Superconductivity in a Nickelate

Superconductivity near 80 Kelvin in single crystals of $La_3Ni_2O_7$ under pressure
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Recommended with a Commentary by Qimiao Si, Rice University

High temperature unconventional superconductivity is still a fairly exclusive club. The copper-based compounds are founding members [1, 2, 3]. About a decade and half ago, the iron-based systems marched into the house [4, 5]. Several years ago, a nickel-based member found its way in. This "infinite-layer nickelate" superconducts with a transition temperature (T_c) of about 15 K [6]. Does this development represent a dawn of a nickel era of high temperature superconductivity [7]?

The highlighted study by H. Sun and collaborators represents an important step towards answering in the affirmative. $La_3Ni_2O_7$ is a nickelate with two nearby Ni-based layers forming a unit that are stacked together (Fig. 1A). When the applied pressure exceeds 14 GPa, it shows signs of superconductivity with a transition temperature of about 80 K. Do we really know that it superconducts? It is too early to answer the question with full confidence, given that the reduced measurement capacities at such high pressures limit the amount of properties that have been established in the relevant pressure regime. A very recent high pressure magnetic measurement indicates that the superconducting volume fraction is about one percent [8]. It is possible that this small diamagnetic effect is caused by the limited quality of this nickelate material that has been made so far (the very first unconventional superconductor ever discovered, $CeCu_2Si_2$, started out in a similar fashion). Indeed, transport measurements have shown high-quality zero resistivity (albeit for samples with very small size) [9].

For the remainder of the commentary, I will assume that superconductivity indeed exists in $La_3Ni_2O_7$. Is it unconventional? Direct evidence is needed. Nonetheless, the paradigm of the field is that superconductivity that develops out of a strongly correlated normal state is most likely unconventional. And there is accumulating evidence that the normal state is indeed sufficiently correlated. I enumerate some of the properties that form this evidence:

- Optical conductivity measurement has suggested that the Drude weight is reduced by an order of magnitude from the expectation of noninteracting electrons [10]. Electron correlations that cause such an effect represent a large strength – on the order of what's observed in the iron chalcogenide superconductors [5].

- At ambient pressure, the magnetic susceptibility above an ordering temperature is large in magnitude, and has a type of temperature dependence [11, 12] that is suggestive of coupled (correlation-induced) local moments.
- Recent RIXS measurement at ambient pressure has provided evidence for high-energy magnetic excitations [13].

In addition, ARPES measurements suggested orbital-dependent correlation effects. A caveat is that some of the bands that should have crossed the Fermi energy have been found not to do so [14]. This could be due to the fact that the ambient-pressure measurement is carried out at temperatures where the system is electronically ordered, which reconstructs the bands.

Finally, transport measurement has provided evidence that superconductivity develops out of a strange metal with a T-linear electrical resistivity (see the highlighted study and Ref. [9], Fig. 1B).

The experiments have opened a floodgate of theoretical studies. The development on the theoretical front is so rapid that it might be more suitable for a later time to do an appropriate survey. Still, what are the essential components of the microscopic physics for $La_3Ni_2O_7$?

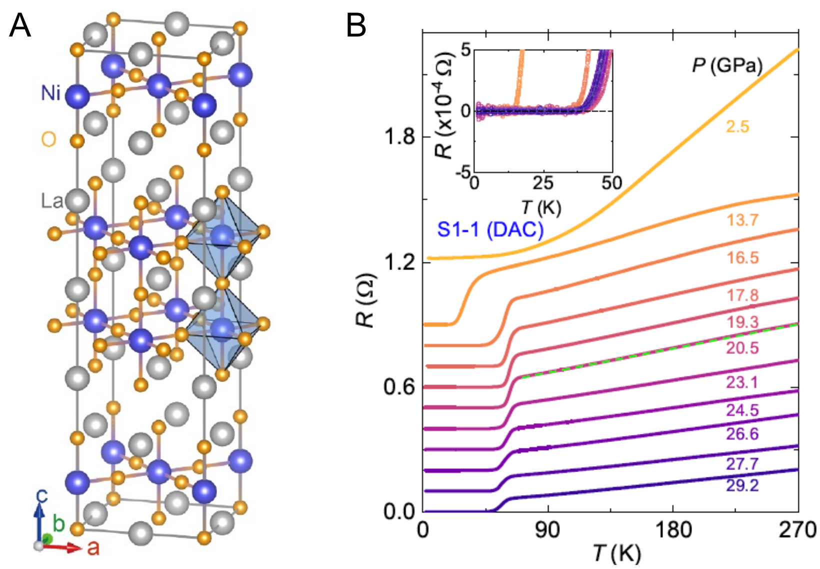

Figure 1: A) Crystal structure of $La_3Ni_2O_7$ (from the highlighted paper). B) Resistance vs. temperature for various pressures. The dashed line indicates a T-linear dependence; the inset shows zero resistance (from Ref. [9]).

Several aspects of the underlying physics in $La_3Ni_2O_7$ appear to have commonality with what happens in other classes of unconventional superconductors. For example, it is tempting to consider the overall temperature-pressure phase diagram as an analogue of the well-established phase diagram for heavy fermion superconductivity near electronic orders, with the temperature (and pressure) scaled up by an order of magnitude.

More microscopically, the bilayer nickelate is expected to have a valence of $Ni^{2.5+}$, with 7.5 electrons per Ni in the $3d$ orbitals. This is to be contrasted with the infinite-layer nickelate (Sr,Nd)NiO_2 thin films, where the valence count gives Ni^{1+}, with nominal 9 electrons in the $3d$ orbitals as in the cuprates. The double Ni layers then host 3 electrons per unit cell, involving two $3d_{z^2}$ orbitals and two $3d_{x^2-y^2}$ orbitals. The multiplicity of the active $3d$ orbitals resembles the iron-based superconductors, with the expectation that the electron correlation effects are orbital-selective. As such, we can expect the superconducting pairing in the bilayer nickelate to be multi-orbital in nature.

Thus, the bilayer nickelate presents a new platform to explore some of the common themes for high temperature superconductivity, including the role of quantum criticality, strange metallicity, and orbital-selective correlations. At the same time, there could well be surprises in store. For example, at the ambient pressure, the bilayer nickelate undergoes an electronic order at around 130 K. What is the nature of this order – does it involve spin, charge or other electronic degrees of freedom? The answer could well provide the clue to new physics that the bilayer nickelate and its cousins have in store.

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