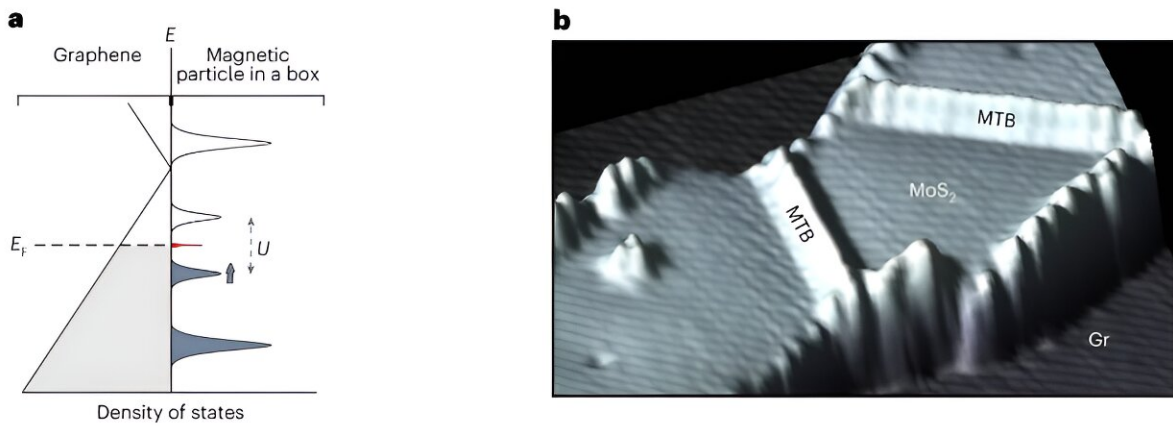


Riddle of the Kondo effect solved with an artificial atom and a 1D wire

November 15 2023, by Eva Schissler



a, Kondo coupling of graphene (bath) with the non-degenerate states (impurity) confined along a MoS₂ MTB. Fermi energy E_f and Coulomb energy U are indicated. The electron inside the highest occupied state is symbolized by an arrow. b, Atomically resolved topography of a single-layer MoS₂ island on graphene, with two MTBs of lengths 7.1 nm (left) and 9.0 nm (right), separating mirror-symmetric domains. Credit: *Nature Physics* (2023). DOI: 10.1038/s41567-023-02250-w

A team of physicists at the University of Cologne has solved a long-standing problem of condensed matter physics: they have directly observed the Kondo effect (the re-grouping of electrons in a metal caused by magnetic impurities) visible in a single artificial atom. This has not been done successfully in the past, since the magnetic orbitals of

atoms usually cannot be directly observed with most measurement techniques.

However, the international research team led by Dr. Wouter Jolie at the University of Cologne's Institute for Experimental Physics used a new technique to observe the Kondo effect in an artificial orbital inside a one-dimensional [wire](#) floating above a metallic sheet of graphene. They report their discovery in the [article](#) "Modulated Kondo screening along magnetic mirror twin boundaries in monolayer MoS₂" published in *Nature Physics*.

When electrons moving through a metal encounter a magnetic atom, they are affected by the atom's spin—the magnetic pole of elementary particles. In trying to screen the effect of the atomic spin, the electron sea groups together close to the atom, forming a new many-body state which is called the Kondo resonance.

This collective behavior is known as the Kondo effect and is often used to describe metals interacting with magnetic atoms. However, other types of interactions can lead to very similar experimental signatures, questioning the role of the Kondo effect for single magnetic atoms on surfaces.

The physicists used a new experimental approach to show that their one-dimensional wires are also subject to the Kondo effect: the electrons trapped in the wires form standing waves, which can be thought as extended atomic orbitals.

This artificial orbital, its coupling to the electron sea, as well as the resonant transitions between orbital and sea can be imaged with the scanning tunneling microscope. This experimental technique uses a sharp metallic needle to measure electrons with atomic resolution. This has allowed the team to measure the Kondo effect with unparalleled

precision.

"With magnetic atoms on surfaces, it is like with the story about the person who has never seen an elephant and tries to imagine its shape by touching it once in a dark room. If you only feel the trunk, you imagine a completely different animal than if you are touching the side," said Camiel van Efferen, the doctoral student who conducted the experiments. "For a long time, only the Kondo resonance was measured. But there could be other explanations for the signals observed in these measurements, just like the elephant's trunk could also be a snake."

The research group at the Institute of Experimental Physics specializes in the growth and exploration of 2D materials—[crystalline solids](#) consisting of just a few layers of atoms—such as graphene and monolayer molybdenum disulfide (MoS_2). They found that at the interface of two MoS_2 crystals, one of which is the [mirror image](#) of the other, a metallic wire of atoms forms.

With their scanning tunneling microscope, they could simultaneously measure the magnetic states and the Kondo resonance, at an astonishingly low temperature of -272.75°C (0.4 Kelvin), at which the Kondo effect emerges.

"While our measurement left no doubts that we observed the Kondo effect, we did not yet know how well our unconventional approach could be compared to theoretical predictions," Jolie added. For that, the team enlisted the help of two [theoretical physicists](#), Professor Dr. Achim Rosch from the University of Cologne and Dr. Theo Costi from Forschungszentrum Jülich, both world-renowned experts in the field of Kondo physics.

After crunching the [experimental data](#) in the supercomputer in Jülich, it turned out that the Kondo resonance could be exactly predicted from the

shape of the artificial orbitals in the magnetic wires, validating a decades-old prediction from one of the founding fathers of condensed matter physics, Philip W. Anderson.

The scientists are now planning to use their magnetic wires to investigate even more exotic phenomena. "Placing our 1D wires on a superconductor or on a quantum spin-liquid, we could create many-body states emerging from other quasiparticles than electrons," explained Camiel van Efferen. "The fascinating states of matter that arise from these interactions can now be seen clearly, which will allow us to understand them on a completely new level."

More information: Camiel van Efferen et al, Modulated Kondo screening along magnetic mirror twin boundaries in monolayer MoS₂, *Nature Physics* (2023). [DOI: 10.1038/s41567-023-02250-w](https://doi.org/10.1038/s41567-023-02250-w)

Provided by University of Cologne

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