YbNiSi$_3$: a new antiferromagnetic Kondo lattice with strong exchange interaction

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(Dated: March 22, 2022)

We report on the structural, thermodynamic and transport properties of high-quality single crystals of YbNiSi$_3$ grown by the flux method. This compound crystallizes in the SmNiGe$_3$ layered structure type of the Cmcm space group. The general physical behavior is that of a Kondo lattice showing an antiferromagnetic ground state below $T_N = 5.1$ K. This is among the highest ordering temperatures for a Yb-based intermetallic, indicating strong exchange interaction between the Yb ions, which are close to +3 valency based on the effective moment of 4.45 $\mu_B$ f.u. The compound has moderately heavy-electron behavior with Sommerfeld coefficient 190 mJ/mol K$^2$. Resistivity is highly anisotropic and for $I \perp b$ exhibits the signature logarithmic increase below a local minimum, followed by a sharp decrease in the coherent/magnetically ordered state, resulting in residual resistivity of 1.5 $\mu\Omega$ cm and $RRR = 40$. Fermi-liquid behavior consistent with a ground-state doublet is clearly observed below 1 K.

Ytterbium compounds continue to be subject of great interest due to the variety of unusual physical properties they can present, in general associated with the fact that this element's $f^{13}$ and $f^{14}$ electronic states are very close in energy, and also hybridize easily with the conduction band. As a consequence, Yb-based compounds can display mixed valency, heavy fermion and Kondo lattice characteristics, which provide opportunities for better understanding the physics of such phenomena. In this sense, Yb is often regarded as the “hole” equivalent of Ce whose $f^0$ and $f^1$ states display the same characteristics, but the latter’s compounds are by far the most explored among these two rare earths, in many cases simply because the Yb-based compounds bear the ‘stigma’ of being considered more difficult to synthesize.

The RTX$_3$ family of intermetallics (R = rare earth; T = transition metal; X = Si, Ge) is one such case. Many of the Ce-based compounds in the family have been synthesized and extensively investigated over the past decade or so, but practically nothing has been reported so far on heavy rare-earth (R = Tb-Lu) members of these series and, in particular, for R = Yb. We thus thought it would be worth initiating such a line of research and here report on our first results for the title compound.

Single crystals of YbNiSi$_3$ were grown from Sn flux using a starting proportion of 1:1:3:20. The high-purity elements (Yb: Ames Laboratory) were loaded and sealed inside an evacuated quartz ampoule, which was then heated to 1150 °C and slowly cooled to 500 °C, at which point the ampoule was removed from the furnace and most of the excess flux was separated by decanting. The crystals have excellent resistance to acid and can be left in a pure HCl bath for as long as necessary to remove any remaining flux droplets from the surface. The resulting crystals are plate-like, with the main surface orthogonal to the crystallographic $b$ direction, as evidenced from the surface x-ray diffraction (XRD) pattern shown in Fig. 1(a) which has only $(0k0)$ reflections. The largest crystal plates were limited mostly by the ampoule wall itself, but the best crystals - those that grew compact, isolated, with smooth surfaces and straight edges - have lengths up to 5 mm and thickness up to 0.3 mm. Many of the crystals display some interesting, rectangular surface topology patterns resulting from the particular flux-growth dynamics of this compound. Electron-probe microanalysis (EPMA) confirmed the stoichiometric 1:1:3 proportion in the crystals and found the Sn inclusions to be less than 0.03%. Our attempts to grow non-magnetic YNiSi$_3$ and LuNiSi$_3$ crystals by the same method were unsuccessful, so the phase diagram seems to be particularly favorable for R = Yb.

Fig. 1(b) shows the XRD pattern of crystals that were crushed into a fine powder. The pattern is consistent with the Cmcm space group of the SmNiGe$_3$ structure type shown in Fig. 1(c), which has close values for the $a$ and $c$ unit cell parameters and a layered structure along the $b$ axis. A Rietveld refinement of this spectrum resulted in $a = 3.8915(1)$ Å, $b = 20.8570(6)$ Å, $c = 3.9004(1)$ Å, and $V = 316.58$ Å$^3$. The crystals’ plate-like morphology described above is therefore consistent with the general observation that the macroscopic dimensions of flux-grown crystals often have an inverse relation to the microscopic lattice parameters. A more detailed structural study will be required though, in order to determine the exact atomic positions in the unit cell of YbNiSi$_3$.

As one might expect from the layered structure of YbNiSi$_3$, the electrical resistivity below room temperature is anisotropic as shown in Fig. 2(a). For Ll$b$ the behavior is metallic, with room temperature resistivity of about 60 $\mu\Omega$ cm which initially decreases on cooling, reaches a local minimum centered at 55 K, then increases again until reaching a peak at 7 K. Below this temperature it begins to decrease very fast. A peak in $d\rho/dT$ places the maximum slope of this drop at 5.0 K, which we will later show to be associated with the Néel temperature $T_N$ of the antiferromagnetically ordered Yb moments, and therefore the strong decrease as a whole can be understood as a combined effect of magnetic ordering at $T_N$ with the onset of coherent scattering of the hybridized Yb moments below $T \sim 7$ K. Figure 2(b) shows the Ll$b$ resistivity plotted against log$T$, where a
FIG. 1: (a) XRD (Cu Ka) pattern of a plate-like crystal surface, revealing only the (0k0) reflections. (b) XRD pattern of YbNiSi$_3$ crystals ground to a fine powder, showing the full set of Bragg reflections. (c) Schematic representation of the atomic positions showing the unit cell (solid line) and layered structure along the b axis.

logarithmic behavior is seen between the local minimum and the peak, a signature of the Kondo effect. The inset of Fig. 2(b) details the resistivity behavior well below the transition, plotted against $T^2$. A Fermi-liquid type $\rho = \rho_0 + AT^2$ behavior is clearly observed below 1 K, with $\rho_0 = 1.48 \mu\Omega \text{ cm}$ and $A = 0.36 \mu\Omega \text{ cm/K}^2$. The residual resistivity ratio (RRR) defined as $\rho(300K)/\rho_0$ is 40. These results attest the clean metallic character and high crystallographic quality of the sample.

The resistivity measurements with $I \parallel b$, shown in Fig. 2(a), were made rather difficult due to the fact that the crystals do not grow large in this direction and we were only able to place 4 contacts on a crystal cut to form a rather irregularly shaped bar along the b axis. Therefore the estimate of the sample cross-section may contain errors of a factor of 2 or even more. Still, it is likely that in this direction the resistivity level is significantly higher than for $I \perp b$ and the temperature dependence resembles that of a semi-metal, initially almost flat and then increasing down to the transition temperature. This change in qualitative behavior may be a manifestation of a strongly anisotropic Fermi surface resultant from the layered structure, since in this direction the conduction band crosses tightly bound Si double-layers as shown in Fig. 1(c).

The inset of Fig. 2(a) shows the measured thermopower $S(T)$. As for most Yb compounds displaying mixed valent behavior, $S(T)$ shows a broad minimum below room temperature. The minimum is located at 72 K and reaches a value of $S = -19 \mu\text{V/K}$. Below this temperature it increases again, reaches a peak very close to $S = 0$ at 12 K and from there $S(T)$ starts decreasing fast again. Since it is expected to vanish at $T = 0$ we can deduce that a second minimum exists. The peak at 12 K places YbNiSi$_3$ in the crossover region between compounds where Yb is essentially +3 and such a peak enters the positive side of $S(T)$, and compounds where Yb displays intermediate valency behavior and this peak is either well into the negative region or simply doesn’t
dependence of the inverse susceptibility at $B$ lines are the polycrystalline averages. Main plot: temperature $T$ tail of the antiferromagnetic transition at 1.7 T for both directions up to 14 T. There is a spin-flop transition at $B = 1.7$ T in the B||b curve. A change in slope near 8 T of both curves marks the crossing of the $T_N(B, T)$ line (a detailed phase diagram will be presented in a future communication), but the magnetization still maintains a positive slope above this transition. If no other meta-magnetic transitions are to be found at even higher fields, then it is clear from the graph that the saturated moment at 2 K should remain below 2 $\mu_B/f.u.$ and therefore significantly smaller than the expected value of 4 $\mu_B/f.u.$ for saturated Yb$^{3+}$ moments.

The upper inset in Fig. 3 details the anisotropic antiferromagnetic transition in the susceptibility $\chi$ at $B = 0.1$ T. A peak in $d(\chi T)/dT$ gives $T_N = 5.0$ K for this field. The behavior of both curves in the magnetically ordered state is indicative of a non-trivial, and possibly canted, arrangement of the magnetic moments. The upturn at low temperatures for B||b appears to be a genuine response of the compound and not a trivial impurity effect, first because it does not appear in the B||b curve, and second because it was reproduced almost exactly in two different batches of samples grown with different elemental purities (3N in the first batch and 4N-5N in the second.)

The lower inset in Fig. 3 shows magnetic isotherms at 2 K for both directions up to 14 T. There is a spin-flop transition at $B = 1.7$ T in the B||b curve. A change in slope near 8 T of both curves marks the crossing of the $T_N(B, T)$ line (a detailed phase diagram will be presented in a future communication), but the magnetization still maintains a positive slope above this transition. If no other meta-magnetic transitions are to be found at even higher fields, then it is clear from the graph that the saturated moment at 2 K should remain below 2 $\mu_B/f.u.$ and therefore significantly smaller than the expected value of 4 $\mu_B/f.u.$ for saturated Yb$^{3+}$ moments.

In order to shed further light on the ground state characteristics of YbNiSi$_3$, the low temperature, zero-field heat capacity was measured on a Quantum Design PPMS system with $^4$He option. The open symbols in the inset of Fig. 4 show the measured $C_p(T)$ data below 20 K. A very sharp lambda-like peak is seen at $T_N = 5.1$ K.

The main graph of Fig. 4 shows the same data presented as $C_p/T$ vs. $T^2$. A linear region is observed between 20 and 10 K, and its extrapolation to $T = 0$ (dotted line) coincides with the levelled value of $\gamma = 190$ mJ/mol K$^2$ that is reached by the lowest temperature data below 1 K. The coincidence of these two independent estimations gives us confidence in claiming that the obtained value is a good representation of the electronic specific heat, therefore placing it as a moderately

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**FIG. 3:** Anisotropic magnetic behavior of YbNiSi$_3$. Solid symbols are for B∥b, open symbols are for B⊥b, and dotted lines are the polycrystalline averages. Main plot: temperature dependence of the inverse susceptibility at $B = 0.1$ T, showing Curie-Weiss behavior at high temperatures. Upper inset: detail of the antiferromagnetic transition at $T_N = 5.1$ K appearing in susceptibility. Lower inset: magnetization isotherms at $T = 2$ K, revealing a spin-flop transition at 1.7 T for B∥b.

**FIG. 4:** Zero-field heat capacity measurement on YbNiSi$_3$ at low temperatures, presented as $C_p/T$ vs. $T^2$. The dotted line is a linear extrapolation from the 10-20 K region. The inset shows the original $C_p$ vs. $T$ data (○), the total entropy $S_{tot}$ (●) and the magnetic entropy $S_{mag}$ (▲).
heavy-electron system. From the slope of the linear region we obtain the lattice coefficient \( \beta = 0.26 \, \text{mJ/mol K}^4 \) and estimate the Debye temperature as \( \Theta_D = 330 \, \text{K} \). We can infer that the first excited CEF levels' energy scale should lie well above 20 K, since no evidence of Schottky anomalies are seen up to this temperature.

In the inset we also present the total entropy \( S_{\text{tot}}(T) \) (solid symbols) obtained by numerical integration of \( C_p/T \) vs. \( T \) and an evaluation of the magnetic entropy \( S_{\text{mag}}(T) \), which was obtained by removing the electronic and lattice contributions estimated above from the specific heat before integration. In either case it becomes clear that the total entropy accumulated up to \( T_N \) is 0.6 Rhn. Thus, we may conclude that a ground state doublet is responsible for the magnetic ordering, and the Yb moments are already significantly screened when the magnetic ordering ensues. With the obtained value of \( \gamma \) we can apply Rajan’s expression \(^{13} \) for the specific heat of the Coqblin-Schrieffer model \( \gamma T_K \approx 11.2 j \) to estimate the Kondo temperature of YbNiSi\(_3\) (\( j = 1/2 \)) as \( T_K = 30 \, \text{K} \).

Finally, we can also use \( \gamma \), in combination with the previously calculated \( A \) coefficient of the Fermi-liquid resistivity model, to estimate \( A/\gamma^2 = 10^{-5} \, \Omega \, \text{cm} \) (mol K/J)\(^2\), which is the well-known Kadowaki-Woods ratio, quite commonly observed in heavy fermion systems featuring a ground-state doublet. \(^{14,15} \)

In many cases where magnetic ordering coexists with mixed valent, Kondo lattice or heavy fermion behavior, quantitative analysis of the material’s low temperature properties becomes rather difficult due to the convolution of several contributions to the thermodynamic and transport properties, a problem which can be further aggravated by difficulties in preparation of samples of high quality. The results we have obtained demonstrate that YbNiSi\(_3\) is a welcome exception to the rule and several physical parameters could be quantitatively determined with good accuracy from our measurements. Furthermore, this compound was found to belong to the very rare group of Yb-based materials with magnetic ordering above 5 K, together with YbPtAl\(^{16}\), YbNiSn\(^{17}\) and YbB\(_2\)^{18} indicating that the intersite indirect magnetic exchange interaction between local moments is strong and dominant, while still displaying very characteristic features of a system with strong on-site Kondo interaction. Therefore, we believe that YbNiSi\(_3\) presents itself as a promising model system for more in-depth investigations on the delicate balance between these two competing energies, as well as other issues related to Yb compounds and Kondo lattices in general. Studies on the high-field properties and magnetic phase diagram, as well as physical and chemical pressure effects in this compound are currently in progress.

Acknowledgments

We are thankful to Y. Shibata for the EPMA analysis, to T. Sasakawa for assistance with the XRD refinements, and to F. Iga for his help in the specific heat measurements. The low-temperature measurements were performed at the Materials Science Center, N-BARD, Hiroshima University. This work was supported by a Grant-in-Aid for Scientific Research (COE Research 13CE2002) of MEXT Japan.

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