Magnetic-field-induced quantum critical behavior in the heavy-fermion superconductor $CeCoIn_5$: ^{59}Co Nuclear Magnetic Resonance study

H. Sakai[1,3], S. E. Brown[2,3], S.-H. Baek[3], F. Ronning[3], E. D. Bauer[3], and J. D. Thompson[3]
1) R. G. for Condensed Matter Physics of Heavy Element Systems, ASRC, JAEA
2) University of California 3) Los Alamos National Laboratory

The need to determine the nature of spin fluctuations and their possible relationship to unconventional superconductivity in heavy fermion systems, and strongly correlated systems more broadly, has posed a long-standing problem. The intermetallic compound $CeCoIn_5$ with a tetragonal crystal structure is an absolutely fascinating material. The superconducting critical temperature T_c for this compound is 2.3 K, which is the highest among Ce-based heavy fermion systems. Moreover, it exhibits the various physical phenomena such as heavy fermion behavior (i.e. large electronic specific heat coefficient γ ~ 1000 mJ mol^{-1} K^{-2}), anisotropic superconductivity, magnetic-field-induced spatially-modulation of superconductivity with coexistence of antiferromagnetism (this is animatedly discussed if it may be Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state), quantum criticality and so on. These rich physical properties in $CeCoIn_5$ are thought to occur in the background of strong antiferromagnetic correlations. Nuclear magnetic resonance (NMR) technique is one of the most suitable tools to evaluate such spin dynamics microscopically, while the usual transport measurements cannot estimate it directly. We have preformed the ^{59}Co-NMR measurements for $CeCoIn_5$ as functions of external magnetic fields (H_0) and temperatures (T), in order to evaluate how the antiferromagnetic spin fluctuations develop toward the anisotropic superconductivity at the lowest temperatures. Since the perturbation energy is quite small of ~10^{-5}–10^{-2} meV in NMR spectroscopy, NMR relaxation rate $1/T_1$ responds promptly to the dynamical susceptibility of the electronic states. In general, NMR $1/T_1$ corresponds to the square of hyperfine coupling constant (A_{hf}^2) times $\Sigma_q \mathrm{Im}\chi(\boldsymbol{q}, \omega)$, the latter of which is the imaginary part of momentum space ($\boldsymbol{q}$)-summed electronic dynamical susceptibility. Although A_{hf} is usually T-independent, the A_{hf} for ^{59}Co nuclei in $CeCoIn_5$ has been found to be T-dependent for ^{59}Co from our previous work [1]. This T-dependent $A_{hf}(T)$ has been used for the successive detailed analyses based on the uniform dynamical susceptibility by Ce 4f electrons. For example, in the case of normal metal (i.e. Fermi-liquid state), $(T_1T)^{-1}/A_{hf}^2$ is known to become constant, and its constant value corresponds to the enhancement of electronic correlations.

In the case of H_0 well above the superconducting critical field $H_{c2}(0)$~ 5 T parallel to the c-axis (see the 8 T data in Fig. 1), the normalized $(T_1T)^{-1}/A_{hf}^2(T)$ shows a constant value in the lowest temperatures below ~1 K. As the external fields decreases toward to 5 T, $(T_1T)^{-1}/A_{hf}^2(T)$ shows a critical increase in the lowest temperatures [2]. As shown in Fig. 1, this critical behavior of $1/T_1$ is well explained by the theoretical model of antiferromagnetic spin fluctuations, i.e. self-consistent renormalization (SCR) theory, which has been applied successfully to characterize the nature of spin fluctuations in many heavy fermion materials [3]. In addition, it is found that the obtained parameters from the fit to $1/T_1$-data can explain the H_0-dependence of macroscopic physical properties such as resistivity, specific heat, and thermal expansion in the same theoretical framework.

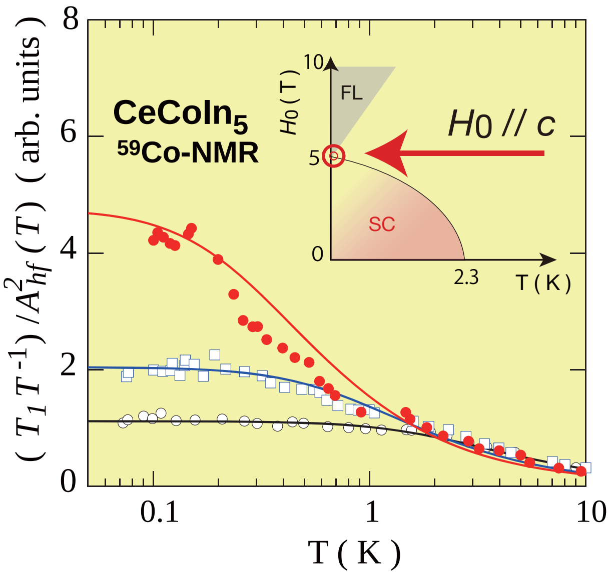

Fig. 1 T-dependence of the normalized $(T_1T)^{-1}/A_{hf}^2(T)$ for ^{59}Co-NMR in $CeCoIn_5$ under the external fields of 8, 6.4, and 5 T parallel to c-axis. The solid curves represent the calculated curves based on the theoretical model of antiferromagnetic spin fluctuations [2]. The inset shows the schematic H_0-T phase diagram in the case of H_0 parallel to the c-axis.

Thus, our results have conclusively proved that the quantum critical behavior near $H_{c2}(0)$ for the heavy fermion superconductor $CeCoIn_5$ is caused by the antiferromagnetic spin fluctuations. Such kind of field-tuned criticality may exist even in the high-T_c cuprates, in which antiferromagnetic spin fluctuations develop well, although it cannot be verified easily since the $H_{c2}(0)$ for these superconductors is extensively higher. Perhaps, this work may provide small-scale, but really identifiable values for building a new theory to design for a new higher-T_c material.

References

[1] H. Sakai *et al*., Phys. Rev. B **82**, 020501(R) (2010).
[2] H. Sakai *et al*., Phys. Rev. Lett. **107**, 137001 (2011).
[3] S. Kambe *et al*., J. Low Temp. Phys. **108**, 383 (1997).