Evidence of a quantum phase transition without symmetry breaking in cerium-cobalt-indium 5

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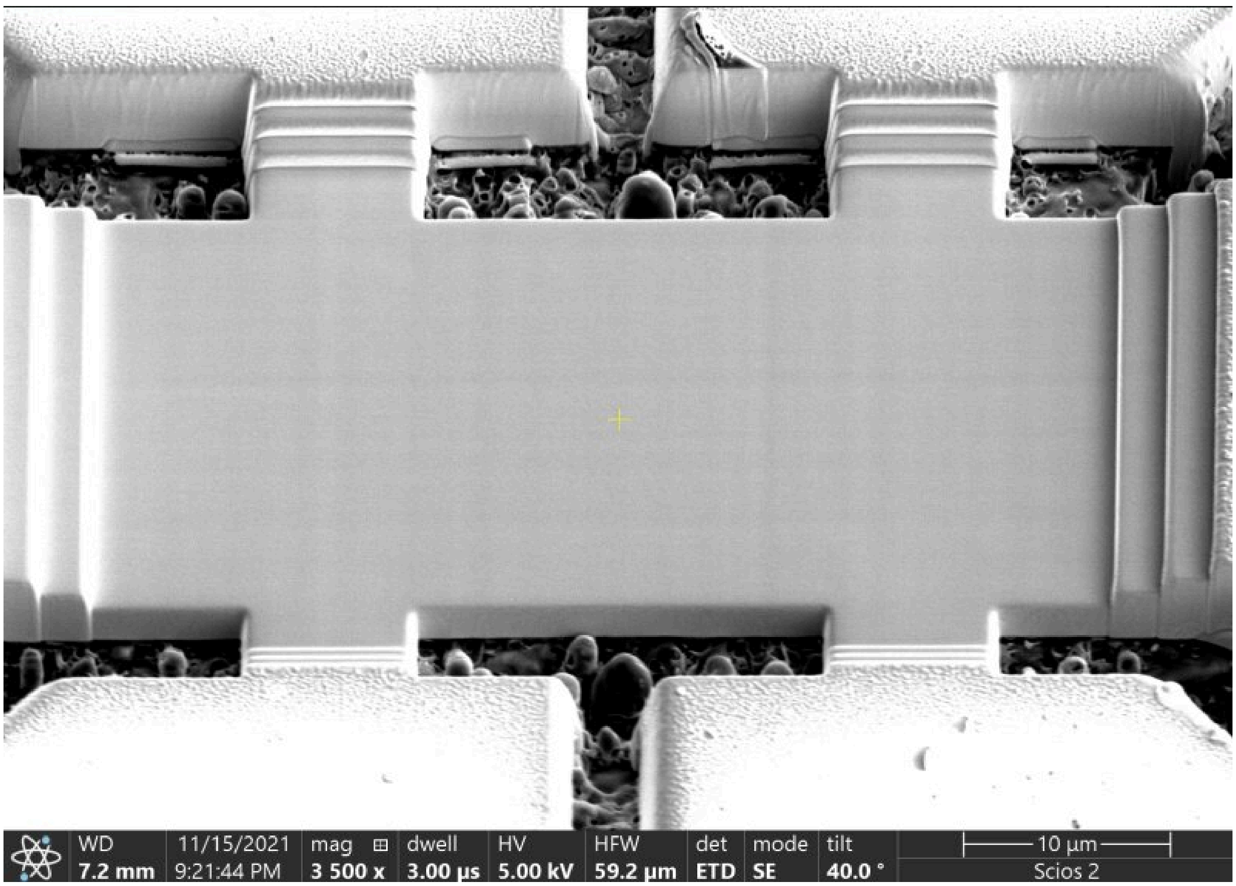

Credit: Shannon C. Haley.

Over the past few decades, many condensed matter physicists have conducted research focusing on quantum phase transitions that are not clearly associated with a broken symmetry. One reason that these transitions are interesting is that they might underpin the mechanism of high-temperature superconductivity.

Researchers at University of California, Berkeley, have recently gathered evidence of a quantum phase transition without symmetry breaking occurring in cerium-cobalt-indium 5 ($CeCoIn_5$), an unconventional superconductor. Their paper, published in *Science*, also introduces a model that could be used to describe the anomalous behavior they observed in $CeCoIn_5$.

"We initially started studying this material with a completely different focus, mainly on critical scaling phenomena in resistivity measurements," Nikola Maksimovic, the lead author of the paper, told Phys.org. "Over the course of about three years, we noticed that our data seemed to point to rapid changes in the material's properties induced by small amounts of chemical substitution. Such a transition was hinted at in previous measurements."

Inspired by previous theoretical work, Maksimovic and his colleagues hypothesized that the widely observed rapid changes in the properties of $CeCoIn_5$ could be explained by a delocalization transition of the cerium f-orbital electron in the material. Therefore, they decided to shift the focus of their research from the measurement of low-temperature resistivity to the characterization of f-electrons in the material.

"We hoped that our work would answer a very fundamental question, whether the f-electron of the cerium atom is localized to the cerium site, or itinerant (i.e., free to move about in the metal)," Maksimovic said. "Our work was also inspired by previous experimental studies on other materials, such as Yb-based metals and copper-oxide ceramics."

To examine the f-electrons in $CeCoIn_5$, the researchers used a well-established experimental technique known as the Hall effect measurement. This technique entails the application of a transverse voltage generated by a magnetic field to a sample.

This voltage can then be converted into a measurement of the density of the mobile electrons in a material. In their experiments, Maksimovic and his colleagues used the Hall effect as a probe to determine whether the f-electrons in a $CeCoIn_5$ sample were mobile or attached to their host atoms.

"These measurements were performed in extreme environments, at about half a kelvin above absolute zero and in magnetic fields up to 73 Tesla," Maksimovic said. "To this end, tiny electrical devices needed to be patterned out of pieces of $CeCoIn_5$ in order to achieve a measurable signal."

The findings gathered by the researchers highlighted a rapid change in the material's low temperature carrier density, which was driven by the chemical substitution of $CeCoIn_5$. Interestingly, the magnitude of the Hall coefficient increase they detected was found to be consistent with an f-electron localized-to-delocalized transition. These results confirmed their initial hypothesis.

Subsequently, Maksimovic and his colleagues set out to characterize the electronic energy spectrum in $CeCoIn_5$ samples with different compositions. To do this, they used a series of state-of-the-art spectroscopy tools, including quantum oscillation and angle-resolved photoemission techniques.

"Based on existing theory of f-electron metals, we presented a model that argues for the fractionalization of electrons in the metal into separate charge and spin carrying excitations near the critical point where the f-electrons are close to delocalizing," Maksimovic said. "Such a 'breaking up' of electrons is a very exotic phase of matter, which is only possible due to the collective quantum properties of certain metals where electrons are strongly correlated."

The new model proposed by this team of researchers and their calculations could explain certain properties of the electrical conductivity of the material. In addition, their findings offer new valuable insight that could enhance the current understanding of $CeCoIn_5$ and other unconventional superconductors.

In the future, this recent work could inspire the development of similar models that relate to high-temperature superconductors, as past studies have found evidence of a qualitatively similar delocalization transition in these materials, which is also induced by chemical substitution.

Meanwhile, Maksimovic and his colleagues plan to search for more direct evidence of distinct spin and charge carrying excitation in $CeCoIn_5$. To do this, they will collect thermal conductivity and electrical conductivity measurements at very low temperatures, as a significant discrepancy between them could indicate that the carriers of heat are different from the carriers of charge.

"During the course of our research, we also noticed that in certain samples exhibited evidence of a transition induced by very high magnetic fields," Maksimovic added. "At present, it is unclear how this is related to the zero-field transition observed in our recent work. We thus now plan on studying the high-field transition further utilizing the resources at the pulsed field facility at Los Alamos National Lab."

More information: Nikola Maksimovic et al, Evidence for a delocalization quantum phase transition without symmetry breaking in $CeCoIn_5$, *Science* (2021). DOI: 10.1126/science.aaz4566

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