Electrical Control of the Kondo Cloud by the Kondo Box

Ngoc Han Tu[1], Minsoo Kim[2], Donghoon Kim[2], Ryo Ito[3], David Pomaranski[4], Jeongmin Shim[2], Ivan. V. Borzenets[5], Arne Ludwig[6], Andreas D. Wieck[6], H.-S. Sim[2], and Michihisa Yamamoto[1,4]

[1]*Centre for Emergent Matter Science (CEMS), RIKEN, Saitama 351-0198, Japan*

[2]*Department of Physics, KAIST, Daejeon, South Korea*

[3] *The National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan*

[4]*Quantum-Phase Electronics Center and Department of Applied Physics, The University of Tokyo*

[5]*Physics & Astronomy Department, Texas A&M University, Texas, United States*

[6]*Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Germany*

michihisa.yamamoto@riken.jp

In metals and semiconductors, an impurity spin is quantum entangled with and thereby screened by surrounding conduction electrons at low temperatures, called the Kondo screening cloud. The Kondo screening cloud was recently observed [1], and it was found to have the universal shape when the density of states of conducting electrons is almost constant. However, quantum confinement of the Kondo screening cloud in a region, called a Kondo box, with a length smaller than the original cloud extension length strongly deforms the screening cloud through the modified density of states and provides a way of controlling the entanglement.

We realize experimentally the Kondo box and develop theoretically an approach of controlling and monitoring the entanglement. It is based on a spin localized in a semiconductor quantum dot, which is screened by conduction electrons along a quasi-one-dimensional channel. The box is formed between the dot and a quantum point contact (QPC) placed on a channel. As the QPC is tuned to make the confinement stronger, electron conductance through the dot as a function of temperature starts to deviate from the known universal function of the single energy scale, Kondo temperature. Nevertheless, the entanglement is monitored by the measured conductance according to our theoretical development. The dependence of the monitored entanglement on the confinement strength and temperature implies that the Kondo screening is controlled by tuning the QPC. Namely, the Kondo cloud is deformed by the Kondo box in the region across the original cloud length. These findings offer a way of manipulating and detecting spatially extended quantum many-body entanglement in solids by electrical means.

As we further increase the QPC confinement, the Kondo box becomes a charge island. Such a regime is not theoretically accessible and the experiment in this regime is considered as a quantum simulation. We find in this regime, a novel coherent transport that we call Kondo tunneling driven by the many-body spin entanglement when the box is at “off-resonance”. It is enhanced by increasing the QPC confinement and is attributed to the scattering phase shift of $\pi/2$ across the Kondo state ($\pi/2$ phase shift in the round trip). Comparison of our experimental finding and our theoretical prediction for the Kondo box without the charging effect suggests that the Kondo tunneling occurs when the time constant RC of the charge island is larger than the time scale of the Kondo state formation, revealing the impact of the Kondo dynamics in the coherent transport.

References

[1] I. V. Borzenets et al., Nature **579**, 210 (2020).

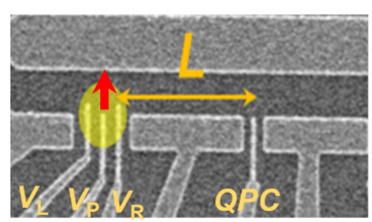

Fig.1. SEM image of the Kondo box. The QPC is placed at length L away from the quantum dot that confines a localized spin.