin and orbital character can coexist in 5*f* actinide systems, in contrast to the case of 4*f* electrons. By means of advanced experimental and theoretical approaches, our research group tries to clarify these exotic behaviors due to the “many-fold” character of both 4 *f* and 5*f* compounds, including transuranium.

In this mid-term project, we also try to break new ground such as topological and spintronic aspects in these compounds.

Odd Parity rank-5 ordering in URu_2Si_2 [1]

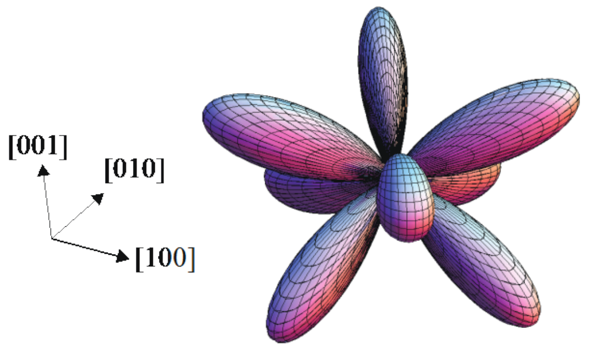

Fig. 1 Schematic electron distribution at the U site for P4/nnc state, which has 422 (D_4) local symmetry. This type of ordering corresponds to electric dotriacontapolar order in the present case, which is a strong candidate for the hidden ordered state of URu_2Si_2.

The heavy fermion superconductor URu_2Si_2 undergoes a second order phase transition at $T_0 \sim 17.5$ K. Since the order parameter of the transition has not ever been clearly identified, such order has been termed “hidden order”. Identifying the hidden order parameter is one of the challenging topics in condensed matter physics at present. In this study, ^{29}Si and ^{101}Ru NMR measurements were performed on high–quality, single–crystal URu_2Si_2 samples with a residual resistivity ratio RRR~70. Our results showed that the Si and Ru sites exhibited 4-fold electronic symmetry around the c-axis in the hidden-order state. Since the U and Si sites were aligned along the c-axis, we concluded further that the electronic state shows 4-fold symmetry around the U site below the hidden–order transition. From this observed local symmetry, possible space groups for the hidden–order state are thought to be P4/nnc or I4/m, based on group theoretical considerations. Since the order vector is considered to be Q = (001), the hidden–order state is then found to be P4/nnc with rank 5 odd-parity, i.e. electric dotriacontapolar order. In the P4/nnc case, the point group at the U site is 422 (D_4). Figure 1 shows an electronic state for the totally symmetric representation of the 422 point group A_{1u}:$xyz(x^2-y^2)$. Now confirmation of this ordered state is in progress.

Superconductivity with quadrupole degrees of freedom [2, 3]

A cubic system with the Γ_3 crystalline electric field (CEF) state is an ideal system to investigate multipole physics, since it does not have dipole but has higher-order multipoles such as quadrupole and octupole. In addition, superconductivity has been observed in PrT_2X_{20} (T = Ir, Rh, X = Zn; T = Ti, V, X = Al) systems with the Γ_3 CEF ground state. To approach these phenomena theoretically, we considered a model composed of *f* electrons with the total angular momentum j = 5/2. The j = 5/2 states split into Γ_7 and Γ_8 levels under a cubic CEF. When we assumed an antiferromagnetic interaction between the Γ_7 and Γ_8 orbitals, the f^2 ground state was the Γ_3 state composed of singlets between these orbitals. Thus, we employed this model as one of the simplest models to describe the Γ_3 state. From this model, we have succeeded in deriving multipole interactions for the Γ_3 systems [4]. In this study, we investigated superconductivity of the same model. In multiorbital systems, we can expect anisotropic superconductivity originating from the orbital anisotropy. For example, *d*-wave spin-triplet state in a model for e_g orbitals on a square lattice [5]. We applied random phase approximation for superconductivity in a multiorbital system to the present model and obtained a *d*-wave spin-singlet state. This pairing state is naturally expected from the f^2-Γ_3 CEF ground state. Such anisotropic superconductivity in a cubic system can lower the symmetry of the system and coexist with quadrupole order as shown in Fig. 2. We will further explore the coexisting phase theoretically to understand experimental phase diagrams of the Γ_3 systems.

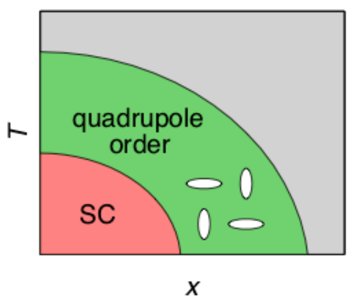

Fig. 2 Phase diagram expected for a superconductor with quadrupole degrees of freedom. *x* denotes a parameter such as external pressure and *T* denotes a temperature. Superconductivity (SC) occurs inside the quadrupole ordered phase.

References

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