Is FeSe a superconductor in the Bose-Einstein condensation limit?

1. **Discovery of orbital-selective Cooper pairing in FeSe**

   Authors: P.O. Sprau *et al*

   Science, **357**, 75–80 (2017)

2. **Tuning across the BCS-BEC crossover in the multiband superconductor $Fe_{1+y}Se_xTe_{1-x}$: An angle-resolved photoemission study**

   Authors: Shahar Rinott *et al*

   Science Advances, **3**: e1602372 (2017)

3. **Giant superconducting fluctuations in the compensated semimetal FeSe at the BCS–BEC crossover**

   Authors: S. Kasahara *et al*

   Nature Communications **7**, 12843 (2016)

Recommended with a Commentary by Dung-Hai Lee, U.C. Berkeley

Since the discovery of iron-based high-temperature superconductors in 2006, the highest superconducting critical temperature (T_c) has been observed in FeSe-based materials. In Fig. 1 we list some of these materials and their T_c. At first sight, one might think bulk FeSe and $Fe_{1+y}Se_xTe_{1-x}$ are the least interesting because of their low T_c. On the contrary, as we shall explain below, they should be regarded as very high T_c superconductors!

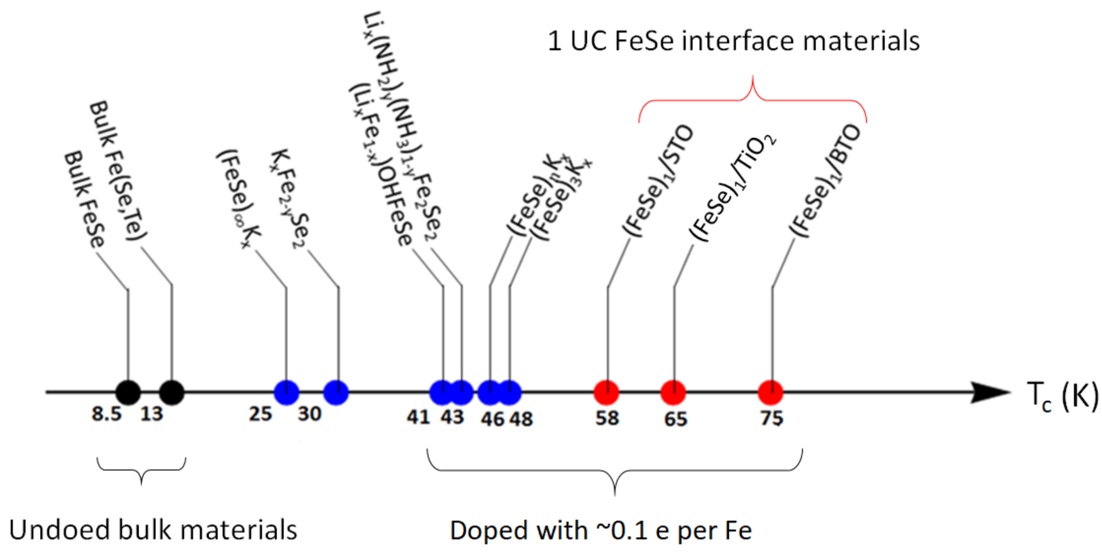

Figure 1: Representative FeSe-based superconductors are plotted versus their T_c. For FeSe films that are a few unit cells thick, the quoted T_c corresponding to the superconducting gap opening temperature as measured by angle-resolved photoemission spectroscopy.

FeSe and $Fe_{1+y}Se_xTe_{1-x}$ are semimetals with roughly equal densities of electron and hole carriers. The reason we regard them as high-temperature superconductors is because they exhibit a very high superconducting gap to Fermi energy ratio (namely, $1/5<\Delta/E_F<1$). Such high ratios put these superconductors in the "BCS-BEC crossover regime." In the BEC limit, T_c is determined by the Bose condensation of tightly bound electron pairs. On the other hand, in the BCS limit, T_c is determined by the Cooper pair formation.

For FeSe, Ref. [1] estimates the ratio between the superconducting gap maximum (as shown by Sprau *et al* the gap is very anisotropic in FeSe) and its Fermi energy to be between 1/3 and 1 which is several orders of magnitude larger than that of all conventional superconductors. It is even higher than the corresponding ratio in the copper-oxide high-temperature superconductors. High Δ/E_F suggests tightly bound Cooper pairs, which is consistent with Kasahara *et al*'s report of "giant superconducting fluctuations" above T_c [3] – a sign of "pre-formed" but not condensed Cooper pairs. It is no surprise that Ref.[1] estimates $k_F\xi$ (the ratio between the Cooper pair size and the average distance between individual charge carriers) to be between 1 to 4. Adding to these results Rinott *et al* reports evidence of BEC in $Fe_{1+y}Se_xTe_{1-x}$ by tracking the locus of the minimum superconducting gap in the momentum space. Unlike in the BCS regime, where the gap minima occur on the normal state Fermi surface, the experimentally observed gap minimum occurs at a single point, **k**=**0**, for samples exhibiting largeΔ/E_F. This feature is consistent with the usual BEC phenomenology (although for materials with both electrons and holes, the BEC phenomenology can be quite different from that of one band systems [2]).

Despite the above "BEC-ish" phenomena, there is no clear indication that the "pseudogap," namely the energy gap of preformed Cooper pair, exists in either FeSe or $Fe_{1+y}Se_xTe_{1-x}$. In addition, STM "quasiparticle interference" measurement of Sprau *et al* reports that the superconducting gap minima of FeSe actually occur on the normal state Fermi surface despite the fact that it exhibits the largestΔ/E_F. Further evidence that Cooper pairing occurs on the Fermi surface (not real space), like in the BCS regime, is that the measured gap size is correlated with a particular orbital weight (the iron $3d_{yz}$ weight) on the Fermi surface. This leads to the proposal that FeSe exhibits "orbital-selective Cooper pairing."

From a theoretical perspective, small Cooper pairs raise the question of how the bound state can form under insufficiently screened Coulomb repulsion. Intuitively when the Cooper pair size is comparable to the average distance between individual charge carriers, the Coulomb repulsion between the members of the pair should not be sufficiently screened. If so, what drives the bound state formation? Facing this puzzle, Let's ask whether there is any known example, even purely theoretical ones, of pairing under unscreened Coulomb interaction. In the literature, there is such a proposal, namely the "resonating-valence-bond" scenario of copper-oxide superconductivity [4], under which such kind of pairing can occur.

As shown in Fig.2 one pictures mobile "holons" (vacant sites) in the mist of spin singlet electron pairs. The Coulomb interaction requires the distribution of holons to be uniform, i.e., no tightly bound holon pairs. However, if the individual holons move coherently, so that the spin singlet electron pairs can form a condensate, the system can be superconducting. In this case, the size of the singlet electron pairs can be smaller than the average distance between the holons.

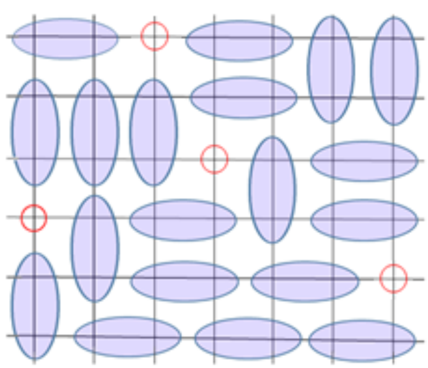

Figure 2 A caricature of resonanting valence bond. The red circles are holons.

In addition to the unusually small Cooper pair size, FeSe also exhibits other puzzling properties. For example, unlike other iron-based materials in which nematicity (spontaneous breaking of the crystal's 90-degree rotational symmetry) is accompanied by magnetic long-range order, FeSe exhibits only nematicity. However, a neutron scattering experiment [3] found large fluctuating magnetic moments. This invites the notion that the interaction between magnetic moments in FeSe is "frustrated," preventing them to order. If so the magnetic moments should form a "quantum paramagnetic state" above T_c. Does the unusual magnetic property of FeSe have anything to do with its unsual Cooper pairing? This is the question I would like to share with the journal club readers.

References

[1] S. Kasahara *et al*, PNAS, **111**, 16309 (2014).

[2] A.V. Chubukov, I. Eremin and D. V. Efremov, Phys. Rev. B **93**, 174516 (2016).

[3] Q. Wang *et al*, Nature Communications, **7**, 12182 (2016).

[4] P.W. Anderson, Science **235**, 1196 (1987).