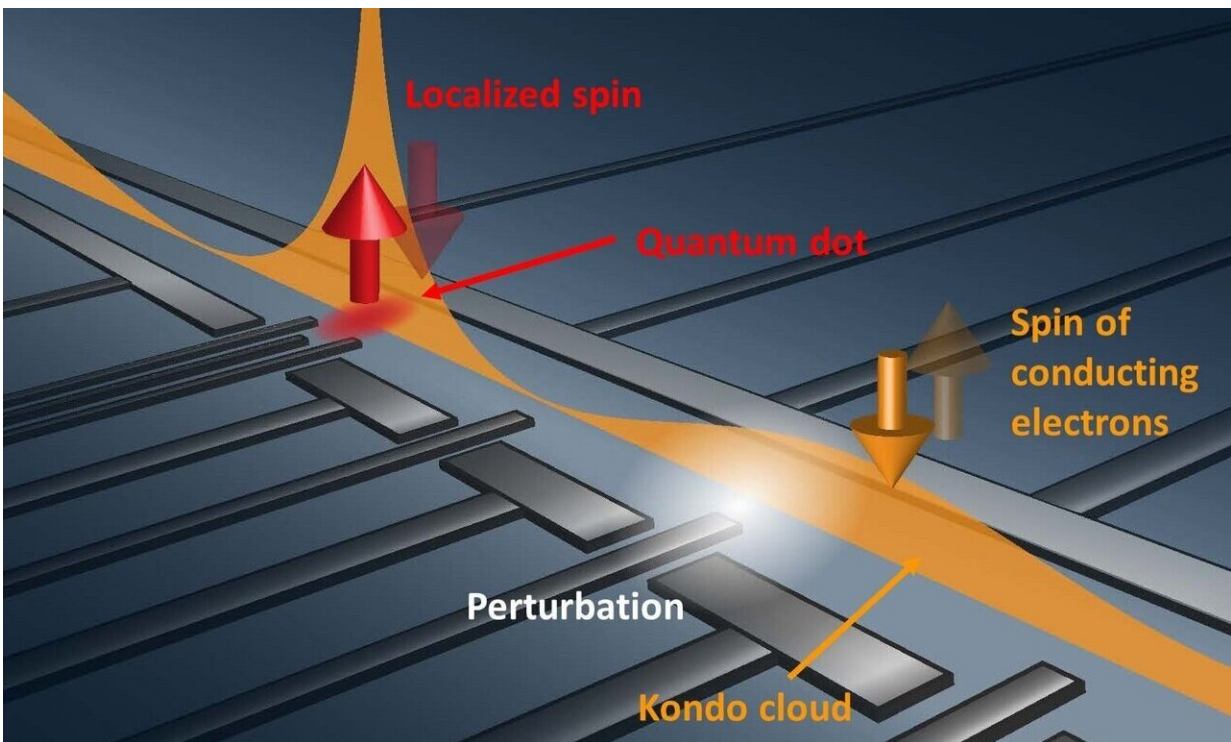


World's first experimental observation of a Kondo cloud

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A schematic illustration of the Kondo cloud detection. Credit: Jeongmin Shim

Physicists have been trying to observe the Kondo cloud quantum phenomenon for many decades. An international research team has recently developed a novel device that successfully measures the length of the Kondo cloud and even allows for controlling it. The findings can be regarded as a milestone in condensed matter physics, and may

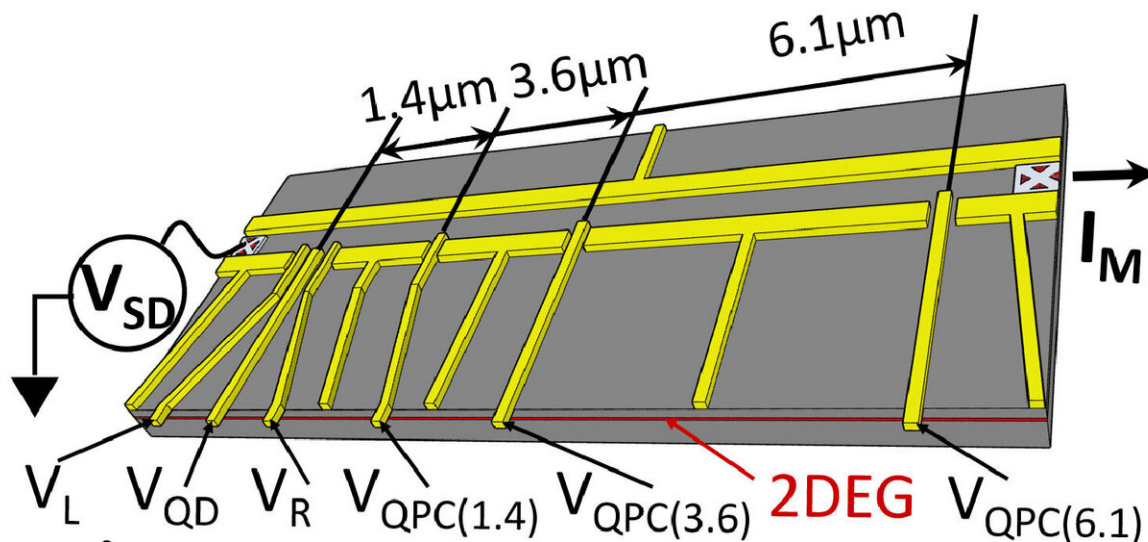
provide insights for understanding multiple impurity systems such as high-temperature superconductors.

This breakthrough was achieved by a team of researchers from RIKEN Center for Emergent Matter Science (CEMS), City University of Hong Kong (CityU), Korea Advanced Institute of Science and Technology (KAIST), the University of Tokyo, and Ruhr-University Bochum. Their research findings were published in *Nature*.

What is the Kondo cloud?

The Kondo effect is a physical phenomenon discovered in the 1930s. In metals, as the [temperature](#) drops, electrical resistance usually drops. However, if there are some [magnetic impurities](#) in the metal, it will show the opposite result. Resistance will drop at first. But when it is below some threshold temperature, the resistance will increase as the temperature decreases further.

This puzzle was solved over 50 years ago by Jun Kondo, a Japanese theoretical physicist for whom the effect was named. He explained that when a magnetic atom (an impurity) is placed inside a metal, it has a spin. But instead of just coupling with one electron to form a pair of spin-up and spin-down, it couples collectively with all the electrons within some areas around it, forming a cloud of electrons surrounding the impurity—this is called the Kondo cloud. When a voltage is applied over it, the electrons are not free to move or are screened off by the Kondo cloud, resulting in resistance increase.



The device consists of a quantum dot coupled to a one dimension channel, in which three gates are embedded at distances of 1.4 μm, 3.6 μm and 6.1 μm from the quantum dot for creating barriers. Credit: City University of Hong Kong / Nature

How big is the cloud?

Some basic properties of the Kondo effect have been proven experimentally and were found to be related to the Kondo temperature (the threshold temperature where the resistance starts to go up at low temperature). However, the measurement of the Kondo cloud's length was yet to be achieved. Theoretically, the Kondo cloud can spread out over several micrometers from the impurity in semiconductors. Professor Heung-Sun Sim at Department of Physics, KAIST, the theorist who proposed the method for detecting the Kondo cloud, commented that "the observed spin cloud is a micrometer-size object that has quantum mechanical wave nature and entanglement. This is why the spin cloud has not been observed despite a long search."

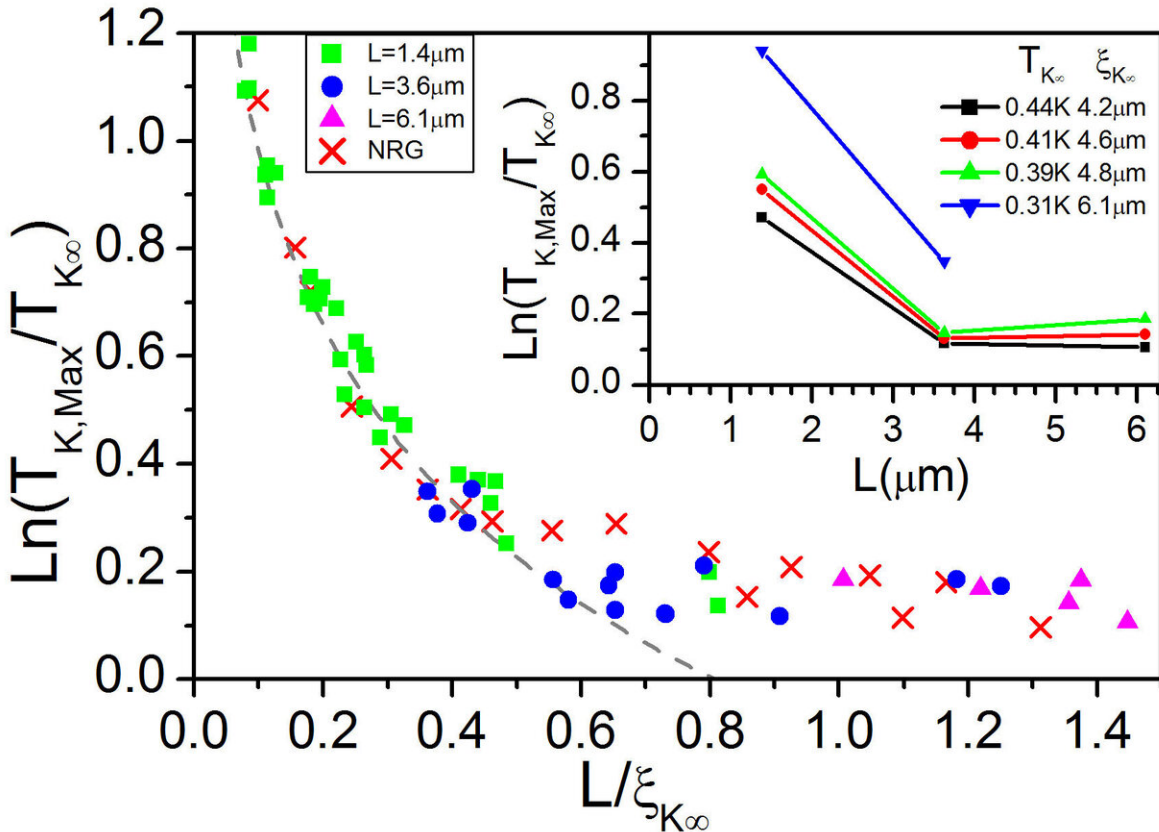
"The difficulty in detecting the Kondo cloud lies in the fact that measuring spin correlation in the Kondo effect requires the fast detection of tens of gigahertz. And you cannot freeze time to observe and measure each of the individual electrons," explained Dr. Ivan Valerievich Borzenets, Assistant Professor at CityU's Department of Physics, who performed the experimental measurement of this research.

Isolating a single Kondo cloud in the device

Thanks to the advance in nanotechnology, the research team fabricated a device that can confine an unpaired electron spin (magnetic impurity) in a quantum dot, like a small conducting island with a diameter of only a few hundreds nanometers. "Since the quantum dot is very small, you can know exactly where the impurity is," said Dr. Borzenets.

Connecting to the quantum dot is a one-dimensional and long channel. The unpaired electron is constricted to couple to the electrons in this channel and form a Kondo cloud there. "In this way, we isolate a single Kondo cloud around a single impurity, and we can control the size of the cloud as well," he explained.

The novelty of the system is that by applying a voltage at different points inside the channel with various distances away from the quantum dot, they induced "weak barriers" along the channel. Researchers then observed the resulting change in electron flow and the Kondo effect with varying barrier strength and position.



The data collected (green blue and purple dots) from the experiment are compared with the theoretical results (red crosses), and they align on the same curve. Credit: City University of Hong Kong / Nature

The secret lies in the oscillation amplitude

By changing the voltages, it was found that the conductance went up and down, no matter where they put the barriers at. And when there were oscillations in conductance, oscillations in the measured Kondo temperature were observed.

When the researchers plotted the oscillation amplitude of Kondo temperature versus the barrier distance from the impurity divided by the

theoretical cloud length, they found that all their data points fall onto a single curve, as theoretically expected. "We have experimentally confirmed the original theoretical result of the Kondo cloud length which is in micrometer scale," said Dr. Borzenets. "For the first time, we have proved the existence of the cloud by directly measuring the Kondo cloud length. And we found out the proportionality factor connecting the size of the Kondo cloud and Kondo temperature."

Provide insights into multiple impurity systems

The team spent almost three years in this research. Their next step is to investigate different ways to control the Kondo state. "Many other manipulations on the device can be done. For example, we can use two impurities at the same time, and see how they will react when the [clouds](#) overlap. We hope the findings can provide insights into the understanding of multiple [impurity](#) systems such as Kondo lattices, spin glasses and high transition-temperature superconductors."

According to Dr. Michihisa Yamamoto, Team Leader at RIKEN CEMS, who led the international collaboration, "it is very satisfying to have been able to obtain real space image of the Kondo cloud, as it is a real breakthrough for understanding various systems containing multiple magnetic impurities. This achievement was only made possible by close collaboration with theorists."

"The size of the Kondo cloud in semiconductors was found to be much larger than the typical size of semiconductor devices. This means that the cloud can mediate interactions between distant spins confined in quantum dots, which is a necessary protocol for semiconductor spin-based quantum information processing. This spin-spin interaction mediated by the Kondo cloud is unique since both its strength and sign (two spins favor either parallel or anti-parallel configuration) are electrically tunable, while conventional schemes cannot reverse the sign.

This opens up a novel way to engineer spin screening and entanglement," Dr Yamamoto explained.

"It is remarkable in a fundamental and technical point of view that such a large quantum object can now be created, controlled, and detected," Professor Heung-Sun Sim concluded.

More information: Observation of the Kondo screening cloud, *Nature* (2020). [DOI: 10.1038/s41586-020-2058-6](https://doi.org/10.1038/s41586-020-2058-6) , [nature.com/articles/s41586-020-2058-6](https://www.nature.com/articles/s41586-020-2058-6)

Provided by City University of Hong Kong

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