Magnetic Excitations in U(Ru$_{1-x}$Rh$_x$)$_2$Si$_2$ ($x \leq 0.03$)

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Abstract

We have investigated magnetic excitations for a mixed phase of hidden order (HO) and the antiferromagnetic (AF) order in U(Ru$_{1-x}$Rh$_x$)$_2$Si$_2$ ($x \leq 0.03$) by means of inelastic neutron scattering. The inelastic peaks observed at $Q = (1, 0, 0)$ and $(1.04, 0)$ in the HO phase for $x = 0$ and 0.015 at 1.4 K are found to be strongly reduced in the AF dominant compositions of $x = 0.02$ and 0.03. Similar behavior is observed as the HO is replaced by the AF order upon cooling for $x = 0.02$. The $x-T$ region in which the strong reduction of inelastic peaks is observed corresponds to the AF-rich region, indicating that the magnetic excitations typical for the HO-phase vanish in the AF phase.

Key words: URu$_2$Si$_2$, hidden order, inhomogeneous magnetism, magnetic excitations

The nature of the ordered state below $T_a = 17.5$ K in URu$_2$Si$_2$ (the ThCr$_2$Si$_2$ type, body-centered tetragonal structure) [1] has been attracting renewed interest since the finding of the unusual evolution of the type-I antiferromagnetic (AF) phase under pressure $P$ [2,3]. Recent $^{29}$Si-NMR [4] and $\mu$SR [5] experiments under $P$ revealed that the evolution of the inhomogeneous AF phase is due to an effect of volume fraction, and indicates that the majority of the system is occupied by the “hidden order” (HO) at ambient pressure below $T_a$.

Quite recently, the elastic neutron scattering experiments performed on the Rh substitution system U(Ru$_{1-x}$Rh$_x$)$_2$Si$_2$ revealed that the 2% substitution of Rh for Ru can also enhance the AF phase without applying $P$ [6,7]. Except the suppression of both the phases at $x \sim 0.04$, the overall features are quite similar to that obtained from the pressure effect for the pure URu$_2$Si$_2$. Because of no restriction of a pressure cell, the Rh dope system is expected to be suitable for the detailed microscopic investigation on the unusual two-phase competition. In this presentation, we report inelastic neutron scattering experiments on U(Ru$_{1-x}$Rh$_x$)$_2$Si$_2$ ($x \leq 0.03$), for the first time, in order to study the low-energy magnetic excitations in this unusual mixed phase.

Single crystals of U(Ru$_{1-x}$Rh$_x$)$_2$Si$_2$ with $x = 0$, 0.015, 0.02 and 0.03 were grown by the Czochralski method in a tetra-arc furnace, and vacuum-annealed at 1000°C for 5 days. The samples with the volume of $\sim 150$ mm$^3$ were cut out of the ingots by means of the spark erosion, mounted in aluminum cans filled with $^4$He gas so that the scattering plane becomes $(h00)$, and then cooled to 1.4 K in a $^4$He refrigerator. The inelastic neutron scattering measurements were performed on the triple-axis spectrometer GPTAS (4G) located at the JRR-3M reactor of the Japan Atomic Energy Research Institute. We made the constant-$Q$ scans at $Q = (1, 0, 0)$ and $(1.04, 0)$ with the fixed final momentum $k_f = 2.65$ Å$^{-1}$. The combination of 40'-80'-40'-80' collimators and one pyrolytic graphite filter was chosen. The energy resolution determined from the FWHM of the vanadium incoherent scattering was $\sim 0.88$ meV.

Figure 1 shows the magnetic-excitation spectra at 1.4 K obtained from the scans at $Q_a = (1, 0, 0)$ and $Q_b = (1, 0.4, 0)$. The contributions of instrumental background and incoherent scattering were carefully subtracted by scanning at the corresponding $|Q|$-invariant positions $(0.707,0.707,0)$ and $(0.762,0.762,0)$, where we observed neither magnon nor phonon scat-
tering. The inelastic-scattering intensity at each $x$ is normalized by the integrated intensities of the nuclear Bragg scattering at $(110)$. The sharp peak at the energy transfer $h\omega \sim 0$ in the spectra at $Q_a$ arises mainly from the higher-order nuclear Bragg reflections and the AF Bragg reflections. For pure $\text{URu}_2\text{Si}_2$, clear peaks are observed at $\sim 2.4$ meV ($Q_a$) and at $\sim 4.6$ meV ($Q_b$), which are in good agreement with the previous results [3,8]. By substituting 1.5% of Rh for Ru, the position of the inelastic peak at $Q_a$ shifts to $\sim 1.2$ meV. Interestingly, the peak at $Q_a$ suddenly disappears at $x = 0.02$ and 0.03, where the AF phase with nearly full volume fraction replaces the HO phase [6]. Such reduction is also seen in the $x$ variations of the spectra at $Q_b$, but a heavily damped peak is still observed at $x = 0.02$ and 0.03 [7].

The reduction of the inelastic peaks in the AF-rich phase is also observed in the temperature scans for $x = 0.02$ (Fig. 2). We found a broad peak anomaly at $Q_a$, with a peak position around 0.5 meV or lower, i.e. at clearly lower energy than in pure $\text{URu}_2\text{Si}_2$. It appears below $\sim 13.5$ K and grows significantly with decreasing temperature. Below 8 K, however, we found no significant anomaly in the whole energy range of $h\omega \lesssim 8$ meV. In our study using elastic neutron scattering and specific heat, $T_c$ and the onset temperature $T_m$ of the large AF Bragg reflection are estimated to be $\sim 13.7$ K and $\sim 8.3$ K. The magnetic excitation at $Q_a$ seen in the HO phase is thus considered to vanish in the AF phase. In contrast to the strong variations of the spectra at $Q_a$, the magnitude of the heavily damped peak observed at $Q_b$ is insensitive to the temperature. It still exists above $T_c$ with almost the same magnitude, suggesting that this magnetic fluctuation is not directly coupled to the two types of order.

The disappearance of the magnetic excitations in the AF phase indicates that the matrix elements on the

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