Magnetism and Superconductivity Compete in Iron-based Superconductors

High-temperature superconductivity (HTSC), one of the long-standing unsolved mysteries of condensed matter physics, is a beautiful example of emergent phenomena in which new orders do not arise from the properties of a material's individual constituents but rather from the competitive or cooperative interactions amongst them. Only two families of HTSC materials are known: cuprates and the more recently discovered iron-based superconductors (FeSC). They both have phase diagrams in which superconductivity emerges in proximity to other complex quantum phases. Understanding the relation between these phases with superconductivity may provide important insights into the emergence of HTSC.

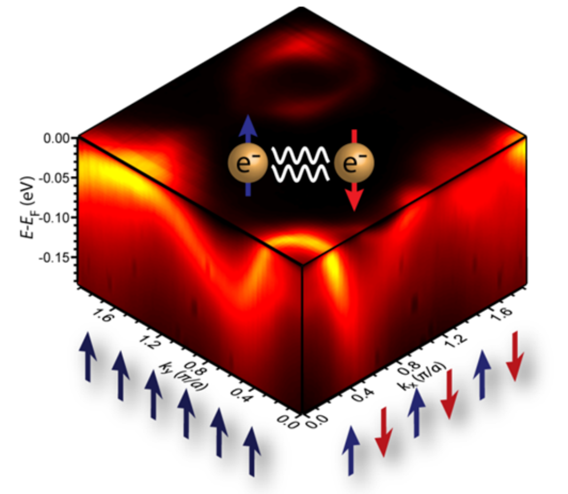

Fig. 1. Measured electronic structure of underdoped $Ba_{1-x}K_xFe_2As_2$ in the orthorhombic spin-density-wave (SDW) ordered state. The antiferromagnetic and ferromagnetic directions are indicated by arrows.

In the cuprates, the phase in proximity to superconductivity is a mysterious pseudogap phase, whose nature remains controversial, making it difficult to study its competition with superconductivity. In the FeSC, on the other hand, the phases are well-defined: a collinear spin density wave (SDW) order and a nematic phase whose boundary is marked by a tetragonal to orthorhombic structural transition. Only the suppression of these orders with chemical doping or pressure allows the emergence of superconductivity. Hence it is important to study how these orders interact with superconductivity.

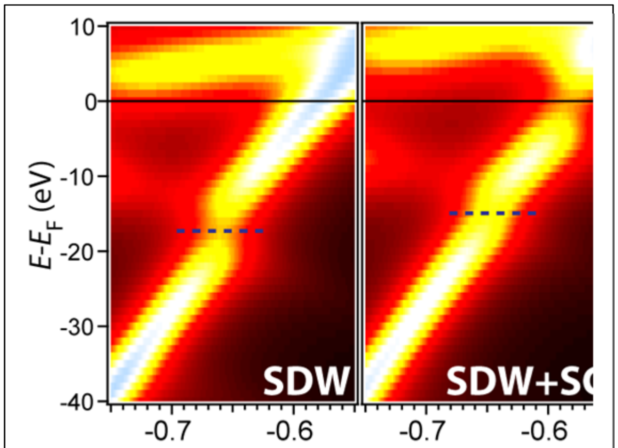

Fig. 2. Tight-binding simulation with superconducting (SC), SDW, and nematic order parameters. Left: Band dispersion in the SDW state showing an SDW gap. Right: Band dispersion in the SDW/SC coexistence phase, where the SDW and nematic orders are both reduced with the inclusion of the SC order parameter. The spectral effect is a reduction in SDW gap magnitude and shift towards the Fermi level with the opening of a superconducting gap, which is consistent with the experimental observations.

In a recent study published in *Nature Communications*, researchers Ming Yi and Donghui Lu along with their co-workers in the groups of Zhi-Xun Shen, Ian Fisher and Tom Devereaux at the Stanford Institute for Materials and Energy Sciences (SIMES) performed angle-resolved photoemission spectroscopy (ARPES) experiments at SSRL's Beam Line 5-4 and Beam Line 10 of the Advanced Light Source (ALS, Lawrence Berkeley National Laboratory) to study the interaction between these phases in the hole-doped FeSC, $Ba_{1-x}K_xFe_2As_2$.

Using ARPES, they were able to map out the electronic structure of these materials (Fig. 1). Furthermore, they were able to simultaneously identify distinct spectroscopic signatures of the order parameters associated with each of the three orders existing in the material: orbitaldependent band shift for the nematic order, band folding and gap for the SDW order, and gap for the superconducting order. With these data, the researchers were able to show that all three orders microscopically coexist in the material.

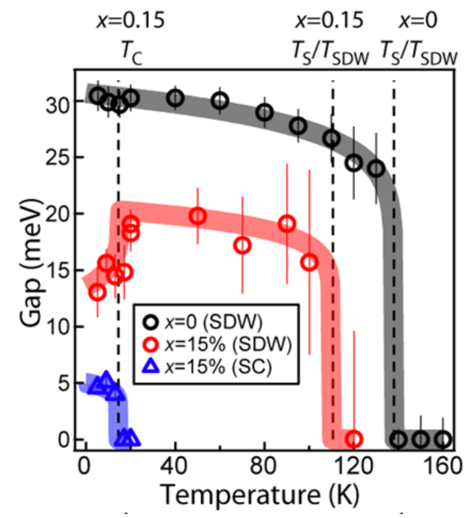

Fig. 3. Measured magnitude of the SDW gap in underdoped $Ba_{1-x}K_xFe_2As_2$ shrinking in magnitude (red) as the superconducting gap (blue) develops, in contrast to an undoped compound (black) where only the SDW order exists.

More interestingly, through a temperature-dependent study, they observed that the SDW gap shrinks in magnitude and shifts in energy as the system enters the superconducting phase. These data, together with additional theoretical simulations, showed that their observations are most consistent with a reduction of both the magnetic and nematic order parameters when superconductivity sets in (Fig. 2). The temperature-dependent SDW gap size behaves very similar to the magnetic moment and crystal orthorhombicity, which are the macroscopic order parameters of the magnetic and nematic orders (Fig. 3). This observation provides the first spectral evidence of competition between the magnetic and nematic orders with superconductivity.

The findings show that, while the magnetic and nematic orders are in proximity to superconductivity, they compete for the same electrons on the microscopic level. This is the first time that a dynamic competition between superconductivity and another order is observed in electron spectroscopy and provides a benchmark for such interactions.

Intriguingly, similar behavior was observed in a recent study in cuprates showing a suppression of the pseudogap spectral features associated with the onset of superconductivity. While the competition in iron pnictides may be simpler than that in the cuprates, the comparison of the two families may provide helpful insights into the mysterious pseudogap phase in the cuprates and help link the two families for an eventual understanding of the mechanism of unconventional superconductors.

Primary Citation

M. Yi, Y. Zhang, Z.-K. Liu, X. Ding, J.-H. Chu, A.F. Kemper, N. Plonka, B. Moritz, M. Hashimoto, S.-K. Mo, Z. Hussain, T. P. Devereaux, I. R. Fisher, H. H. Wen, Z.-X. Shen, and D. H. Lu, "Dynamic Competition between Spin-Density Wave Order and Superconductivity in Underdoped $Ba_{1-x}K_xFe_2As_2$", *Nat. Commun.* **5**, 3711 (2014), DOI: 10.1038/ncomms4711.

Contact

Donghui Lu, Stanford Synchrotron Radiation Lightsource

SSRL is primarily supported by the DOE Offices of Basic Energy Sciences and Biological and Environmental Research, with additional support from the National Institutes of Health, National Institute of General Medical Sciences.