The Hall effect links superconductivity and quantum criticality in a strange metal

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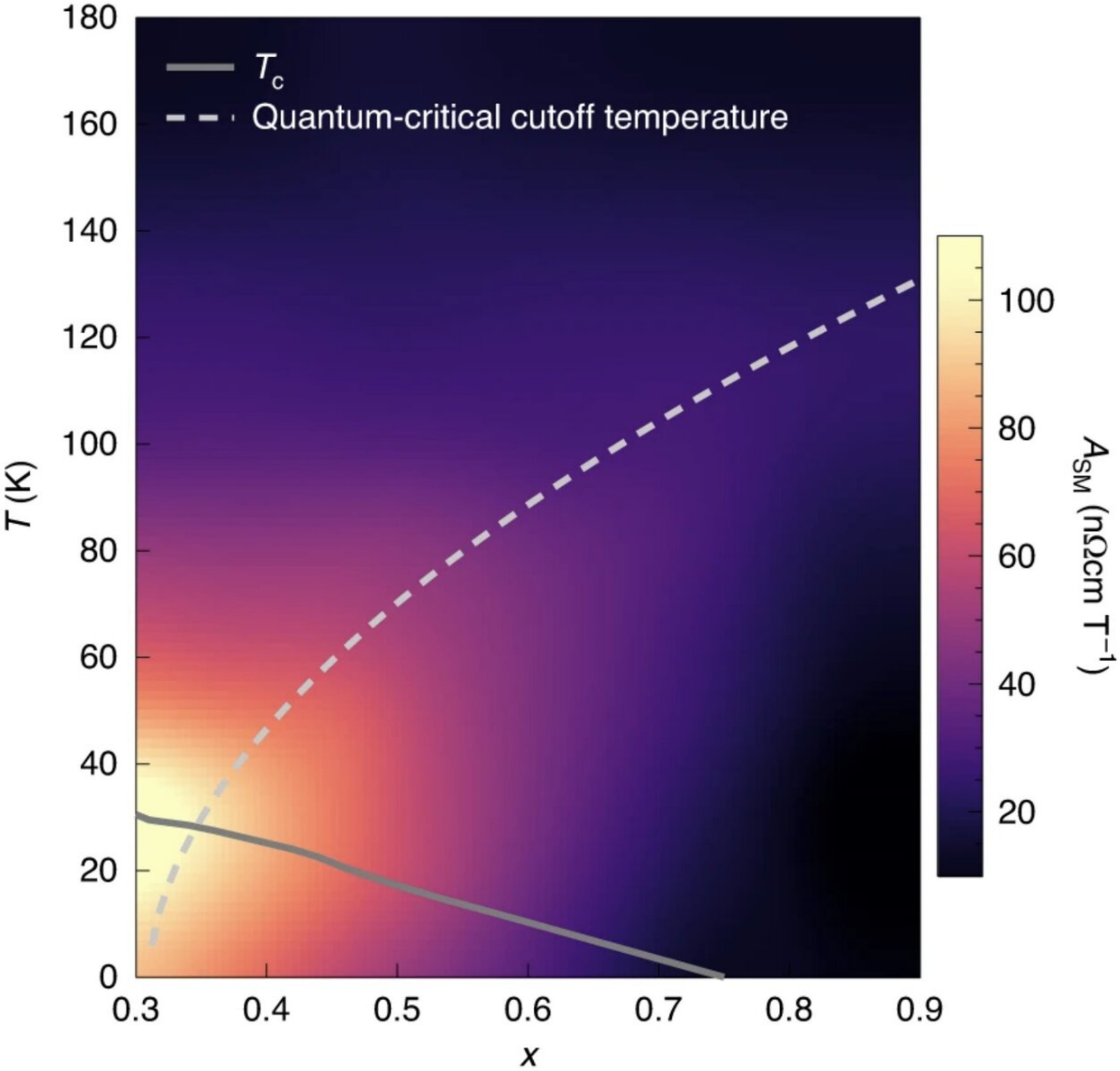

The amplitude of the strange metal contribution in the Hall effect as a function of composition x and temperature T, estimated from the field dependence of R_H. The white dotted line is a guide to the eye, emphasizing the boundary of the region where the strange metal R_H is independent of x. Above the line the strange metal Hall depends only on temperature and independent of composition x, below the line these contributions persist to zero temperature, suggesting a direct connection to the superconducting ground state. Credit: Nature Physics (2020). Hayes et al.

Over the past few decades, researchers have identified a number of superconducting materials with atypical properties, known as unconventional superconductors. Many of these superconductors share the same anomalous charge transport properties and are thus collectively characterized as "strange metals."

Researchers at the University of California, Berkeley (UC Berkeley) and Los Alamos National Laboratory have been investigating the anomalous transport properties of strange metals, along with several other teams worldwide. In a recent paper published in *Nature Physics*, they showed that in one of these materials, $BaFe_2(As_{1-x}P_x)_2$, superconductivity and quantum criticality are linked by what is known as the Hall effect.

For decades, physicists have been unable to fully understand T-linear resistivity, a signature of strange metals that has often been observed in many unconventional superconductors. In 2016, the team at UC Berkeley and Los Alamos National Lab observed an unusual scaling relationship between the magnetic field and temperature in superconductor $BaFe_2(As_{1-x}P_x)_2$.

Scaling phenomena are typically observed just before a system transitions from one phase to another (e.g. from liquid to gas), moments called critical points. This inspired the researchers to investigate whether a similar phenomenon also occurred in the Hall effect, a related charge transport phenomenon.

"The scaling behavior arises because near a critical point, some properties become scale invariant," James G. Analytis, one of the researchers who carried out the study, told Phys.org. "This is because there are phase fluctuations at the critical point that occur at all length and time scales. The same basic phenomenon leads to critical opalescence in a liquid-gas transition, but in the present case, the fluctuations have their origin in the Heisenberg uncertainty principle. In our recent study, we did not observe the scaling behavior as clearly as we did before, but we found something we did not expect."

To conduct their experiments, Analytis and their colleagues synthesized $BaFe_2(As_{1-x}P_x)_2$ crystals at the Lawrence Berkeley National Laboratory (LBNL) and then placed them under high magnetic fields at Los Alamos National Lab's high field facility, which is managed by the NSF-funded National High Magnetic Field Lab (NHMFL). At this field facility, researchers can collect measurements for a significant amount of magnet time.

"It is highly competitive to get this magnet time, which allows you to measure up to 65 T," Analytis explained. "Each material needs to be measured separately, with multiple samples to ensure reproducibility. In all, we probably spent about four weeks of magnet time to gather our data."

The experiments carried out by Analytis and his colleagues yielded a number of interesting results. First, the researchers found that the Hall effect appears to be composed of two different 'terms': a conventional one that is simply related to the number of electrons in the system, and a strange-metal term that peaks when $BaFe_2(As_{1-x}P_x)_2$ is approaching its quantum critical point.

"Separating the Hall effect into two contributions is quite natural in ferromagnetic metals because the system has two clear contributions; the carriers in the metal and the magnetically ordered spins," Analytis explained. "The second contribution is called the anomalous Hall effect. What we see appears to be analogous to an anomalous Hall effect, but I emphasize that there is no ferromagnetism. Here, the anomalous contribution appears to arise from magnetic fluctuations near the critical point."

Two key facts illustrate the link between quantum criticality and superconductivity unveiled by Analytis and his colleagues: The first is that in strange metals, superconductivity occurs in a whole phase diagram; the second is that the Hall effect is essentially a measure of the number of particles (i.e., electrons or holes) in a system.

The researchers observed that the anomalous effect observed in $BaFe_2(As_{1-x}P_x)_2$ as it approaches its quantum critical point only ceases when superconductivity does. Moreover, they found that the zero-temperature magnitude of the Hall effect's anomalous term were correlated to the magnitude of the superconducting Tc. This suggests that the strange metal's contribution to the Hall effect is, in fact, a measure of the emergent entities that are responsible for superconductivity.

"There was a second observation connected to the scale invariance observed before," Analytis said. "In a region of the phase diagram known as the 'critical fan' (the region thought to be dominated by fluctuations), the strange metal contribution depends only on the temperature, as if temperature sets the scale of the fluctuations in the system. Most importantly, the strange metal contribution was independent of composition X, even though the conventional contribution changed by a factor of three or more; which means that the strange metal Hall effect is not simply an additional source of charge, but that it arises from the collective motion of all the electrons as they approach a quantum critical phase transition."

When studying high Tc, researchers typically try to understand the emergent excitations that are responsible for superconductivity in a material. In conventional superconductors, these excitations are now known to be characterized as simple electrons or holes.

The recent study by Analytis and his colleagues could ultimately illuminate the nature of the excitations responsible for superconductivity in strange metals, which has so far remained elusive. Moreover, the researchers have identified a strategy that can be used to measure whether these excitations are present in a material or not.

"It would be very exciting to see whether the properties we unveiled extend to other superconductors," Analytis said. "Right now, we would like to extend these measurements to different parts of the phase diagram and to different compounds. These are all long and complicated experiments requiring extensive synthesis and time in high field labs (like the NHMFL), but at least we know exactly what we are looking for, now."

In their next studies, the researchers would also like to start looking for strategies and tools that could be used to probe the spin degrees of freedom in unconventional superconductors directly. In fact, most existing methods tend to examine a material's charge degrees of freedom, which considerably limits their generalizability across different materials.

"The Hall effect will always mix these up, and we got lucky that in these materials, they separate into 'conventional' and 'strange metal' contributions," Analytis said. "But in order to see universalities across different materials classes, it will be important to develop new probes with more direct sensitivity to the 'strange metal' part of the system."

More information: Superconductivity and quantum criticality linked by the Hall effect in a strange metal. *Nature Physics* (2020). DOI: 10.1038/s41567-020-0982-x.

Scaling between magnetic field and temperature in the high-temperature superconductor BaFe2(As1-XPx)2. *Nature Physics* (2016). DOI: 10.1038/nphys3773.

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