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Charge nematicity and electronic Raman scattering in iron-based superconductors

Nématicité de charge et diffusion Raman électronique dans les supraconducteurs au fer

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ABSTRACT

We review the recent developments in electronic Raman scattering measurements of charge nematic fluctuations in iron-based superconductors. A simple theoretical framework of a *d*-wave Pomeranchuk transition is proposed in order to capture the salient features of the spectra. We discuss the available Raman data in the normal state of 122 iron-based systems, particularly Co-doped $BaFe_2As_2$, and we show that the low-energy quasi-elastic peak, the extracted nematic susceptibility and the scattering rates are consistent with an electronic-driven structural phase transition. In the superconducting state with a full gap, the quasi-elastic peak transforms into a finite-frequency nematic resonance, evidences for which are particularly strong in the electron-doped systems. A crucial feature of the analysis is the fact that the electronic Raman signal is unaffected by the acoustic phonons. This makes Raman spectroscopy a unique probe of electronic nematicity.

RÉSUMÉ

Nous présentons dans cette revue les mesures de fluctuations de charge nématiques par diffusion Raman électronique dans les supraconducteurs au fer. A cadre théorique simple d'une transition de Pomeranchuk d'onde *d* est proposé afin comprendre les spectres Raman. Nous discutons ensuite des données Raman publiées dans l'état normal des composés 122, en particulier $BaFe_2As_2$ dopé au Co, et nous montrons que le pic quasi-élastique observé, la susceptibilité nématique extraite et le taux de diffusion sont en accord avec l'idée d'une transition structurale pilotée par les degrés de liberté électroniques. Dans l'état supraconducteur et en l'absence de noeuds dans le gap, le pic quasi-élastique se transforme en une résonance nématique à fréquence finie. La signature expérimentale de cette résonance nématique est particulièrement claire dans le cas des systèmes dopés électron. Un aspect crucial de l'analyse est le fait que la diffusion Raman électronique n'est

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pas affectée par les phonons acoustiques, faisant de cette technique une sonde unique de la nématicité électronique.

1. Introduction

The study of correlated phases of matter obtained a big boost with the discovery of the iron-based superconductors (Fe SC) in 2008 [1]. These systems are interesting not just because they exhibit superconductivity at temperatures as high as 55 K, but also because they are a rich playground where the lattice and the electronic charge, spin, and orbital degrees of freedom all play important roles. This complex interplay invariably leads to competition between various interesting phases that can be stabilized by varying temperature, by doping carriers, and by applying pressure. Understanding this rich physics is a considerable challenge, and consequently the topic continues to be an active area of research in condensed matter systems [2,3].

Unlike the cuprate high-temperature superconductors where the parent compounds are Mott insulators, the Fe SC systems are multi-band and multi-orbital metals at all doping values. The undoped and the lightly doped compounds undergo a structural transition from a high-temperature ($T > T_S$) tetragonal unit cell to a low-temperature ($T < T_S$) orthorhombic phase (in the case of $Fe_{1+y}Te_{1-x}Se_x$ the low-T phase is monoclinic for small x), which is followed in close proximity in temperature by a magnetic transition at T_N, below which the system is antiferromagnetic. These transitions are suppressed with electron or hole doping, and beyond a certain doping value the system becomes superconducting with an unusually high transition temperature T_C. Initial investigations of the superconductivity and its origin have focused mainly on the interplay between a stripe-like antiferromagnetism (where the magnetic ordering wave-vector is $(\pi, 0)$ or $(0, \pi)$ in the 1Fe/cell notation) and superconductivity. While the issue is not entirely settled, it is popularly believed that the fluctuations associated with the stripe antiferromagnetism give rise to a $s^{\pm}$ superconducting pairing symmetry [4–6] in most, but possibly not all [7], Fe SC families.

Ever since the reports of strongly anisotropic in-plane transport in the 122 systems [8] in the orthorhombic phase, a lot of attention has been given to study the property of nematicity in these materials. A nematic phase of matter is one that breaks rotational symmetry spontaneously, while preserving translational symmetry. Such phases have been studied extensively since the 1970s in classical soft matter systems [9], but relatively less is known about their quantum counterparts in electronic systems. However, their existence has been widely postulated for strongly correlated materials such as quantum Hall systems, cuprates, bilayer ruthenates [10], and most recently in the Fe SC. In the presence of a crystalline lattice, a nematic phase breaks discrete rotational symmetry, and as a consequence the associated order parameter is an Ising variable. In the context of the Fe SC, this order parameter is non-zero in the orthorhombic phase where the C_4 symmetry of the Fe unit cell is broken at the structural transition T_S. Note that, in certain systems, the structural and the magnetic transition are simultaneous ($T_S = T_N$), and, since the magnetic order by itself breaks C_4 symmetry, it is not clear whether the nematicity is a mere by-product of the magnetic order. Consequently, the issue of nematicity is more sharply posed for those systems where the structural transition precedes the magnetic one ($T_S > T_N$), leaving a finite temperature interval where C_4 symmetry is broken while the system remains paramagnetic [11–14]. The extreme example of this trend appears to be FeSe where only a structural transition [15,16] is detected and the system remains paramagnetic down to its SC phase [17,18], hinting that nematic degrees of freedom may not be necessarily linked to magnetic ones.

The microscopic origin of the nematic order is currently not known with certainty. One scenario is that the structural transition is, in fact, an instability driven by the anharmonic lattice potential, in which case the primary order parameter is the lattice orthorhombicity, and the electronic degrees of freedom are secondary order parameters that passively follow the symmetry breaking induced by the lattice strain. A second scenario is that the C_4 symmetry breaking is driven by electronic interactions, in which case the primary order parameter is electronic in origin. Within this picture, one possibility is the spin-nematic transition whereby the spins of the two Fe sublattices phase-lock, which breaks C_4 symmetry, without developing a spontaneous magnetization, i.e., without breaking time reversal symmetry [19–27]. A second possibility is ferro-orbital ordering [28–32], where either the occupations or the hopping matrix elements (or both) of the d_{xz} and the d_{yz} orbitals of Fe become inequivalent. Besides these two scenarios, other possibilities include a d-wave Pomeranchuk instability [33], in which the Fermi surfaces undergo symmetry-breaking distortions due to interaction effects, as well as a valley density wave [34].

On the experimental side, initial studies have focused on the strong anisotropy of the electronic properties in the orthorhombic C_4 symmetry-broken phase. Transport [8,35–39], optical conductivity [40–44], ARPES [45,46], and neutron scattering [47–49] (reviewed in a separate contribution to this issue [50]) performed on mechanically detwinned crystals all reported considerable electronic anisotropies. While it has been argued that the magnitudes of the measured anisotropies are too large to be due to the lattice orthorhombicity (which is 0.4 percent at most), such arguments can be at best quantitative, and therefore they do not convincingly rule out the lattice-driven scenario. Furthermore, even within the electronic-driven scenario, the above experiments cannot uniquely identify whether the primary order parameter is composed of electronic charge, spin or orbital degrees of freedom [51].