Nematic and metanematic transitions in iron-based superconductors

Strongly interacting electrons can exhibit novel collective phases, among which the electronic nematic phases are perhaps the most surprising, as they spontaneously break rotational symmetry of the underlying crystal lattice [1]. In the iron-pnictide superconductors, such nematicity has recently been observed in several experiments, and has commonly been associated with the tetragonal-to-orthorhombic structural phase transition at T_s, below which a sizable difference between a and b lattice parameters is observed with an orthorhombicity on the order of 10^{-3}.

We found in $BaFe_2(As_{1-x}P_x)_2$ systems (Fig. 1(a)) that the electronic nematicity sets in at T^*, which is much higher than T_s [2]. The chemical composition dependence of the nematic transition temperature T^* covers the superconducting dome, as shown in Fig. 1(b). The new phase diagram found in this study resembles the pseudogap phase diagram in high-T_c cuprate superconductors, and may hold an important clue to the mechanism of superconductivity in this class of materials.

Magnetic torque measurements in small pure crystals under in-plane magnetic field rotation, which have recently been developed as powerful probes for rotational symmetry breaking [3], have shown that the two-fold oscillation associated with the electronic nematicity starts to develop below the x-dependent temperature T^* [2]. The analysis of the phase of the two-fold oscillation reveals that the in-plane susceptibility shows elongated anisotropy along the Fe-Fe direction, which matches the orthorhombicity direction in the lower-temperature antiferromagnetic phase below $T_N \sim T_s$ (Fig. 1(c)).

To search for a tiny orthorhombic lattice

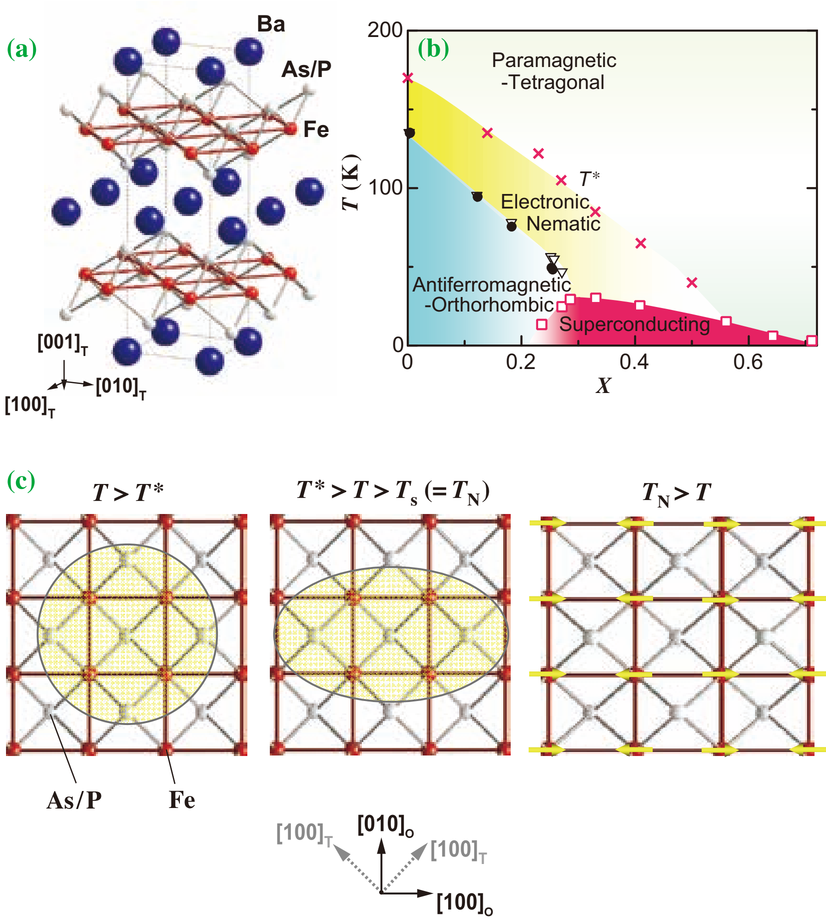

Fig. 1. **(a)** Crystal structure of $BaFe_2(As_{1-x}P_x)_2$. **(b)** Temperature-composition phase diagram. Nematicity appears below T^* (red crosses), which is above T_s (open triangles) and the antiferromagnetic transition temperature T_N (closed circles). T^* line extends to a high composition range covering the superconducting T_c dome (open squares). **(c)** Schematic paramagnetic electronic anisotropy (yellow circles) in the iron planes and the spin configuration below T_N (yellow arrows).

distortion associated with the electronic nematicity, we have performed single-crystal structural analysis at beamline **BL02B1** with a photon energy of 17.7 keV as a function of temperature at several different compositions x. We focus our attention to high-angle Bragg peaks $(hh0)_T$ with h = 7 or 8, which are very sensitive to a small distortion along the Fe-Fe direction. Typical diffraction data as a function of temperature is shown in Fig. 2 for x = 0 and 0.27. At high temperatures above T^*, the Bragg peak is relatively sharp. Below T_s, the peak is completely split into two peaks, indicating the orthorhombic symmetry of the crystal. In the intermediate temperature range between T^* and T_s, the Bragg peak is broader and has some tail structure, and it can be fitted to overlapping two peaks (Figs. 2(c) and 2(d)). This evidences a small but finite orthorhombic lattice distortion below the nematic temperature T^*. We stress that the high-resolution synchrotron X-ray measurements focusing on the high-angle Bragg peaks were the key for detecting such a small distortion in the electronic nematic state.

The orthorhombicity found in the temperature range below T^* immediately indicates that the rotational symmetry in the system is already broken above T_s, at which the tetragonal-orthorhombic crystal structure transition was originally assigned. This raises a question why we have a big jump in the peak splitting at T_s. Our study implies that the true second-order phase transition occurs at the nematic temperature T^*, which accompanies the spontaneous breaking of the fourfold tetragonal symmetry, whereas the apparent transition at T_s is not a true phase transition but rather what we refer to as a 'meta-nematic' transition in analogy to the theory of magnetism. A simple Landau free-energy analysis containing the electronic and lattice contributions leads to two different transition temperatures at which the electronic nematic and orthorhombic lattice order parameters set in, but when a coupling term between the electronic and lattice systems is introduced, both order parameters become finite below T^* and show a jump at T_s [2]. The fact that T^* is higher than T_s suggests that the nematic transition has an electronic origin.

The electronic nematic phases have been discussed for several strongly correlated electron systems, such as the pseudogap phase in high-T_c cuprate superconductors [4], the hidden order phase of the heavy-fermion compound URu_2Si_2 [3], and the field-induced phase of Sr_2RuO_7 [5]. The high-resolution synchrotron X-ray used in the present study will be a useful tool for studying these intriguing phases.

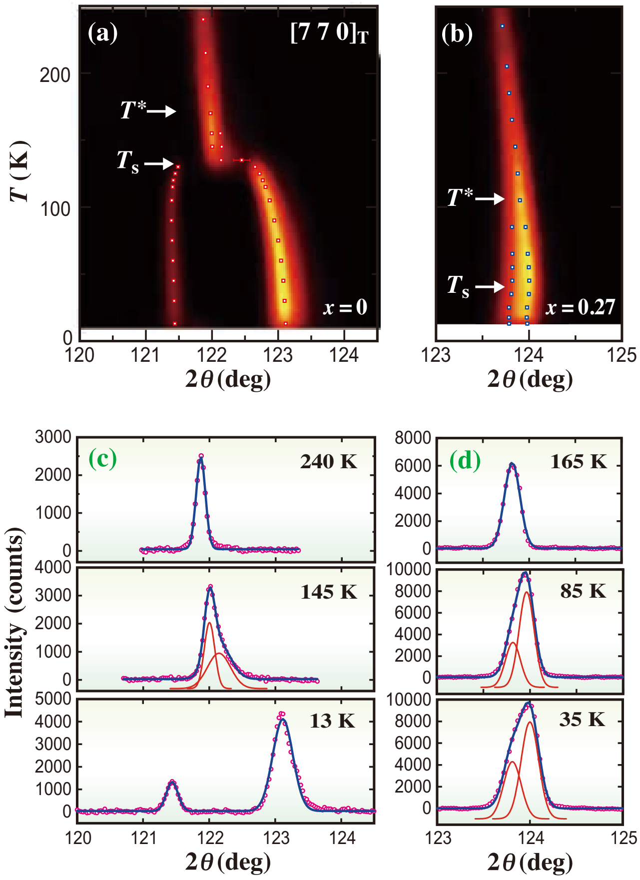

Fig. 2. **(a)** Temperature dependence of the Bragg peak $[770]_T$ for $x = 0$. **(b)** Same plot as that for $x = 0.27$. **(c)(d)** Examples of peak fitting at several temperatures.

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