Ferromagnetic quantum criticality: emergence of modulated magnetic phases and spin reorientation

During this program, we successfully synthesized single crystals of two systems: $CeRh_3B_2$ and $UFe_{10}Si_2$. Our initial characterizations indicate that these systems are ideal candidates to study two possible outcomes of the suppression of ferromagnetism. Namely, we investigate the emergence of modulated magnetic orders in $CeRh_3B_2$ with Ru substitutions, and spin reorientation tri-criticality with field aligned along the hard axis in $UFe_{10}Si_2$.

When a paramagnetic-ferromagnetic phase transition is suppressed by a clean tuning parameter such as pressure, particle-hole excitations either induce the transition to become of the first order [1], or they induce the appearance of new modulated magnetic phases [2]. These phases have small magnetic wavevector *q* and can correspond to helical or conical orders. On the other hand, when using chemical substitutions, the introduction of disorder can reduce long wavelength correlations and the transition may remain of the second order until being suppressed at a ferromagnetic quantum critical point [3]. It is therefore difficult to identify a system which can be tuned by chemical substitutions without suppressing the effect of particle-hole excitations. Here, we introduce the system $Ce(Rh_{1-x}Ru_x)_3B_2$ which appears to be a promising system to observe the appearance of modulated magnetic phases near the suppression of ferromagnetism.

$CeRh_3B_2$ orders ferromagnetically below $T_C=115$ K [4] and has attracted the attention as the Ce magnet with the highest Curie temperature among Ce systems with non-magnetic elements. Studies of polycrystalline samples with Ru substitutions showed that T_C is suppressed near $x=0.08$ and a so-called "complex order" is observed in the range $0.1<x<0.4$ [5]. The phase diagram is shown in Fig.1a. A complex antiferromagnetic structure was proposed, but the nature of the samples (polycrystalline) did not motivate further investigations. During this program, we succeeded in synthesizing single crystals of $Ce(Rh_{0.8}Ru_{0.2})_3B_2$ using the Czochralski technique. Our magnetization measurements confirm an antiferromagnetic transition (sharp anomaly near $T_N=70$ K in Fig.1b) with the c-axis being the easy magnetization axis. However, the magnetization does not decrease significantly below T_N and increases again upon cooling below *20* K. This could be characteristic of a helical or conical type of magnetic order, as predicted to appear near the suppression of ferromagnetism [3]. In the near future, we will perform specific heat and magnetoresistance measurements to quantify the remaining entropy at low temperature, neutron scattering experiments to clarify the magnetic order, and NMR measurements to investigate the spin fluctuations. Our work will establish that chemical substitutions in $CeRh_3B_2$ do not introduce much disorder, demonstrating that $CeRh_3B_2$ is an ideal system to study the suppression of ferromagnetism and the emergence of modulated magnetic phases.

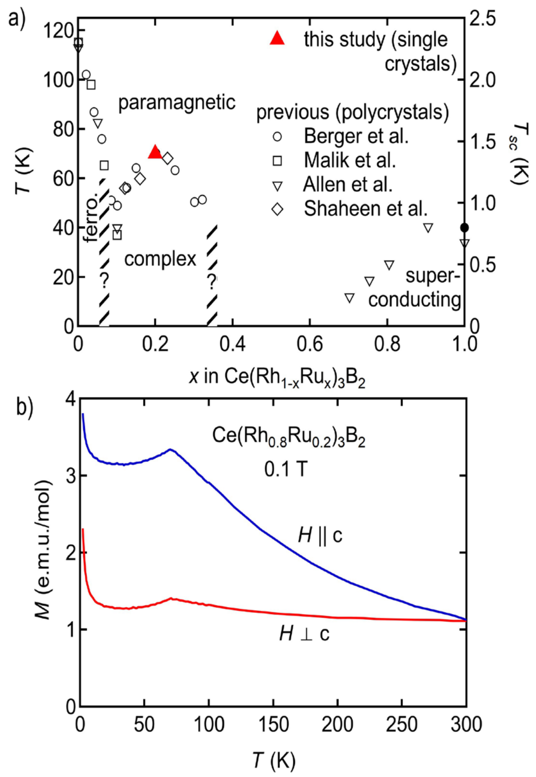

Figure 1: a) Phase diagram of $Ce(Rh_{1-x}Ru_x)_3B_2$ from polycrystalline samples b) Temperature dependence of the magnetization measured on our single crystal.

Besides pressure and chemical substitutions, another useful tuning parameter is the magnetic field. The application of a magnetic field breaks the time-reversal symmetry and smears out a second-order paramagnetic-ferromagnetic transition. However, when the transition is of the first order, the magnetic field will induce a metamagnetic transition which eventually become a crossover at high-temperatures leading to a so-called "wing-structure" phase diagram [1,3]. Interestingly, in systems with strong magnetic anisotropy, the magnetic field can be used to suppress the paramagnetic-ferromagnetic transition even when it is of the second order, providing that the field is applied along the hard magnetization axis. As the field is increased, the transition eventually becomes of the first order before being completely suppressed at a quantum phase transition. Re-entrant superconductivity has been observed near such quantum phase transition in UCoGe and URhGe (it is possible that the metamagnetic transition in UTe_2 is of the same nature). One difficulty in studying the effect of magnetic field in these systems is that the anisotropy is very large while T_C is relatively small, which requires large magnetic fields (~11-35 T) and very low temperatures (~100 mK). In this program, we identified a system with a moderate magnetic anisotropy, but a very large Curie temperature: $UFe_{10}Si_2$.

$UFe_{10}Si_2$ has a Curie temperature of 653 K [6]. First principle calculations as well as exsting data indicate a magnetic anisotropy energy between 2 and 3 MJ/m^3: the moments are aligned along the c axis, and a metamagnetic jump is observed near 3-4 T when the field is applied along the a axis. In this program, we attempted to grow single crystals using the Czochralski technique. Several grains tend to nucleate during the synthesis, but we were able to isolate several samples with good crystallinity.

Our preliminary characterization measurements demonstrate that we can track the metamagnetic transition in the magnetoresistance (Fig.2): a sharp drop is observed near 3.7 T when the field is applied along the a-axis. With increasing the temperature, the transition clearly broadens, as visible by comparing measurement at 2 K and 300 K for example. This indicates that there is a change of nature of the transition, probably from first order at low temperatures to second order at high temperatures. Indeed, when the transition is of the second order, it will be very sensitive to the alignment of magnetic field and remain sharp only if the field is precisely perpendicular to the c-axis. In the near future, we need to perform more precise measurements to identify the location of a tri-critical point where the transition changes from second to first order. Our work will establish a rare example of a spin-reorientation tri-critical point at low field and high temperature. Such system provides a key playground to investigate the physics behind the tri-critical point and enable comparison with systems with re-entrant superconductivity.

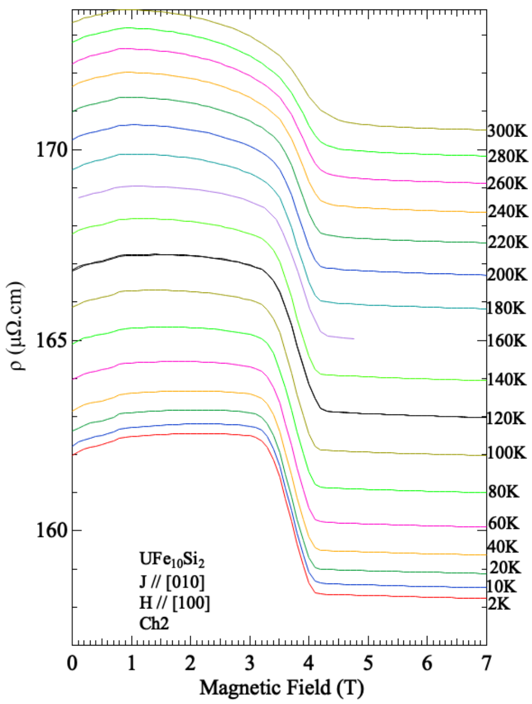

Figure 2: Magnetic field dependence of the electrical resistivity of UFe10Si2 at different temperatures with the field applied along the a-axis.

Keywords: ferromagnetic, Czochralski growth, magnetoresistance

Full Name: Dai Aoki (IMR Tohoku University) and Valentin Taufour (Department of Physics, University of California Davis)
E-mail: aoki@imr.tohoku.ac.jp and vtaufour@ucdavis.edu

References

[1] V. Taufour, D. Aoki, G. Knebel, and J. Flouquet *Phys. Rev. Lett.*, 105, 217201, 2010.
[2] V. Taufour, et al., *Phys. Rev. Lett.*, 117, 037207, 2016.
[3] M. Brando, D. Belitz, F.M. Grosche, and T. R. Kirkpatrick, *Rev. Mod. Phys.*, 88, 025006, 2016.
[4] S. K. Dhar, S. K. Malik, and R. Vijayaraghavan *Journal of Physics C: Solid State Physics*, 14, 11, L321, 1981.
[5] S. Berger, et al., *Phys. Rev. B*, 64, 134404, 2001.
[6] A. Andreev, S. Zadvorkin, and E. Tarasov, *J. Alloys Compd.*, 189, 2, 187, 1992.