Magnetic ordering and dense Kondo behavior in EuFe$_2$P$_2$

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The ternary iron phosphide EuFe$_2$P$_2$ with ThCr$_2$Si$_2$-type structure has been systematically studied by the measurements of crystal structure, magnetization, Mössbauer effect, transport properties and specific heat. The structural refinement result confirms no direct P-P covalent bonding. The Mössbauer spectra indicate no magnetic moment for the Fe atoms and, that the Eu ions are divalent in the whole temperatures. The Eu$^{2+}$ spins order ferromagnetically at $T_C=29$ K, followed by a possible helimagnetic ordering below $T_{HM}=26$ K, where the Eu$^{2+}$ moments tilt a little from the c-axis. External magnetic field increases the $T_C$ gradually, but suppresses the $T_{HM}$ rapidly. (Magneto)resistivity data indicate characteristic dense Kondo behavior above the Curie temperature. The result is discussed in terms of the interplay between intersite RKKY and intrasite Kondo interactions.

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I. INTRODUCTION

The interplay between 4f and conduction electrons in intermetallic compounds has led to a wide variety of novel ground states, attracting sustained interest in condensed matter physics community. In the pnictide family, Eu$T_2$P$\_{\nu}$ ($T$=transition metals; $P\_{\nu}$=As or P) offers us a rare opportunity to access such an interplay. The ternary compound crystallizes in ThCr$_2$Si$_2$-type structure, consisting of Eu-sublattice with 4f electrons and $T$-sublattice with 3d electrons. Europium is known as a special rare-earth element due to the two stable valence configurations: Eu$^{2+}$ and Eu$^{3+}$, showing a large moment ($J=S=7/2$) and zero moment ($J=0$), respectively. In most cases, europium shows the lower valence with high magnetic moment, which renders magnetically ordered ground states. However, mixed valence state for Eu was evidenced by Mössbauer investigations in a "collapsed" phase EuNi$_2$P$_2$. By applying pressures, a structural transition toward the collapsed phase was observed in EuCo$_2$P$_2$ and EuFe$_2$P$_2$, accompanying with a partial valence transition. In earlier studies, valence fluctuations of Eu were also demonstrated in EuCu$_2$Si$_2$ system.

The europium iron pnictide EuFe$_2$P$_{\nu}$, first synthesized more than 30 years ago, exhibits totally different physical properties for $P\_{\nu}$=As and P. EuFe$_2$As$_2$ undertakes a spin-density-wave (SDW) transition in the Fe sublattice at 200 K, followed by an AFM ordering of Eu$^{2+}$ moments at 20 K. By contrast, as reported in Ref. 3, the Fe atoms do not carry local moments while the Eu$^{2+}$ spins order ferromagnetically at 27 K in EuFe$_2$P$_2$. Surprisingly, by doping P into EuFe$_2$As$_2$, both superconductivity coming from Fe 3d electrons and ferromagnetism due to Eu 4f moments were observed in EuFe$_2$(As$_{0.7}$P$_{0.3}$)$_2$. 12

While EuFe$_2$As$_2$ has been extensively studied recently, few works have been devoted to EuFe$_2$P$_2$. To the best of our knowledge, the transport and thermodynamic properties of EuFe$_2$P$_2$ have not been reported so far. Moreover, the contrasting behaviors between an iron arsenide and its sister phosphide are explicitly demonstrated in CeFe$P$$_n$O system: CeFeAsO serves as a parent compound for high temperature superconductors, but CeFePO has been recognized as a heavy Fermion metal with ferromagnetic correlation. Therefore, what EuFe$_2$P$_2$ behaves is an important issue to be investigated. In this paper, we performed a systematic study on EuFe$_2$P$_2$ by the measurements of crystal structure, transport properties, specific heat, as well as magnetic properties and Mössbauer spectra. The Eu valence state is confirmed to be 2+ in the whole temperatures, and the Eu$^{2+}$ moments order in a complex manner rather than the simple reported ferromagnetism at low temperatures. Strikingly, EuFe$_2$P$_2$ shows a dense Kondo behavior. Our result

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demonstrates that, as an Eu-containing compound, EuFe$_2$P$_2$ sets a rare example displaying the interplay between Kondo and Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions.

II. EXPERIMENTAL DETAILS

Polycrystalline samples of EuFe$_2$P$_2$ were synthesized by solid state reaction between EuP and Fe$_2$P, as reported previously. EuP was presynthesized by heating europium grains and phosphorus powders very slowly to 1173 K, then holding for 36 h. Fe$_2$P was presynthesized by reacting iron and phosphorus powders at 973 K for 24 h from stoichiometric amounts of the elements. All the starting materials have the purity better than 99.9 \%. Powders of EuP and Fe$_2$P were weighed according to the stoichiometric ratio, thoroughly ground and pressed into pellets in an argon-filled glove-box. The pellets were then sealed in an evacuated quartz tube and sintered at 1273 K for 36 h then cooled slowly to room temperature.

Powder X-ray diffraction (XRD) was carried out using a D/Max-rA diffractometer with Cu K$_\alpha$ radiation and a graphite monochromator. The structural refinement was performed using the Programme Rietan 2000. The electrical resistivity was measured using a standard four-probe method. Thermoelectric power measurements were carried out by a steady-state technique with a temperature gradient $\sim$ 1 K/cm. Magnetoresistance (MR) and specific heat measurements were performed on a Quantum Design Physical Property Measurement System (PPMS-9). The dc magnetization was measured on a Quantum Design Magnetic Property Measurement System (MPMS-5).

Mössbauer studies were performed using a conventional constant acceleration drive. The sources were 50 mCi $^{57}$Co-Rh for $^{57}$Fe spectra and 200 mCi $^{151}$Sm$_2$O$_3$ source for the $^{151}$Eu spectra. The absorbers were measured in a Janis model SHI-850-5 closed cycle refrigerator. The spectra were analyzed in terms of least square fit procedures to theoretical expected spectra, including full diagonalization of the hyperfine interaction spin Hamiltonian. The analysis of the $^{151}$Eu spectra considered also the exact shape of the source emission line, as shown in Ref. 28. The velocity calibration was performed with an α-iron foil at room temperature. The reported isomer shift (I.S.) values for iron are relative to the Fe foil, for europium relative to the oxide source at room temperature.

III. RESULTS AND DISCUSSION

A. Crystal Structure

Figure 1 shows the powder XRD pattern for the as-prepared EuFe$_2$P$_2$ sample. No obvious secondary phase can be detected. By employing ThCr$_2$Si$_2$-type structure with the space group of I4/mmm, the crystal structure was successfully refined (the reliable factor $R_{wp}=0.098$; the goodness of fit is 1.61). The fitted lattice parameters are $a=3.8178(1)$ Å and $c=11.2372(3)$ Å, in agreement with the literature values $a=3.818(1)$ Å and $c=11.224(4)$ Å. Compared with the counterpart of arsenide EuFe$_2$As$_2$, the $a$ and $c$ axes decrease by 2.3 \% and 7.3 \%, respectively. The larger decrease in $c$ axis suggests stronger interlayer coupling.

Detailed structural comparison between EuFe$_2$P$_2$ and EuFe$_2$As$_2$ can be seen in Table 1. The position of phosphorus is closer to the iron planes, which leads to 13.7 \% decrease in the thickness of Fe$_2$P$_2$ layers. On the other hand, the spacing of Fe$_2$P$_{2n}$ layers, namely the $Pn - Pn$ distance, only decreases by 2.1 \%. One note that the P-P distance (3.263 Å) in EuFe$_2$P$_2$ is much larger than the threshold value of $\sim$2.3 Å for the P-P bonding along the c axis. Therefore, unlike the collapsed phase EuNi$_2$P$_2$, there is no covalent P-P bonding in EuFe$_2$P$_2$ at ambient condition. This result is consistent with the previous report. In the concept of bond valence sum, the formal valence of Eu is calculated to be 1.89 using the Eu–P bondlength data and the related parameters.

B. Magnetization

Although the XRD experiment shows no obvious secondary phase, the magnetic measurement indicates a step-like decrease of susceptibility from 200 to 300 K (not shown here). Similar phenomena was observed previously in the EuFe$_2$(As$_{0.7}$P$_{0.3}$)$_2$ sample, which is due to the presence of trace amount of ferromagnetic impurity Fe$_2$P with a Curie point at 306 K. The molar fraction of Fe$_2$P was estimated to be below 1\% from the $M(H)$ curves at 100 K. Figure 2(a) shows the tempera-
the theoretical value of $\mu$ is displayed in figure 3. For high magnetic fields, say $H=1$ kOe, the magnetization approximately saturates to $\mu_{B}/f.u.$ at $29.5$ at $2$ K. The data of $35$ K $\leq T \leq 120$ K follow the modified Curie-Weiss law,

$$\chi = \chi_0 + \frac{C}{T - \theta},$$

where $\chi_0$ denotes the temperature-independent term, $C$ the Curie-Weiss constant and $\theta$ the paramagnetic Curie temperature. The fitted value of $\chi_0$ is as high as $0.22$ emu/mol, which is mainly ascribed to the ferromagnetic Fe$_2$P impurity. The fitting also yields the effective magnetic moments $P_{eff}$=7.94 $\mu_B$ per formula unit and $\theta$=29 K. The $P_{eff}$ value is consistent with the theoretical value of 7.94 $\mu_B$ for a free Eu$^{2+}$ ion (The slightly larger value is also due to the influence of the tiny Fe$_2$P impurity).

A ferromagnetic transition is manifested by the rapid increase in $\chi$ below $30$ K, as well as the divergence of ZFC and FC data. This result is basically consistent with the previous report claiming ferromagnetic (FM) transition at $27$ K by Mössbauer and magnetic susceptibility investigations. However, the Curie point ($T_C$) has $2$ K difference. In fact, precise determination of the $T_C$ by a single $M(T)$ curve is difficult because of the large moments of Eu$^{2+}$. We thus measured series of $M(H)$ curves nearby $T_C$. The data are shown in the plot of $M^2$ vs. $H/M$ (so-called Arrot plot), which clearly indicates that the Curie temperature is $29$ K.

Below the $T_C$, we note a kink at $26$ K in the $\chi(T)$ data [shown in the inset of figure 2(a)], which is quite different from those of the conventional ferromagnet. The temperature dependence of magnetization under various fields is displayed in figure 3. For high magnetic fields, say $\mu_0 H=1$ T, the magnetization approximately saturates to the theoretical value of $gS=7.0$ $\mu_B$/f.u. at $2$ K. In the case of low fields, however, there is another magnetic transition below $T_C$, characterized by the temperature-independent magnetization. This phenomenon is very much similar to that in Eu(Fe$_{0.88}$Co$_{0.11}$)$_2$As$_2$, where a helimagnetism was proposed. In the helimagnetic (HM) state, as illustrated in the inset of figure 1, the Eu$^{2+}$ spins align ferromagnetically within the Eu atomic planes, but the interlayer spin directions differ in a fixed angle. Note that the $^{151}$Eu Mössbauer study below indicates that the spin direction tilts about $20^\circ$ from the $c$-axis, which gives rise to the observed macroscopic ferromagnetism. External field suppresses the $T_{HM}$ rapidly, but increases the $T_C$ gradually. The stabilization of FM state by the external field was explained in our previous paper.

The dominant ferromagnetism in EuFe$_2$P$_2$ is fur-
ther demonstrated by the field-dependent magnetization, shown in figure 4. The magnetization increases steeply with initially increasing $H$ and tends to saturate for $H \geq 10^4$ Oe. The saturated magnetic moment is $\sim 6.7 \, \mu_B$/f.u., close to the expected value of $7.0 \, \mu_B$/f.u. In addition, a small hysteresis loop is presented on closer examination. All these features are consistent with basically ferromagnetic alignment of Eu$^{2+}$ moments.

C. Mössbauer Spectra

Mössbauer Spectroscopy (MS) studies of $^{151}$Eu and $^{57}$Fe in the system EuFe$_2$P$_2$ at temperatures 5 K to 297 K have been performed. A previous study of this compound has been reported in Ref. [3].

$^{151}$Eu spectra [figure 5(a)] display pure quadrupole interactions down to the magnetic ordering temperature of the Eu sublattice. The values of the measured I.S. are $-11.0(1)$ mm/s at 297 K, $-11.4(1)$ mm/s at 40 K and $-11.3(1)$ mm/s at 5 K, proving that the Eu ions are divalent at all temperatures. The quadrupole interaction values ($\frac{1}{2}e^2qQ_0$) are: $-2.32(2)$ mm/s at 297 K, $-2.55(2)$ mm/s at 40 K. At 5 K, the quadrupole shift is $-2.95(2)$ mm/s and the magnetic hyperfine field ($H_{\text{eff}}$) is 30.1(1) T. The quadrupole shift value at 5 K, when analyzed in the approximation that the magnetic interactions are much larger than the quadrupole interaction, indicates that $H_{\text{eff}}$ points along the crystalline c-axis, the major axis of the axial electric field gradient producing the quadrupole interaction. However, analyzing the spectrum with a full diagonalization of the hyperfine Spin Hamiltonian gives a better fit when the hyperfine field tilts away from the c-axis by 20(5)$^\circ$. This is in contrast to EuFe$_2$As$_2$ [figure 5(b)], where the Eu moments order antiferromagnetically (of A-type) and the hyperfine field is perpendicular to the c-axis. The same phenomenon is also observed in Eu(Fe$_{0.9}$Ni$_{0.1}$)$_2$As$_2$, where the Eu moment is ferromagnetically ordered.[34] The observed $H_{\text{eff}}$ in EuFe$_2$P$_2$ is higher than that ($H_{\text{eff}}=26.2$ T) in EuFe$_2$As$_2$.

The $^{57}$Fe Mössbauer spectra display a pure quadrupole splitting down to $T_C$. The measured I.S. are: 0.28 mm/s at room temperature, 0.38 mm/s at 34 K and 0.39 mm/s at 5 K. The quadrupole interaction ($\frac{1}{2}e^2qQ_0$) values are: 0.16(1) mm/s at 297 K, 0.15(1) mm/s at 30 K and below $T_c$, at 5 K, 0.17(1) mm/s. A small foreign phase (probably Fe$_2$P) of less than 5% is also present. In figure 6 one can observe the change in the spectrum between 34 K to 5 K. No Fe magnetic moment is evidenced. At 5 K the spectrum displays a small magnetic hyperfine field [$H_{\text{eff}}=0.97(2)$ T], acting on the iron nucleus. This small field is a transferred field from the ferromagnetically ordered Eu sublattice, as previously observed. [3] It was also observed in ferromagnetic Eu(Fe$_{0.9}$Ni$_{0.1}$)$_2$As$_2$. This transferred field seems to point along the c-axis, however analyzing the spectrum with a full diagonalization of the hyperfine Spin Hamiltonian produces a better fit when the $H_{\text{eff}}$ tilts from the c-axis by 15(5)$^\circ$. Thus our measurements show, that the transferred field on the iron site, points in the same direction as that of the Eu magnetic moment.
D. Transport Properties

1. Resistivity and Magnetoresistivity

For intermetallic compounds, dense polycrystalline samples largely exhibit intrinsic transport properties as single crystals do because of well electrical contact between crystalline grains. Thus our sample, which had metal luster by polishing, may reflect the intrinsic transport properties. Figure 7(a) displays the temperature dependence of resistivity ($\rho$) for EuFe$_2$P$_2$. The room temperature resistivity is $\sim 0.15$ m$\Omega$·cm, which is nearly the same to that of polycrystalline sample of BaFe$_2$P$_2$.[14] but about one order of magnitude smaller than the value of EuFe$_2$As$_2$.[10] Unlike EuFe$_2$As$_2$ which shows two anomalies in $\rho$ at 20 and 200 K, there is only one resistivity anomaly in EuFe$_2$P$_2$, i.e., a kink at 29.2 K, corresponding to the aforementioned ferromagnetic transition in Eu sublattice. The residual resistivity ratio (RRR), defined as $\rho_{300 K}/\rho_{2 K}$, is $\sim 40$, much reduced in comparison with that of BaFe$_2$P$_2$ ($\sim 70$).[14] This result suggests additional magnetic scattering due to the Eu$^{2+}$ moments in EuFe$_2$P$_2$. For simplicity, we roughly assume that the resistivity contribution from electron-phonon scattering, denoted by $\rho_{e-ph}(T)$, is the same for both materials. Then, the resistivity contribution from magnetic scattering [$\rho_{mag}(T)$] in EuFe$_2$P$_2$ can be obtained simply by a subtraction. As can be seen in figure 7(a), the $\rho_{mag}(T)$ data show a maximum at $\sim 55$ K, which is reminiscent of dense Kondo behavior in other systems such as CeTb$_2$[31] and CeNiGe$_3$ material.[32] It is noted that upon applying a pressure up to 4 GPa, a broad resistivity peak appears around 100 K without the subtraction of $\rho_{e-ph}(T)$. [33] This pressure-enhanced Kondo effect is very common.[34] because the $4f$ level tends to approach Fermi energy with increasing pressure.

Under an 8 T field, there is negligible effect on $\rho(T)$ above 80 K. However, anomalous temperature-dependent MR is observed below 80 K, as illustrated clearly in figure 7(b). Namely, a negative MR grows with decreasing temperature below 80 K and reaches its minimum of $\sim 35\%$ at the FM ordering temperature. Then the negative MR decreases with further decreasing temperature and finally undergoes sign reversal around 10 K, below which positive MR increases with decreasing temperature and achieves 35% at 2 K. It is noted that the resistivity kink at 29.2 K under zero field shifts to higher temperature (over 50 K) and becomes very much broadened by the external 8 T field. All the above MR behavior resembles those in CeNiGe$_3$[32] except that the latter system has an AFM ground state.

The isothermal field dependence of MR for EuFe$_2$P$_2$ [figure 8(a)] gives further support for the dense Kondo behavior. For 40 K $\leq T \leq$ 80 K, the negative MR increases monotonically with increasing $H$ and decreasing $T$, in agreement with a characteristic Kondo-type behavior. According to a theoretical result,[35] The magnetoresistance, $\Delta \rho/\rho_0$, can be scaled with $H/(T + T^*)$, where $T^*$ is a measure of the single impurity Kondo energy scale. Figure 8(b) shows that the MR data between 40 K and 80 K basically fall on the same curve for $T^* = -29$ K. The negative sign of $T^*$, with the abso-
Thermopower is about again with increasing temperature. Above 100 K, the sign changes from negative to positive then to negative \(\text{Fe}_200\) to 300 K may due to the influence of trace amount of temperature (Note that the small gradual change from contrast with the \(\text{cate that electron transport is dominant. This is in con-
\(\text{S}^\text{negative values of EuFe}_2\). \(\text{FIG. 8: (Color online) (a) Isothermal magnetoresistance for EuFe}_2\text{P}_2\) at different temperatures. (b) Scaling behavior of the magnetoresistance in EuFe}_2\text{P}_2\).

\subsection*{2. Thermoelectric Power}

Figure 9 shows the temperature dependence of thermoelectric power or Seebeck coefficient \((S)\) in EuFe\(_2\)P\(_2\). The negative values of 1 in the whole temperature range indicate that electron transport is dominant. This is in contrast with the \(S(T)\) behavior in EuFe\(_2\)As\(_2\), which shows sign changes from negative to positive then to negative again with increasing temperature.\([10]\) Above 100 K, the thermopower is about \(-10\mu\text{V/K}, almost independent of temperature (Note that the small gradual change from 200 to 300 K may due to the influence of trace amount of Fe\(_2\)P). Below 90 K, \(|S|\) starts to decrease, and it shows a linear behavior from 15 to 45 K. According to Behnia \textit{et al}.\([36]\) the slope \(dS/dT\) correlates closely with the electronic specific heat coefficient \(\gamma\) by a dimensionless quantity,

\[ q = \frac{S N_A e}{T \gamma}, \quad (2) \]

where \(N_A e\) is the so-called Faraday number. For strongly correlated electron systems, the \(q\) value is close to unity.\([36]\) Thus the electronic specific heat coefficient in EuFe\(_2\)P\(_2\) can be estimated to be \(\sim 220 \text{ mJ K}^{-1} \text{ mol}^{-1}\), which is very close to the \(C/T\) value at 2 K (see below). This remarkably large value of \(\gamma\) is consistent with the Kondo behavior shown above.

Under a magnetic field of 8 T, the thermopower has a subtle change. By a simple subtraction, one can see a two-peak structure in the inset of figure 9. While the sharp peak at low temperatures is related to the FM state, the broad peak centered at 70 K should be associated with the dense Kondo effect, which is supposed to be suppressed by the external field. Further theoretical investigation is needed to clarify this phenomenon.

\subsection*{E. Specific Heat}

Figure 10 shows the specific heat measurement result for EuFe\(_2\)P\(_2\), especially in the lower temperature ranges. Under zero field, a specific heat anomaly appears below 29 K, corresponding to the FM and HM transitions of Eu\(^{2+}\) sublattice. The HM transition at \(T_{HM}=26\) K is inferred by comparing the \(C(T)\) behavior with that of EuFe\(_2\)As\(_2\), as shown in the upper inset of figure 10. While EuFe\(_2\)As\(_2\) shows a sharp peak at 19 K, EuFe\(_2\)P\(_2\) exhibits a round broader peak at 27 K, suggesting a superposition of two nearby transitions. The successive transition is further demonstrated by the decrease in \(T_{HM}\) and an increase in \(T_C\) with the applied field of 0.2 T. The released magnetic entropy up to the Curie temperature was estimated (the phonon background is assumed to obey Debye model) about 80% of Rln8 (where \(R\) represents gas constant), implying the contribution from Kondo state at high temperatures.

Owing to the FM/HM transitions, it is difficult to extract the electronic specific heat coefficient by a conventional method. Thus we simply consider \(C/T\), shown
in the lower inset of figure 10. Since the phonon and magnon contributions are estimated to be negligibly small at 2 K (since $\theta_D > 2$ K and $T_C > 2$ K), the real electronic specific heat coefficient would be not so much smaller than $C/T |_{T=2K} \approx 250$ mJ K$^{-1}$ mol$^{-1}$. This result is consistent the above indirect estimation from the thermopower measurement.

Under magnetic fields, the specific heat anomaly moves to higher temperatures and, the peak becomes more and more broadened with increasing fields. This result is consistent with the above magnetization measurement, suggesting dominant FM alignment and stronger FM correlations in EuFe$_2$As$_2$, in comparison with the A-type antiferromagnet EuFe$_2$As$_2$.\[14\] [18] [19]

F. Further Discussion

Now let us discuss why the sister compounds EuFe$_2$P$_2$ and EuFe$_2$As$_2$ behave so differently. First, according to the argument by Si et al.\[37\] the loss of Fe moments is due to the relatively weak 3$d$ electron correlation in iron phosphides. So far, there is no report on the appearance of Fe local moments in the iron phosphides with ThCr$_2$Si$_2$-type structure. Second, the difference in the magnetic order of Eu 4$f$ moments has to be explained in terms of an indirect RKKY interactions because the Eu-interlayer spacing is much larger than the expected spacing for a direct exchange. The RKKY exchange coupling $J_{RKKY} \propto -\cos \theta \sin \theta / \sin 2\theta$, where $\theta = 2k_F R$, $R$ denotes the distance between two magnetic moments and $k_F$ the Fermi wave-vector. Upon changing $2k_F R$, $J_{RKKY}$ alters greatly, or even changes the sign. In going from EuFe$_2$As$_2$ to EuFe$_2$P$_2$, $R$ decreases from 6.06 to 5.64 Å. Even if $k_F$ remains constant, the decrease in $R$ may alter $J_{RKKY}$ remarkably, which would result in a crossover from AFM to FM ordering. Note that the FM order of Eu$^{2+}$ moments in EuFe$_{2-x}$Ni$_x$As$_2$ system was explained as a result of the decrease in $\alpha$.\[30\] In fact, the change in $J_{RKKY}(R, k_F)$ can be very minute, as manifested by the helimagnetism in Eu(Fe$_{0.89}$Co$_{0.11}$)$_2$As$_2$.\[28\] It is in principle possible that successive magnetic transitions may occur when decreasing temperature.

The observed dense Kondo behavior in EuFe$_2$P$_2$ could be attributed to the proximity of the 4$f$ level to Fermi energy.\[2\] To our knowledge, dense Kondo behavior in Eu-containing compounds is rarely discovered,\[38\] primarily because Eu$^{2+}$ carries a large moment. Kondo effect involves the intrasite coupling between local moment and conduction carriers, while the RKKY interaction is a long-range intersite magnetic exchange through conduction carriers. Therefore, the interplay between Kondo and RKKY interactions is inevitable. In the ground state of EuFe$_2$P$_2$, according to the well-known Doniach scenario,\[29\] the RKKY interaction prevails against the Kondo effect in EuFe$_2$P$_2$. Since applying pressure enhances the Kondo effect,\[33\] the isovalent chemical doping in EuFe$_2$P$_2$ should be promising to tune the ground state in this intriguing system.

IV. CONCLUDING REMARKS

In summary, we have performed a systematic research on a ternary iron phosphide EuFe$_2$P$_2$. This compound shows contrasting physical properties with its analogue EuFe$_2$As$_2$, although both materials contain Eu$^{2+}$ and without P-P covalent bonding. The result indicates dominant FM ordering for the Eu sublattice. However, the ground state has a possible helimagnetic ordering with the moments basically parallel to the $c$ axis. Future neutron diffractions are expected to resolve this issue. On the other hand, the magnetotransport properties governed by the itinerant Fe 3$d$ electrons show a dense Kondo behavior. Future measurements using single crystalline samples may confirm this point, and more information on the anisotropic property are also expected.

Moreover, alloys of EuFe$_2$P$_2$ and EuFe$_2$As$_2$ exhibits coexistence of high temperature superconductivity and local moment ferromagnetism.\[12\] Therefore, EuFe$_2$P$_2$ and its related materials deserve further exploration with regard to the interplay of Kondo, RKKY, and Cooper-pairing interactions among 4$f$ and conduction electrons.

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[1] H. B. Radousky, *Magnetism in Heavy Fermion Systems*, (World Scientific, Singapore, 2000).

[2] G. R. Stewart, Rev. Mod. Phys. 56, 755 (1984).

[3] E. Morsen, B. D. Mosel, W. Muller-Warmuth, M. Reehuis, and W. Jeitschko, J. Phys. Chem. Solids 49, 85 (1988).

[4] C. Huhnt, W. Schlabitz, A. Wurth, A. Mewis, and M. Reehuis, Physica B 252, 44 (1998).

[5] B. Ni, M. M. Abd-Elmeguid, H. Micklitz, J. P. Sanchez, P. Vulliet, and D. Johrendt, Phys. Rev. B 63, 100102(R) (2001).

[6] E. R. Bauninger, D. Froindlich, I. Nowik, S. Ofer, I. Felner, and I. Mayer, Phys. Rev. Lett. 30, 1053 (1973).

[7] C. U. Segre, M. Croft, J. A. Hodges, V. Murgai, L. C. Gupta, and R. D. Parks, Phys. Rev. Lett. 49, 1947 (1982).

[8] R. Marchand, and W. Jeitschko, J. Solid State Chem. 24, 351 (1978).

[9] H. Raffius, E. Mörsen, B. D. Mosel, W. Müller-Warmuth, W. Jeitschko, L. Terbühne, and T. Vomhof, J. Phys. Chem. Solids 54, 135 (1993).

[10] Z. Ren, Z. W. Zhu, S. Jiang, X. F. Xu, Q. Tao, C. Wang, C. M. Feng, G. H. Cao, and Z. A. Xu, Phys. Rev. B 78, 052501 (2008).

[11] M. Tegel, M. Rotter, V. Weib, F. M. Schappacher, R. Pottgen, and D. Johrendt, J. Phys: Condens. Matter 20, 452201 (2008).

[12] Z. Ren, Q. Tao, S. Jiang, C. M. Feng, C. Wang, J. H. Dai, G. H. Cao, and Z.-A. Xu, Phys. Rev. Lett. 102, 137002 (2009).

[13] H. S. Jeevan, Z. Hossain, D. Kasinathan, H. Rosner, C. Geibel, and P. Gegenwart, Phys. Rev. B 78, 092406 (2008).

[14] S. Jiang, Y. K. Luo, Z. Ren, Z. W. Zhu, C. Wang, X. F. Xu, Q. Tao, G. H. Cao, and Z.-A. Xu, New J. Phys. 11, 025007 (2009).

[15] D. Wu, N. Barisic, N. Drichko, S. Kaiser, A. Faridian, M. Dressel, S. Jiang, Z. Ren, L. J. Li, G. H. Cao, Z. A. Xu, H. S. Jeevan, and P. Gegenwart, Phys. Rev. B 79, 155103 (2009).

[16] C. F. Miculea, M. Nicklas, H. S. Jeevan, D. Kasinathan, Z. Hossain, H. Rosner, P. Gegenwart, C. Geibel, and F. Steglich, Phys. Rev. B 79, 212509 (2009).

[17] T. Terashima, M. Kimata, H. Satsukawa, A. Harada, K. Hazama, S. Uji, H. S. Suzuki, T. Matsumoto, and K. Murada, J. Phys. Soc. Jpn. 78, 083701 (2009).

[18] J. Herrero-Martin, V. Scagnoli, C. Mazzoli, Y. Su, R. Mittal, Y. Xiao, Th. Brueckel, N. Kumar, S. K. Dhar, A. Thamizhavel, and L. Paolasini, Phys. Rev. B 80, 134411 (2009).

[19] Y. Xiao, Y. Su, M. Meven, R. Mittal, C. M. N. Kumar, T. Chatterji, S. Price, J. Persson, N. Kumar, S. K. Dhar, A. Thamizhavel, and Th. Brueckel, Phys. Rev. B 80, 174424 (2009).

[20] G. F. Chen, Z. Li, D. Wu, G. Li, W. Z. Hu, J. Dong, P. Zheng, J. L. Luo, and N. L. Wang, Phys. Rev. Lett. 100, 247002 (2008).

[21] E. M. Bruning, C. Krellner, M. Baenitz, A. Jesche, F. Steglich, and C. Geibel, Phys. Rev. Lett. 101, 117206 (2008).

[22] F. Izumi, Mater. Sci. Forum 321-324, 198 (2000).

[23] I. Nowik and I. Felner, Hyperfine Interactions 28, 959 (1986).

[24] R. Hoffman and C. Zhang, J. Phys. Chem. 89, 4175 (1985).

[25] I. D. Brown and D. Altermatt, Acta Cryst. B41, 244 (1985).

[26] N. E. Brese and M. O’Keefe, Acta Cryst. 47, 192 (1991).

[27] S. Chiba, J. Phys. Soc. Jpn. 15, 581 (1960).

[28] S. Jiang, H. Xing, G. F. Xuan, Z. Ren, C. Wang, Z. A. Xu, and G. H. Cao, Phys. Rev. B 80, 184514 (2009).

[29] I. Nowik and I. Felner, Physica C 469, 485 (2009).

[30] Z. Ren, X. Lin, Q. Tao, S. Jiang, Z. W. Zhu, C. Wang, G. H. Cao, and Z.-A. Xu, Phys. Rev. B 79, 094426 (2009).

[31] Y. Muro, N. Takekawa, and M. Ishikawa, J. Alloys and Compounds 257, 23 (1997).

[32] A. P. Pikul, D. Kaczorowski, T. Plackowski, A. Czopnik, H. Michor, E. Bauer, G. Hilscher, P. Rogl, and Yu Grin, Phys. Rev. B 67, 224417 (2003).

[33] Y. Uwatoko and coworkers, Private Communications.

[34] J. D. Thompson and Z. Fisk, Phys. Rev. B 31, 389 (1985).

[35] P. Schlottmann, Phys. Rep. 181, 1 (1989).

[36] K. Behnia, D. Jaccard, and J. Flouquet, J. Phys: Condens. Matter 16, 5187 (2004).

[37] Q. Si and E. Abrahams, Phys. Rev. Lett. 101, 076401 (2008).

[38] C. D. Cao, R. Klingeler, N. Leps, H. Vinzelberg, V. Kataev, F. Muranyi, N. Tristan, A. Teresiak, S. Q. Zhou, W. Loser, G. Behr, and B. Buchner, Phys. Rev. B 78, 064409 (2008).

[39] S. Doniach, *Valence Instabilities and related narrow band phenomena*, edited by R. D. Parks, (Plenum, New York, 1977).
**Graphs of Eu$^{57}$Fe$_2$P$_2$ at 34 K and 5 K.**

- **34 K**
  - Relative Transmission vs. Velocity (mm/s)
  - The graph shows a peak at 34 K.

- **5 K**
  - Relative Transmission vs. Velocity (mm/s)
  - The graph shows a peak at 5 K.
Figure (b) shows a plot of $\rho$ (mΩ cm) versus $T$ (K) for two samples, Sample 1 and Sample 2. The plot includes a zoomed-in inset that highlights the temperature $T_C = 29.2$ K, indicating a critical point for the transition. The main graph displays a smooth increase in resistance with temperature, while the inset shows a sharp decrease around $T_C$, suggesting a phase transition.
$S (\mu \text{V/K})$

$\Delta S (\mu \text{V/K})$

$\frac{dS}{dT} = 0.225 \ (\mu \text{V/K}^2)$