Magnetic-field dependence of spin correlation in chiral lattice semimetal Ce$_3$Co$_4$Sn$_{13}$

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It is an attractive issue to investigate electronic correlation phenomena associated with topological symmetries. For example, massless Dirac/Weyl fermions have been extensively studied, which are characterized by linear dispersion for electron bands and have been identified for the two-dimensional systems. Recently, Dirac/Weyl electrons are also searched in three-dimensional (3D) bulk systems. It was discussed in a theoretical study that such 3D Weyl fermions intrinsically appear in chiral symmetry lattices [J. L. Mánñs, Phys. Rev. B 85, 155118 (2012)].

In the case of $f$-electron systems based on rare-earth alloy compounds, the $c$–$f$ effect has been a key issue. Kondo semimetals or semiconductors exhibit band gap features as a consequence of such a hybridization effect. We expect that the Weyl fermions are formed in a Kondo semimetal taking a chiral symmetry structure. Considering such electronic state, we have investigated a class of Ce$_3$Tr$_4$Sn$_{13}$ (Tr: transition-metal elements).

Ce$_3$Co$_4$Sn$_{13}$ undergoes a structural phase transition at 160 K [C. S. Lue et al., Phys. Rev. B 85, 205120 (2012)]. We evidenced that the low-temperature crystal structure takes the chiral space group $I2_13$ [Y. Otomo et al., Phys. Rev. B 94, 075109 (2016)]. The electrical resistivity data of Ce$_3$Co$_4$Sn$_{13}$ is less dependent on temperature compared to metallic behaviors of La$_3$Co$_4$Sn$_{13}$ without $4f$ electrons. These facts are expected to indicate the formation of Weyl semimetal state in Ce$_3$Co$_4$Sn$_{13}$. The electronic Sommerfeld coefficients of these compounds was evaluated to be approximately 4 J/(mol-Ce K$^2$) at 1 K [A. L. Cornelius et al., Physica B 378–380, 113 (2006), A. Ślebarski et al., Phys. Rev. B 86, 205113 (2012), E. L. Thomas et al., J. Solid State Chem. 179, 1642 (2006)]. This fact was understood as HF systems. However, our recent inelastic neutron scattering (INS) experiment revealed the emergence of spin excitations in the range up to 1 meV below 20 K [K. Iwasa et al., Phys. Rev. B 95, 195156 (2017)]. On the other hand, Ce$_3$Co$_4$Sn$_{13}$ does not exhibit any magnetic ordering down to 0.5 K, and previous study on Ce$_3$Co$_4$Sn$_{13}$ reported the field-induced antiferromagnetic correlations at 4.2 K [A. D. Christianson et al., Physica B 403, 909 (2008)]. Based on the $I2_13$ structure, the two inequivalent Wyckoff sites for the Ce ions take different CEF schemes [K. Iwasa et al., Phys. Rev. B 95, 195156 (2017)]. Thus, the magnetic-field-induced antiferromagnetic correlation can be understood different magnetic moments at the two Ce-ion sites. In order to obtain microscopic information for the Ce $4f$-electron state, we performed INS measurements under the magnetic fields up to 6 T below 20 K, by using the cold-neutron spectrometer 4F2 installed in the Orphée reactor of Laboratoire Léon Brillouin.

Upper part of Fig. 1 shows INS spectra at the scattering vector $Q = (1, 0, 0)$ for the original high-temperature unit cell of Ce$_3$Co$_4$Sn$_{13}$ measured at 1.6 and 20 K under magnetic fields of zero and 4 T applied along the $[0, -1, 1]$ axis. The data at 1.6 K and 4 T show a slight intensity enhancement near the excitation energy of 0.25 meV. The data measured at $Q = (1.25, 0, 0)$ also show an increase in the inelastic-scattering intensity, although...
the result is not shown here. In addition, we observed a drastic increase in intensity in the elastic scattering region of \( Q = (1, 0, 0) \), as shown by open marks of Fig. 1. Asymmetric spectral shape is considered to be due to alignment of four single-crystal samples. This intensity enhancement occurs below approximately 10 K. In contrast, such elastic-intensity enhancement was not observed at \( Q = (1.25, 0, 0), (1.5, 0, 0), \) and \( (1, 1, 1) \), where the signals of collective spin excitation were observed in previous zero-field INS measurements. Lower part of Fig. 1 shows a temperature dependence of the elastic-scattering intensity at \( Q = (1, 0, 0) \). The intensity at 1.6 K (red circles) shows a convex curve of magnetic fields, and is saturated above approximately 5 T. In contrast, the intensity at 5 K (green squares) follows a function of the squared magnetic field, as shown by a solid line fitted to the data. The data at 20 K (blue diamonds) exhibit no magnetic-field dependence. The data at 5 K indicate that the magnitude of field-induced magnetic moment shows a linear relationship to the magnetic fields, which corresponds to a paramagnetic behavior. However, the convex behavior of the data at 1.6 K is in marked contrast to the paramagnetic-like behavior. This phenomenon is rather close to that of a ferromagnetic spin correlation.

The spin correlation of the 4f electrons in Ce₃Co₄Sn₁₃, which is characterized by the signal near \( Q = (1, 0, 0) \), is enhanced by applied magnetic fields below 10 K. According to the study on electrical resistivity [J. R. Collave et al., J. Appl. Phys. 117, 17E307 (2015)], the resistivity is suppressed by applied magnetic fields. This phenomenon indicates that the magnetic-field induced increase in carrier number causes a stronger RKKY-type interaction. Therefore, we expect magnetic-field tuning of the quantum criticality in the chiral-lattice symmetry of Ce₃Co₄Sn₁₃.

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![Fig. 1. (Upper part) INS spectra at \( Q = (1,0,0) \) measured at several temperatures and magnetic fields. (Lower part) Magnetic-field dependences of elastic-scattering intensity at \( Q = (1, 0, 0) \).](image-url)