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著者	Chatani K.
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Superconductivity and itinerant antiferromagnetism in Cr-Ru alloys

K. Chatani
Department of Physics, Tohoku University

We report experimental results from systematic studies on the interplay between the antiferromagnetic SDW and the superconductivity in $Cr_{1-x}Ru_x$ alloys. Unlike previous reports the two phases never coexist and the phase transition as the function of x appears to be of the first order. This clean evidence leads to a conclusion that the antiferromagnetic SDW is stabilized by the excitonic phase formation competing with the Bose condensation of the superconductivity in $Cr_{1-x}Ru_x$ alloys.

Introduction

Since the discovery of high temperature superconductivity in Cu oxides, the phase transition from the antiferromagnetic to superconducting state upon doping carriers or the coexistence of two phases near the phase boundary has evoked further exploration of an inherent relation between the antiferromagnetism and the superconductivity. In this respect, we paid attention to another metallic system of Cr alloys, where the superconducting state cuts into the antiferromagnetic long range ordered (LRO) phase suggesting the coexistence of two phases, according to the recent publications [1, 2]. The microscopic mechanism of the antiferromagnetic Spin Density Wave (SDW) in the metallic Cr is well understood, and therefore detailed studies on the phase transition can bring a deep insight into the subject of the interplay between antiferromagnetism and superconductivity.

Sample Preperation

Ru and Re have high melting temperature more than 2000°C. Moreover the vapor pressure of Cr is extremely high near below melting point, hence the great care is necessary for the sample preparation obtaining a uniform alloy with a control of the chemical composition. We applied an established experimental technique of high temperature heat treatment by using a sealed W crucible [3], which prevents the evaporation of Cr element at elevated temperatures as high as 1500°C. The transition temperature becomes very sharp by high temperature annealing at 1500°C for typically 150 hrs. in the sealed W crucible, as shown in Fig. 1. The data of thermal evolution of the magnetic susceptibility show a quite remarkable change that a broad hump around 100~200K reported in the earlier paper [2] is completely washed out and that it changes to rather temperature independent magnetic susceptibility.

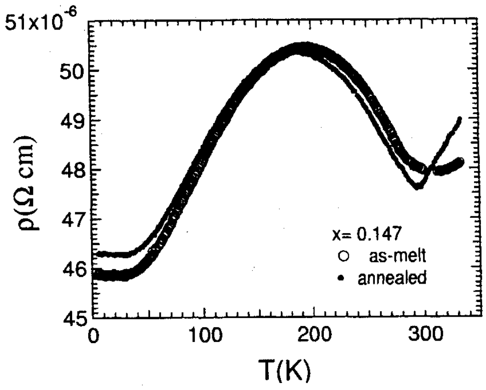

FIG. 1: Annealing effect on the resistivity near at T_N.

Experimental Results

The experimental data of thermal evolution of electronic resistance is summarized in Fig. 2. A sharp minimum at T_N follows the anomalous increase of the resistivity at low temperature upon raising temperatures, in which T_N was directly determined in terms of magnetic neuron diffraction. Furthermore, the resistance drops to zero in the samples not showing the antiferromagnetic LRO ($x > 0.17$). The result of magnetic neutron diffraction shows that a simple antiferromagnetic LRO structure is realized of the antiparallel arrangement between nearest neighbor spins in *bcc* crystals. No trace of the magnetic elastic scattering component was visible in a $x = 0.181$ single crystal above 1 K. The superconductivity was also clearly confirmed by the specific heat measurement. Thermal evolution

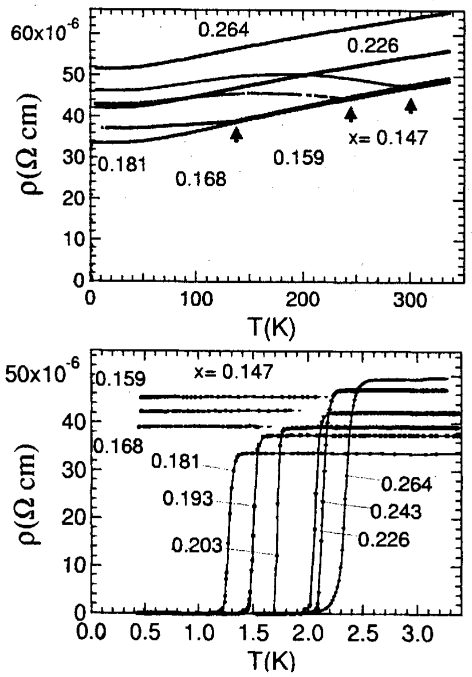

FIG. 2: Thermal evolution of resistivity together with the expanded version at low temperatures where the superconductivity appears.

of the specific heat with an enhanced anomaly defined as the λ transition at T_c, follows the single exponential behavior below T_c. Together with the fact that the upper critical field were analyzed so that the superconducting phase diagram under the external magnetic field is well summarized to a unified function with respect to the scaled variables, we can readily conclude that the superconductivity of $Cr_{1-x}Ru_x$ ($x > 0.17$) is driven by the BCS mechanism, and superconducting properties are quite independent of the chemical concentration even x approaches x_c.

Conclusion

The analytical results shows that the SDW becomes unstable when the magnetic part of Fermi surface disappears, and the antiferromagnetic SDW and the superconductivity are exclusive in Cr-Ru alloy system. The fact is reasonably comprehended by the conceivable notion that the antiferromagnetic SDW state in Cr and its alloys is the excitonic phase where electrons are coupled with holes with opposite spins. Therefore, both states cannot coexist without a certain synergestic mechanism that the superconductivity may not destruct the antiferromagnetism. We also determined that the symmetry of the superconductivity in Cr-Ru alloys is the s-wave. We could not rule out a possiblity that the critical spin fluctuations may appear near the phase boundary. The search for the quantum critical behavior at around $x = x_c$ remains to future investigations.

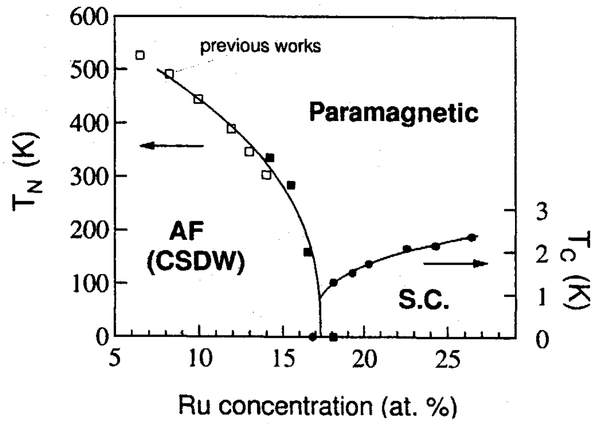

FIG. 3: Transition temperature vs alloy concentration, x for $Cr_{1-x}Ru_x$ alloys. Solid lines are fitted results of $T_C \sim 1.15(x - 16.8)^{0.32}$ and $T_N \sim 202(-x + 17.1)^{0.40}$. Note the large difference of temperature scale between T_N and T_C.

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