Quantum Criticality and Superconductivity in SmFe_{1-x}Co_xAsO

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Abstract. One of the iron pnictide superconductors, SmFe_{1-x}Co_xAsO shows a domelike $T_C$ curve against Co concentration $x$. The parent compound SmFeAsO shows the crystal structure transition and antiferromagnetic spin density wave (SDW) ordering. With increasing $x$, the structural transition temperature $T_D$ and SDW ordering temperature $T_N$ decrease and reach 0 K at the critical concentration $x_C$. It is not so clear that the critical concentrations for $T_D$ and for $T_N$ coincide to each other or not. In our present report, we investigated the structural transition by the low temperature x-ray diffraction and the SDW ordering, and the superconducting transition by measuring the magnetization using the SQUID magnetometer, MPMS. We determined the phase diagram of $T_D$, $T_N$ and the superconductive transition temperature $T_C$ against the Co concentration $x$ near the $x_C$ precisely. We found that the maximum of $T_C$ in domelike shape locates near the $x_C$, suggesting the QCP.

1. Introduction
The mechanism of high-temperature superconductivity in cuprates has been discussed for many years. Considering the non-Fermi-liquid behavior in the normal state and a domelike superconducting transition temperature $T_C$ curve plotted against hole-doping concentration, the importance of the spin fluctuations around the SDW quantum critical point (QCP) has been pointed out [1]. In the FeAs-based parent compounds, there is a structural phase transition in the temperature range of 100-200 K and the SDW ordering [2]. Various chemical-doping approaches can suppress the structural phase transition and SDW ordering, and superconductivity consequently appears at $T_C$. Domelike $T_C(x)$
curves are widely observed in these iron-based pnictides, i.e., Co-doped SmFe$_{1-x}$Co$_x$AsO system [3]. With increasing Co concentration, the structural phase transition temperature $T_D$ and SDW ordering temperature $T_N$ decrease and reach 0 K at the critical concentration $x_C$. The maximum of $T_C$ occurs near $x_C$, suggesting the QCP. In our present paper, we report the investigation of the structural phase transition and SDW ordering in Co-doped SmFe$_{1-x}$Co$_x$AsO system, very precisely near QCP, observed by low-temperature x-ray diffraction (XRD), and by measuring the magnetization, respectively.

2. Experiments and discussions

2.1 Phase diagram

The sample preparation method is the same as described in our previous papers [2]. The sample purity was first verified by powder XRD measurements at room temperature using D/Max-rA diffractometer with Cu K$_\alpha$ radiation and a graphite monochromator. The low-temperature XRD was measured down to about 1.5 K. The low-temperature XRD measuring method was also described in our previous paper [2]. The magnetization was measured by MPMS, Quantum Design Co. For SmFe$_{1-x}$Co$_x$AsO ($x = 0, 0.01, 0.025$), the SDW transition was observed as the peak position in the temperature dependence of the derivative of resistivity. The structure change can be observed clearly as the split of the x-ray diffraction spectrum such as (220) reflection. For $x = 0.05$, such an anomalous change in resistivity almost disappears, and only a tiny kink around 45 K can be distinguished. For the crystal change, the clear split of the x-ray diffraction spectrum cannot be observed but a broadening of the diffraction spectrum, that is, an increase of Full Width at Half Maximum with decreasing temperature is observed near $T_D$. For $x = 0.07, 0.075, 0.08$ and $0.1$, the crystal structure change and the SDW transition can be expected to occur in the superconducting state from the phase diagram shown in Fig.9 of Ref.[3]. Fig.1a and 1b show the temperature dependence of the magnetization. Fig.1a shows the magnetization measured with decreasing temperature in a magnetic field of 10 Oe. Fig.1b shows the magnetization...
measured with increasing temperature in a magnetic field of 10 Oe after zero-field cooling to 1.8 K. In both magnetization, the Meissner effect was observed and the diamagnetism measured during a magnetic-field cooling is smaller than that measured after zero-field cooling, as expected. As shown in Fig. 1a, an abrupt decrease in the Meissner diamagnetism was observed between 3 and 4 K, whereas a sharp jump of magnetization at 5 K was observed in Fig. 1b. These results can be explained as follows. When a superconducting compound is cooled in a magnetic field, the magnetic field can penetrate into the crystal to some extent. Then the small magnetization change due to the SDW transition at 3-4 K can be observed. However, after zero-field cooling, the applied small magnetic field of 10 Oe cannot penetrate into the crystal. Thus the SDW transition cannot be detected with increasing temperature. At about 5 K, the crystal structure transition should occur. Then the crystal structure transition should be accompanied by the penetration of the magnetic field along the domain boundaries. Therefore, a large change in the magnetization can be observed at the structure phase transition. To make sure the structure change at 5 K, the low temperature XRD was performed, but the split of the XRD spectrum was not observed. For SmFe$_{0.925}$Co$_{0.075}$AsO compound, however, Rietveld analysis, which was performed at 7 K and 4 K, suggested the occurrence of the crystal distortion at 4 K. In the Rietveld analysis, we first assumed a tetragonal structure at all temperatures. Once we obtained the fitting parameter, using the same profile function, we attempted to fit the spectrum by assuming an orthorhombic structure at 7 K and 4 K. The resultant lattice constants are obtained as follows in unit of angstrom. At 7K: $a = 3.93891$, $b = 3.93894$, $c = 8.3848$. At 4 K: $a = 3.93815$, $b = 3.93986$, $c = 8.44378$. It is found that at 4 K the crystal distortion occurred. In the SmFe$_{1-x}$Co$_x$AsO system, the phase diagram shown in Fig. 2 was obtained by using the results of magnetization measurements for $x = 0.07$, 0.075, 0.08 and also by using the results of XRD and the resistivity measurements shown in Ref. [3] for $x = 0$, 0.01, 0.025 and 0.05. In Fig. 2, the temperature axis is in logarithmic scale. For $x = 0.08$ and 0.1, the structure change cannot be observed down to 1.8 K. From the phase diagram shown in Fig. 2, there is a possibility that the QCP of structure phase transition locates at the different concentration from the QCP of SDW transition.

2.2 Quantum critical fluctuations

![Figure 2: Electric Phase diagram for SmFe$_{1-x}$Co$_x$AsO](image)
Both phase transitions, that is, the structural and magnetic phase transitions will have the QCPs. Then we can expect the quantum critical fluctuation for both phase transitions near the QCP. The magnetic fluctuation has been discussed in relation to the origin of the high $T_C$ superconductivity. But here we will discuss the quantum critical fluctuation of the structural phase transition. The integrated intensity (I.I.) of the x-ray diffraction spectrum can be represented by the Debye-Waller factor. At high temperatures, the I.I. is rather small due to the thermal fluctuation. At low temperatures, the I.I. recovers to the intensity $I_0$ of the rigid lattice to some extent. But when the softening of the lattice or the quantum critical fluctuation occurs, the I.I. starts to decrease with decreasing temperature. In Fig. 3, the I.I. of $x = 0.075$ compound in SmFe$_{1-x}$Co$_x$AsO is plotted against temperature. The inset shows the I.I. for $x = 0.025$ compound. The I.I. is normalized to the maximum value above $T_D$. In low Co concentration compounds, such as $x = 0, 0.01$, they are not shown here, and $0.025$, shown in the inset, the I.I. show rather similar behavior. It decreases down to about 0.975 and then it starts to increase again. On the other hand, the I.I. for $x = 0.075$ decreases down to 0.915. The Co concentration of 0.075 is so close to the critical concentration, we can expect the quantum critical fluctuation which will give the decrease of the I.I. at very low temperatures. Fig. 3 also supports the crystal distortion at around 5 K. It will be very interesting to measure the I.I. for real critical concentration of crystal phase transition, that can be $x = 0.12$~$0.15$. We are going to do these experiments.

References

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