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Heavy quasiparticles formed in the ferromagnetic Yb layers in the Kondo helical magnet YbNi$_3$Al$_9$ as revealed by specific-heat measurements

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We report specific-heat and magnetocaloric-effect studies on single-crystalline Kondo helical magnet YbNi$_3$Al$_9$. Molecular field analysis of a Schottky peak due to the Zeeman splitting of the Yb-ion doublet crystalline-ground state demonstrates that the interlayer antiferromagnetic exchange interactions are 2 orders of magnitude smaller than that of the intralayer ferromagnetic coupling among Yb ions, reflecting realization of magnetically well separated Yb layers. The Sommerfeld coefficient $\gamma$, which is 110 mJ/K$^2$ mol in zero field, decreases smoothly with increasing field without any noticeable anomalies at the helical magnetic phase boundary. This fact confirms that heavy quasiparticles are formed on a part of the Fermi surface away from “hot sheets” that have nesting instabilities responsible for the helical magnetic structure. These results indicate that YbNi$_3$Al$_9$ is a novel system where heavy quasiparticles are confined within the two-dimensional Yb layers.

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I. INTRODUCTION

Strongly correlated electron systems associated with $f$ electrons have rich variety of ground states including the heavy-fermion (HF) state, unconventional superconductivity, multipolar ordering, and several types of quantum critical behaviors. Many of them studied so far are three-dimensional (3D) types. Since the electron-electron correlation effect is expected to be significantly enhanced if interacting electrons are confined into lower dimensions, it is important to search for such low-dimensional $f$-electron systems. One approach reported recently is to produce artificial multilayers. In CeIn$_3$/LaIn$_3$ and CeCoIn$_5$/YbCoIn$_5$ multilayers, suppression of a magnetic ordering ending up with a HF state and dimensionality tuning of superconductivity have been realized, respectively. In such systems, however, bulk properties including specific heat and magnetization are extremely difficult to be measured. Therefore, to search for “natural” low-dimensional $f$ electron bulk materials is desired.

Here we report one candidate material YbNi$_3$Al$_9$, in which heavy quasiparticles are most probably confined in two-dimensional (2D) Yb layers. This compound crystallizes in the trigonal ErNi$_3$Al$_0$-type structure with the space group $R3_2$ ($D_3^2$, no. 155) (see Fig. 1). Yb ions form a 2D honeycomb lattice in Yb$_2$Al$_3$ layers which stack along the $c$ axis with a distance of $d_{c}$ = $c$/3 = 9.121 Å. In between, seven triangular lattice layers of Al or Ni with the sequence of Al-Ni-Al stack along the $a$ axis with the propagation vector $q = 0.8 \times c^*$, which has been determined by a neutron-scattering experiment. Below $T_{IM}$, the magnetization ($M$) curve shows a metamagnetic jump up to 1.2 $\mu$$_B$ at $H_{IM}$ $\simeq$ 0.1 T at 2 K for $H \parallel a$, while it increases gradually for $H \parallel c$ ($M = 0.04 \mu_B$ at $\mu_0H = 0.1$ T). Strong correlations in the conduction electrons are inferred from the $\log T$ dependence of resistivity above $\sim$40 K, which is attributable to the Kondo effect in the Yb crystalline-electric-field (CEF)-split levels. Below $T_{IM}$, the electronic specific-heat coefficient $\gamma$ in zero field is 110 mJ/K$^2$ mol, providing thermodynamic evidence for quasiparticle mass enhancement.

In this paper, we report on low-temperature specific-heat and magnetocaloric effect (MCE) measurements of single-crystalline YbNi$_3$Al$_9$ in applied fields. The results indicate that heavy quasiparticles are confined within the 2D Yb layers.

II. EXPERIMENTAL DETAILS

A single crystal of YbNi$_3$Al$_9$ with a dimension of 5 $\times$ 5 $\times$ 3 mm$^3$ grown by the Al self-flux method using raw materials of 3N (99.9% pure)-Yb, 4N-Ni, and 5N-Al has been used for the present study (see Ref. 11 for more details about the sample preparation). Strong de Haas–van Alphen (dHvA) signals obtained from similarly prepared single crystals attest to their high quality. Specific heat $C(H,T)$ has been measured by a quasiadiabatic heat-pulse method using a dilution refrigerator equipped with an 8-T superconducting magnet. The magnetic field is always applied along the $a$ axis, i.e., parallel to the Yb 2D honeycomb lattice plane. With the same setup, MCE measurements have been performed by monitoring the variation of the sample temperature with sweeping the magnetic field between 0 and 0.3 T with a rate of 0.015 T/min. Magnetization measurements have been made using a commercial superconducting quantum interference device (SQUID) magnetometer MPMS (Quantum Design).
III. RESULTS

Figure 2 shows specific heat divided by temperature $C/T$ measured with $H \parallel a$. A clear $\lambda$-type anomaly appearing at $T_{\text{HM}} = 3.41$ K in $\mu_0 H = 0$ T corresponds to the helical magnetic ordering. This value of $T_{\text{HM}}$ is slightly higher than 3 K, which has been reported previously. With increasing $H$, as shown in the inset, the peak initially shifts to lower temperatures for $\mu_0 H < 0.15$ T, reflecting the antiferromagnetic nature of the ordered phase. At $\mu_0 H = 0.075$ T, the peak shows a maximum. Above 0.15 T, the peak becomes broader and shifts to higher temperatures with increasing $H$.

It is clear from the comparison with the $M-H$ curve shown in Fig. 3(a) that the metamagnetic anomaly appears at the boundary of the helical magnetic phase and it corresponds to a sharp peak in $C/T$ for $\mu_0 H < 0.15$ T. At low temperatures, it is difficult to detect the phase boundary by specific-heat measurements, since the boundary runs parallel to the $T$ axis in the $H$-$vs$-$T$ space. Therefore, we have performed MCE measurements to detect the phase boundary.

Representative $T$-$vs$-$H$ curves of the MCE measurements are displayed in Figs. 3(b)–3(d). For $T \sim 2.8$ K ($< T_{\text{HM}}$), irreversible contributions appearing in the $T$-$vs$-$H$ curve is rather small, indicating that the sample is roughly in an adiabatic
condition (isentropic process), i.e., the thermodynamic relation $(dS/dH)_{T} = -(C_{H}/T)(dT/dH)_{3}$ holds approximately. $dT/dH < 0$ in the helical phase and $dT/dH > 0$ in the ferromagnetically polarized phase. In $0.09 < \mu_{0}H < 0.13$ T, where the metamagnetic anomaly appears, $dT/dH$ has larger negative values. With decreasing temperature, the irreversible heating contribution becomes pronounced, especially in the $H$ regions where the metamagnetic anomaly appears. For $T \sim 1.5$ K, the heating contribution masks the intrinsic cooling behavior in the $H$ increasing process, while it cooperatively enhances the intrinsic heating behavior in the $H$ decreasing process. For $T \sim 0.2$ K, the irreversible heating at the metamagnetic transition (probably due to magnetic domain wall motion) becomes more dominant; the heating behavior appears in both sweeping processes and the intrinsic behavior of the isentropic process is no longer visible. From the $H$ shift of the heating region between $H$ increasing and decreasing processes, we infer that the hysteretic behavior of the order of $\sim 0.02$ T appears in the metamagnetic transition at 0.2 K.

From these results, the helical phase boundary in the $H$-$T$ phase diagram has been determined as shown in Fig. 4(a). The critical field $H_{M}$ at $T = 0$ K is estimated to be 0.14 T.

**IV. DISCUSSION**

In the measured temperature range, $C$ of YbNi$_{3}$Al$_{9}$ has contributions from electrons ($C_{el} = \gamma T + C_{f}$), phonons ($C_{ph} = \beta T^{3}$), and nuclear spins ($C_{nuc} = A/T^{2}$). Measured specific heat of LuNi$_{3}$Al$_{9}$ can be well expressed as $C = \gamma_{0} T + \beta_{0} T^{3}$, with $\gamma_{0} = 6.4$ $\text{mJ/K}^{2}\text{mol}$ and $\beta_{0} = 0.35$ $\text{mJ/K}^{4}\text{mol}$ at low temperatures. We tentatively use $\beta_{0}$ for $\beta$ of YbNi$_{3}$Al$_{9}$. $C_{ph}$ has only a minor contribution to the total $C$ in $T < 10$ K, as shown in Fig. 2 by a thin solid line. $C_{nuc}$ appears as an upturn below $0.4$ K for all $H$ data, $C_{f}$, representing contributions from 4$f$ electrons of the Yb ions, can be phenomenologically expressed as $BT^{3} \exp(-\Delta/ T)$ at low $T$ below $\sim 2$ K. The $C(T)$ data in $T \lesssim 2$ K have been fitted by a sum of these terms and the $H$ dependence of $\gamma$ is obtained as displayed in Fig. 5. In zero field, $\gamma = 110$ $\text{mJ/K}^{2}\text{mol} \simeq 17\gamma_{0}$. This fact indicates that the quasiparticle mass is significantly enhanced even in the helical magnetic state. Note that $\gamma$ decreases gradually with increasing $H$ without showing any noticeable anomalies across the phase boundary of the helical magnetic state, indicating that the mass enhancement mechanism is not directly associated with the HM ordering or HM fluctuations.

Using the determined values of $A(H)$, $C_{el}(T,H)$ data have been obtained. The electronic entropy $S_{el}$ calculated using the $C_{el}(T,H)$ data is shown in Fig. 6. $S_{el}$ is 4.2 $\text{J/K}^{2}\text{mol}$ at $T = T_{HF}$ and reaches $R \ln 2$ at $\sim 8.5$ K. This is consistent with the fact that the valence of Yb ions is almost 3+$^{+}$, and the $J = 7/2$ multiplet of the Yb ions splits into four doublets due to the CEF effect (the site symmetry of the $6c$ site is $C_{3}$) and the magnetic behaviors in $T < 10$ K are dominated by the CEF ground-state doublet. The entropy released above $T_{HF}$, i.e., $R \ln 2 - S_{el}(T_{HF})$, is attributable to the Kondo effect ($T_{K} \geq 3$ K) and/or the magnetic short-range ordering (ferromagnetic in the layers and helical between the layers).

In the field-induced ferromagnetic (FM) phase ($H > H_{M}$), the peak in $C/T$ becomes broader and shifts to higher temperatures with increasing $H$, as shown in Fig. 2. This peak results from the Schottky-type thermal excitations between the two Zeeman-split energy levels of the CEF ground-state doublet; excitations to the first excited CEF level can only be seen above 7 K as a slight increase in $C$ in zero field. The peak height $C_{peak}$ shown in Fig. 7 is much higher than 3.65 $\text{J/K}^{2}\text{mol}$, which is expected for a doublet with a fixed energy separation, and depends on $H$ significantly. This

**FIG. 4.** (Color online) $H$-$T$ phase diagram for low fields (a) and high fields (b) determined by specific-heat measurements (▲: Schottky peak in the FM phase, ■: helical phase transition) and MCE (●). Dashed line shows a MF model calculation for the specific-heat peak position $T_{ph}(H)$ (see text).

**FIG. 5.** (Color online) $H$ dependence of $\gamma$. The dashed line is a guide to the eye.

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behavior indicates pronounced ferromagnetic interactions among Yb ions.

In the paramagnetic (PM) or field-induced FM phase, we analyze the $C(T, H)$ data taking into account the ferromagnetic interactions in a mean-field (MF) approximation. In our model, the Hamiltonian can be expressed as

$$\mathcal{H} = -g \mu_B s (H + \lambda g \mu_B \bar{s}) + \frac{1}{2} \lambda (g \mu_B \bar{s})^2,$$

where a Yb magnetic moment is represented by $g \mu_B \bar{s}$ using an in-plane pseudospin $\bar{s}$ ($\bar{s}$: thermal average), effective $g$ factor, and the Bohr magneton $\mu_B$. The MF coefficient $\lambda$ is described as $\lambda = 2 J_{FM}/(g \mu_B)^2$ using the exchange integral $J_{FM}$. When $T$ is decreased, $\bar{s}(T, H)$ shows a significant development at a certain $T$ range depending on the applied $H$. Because the energy separation of the CEF ground-state doublet ($\propto H + \lambda g \mu_B \bar{s}$) develops accordingly, this behavior results in the enhancement in $C_{\text{peak}}$. The parameter set $\lambda$ and $g$ have been determined so that the MF calculations reproduce reasonably well the Schottky peak position $T_p(H)$ in the $H$-$T$ phase diagram and the value of magnetization. The best fit has been obtained with $\lambda = 1.466 T/\mu_B$ and $g = 3.6$, and the MF calculation of $T_p(H)$ is shown in Figs. 4(a) and 4(b).

In the $H$-$T$ phase diagram of Fig. 4, the Schottky peak position is nicely reproduced by the calculated $T_p(H)$ in the PM phase. In the $H \to 0$ limit, the MF-calculated $T_p(H)$ provides a fictitious FM transition temperature $T_{FM} = 3.18$ K in zero field. The $H$ dependence of $C_{\text{peak}}$ shown in Fig. 7 is also qualitatively reproduced. In YbNi$_3$Al$_4$, however, the $g$ value should depend on $H$ to some extent, since the CEF excited levels mix gradually into the ground-state doublet due to the Zeeman effect. Deviations from the model calculation visible in Figs. 4 and 7 may be partly due to the simplification of the constant $g$. Another factor neglected in this model is the Kondo effect. According to the exact solution for the $s$-$d$ impurity model, $C_{\text{peak}}$ is suppressed below 3.65 J/K mol in zero field and it increases gradually with increasing $H$, approaching $3.65$ J/K mol for $g \mu_B H/(k_B T) \gg 1$. The slow decrease in $C_{\text{peak}}$ in high fields shown in Fig. 7 might be due to combination of the Kondo effect and the FM interactions.

The helical magnetic ordering indicates the existence of mutually competing interlayer magnetic couplings. We use a simple model which includes $J_0 (> 0)$, $J_1$ and $J_2$ representing exchange constants between magnetic moments in a FM Yb plane, with the adjacent Yb planes and with the next-nearest Yb planes, respectively. This model has an energy minimum solution with an HM structure with an interlayer magnetic moment turn angle $\phi$ ($\cos \phi = -J_1/J_2$) given by

$$E_{ex} = -\bar{s}^2 (J_0 + J_1 \cos \phi + J_2 \cos 2\phi).$$

The propagation vector $q = 0.8 \times c^*$ determined by the neutron-scattering study$^{13}$ corresponds to $\phi = 96^\circ$. Inserting this value into Eq. (2), the effective exchange integral for the HM phase is given by $J_{HM} = J_0 - 2.43 J_1$. In the field-induced FM phase ($\phi = 0^\circ$), the effective exchange integral is given by $J_{FM} = J_0 + 3.38 J_1$. From $T_{HM}/T_{FM} = 3.41$ K: 3.18 K $\Rightarrow$ $J_{HM}/J_{FM}$, the ratio $J_0/J_1/J_2 = 1: -0.01 : -0.03$ is obtained. Significantly weak interlayer magnetic couplings, reflected in the 2 orders of magnitude smaller values of $J_1$ and $J_2$ than that of $J_0$, is consistent with the fact that Yb layers are largely separated; note that the strength of Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction decays with the distance as $1/r^3$.

Normalized magnetoresistance $\rho(H)/\rho(0 \text{T})$ for $j \parallel c$ and $H \parallel a$ (shown in Fig. 8) drops about 30% at $H_{M}$, which is in marked contrast with the absence of any signature in $\gamma$ at the HM boundary. Based on this fact, we consider a simple two-carrier model, in which the Fermi sheets are separated into two parts FS$_1$ and FS$_2$. FS$_1$ disappears in the HM phase due to the nesting with the propagation vector $q$. In the nonordered phase, it is expected that FS$_1$ plays a considerable role in the electric transport along the $c$ axis, since it should have a rather flat surface perpendicular to the $c$ axis.$^{21}$ FS$_2$ carries heavy quasiparticles contributing dominantly to the $\gamma$ value. In the Drude picture, the contribution from FS$_1$ to the electric conductivity can be expressed as $\sigma_i = n_i e^2 \tau_i/m_i^*$, where $n_i$, $\tau_i$, and $m_i^*$ represent the carrier density, the relaxation time, and
and the effective mass of FS$_2$, respectively. From the 30% drop in $\rho(H)/\rho(0\ T)$ at $H_M$, $(n_2/m_2)/(n_1/m_1 + n_2/m_2) = 0.7$, tentatively assuming $\tau_1 = \tau_2$. Because $\gamma$ does not show any noticeable increase at $H_M$ within the experimental accuracy, $(n_1/m_1 + n_2/m_2)/n_2m_2 \lesssim 1.02$. These two equations yield $m_2/m_1 \gtrsim 4.6$ and $n_2/n_1 \gtrsim 11$, indicating that the heavy quasiparticles are formed mainly on FS$_2$ not on FS$_1$. Note that if $\tau_1 < \tau_2$ is assumed, taking into account that FS$_1$ is a "hot sheet" associated with HM fluctuations, the lower bound value of $m_2/m_1$ becomes even larger. This anisotropic mass enhancement is consistent with recent dHvA measurements, in which the cyclotron effective masses of $m^*_c/m_0 = 3-12$ and $1-5 (m_0$: the free electron mass) have been observed for $H \parallel c$ and $H \perp c$, respectively.\textsuperscript{14} The present model is also consistent with the fact that $\rho(H)$ data for $j \parallel a$ with $H \parallel b$ (not shown) does not show a noticeable jump at $H_M$, since FS$_1$ does not carry current along the $a$ axis.

The realization of the helical magnetic ordering in YbNi$_3$Al$_9$ is caused by the weak but competing interlayer antiferromagnetic couplings ($J_1, J_2 < 0$). Such magnetic frustration may be able to cause quasiparticle mass enhancement, as discussed for LiV$_2$O$_4$\textsuperscript{22} and for geometrically frustrated systems.\textsuperscript{23} However, since the observed heavy quasiparticles do not reside in FS$_1$, which is responsible for the realization of the helical magnetic ordering, such a scenario is unlikely in YbNi$_3$Al$_9$.

The present findings suggest that the heavy quasiparticles are bound in the 2D Yb ferromagnetic layers (on part of FS$_2$). Heavy quasiparticles formed in ferromagnetic states have been reported so far in CeRu$_2$Ge$_2$ ($\gamma = 20 \text{ mJ/K}^2\text{ mol}$, ferromagnetic transition temperature $T_{FM} = 8 \text{ K}$),\textsuperscript{24} CeRuPO ($\gamma = 77 \text{ mJ/K}^2\text{ mol}$, $T_{FM} = 15 \text{ K}$),\textsuperscript{25} CeAgSb$_2$ ($\gamma = 65 \text{ mJ/K}^2\text{ mol}$, $T_{FM} = 9.6 \text{ K}$),\textsuperscript{26} SmOs$_3$Sb$_2$ ($\gamma = 820 \text{ mJ/K}^2\text{ mol}$, $T_{FM} = 3 \text{ K}$),\textsuperscript{27} UIr$_2$Zn$_20$ ($\gamma = 450 \text{ mJ/K}^2\text{ mol}$, $T_{FM} = 2.1 \text{ K}$),\textsuperscript{28} UGe$_2$ ($\gamma = 35 \text{ mJ/K}^2\text{ mol}$, $T_{FM} = 52 \text{ K}$, superconducting transition temperature $T_{SC} \sim 1 \text{ K}$ at 1.3 GPa),\textsuperscript{29,30} URhGe ($\gamma = 164 \text{ mJ/K}^2\text{ mol}$, $T_{FM} = 9.5 \text{ K}$, and $T_{SC} = 0.27 \text{ K}$),\textsuperscript{31,32} and UC$_2$O$_6$Ge ($\gamma = 57 \text{ mJ/K}^2\text{ mol}$, $T_{FM} = 3 \text{ K}$, $T_{SC} = 0.8 \text{ K}$).\textsuperscript{33} As the crystal structures of these compounds suggest, all of their electronic states have 3D characters. Even in such 3D systems, mechanisms of quasiparticle mass enhancement (or magnetic moment screening due to the Kondo effect) in FM states remain to be elucidated, not only experimentally but also theoretically.\textsuperscript{34} To our knowledge, YbNi$_3$Al$_9$ is probably the first realization of the 2D version of such a system. We believe that YbNi$_3$Al$_9$ will provide an unparalleled opportunity to investigate 2D heavy quasiparticles in FM layers.

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\textsuperscript{18}Note that the obtained value of $\gamma$ depends on the functional form of $C_{\gamma}$. The data shown in Fig. 5 have been obtained with setting $\Delta = 0$. If $\Delta$ is included in the fitting parameter set, $\gamma = 140$ and $44 \text{ mJ/K}^2\text{ mol}$ for $H_0 = 0$ and 5 T is obtained, respectively. Nevertheless, the overall behavior of $\gamma$ vs $H$ does not change

FIG. 8. (Color online) $H$ dependence of normalized magnetoresistance $\rho(H)/\rho(0\ T)$. The dashed line is a guide to the eye.
and no noticeable jump still appears at $H_{sd}$. In $\mu_0 H \gtrsim 4$ T, $C_d$ is strongly suppressed and the $\gamma T$ term dominates around 1 K, where $C/T$ appears to be almost $T$ independent, as shown in Fig. 2. Thereby, the $\gamma$ value can be obtained more accurately as reflected in the smaller error bar. In $\mu_0 H = 5$ T, $\gamma_{Yb}/\gamma_{Lu} \sim 17$. This value is reasonable since the ratio of the dHvA cyclotron effective mass $m^*_c(Yb)/m^*_c(Lu) = 3–25$ (depending on the branch) has been observed in this field region.\(^{14}\)


\(^{18}\)This feature is in line with the fact that YbNi$_3$Al$_9$ does not show any noticeable quantum critical behaviors. In contrast, YbAlB$_4$ shows pronounced quantum critical behaviors and they are considered to be associated with the strong valence fluctuation of Yb ions. See S. Nakatsuji, K. Kuga, Y. Machida, T. Tayama, T. Sakakibara, Y. Karaki, H. Ishimoto, S. Yonezawa, Y. Maeno, E. Pearson \textit{et al.}, Nat. Phys. 4, 603 (2008), and Y. Matsumoto, S. Nakatsuji, K. Kuga, Y. Karaki, N. Horie, Y. Shimura, T. Sakakibara, A. H. Nevidomskyy, and P. Coleman, Science 332, 316 (2011).


\(^{21}\)Since 5 Al layers and 2 Ni layers are sandwiched between each Yb$_2$Al$_3$ layer along the $c$ axis and the carriers on FS$_1$ have the Fermi velocity $v_F \parallel c$, the carriers on FS$_1$ should have mainly Al-3$p$ or Ni-3$d$ characters. This feature explains the reason why $m_1$ is not much enhanced, as demonstrated in this model calculation.


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