# Investigation of the Quantum Criticality of $URu_2Si_2$ and Its Novel Emergent Phases Around 40 T: A High Field $^{29}$Si-NMR Study (Following up the Project ID: P01917)

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## Introduction

The so-called "hidden-order" (HO) phase transition in the heavy-fermion compound $URu_2Si_2$, at transition temperature $T_O$ = 17.5 K, has posed a long-standing mystery. $URu_2Si_2$ is also a very attractive material displaying intriguing *H-T* phase diagrams [1, 2] determined by the electronic transport measurements such as resistivity and Hall effect. In particular, an anomaly in the Hall resistivity around 22 T has been reported within the HO phase [1]. It is also reported that the critical field of HO phase is about 35 T by means of resistivity measurements [2]. High field NMR is a very suitable microscopic technique to investigate these anomalies in $URu_2Si_2$. The single crystals studied in this project were enriched with 99.8% of $^{29}$Si isotope, a very suitable nucleus ($I$=1/2) for NMR measurements. It should be noted that the natural abundance of $^{29}$Si is only 4.7 %, which is too diluted.

## Experimental

Several single crystals of $URu_2Si_2$ enriched with 99.8% of $^{29}$Si isotope have been grown by the Czochralski-pulling method, and annealed by the solid-state electro-transport (SSE) method. A single crystal of $URu_2Si_2$ with a dimension of ~2×1.5×1(t) mm$^3$ was used, of which the sample quality had been verified by means of resistivity and NMR measurements. During our last high field experiments at Cell 15, the NMR shift measurements with applied magnetic fields up to ~40 T were performed. The field scan of the NMR shifts was carried out at a constant temperature of 400 mK.

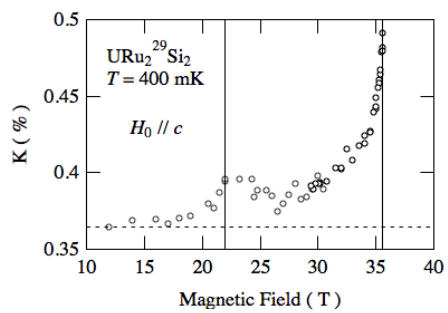


**Figure 1.** Field dependence of $^{29}$Si-NMR shift along the *c*-axis at 400 mK.

## Results and Discussion

Our goal is to detect the anomaly at 22 T by means of shift measurements at the lowest temperatures. The results from the shift measurements in field up to $H_{c1}$=35.6 T are summarized in **Figure 1**. In the case of $H_0//a$, the shift $K_a$ is nearly field-independent. In contrast, for $H_0//c$, the shift $K_c$ revealed anomalies around 22 T. Since the shift is a measure of the electronic density of states via local susceptibility, the anomaly around 22 T may indeed be related to the reconstruction of the Fermi surface as previously proposed by Shishido et al [1]. From the point of view of hyperfine interaction, this important finding clearly demonstrates that the electronic state above ~22 T below $H_{c1}$ is still similar to that within the HO phase at lower fields. The small anomalous shift around 22 T may be attributed to a Lifshitz transition. Above $H_{c1}$, the sudden decrease in $^{29}$Si-NMR spectra is caused by the first order transition at $H_{c1}$. Here, a drastic change of 5f electronic states appears to suppress the HO phase.

## Conclusions

Our NMR results are the first microscopic evidence for the change of the magnetic susceptibility across the anomaly observed at 22 T, which could not be clarified by previous transport measurements. Based on our high field NMR data, the transition at $H_{c1}$~35 T between the hidden order and the novel field-induced phase is a first order transition. In order to clarify the electronic states above $H_{c1}$, the temperature scan at higher fields is important since there is no first order transition in the *H-T* phase diagram.

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## References

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[2] Kim K. H. *et al*., Phys. Rev. Lett. **91**, 256401 (2003).