Interplay between magnetism and superconductivity in orthorhombic compounds UCoGe, URhGe and UIrGe

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I came to JAEA from Charles University in Prague in 2014. My scientific field of interest is single crystals growth and research of the magnetism and strongly correlated electron phenomena. I continued my work here in JAEA and I would like to thank all my colleagues for outstanding support in my research. We have prepared a series of new actinide materials and gained results revealing fine details of interplay between ferromagnetism and superconductivity. We also spent here very nice time with my wife Alena and sons Jirka and Martin. We have found new friends in Tokai and it was also a great opportunity for us to travel around Japan and visit many beautiful places.

The research of quantum phase transitions is unique part of the physics exploring novel electronic phenomena in materials. Uranium intermetallic compounds excel in this field due to the specific uranium 5*f* electrons on the boundary of localized and itinerant characters which makes them extremely sensitive on external influences. The boundary between the localized and itinerant characters was empirically established at the uranium ions distance $d_{\text{U-U}}$ = 3.5 Å called as a Hill criterion [1]. Materials with larger $d_{\text{U-U}}$ than that criterion are usually magnetically ordered, superconductivity often appears in the materials with shorter $d_{\text{U-U}}$ than the limit. The most interesting phenomena can be elicited in the crossover regime in particular cases understood in the scenario of a quantum phase transition.

Many uranium materials can be pushed to the crossover regime typically by external pressure. However, there is a narrow group of compounds which fulfil the Hill criterion naturally. Isostructural compounds URhGe and UCoGe crystallizing in TiNiSi-type structure are such cases and fundamental coexistence of ferromagnetism (FM) and superconductivity (SC) was discovered as a result of the critical ferromagnetic fluctuations [2, 3].

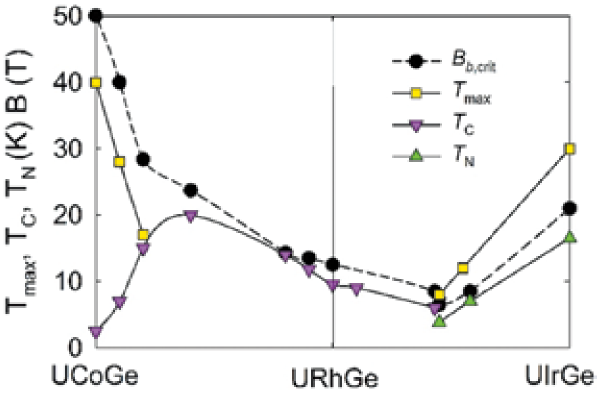
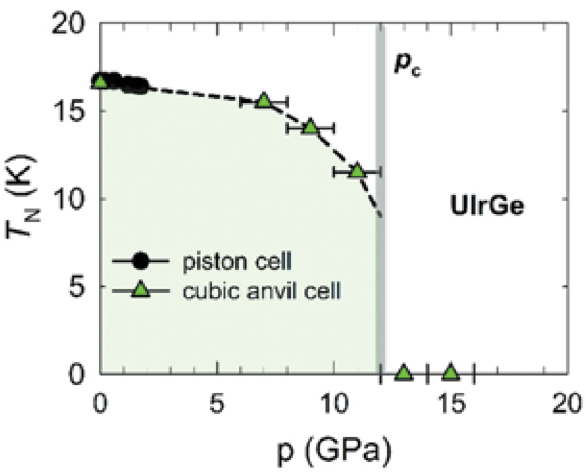


Fig. 1
Magnetic phase diagram of the orthorhombic TiNiSi-type compounds UCoGe, URhGe and UIrGe.

The *H-T* phase diagram of URhGe is famous also due to SC re-entrance enforced by external magnetic field H_R [4]. Similar scenario was also detected in UCoGe [5]. The subject of our research is FM state of these compounds because in comparison to URhGe, the H_R does not coincide with reentrant SC dome in UCoGe. We have used the opportunity in JAEA and grown a series of the high quality single crystals of composition $UCo_{1-x}Rh_xGe$. We have performed high magnetic field experiments in cooperation with International MegaGauss Science Laboratory in ISSP, University of Tokyo and studied the evolution of the value of H_R as a function of temperature through whole concertation range. We have found the H_R following Curie temperature T_C between URhGe and $UCo_{0.7}Rh_{0.3}Ge$ having almost constant H_R/T_C ratio. However, the H_R/T_C ratio suddenly increases in the region $UCo_{0.7}Rh_{0.3}Ge$ - UCoGe and H_R follows different critical temperature so called T_{max} (Fig. 1). T_{max} is a mystery of many compounds with strongly correlated electron phenomena. T_{max} appears as a broaden maximum in the temperature dependent magnetic susceptibility and is connected with a broad metamagnetic transition typically in high magnetic fields. In the case of UCoGe T_{max} = 40 K and related metamagnetic transition appears at magnetic field almost 50 T. The effect which stands behind of T_{max} is so far not resolved and will be subject of our further research. It is however surprising finding that the T_{max} is most likely the key to the features of the re-entrant SC dome in FM SC UCoGe and URhGe.

By systematic explorations of the $UCo_{1-x}Rh_xGe$, we have recognized that next to this system may exist another candidate UIrGe compound. UIrGe compound is intriguing by $d_{\text{U-U}}$ also in the proximity to Hill criterion. Another important feature is that UIrGe is isoelectronic to UCoGe and URhGe, because all three transition metals belong to the same group [6]. It is known that UIrGe orders antiferromagnetically (AFM) at T_N = 16.5 K. Then, FM/AFM boundary is presented in $URh_{1-x}Ir_xGe$ system although both parent compounds have almost the identical value of $d_{U\text{-}U}$. UIrGe clearly represents a promising candidate where electron correlation phenomena can be raised when a requisite external variable will be applied to reach the transformation FM/AFM boundary.



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We have tried to vanish the AFM order in the UIrGe compound by hydrostatic pressure up to 15 GPa and examined the presence of a potential non-Fermi liquid state (NFL) associated to potential quantum phase transition at critical pressure. The research was realized in cooperation with The High-Pressure Group in ISSP, University of Tokyo on so far the best available single crystals prepared here in JAEA.

We have successfully constructed the first *p-T* phase diagram of UIrGe compound. The T_N seems to suddenly vanish by first order transition at critical pressure $p_c \approx$ 12 GPa.

Within the group of three isoelectronic compounds, UIrGe is second one together with UCoGe where magnetism can be suppressed by hydrostatic pressure. The advance experiment down to temperature 20 mK and pressure 15 GPa is progress to search the SC in UIrGe. The $URh_{1-x}Ir_xGe$ system also revealed the importance of the characteristic T_{max} temperature which again suddenly appears at AFM side of the phase diagram $URh_{1-x}Ir_xGe$ system (Fig. 1).

The trio of UCoGe, URhGe and UIrGe compounds represents a unique group for research of the theory of magnetic phase transitions extended about consequences to theory of unconventional superconductivity with many unresolved details. We will continue the research in this field.

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Left photo: Hokkaido in 2015. Bicycle expedition around lakes Mashu and Kussharo and Mt. Io.
Right photo: Spring at Mt. Fuji.