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Anomalous Zn- and Ni-substitution effects on superconductivity in the superconducting weak ferromagnets $RuSr_2RCu_2O_8$ (R = Gd, Eu)

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ABSTRACT

The effect of magnetic Ni and non-magnetic Zn impurities on superconducting transition temperature T_c in $RuSr_2R(Cu_{1-x}(Ni,Zn)_x)_2O_8$ with R = Gd or Eu (Ni- and Zn-substituted Ru1212Gd(Eu)) was extensively studied. It is found that the suppression rate dT_c/dx of $RuSr_2R(Cu_{1-x}(Ni,Zn)_x)_2O_8$ is comparable to that of underdoped $YBa_2(Cu_{1-x}(Ni,Zn)_x)_3O_{7-\delta}$. The suppression of superconductivity in Ni-substituted Ru1212Eu samples is more significant than that in Zn-substituted ones, indicative of Ni being a more effective pair-breaker than Zn. In strong contrast, the magnetic Ni impurity atoms have a weaker effect on superconductivity than non-magnetic Zn atoms in Ru1212Gd, similar to what was observed in the high-T_c cuprates. These intriguing findings strongly suggest that the impurity-induced local disturbance of the 3*d*-spin correlation at Cu sites around Ni/Zn is distinctly different between Ru1212Gd and Ru1212Eu.

1. Introduction

Coexistence of superconductivity and weak ferromagnetism (WFM) has been reported in ruthenocuprates $RuSr_2ReCu_2O_8$ (Ru-1212) with Re = Gd, Eu, Y, and Sm [1,2]. The structure of Ru-1212 is similar to that of YBa_2CuO_3 with replacement of the Cu–O chains by the RuO_2 planes. The RuO_6 octahedra share apical oxygens (O_{apical}) with two layers of CuO_5 square pyramids. It is generally believed that superconductivity originates from the CuO_2 planes and magnetism is associated with Ru moments in the RuO_2 planes. The Ru-1212 provides an unprecedented opportunity to study how the superconducting CuO_2 bilayer coupling propagates through the magnetic RuO_2 layers. Neutron experiments have shown that the magnetic transition involving the Ru sites causes a structural response in the CuO_2 planes, suggesting a substantial hybridization between the Ru-t_{2g} and the Cu-3$d_{x^2-y^2}$ orbitals [3]. The RuO_2 planes act as a charge reservoir which dopes holes into the CuO_2 planes via charge transfer arising from overlap of the Ru-t_{2g} and the Cu-3$d_{x^2-y^2}$ orbitals through O_{apical}. Extended X-ray absorption fine structure reveals that the temperature dependence of the Debye–Waller factor of the Cu–O_{apical} exhibits a peak feature, different from what was expected for thermal disorder, near magnetic ordering temperature of 135 K, indicative of a magnetoelastic coupling [4]. In spite of numerous investigations, the effect of in-plane impurity substitution on superconductivity in Ru-1212 to date is still lacking. In this work, we will show that Ni(Zn) is a more effective pair-breaker than Zn(Ni) for $RuSr_2EuCu_2O_8$ and $RuSr_2GdCu_2O_8$, respectively. This finding strongly suggests that the impurity-induced local disturbance of the 3*d*-spin correlation at Cu sites around Ni/Zn is distinctly different between Ru1212Gd and Ru1212Eu.

2. Experimental

The polycrystalline samples of $RuSr_2R(Cu_{1-x}M_x)_2O_8$ (R = Gd, Eu and M = Zn, Ni) were prepared by the solid-state reaction method. Detailed synthesis processes can be found elsewhere [5]. X-ray powder diffraction investigations indicate that the samples studied are single-phase compounds with tetragonal *P4/mbm* structure. The resistivity measurements were performed in a quantum design physical properties measurement system (PPMS).

3. Results and discussion

The temperature dependence of the resistivity for $RuSr_2Gd(Cu_{1-x}M_x)_2O_8$ and $RuSr_2Eu(Cu_{1-x}M_x)_2O_8$ with M = Zn or Ni is displayed in Fig. 1a–d. It is found that T_c decreases and normal-state resistivity increases with increasing impurity content. An upturn in $\rho(T)$ is observed at low temperatures for lower-T_c samples. This behavior is likely due to a combination of single impurity scattering and localization effects [6]. More interestingly, the superconducting transition width, δT_c, is insensitive to impurity content, indicating that the broad δT_c ($\sim$15 K) for Ru1212Gd and Ru1212Eu

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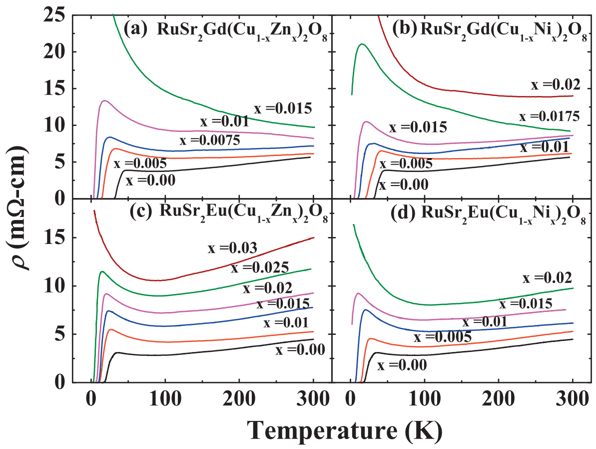

Fig. 1. ρ versus T for (a and b) $RuSr_2Gd(Cu_{1-x}M_x)_2O_8$ and (c and d) $RuSr_2Eu(Cu_{1-x}M_x)_2O_8$ with M = Zn or Ni.

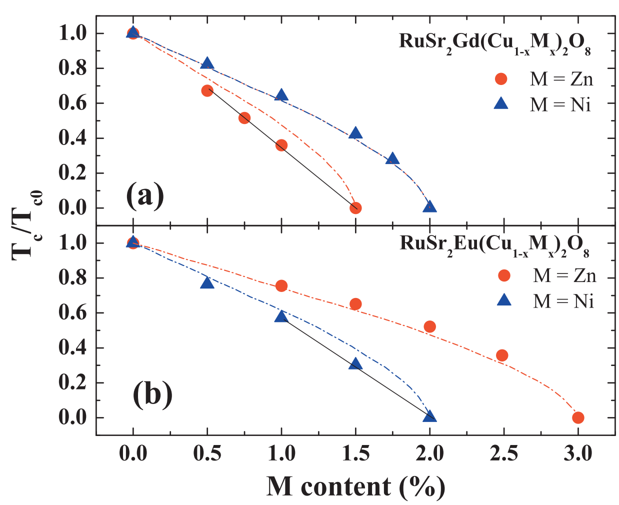

Fig. 2. T_c/T_{c0} versus impurity content for (a) $RuSr_2Gd(Cu_{1-x}M_x)_2O_8$ and (b) $RuSr_2Eu(Cu_{1-x}M_x)_2O_8$ with M = Zn or Ni. The dashed curves are obtained by fitting data to A–G formula.

is intrinsically governed by a spontaneous vortex state associated with a net magnetic moment of $\sim$0.1 μ_B per Ru [7].

To have a better understanding on the impurity-induced T_c suppression in samples studied, the normalized superconducting transition temperature T_c/T_{c0} as a function of impurity content for Ru1212Gd and Ru1212Eu is plotted in Fig. 2a and b, respectively. T_c is determined from the point on the $\rho(T)$ curve where resistivity starts decreasing dramatically. It appears that the suppression rate dT_c/dx of $RuSr_2R(Cu_{1-x}(Ni,Zn)_x)_2O_8$ is comparable to that of underdoped $YBa_2(Cu_{1-x}(Ni,Zn)_x)_3O_{7-\delta}$. This provides a supportive evidence for $RuSr_2RCu_2O_8$ (R = Gd, Eu) being underdoped superconductors determined from transport measurements [8]. Furthermore, a linear variation of T_c with impurity content observed in the higher doping regime for $RuSr_2Gd(Cu_{1-x}Zn_x)_2O_8$ and $RuSr_2Eu(Cu_{1-x}Ni_x)_2O_8$ slightly deviates from the theoretical prediction from AG pair-breaking theory [9] as displayed by dashed curves in Fig. 2. It has been argued that T_c could be dominated by phase fluctuations of the order parameter for low superfluid density (underdoped) superconductors [10]. A reasonable explanation of the striking feature would then be a crossover from the pair-breaking to the phase fluctuation regime in the presence of higher disorder as impurity content increases.

In strong contrast to what was observed in Ru1212Gd and other high-T_c cuprates, T_c suppression in Ni-substituted Ru1212Eu is more significant than that in Zn-substituted Ru1212Eu, indicative of Ni being a more effective pair-breaker than Zn. A possible scenario is that the electronic structure of quasi-two-dimensional CuO_2 layer for Ni- and Zn-substituted Ru1212Eu, in addition to the depairing effect by the potential scattering, is also modulated in a subtle way through the magnetoelastic coupling. More investigations are needed to clarify the intriguing impurity-induced T_c suppression in $RuSr_2RCu_2O_8$ (R = Gd, Eu).

Acknowledgements

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