Magnetic fields befriend superconductivity

1. **Robust field re-entrant superconductivity in ferromagnetic infinite-layer rare-earth nickelates**
   Authors: Mingwei Yang, Jiayin Tang, Xianfeng Wu, Heng Wang, Wenjing Xu, Haoliang Huang, Zhicheng Pei, Wenjie Meng, Guangli Kuang, Jinfeng Xu, Sixia Hu, Chuanying Xi, Li Pi, Qingyou Lu, Ziqiang Wang, Qikun Xue, Zhuoyu Chen, Danfeng Li
   https://doi.org/10.48550/arXiv.2508.14666

2. **Extreme magnetic field-boosted superconductivity in a high-temperature superconductor**
   Authors: Km Rubi, King Yau Yip, Elizabeth Krenkel, Nurul Fitriyah, Xing Gao, Saurav Prakash, S. Lin Er Chow, Tsz Fung Poon, Mun K. Chan, David Graf, A. Ariando, Neil Harrison
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Recommended with a Commentary by Srinivas Raghu, Stanford University

Superconductivity that survives to high magnetic fields is a fascinating phenomenon. Ordinarily, magnetic fields are detrimental to pairing for two reasons: the orbital effect and the Zeeman effect. The former results in vortex nucleation, which reduces superfluid stiffness, whereas the latter reduces the spin-gap in singlet superconductors. It would seem natural to expect then, that magnetic fields are antithetical to superconductivity.

Over the years, a handful of experimental studies have contradicted this expectation. They have shown that superconductivity can persist in, and even can be nucleated by large magnetic fields. Examples include the Chevrel compounds[1], organic materials such as λ-$(BETS)_2FeCl_4$[2], U-based ferromagnetic superconductors[3] such as URhGe[4] and UTe_2[5], and magic angle graphene[6]. The most recent addition to this family and the topic of this commentary is an infinite layer nickelate system doped with Sm, Eu, Ca and Sr (SECS). Relative to the phase diagram of infinite layer nickelates studied intensely in the past few years (see e.g. Ref. [7]), the $(SECS)NiO_2$ system is considerably overdoped. The observation of reentrant superconductivity in this system is significant, as the $(SECS)NiO_2$ system has a higher T_c (ranging up to 30 Kelvin) than the other materials exhibiting reentrant pairing. For theorists like myself, these observations, taken in the broader context, invite us to speculate whether reentrance in all these materials has a common underlying origin, or whether a case-by-case examination is necessary.

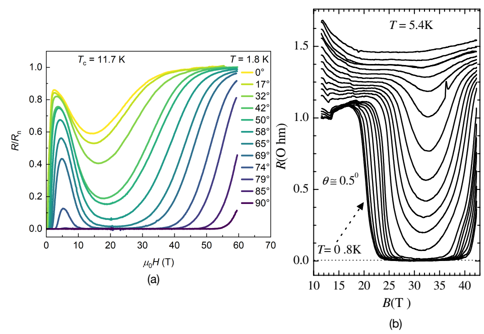

Figure 1: (a) Magnetoresistance for a 11.7 Kelvin T_c nickelate material clearly showing reentrant superconducting behavior. The behavior is also angle dependent, being maximal when the field lies in the basal plane. (b) For comparison, the magnetoresistance data in the organic material λ-$(BETS)_2FeCl_4$[2] is shown. While the system is an insulator at zero field, the magnetoresistance data clearly shows reentrant behavior.

In both highlighted experimental papers, the evidence for reentrant behavior comes from the magnetoresistance (MR). The MR is angle-dependent. In figure 1(a), I show the MR data for a 11.7 Kelvin nickelate. When the field is applied at 30-60 degrees with respect to the crystalline c-axis, the MR curves are non-monotonic; superconductivity at zero field is first destroyed and then returns at higher fields. Increasing this angle further towards 90-degrees (i.e. placing the field in the basal plane of the quasi-two dimensional system) preserves superconductivity in excess of 60 Tesla. For comparison, I have also included the MR data for the organic insulator λ-$(BETS)_2FeCl_4$ (Ref. [2]) in Fig. 1(b). While the zero field limits are different (the nickelate has a zero-field superconducting ground state whereas the organic material is an insulator at zero field), MR data shows field-induced superconductivity in both systems, and is angle-dependent. In the organic material, it was shown that the inclusion of iron moments was crucial in stabilizing the field-induced superconducting phase. Likewise, in $(SECS)NiO_2$, Eu, Sm rare earth atoms play a crucial role in the observation of field-induced superconductivity. Similarly, rare earth atoms were present also in the Chevrel compound that exhibited reentrant superconductivity.

The rare earth atoms are believed to play an important role because they couple to the superconducting electrons via exchange forces. If these exchange forces were to result in an induced mean-field that *opposed* the external magnetic field, the superconducting electrons would then "feel" a vastly reduced effective magnetic field. Stated more precisely, the free energy of a paramagnetic metal always decreases in an applied field. When the free energy of the normal state falls below that of the superconductor, superconductivity is destroyed. This purely thermodynamic consideration takes into account both the orbital and the Zeeman suppression of superconductivity. By contrast, suppose the normal state included local moments, which interact with the superconducting electrons via exchange forces. If the exchange induced effective Zeeman field opposes the external field, the normal state free energy will increase with field. And above a critical "reentrant" field, the normal state free energy will exceed the superconducting one, resulting in field-induced superconductivity. Since the critical fields are determined by crossing of free energies, the transition is first order in nature. This is the essence of the so-called Jaccarino-Peter compensation effect[8] that seems to account for the phenomena observed a variety of systems including the chevrels, organics, and most recently, in the $(SECS)NiO_2$ system. Indeed, the present observations can be accounted for within a BCS model that takes into account the exchange interactions with the rare earth elements, as well as the orbital and spin effects of magnetic fields. While the story is compelling, it would be great to have direct evidence of the spin compensation, say by measuring the Curie susceptibility.

These recent studies bring some basic issues back to the forefront. The most obvious one is the relative importance of the orbital contribution to H_{c2}. The Jaccarino-Peter compensation mechanism does not account for certain orbital effects of the field, such as vortex nucleation. This can change if the metal electrons forming Cooper pairs have significant spin-orbit interactions, but spin-orbit coupling is probably not important in the nickelates because angular momentum is quenched. Thus, the orbital effect can still be important in determining the field at which reentrant superconductivity is eventually destroyed. The angle dependence of H_{c2} sheds some light on this matter. In quasi-two dimensional materials such as the nickelates, orbital limitation is weaker when the field lies in the basal plane. This is precisely where the H_{c2} is highest, suggesting a significant role played by the Zeeman effect in determining the upper critical field (known as Pauli limiting). By contrast, in UTe_2 for example, the extreme field boosted superconductivity occurs when the field is not along any crystalline axis. For such field orientations, the orbital effect likely remains important, and cannot be ignored when it comes to the physics of H_{c2}. To my mind, it suggests that the extreme field booted superconductor in UTe_2 has a different mechanism than the one we see in the infinite layer nickelates. But the Jaccarino-Peter mechanism has been invoked as an explanation in both systems (see Ref. [9] in the case of UTe_2).

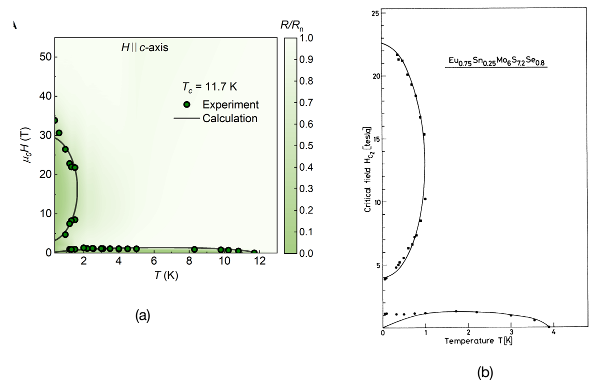

Figure 2: Phase diagram of $(SECS)NiO_2$ (a) and a Chevrel compound (b) (taken from Ref. [1]) showing obvious similarities. The calculation in (a) refers to a BCS model with spin exchange forces, in addition to orbital and spin effects of magnetic fields, known as the Werthamer-Helfand-Hohenberg (WHH) theory.

Another important issue is whether the reentrant superconducting phase has the same pairing symmetry as the superconductor that occurs at zero field (if the latter indeed occurs). If exchange induced spin compensation is the primary driving force of reentrant behavior, one might naively expect that the zero field and high field states are similar to one another. Indeed, in the $(SECS)NiO_2$ system, this appears to be the case; higher T_c samples appear to "fill in" the phase diagram as a function of field and temperature. What used to be reentrant behavior in the lower T_c samples becomes a single, superconducting phase that is hard to destroy in higher T_c samples. By contrast, in U-based systems, multiple superconducting phases have been observed as a function of magnetic field strength. This issue is moot in the organic superconductor in Ref. [2], since superconductivity is altogether absent at zero fields and requires a finite field to even exist. In this case, other phases (like magnetism) may compete with the zero field putative superconductor and the field acts both to suppress competing order and to nucleate superconductivity.

More work needs to be done to determine whether the same spin compensation mechanism applies to all the materials mentioned here. Even in the nickelates, the role of disorder and phase fluctuations (both of which reduce the coherence length and increase a mean-field notion of H_{c2}) likely plays an important role in the story. In UTe_2 spectroscopic studies, along with fits to magnetic susceptibility measurements from atomic models ought to help unravel whether the compensation mechanism is at play despite the fact that the high field superconducting state occurs far from any crystalline axis. Lastly, the observation of reentrant pairing in magic angle graphene is encouraging and hopefully, more studies involving synthetic systems can lead to observations of spin-compensated reentrant superconductivity in a highly controllable and tunable setting.

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