First order transition from antiferromagnetic SDW to superconductivity in Cr-Ru

Yasuo Endoh [a,1], Ken'ichi Chatani [b],

[a] *Institute for Materials Research, Tohoku University, Katahira, Sendai, 980-8577 Japan, CREST*

[b] *Department of Physics, Tohoku University, Aramaki Aoba, Sendai, 980-8578 Japan, CREST*

Abstract

Systematic studies on the interplay between the antiferromagnetic SDW and the superconductivity in $Cr_{1-x}Ru_x$ alloys are reported. The phae transition of the two phases as the function of x appears to be of the first order. 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.

Key words: phase transition;antiferromagnetic SDW;superconductivity;Cr-Ru

The discovery of high temperature superconductivity (HTSC) in Cu oxides [1] stimulated us the subject of phase transition of the antiferromagnetic and superconducting states upon doping carriers [2]. The details of coexistence or critical behaviors in any system, particularly the strongly correlated electron system (SCES) reflect the microscopic mechanism of superconductivity. In this respect, we focussed on metallic Cr system, where the superconducting phase seems to coexist with the antiferromagnetic long range ordered (LRO) phase according to the recent publications [3][4].

The microscopic mechanism of the antiferromagnetic SDW in metallic Cr is now well understood by the electron and hole interaction with opposite spins, or the nesting of the Fermi surface below the ordering temperature, T_N [5]. Then substitution of Ru or Re to Cr gives rise to an increase of electron density at Fermi energy, and accordingly an increase of the nesting Q space, so that T_N as well as the nesting wave vector rapidly increases [9]. Further substitution suppresses the antiferromagnetic SDW probably due to the breakdown of this mechanism. The superconducting phase appears in both Cr-Ru[4] and Cr-Re[3][7], when T_N quickly drops upon increasing either Ru or Re concentration in these Cr alloys.

Ru and Re have high melting temperature more than 2000°C and the vapor pressure of Cr is extremely high near below melting point, and hence the sample preparation obtaining a uniform alloy is extremely difficult. We applied an established experimental technique of high temperature heat treatment by using a sealed W crucible [8], which prevents the evaporation of Cr element at elevated temperatures as high as 1500°C.

Bulk properties of the conductivity in the $Cr_{1-x}Ru_x$ alloy system show a clear phase transition from the antiferromagnetic SDW to the superconducting phase as the increase of x. The effect of the antiferromagnetic SDW LRO on conductivity is quite obvious that a sharp minimum at T_N follows the anomalous increase of the resistivity at low temperatures upon raising temperature, 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 ($x > 0.17$). In brief, the magnetic contribution to the resistivity below T_N was found to be well represented by a universal scaled function which follows $1 - (T/T_N)^2$, when the order parameters extrapolated to 0 K are normalized to be unity. The experimental fact that the anomalous increase of

[1] E-mail:y-endoh@imr.edu

resistivity below T_N is attributed to the antiferromagnetic SDW formation was confirmed by the detailed measurement from the single crystal of $x = 0.142$.

The magnetic neutron diffraction shows that a simple antiferromagnetic LRO structure is realized of the antiparallel arrangement between nearest neighbor spins in *bcc* crystals. The incommensurate spin structure realized in pure *bcc* Cr was not observed at all. No trace of the magnetic elastic scattering component was visible in a $x = 0.181$ single crystal above 1 K. The antiferromagnetic order parameter was confirmed to follow $\sqrt{1-(T/T_N)^2}$. Therefore, as far as the antiferromangnetism of the $Cr_{1-x}Ru_x$ alloys is concerned, the simple antiferromagnetic SDW structure extends to $x < 0.17$. It should be emphasized here that the anomalous increase of resistivity in the antiferromagnetic SDW LRO state for all samples of $x < 0.17$ is quantitatively related to the antiferromagnetic order parameter. Therefore, the fact of the magnetic conductivity observed here indicates that the antiferromagnetic SDW is formed by the excitonic phase by the nesting of the electron and hole bands even though T_N drops substantially near x_c.

Resistivity of the samples for $x > 0.17$ shows a discontinuous drop at T_c. The superconductivity was also clearly confirmed by the specific heat measurement. Thermal evolution of the specific heat with an enhanced anomaly defined as the λ transition at T_c, follows the single exponential behavior below T_c. Thermal evolution of the specific heat near and well below T_c could be analyzed by applying the standard BCS theory of the s-wave superconductivity. For instance, the specific heat jump at T_c gives a close value to the BCS result, $1.43C_{en}$ (electronic specific heat). Another important result is that the low temperature specific heat above T_c is well approximated by the sum of a linear electronic term plus a cubic vibrational term, from which we could extract the effective electron mass and the Debye temperature parameters. These values are approximately 6 mJ/mol·K^2 and 400 K respectively, which are compared with 1.4 mJ/mol·K^2 and 600 K for pure Cr, respectively.

The electronic phase diagram of the $Cr_{1-x}Ru_x$ alloy is now well established near the phase boundary between the antiferromagnetic SDW and the superconducting states around $x = 0.17$. The analytical results by this simple expression shows that the SDW becomes unstable when the band truncation disappears. We could obtain the power law of T_N as the function of x with ∼0.4 of the index value, under a simple assumption that the band parameters are proportional to T_N. On the other hand, the critical value of of x for the superconductivity was determined to be, $x_c \sim 0.17$. Our trial to find a bicritical behavior or any enhancement of the critical behavior by preparing $x = 0.17$ sample was not successful.

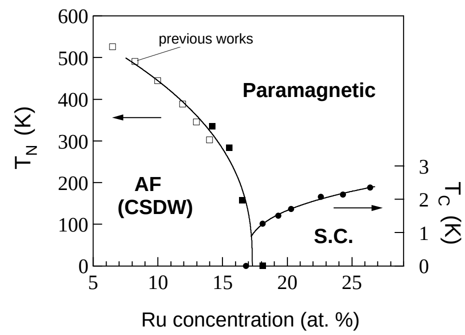

Fig. 1. Transition temperature vs alloy concentration, x for $Cr_{1-x}Ru_x$ alloys. Solid lines are fitted results of $T_C \sim 1.15(x-16.8)^{0.32}$ and $T_N \sim 202(-x+17.1)^{0.40}$. Note the large difference of temperature scale between T_N and T_C.

To conclude, the antiferromagnetic SDW and the superconductivity are exclusive in Cr-Ru alloy system, possibly in other Cr alloys. The fact is reasonably comprehended by the conceivable notion that the antiferromagnetic SDW state in Cr and its alloys is the excitonic phase. 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.

Acknowledgements

The authors are indebted by the stimulated discussions by S. Maekawa and N. Nagaosa. The present work has been partly supported by the Scientific Research Grant sponsored by JSPS.

References

[1] J. G. Bednorz and K. A. Müller, Z. Phys. B **64**, 189 (1986).

[2] M. A. Kastner, R. J. Birgeneau, G. Shirane and Y. Endoh, Rev. Mod. Phys. **70**, 897 (1998).

[3] Y. Nishihara, Y. Yamaguchi, T. Kohara, and M. Tokumoto, Phys. Rev. B **31**, 5775 (1985).

[4] Y. Nishihara, Y. Yamaguchi, M. Tokumoto, K. Takeda, and K. Fukamichi, Phys. Rev. B **34**, 3446 (1986).

[5] P. A. Fedders and P. C. Martin, Phys. Rev. **143**, 245 (1966).

[6] W. M. Lomer, Proc. Phys. Soc. London **80**, 489 (1962).

[7] J. Muheim and J. Müller, Phys. Kondens. Mater **2**, 377 (1964).

[8] T. Suzuki, A. Ochiai, H. Kitazawa, Y. S. Kwon, A. Oyamada, H. Shida, S. Ozeki, O. Nakamura, A. Omino and T. Kasuya, The Science Report of the Tohoku University Vol. 11, No 2/3, 175-227 (1991) .

[9] E. Fawcett, Rev. Mod. Phys. **66**, 25 (1994).