Critical phenomenon of the layered chiral helimagnetic YbNi₃Al₉

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Abstract

Two-dimensional layered YbNi₃Al₉ exhibits a chiral helimagnetic ground state, which is a candidate for the field-modulated chiral magnetic soliton. In this work, the magnetism and critical phenomenon of YbNi₃Al₉ are investigated. As \( H \perp c \), a magnetic step with loop can be observed in the field-dependent magnetization, which may be corresponding to the possible chiral magnetic soliton phase transition. Based on the analysis of isothermal magnetization around \( T_C \), the critical exponents are obtained as \( \beta = 0.1370(2) \), \( \gamma = 1.7955(4) \), and \( \delta = 14.1043(7) \), which fulfill the Widom scaling relation and Rushbrooke’s law. Moreover, the obtained critical exponents are testified by the modified Arrott plot and scaling hypothesis. The critical exponents of YbNi₃Al₉ are close to the theoretically prediction of 2D-Ising model with the spatial-dimensionality \( n = 2 \) and spin-dimensionality \( d = 1 \), indicating one-dimensional magnetic coupling in the two-dimensional framework. Based on universality scaling, we construct the detailed \( H-T \) phase diagram around the phase transition with \( H \perp c \), which reveals that the field-induced magnetic transition for \( H \perp c \) is of the first-order type.

1. Introduction

Chiral topological magnetizatic configurations, such as chiral magnetic skyrmion, chiral bobber and chiral magnetic soliton, have attracted great attention due to their excellent properties of topological protection, nanometric size, and current-driven motion [1–9]. These topological spiral spin-textures usually emerge in systems with Dzyaloshinskii–Moriya (DM) interaction [10]. In a noncentrosymmetric structure, a DM interaction stems from the spin-orbital coupling due to the lack of inversion symmetry, the exchange energy of which is one or two orders of magnitude weaker than the magnetic exchange [10, 11]. The competition between the DM interaction and the ferromagnetic exchange usually results in a chiral helimagnetic ordering ground state. When external magnetic field is applied properly along certain direction, the chiral helimagnetic ordering phase can be modulated into topological spiral spin-textures, which exhibit characteristics of quasi-particles with nanoscale [1–3]. Moreover, these topological spiral spin-textures can be delicately manipulated and tuned by means of magnetic field [9], microwave [12], electric current [13–15], pressure [16], and dimensional confinement [17]. Owing to the new fundamental physics and potential technological applications, chiral magnetic materials have been studied intensively in solid magnets.

Among these topological spin-textures, a chiral magnetic soliton (CMS) has been predicted theoretically, the configuration of which is magnetic superlattice consisting of magnetic kinks with a ferromagnetic background [10, 11, 18–20]. Experimentally, the CMS has been confirmed by the Lorentz microscopy and small-angle electron diffraction in the monoaxial helimagnetic CrNb₃S₆ [9, 21]. The layered Cr₉-intercalated CrNb₃S₆ exhibits a hexagonal space-group belonging to the space-group \( P_6/m \) [22]. When a magnetic field is applied perpendicularly to the \( c \)-axis, a CMS lattice with the periodicity of \( L_p = 48 \) nm appears below \( T_C \sim 127 \) K [22]. However, other experiments also show the CMS can persist in a crossover region above \( T_C \) [23, 24].
transport and magnetic properties display discrete characteristics resulted from the modulation of CMS [14, 25, 26]. Moreover, the response of the CMS to the microwave also implies possible applications in microwave areas [27–30]. It is manifested that the kinks associated with the CMS are robust against defects and thermal fluctuations due to the topologically geometrical protection [31, 32]. Recently, the CMS lattice is discovered in the Cu-doped Yb(Ni$_{1-x}$Cu$_x$)$_3$Al$_9$ system [33–35]. In addition, the YbNi$_3$Al$_9$ with chiral helimagnetic ground state is also suggested to be a candidate for CMS [35]. The layered YbNi$_3$Al$_9$ is crystallized as trigonal structure belongs to the space-group $R32$ [36]. When a magnetic field is applied perpendicularly to the $c$-axis, a chiral helimagnetic ordering with $L_0 = 3.4$ nm forms below $T_C \sim 3.4$ K, which is much shorter than that in CrNb$_3$S$_6$ [35]. In the Cu-doped Yb(Ni$_{1-x}$Cu$_x$)$_3$Al$_9$ ($x = 0.06$), the CMS lattice is determined as $L_0 = 6.1$ nm with higher $T_C \sim 6.4$ K by the resonant x-ray diffraction [34].

As for YbNi$_3$Al$_9$, the spiral spin-texture and magnetism originate from 4$f$-electrons of Yb ions, which is very different from the 3$d$-electrons of Cr ions in CrNb$_3$S$_6$ [37]. Due to the anisotropic hybridization between $f$-electrons and conductive electrons, YbNi$_3$Al$_9$ exhibits other fascinating phenomena such as antiferromagnetic heavy fermion behavior and Kondo lattice effect, which imply very complex interaction and coupling in this system [38–40]. In this work, the anisotropic magnetic properties and critical phenomenon of YbNi$_3$Al$_9$ have been investigated. Two different kinds of magnetic steps with loops are revealed respectively in the field-dependent magnetization curves when the field is applied perpendicularly and parallel to the $c$-axis. The critical behavior of YbNi$_3$Al$_9$ indicates the the magnetic interaction is of 2D-Ising type. Furthermore, based on universality scaling, the detailed $H$–$T$ phase diagram with $H \perp c$ is constructed, which suggests the first-order characteristic of the field-induced magnetic transition for $H \perp c$.

2. Experimental methods

Single-crystals of YbNi$_3$Al$_9$ were grown by the self-flux technique method using excessive Al as a flux. Powders of Yb (purity 3N), Ni (4N), and Al (5N) with a ratio of Yb : Ni : Al = 1 : 3 : 20 were sealed in a vacuumed quartz tube, and heated to 1173 K. After hold for 12 h, the temperature was cooled to 973 K at a rate of 2 K h$^{-1}$. The excess flux was removed by centrifugation at 973 K. Finally, the sample was soaked in hydrochloric acid to exclude extra flux. The chemical compositions of the single crystal were carefully checked by energy dispersive x-ray (EDX) spectrometry. The crystal structure and orientation were determined by x-ray diffraction (XRD) using high-intensity graphite monochromatized Cu $K\alpha$ radiation. The single crystals were ground into powder to gain the powder XRD pattern, which was refined by the Rietveld method. The magnetization was measured using a Quantum Design vibrating sample magnetometer (SQUID-VSM). To ensure precise field and magnetization, the data was collected after relaxing for 2 min with a no-overshoot mode. In particular, when measuring the initial isothermal magnetization, the sample was cooled to the target temperature under zero field after heated above $T_C$ adequately for 10 min.

3. Results and discussion

For layered YbNi$_3$Al$_9$, ions of Yb form honeycomb arrays within the $ab$-plane, each of which contains a triangular array of Al ions to form a layer of Yb$_2$Al$_3$ [39]. Figure 1(a) illustrates Yb$_2$Al$_3$ layers in YbNi$_3$Al$_9$, which are separated by three stacking layers of a triangular lattice composed of Al and Ni ions. The magnetism of YbNi$_3$Al$_9$ is mainly determined by Yb ions [40]. Figure 1(b) depicts the EDX spectrum for the single-crystal YbNi$_3$Al$_9$, the inset of which presents the morphology of the single crystal with a typical size of $2 \times 2$ mm$^2$. The chemical compositions are determined as Yb : Ni : Al = 1 : 2.94 : 8.93, approaching the desired proportion closely. Figure 1(c) shows the XRD patterns of the powder and single crystals. The powder XRD pattern (top in figure 1(c)) is well refined according to the space group $R32$, which demonstrates single phase of the sample without impurities. Rietveld refinement results provide the lattice constant $a = b = 7.242(1)$ Å and $c = 27.263 (8)$ Å. The diffraction peaks of the single-crystal XRD pattern (bottom in figure 1(c)) are indexed as $(0 0 L)$. The single-crystal XRD result reveals that the plane surface of the single crystal is the $ab$-plane, while the $c$-axis is perpendicular to the $ab$-plane. The bottom inset of figure 1(c) presents the rock curve, which displays a characteristic of single peak. The full-width-at-half-maximum (FWHM) of the rock curve is $\Delta \theta = 0.06^\circ$. The single peak and narrowness of the rock curve attest high quality of the single crystal used.

Figures 2(a) and (b) show angle-dependent magnetization [$M(\varphi)$] at $T = 2$ K for the in-plane and out-of-plane $M(\varphi)$. The in-plane $M(\varphi)$ is measured by the field rotated in the $ab$-plane, while the out-of-plane one is carried out by the field rotated from the $ab$-plane to the $c$-axis. In figure 2(a), the in-plane $M(\varphi)$ curves present circular shapes, suggesting an isotropic magnetization in the $ab$-plane. In figure 2(b), the out-of-plane $M(\varphi)$ curves exhibit dumbbell shapes, manifesting an anisotropic magnetization between the $ab$-plane and the $c$-axis. Here, slight asymmetry can be observed from the out-of-plane $M(\varphi)$ curves, which may be due to the irregular
shape of the single crystal in this experiment. The magnetization exhibits the maximum and minimum as $H \perp c$ and $H//c$ respectively, which are consistent with results of other chiral helimagnetic materials [41, 42]. Figures 2(c) and (d) present the temperature dependence of magnetization [$M(T)$] under selected field for $H \perp c$ and $H//c$ respectively, which exhibit different behaviors. For $H \perp c$ in figure 2(c), a magnetic phase transition can be noted on the $M(T)$ curve as temperature decreases when $H \leqslant 3$ kOe. Above the phase transition temperature, the $M(T)$ curve shows a paramagnetic behavior. However, when $H > 3$ kOe, the $M(T)$ curve does not show any magnetic phase transition in the whole temperature range, which just exhibits a paramagnetic behavior. The inset of figure 2(c) shows the magnified $M(T)$ (left-axis) and derivative curves $-dM/dT$ (right-axis) under $H = 500$ Oe. A bifurcation at $\sim 2.8$ K occurs between the zero-field-cooling (ZFC) and field-cooling (FC) curves. From the peak of $-dM/dT$ curve, the phase transition temperature is determined as $T_C \approx 5$ K. For $H//c$ in figure 2(d), such a magnetic transition also occurs to each $M(T)$ curve. However, unlike that with $H \perp c$, the phase transition for $H//c$ cannot be suppressed by the external field up to 10 kOe. The inset of figure 2(d) depicts the magnified $M(T)$ (left-axis) and $-dM/dT$ (right-axis) curves under $H = 500$ Oe. Compared with the results for $H \perp c$, ZFC and FC curves for $H//c$ are almost coincide with each other. From the peak of $-dM/dT$ curve, $T_C$ is determined as $T_C \approx 4.6$ K for $H//c$. Although magnetic transitions occur to both $M(T)$ curves for $H \perp c$ and $H//c$, their behaviors are actually different.

Figures 3(a) and (b) depict the field-dependent isothermal magnetization [$M(H)$] for $H \perp c$ and $H//c$, respectively. More apparently, $M(H)$ behaviors are absolutely different for $H \perp c$ and $H//c$. For $H \perp c$ in figure 3(a), $M(H)$ curve below $T_C$ increases rapidly in lower field region, and shows a saturation behavior in higher field region. When temperature exceeds $T_C$, $M(H)$ curve exhibits a linear behavior indicative of a paramagnetic behavior. Figure 3(c) shows the magnified $M(H)$ curves in lower field region for $H \perp c$. A magnetic step with loop at $\sim 4$ kOe occurs to each $M(H)$ curve below $T_C$. For $H//c$ in figure 3(b), all $M(H)$ curves show linearly behaviors except magnetic steps for those below $T_C$. Figure 3(d) displays the magnified $M(H)$ curves in lower field region for $H//c$. A magnetic step with loop at $\sim 15$ kOe occurs to each $M(H)$ curve below $T_C$, which is also observed in previous report [38]. The appearance of magnetic steps with loops on $M(H)$ curves usually implies a field-induced phase transition [43]. However, for YbNi$_3$Al$_9$, the magnetic steps for $H \perp c$ and $H//c$ occur at different fields, which suggest that these two kinds of magnetic steps are caused by different magnetic phase transitions.

In order to have a further understanding the magnetic steps with loops, more detailed $M(H)$ curves for $H \perp c$ and $H//c$ are measured for $T < T_C$, as shown in figures 4(a) and (b). The width of the magnetic step ($\Delta H$) is
defined in figures 4(a) and (b), which are extracted and plotted in figures 4(c) and (d) (ΔH₁ for H ⊥ c and ΔH₂ for H//c). For both H ⊥ c and H//c, ΔH₁ and ΔH₂ decrease as temperature increases. For H ⊥ c, ΔH₁ decreases from ~212 Oe at 1.8 K and disappears at ~4 K as temperature increases. For H//c, ΔH₂ decreases from ~718 Oe at 1.8 K and disappears at ~3.4 K as temperature increases. As is known, when H ⊥ c, a possible CMS phase may appear by modulation of external field [33, 35]. The magnetic steps with loops for H ⊥ c might be correlated to the transition from the possible CMS to forced ferromagnetic state [42, 44]. Theoretical calculation has suggested that magnetic loops caused by intrinsic magnetic hysteresis appear in a CMS system due to the surface barrier [44, 45]. Moreover, the transition from CMS phase to FFM state is incommensurate-to-commensurate one of the first-order type [9, 44]. The loop of M(H) caused by the hysteresis indicates that the transition for H ⊥ c in YbNi₃Al₉ is of a first-order type. As for the transition for H//c, the decrease of M(T) curves in low temperature indicates an antiferromagnetic ground state. It is demonstrated that the antiferromagnetic exchange interaction exist in the inter-layers, which is two orders of magnitude smaller than that of the intra-layer ferromagnetic coupling among Yb ions [46]. The hysteresis of M(H) also suggests that the transition for H//c is first-ordered. However, the transition for H//c may be caused by the destruction of antiferromagnetic ordering. Moreover, it is noted that M(H) for H//c keeps increasing in the higher field region, which suggests that the magnetic moments for H//c cannot be totally polarized until 7 T.

As is well known, exotic magnetic phase transitions occur to YbNi₃Al₉ when H ⊥ c. Layered YbNi₃Al₉ exhibits a chiral helimagnetic ordering ground state with propagation vector along the c-axis. When H ⊥ c, the chiral helimagnetic ordering may be modulated into a CMS phase [35]. When the field exceeds Hcoh, it is polarized into a forced ferromagnetic phase. It can be seen that multiple field-induced magnetic phase transitions occur when H ⊥ c. Figure 5(a) shows the field-dependent isothermal initial magnetization (initial M(H)) around Tc with H ⊥ c. As field increases, the initial M(H) curves below Tc exhibit saturation behaviors. Figure 5(b) depicts the magnified initial M(H) curves below Tc in lower field region, where the inset shows that at T = 1.8 K. Two points of inflection are observed in each initial M(H) curve below Tc, which are marked as H₁ and H₂ in the inset of figure 5(b).

The Arrott plot is an effective method to judge phase transitions. For a magnetic system, according to the Landau theory of phase transition, in the vicinity of the phase transition the Gibbs free energy G is describe as

Figure 2. (a) and (b) The angle-dependent magnetization [M(\varphi)] with field rotated in the ab-plane (in-plane M(\varphi)) and from the c-axis to the ab-plane (out-of-plane M(\varphi)); (c) and (d) temperature dependence of magnetization [M(T)] under selected fields for YbNi₃Al₉ with H ⊥ c and H//c (insets show the magnified M(T) (left-axis) and −dM/dT (right-axis) for H = 500 Oe).
where $a$ and $b$ are temperature-independent coefficients. With the equilibrium condition of energy minimization ($\partial G/\partial M = 0$), there is [47]:

$$G(T, M) = G_0 + a \left( \frac{T - T_C}{T_C} \right) M^2 + bM^4 - MH,$$

where $\varepsilon = (T - T_C)/T_C$ is the reduced temperature. The Arrott plot consists of $M^2$ versus $H/M$ around $T_C$, which should be a series of straight lines with the same slope for the Landau mean-field model [48]. The line of $M^2$ versus $H/M$ at $T_C$ should just pass through the origin. Moreover, the order of phase transition can be judged from the slope of the straight line according to Banerjee’s criterion, where the positive and negative slopes are indicative of a second-order and a first-order phase transitions respectively [49]. Figure 5(c) depicts the Arrott plot for YbNi$_3$Al$_9$, which shows that $M^2$ versus $H/M$ relations do not display a series of parallel straight lines. The nonlinear behaviors suggest that the Landau mean-field theory is invalid for YbNi$_3$Al$_9$. Figure 5(d) magnifies the $M^2$ versus $H/M$ below $T_C$ in the low field region, where the inset depicts that at $T = 1.8$ K. It can be seen that the slopes of $M^2$ versus $H/M$ in lower field are negative, which changes to positive in higher field. The change of slope usually implies a field-induced magnetic transition [43]. Combining the magnetic step and loop on $M(H)$ curve, it is indicated that the field-induced magnetic transition is of a first-order type.

The field-induced phase transition can be clarified by the critical phenomenon and universality scaling, which uncover the intrinsic magnetic coupling [43, 50]. Since the correlation between the critical exponents and magnetic entropy change ($\Delta S_M$), the critical exponents can be deduced by $\Delta S_M(T, H)$. As we know, $\Delta S_M(T, H)$ is expressed as [51]:

$$\Delta S_M(T, H) = \Delta S_M(T, H) - \Delta S_M(T, 0) = \int_0^{H_{\text{max}}} \left[ \frac{\partial M(T, H)}{\partial T} \right]_{H} dH.$$
Subsequently, $\Delta S_M(T)$ under different fields can be obtained according to figure 5(a). Figure 6(a) show the temperature dependence of $-\Delta S_M[-\Delta S_M(T)]$, where a peak appears on each $-\Delta S_M(T)$ curve. The peak is corresponding to $T_C$, which determines $T_C = 5.0(3)$ K.

It is well known that the field-dependent parameters of $|D_{STH}|$ fulfill a series of power laws [52, 53]:

\[
\begin{align*}
|\Delta S_M^{\text{max}}(T)| & \propto H^n, \\
\delta_{\text{FWHM}} & \propto H^b, \\
\text{RCP}(S) & \propto H^c 
\end{align*}
\]

where $n, b,$ and $c$ are exponents. The $|\Delta S_M^{\text{max}}|$ and $\delta_{\text{FWHM}}$ are the maximum and FWHM of $|\Delta S_M(T)|$ respectively, and RCP is relative cooling power defined as $\text{RCP} = |\Delta S_M^{\text{max}}| \times \delta_{\text{FWHM}}$. The field-dependent $|\Delta S_M^{\text{max}}|$, $\delta_{\text{FWHM}}$, and RCP are plotted in figures 6(b), (c), and (d), respectively. By fitting to equations (4), it is obtained that $n = 0.5534(5), b = 0.5262(8),$ and $c = 1.0709(1).$ On the other hand, $n, b,$ and $c$ are correlated with the critical exponents ($\beta, \gamma, \delta,$ and $\Delta$) as [54]:

\[
\begin{align*}
 n &= 1 + \frac{\beta - 1}{\beta + \gamma} \\
 b &= \frac{1}{\Delta} \\
 c &= 1 + \frac{1}{\delta}
\end{align*}
\]

(5)

Meanwhile, these critical exponents should obey the Widom scaling relation [55]:

\[
\delta = 1 + \frac{\gamma}{\beta}
\]

(6)

Based on equations (5) and (6), it is obtained that $\beta = 0.1370(2), \gamma = 1.7955(4), \delta = 14.1043(7),$ and $\Delta = 1.9001(3).$ Moreover, these critical exponents can be further examined by the Rushbrooke’s law [56]:

![Figure 4. (a) and (b) Isothermal magnetization as a function of field $M(H)$ around the phase transition for $H \perp c$ and $H//c$, respectively (curves are elevated vertically for clear clarification); (c) and (d) width of $M(H)$-loop ($\Delta H$) as a function of temperature for $H \perp c$ and $H//c$.](image-url)
\[ \begin{align*}
\alpha &= 2 - 2\beta/\gamma \\
\Delta &= \delta/\beta'
\end{align*} \]

where \( \alpha \) is the critical exponent. It is obtained that \( \alpha = -0.0695(8) \) and \( \Delta = 1.9325(8) \), which demonstrate that the obtained critical exponents are self-consistent and reliable.

For a general ferromagnetic system, \( M \) versus \( H/M \) usually fulfills the Arrott–Noakes equation of state in the asymptotic critical region

\[ (H/M)^{1/\gamma} = (T - T_c)/T_c + (M/M_0)^{1/\beta}, \]

where \( M_0 \) is a constant. The relations of \( M^{1/\beta} \) versus \( (H/M)^{1/\gamma} \) constitute the modified Arrott plot (MAP). The MAP for YbNi3Al9 based on the obtained critical exponents are redrawn in figure 7 (a), in which \( M^{1/\beta} \) versus \( (H/M)^{1/\gamma} \) curves present a series of parallel lines in higher field region. The MAP attests the accuracy of the critical exponents [57].

As is known, the universality is a criterion to test the magnetic phase transition. According to the prediction of the scaling hypothesis, physical behaviors at the vicinity of the phase transition should obey the universality scaling. Defining the renormalized magnetization \( m \equiv \varepsilon^{-\beta/\gamma} M(H, \varepsilon) \) and the renormalized field \( h \equiv \varepsilon^{-\beta/\gamma} H \), scaling equations in the asymptotic critical region is expressed as [56]:

\[ m = f_\varepsilon(h) \]

where \( f_\varepsilon \) are regular functions with \( f_\varepsilon \) for \( T > T_c \) and \( f_\varepsilon \) for \( T < T_c \). Figure 7(b) shows the \( m(h) \) curves on log-log scale for YbNi3Al9. Based on the scaling equation, all \( m(h) \) curves at different temperatures should collapse into two independent branches for \( T > T_c \) and \( T < T_c \) respectively, even those in lower field region [58, 59]. As shown in figure 7(b), \( m(h) \) curves for \( T > T_c \) and \( T < T_c \) collapse onto two independent branches in the higher field region, which is in agreement with the scaling equation. For \( T > T_c \), all \( m(h) \) curves collapse into a single branch in both higher and lower field regions. However, for \( T < T_c \), \( m(h) \) curves only collapse into a single branch in higher field region, while those in the lower field region become dispersive regularly. Two points of inflection are observed on each \( m(h) \) for \( T < T_c \) where the one in lower field region is marked as \( H'_1 \) and that in

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**Figure 5.** (a) Initial isothermal magnetization [initial \( M(H) \)] around \( T_c \) for \( H \perp c \); (b) magnified initial \( M(H) \) below \( T_c \) in low field region (inset shows that at \( T = 1.8 \) K); (c) Arrott plot of \( M^2 \) versus \( H/M \); (d) magnified Arrott plot in low field region (inset shows that at \( T = 1.8 \) K).
higher field region as $H_1'$. These points of inflection are indications of field-induced magnetic phase transitions [41–43, 50]. Similar inflections caused by the CMS transition is also observed in CrNb$_3$S$_6$. Thus, the points of inflection in YbNi$_3$Al$_9$ possibly suggest a CMS transition [42].

The obtained critical exponents of YbNi$_3$Al$_9$, including the theoretical values and those of related materials, are listed in Table 1 for comparison [41, 43, 60, 61]. The critical exponents of YbNi$_3$Al$_9$ are mostly close to the theoretical prediction of 2D-Ising model suggesting a low-dimensional magnetic interaction. For the magnetic interaction of the 2D-Ising type, there are spatial-dimensionality $d = 2$ and spin-dimensionality $n = 1$. The
$d = 2$ is consistent with the 2D-layered characteristic of YbNi$_3$Al$_9$. The $n = 1$ indicates the magnetic interaction is established through one-dimensional magnetic coupling, which indicates that the magnetic coupling between the inter-layers is very weak. The critical behavior of YbNi$_3$Al$_9$ is very different from that of CrNb$_3$S$_6$ also hosting a chiral helimagnetic state. For CrNb$_3$S$_6$, it belongs to the 3D-Heisenberg model, the magnetic coupling of which is established not only in the $ab$-plane but also along the $c$-axis \cite{42}. It can be seen that field-induced transitions and multiple phases appear when $H \perp c$ in YbNi$_3$Al$_9$. Based on the critical analysis and universality scaling, the detailed $H$–$T$ phase diagram around $T_C$ with $H \perp c$ is summarized for YbNi$_3$Al$_9$, which is shown in figure 8. The $H_1$ and $H_2$ are determined from initial $M(H)$ curves, and $H'_1$ and $H'_2$ are extracted from $m(h)$ curves. In the $H$–$T$ phase diagram, $T_C$ are determined by $dM/dT$ curves under different field. As is well known, YbNi$_3$Al$_9$ exhibits a chiral helimagnetic magnetic (CHM) ground state with the propagation vector along $c$-axis under zero field. As the field increases, the CHM state is modulated into a possible CMS phase, which can persist up to $\sim 4$ kOe at 1.8 K. With the further increase of field, the possible CMS is polarized into a forced ferromagnetic (FFM) state. The magnetic step with loop appears on the boundary

**Table 1.** Critical exponents of YbNi$_3$Al$_9$, different theoretical models, and related chiral helimagnetic materials (MEC = magnetic entropy change; MAP = modified Arrott plot).

| Composition | Technique | References | $T_C$(K) | $\beta$   | $\gamma$ | $\delta$       |
|-------------|-----------|------------|-----------|-----------|-----------|----------------|
| YbNi$_3$Al$_9$ | MEC       | This work  | 5.0(3)    | 0.1370(2) | 1.7955(4) | 14.1043(7)    |
| CrNb$_3$S$_6$   | MAP       | \cite{42}  | 126.4(7)  | 0.370(4)  | 1.380(2)  | 4.853(6)      |
| MnNb$_3$S$_6$   | MEC       | \cite{41}  | 44.5(5)   | 0.3681(1) | 1.3917(2) | 4.7805(7)     |
| MnSi           | MAP       | \cite{50}  | 30.5      | 0.242(6)  | 0.915(3)  | 4.734(6)      |
| FeGe           | MAP       | \cite{60}  | 278.6     | 0.368     | 1.382     | 4.787         |
| 2D-Ising       | Theory    | \cite{48}  | $\cdots$  | 0.125     | 1.75      | 15.0          |
| 3D-Ising       | Theory    | \cite{48}  | $\cdots$  | 0.325     | 1.241     | 4.82          |
| XY             | Theory    | \cite{48}  | $\cdots$  | 0.346     | 1.316     | 4.81          |
| Heisenberg     | Theory    | \cite{48}  | $\cdots$  | 0.365     | 1.386     | 4.8           |
| Mean-field     | Theory    | \cite{61}  | $\cdots$  | 0.5       | 1.0       | 3.0           |
| Tricritical mean-field | Theory | \cite{61} | $\cdots$ | 0.25      | 1.0       | 5.0           |

**Figure 8.** $H$–$T$ phase diagram in the vicinity of the phase transition with $H \perp c$ for YbNi$_3$Al$_9$ \[CMS corresponds to possible chiral magnetic soliton phase; CHM denotes chiral helimagnetism; FFM is forced ferromagnetic state; and PM represents paramagnetic state; symbols of $T_C$, $H_1$, $H_2$, $H'_1$, and $H'_2$ are obtained from $M(T)$, $IM(H)$, and $m(h)$ curves].
between the possible CMS and FFM phases, which indicates the phase transition from the possible CMS to FFM is of the first-order type.

4. Conclusion

In summary, the magnetism and critical behaviors of the chiral helimagnetic YbNi$_3$Al$_9$ are investigated. A magnetic step with loop is found on $M(H)$ curve for $H \perp c$, which may be corresponding to the possible CMS transition in this system. The critical exponents are obtained as $\beta = 0.1370(2)$, $\gamma = 1.7955(4)$, and $\delta = 14.1043(7)$, which fulfill the Widom scaling relation and Rushbrooke's law. Moreover, based on the obtained critical exponents, the $M-T-H$ curves are testified by the modified Arrott plot and the scaling hypothesis. The critical exponents of YbNi$_3$Al$_9$ are close to the theoretically prediction of 2D-Ising model with $n = 2$ and $d = 1$, indicating one-dimensional magnetic interaction in a two-dimensional framework. Based on universality scaling, the detailed $H-T$ phase diagram with $H \perp c$ is constructed. It is revealed that the field-induced magnetic transition from possible CMS phase to FFM state is of the first order type.

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