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Unusual double-peak specific heat and spin freezing in a spin-2 triangular lattice antiferromagnet $FeAl_2Se_4$

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We report the properties of a triangular lattice iron-chalcogenide antiferromagnet $FeAl_2Se_4$. The spin susceptibility reveals a significant antiferromagnetic interaction with a Curie-Weiss temperature $\Theta_{CW} \simeq -200$K and a spin-2 local moment. Despite a large spin and a large $|\Theta_{CW}|$, the low-temperature behaviors are incompatible with conventional classical magnets. No long-range order is detected down to 0.4K. Similar to the well-known spin-1 magnet $NiGa_2S_4$, the specific heat of $FeAl_2Se_4$ exhibits an unusual double-peak structure and a T^2 power law at low temperatures, which are attributed to the underlying quadrupolar spin correlations and the Halperin-Saslow modes, respectively. The spin freezing occurs at ~ 14K, below which the relaxation dynamics is probed by the ac susceptibility. Our results are consistent with the early theory for the spin-1 system with Heisenberg and biquadratic spin interactions. We argue that the early proposal of the quadrupolar correlation and gauge glass dynamics may be well extended to $FeAl_2Se_4$. Our results provide useful insights about the magnetic properties of frustrated quantum magnets with high spins.

I. INTRODUCTION

Magnetic frustration arises in systems with competing spin interactions that cannot be optimized simutaneously[1] In general, sufficiently strong frustration could lead to degenerate or nearly degenerate classical spin states and thus induce exotic and unconventional quantum states of matter such as quantum spin liquids when the quantum mechanical nature of the spins is considered. The conventional wisdom and belief tells us that it is more likely to find these quantum states in magnetic systems with spin-1/2 degrees of freedom on frustrated lattices where quantum fluctuations are deemed to be strong. This explains the major efforts and interests in the spin-1/2 triangular lattice magnets like Cs_2CuCl_4[2,3], κ-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$[4–6], $EtMe_3Sb[Pd(mit)_2]_2$[7] and $YbMgGaO_4$[8–15] the spin-1/2 kagomé lattice magnets like herbertsmithite $ZnCu_3(OH)_6Cl_2$, volborthite[16] $Cu_3V_2O_7(OH)_2 \cdot 2H_2O$ and kapellasite[17] $Cu_3Zn(OH)_6Cl_2$, various spin-1/2 rare-earth pyrochlore magnets[18], and other geometrically frustrated lattices with spin-1/2 moments or effective spin-1/2 moments[19]. Despite the tremendous efforts in the spin-1/2 magnets, the magnets with higher spin moments can occassionally be interesting. The exceptional examples of this kind are the well-known Haldane phase[20,21] for the spin-1 chain and its high dimensional extension such as topological paramagnets[22,23]. The former has been discovered in various Ni-based 1D magnets[24–26]. Another well-known example is the spin-1 triangular lattice antiferromagnet[27–29] $NiGa_2S_4$, where the biquadratic spin interaction[30–32], completely absent for spin-1/2 magnets, brings the spin quadrupolar order/correlation (or spin nematic) physics and phenomena into the system. Therefore, what matters is not just the size of the spin moment, but rather the interactions among the local moments and the underlying lattices. $FeGa_2S_4$, a spin-2 triangular lattice antiferromagnet that is isostructural with $NiGa_2S_4$, also shows the spin quadrupolar order/correlation (or spin nematic) physics and phenomena[28].

Inspired by the potentially rich physics in high-spin systems, in this paper, we study a spin-2 triangular lattice antiferromagnet $FeAl_2Se_4$ with both polycrystalline and single crystalline samples. Analogous to the Ni^{2+} local moments in $NiGa_2S_4$[27–29], the Fe^{2+} local moments in this material form a perfect triangular lattice and provide a perfect setting to explore the quantum physics of high spin moments on frustrated lattice. We find that the Fe local moments remain disordered down to 0.4K

despite a rather large antiferromagnetic Curie-Weiss temperature $\Theta_{CW} \simeq -200$K. The magnetic susceptibility of single crystal samples show a bifurcation at about 14K for field cooling and zero-field cooling measurements, suggesting a glassy like spin freezing. This is further assured from the ac susceptibility measurements at different probing frequencies. The specific heat of $FeAl_2Se_4$ shows an unusual double-peak structure at two well-separated temperatures, indicating two distinct physical processes are occurring. Below the spin freezing temperature, a T^2 power law specific heat is observed. Based on the early theoretical works[30–33] on $NiGa_2S_4$, we propose that the double-peak structure in heat capacity arises from the growth of correlation of two distinct types of spin moments, and the T^2 power law is the consequence of the Goldstone-type spin waves (*i.e.* the Halperin-Saslow modes). We further suggest that the spin freezing is due to the disorder that may induce the gauge glass physics into the would-be ordered state of this system.

The remaining parts of the paper are organized as follows. In Sec. II, we provide the data and the measurements of the crystal structure for $FeAl_2Se_4$. In Sec. III, we explain the thermodynamic measurements on this material. In Sec. IV, we focus on the specific heat and point out the double-peak structure in the specific heat and the low temperature power law behavior. In Sec. V, based on the dc susuceptibility, we further demonstrate the spin freezing from the ac susceptibility measurement. In Sec. VI, we discuss the broad impact and relevance of the physics in $FeAl_2Se_4$ to other systems and point out the future experiments.

II. CRYSTAL STRUCTURE

Our polycrystalline and single crystal $FeAl_2Se_4$ samples were prepared from the high temperature reactions of high purity elements Fe, Al and Se. In Fig. 1(a), we show the room temperature X-ray diffraction pattern on the powder samples that are obtained by grinding the single crystal samples. All the reflections could be indexed with the lattice parameters $a = b = 3.8335(1)$Å, $c = 12.7369(5)$Å. The systematic absences are consistent with space group $P\bar{3}m1$ (No. 164) isostructural to the previously reported compound $NiGa_2S_4$[27]. The structural parameters are listed in Table. I in the Appendix B. In Fig. 1(b), we show the X-ray diffraction pattern of the single crystal samples. It clearly indicates that the cleaved surface of the flaky crystal is the (001) plane and normal to the crystallographic c axis. The composition was examined by inductively coupled plasma atomic emission spectrometer, giving the atomic ratios of Fe: Al: Se close to $1:2:4$. The compound is built by stacking of layers consisting of edge-sharing $FeSe_6$ octahedra that are connected by a top and a bottom sheet of $AlSe_4$ tetrahedra. The layers are separated with each other by a van der Waals gap. The central $FeSe_6$ octahedra layer is isostructural to the CoO_2 layer of the well-known superconducting material[34] $Na_xCoO_2 \cdot yH_2O$.

FIG. 1. (Color online.) (a) Powder X-ray diffraction and Ritveld refinement profile of $FeAl_2Se_4$ room temperature. The inset shows the schematic crystal structure of $FeAl_2Se_4$ and the distorted $FeSe_6$ octahedra. (b) The X-ray diffraction pattern of $FeAl_2Se_4$ crystal indicates that the (00l) reflections dominate the pattern. Inset shows the photography of $FeAl_2Se_4$ crystal with a length scale of 2 mm and an exhibition of the Fe sublattice.

In the crystal field environment of $FeAl_2Se_4$, the Fe^{2+} ion has an electronic configuration $t_{2g}^4 e_g^2$ that gives rise to a high spin state and a spin $S = 2$ local moment. The six Fe-Se bonds are of equal length and are 2.609(3)Å. Se-Fe-Se angles are $94.55(8)^\circ$, marked as α, and $85.45(8)^\circ$, marked as β, as displayed in the inset of Fig. 1(b). The different Se-Fe-Se angles represent a slight rhombohedral distortion of the $FeSe_6$ octahedra, resulting in a small crystal field splitting among the t_{2g} orbitals. The degenerate or nearly degenerate t_{2g} orbitals and the partially filled t_{2g} shell may lead to an active orbital degree of freedom. This will be further discussed from the magnetic entropy measurement.

Finally, in $FeAl_2Se_4$, the nearest intralayer Fe-Fe distance is $d_1 = 3.8335(1)$Å and the nearest interlayer Fe-Fe distance is $d_2 = 12.7369(5)$Å, indicating an ideal two-dimensional character in terms of the lattice structure.

III. THERMODYNAMIC MEASUREMENTS

To identify the magnetic properties of $FeAl_2Se_4$, we first implement the thermodynamic measurements. The temperature dependent *dc* magnetic susceptibility and its inverse χ^{-1} under the external magnetic fields of 0.01T, 2T and 8T are shown in Fig. 2. A bifurcation (denoted as T_f) at 14K can be seen under a field of 0.01T, and can be suppressed down to 8K when the applied field is raised up to 8T. This is a signature of spin freezing. The temperature dependent susceptibility from 150K to 300K obeys a simple Curie-Weiss law $\chi = C/(T - \Theta_{\rm CW})$, where C is the Curie constant and $\Theta_{\rm CW}$ is the Weiss temperature as illustrated in the inset of Fig. 2(a). The effective magnetic moments, 4.80-5.20μ_B, were obtained from the Curie constants. The Weiss temperature $\Theta_{\rm CW} = -200$K, that is more negative than that for the isostructural material[28] $FeGa_2S_4$ ($\Theta_{\rm CW} = -160$K), indicates stronger antiferromagnetic interactions. When the temperature is lower than 150K, $FeAl_2Se_4$ shows a deviation from the Curie-Weiss behavior. The frustration index, defined by $f = |\Theta_{\rm CW}/T_f|$ with T_f the spin freezing temperature, is estimated as 14. This is a relatively large value, and we thus conclude that $FeAl_2Se_4$ is a magnetically frustrated system. Fig. 2(b) shows the magnetic susceptibility measurements of $FeAl_2Se_4$ single crystals with $H \parallel ab$ (χ_{ab}) and $H \parallel c$ (χ_c). Unlike $NiGa_2S_4$ and $FeGa_2S_4$[28], here we find an easy-axis anisotropy with χ_c/χ_{ab} about 2.4 at 10K instead of easy-plane anisotropy. This is due to the partially filled t_{2g} shell in the Fe^{2+} ion where the spin-orbit coupling is active and induces the anisotropy in the spin space.

The magnetic heat capacity after subtracting the phonon contributions is used to reveal the spin contribution. The heat capacity of an isostructural non-magnetic material $ZnIn_2S_4$ is measured to account for the lattice contribution of $FeAl_2Se_4$. We obtained the thermal variation of the Debye temperature $\Theta_D(T)$ using the Debye equation. $\Theta_D(T)$ of $FeAl_2Se_4$ was then estimated by applying a scale factor according to $\Theta_D(T) \propto M_0^{-1/2} V_0^{-1/3}$, where M_0 and V_0 are molar mass and volume, respectively. Thus, the lattice contribution C_L was estimated by the scaled $\Theta_D(T)$ data. The magnetic part, C_m, was then estimated through subtracting the lattice contributions C_L[27]. No clear anomaly associated with any magnetic transition can be detected from the specific heat data down to 0.4K, indicating a ground state without any true long range spin ordering. Similar to $NiGa_2S_4$ and $FeGa_2S_4$[28], $FeAl_2Se_4$ exhibits a double-peak variation of C_m/T: one at ~ 10K, and the other at ~ 65K, as shown in Fig. 3(a). We will revisit the double-peak structure of the heat capacity later.

The magnetic entropy, $S_m(T) = \int_0^T C_m/T\, dT$, increases gradually over the entire measured temperature range but with a plateau near $T \sim 25$K, indicating high degeneracy of low-energy states due to magnetic frustration. The total entropy reaches $R\ln(5)$ at $T \sim 135$K, corresponding to the value for the $S = 2$ system. Then it further increases towards $R\ln(15) = R\ln(5) + R\ln(3)$. The latter term is from the orbital degree of freedom due to two holes present in the t_{2g} orbitals[28]. The low-temperature part of C_m/T, as shown in Fig. 3(b), displays a near linear T dependence around 4K and then deviates from the line with further increasing temperature, similar to the behavior that was observed in $NiGa_2S_4$ and $FeGa_2S_4$. Besides, the linear-T coefficient γ for C_m/T of 5.9mJ/molK^2 at $T \to 0$K can be obtained for $FeAl_2Se_4$, slightly larger than that in $FeGa_2S_4$ (3.1mJ/molK^2). The observed T^2 specific heat can be attributed to the Halperin-Saslow modes[35] in two dimensions that give a specific heat of the form

$$C_m = N_{\rm A}\frac{3\pi k_B V}{c}\Big[\zeta(3)\sum_j \Big(\frac{k_B T}{\pi\hbar v_j}\Big)^2 - \frac{1}{L_0^2}\Big], \qquad (1)$$

where $V = \sqrt{3}a^2c/2$ is the unit-cell volume with a the Fe-Fe spacing, L_0 is the coherence length for the spin excitations and v_j is the velocity in the j-th direction. From $C_m/T^2 = 0.010$J/molK^3, the estimated average v_j is 1400m/s. For ordinary AFMs that order at $T \sim \Theta_{\rm CW}$,

FIG. 2. (Color online.) (a) Zero-field-cold (ZFC) and field-cold (FC) $\chi(T)$ data taken at different applied eld from 2K to 300K. Inset: the inverse susceptibility $\chi^{-1}(T)$ data with the applied field of 8T. The solid red lines are linear fits with a Curie-Weiss law $\chi = C/(T - \Theta_{\rm CW})$. (b) Temperature dependence of the magnetic susceptibility χ_{ab} and χ_c obtained for $FeAl_2Se_4$ under 0.1T from 10K to 400K. Inset: the ratio of χ_c/χ_{ab} vs T.

FIG. 3. (Color online.) (a) Temperature dependence of magnetic entropy (right axis) and C_m/T (left axis) for $FeAl_2Se_4$. (b) The low-temperature part of magnetic heat capacity C_m/T for $NiGa_2S_4$, $FeGa_2S_4$ and $FeAl_2Se_4$. Inset shows the $\Delta(C_m/T)\Theta_{\rm CW}/[R\ln(2S+1)]$ vs $T/\Theta_{\rm CW}$ for $NiGa_2S_4$ ($S=1$, $\Theta_{\rm CW}=-80$K), $FeGa_2S_4$ ($S=2$, $\Theta_{\rm CW}=-160$K) and $FeAl_2Se_4$ ($S=2$, $\Theta_{\rm CW}=-200$K) at 0T in full logarithmic scale.

the average v_j is estimated as

$$v_j^2 \approx (3\sqrt{3}\zeta(3)/4\pi)(ak_{\rm B}\Theta_{\rm CW}/\bar{h})/\ln(2S+1), \quad (2)$$

which gives $v_j \approx 5600$m/s. The smaller value in our case indicates softening due to the magnetic frustration, and is consistent with $NiGa_2S_4$ and $FeGa_2S_4$[27–29]. Using the susceptibility data $\chi(T\to 0)=0.0025$emu/mol, the estimated spin stiffness $\rho_s=\chi(v/\kappa)^2=49.5$K, where $\kappa=g\mu_B/\hbar$, which is larger than those obtained in $FeGa_2S_4$ ($\rho_s=35.8$K) and $NiGa_2S_4$ ($\rho_s=6.5$K). To further compare $FeAl_2Se_4$ with the other two counterparts, inset of Fig. 3(b) shows $\Delta(C_m/T)\Theta_{\rm CW}/[R\ln(2S+1)]$ vs $T/\Theta_{\rm CW}$ for $NiGa_2S_4$ ($S=1$, $\Theta_{\rm CW}=-80$K), $FeGa_2S_4$ ($S=2$, $\Theta_{\rm CW}=-160$K) and $FeAl_2Se_4$ ($S=2$, $\Theta_{\rm CW}=-200$K) at zero field (0T) in full logarithmic scale, where $\Delta(C_m/T)\Theta_{\rm CW}=C_m/T-\gamma$. As shown in Fig. 3(b), the low-temperature data for $FeAl_2Se_4$ nearly collapse on top of $NiGa_2S_4$ and $FeGa_2S_4$, indicating similar Halperin-Saslow modes present in all three compounds.

IV. DOUBLE-PEAK HEAT CAPACITY

Here we discuss the origin of the double-peak structure in the heat capacity of $FeAl_2Se_4$. As noted, such a double-peak structure was first observed in the spin-1 magnet $NiGa_2S_4$[27]. The theoretical studies have invoked a spin model with both Heisenberg and biquadratic exchange interactions[30–32], where the biquadratic exchange interaction, $-(\boldsymbol{S}_i\cdot\boldsymbol{S}_j)^2$, arises from the spin-lattice coupling. Since $FeAl_2Se_4$ is isostructural to $NiGa_2S_4$, we expect similar model and interactions to apply. The presence of the biquadratic exchange allows the system to access the spin quadrupole moments effectively and hence enhance the quadrupolar correlation. In addition to the usual magnetic (dipole) moment S^μ, Both spin-1 and spin-2 moments support the quadrupole moments,

$$Q_{\mu\nu}=\frac{1}{2}(S^\mu S^\nu+S^\nu S^\mu)-\frac{1}{3}S(S+1)\delta_{\mu\nu} \quad (3)$$

with $\mu=x,y,z$. Since the quadrupole and dipole moments are quite distinct and have different symmetry properties, they ought to behave differently. Moreover, it is the biquadratic interaction that directly couples the quadrupole moments of different sites. It was then argued and shown numerically[30] that the system develops significant quadrupolar correlations at a distinct higher temperature than the one associated with the rapid growth of the magnetic correlations when the system is close to the quantum phase transition from spiral (dipolar) spin order to quadrupolar order. These two temperature scales associated with the rapid growth of magnetic and quadrupolar correlations result in an unusual double-peak structure of the heat capacity. Based on the fact that $FeAl_2Se_4$ has an identical lattice structure and an even larger spin Hilbert space, we expect the same mechanism to account for the double-peak heat capacity in $FeAl_2Se_4$.

V. SPIN FREEZING AND AC SUSCEPTIBILITY

To further characterize the low-temperature magnetic properties of $FeAl_2Se_4$ at temperatures near the spin freezing, we measure the temperature dependent ac susceptibility from 5K to 25K for a number of frequencies. As shown in Fig. 4, a peak in the real part at ∼15 K is present, which is the signature of the susceptibility bifurcation. A small but clear peak shift towards high temperatures can be observed when the probing frequency is increased. This suggests a spin relaxation behavior. The shift of the peak temperature as a function of frequency described by the expression, $(\Delta T_f)/(T_f\Delta\log\omega)$, is usually used to distinguish spin glass and spin glass like materials[36,37]. The value obtained for $FeAl_2Se_4$ is 0.042, which is slightly larger than expected for a canonical spin glass but is in the range of spin glass like materials.

FIG. 4. (Color online.) Temperature dependence of the real part of the ac magnetic susceptibility as a function of frequency. It should be noted that the small peak emerging at approximately 7K is frequency independent, the origin is unknown.

Usually the spin freezing with the glassy behavior is due to disorder and/or frustration that are present in $FeAl_2Se_4$. Like the S vacancies in $NiGa_2S_4$, we suspect the Se vacancies to be the dominant type of impurities and sources of disorder. Without disorders, the system may simply develop the spin density or spiral magnetic orders. With (non-magnetic bond) disorders, the phase transition associated with the discrete lattice symmetry breaking would be smeared out in $FeAl_2Se_4$. No sharp transition was observed in the heat capacity measurement on $FeAl_2Se_4$. By assuming a complex XY order parameter for each magnetic domain in the spin freezing regime, the authors in Ref. 30 invoked a phenomenological gauge glass model[38,39] where the complex orders from different magnetic domains couple with the disorder in a fashion similar to the coupling with a random gauge link variable. They propose that the system would realize a gauge glass ground state, and the Goldstone-type spin waves in a long-range ordered state turn into the Halperin-Saslow modes[33,35] in the gauge glass model. These gapless modes in two diemnsions contribute to the T^2 specific heat[35] in the spin freezing regime. Due to the phenomenological nature of the model, we think the gauge glass model and the conclusion should also describe and apply to the low-temperature physics in the spin freezing regime of $FeAl_2Se_4$.

VI. DISCUSSION

Although the large spin moments tend to behave more classically than spin-1/2 moments, the large spin moments have a larger spin Hilbert space and would allow more possibilities for the quantum ground states. If the interaction can access these Hilbert space effectively, interesting quantum states may be stabilized. From our experimental results in $FeAl_2Se_4$, we find that the system exhibits two-peak structure in the heat capacity. We argue that these two peaks correspond to the separate growth of quadrupolar correlation and magnetic (dipolar) correlation. From the early experience with the spin-1 triangular lattice magnet $NiGa_2S_4$[27–33], we expect this physics is certainly not exclusive to $FeAl_2Se_4$, and it is not even exclusive to spin-2 magnets nor to triangular lattice magnets. This type of physics, *i.e.* the rich moment structure and their correlations, may broadly exist in frustrated magnets with high spin moments if the interaction can access these high-order multipole moments effectively. In the cases of $FeAl_2Se_4$ and $NiGa_2S_4$, it is the spin-lattice-coupling induced biquadratic interaction that enhances the quadrupolar order and correlation. Besides these two known examples, for other high spin systems such as the $4d/5d$ magnets[40,41] and $4f$ rare-earth magnets[42–45], the spin-orbit coupling and entanglement could induce strong multipolar interaction and provide another mechanism to access and enhance the quadrupolar (and more generally multipolar) spin orders and correlations. Thus, we think our results and arguments could stimulate interests in frustrated magnets with high spins and rich moment structures.

To be specific to $FeAl_2Se_4$, there are a couple directions for future experiments. Since the biquadratic interaction is suggested to arise from the spin-lattice coupling, it is useful to substitute some Se with S to modify the spin-lattice coupling and hence the biquadratic interaction. This should affect the quadrupolar correlation and the specific heat. Neutron scattering measurement can be quite helpful to probe both the low-energy modes like the Halperin-Saslow modes and the spin correlation in different temperature regimes[46]. Nuclear magnetic resonance and muon spin resonance experiments can also be useful to reveal the dynamical properties of the system at different temperatures. On the theoretical side, it would be interesting to establish a general understanding and a phase diagram of a spin-2 model with both Heisenberg and biquadratic interactions on the triangular lattice.

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Appendix A: Materials and methods

Polycrystalline samples of $FeAl_2Se_4$ were prepared by the reaction of Fe (99.99%, Alfa-Aesar), Al (99.95%, Alfa-Aesar), and Se (99.999%, Shiny) powders. These

TABLE I. Room temperature structure details of $FeAl_2Se_4$.

Space group	P-3m1 (164)
a (Å)	3.8336(1)
c (Å)	12.7369(5)
V (Å^3)	162.11(1)
Atomic parameters	
Fe(1b)	(0,0,1/2)
Al(2d)	(1/3,2/3, 0.2001(8))
Se1(2d)	(1/3,2/3, 0.8658(4))
Se2(2d)	(1/3,2/3,0.3915(3))
Selected bond lengths and angles	
d Fe-Se (Å)	2.609(3)
α Se-Fe-Se (°)	94.55(8)
β Se-Fe-Se (°)	85.45(8)
Agreement factors	
R_p	2.29%
R_{wp}	2.94%

reagents were intimately ground together using an agate pestle and mortar and placed in an alumina crucible. The crucible was placed inside a quartz tube which was evacuated, sealed and partially backlled with ultrahigh-purity argon. The samples were fast heated at 500°C for 8h, then kept at 900°C for several days, and finally cooled naturally to room temperature by switching off the furnace. Crystals were prepared by the reaction of Fe (99.99%, Alfa-Aesar) pieces, Al (99.95%, Alfa-Aesar) wire, and Se (99.999%, Shiny) shot in an appropriate molar ratio. These reagents were simply put together in an alumina crucible. similar to the procedure for preparing polycrystalline sample, the growth of crystals was performed at 1070°C for a duration of 24 hours and then cooled slowly to 470°C then naturally cooled down to room temperature by switching off the furnace. All measurements performed on the powder sample were grounded from the single crystal sample. Dc magnetization and heat capacities were measured on a PPMS using the relaxation technique. Resistivity was measured on a PPMS using the standard four-probe conguration. AC magnetization were measured on a Magnetic Properties Measurement System (MPMS, Quantum Design) using powders.

Appendix B: The structure details of $FeAl_2Se_4$

In Table. I, we list the detailed structure information about $FeAl_2Se_4$.

Appendix C: Specific heat for $FeAl_2Se_4$, $ZnIn_2S_4$ and resistivity of $FeAl_2Se_4$

In Fig. 5, we plot the temperature dependence of the specific heat of $FeAl_2Se_4$ at various fields. In addition, the result for the non-magnetic material $ZnIn_2S_4$ is also provided.

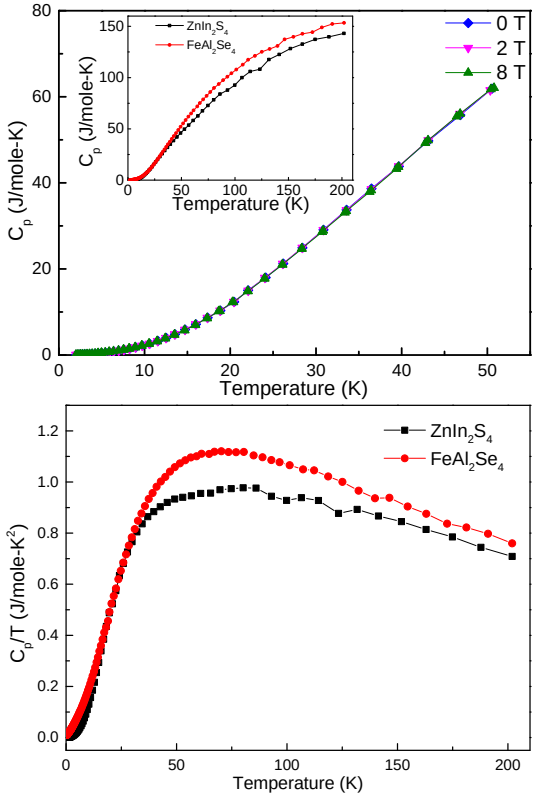

FIG. 5. The specic heat data measured at different fields. Inset of (a): Temperature dependence of specic heat for $FeAl_2Se_4$ and $ZnIn_2S_4$ between 200 and 0.4 K.

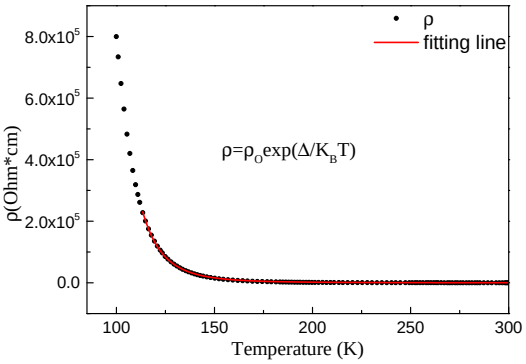

FIG. 6. (Color online.) Temperature dependence of the resistivity $\rho(T)$ of $FeAl_2Se_4$. Red line indicates the fitting results of $\rho(T)$ using the thermal activation model.

In Fig. 6, we provide the variation of resistivity with temperature for $FeAl_2Se_4$. An insulating ρ vs T dependence is clearly seen. The $\rho(T)$ obeys the thermally activated behavior $\rho = \rho_0 \exp(E_a/k_BT)$, where E_a is the activation energy with fitted value of 0.106 eV, consistent with the black color of the compound.

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