Nematic order in iron superconductors – who is in the driver’s seat?

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Although the existence of nematic order in iron-based superconductors is now a well-established experimental fact, its origin remains controversial. Nematic order breaks the discrete lattice rotational symmetry by making the $x$ and $y$ directions in the Fe plane non-equivalent. This can happen because of (i) a tetragonal to orthorhombic structural transition, (ii) a spontaneous breaking of an orbital symmetry, or (iii) a spontaneous development of an Ising-type spin-nematic order – a magnetic state that breaks rotational symmetry but preserves time-reversal symmetry. The Landau theory of phase transitions dictates that the development of one of these orders should immediately induce the other two, making the origin of nematicity a physics realization of a “chicken and egg problem”. The three scenarios are, however, quite different from a microscopic perspective. While in the structural scenario lattice vibrations (phonons) play the dominant role, in the other two scenarios electronic correlations are responsible for the nematic order. In this review, we argue that experimental and theoretical evidence strongly points to the electronic rather than phononic mechanism, placing the nematic order in the class of correlation-driven electronic instabilities, like superconductivity and density-wave transitions. We discuss different microscopic models for nematicity in the iron pnictides, and link nematicity to other ordered states of the global phase diagram of these materials – magnetism and superconductivity. In the magnetic model nematic order pre-empts stripe-type magnetic order, and the same interaction which favors nematicity also gives rise to an unconventional $s^{+}$ superconductivity. In the charge/orbital model magnetism appears as a secondary effect of ferro-orbital order, and the interaction which favors nematicity gives rise to a conventional $s^{+}$ superconductivity. We explain the existing data in terms of the magnetic scenario, for which quantitative results have been obtained theoretically, including the phase diagram, transport properties of the nematic phase, scaling of nematic fluctuations, and the feedback of the nematic order on magnetic and electronic spectra.

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I. INTRODUCTION

The discovery of iron-based superconductors (FeSCs) with transition temperatures $T_c$ as high as 65K has signaled the beginning of a new era in the investigation of unconventional superconductivity (for a review, see [1]). The key first step to unveil the nature of the superconducting phase is to understand the normal state from which superconductivity arises. In most FeSCs, superconductivity is found in proximity to a magnetically ordered state (transition temperature $T_{\text{mag}}$), which led early on to the proposal that magnetic fluctuations play the key role in promoting the superconducting pairing [2, 3]. A more careful examination of the phase diagram, however, revealed that there is another non-superconducting ordered state besides magnetism. Namely, at a certain temperature $T_{\text{nem}}$, the system spontaneously breaks the symmetry between the $x$ and $y$ directions in the Fe plane, reducing the rotational point group symmetry of the lattice from tetragonal to orthorhombic, while time-reversal symmetry is preserved. In some materials, such as hole-doped (Ba$_{1-x}$K$_x$)Fe$_2$As$_2$, the tetragonal-to-orthorhombic and magnetic transitions are simultaneous and first-order ($T_{\text{nem}} = T_{\text{mag}}$), whereas in electron-doped Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ and isovalent-doped BaFe$_2$(As$_{1-y}$P$_y$)$_2$, they are split ($T_{\text{nem}} > T_{\text{mag}}$) and second-order [4, 5] (see Fig. 1). As doping increases, the $T_{\text{nem}}$ line tracks the $T_{\text{mag}}$ line across the phase diagram, approaching the superconducting dome. It is therefore essential to understand the origin of this new order as it may support or act detrimentally to superconductivity.

The order parameter for a transition in which a rotational symmetry is broken but time-reversal symmetry is preserved is a director (i.e. a vector without an arrow), similar to the order parameter in the nematic phase of liquid crystals [6]. By analogy, the orthorhombic state in FeSCs has been called a “nematic state”. Unlike isotropic liquid crystals, however, in FeSCs the lattice symmetry forces the director to point only either along $x$ or $y$ directions, what makes the nematic order parameter Ising-type (Ising-nematic).

At first sight, one might view this tetragonal-to-orthorhombic transition as a regular structural transition driven by lattice vibrations (phonons). However, experiments find anisotropies in several electronic properties, such as the dc resistivity [7, 11], to be much larger than...
FIG. 1: Schematic phase diagram of hole-doped and electron-doped iron pnictides of the BaFe$_2$As$_y$ family. The blue area denotes stripe-type orthorhombic magnetism, the red area denotes nematic/orthorhombic paramagnetic order, and the yellow area, superconductivity. The green area corresponds to a magnetically-ordered state that preserves tetragonal ($C_4$) symmetry, as observed recently [45]. The shaded red region denotes a regime with strong nematic fluctuations. Bent-back dotted lines illustrate the magnetic and nematic transition lines inside the superconducting dome. Second-order (first-order) transitions are denoted by solid (dashed) lines. The insets show the temperature-dependence of the nematic ($\varphi$) and magnetic ($M$) order parameters in different regions of the phase diagram: region (I) corresponds to simultaneous first-order magnetic and nematic transitions; region (II), to split second-order nematic and first-order magnetic transitions; and region (III) to split second-order transitions.

The anisotropy of the lattice parameters. This led to the idea that the tetragonal-to-orthorhombic transition may be driven by electronic rather than lattice degrees of freedom. If this is the case, then the transition into the nematic phase is driven by the same fluctuations that give rise to superconductivity and magnetic order, and therefore is an integral part of a global phase diagram of FeSCs. Electronic nematic phases have been recently proposed in other unconventional superconductors, such as high-$T_c$ cuprates and heavy-fermion materials [8]. An electronically driven nematic state in FeSCs would be in line with a generic reasoning that the pairing in all these correlated electron systems has the same origin.

The discussion on the “nematicity” in FeSCs has been largely focused on two key issues: (i) Can the experiments distinguish “beyond reasonable doubt” between phonon-driven and electron-driven tetragonal symmetry breaking? (ii) If this transition is driven by electrons, which of their collective degrees of freedom are driving it - charge/orbital fluctuations or spin fluctuations? Answering the last question is crucial for the understanding of superconductivity in FeSCs because we argue below that charge/orbital fluctuations favor a sign-preserving $s^+$-wave state ($s^+$) whereas spin fluctuations favor a sign-changing $s^-$-wave ($s^-$) or a $d$-wave state. Here we give our perspective on these issues, discuss the phenomenology of the nematic state, its experimental manifestations, and the underlying microscopic models.

II. PHENOMENOLOGY OF THE NEMATIC PHASE

To describe the nematic state, the first task is to identify the appropriate order parameter. The experimental manifestations of nematic order can be clustered into three classes. Taken alone, each class points to a different origin of the nematic phase (see Fig. 2 for schematic representation):

- Structural distortion – the lattice parameters $a$ and $b$ along the $x$ and $y$ directions become different. Such an order is normally associated with a phonon-driven structural transition;
- Charge orbital order – the occupations $n_{xz}$ and $n_{yz}$ (and on-site energies) of the $d_{xz}$ and $d_{yz}$ Fe-orbitals become different [11]. The appearance of such an order is normally associated with divergent charge fluctuations;
- Spin-nematic order – the static spin susceptibility $\chi_{mag}(q)$ becomes different along the $q_x$ and $q_y$ directions of the Brillouin zone before a conventional SDW state develops [7]. The appearance of such an order is normally associated with divergent quadrupole magnetic fluctuations.

The fact that these three order parameters are non-zero in the nematic phase leads to a dilemma, which can be best characterized as the physics realization of a “chicken and egg problem”: all three types of order (structural, orbital, and spin-nematic) must be present no matter who drives the nematic instability. This follows from the fact that bi-linear combinations of the order parameters which break the same symmetry (in our case, the tetragonal symmetry of the system) are invariant under symmetry transformations and must therefore appear in the Landau free energy. Suppose that one of the three order parameters is the primary one, i.e. its fluctuations drive the nematic instability. Let’s call it $\psi_1$ and the other two $\psi_2$ and $\psi_3$. The free energy has the generic form

$$F[ψ_1, ψ_2, ψ_3] = \frac{1}{2} \chi_1^{-1} ψ_1^2 + \frac{b}{4} ψ_1^4 + \lambda_{12} ψ_2 ψ_2 + \frac{1}{2} \chi_2^{-1} ψ_2^2 + \lambda_{13} ψ_1 ψ_3 + \frac{1}{2} \chi_3^{-1} ψ_3^2 + \ldots (1)$$

Because the nematic transition is driven by $ψ_1$, the coefficient $\chi_1$, which corresponds to the order parameter susceptibility in the disordered state, diverges at $T = T_{nem}$ and becomes negative for $T < T_{nem}$, while $\chi_2$ and $\chi_3$ remain finite and positive (although fluctuations of $ψ_2$ and $ψ_3$ may shift slightly $T_{nem}$). For $T < T_{nem}$, $ψ_1$ orders on its own: $⟨ψ_1⟩ = ± (−χ_1^{-1}/b)^{1/2}$. If $λ_{ij}$ in
The corresponding distortion of the Fermi surface is also uniform spin susceptibility orthorhombic (solid line) unit cell \[5\]. (b) Anisotropy in the magnetization along the \(i\) direction induced by a magnetic field \(h_i\) applied along the \(j\) direction \[7\]. (c) Splitting of the \(d_{xz}\) and \(d_{yz}\) orbitals (orange and blue lines, respectively) \[11\]. The corresponding distortion of the Fermi surface is also shown (see also Fig. 5a).

were zero, the other two fields \(\psi_2\) and \(\psi_3\) would not order, but once \(\lambda_{ij}\) are finite, a non-zero \(\langle \psi_1 \rangle\) instantly induces finite values of the secondary order parameters \(\langle \psi_2 \rangle = -\lambda_{12}\chi_2\langle \psi_1 \rangle\), \(\langle \psi_3 \rangle = -\lambda_{13}\chi_3\langle \psi_1 \rangle\). As a consequence, there is only one nematic transition temperature at which all three \(\langle \psi_i \rangle\) become non-zero (e.g., lattice symmetry is broken at the same temperature where electronic nematic order emerges), and it is not possible to determine who causes the instability by looking solely at equilibrium order parameters. An additional experimental complication is the presence of nematic twin domains below \(T_{\text{nem}}\), what effectively averages \(\langle \psi_1 \rangle\) to zero. This problem can be circumvented by applying a small detwining uniaxial stress \[8\] \[10\], which acts as a conjugate field to \(\psi_1\) and breaks the tetragonal symmetry at all temperatures, making \(T_{\text{nem}}\) an ill-defined quantity.

One way to select the primary order is to carefully study fluctuations in the symmetry-unbroken phase at \(T > T_{\text{nem}}\). Because the primary order parameter \(\psi_1\) acts as an external field for the secondary order parameters, \(\psi_2\) and \(\psi_3\), fluctuations of the former renormalize the susceptibilities of the latter to

\[
\tilde{\chi}_2 \approx \chi_2 \left(1 + \lambda_{12}^2\chi_2\chi_1\right) , \quad \tilde{\chi}_3 \approx \chi_3 \left(1 + \lambda_{13}^2\chi_3\chi_1\right),
\]

where \(\chi_1 = \langle \psi_1^2 \rangle\) is the susceptibility of the primary field. The renormalized susceptibilities of the secondary fields do diverge at the nematic transition, however for small enough \(\lambda_{12}\) and \(\lambda_{13}\), \(\tilde{\chi}_2\) and \(\tilde{\chi}_3\) begin to grow only in the immediate vicinity of \(T_{\text{nem}}\), where \(\chi_1\) is already large. If one can measure the three susceptibilities independently, Eq. \((2)\) in principle provides a criterion to decide which order parameter drives the instability. The implementation of this procedure is possible (see next section), but is complicated by two factors. First, it only works if \(\lambda_{12}\) and \(\lambda_{13}\) are relatively weak, what normally implies that the systems falls into the weak/moderate coupling category. If the coupling is large, all three order parameters become so inter-connected that the question “who is in the driver’s seat?” becomes meaningless. Second, in some FeSCs the nematic transition is first order, in which case all three susceptibilities jump from one finite value to another, even before the susceptibility of the primary field gets enhanced.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2}
\caption{Manifestations of nematic order in the iron pnictides: (a) Structural distortion from a tetragonal (dashed line) to an orthorhombic (solid line) unit cell \[3\]. (b) Anisotropy in the uniform spin susceptibility \(\chi_{\alpha\beta} = m_\alpha/h_\beta\), where \(m_\alpha\) denotes the magnetization along the \(i\) direction induced by a magnetic field \(h_i\) applied along the \(j\) direction \[7\]. (c) Splitting of the \(d_{xz}\) and \(d_{yz}\) orbitals (orange and blue lines, respectively) \[11\]. The corresponding distortion of the Fermi surface is also shown (see also Fig. 5a).}
\end{figure}

III. EXPERIMENTAL EVIDENCE FOR ELECTRONIC NEMATICITY

A. Measurements in the nematic phase

The first evidence for the electronic character of the tetragonal-to-orthorhombic transition came from resistivity measurements in detwinned samples \[9\] \[10\], which revealed that resistivity anisotropies are significantly larger than relative lattice distortions and also display a nontrivial dependence on doping and disorder \[15\]. Other non-equilibrium quantities, such as thermopower \[13\] and optical conductivity \[14\] \[15\], were also found to display large anisotropies, which in optical measurements were observed to extend to energies of several hundreds of meV. Anisotropies in observables related to charge and spin were also seen: angle-resolved photoemission spectroscopy (ARPES) found a splitting between the on-site energies of the \(d_{xz}\) and \(d_{yz}\) orbitals, indicative of ferroorbital order \[11\] and torque magnetometry revealed different uniform magnetic susceptibilities along the \(x\) and \(y\) directions \[7\]. The onset of magnetic anisotropy coincides with the observation of a non-zero orthorhombic distortion, in agreement with the discussions of the previous section. Strong signatures of emerging magnetic anisotropy were also found in the behavior of the nuclear magnetic resonance (NMR) lines across \(T_{\text{nem}}\) \[16\].

The direct observation of electronic anisotropy in the nematic state was made possible by scanning tunneling microscopy (STM). The first measurements, performed deep inside the magnetic phase, found that the local density of states around an impurity is characterized by a dimer-like structure extended along the magnetic ordering vector direction \[18\]. Subsequent measurements showed that these dimers persist above \(T_{\text{mag}}\), in the temperature regime of the nematic state \[19\]. An additional piece of evidence in favor of the electronic character of the nematic transition came, ironically, from x-ray measurements of the orthorhombic distortion inside the SC phase. These measurements found a strong suppression of the distortion below \(T_c\) \[21\], what is a characteristic signature of the competition for the same electronic states between two electronically-driven orders.
B. Measurements in the tetragonal phase

A few recent measurements focused on fluctuations in the tetragonal state, in particular, on the shear modulus $C_4$, which is the inverse susceptibility of the structural order parameter $\chi_{\text{struct}}$. If the structural transition is driven not by the lattice but by some other electronic degree of freedom, Eq. (2) provides a natural way to connect the shear modulus to the electronic nematic susceptibility $\chi_1$. An experimentally observed softening of the shear modulus above $T_{\text{nem}}$, as was successfully fitted by Eq. (2) using both magnetic and charge/orbital phenomenological models for $\chi_1$, indicating that structural distortion is very likely not the primary order.

Perhaps the strongest evidence that the nematic transition is electronically-driven came from the recent measurements of the anisotropy of the resistivity [24]. Using a piezoelectric, the measurements were performed by using strain (the structural distortion) as the control parameter, rather than stress, as in previous setups. The strain $\delta$ is one of the order parameter fields in the free energy Eq. (1). Using the resistivity anisotropy $\rho_{\text{anis}} = \rho_{xx} - \rho_{yy}$ as a proxy of the nematic order parameter, it was experimentally shown that the susceptibility $\partial \rho_{\text{anis}} / \partial \delta$ diverges near the nematic transition. This is only possible if the structural distortion is a conjugate field to the primary order parameter, rather than the primary order parameter itself – otherwise $\rho_{\text{anis}}$ would be simply proportional to the order parameter $\delta$, with a constant prefactor.

IV. MICROSCOPIC MODELS FOR ELECTRONIC NEMATICITY

A successful microscopic theory for electronic nematicity must describe the global phase diagram of FeSCs, i.e. not only the nematic order but also magnetism and superconductivity. A popular starting point is the multi-orbital Hubbard model, which describes hopping between all Fe-As orbitals and local interactions, such as intra-band and inter-band Hubbard repulsions and Hund’s exchange [2]. There is a general agreement among researches that this model does contain all information about the phase diagram. The model has been analyzed at both weak/intermediate coupling, when the system is a metal, and at strong coupling, when electrons on at least some orbitals were assumed to be localized or “almost localized”. The nematic order has been obtained in both limits, what is yet another indication that it is a generic property of FeSCs. We adopt the itinerant approach, since most FeSCs are metals. In this itinerant scenario, the low-energy electronic states lie around hole-like Fermi-surface pockets at the center of the Fe-square lattice Brillouin zone and electron-like Fermi-surface pockets at the borders of the Brillouin zone, see Fig. 5a. The microscopic reasoning for either magnetic or orbital scenarios of electronic nematicity follows from two different assumptions about the sign of the effective inter-pocket interaction $U$ [26], which is a combination of the Hubbard and Hund interactions dressed up by coherence factors associated with the transformation from the orbital to the band basis. As we will see, each scenario leads to a prediction of a particular superconducting pairing state.

A. Magnetic scenario

The magnetic mechanism for the nematic order follows from the observation that in most FeSCs the observed magnetic order on the Fe atoms is of stripe type, with ordering vectors $Q_X = (\pi, 0)$ or $Q_Y = (0, \pi)$ i.e. spins are parallel to each other along one direction and anti-parallel along the other (see Fig. 3a). This order breaks not only the $O(3)$ spin-rotational symmetry (and time-reversal symmetry), but it also breaks the $90^\circ$ lattice rotational symmetry down to $180^\circ$ by choosing the ordering vectors to be either $Q_X$ or $Q_Y$. This additional tetragonal symmetry breaking enhances the order parameter manifold to $O(3) \times Z_2$ [26, 28]. In terms of the two magnetic order parameters $M_X = \sum_{k} c_{k+Q_X} \sigma_{\alpha} c_{\alpha} \sigma_{\beta} c_{k+Q_Y}$ and $M_Y = \sum_{k} c_{k+Q_Y} \sigma_{\alpha} c_{\alpha} \sigma_{\beta} c_{k+Q_X}$, associated with the ordering vectors $Q_X$ and $Q_Y$, the breaking of the $O(3)$ symmetry implies $\langle M_i \rangle \neq 0$ while the breaking of the
$Z_2$ symmetry implies $\langle M^2_X \rangle \neq \langle M^2_Y \rangle$. In a mean-field approach both $O(3)$ and $Z_2$ symmetries are broken simultaneously at $T_{\text{mag}}$. However, fluctuations split the two transitions and give rise to an intermediate phase at $T_{\text{mag}} < T < T_{\text{nem}}$ where tetragonal symmetry is broken but the spin-rotational $O(3)$ symmetry is not, i.e. $\langle M^2_X \rangle \neq \langle M^2_Y \rangle$ while $\langle M_i \rangle = 0$. This is by definition a nematic order, which, viewed this way, is an unconventional magnetic order which preserves time-reversal symmetry (a spin nematic). In real space, the stripe magnetic state can be viewed as two inter-penetrating Neel sublattices with staggered magnetizations $M_1 = M_X + M_Y$ and $M_2 = M_X - M_Y$. In terms of these quantities, the nematic state is characterized by $\langle M_1 \cdot M_2 \rangle \neq 0$ while $\langle M_i \rangle = 0$ (see Fig. 3).

Within a microscopic description, the instability towards a stripe magnetic order is associated with the divergence of the static spin susceptibility $\chi_{\text{mag}}(Q)$. Without any interactions, the bare particle-hole susceptibility $\chi_0(Q)$ is by itself sizable at $Q_X$ and $Q_Y$ because these wave-vectors connect electronic states at the hole and electron pockets. When the inter-pocket interaction $U$ is positive (repulsive), there is an additional RPA-type enhancement of the spin susceptibility, roughly as $\chi_{\text{mag}}(Q) = \chi_0(Q)/(1 - U\chi_0(Q))$, and at some $T = T_{\text{mag}}$, $\chi_{\text{mag}}(Q)$ diverges. This however does not guarantee that the magnetic order is of stripe type as the latter emerges only if below $T_{\text{mag}} (M_X \neq 0)$ and $(M_Y \neq 0)$, or vise versa. To determine which magnetic state develops, one needs to calculate higher order terms in the magnetic free energy $\chi_{\text{mag}}(Q)$. The result is that as long as small dopings, the system selects the stripe order. The static nematic susceptibility $\chi_{\text{nem}}$ (the correlator of $M^2_X - M^2_Y$) can be obtained by including fluctuations of the nematic order parameter $M^2_X - M^2_Y$, yielding:

$$\chi_{\text{nem}} = \frac{T \sum_Q \chi_{\text{mag}}^2(Q)}{1 - gT \sum_Q \chi_{\text{mag}}^2(Q)}$$

where $T$ is the temperature, and $g \propto U^2$ is the composite coupling which, when positive, sets the magnetic order to be of stripe type. In dimensions $d < 4$, $\sum_Q \chi_{\text{mag}}^2(q)$ diverges at $T_{\text{mag}}$ (assuming that the magnetic transition is second order). Eq. 3 then shows that the nematic susceptibility diverges at a higher $T_{\text{nem}} > T_{\text{mag}}$: when $g \sum_Q \chi_{\text{mag}}^2(q) = 1$, i.e. at sufficiently large but still finite magnetic correlation length. This mechanism naturally ties the nematic and magnetic ordering temperatures to each other over the entire phase diagram. In between $T_{\text{nem}}$ and $T_{\text{mag}}$, the $Z_2$ symmetry is broken but $O(3)$ is not, i.e., $\langle M^2_X \rangle \neq \langle M^2_Y \rangle$ but $\langle M_i \rangle = 0$. The difference between $T_{\text{nem}}$ and $T_{\text{mag}}$ is stronger in quasi-2D systems where $T_{\text{mag}}$ is further decreased by thermal fluctuations, while $T_{\text{nem}}$ remains unaffected 38, 39.

More detailed microscopic calculations show that for some system parameters the nematic transition is second order, but for other input parameters it becomes first-order 30. In the latter case, a jump in the nematic order parameter induces a jump in the magnetic correlation length, which may instantaneously trigger a first-order magnetic transition. In any case, when the Fermi pockets are decomposed into their orbital characters, one finds within the same microscopic model that the emergence of spin-nematic order gives rise to orbital order $\Delta n = n_{xz} - n_{yz}$, since the electron pocket at $Q_X$ has mostly $d_{xy}$ character, whereas the electron pocket at $Q_Y$ has mostly $d_{xz}$ character. Similarly, a spin-nematic order induces a structural distortion $a \neq b$ 32, 33.

We see therefore that the repulsive inter-pocket interaction $U > 0$ enhances spin fluctuations, which gives rise to both magnetism and nematicity. To describe the global phase diagram of FeSCs, one needs also to investigate superconductivity. Spin fluctuations peaked at $Q_X$ and $Q_Y$ strongly enhance inter-pocket repulsion, which becomes larger than intra-pocket repulsion. In this situation, the system is known to develop either an unconventional $s^+$ superconductivity, in which the gap functions have different signs in the hole and in the electron pockets, or a $d_{x^2-y^2}$ superconductivity 4, 8. We emphasize that spin-nematic order and $s^+$ superconductivity are both intrinsic consequences of the same magnetic scenario.

Other microscopic models also find nematic order in proximity to a magnetic instability. For instance, explicit evaluation of the ferro-orbital susceptibility using the multi-orbital Hubbard model finds that it is enhanced only in the presence of spin fluctuations 34, similarly to what is described by Eq. 3. Studies of models with both localized and itinerant orbitals also found 37, 39 that the proximity to magnetism is an important ingredient for orbital order. In purely localized-spin models the interplay between magnetism and ferro-orbital order is blurred by the complicated form of the effective Hamiltonian, which deviates from a simpler Kugel-Khomskii type 35, 50.

### B. Charge/orbital scenario

In its simplest form, the charge/orbital scenario for the nematic order parallels the magnetic scenario, the only difference being the sign of the interaction $U$ between electron and hole pockets. If this interaction turns out to be negative, it is the charge/orbital susceptibility rather than the spin susceptibility that is enhanced as $\chi_{\text{orb}}(Q) = \chi_0(Q)/(1 + U\chi_0(Q))$, diverging at $Q_X$ and $Q_Y$ at a certain $T_{\text{orb}}$. This divergence would signal the onset of a charge density-wave state with ordering vectors $Q_X$ or $Q_Y$ (or both) and order parameters $W_X = \sum_k \delta_{\alpha\beta} c_{k+Q_X}^\dagger d_{\alpha\beta} c_k$ and $W_Y = \sum_k \delta_{\alpha\beta} c_{k+Q_Y}^\dagger d_{\alpha\beta} c_k$. This order breaks translational symmetry and, like in the magnetic scenario, breaks also an additional $Z_2$ symmetry if only one order parameter becomes non-zero. It is natural to expect, although no
explicit calculations have been done to the best of our knowledge, that fluctuations split the temperatures at which the translational and the $Z_2$ symmetries are broken, in a manner similar to Eq. (3). Then, in the intermediate temperature range $T_{\text{orb}} < T < T_{\text{nem}}$, the system spontaneously develops ferro-orbital order in which $\langle W_X^2 \rangle \neq \langle W_Y^2 \rangle$ while $\langle W_X \rangle = \langle W_Y \rangle = 0$. A structural distortion and the difference between $\langle M_X^Z \rangle$ and $\langle M_Y^Z \rangle$ appear instantly once ferro-orbital order sets in. However, magnetic order only appears at a smaller temperature, presumably via changes in the magnetic correlation length induced by the ferro-orbital order.

For the Cooper pairing, the orbital scenario implies that the inter-pocket interaction is attractive and enhanced. Once this interaction exceeds the intra-pocket repulsion, the system develops a superconducting instability towards an $s^{++}$ state – a conventional pairing state where the gap functions have the same sign in all pockets.

What we described above is the simplest scenario for orbital order. More complex models have been also proposed to account for the nematic transition without involving magnetic degrees of freedom. In Ref. [40], it was proposed that nematicity could arise as an unequal hybridization between localized $d_{xy}$ orbitals and itinerant $d_{xz}/d_{yz}$ orbitals. In Ref. [41] it was suggested that both spin and charge interactions are present and that the larger interaction in the spin channel gives rise to magnetic order at, say, $Q_X$. However, before this happens, a weaker charge interaction gives rise to charge order at the other momentum $Q_Y$ (a pocket density-wave state), which would break the tetragonal symmetry of the system. Whether such a pocket density-wave is experimentally realized in FeSCs remains to be seen.

V. COMPARISON BETWEEN THEORY AND EXPERIMENT

Although the experimental evidence presented in Section III favors an electronic nematic instability, disentangling the orbital and magnetic scenarios is difficult on a qualitative level, what begs for a more direct comparison between microscopic models and experimental results. In this regard, the doping evolution of the magnetic and structural transitions is an important benchmark. BaFe$_2$As$_2$, one of the compounds most extensively investigated, displays a second-order nematic transition at $T_{\text{nem}}$ followed by a a first-order “meta-nematic transition” at a lower $T$, where the system simultaneously undergoes a first-order magnetic transition. The meta-nematic transition has been observed by x-ray [2] and torque magnetometry [7], although the data disagree on the precise value of $T_{\text{nem}}$. As charge carriers are introduced in the system via Co substitution in the Fe sites, the splitting between the two transitions increases, and eventually the meta-nematic transition disappears and the magnetic transition becomes second-order.

![FIG. 4: Schematic representation of the evolution of the magnetic and nematic transitions as function of the inverse nematic coupling $g$, according to the microscopic itinerant spin-nematic model. Second-order (first-order) lines are denoted by solid (dashed) lines. Regions (I)-(III) correspond to those of the phase diagram in Fig. 1. The arrows show how the nematic order parameter $g$ is expected to change as function of various control parameters.](image)

How does this compare to theory? For the magnetic scenario, a detailed theoretical analysis [30] shows that three types of system behavior are possible in systems that are moderately anisotropic, depending on the value of the nematic coupling $g$ (see Fig. 4). At large $g$, nematic and magnetic transitions are simultaneous and first order. At intermediate $g$, nematic order develops via a second-order transition, and there is a meta-nematic transition at a lower $T$, where magnetic order also develops discontinuously. At smaller $g$, nematic and magnetic transitions are separate and second-order, with an intermediate spin-nematic phase between $T_{\text{nem}}$ and $T_{\text{mag}}$. The microscopic calculations found that $g$ decreases with electron doping, and the theoretical phase diagram in Fig. 4 is fully consistent with the one for the electron-doped Ba(Fe$_{1−x}$Co$_x$)$_2$As$_2$ if we place the $x = 0$ point in the region II in Fig. 4. No calculations of how the nematic and magnetic transitions evolve with carrier concentration have been done within the charge/orbital scenario.

One can take the comparison with the data even further and compare the two versions of the magnetic scenario – for itinerant and for localized spins. Both predict stripe magnetic order and pre-emptive $Z_2$ symmetry-breaking but differ in the details. In particular, in localized models $g$ is generally small and is unaffected by carrier concentration [28, 42]. This makes the description of the doping dependence in the localized spin approach somewhat problematic, although not impossible [51]. A more essential difference is that in localized
models the coupling $g$ is always positive, while in itinerant models $g$ may become negative at large enough hole doping \cite{43, 44}. For negative $g$, there is no tetragonal symmetry breaking either above or below the magnetic transition as the system selects a tetragonally-symmetric combination of both $Q_X$ and $Q_Y$ orders. A symmetry-preserving magnetic state with orders at $Q_X$ and $Q_Y$ has been recently observed in Ba$_{1-x}$Na$_x$Fe$_2$As$_2$ \cite{43} and Ba(Fe$_{1-x}$Mn$_x$)$_2$As$_2$ \cite{43} at large enough doping – a strong argument in favor of the itinerant magnetic scenario.

Another key quantity to compare experiment and theory is the resistivity anisotropy. Deep in the magnetically ordered state, the anisotropic folding of the Fermi surface plays the major role in determining the resistivity anisotropy \cite{10, 47}. In the nematic state, $T > T_{mag}$, orbital order and spin-nematic order have different effects on the dc resistivity: while the former causes an anisotropy in the Drude weight \cite{37, 48}, the latter gives rise to anisotropy in the scattering rate \cite{49}. The calculated anisotropy in the Drude weight has the opposite sign to the one observed experimentally \cite{37, 48}, whereas the calculated anisotropy in the magnetic scattering rate was shown to agree with experiments, including a sign-change of the anisotropy between electron-doped and hole-doped materials \cite{50}.

One can also compare theoretical and experimental results for the feedback effects from the nematic order on the electronic and the magnetic spectrum \cite{30, 37, 31}. In the magnetic scenario, nematic order enhances the magnetic correlation length, what gives rise to strong magnetic fluctuations and a possible pseudogap in the electronic spectrum. A significant increase of magnetic fluctuations below $T_{nem}$ has been observed via NMR in compounds where $T_{nem}$ and $T_{mag}$ are well separated \cite{52}. Also, recent ARPES experiments found the pseudogap behavior (a suppression in the density of states at low energies) whose onset coincides with the nematic transition \cite{53}. Within the orbital scenario, the key feedback from the orbital order is a Pomeranchuk distortion of the Fermi surface induced by orbital order \cite{37}.

Nematic fluctuations above $T_{nem}$ have also been used to compare experiment and theory. Orbital fluctuations have been argued to affect the density of states at the Fermi level \cite{54} and leave signatures in point-contact spectroscopy consistent with the data \cite{55}. Alternatively, one can employ Eq. (2) to compare the renormalized lattice susceptibility (the shear modulus $C_s$), assumed to be non-critical, with the susceptibility $\chi_1$ associated with either the orbital or the spin-nematic order parameter. Eq. (2) must be satisfied if the corresponding electronic order drives the nematic instability. \cite{56}, a quasi-elastic peak in the Raman response was attributed to charge/orbital fluctuations and used to extract the corresponding orbital susceptibility. On the other hand, the spin-nematic susceptibility, being proportional to $\sum_{q} \chi^2_{mag}(q)$ (see Eq. (3), can be measured via the NMR spin-lattice relaxation rate $1/T_1$. Comparison with shear modulus data for a family of electron-doped FeSCs found that there is a robust scaling between $C_s$ and $1/T_1$ data \cite{57}. This provides strong support to the idea that the nematic transition is magnetically-driven.

\section{VI. PERSPECTIVES}

The bulk of experimental and theoretical results which we presented in this mini-review supports the idea that nematic order in FeSCs is of electronic origin, what places it at par with other known electronic instabilities such as superconductivity or density-wave orders. It is likely that magnetic fluctuations drive the nematic instability. In any case, all three orders – spin-nematic, orbital, and structural, appear simultaneously below $T_{nem}$. The important question not addressed until very recently is the role of nematicity for high-temperature superconductiv-
ity. It is unlikely that nematic fluctuations can mediate superconductivity as spin or charge fluctuations do, but nematic fluctuations may nevertheless enhance $T_c$ by reducing the bare intra-pocket repulsion. Below $T_c$, however, nematic order has been found to compete with superconductivity \cite{20, 58}, like density-wave orders do. A special case in which nematicity strongly affects $T_c$ is when s-wave and d-wave superconducting instabilities are nearly degenerate, what was suggested to be the case for strongly hole-doped and strongly electron-doped FeSCs \cite{59}. In this situation nematic order leads to a sizeable enhancement of $T_c$ by lifting the frustration associated with the competing pairing states \cite{60, 62}. These results clearly point to the need of additional investigations of the interplay between nematicity and superconductivity.

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