博士論文（要約）

Electronic nematicity and its quantum criticality in iron-based superconductors

（鉄系超伝導体におけるネマティシティとその量子臨界性）

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1. Overview

For over 100 years, superconductivity has been known as the exotic quantum phenomenon which emerges in solids. According to the theory developed by John Bardeen, Leon Cooper and John Robert Schrieffer more than 40 years after the discovery of this phenomenon, the so called BCS theory, superconductivity can be microscopically understood as the multiple pairs of two electrons bound by the electron-lattice interaction. While the superconductivity in ordinal metals can be successfully described by this framework, some solids with strong electron-electron interactions, such as cooper-oxides and heavy fermion materials, were found to have superconducting transition temperatures T_c higher than those predicted by their phonon energies. This indicates that the paring of two electrons in these compounds is not mediated by phonons, which classifies them as unconventional superconductors. The key feature of unconventional superconductors is that most of their mother materials exhibit antiferromagnetic orders. Since their T_c often have maximum near the antiferromagnetic quantum critical point (QCP), where their magnetic orders are continuously suppressed to zero temperature by the external parameters, the possible relation between quantum critical spin fluctuations developing around antiferromagnetic QCP and high-temperature superconductivity has arisen and been focus of the intense research for the past decades.

In this study, we focus on the iron-based superconductors, which also exhibit an unconventional superconductivity. In 2008, Hideo Hosono and co-workers reported the superconductivity in F-doped LaFeAsO with T_c = 26 K [1]. After this surprising discovery, several different classes of superconductors in this family were found to date, and now it is known as one of the high-temperature superconductors. As with other unconventional superconductors, most of iron-based superconductors show antiferromagnetic orders, and the superconductivity emerges in the vicinity of the magnetic phase. However, some of them also show the tetragonal-to-orthorhombic structural transitions at or above the magnetic transition temperature. Inside the orthorhombic phase, there is a sizeable electronic in-plane anisotropy, which cannot be explained by the tiny lattice distortion [2], and now it is well established that the electronic contribution is significant for the four-fold rotational symmetry breaking at the structural transition. Borrowing the language from the field of the liquid crystals, electron fluid which spontaneously breaks the rotational symmetry of the underlying lattice is referred to as an electronic nematic phase. The electronic nematic phase covers a wide range of temperature versus the composition phase diagram, and coexists with the superconductivity. This situation raises the important questions about how the electronic nematic behavior, i.e. nematicity, has an impact on the phase diagram, and especially the superconductivity. In this thesis, we discuss the electronic nematicity in the two iron-based superconductors $FeSe_{1-x}Te_x$ and $Ba_{1-x}Rb_xFe_2As_2$ through the single crystal synthesis, charge transport measurements under the high magnetic field, and evaluation of the nematic fluctuations, which provide the answer to the key component of these questions and deepen our understanding of the electronic nematicity itself.

2. Experimental methods

In general, to detect the phase transition which accompanies the symmetry breaking, measuring the susceptibility associated with the ordered phase is a powerful way. Here to probe the susceptibility for the electronic nematic phase (i.e. nematic susceptibility), we utilized the elastoresistivity technique [3], which measures a response of the resistivity with respect to the induced strain. In this technique, the sample is directly glued on the top of the piezoelectric device, and the anisotropic uniaxial strain ($\varepsilon = \varepsilon_{xx} - \varepsilon_{yy}$) is transmitted to the sample via the distortion of the device. The strain was controlled by applying the voltage to the piezo stacks, and monitored by the strain gauge attached underneath the device. While the strain is induced to the crystals, we also track the change in the resistivity along two x and y directions of the one sample (ρ_{xx} and ρ_{yy}) using a van der Pauw method. Since the resistivity anisotropy $\eta = (\rho_{xx} - \rho_{yy})/(\rho_{xx} + \rho_{yy})$ works as an order parameter of the electronic nematic phase, and the uniaxial strain corresponds to the symmetry breaking field for it, here we can define the nematic susceptibility as $d\eta/d\varepsilon$.

Electronic nematic phase of iron-based superconductors with D_{4h} point group has two candidate irreducible representations, B_{1g} and B_{2g}. In the elastoresistivity technique, nematic susceptibility of each symmetry channel can be measured by inducing the strain along the corresponding direction of its nematic phase.

3. Non-magnetic nematic quantum criticality in $FeSe_{1-x}Te_x$

FeSe has the simple crystal structure, and it exhibits a tetragonal-to-orthorhombic structural transition at T_s ~ 89 K. In contrast to other iron-based superconductors, FeSe is unique in respect that it displays no long-range magnetic order down to zero temperature. Furthermore, it is known that T_s of FeSe can be continuously suppressed by Te substitution for Se without inducing the magnetic order, and ultimately driven to zero temperature at x ~ 0.50. Therefore, $FeSe_{1-x}Te_x$ offers a means to directly discuss the interplay between electronic nematicity and superconductivity.

To see how the nematic fluctuations covers the composition versus temperature phase diagram of $FeSe_{1-x}Te_x$, we have systematically measured the elastoresistivity in $FeSe_{1-x}Te_x$ single crystals. In all the samples spanning from $x = 0$ to $x = 0.51$, B_{2g} nematic susceptibilities follow the Curie-Weiss temperature dependence above T_s, demonstrating that this series of compounds show the 2nd-order nematic phase transitions at T_s without magnetism. At $x = 0.38$, nematic susceptibility strongly diverges toward 0 K, which signifies the presence of non-magnetic nematic quantum critical point in $FeSe_{1-x}Te_x$. Remarkably, in $FeSe_{1-x}Te_x$, superconducting transition temperature T_c is enhanced toward the nematic QCP. From the additional elastoresistivity measurements in S-substituted FeSe, we found that this trend is contrasted with the phase diagram of $FeSe_{1-x}S_x$, in which T_c shows a sudden drop across the non-magnetic nematic QCP. Thus, superconducting dome of $FeSe_{1-x}Te_x$ centered on the non-magnetic nematic QCP is a unique character, and indicates that nematic fluctuations enhance the paring of electrons in this system.

Next, to unveil how the nematic critical fluctuations interact with quasiparticles, we used pulsed high magnetic field to measure the low-temperature resistivity masked by superconducting transition at the International MegaGauss Science Laboratory, the Institute for Solid State Physics. We found that although low-temperature resistivity at $x = 0.05$ follows a T^2 dependence, which is a hallmark of the Fermi liquid behavior, for $x = 0.16$, resistivity shows an approximately T-linear dependence down to the lowest temperature. In the samples with $x > 0.16$, the power-law analysis gives exponents of resistivity curves between 1 and 2, showing deviations from the Fermi liquid behaviors in the low temperature region. The observed behavior of electrical resistivity near the nematic QCP of $FeSe_{1-x}Te_x$ is distinct from that of $FeSe_{1-x}S_x$, in which resistivity follows T-linear dependence just above the nematic quantum critical point [4].

4. Unusual electronic nematicity in $Ba_{1-x}Rb_xFe_2As_2$

Electronic nematicity in underdoped and optimally doped iron-based superconductors have B_{2g} symmetries, which align along the tetragonal [110] directions. Recently, the emergence of electronic nematic order with B_{1g} symmetry, whose director is 45 degree tilted from that of B_{2g} symmetry, was suggested in the heavily overdoped iron pnictide superconductors $RbFe_2As_2$ [5]. This novel nematic order might give us the new insights on the mechanism of the electronic nematic phase in iron-based superconductors, and stimulates our interest on how B_{2g} nematic order crosses over to B_{1g}. $Ba_{1-x}Rb_xFe_2As_2$ is an ideal system to see this because one can expect that the symmetry of the nematic order changes from B_{2g} in $BaFe_2As_2$ to B_{1g} in $RbFe_2As_2$ by increasing Rb contents x.

Since there were no reports for the single crystals synthesis of $Ba_{1-x}Rb_xFe_2As_2$ with various Rb concentration x, we first worked on the crystal growth in collaboration with Shigeyuki Ishida, Akira Iyo, and Hiroshi Eisaki in National Institute of Advanced Industrial Science and Technology. Using FeAs-flux methods, we have successfully grown the $Ba_{1-x}Rb_xFe_2As_2$ single crystals with several Rb contents x, which shows a systematic change in the lattice parameter. Furthermore, from the analysis of the resistivity curves, we found that there is a fan shape region in the phase diagram, in which resistivity exhibits an anomalous T-linear temperature dependence.

After characterizing the synthesized $Ba_{1-x}Rb_xFe_2As_2$ single crystals, we have traced the evolution of the two B_{1g} and B_{2g} nematic susceptibility, $\chi_{\mathrm{nem}}^{[100]}$ and $\chi_{\mathrm{nem}}^{[110]}$, with increasing the Rb contents x. For $x = 0.65$, $\chi_{\mathrm{nem}}^{[110]}$ is much larger than $\chi_{\mathrm{nem}}^{[100]}$, implying that B_{2g} nematic instability remains dominant in this composition. However, by further increasing the Rb concentration, $\chi_{\mathrm{nem}}^{[100]}$ displays stronger temperature dependence. For $x = 0.80$ and $x = 0.86$, B_{1g} nematic susceptibilities exhibit kink anomalies at T_{nem}. This means the softening of the B_{1g} nematic fluctuations, indicating that T_{nem} is the onset of B_{1g} nematic order, whose director is 45 degree rotated from the usual B_{2g} nematicity.

In parent compound $BaFe_2As_2$ and heavily overdoped $Ba_{1-x}Rb_xFe_2As_2$, one nematic susceptibility is more significant than the other. This demonstrates that $BaFe_2As_2$ and $RbFe_2As_2$ display B_{1g} and B_{2g} Ising nematic orders, respectively. In contrast, in the intermediate composition $x = 0.75$, two nematic susceptibilities show the almost identical temperature dependence with comparable magnitude and similar Curie-Weiss temperature. This means that there is nematic ordering tendency along both tetragonal [100] and [110] directions. Since B_{1g} and B_{2g} representations are irreducible representations of in-plane electronic nematic orders, we can say that nematic fluctuations in this region has not Ising but XY-like character associated with continuous rotational symmetry breaking. Although negative Curie-Weiss temperature in $x = 0.75$ means that there is no XY-nematic transition at finite temperature, our results open up a new route to the novel quantum phase of matter in iron-based superconductors.

5. Summary

In this study, we discussed the electronic nematicity in iron-based superconductors $FeSe_{1-x}Te_x$ and $Ba_{1-x}Rb_xFe_2As_2$. We found the non-magnetic nematic quantum critical point lying beneath the superconducting dome in $FeSe_{1-x}Te_x$. In contrast to $FeSe_{1-x}S_x$, the divergent nematic fluctuations at its quantum critical point appears to strengthen the Cooper-paring in $FeSe_{1-x}Te_x$. Inside the nematic phase of $FeSe_{1-x}Te_x$, we found the non-Fermi liquid behavior in the low-temperature resistivity, which is seemingly different from the T-linear resistivity above the nematic quantum critical point of $FeSe_{1-x}S_x$. In $Ba_{1-x}Rb_xFe_2As_2$, we observed the channel change in the nematic instability by hole doping, and provide evidence for B_{1g} nematic orders in the heavily overdoped region. Between B_{1g} and B_{2g} Ising nematic phases, there is emergent XY-like nematic fluctuations. Our results presented in this thesis will give new insights on the role of electronic nematicity in iron-based superconductors.

References

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