How do electrons become entangled?

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(PhysOrg.com) -- A Princeton researcher and his international collaborators have used lasers to peek into the complex relationship between a single electron and its environment, a breakthrough that could aid the development of quantum computers.

The technique reveals how an isolated electron and its surroundings develop a relationship known as a Kondo state – a state of matter that is of great interest to physicists and engineers. The results not only yield insights into a long-standing quandary in theoretical physics, but also may help scientists understand how to store information at the smallest possible scales, which would open vast new realms of computing power.

"What we've done is illuminate the private life of a single electron," said Hakan Tureci, an assistant professor of electrical engineering at Princeton and a lead researcher on the project. "It's taken nearly a century to isolate, control and probe a single electron in this way – an extraordinary feat enabled by quantum theory, cryogenics and nanotechnology."

The research was conducted by an international team of scientists from the United States, Germany and Switzerland. The researchers on the project included Tureci, Atac Imamoglu, a professor at Swiss Federal Institute of Technology Zurich in Switzerland, Jan von Delft, a professor at LMU Munich, and Leonid Glazman, a professor at Yale University.

The key theoretical results and a proposal for testing the ideas experimentally were published March 11 in the journal Physical Review

Letters.

These theoretical projections were recently confirmed in experiments led by Imamoglu, which were published today in the journal *Nature*.

The research brings fresh insight to the study of the Kondo problem, a phenomenon first observed in the 1930s, when researchers were surprised to find that resistance to electricity flowing through certain metals increases at very low temperatures. Normally, resistance through metals decreases as temperature is lowered, but that was not the case with these metals.

The phenomenon was explained 30 years later by Japanese scientist, Jun Kondo, as resulting from the presence of cobalt or other magnetic impurities in the metals.

Scientists have further realized that the Kondo effect results from a relationship between electrons known as "entanglement" in which the quantum state of one electron is tied to those of neighboring electrons, even if the particles are later separated by considerable distances. In the case of Kondo effect, a trapped electron is entangled in a complex manner with a cloud of surrounding electrons.

Researchers have been intrigued by the Kondo effect in part because understanding how a trapped electron becomes entangled with its environment could help overcome barriers to quantum computing, which could lead to far more powerful computers than currently exist.

Previous observation methods allowed scientists to make measurements of the Kondo state, but could not provide information on how electrons developed such a relationship with their surroundings.

To better understand how an electron gradually becomes entangled in this manner with its environment, Tureci and his collaborators investigated the idea of using a laser to probe electrons evolving into the Kondo state. They first developed a theory about how laser light scattered off electrons could carry information about this process.

Depending on the state of the electron, they surmised, it should absorb different colors of laser light to varying degrees. The light reflected back would carry a signature of the entangled quantum state, offering a window into the relationship between the trapped electron and its environment.

To isolate the electrons, they proposed using nanostructured devices, small machines built one atom at a time that trap the electrons in small wells. The particles are only provided limited isolation in the wells and so eventually become entangled with a cloud of surrounding electrons in the device.

Tureci's collaborators in Switzerland tested the idea by projecting a laser beam on the device and measuring the light that was transmitted.

The light signature matched theoretical predictions. The researchers also found that they could use the light signatures to confirm when they turned the Kondo state off using a magnetic field.

"By doing this experiment," Tureci said, "we showed that you can extract this information that was previously unavailable in earlier experiments on the Kondo effect."

He said the finding could provide insight into quantum computing because entanglement, depending on its nature, could allow new ways of storing and processing information or could threaten to destabilize the computing process.

Whereas current computers use transistors to store "bits" of information as ones or zeros, scientists believe quantum computers might one day use trapped electrons that are entangled with one another as "qubits," the basic information units of quantum computing, which can have the odd quality of representing a blend of "one" and "zero" simultaneously.

A series of qubits could thus store exponentially more information than the 0 and 1 combination of classical bits.

While quantum computers could theoretically be far smaller and faster than transistor-based machines, using electrons or other sub-atomic particles as storage devices is no trivial feat.

The undesirable entangled relationship between electrons and their environment, such as that seen in the Kondo effect, can destabilize the desired relationship between trapped electrons that form the qubits and gradually destroy the information they store.

"Our technique offers a window into the Kondo state, allowing us a chance to study electrons that are highly entangled with their environments and understand how they got that way," Tureci said.

More information: Latta, C., Haupt, F., Hanl, M., Weichselbaum, A., Claassen, M., Wuester, W., Fallahi, P., Faelt, S., Glazman, L., von Delft, J., Türeci, H. E., & Imamoglu, A. Quantum quench of Kondo correlations in optical absorption, *Nature*.

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