Magnetic transistor could 'dial in' quantum effects

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A team of theoretical and experimental physicists from Rice University is preparing a unique probe in hopes of "dialing in" elusive quantum states called "quantum criticalities." The team is using nanotechnology to create a probe capable of trapping and tuning a single electron to create the rarified physical state in nearby magnetic electrodes.

The probe, a transistor thousands of times smaller than a living cell, is described in research published online this week by the Proceedings of the National Academy of Sciences.

"The traditional theory of metals, which has held sway for 50 years and has fostered terrific technological advances in computing and materials science, breaks down completely in matter that exists in a 'quantum critical state,'" said Qimiao Si, professor of physics and astronomy at Rice and the lead theoretician on the project. "Previous experiments indicate that quantum criticality is characterized by the inherent quantum effect of entanglement, and the nanoscale magnetic probe we've proposed could provide a controlled and tunable setting to study entanglement at a quantum critical point."

The term "quantum critical point" refers to a phase transition. Just as water goes through a phase transition when it turns to ice or steam, all matter is subject to phase transitions due to fluctuations produced by the peculiar forces of quantum mechanics.

The probe proposed by Si and colleagues is based on a transistor with an active channel measuring just a few billionths of meter across. The transistor also uses a pair of electrodes made of ferromagnetic metal. The researchers plan to trap a single electron in the active channel between the electrodes. Then, they will capitalize on a uniquely quantum effect -- the tendency of a trapped electron to "tunnel," or wink out of existence in one place and appear in another -- to establish a quantum critical state in the metallic electrodes that trap the tiny particle.

"In principle, we can use the gate voltage in this setup to tune the physical state," said Douglas Natelson, assistant professor of physics and astronomy and of electrical and computer engineering. "We should be able to move the system from a quantum critical state and back again, simply by turning the knob on the voltage. That's a level of precision that's never been possible in another experimental system, and it's really nanotechnology -- the control of matter at the atom-by-atom level -- that will make it possible."

Elementary particles like electrons have an intrinsic angular momentum known as spin. The probe's design will allow the physicists to confine an electron with its spin on one molecule inside the transistor. In one quantum state, the tunneling effect causes the constrained electron spin to become "entangled" with the spins of electrons in the nearby metal electrodes. The magnetic nature of the electrodes also dictates the existence of a collective oscillation among the spins of electrons in the electrodes. These oscillations – known as "spin waves" -- will interact with the magnetic moment of the constrained electron's spin and try to break the entanglement. The quantum critical point occurs when it is broken and the material transitions from one quantum phase to the next.

Natelson has already used the technique to study electron spin in similar molecules while using non-magnetic gold metal electrodes. Results of those experiments are due to be published shortly in the journal Physical Review Letters.

"The usage of the ferromagnetic electrodes in the proposed probe brings in spin waves, which couple to the local magnetic moment of the molecule as a fluctuating magnetic field," said theorist and co-author Stefan Kirchner, a postdoctoral fellow of physics and astronomy at Rice. "It is this coupling that gives rise to the ability to tune the degree of – and even destroy – the magnetic quantum entanglement."

The effect is manifested in the unique way that the electrical conductance of the transistor depends on temperature and frequency.

Though nano in scale, the new probe serves as a realistic model system to elucidate physics that cannot be explained by the traditional theory of metals, including phenomena associated with bulk materials like rare-earth-based heavy fermion metals and copper-based high temperature superconductors. For example, the nanoprobe allows the physicists to introduce competition between two quantum effects -- magnetic quantum entanglement and coupling with spin waves. By accessing the quantum critical point that lies at the phase change associated with these competing forces, the researchers can draw a direct linkage between the quantum criticality in the new probe and quantum criticalities in bulk materials like heavy fermion metals.

In a 2001 paper in Nature, Si and collaborators offered a new theory regarding a similar destruction of the magnetic quantum entanglement that appears at the quantum critical point of heavy fermion metals. The new probe could provide direct experimental evidence of this proposed effect.

"Based on previous experiments and theoretical predications, the new probe should provide us with much-anticipated evidence about the precise way that quantum criticality forms in nature," Si said. "With this unique experimental data, we hope to gain an in-depth understanding of the phenomena that may well be what engineers need in order to harness the power for high-temperature superconductivity."

Source: Rice University

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