Physicists Observe 'Billions of Billions' of Entangled Electrons

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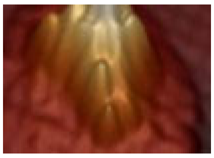

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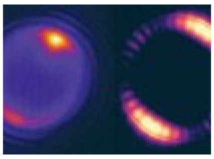

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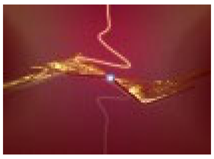
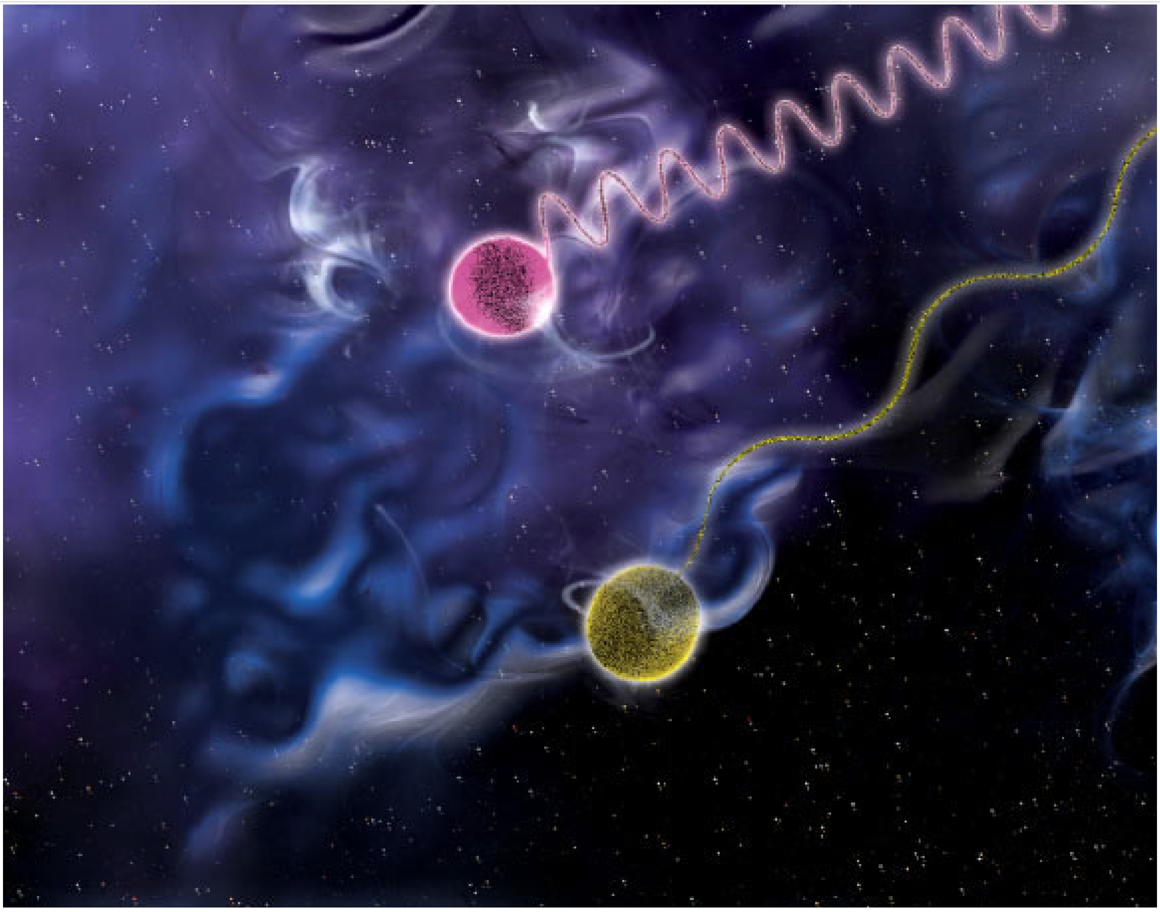


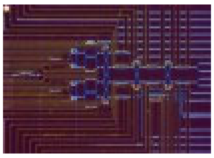
Scientists Use Light to Transport Electrons at Ultrafast Speeds

An international team of physicists says they have observed quantum entanglement among 'billions of billions' of flowing electrons in thin films of $YbRh_2Si_2$, a model strange-metal compound.



In this illustration, one photon (purple) carries a million times the energy of another (yellow). Image credit: NASA / Sonoma State University / Aurore Simonnet.

"Quantum entanglement is the basis for storage and processing of quantum information. At the same time, quantum criticality is believed to drive high-temperature superconductivity," said co-author Dr. Qimiao Si, a physicist in the Department of Physics and Astronomy at the Center for Quantum Materials at Rice University.



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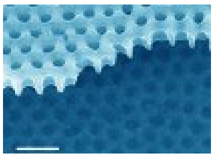


Scientists Uncover New State of Matter in Superconductor

"So our findings suggest that the same underlying physics — quantum criticality — can lead to a platform for both quantum information and high-temperature superconductivity. When one contemplates that possibility, one cannot help but marvel at the wonder of nature."

In their experiments, Dr. Si and colleagues examined the electronic and magnetic behavior of $YbRh_2Si_2$ as it both neared and passed through a critical transition at the boundary between two well-studied quantum phases.

To get the result, the researchers overcame several challenges.

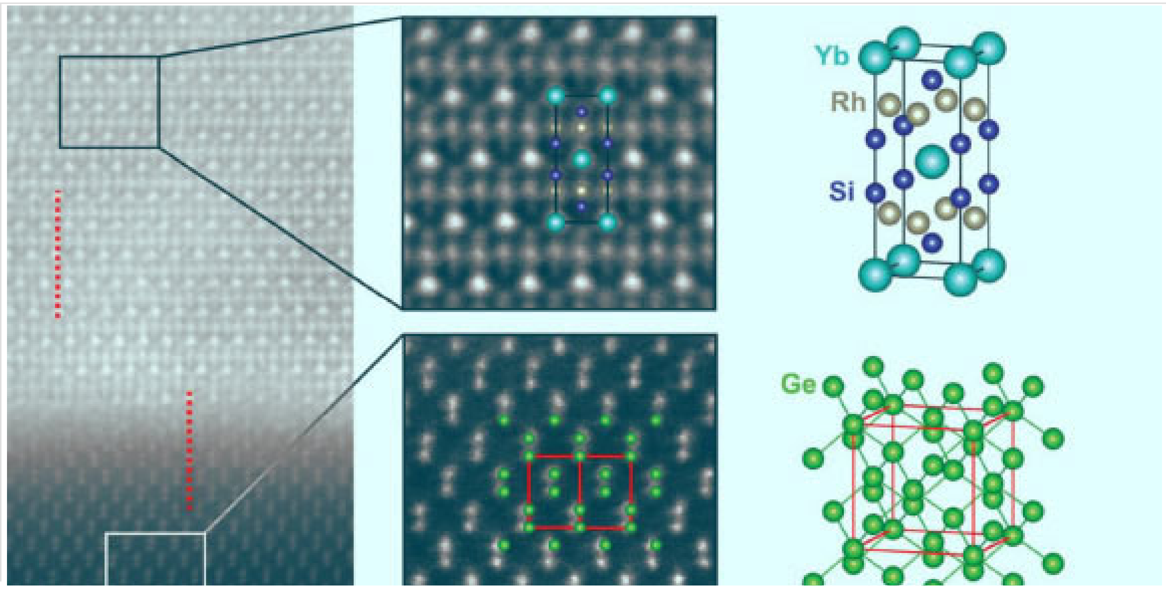
First, they had to develop a highly complex materials synthesis technique to produce ultrapure films of $YbRh_2Si_2$.

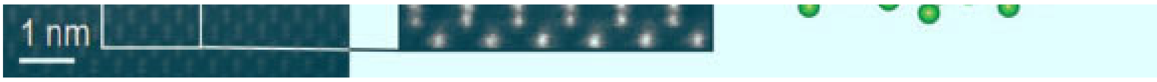
At absolute zero temperature, the material undergoes a transition from one quantum phase that forms a magnetic order to another that does not. The authors performed terahertz spectroscopy experiments on the films at temperatures as low as 1.4 Kelvin.

The terahertz measurements revealed the optical conductivity of the $YbRh_2Si_2$ films as they were cooled to a quantum critical point that marked the transition from one quantum phase to another.

"With strange metals, there is an unusual connection between electrical resistance and temperature," said senior author Dr. Silke Bühler-Paschen, a physicist in the Institute for Solid State Physics at Technischen Universität Wien and the Department of Physics and Astronomy at the Center for Quantum Materials at Rice University.

"In contrast to simple metals such as copper or gold, this does not seem to be due to the thermal movement of the atoms, but to quantum fluctuations at the absolute zero temperature."





Atomic-resolution STEM image of the interface between film (top left) and substrate (bottom left), representative enlarged views with simulated overlays (center), and the corresponding unit cells (right). Image credit: Prochaska *et al*, doi: 10.1126/science.aag1595.

To measure optical conductivity, the team shined coherent electromagnetic radiation in the terahertz frequency range on top of the films and analyzed the amount of terahertz rays that passed through as a function of frequency and temperature.

The experiments revealed frequency over temperature scaling, a telltale sign of quantum criticality.

Making the films was even more challenging. To grow them thin enough to pass terahertz rays, the scientists developed a unique molecular beam epitaxy system and an elaborate growth procedure.

Ytterbium, rhodium and silicon were simultaneously evaporated from separate sources in the exact 1-2-2 ratio. Because of the high energy needed to evaporate rhodium and silicon, the system required a custom-made ultrahigh vacuum chamber with two electron-beam evaporators.

"Our wild card was finding the perfect substrate: germanium," said first author Lukas Prochaska, a graduate student in the Institute for Solid State Physics at Technischen Universität Wien.

"The germanium was transparent to terahertz, and had certain atomic distances (that were) practically identical to those between the ytterbium atoms in $YbRh_2Si_2$, which explains the excellent quality of the films."

"Conceptually, it was really a dream experiment," Dr. Si said.

"Probe the charge sector at the magnetic quantum critical point to see whether it's critical, whether it has dynamical scaling."

"If you don't see anything that's collective, that's scaling, the critical point has to belong to some textbook type of description. But, if you see something singular, which in fact we did, then it is very direct and new evidence for the quantum entanglement nature of quantum criticality."

The results appear in the journal *Science*

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L. Prochaska *et al* 2020. Singular charge fluctuations at a magnetic quantum critical point. *Science* 367 (6475): 285-288; doi: 10.1126/science.aag1595