Direct measurement of the evolution of magnetism and superconductivity toward the quantum critical point

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Quantum critical phenomena are one of the central issues in condensed matter physics. In the vicinity of the quantum critical point (QCP), where two different interactions compete, quantum fluctuations play a major role in realizing unconventional superconductivity as well as other exotic ground states. This quantum critical phenomenon could be observed when the phase transition occurs at T = 0 by tuning parameters other than temperature, such as magnetic field, pressure, and chemical substitutions. For instance, in a heavy fermion system, the magnetic Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction conflicts with the nonmagnetic Kondo effect along with the Doniach phase diagram [1], and deviations from the Fermi liquid theory, which is a basic concept of interacting fermions, are found in some systems. Such a “non-Fermi liquid” (NFL) state is observed in thermodynamic and transport properties. Furthermore, unconventional superconductivity often appears in a region of the phase diagram enclosed by a dome-shaped boundary near the QCP. The properties of the system in the superconducting (SC) dome are dominated by quantum criticality, and the mechanism of the superconductivity is strongly related to the quantum critical spin fluctuations. Revealing the spin state in the SC dome where a strong impact of quantum critical fluctuations must be manifested. Therefore, the direct measurements of the magnetic and superconducting order parameters are thus significant to identify the physical properties near the QCP. From an experimental point of view, the signals from the magnetic order in the SC dome are expected to be very small compared with large SC signals, and a highly sensitive magnetic probe is required.

As an example of the quantum critical compounds, tetragonal $CeCoIn_5$ is one of the extensively investigated heavy fermion compounds, which exhibit superconductivity at ambient pressure (T_c = 2.3 K at B = 0) [2]. $CeCoIn_5$ shows NFL behaviors in various quantities just above the SC upper critical field H_{c2} [3], suggesting that the magnetic field can induce quantum critical fluctuations. Meanwhile, it is well known that the superconductivity of $CeCoIn_5$ is strongly correlated with magnetism. Recently, the coexistence of superconductivity and magnetic ordering was also suggested in the case of the Zn substitution system $CeCo(In_{1-x}Zn_x)_5$ [4,5]. By substituting In with a tiny amount of Zn, a small modification in the system, corresponding to the energy scale on the order of a few Kelvins, occurs without any structural phase transition, and it is possible to tune only magnetism and superconductivity. In this regard, $CeCo(In_{1-x}Zn_x)_5$ is one of the ideal systems to investigate the role of magnetic quantum criticality in the evolution of superconductivity. In $CeCo(In_{1-x}Zn_x)_5$, the SC transition temperature T_c continuously reduces from 2.3 K (x = 0) to 1.4 K (x = 0.07) upon Zn doping, and then, the antiferromagnetic (AFM) order, with a transition temperature of T_N = 2.2 K, is found for x > 0.05 at B = 0. However, in the doping range where x < 0.05, T_N becomes smaller than T_c, indicating that a significant response due to superconductivity masks the weak signal of the AFM state and its quantum critical fluctuations in the SC dome, and it is unclear whether the quantum phase transition and spin fluctuations exist even deeper inside the SC phase. To reveal the possible weak magnetism and quantum criticality both inside and outside the SC dome in $CeCo(In_{1-x}Zn_x)_5$, we employed muon spin rotation/relaxation at J-PARC and elastic neutron scattering measurements at ILL.

It was found that a magnetically ordered state develops at x ~ 0.03, coexisting with the superconductivity [6]. The obtained phase diagram of $CeCo(In_{1-x}Zn_x)_5$ is shown in Fig. 1. The magnitude of the ordered magnetic moment is continuously reduced with decreasing x, and it disappears below x ~ 0.03, indicating a second-order phase transition and the presence of the QCP at this critical Zn concentration. Furthermore, the magnetic penetration depth in the SC phase diverges toward the QCP. These facts provide evidence for the intimate coupling between quantum criticality and Cooper pairing.

The present result indicates that magnetism due to quantum effects plays a significant role in the emergence of superconductivity, leading to the elucidation of the relationship between the magnetic and possible mechanism of the emergence of superconductivity.

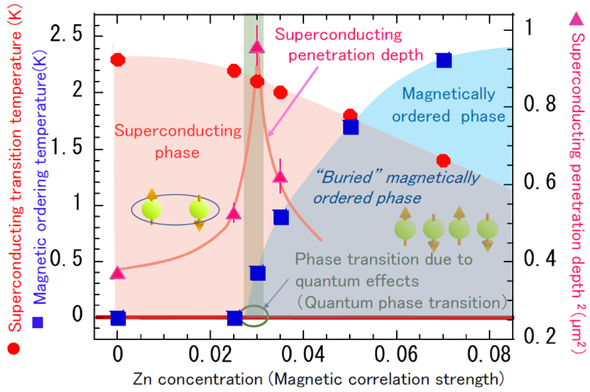

Fig. 1 Obtained phase diagram of $CeCo(In_{1-x}Zn_x)_5$.

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