The unconventional superconducting (SC) pairing state realized in strongly correlated electron systems, including heavy fermion and high-\(T_c\) cuprates, often develops, to varying extents, in the proximity of a magnetically ordered state. Therefore, it is widely believed that the magnetic fluctuations play important roles for the Cooper pairing. In fact, strong coupling between the magnetic excitation spectra and SC order parameter has been reported in high-\(T_c\) cuprates [1] and a heavy fermion compound [2]. To obtain further insights into the microscopic mechanism of unconventional superconductivity, more detailed information of the electronic structure, especially the position on the Fermi surface which plays an active role for the pairing formation, is strongly required. In the case of high-\(T_c\) cuprates with a simple two-dimensional (2D) Fermi surface, the hot spots, at which the scattering rate is dramatically enhanced, appear at certain parts of the Fermi surface, as a consequence of the strong 2D antiferromagnetic (AFM) fluctuations due to the nesting of the Fermi surface [3]. On the other hand, such information is still lacking in heavy fermion systems to date, mainly because the complicated 3D Fermi surface often makes it difficult to specify the actual active position on the Fermi surface.

A new heavy fermion family of CeMIn\(_5\), where \(M\) can be either Ir, Co or Rh, has attracted much interest on account of the relationship between the superconductivity and magnetism [4,5]. CeCoIn\(_5\) and CeIrIn\(_5\) are superconductors with the SC transition temperatures of \(T_c = 2.3\) K and 0.4 K, respectively. The presence of strong AFM fluctuations associated with the quantum critical point (QCP) nearby has been reported in the normal state of CeCoIn\(_5\) [6,7]. This, together with the \(d\)-wave (presumably \(d_{x^2−y^2}\)) gap symmetry [8], indicates importance of the AFM fluctuations for the superconductivity of CeCoIn\(_5\). On the other hand, in another compound CeRhIn\(_5\), the superconductivity is highly suppressed, and an AFM order appears below \(T_N = 3.8\) K. The propagating vector is determined to be \(q_I = (\frac{1}{2}, \frac{1}{2}, \delta)\) with \(\delta = 0.297\), that is incommensurate with a tetragonal crystal lattice, by neutron diffraction measurements [9]. Furthermore, a new commensurate AFM order with \(q_c = (\frac{1}{2}, \frac{1}{2}, \frac{1}{2})\) has been found in CeRh\(_{1−x}\)Ir\(_x\)In\(_5\) [10], and then the superconductivity coexists with the two distinct magnetic orders in a wide composition range (0.25 \(\leq x \leq 0.6\)). Very recent neutron diffraction measurements further reported a similar coexistence even in CeRh\(_{0.6}\)Co\(_{0.4}\)In\(_5\) [11]. Such an unusual coexistence of three different types of cooperative ordered states is quite unique among the unconventional superconductors. Then, it is important to understand their magnetic properties for elucidating the mechanism of the unconventional superconductivity in the CeMIn\(_5\) systems.

We here report the results of the elastic neutron diffraction measurements on CeRh\(_{1−x}\)Co\(_x\)In\(_5\), ranging from the AFM metallic to the unconventional SC states. We found that, in sharp contrast to CeRh\(_{1−x}\)Ir\(_x\)In\(_5\), the superconductivity is strongly suppressed by the incommensurate AFM order characterized by \(q_I = (\frac{1}{2}, \frac{1}{2}, 0.298)\), while it coexists with the commensurate AFM order with \(q_c = (\frac{1}{2}, \frac{1}{2}, \frac{1}{2})\). These results provide important information of the positions on the Fermi surface which are responsible for the unconventional superconductivity in CeRh\(_{1−x}\)Co\(_2\)In\(_5\). This is the first report to provide such information in the heavy fermion compounds. We will also discuss a difference in the SC states of CeCoIn\(_5\) and CeIrIn\(_5\), based on the different types of the coexistence of the magnetism and superconductivity.
Single crystals of CeRh$_{1-x}$Co$_x$In$_5$ for $x = 0, 0.2, 0.3, 0.4, 0.6, 0.7, 0.75$ and 1 were prepared by the self-flux method \[12\]. Elastic neutron diffraction experiments were carried out on the $x = 0.3, 0.4, 0.6, 0.7$ and 0.75 samples at the triple-axis spectrometer GPTAS (4G) installed at the JRR-3 reactor in Japan Atomic Energy Agency. The samples with the typical size of $\sim 5 \times 5 \times 0.5$ mm$^3$ were set with $(h\ell l)$ scattering plane, and were cooled down to 0.7 K. The neutrons with momentum of $k = 3.814$ Å$^{-1}$ or $2.67$ Å$^{-1}$ were used for the measurements. The $40'-40'-40'$' collimators and two pyrolytic graphite filters, which eliminate the higher-order reflections, were used. To check the sample quality, we have also measured the specific heat and resistivity of the samples with the same compositions as those used for the neutron diffraction measurements (the same bath) and the $x = 0, 0.2$ and 1 samples.

Figures 1(a), (b) and (c) respectively show the neutron diffraction profiles along the $l$ direction ($Q = (1/2, 1/2, l)$) for CeRh$_{1-x}$Co$_x$In$_5$ with $x = 0.3, 0.4$ and 0.6 at $T = 1.5$ K ($T < T_N$) and 5 K ($T > T_N$). Magnetic Bragg peaks are observed at 1.5 K at $q_c = (2, 2, \ell)$ for $x = 0.3, 0.4$ and 0.6, indicating appearance of commensurate AFM orders, while such a peak is not observed for $x \geq 0.7$ (not shown) at least down to 0.7 K. For $x = 0.3$, in addition to the commensurate AFM peak, another magnetic Bragg peak is observed at $q_I = (1/2, 1/2, 0.298)$, which indicates an incommensurate AFM order. Note that a similar incommensurate AFM peak is observed in CeRhIn$_5$.

Temperature dependences of the integrated intensities of the Bragg peaks for $x = 0.3, 0.4$ and 0.6 are depicted in Figs. 1(d), (e) and (f), respectively. The commensurate AFM Bragg peaks (filled circles) develop below 3.0 K, 3.1 K, and 2.8 K for $x = 0.3, 0.4$, and 0.6. The incommensurate AFM Bragg peak with $q_I = (1/2, 1/2, 0.298)$ appears below 3.7 K for $x = 0.3$ (filled triangles). The averaged magnetic moments $M$, for the commensurate AFM order and $M_I$ for the incommensurate one are evaluated to be $M_c = 0.28(2)$ $\mu_B$/Ce and $M_I \sim 0.4$ $\mu_B$/Ce for $x = 0.3$, $M_c = 0.31(4)$ $\mu_B$/Ce for $x = 0.4$ and $M_c = 0.30(2)$ $\mu_B$/Ce for $x = 0.6$. For evaluating the moments, we assumed the spins lying on the basal plane, similar to the helical AFM moments in CeRhIn$_5$ \[10\]. These values are close to those reported in CeRh$_{1-x}$Ir$_x$In$_5$ \[10\]. It should be emphasized here, however, that there is a crucial difference that the incommensurate AFM peak is not observed for $x \geq 0.4$, within the experimental accuracy.

A further support of the absence of the incommensurate AFM order at $x \geq 0.4$ is provided by specific heat measurements which probe the bulk thermodynamic properties. Figure 2 shows the temperature dependence of the magnetic specific heat divided by temperature, $C_{mag}/T$, for $x = 0, 0.2, 0.4, 0.6$ and 1. Here $C_{mag}/T$ is obtained by subtracting nonmagnetic contributions estimated by $C/T$ of LaRhIn$_5$. In $x = 0.4$, two anomalies of the specific heat associated with the commensurate AFM and SC transitions are observed at $T = 2.9$ K and 1.2 K, respectively, and no further anomaly is not observed. These results are consistent with the present neutron diffraction measurements.

The $x$-$T$ phase diagram for CeRh$_{1-x}$Co$_x$In$_5$ determined by the present neutron diffraction, specific heat and resistivity measurements is depicted in Fig. 3(a). The incommensurate AFM order, which is observed in the pure CeRhIn$_5$ system, appears below $x = 0.3$ and
is absent at $x \geq 0.4$. The SC state is not observed down to 0.7 K at $x = 0.2$, while it suddenly appears at $x \sim 0.3$. The commensurate AFM order simultaneously appears here, and stays on the intermediate $x$ region ($0.3 \leq x \leq 0.6$), together with the superconductivity.

We now compare our phase diagram (Fig. 3a)) with that of CeRh$_{1-x}$Co$_x$In$_5$ reported previously. The composition ($x$) dependence of $T_c$ is consistent with the results reported in ref. [12], but the $x$ dependence of the magnetic transition temperature shows a clear difference. Namely, the present results show step-like behavior in contrast to a smooth curve from $x = 0$ to the QCP ($x \sim 0.75$) in ref. [12]. At the present stage, we do not know the origin of this difference. Judging from the disappearance of both the superconductivity and the commensurate AFM order at $x = 0.3$ and the discontinuity of $T_N$, however, we conclude that the phase boundary between the incommensurate and commensurate AFM phases is of first order, and then the coexistence of the commensurate and incommensurate AFM orders observed at $x = 0.3$ is attributed to small inhomogeneity in the composition at the first order phase boundary. A similar coexistence reported in ref. [11] for $x = 0.4$ might be due to the similar inhomogeneity, as was occurred in our $x = 0.3$ sample.

For further comparison, we schematically illustrate the phase diagram of the related material CeRh$_{1-x}$Ir$_x$In$_5$ reported in refs. [10] and [16] in Fig. 3b). The two phase diagrams shown in Fig. 3 bear some resemblance; First, simultaneous appearance of the superconductivity and commensurate AFM order is observed at low $x$ regime. Second, the superconductivity coexists with the commensurate AFM order in the intermediate $x$ regime. However, a significant difference also exists there. Namely, while the incommensurate AFM order coexists with the superconductivity in CeRh$_{1-x}$Ir$_x$In$_5$, there is no intrinsic coexistence of the incommensurate AFM order with the commensurate AFM order and the superconductivity in CeRh$_{1-x}$Co$_x$In$_5$, implying that the superconductivity is strongly suppressed by the incommensurate AFM order in the latter system. A possible origin for this will be discussed later.

It may also be meaningful to compare the present results to some other experimental results on CeRhIn$_5$ under pressure. Recently, specific heat measurements under hydrostatic pressure revealed that the incommensurate AFM order suddenly disappears above a critical pressure $p_c \sim 2$ GPa where a bulk SC phase sets in [14]. On the other hand, very recent NQR experiments have revealed a magnetic transition from incommensurate to commensurate at 1.67 GPa. The superconductivity coexists with the commensurate AFM order, and $T_c$ steeply increases above it [15]. Therefore, the absence of the coexisting phase of the incommensurate AFM order and the superconductivity seems to be a common feature in the CeRh$_{1-x}$Co$_x$In$_5$ system and CeRhIn$_5$ under pressure.

The present result that, in CeRh$_{1-x}$Co$_x$In$_5$, the superconductivity competes with the incommensurate AFM order but coexists with the commensurate one can provide an important insights for the mechanism of the unconventional superconductivity in this system. Namely, the area of the Fermi surface which disappears by the gap formation due to the incommensurate AFM order plays an active role for the superconductivity. However, the area which disappears at the commensurate AFM order may not be important for the superconductivity, because the superconductivity coexists with the commensurate AFM order.

Then it is tempting to discuss which area on the Fermi surface is connected by the $q_{I'\perp}$ and $q_{c}$ wave numbers. According to the de Haas-van Alphen experiments, the 14th band has the heaviest mass [18]. We therefore assume that the 14th band is the main band for the superconductivity. It is necessary to search all nesting positions connected by $q_1$ and $q_c$ in the 3D Fermi surface, but we discuss here the area symmetric about the Γ-point for simplicity. Figures 3a), (b), and (c) illustrate the cross section of the 14th band perpendicular to $k_z$ at $k_z = 0.149, 0.351$ and $\frac{1}{4}$, respectively. The distances between the pairs of these sections inverted with respect to the Γ-point equal to the $z$-components of $q_1$, (0 0 1)−$q_1$, and $q_c$, respectively. The blue dotted lines represent the boundaries of the Brillouin zone when the AFM orders set in. Thus the positions of the Fermi surface which intersect the blue lines are supposed to be strongly influenced by the AFM orders. At a first glance, the area at
The red area connected by $(0 0 1)$ in Fig. 4(d) illustrates the cylindrical part of the 14th band. The blue dotted lines represent the boundary of the AFM order strongly suppresses the superconductivity in CeRh$_{1-x}$Ir$_x$In$_5$ system, in which both the commensurate and incommensurate magnetic orders coexist with superconductivity. Based on these results, it is suggested that particular positions on the Fermi surface nested by $(0 0 1) - \mathbf{q}_I$ may play an active role in forming the SC state in CeCoIn$_5$. The present results further imply that the incommensurate spin fluctuation originating from the nesting characterized by $(0 0 1) - \mathbf{q}_I$ plays an important role for the pairing interaction. To confirm this, the neutron quasi- and in-elastic scattering experiments through the SC transition is strongly desired.

In summary, the neutron diffraction measurements reveal that, in CeRh$_{1-x}$Co$_x$In$_5$, the superconductivity competes with the incommensurate AFM order, while it coexists with the commensurate one. This is in sharp contrast to CeRh$_{1-x}$Ir$_x$In$_5$ system, in which both the commensurate and incommensurate magnetic orders coexist with superconductivity. Based on these results, it is suggested that particular positions on the Fermi surface nested by $(0 0 1) - \mathbf{q}_I$ may play an active role in forming the SC state in CeCoIn$_5$. The present results further imply that the incommensurate spin fluctuation originating from the nesting characterized by $(0 0 1) - \mathbf{q}_I$ plays an important role for the pairing interaction. To confirm this, the neutron quasi- and in-elastic scattering experiments through the SC transition is strongly desired.

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