Absence of magnetic field effect on static magnetic order in electron-doped superconductor Nd_{1.86}Ce_{0.14}CuO_4

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Neutron-scattering experiments were performed to study the magnetic field effect on the electron-doped cuprate superconductor Nd_{1.86}Ce_{0.14}CuO_4, which shows the coexistence of magnetic order and superconductivity. The (4 4 0) magnetic Bragg intensity, which originates from the order of both the Cu and Nd moments at low temperatures, shows no magnetic field dependence when the field is applied perpendicular to the CuO_2 plane up to 10 T above the upper critical field. This result is significantly different from that reported for the hole-doped cuprate superconductors, in which the quasi-static magnetic order is noticeably enhanced under a magnetic field.

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Extensive neutron-scattering studies have been performed on high-$T_c$ superconductors in order to clarify the interplay between the superconductivity and magnetism. In particular, in the hole-doped cuprate superconductor La_{2-x}Sr_xCuO_4 and related systems, static and dynamic properties of spin correlations have been studied in considerable detail. A remarkable feature in the superconducting phase is that static and low-energy spin correlations are incommensurate and the magnetic peaks are found at $(\frac{1}{2} \pm \delta)$ and $(\frac{1}{2} \pm \delta \pm \frac{1}{2})$. In the optimally doped region, there exists an excitation gap and low-energy excitations are suppressed. On the other hand, in the region where hole concentration is $\sim \frac{1}{4}$, elastic incommensurate peaks, originating from both the spin density wave and charge density wave, are observed distinctly, suggesting the stripe model. In this underdoped region, the coexistence of magnetic order and superconductivity is implied.

In the electron-doped cuprate superconductor, however, the number of neutron-scattering studies is rather limited, probably because a large single crystal is difficult to grow. Yamada et al. reported that the superconducting Nd_{1.85}Ce_{0.15}CuO_4 (superconducting transition temperature $T_c \sim 18$ K) shows a broad magnetic excitation peak at the commensurate position $(\frac{1}{4} \frac{1}{4})$. It is also found that an excitation gap exists around 4.5 meV. Thus, both hole- and electron-doped cuprate superconductors show the gap behavior in magnetic excitations although the magnetic correlations are incommensurate and commensurate in hole- and electron-doped cuprate superconductors, respectively. The coexistence of magnetic order and superconductivity is also suggested in the electron-doped systems.

Neutron-scattering under a magnetic field is one of the important techniques that can be used to study the interplay between magnetism and superconductivity. The magnetic field effect has been studied in superconducting La_{2-x}Sr_xCuO_4 ($x=0.10$ and $0.12$) and La_2CuO_4+y. These investigations showed that the static parallel stripe order is enhanced under a magnetic field perpendicular to the CuO_2 planes. The enhancement of the elastic magnetic intensity is ascribed to the vortices which stabilize the static magnetic order in a larger region than the vortex cores. Theoretical studies have also been performed intensively on the static magnetic ordering induced near the vortex cores, which is consistent with the experiments.

In the case of the electron-doped cuprate superconductor Nd_{2-x}Ce_xCuO_4, magnetic field studies have been performed only for undoped Nd_{2}CuO_4 to the best of our knowledge. The main purpose of that study was to determine whether the magnetic structure is collinear or noncollinear. The magnetic field was applied in the CuO_2 plane and the magnetic structure was found to be noncollinear. In the present study, we examined the magnetic field effect of the static magnetic correlations in Nd_{1.86}Ce_{0.14}CuO_4 ($T_c \sim 25$ K). Since the coherence length is $\sim 100$ Å in the electron-doped system, which is several times larger than that in La_{2-x}Sr_xCuO_4, a large magnetic field effect can be expected. Furthermore, the upper critical field $H_{c2}$ is less than 10 T in the electron-doped system so that normal-state properties can easily be studied. It is found that the elastic magnetic peak is magnetic field independent up to 10 T above $H_{c2}$, suggesting that the interplay between magnetic order and superconductivity in this system is considerably different from that in the hole-doped system.

The single crystal of Nd_{1.86}Ce_{0.14}CuO_4 was grown by the traveling solvent floating-zone method. The crystals were annealed in an Ar atmosphere at 920 °C for 12 h. $T_c$ is $\sim 25$ K as determined from a susceptibility measurement, and is shown in Fig. 1. From the data, the superconducting property is considered to be that of bulk in nature. The crystal used in this study is the one that was used in the previous study. The Ce concentration dependence of magnetic and supercon-
conducting properties shows a systematic change in the transition temperatures, indicating that the doped electrons are homogeneously distributed. For \( x = 0.14 \), which was used in this study, similar volume of a magnetic ordered phase and superconducting phase coexist. It is likely that a slightly inhomogeneous distribution of electrons causes two phases that are spatially separated. This phase separation behavior is basically similar to that in \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \).

The neutron-scattering experiments were carried out on the three-axis spectrometer TAS2 installed in the guide hall of JRR-3M at the Japan Atomic Energy Research Institute. The typical horizontal collimator sequence was guide-20'-S-20'-80' with a fixed incident neutron energy of \( E_i = 13.7 \text{ meV} \). Contamination from higher order beams was effectively eliminated using pyrolytic graphite filters. The single crystal was oriented in the \((HK0)\) scattering plane. The neutron-scattering experiments under magnetic fields were performed up to 10 T using a new type of split-pair superconducting magnet cooled by cryocoolers. The field was applied vertically to the scattering plane.

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**FIG. 1.** Temperature dependence of magnetic susceptibility under a zero-field-cooled condition with the magnetic field of 10 Oe for \( \text{Nd}_{1.86}\text{Ce}_{0.14}\text{CuO}_4 \).

In the \((HK0)\) scattering zone, magnetic Bragg peaks are observed at \((\frac{1}{2} + m, \frac{1}{2} + n, 0)\), where \( m \) and \( n \) are integers, except at \((\pm \frac{1}{2} \pm m, \pm \frac{1}{2} \pm m, 0)\) and \((\pm \frac{1}{2} \pm m, \mp \frac{1}{2} \pm m, 0)\). It is also reported that superlattice peaks, which originate from a superstructure caused by the heat treatment and are almost temperature independent, are superposed on these magnetic peak positions. Figure 2 shows the temperature dependence of the \((\frac{1}{2} \pm 0)\) Bragg intensity under zero magnetic field. The intensity at \((\frac{1}{2} + m, \frac{1}{2} + n, 0)\) is described as

\[ I = C \left\{ M_{\text{Cu}}(T)f_{\text{Cu}} + 2M_{\text{Nd}}(T)f_{\text{Nd}} \right\}^2 + I_{\text{lattice}} \quad (1) \]

where \( C \) is a constant, \( I_{\text{lattice}} \) is the superlattice scattering intensity, and \( M(T) \) and \( f \) are ordered staggered moments and form factors for the \( \text{Cu}^{2+} \) and \( \text{Nd}^{3+} \) ions, respectively. Above 100 K, this reflection almost originates from the superstructure. With decreasing temperature, the \( \text{Cu} \) and \( \text{Nd} \) moments order gradually and a contribution from the order of the \( \text{Cu} \) moments becomes comparable to that from the superstructure around 50 K. Below \( \sim 20 \text{ K} \) the order of the \( \text{Nd} \) moments develops rapidly so that most of the scattering intensity originates from the magnetic order and the contribution of the \( \text{Nd} \) moments becomes comparable to that of the \( \text{Cu} \) moments. It was reported that \( M_{\text{Cu}}(10 \text{ K}) \sim 0.1\mu B \) and \( M_{\text{Nd}}(10 \text{ K}) \sim 0.05\mu B \) in \( \text{Nd}_{1.86}\text{Ce}_{0.14}\text{CuO}_4 \) if the moments are assumed to be homogeneously distributed.

Figure 3 shows the magnetic field dependence of the neutron elastic intensity at \((\frac{1}{2}, \frac{3}{2}, 0)\) in \( \text{Nd}_{1.86}\text{Ce}_{0.14}\text{CuO}_4 \). The magnetic field is applied perpendicular to the \( \text{CuO}_2 \) plane. The magnetic peak width is slightly broader than the instrumental resolution but the superlattice peak is almost resolution-limited in the \((HK0)\) plane. At 75 K, where most of the scattering intensity comes from the structural distortion, there is no magnetic field effect up to 10 T, which is reasonable. At 45 K above \( T_c \), where about one third of the intensity comes from the static magnetic order, mostly of the \( \text{Cu} \) moments, the magnetic field effect is still missing. Finally, at 15 K below \( T_c \), where about 80% of the intensity is magnetic in origin and the \( \text{Cu} \) and \( \text{Nd} \) contributions are comparable, there is almost no magnetic field dependence even at 10 T, which is above \( H_{\Delta 2} \). This result is significantly different from that reported for the hole-doped system, in which the quasi-static magnetic order is enhanced under a magnetic field.

\begin{center}
\includegraphics[width=0.5\textwidth]{Fig2.png}
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**FIG. 2.** Temperature dependence of the \((\frac{1}{2}, \frac{3}{2}, 0)\) Bragg peak under zero magnetic field in \( \text{Nd}_{1.86}\text{Ce}_{0.14}\text{CuO}_4 \).

As mentioned at the beginning for hole-doped
La\textsubscript{2−x}Sr\textsubscript{x}CuO\textsubscript{4}, it is theoretically predicted that the static magnetic order is stabilized and enhanced around the vortex cores with an application of magnetic field, indicating that dynamic spin fluctuations in the superconducting phase can be easily pinned by the vortices. If such a strong pinning effect also exists in the electron-doped system, the magnetic field should enhance the static magnetic order. Since almost the same volume of magnetic and superconducting phases coexist in Nd\textsubscript{1.86}Ce\textsubscript{0.14}CuO\textsubscript{4} enhancement of the elastic magnetic intensity is expected to be well observable.

Although the correlation length of the magnetic ordered phase in the CuO\textsubscript{2} plane is similar in the both systems (~100 Å), the deference between the two systems is the correlation length perpendicular to the CuO\textsubscript{2} plane. In nearly optimum-doped region of La\textsubscript{2−x}Sr\textsubscript{x}CuO\textsubscript{4}, magnetic correlations are almost two-dimensional. On the other hand, the correlation length in Nd\textsubscript{1.86}Ce\textsubscript{0.14}CuO\textsubscript{4} is estimated to be about 100 Å which is fairly large. Therefore, the magnetic ordered state is expect to be robust in Nd\textsubscript{1.86}Ce\textsubscript{0.14}CuO\textsubscript{4} against magnetic fields, which is consistent with the experimental results. Even in this case, however, a static magnetic order might appear in the superconducting region when the magnetic field exceeds \(H_{c2}\) and the superconducting region turns to be in the normal-state. Therefore, the absence of the magnetic field effect is surprising.

A puzzling question is how do the magnetically ordered phase and superconducting phase coexist in the electron-doped system. We mentioned that the two phase behavior probably originates from the phase separation of the doped carriers, which is also probable in La\textsubscript{2−x}Sr\textsubscript{x}CuO\textsubscript{4}.

\begin{figure}[h]
\begin{center}
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Neutron elastic intensity around the commensurate position (1/2,3/2,0) in Nd\textsubscript{1.86}Ce\textsubscript{0.14}CuO\textsubscript{4} under magnetic fields \(H=0\) and 10 T and at \(T=15\), 45, and 75 K. Magnetic field is applied perpendicular to the CuO\textsubscript{2} plane. The solid lines are the results of fits to a Gaussian function for the zero field data.}
\end{center}
\end{figure}

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