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# Editorial: High-$T_c$ Superconductivity in Electron-Doped Iron Selenide and Related Compounds

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**Editorial on the Research Topic**

**High-Tc Superconductivity in Electron-Doped Iron Selenide and Related Compounds**

Iron-selenide superconductors comprise a particularly interesting group of materials inside the family of iron-based superconductors. The simplest member of the group is bulk FeSe, which has a modest critical temperature of $T_c = 9$ K. Like iron-pnictide superconductors, bulk FeSe shows a structural transition at $T_s =$ 90 K from a tetragonal to an orthorhombic phase driven by nematic ordering of the electronic degrees of freedom. Angle-resolved photoemission spectroscopy (ARPES), for example, reveals a small hole Fermi surface pocket at the center of the Brillouin zone and two electron Fermi surface pockets at the corner of the Brillouin zone, each with unequal $d_{xz}/d_{yz}$-orbital character. Unlike in iron-pnictide superconductors, however, no magnetic order coexists with the nematic order at temperatures below the structural transition. Inelastic neutron scattering (INS) spectroscopy finds a spin resonance inside the energy gap of the superconducting phase in bulk FeSe, however, at wavevectors corresponding to a stripe spin-density wave (SDW) [1]. It strongly suggests $s^{+-}$ superconductivity across the hole and electron Fermi surface pockets driven by associated antiferromagnetic spin fluctuations. INS also finds spin fluctuations at the Néel wavevector $(\pi, \pi)$ above the superconducting energy gap [2]. This suggests that superconductivity, nematic order, stripe-SDW order, and some type of Néel antiferromagnetic order compete at low temperature in bulk FeSe. One of the editors of the research topic has proposed that the latter is hidden Néel order [3, 4]. The superconducting critical temperature increases dramatically to 30–40 K and above upon doping iron selenide with electrons. The latter has been achieved in various ways; for example, by alkali-metal intercalation, by placing a monolayer of FeSe on a substrate, and by organic-molecule intercalation. ARPES finds that the hole bands at the center of the Brillouin zone lie buried below the Fermi level. INS finds a spin resonance inside the superconducting energy gap, but it lies midway between the SDW and Néel wavenumbers [5]. INS also finds peaks and rings of low-energy spin excitations above the energy gap around the Néel wavevector [6, 7]. ARPES and scanning tunneling microscopy (STM) find a non-zero superconducting energy gap. The situation with electron-doped FeSe is rather puzzling then, with high-$T_c$ superconductivity existing over electron Fermi surface pockets alone! This is not expected in iron-selenide superconductors, where electron-electron repulsion is strong [8]. The latter requires that the sign of the pair wave function oscillates over the Brillouin zone [4].

It is our pleasure to introduce eight articles from the Research Topic that address many of the unsolved problems that have emerged in the field of iron-selenide superconductors, some of which we have listed above. The contributions to the Research Topic contain articles on both theory and experiment, with four papers reporting on original research, and with four review papers. Chen et al. review how nematicity in bulk iron selenide can be scrutinized by exploiting detwinning techniques [9], while Coldea reviews the

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series of nematic superconductors $FeSe_{1-x}S_x$ [10]. Both articles tackle the interplay between nematicity and superconductivity that exists in bulk FeSe, with or without chemical substitutions. Yeh et al. show that insulating $Fe_4Se_5$ becomes a superconductor with $T_c$ = 8 K after proper annealing [11]. They thereby argue that $Fe_4Se_5$ is the insulating parent compound for iron-selenide superconductors. It would clearly be useful to compare future studies of the low-energy spin excitations in $Fe_4Se_5$ with those of its electron-doped counterpart $Rb_2Fe_4Se_5$ [5, 6]. Finally, Dong et al. review a new soft-chemical technique to grow high-quality single crystals of organic-molecule intercalated FeSe [12]. Their samples have critical temperatures of $T_c$ = 42 K, and they notably show record critical currents.

On the theory side, Yu et al. review $3d$-orbital-selective physics in iron superconductors [13]. They point out how the $d_{xy}$ orbital is the one most susceptible to Mott localization in iron-selenide superconductors [8]. They also emphasize how the relatively small energy splitting between the $d_{xz}/d_{yz}$ orbitals that is seen by ARPES in the nematic phase of bulk FeSe, $\Delta E_\Gamma$ and $\Delta E_M < 50$ meV, can be reconciled with the large orbitally-dependent wavefunction renormalizations seen by STM in the same phase, $Z(d_{yz})/Z(d_{xz}) = 4$. Dzero and Khodas study the effect of point disorder on the stripe SDW state by exploiting a quasi-classical Green's function technique [14]. They find that the tetragonally symmetric stripe SDW state is more robust with respect to disorder than the orthorhombically symmetric one. This result could have bearing on the absence of magnetic order in the nematic phase of bulk FeSe, for example. Last, Ptok et al. study a two-band model for iron superconductors that includes intra-band and inter-band coupling between Cooper pairs [15]. They notably find Cooper pair states in relative orbitals of mixed symmetry. Finally, Gupta et al. applied muon-spin rotation/relaxation ($\mu$SR) on the iron-pnictide superconductor $NdFeAsO_{0.65}F_{0.35}$, thereby obtaining London penetration lengths [16]. Interestingly, a two-band analysis of their data yields only weak inter-band coupling of the Cooper pairs.

The brief survey above of the author contributions to the Research Topic conveys the richness of the field of iron-selenide superconductivity and related materials. We believe that you will enjoy reading the Research Topic.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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