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Structural control of d-f interaction in the CeFe\(_{1-x}\)Ru\(_x\)AsO system

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Abstract – The isovalent substitution effect of Ru in CeFe\(_{1-x}\)Ru\(_x\)AsO (0 \(\leq \) x \(\leq \) 1) has been systematically studied by powder X-ray diffraction, electrical resistivity, magnetization, and specific heat measurements. The antiferromagnetic (AFM) ordering of both d and 4f electrons are suppressed upon Ru doping, followed by Pauli paramagnetism (d electrons) and local moment paramagnetism (4f electrons) with strong ferromagnetic fluctuation, respectively. Neither superconductivity above 2K nor pronounced Kondo screening are observed in the substitution phase diagram. Combined with published results of the cerium-based quaternary compounds CeM\(_x\)O (M = Fe, Ru; X = P, As), our data suggest that the end member CeRuAsO is on the verge of becoming an FM Kondo lattice. Meanwhile, the ground state of 4f electrons in the quaternary CeM\(_x\)O system should be determined by both the interlayer d-f Kondo coupling \(J_{Kondo}\) and the intralayer Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction \(J_{RKKY}\), which are both very sensitive to the change in crystal structure.

Introduction. – The discovery of 26 K superconductivity in LaFeAsO\(_{1-x}\)F\(_x\) [1] aroused broad interest in the iron-based ZrCuSiAs-type compounds. It is now clear that both electron [1–3] and hole doping [4] can induce superconductivity in LaFeAsO. Generally, the superconducting transition temperature \(T_c\) exceeds the McMillan limit when La is replaced by other heavier rare-earth elements [2,5–10]. As to the isovalent substitution (say phosphorus for arsenic) in the so-called “1111” phases, however, the rule of thumb above does not work any more. While P doping induces unconventional superconductivity in LaFeAs\(_{1-x}\)P\(_x\)O with \(T_c\) of 10 K [11], the superconducting \(T_c\) of the SmFeAs\(_{1-x}\)P\(_x\)O system is only 4.1 K [12].

Aside from P (for As), Ru (for Fe) is another isovalent substitution which is supposed not to introduce extra carriers. Summarizing the experiments on these two isovalent dopants in “1111” phases, one can easily find the difference: Firstly, nearly twice as much Ru content as that of P substitution is required to destroy the antiferromagnetic (AFM) state of d electrons [11,13]. Secondly, no superconductivity higher than 2 K has been reported with Ru substitution so far. In the “122” phases, however, both P and Ru substitution can achieve high-\(T_c\) superconductivity with similar optimal doping level and \(T_c\) [14–19]. It is rather remarkable that the superconductivity observed in P doped “1111” phases is theoretically ascribed to quantum critical behavior [20], which is induced by the enhanced itinerancy of d electrons [21,22]. Interestingly, recent experimental work showed that the substitution of Ru for Fe in BaFe\(_{2-x}\)Ru\(_x\)As\(_2\) can also enhance the itinerancy of d electrons [23,24].

Among the LnM\(_x\)O (Ln = lanthanide; M = Fe, Ru; X = P, As) system, the Ce-based compounds are unique for studying the interaction between the d and f electrons. While CeFeAsO is an itinerant AFM bad metal with localized Ce 4f electrons that undergo AFM ordering below 4 K [6,25], CeFePO acts as a paramagnetic (PM) heavy-fermion metal with ferromagnetic (FM) fluctuation [26]. For Ru-based “1111” compounds, CeRuPO has been reported as a rare example of an FM Kondo lattice [27], yet the physical properties of CeRuAsO are still unclear, except for the metallic resistivity down to 4 K [28]. The substitution phase diagram between...
CeFeAsO and CeFePO shows that, the ordering of Ce 4f electrons changes from AFM to FM at the P doping level of $x = 0.37$, combined with the the disappearance of Fe$^{2+}$ long-range AFM order. For the range of $x \geq 0.95$, the localized 4f electrons are screened by the spin of the conduction sea, resulting in heavy-fermion behaviors [29]. Thus, considering the the similarity between Ru and P substitution and the rich physics relating to d-f coupling in the Ce-based “1111” compounds, it is interesting to know the Ru doping effects in CeFeAsO system.

In this paper, the evolution of physical properties in CeFe$_{1-x}$Ru$_x$AsO ($0 \leq x \leq 1$) has been systematically studied by X-ray powder diffraction (XRD), electric resistivity, magnetic susceptibility, isothermal magnetization and specific heat. Our results show that, while Ru substitution gradually suppressed the AFM state of $d$ electrons, just like what it did in other iron-based “1111” compounds, the AFM of 4f local moment vanishes simultaneously followed by strong FM fluctuation, which was not observed in its analogue PrFe$_{1-x}$Ru$_x$AsO system [30]. Compared with CeFeAsS$_{1-x}$P$_2$O on the other hand, no pronounced heavy-fermion behavior is observed. Combined with other published works about CeMXO ($M = \text{Fe}, \text{Ru}; X = \text{P}, \text{As}$) compounds, we suggest that the ground state of cerium 4f orbital is dependent on both the vertical distance between Ce and Fe/Ru planar layers ($D_{\text{Ce-Fe/Ru}}$) and the distance between the nearest Ce atoms ($D_{\text{Ce-Ce}}$).

**Experimental.** – Polycrystalline samples of CeFe$_{1-x}$Ru$_x$AsO were synthesized using a solid-state reaction in an evacuated quartz tube. All the starting materials, including Ce, Ru, Fe, As, and CeO$_2$ have high purity ($\geq 99.9\%$). CeAs was presynthesized by reacting stoichiometric Ce powder and As powder in vacuum at 350°C for 10 hours and then at 700°C for 12 hours. Similarly, RuAs and FeAs were prepared by reacting Ru/Fe powder and As powder at 500°C and then at 700°C. Then powders of CeAs, CeO$_2$, RuAs, FeAs, Fe and Ru were weighed according to the stoichiometric ratio of CeFe$_{1-x}$Ru$_x$AsO. The weighed powders were mixed thoroughly by grinding, and pressed into pellets under a pressure of 4000 kg cm$^{-2}$. All the reagents were handled in a glove box under high purity argon atmosphere. The pellet was put into a small crucible and sealed in an evacuated quartz ampoule. The sealed ampoule was slowly heated to 1150°C, held at that temperature for 50 hours and finally furnace-cooled to room temperature. The solid-state reaction was repeated with intermediate regrounding.

Powder X-ray diffraction (XRD) was performed at room temperature using a D/Max-RA diffractometer with Cu $K_{\alpha}$ radiation and a graphite monochromator. The XRD diffractometer system was calibrated using standard Si powders. Lattice parameters were calculated by a least-squares fit using at least 20 XRD peaks in the range of $20^\circ \leq 2\theta \leq 80^\circ$. Crystal structure details were obtained by Rietveld refinement using the step-scan XRD data with $20^\circ \leq 2\theta \leq 120^\circ$ for all the samples. The refined lattice constants are essentially the same as those from the least-squares fit within the scope of estimated errors. The typical R-factors of the refinements are: $R_F \sim 2\%$, $R_B \sim 3\%$, and $R_{wp} \sim 11\%$. The goodness-of-fit parameter, $S = R_{wp}/R_{exp} \sim 1.5$, indicating good reliability of the refinement [31]. The electrical resistivity was measured with the standard four-terminal method, after checking the linear $I$-$V$ characteristic. Magnetic susceptibility and isothermal magnetization measurements were performed on a Quantum Design magnetic property measurement system (MPMS-5). Specific-heat measurements were carried out on a Quantum Design physical property measurement system (PPMS-14).

**Results and discussion.** – Figure 1(a) shows the XRD patterns of the synthesized CeFe$_{1-x}$Ru$_x$AsO samples. The XRD peaks can be well indexed based on a tetragonal cell of CeFeAsO with space group $P4/nmm$ (No. 129). No obvious impurity peak is found, suggesting that Ru is successfully doped into the lattice. As is shown in fig. 1(b), while the (003) peak shifts to higher angle the (110) peak shifts to lower one, indicating the expansion and shrinkage of $a$-axis and $c$-axis, respectively. This observation is consistent with the calculated lattice parameters as functions of nominal Ru content, which are shown in fig. 1(c). We note that such an anisotropic structural evolution were also observed in $4d/5d$ transition metal substitution experiments in other “1111” phases [13,30,32–34].
Table 1: Comparison of structure details in CeFePO, CeRuPO, CeRuAsO and CeFeAsO. The space group is P4/nmm. The atomic coordinates (x, y, z) are as follows: Ce (4/3, 1/2, z); O (1/3, 1/2, 0); Fe/Ru (4/3, 1/2, 1/2); As/P (1/3, 1/2, 1/2). H_{Ce2O2} and H_{Fe2As2} represent the thickness of the Ce2O2 and Fe2As2 layers respectively. D_{Ce–Fe/Ru} indicates the vertical distance between the planar layers of Ce and Fe/Ru.

<table>
<thead>
<tr>
<th>Systems</th>
<th>CeFePO [26,29]</th>
<th>CeRuPO [35]</th>
<th>CeRuAsO</th>
<th>CeFeAsO</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Å)</td>
<td>3.919(3)</td>
<td>4.026(1)</td>
<td>4.098(2)</td>
<td>4.002(1)</td>
</tr>
<tr>
<td>c (Å)</td>
<td>8.330(5)</td>
<td>8.256(2)</td>
<td>8.386(4)</td>
<td>8.646(3)</td>
</tr>
<tr>
<td>z of Ce</td>
<td>0.1508</td>
<td>0.1472</td>
<td>0.1408</td>
<td>0.1411</td>
</tr>
<tr>
<td>z of As/P</td>
<td>0.6384</td>
<td>0.6419</td>
<td>0.6546</td>
<td>0.6547</td>
</tr>
<tr>
<td>H_{Ce2O2} (Å)</td>
<td>2.512</td>
<td>2.431</td>
<td>2.356</td>
<td>2.440</td>
</tr>
<tr>
<td>H_{Fe2As2} (Å)</td>
<td>2.306</td>
<td>2.343</td>
<td>2.593</td>
<td>2.675</td>
</tr>
<tr>
<td>D_{Ce–Fe/Ru} (Å)</td>
<td>2.901</td>
<td>2.913</td>
<td>3.014</td>
<td>3.103</td>
</tr>
</tbody>
</table>

Based on Rietveld refinement and some other published works, table 1 summarizes the structural data on CeFePO, CeRuPO, CeRuAsO and CeFeAsO. From the table we can find that: i) Compared with P substitution which results in a thickened Ce2O2 layer and a compressed Fe2As(P)2 layer, the “chemical pressure” along the c-axes induced by Ru substitution is exerted uniformly on both Ce2O2 and (Fe/Ru)2As2 layers. We note that a similar phenomenon was also observed in PrFe1−xRu2AsO [30]. This may explain the absence of superconductivity in Ru-doped “1111” phases as a selective chemical pressure on the Fe2As2 layer rather than a uniform one on both layers is required [11]. ii) The D_{Ce–Fe/Ru} shrinks from 3.103 Å to 3.014 Å in CeFe1−xRu2AsO while that of the CeFeAs1−xP2O decreases from 3.103 Å to 2.901 Å. So the maximum shrinkage of D_{Ce–Fe/Ru} in CeFe1−xRu2AsO (x = 1) is equivalent to that of x = 0.45 in the CeFeAs1−xP2O system. As far as the relationship between d-f coupling and D_{Ce–Fe/Ru} is concerned [29,36], these structural characteristics are consistent with the absence of heavy-fermion behavior in CeFe1−xRu2AsO (as will be discussed later).

Figure 2 shows the temperature dependence of electrical resistivity (ρ-T) of CeFe1−xRu2AsO. Although no superconductivity is observed throughout the whole temperature range, the figure still provides important information: Firstly, an anomaly characterized by a drop in ρ was observed below 140 K for the end-member CeFeAsO, consistent with the previous reports [6]. This anomaly was ascribed to the structure distortion and the accompanying Fe-AFM transition [25]. Upon Ru doping, the anomaly is suppressed monotonically and cannot be identified clearly for x > 0.6. Meanwhile an upturn is observed at low temperature, which is most likely due to remnant AFM instability. Secondly, the room temperature resistivity decreases gradually from 21 mΩcm (CeFeAsO) to 4 mΩcm (CeRuAsO) upon Ru doping. Indeed the resistivity of polycrystalline sample may not reflect the intrinsic property due to the possible metallic impurities dwelling at grain-boundaries such as FeAs and RuAs. However, the monotonic decrease in room temperature resistivity does suggest the enhanced metallic behavior, considering the high sample quality shown by the XRD profile. We note that a similar increased conductivity is also observed in PrFe1−xRu2AsO. At the same time, both ab initio calculation [37] and NMR [38] measurement in the similar LaFe1−xRu2AsO system indicated that Ru for Fe substitution yields a progressive decrease of the density of states at the Fermi level. This suggest that Ru substitution in iron-based “1111” compounds may enhance the itinerancy of d electrons.

The dc magnetic susceptibility was measured under a field of 1000 Oe (fig. 3). The susceptibility increases with decreasing temperature in the high-temperature region, following the Curie-Weiss law for all the samples of 0 ≤ x ≤ 1. The effective moments μ_{eff} derived from the data above 200 K ranges from 2.50μB to 2.61μB, which are very close to that of a free Ce^{3+} ion (2.54μB). As the temperature drops, the 1/χ − T relation for all the samples gradually deviates from linearity denoting the crystalline electric field effect. In the low-temperature region, the
Fig. 3: (Color online) Temperature dependence of the dc magnetic susceptibility below 10 K for CeFe$_{1-x}$Ru$_x$AsO. The inset shows the 1/$\chi$-T relations for end members CeFeAsO and CeRuAsO.

The susceptibility of CeFeAsO exhibits a peak at 4.1 K, denoting the formation of the Ce$^{3+}$ AFM order. Upon Ru doping, the AFM peak is suppressed to lower temperature and cannot be identified for $x \geq 0.4$, where an increasingly robust susceptibility upturn is observed. Although there is not any substantial divergence between zero-field-cooling (ZFC) and field-cooling (FC) curves, such a Ru content dependent susceptibility upturn does suggest the eve of FM transition, considering the good sample quality. We note that in the analog PrFe$_{1-x}$Ru$_x$AsO system, the Néel temperature ($T_N$) of Pr$^{3+}$ AFM is Ru content independent [30]. This indicates that the CeFe$_{1-x}$Ru$_x$AsO system is similar to CeFeAs$_{1-x}$P$_x$O rather than PrFe$_{1-x}$Ru$_x$AsO where the d-f orbital coupling can be safely disregarded.

The evolution of the 4$f$ coupling can be further demonstrated by isothermal field-dependent magnetization measurements (fig. 4(a)). The temperature is fixed at 2 K. For the end member CeFeAsO, a kink in the magnetization curve is observed, consistent with Luo et al. [29]. Upon Ru doping, the kink disappears, while the magnetization curve begins to deviate from linearity and tends to saturate at high field, suggesting the enhanced FM interaction. No hysteresis loops were observed for any of the magnetization curves, which can be explained as the absence of long-range FM order. The maximum of saturated $M$ appears at around $x = 0.8$ with a value of 0.96 $\mu_B$, close to the 1 $\mu_B$ expected for a Ce$^{3+}$ in a local tetragonal CEF surrounding where $\Gamma_6$ doublet (|$\pm 1/2$|) was proposed to be the ground state [26,39]. One may note that the saturated $M$ value begins to decrease gradually for $x \geq 0.8$ and reaches a value of 0.85 $\mu_B$ for $x = 1$. We ascribe this decrease of saturation moment to the crystal field effects. Figure 4(b) shows the derivative of magnetization with respect to magnetic field. Accordingly, the relationship between the derived FM saturation field and Ru substitution level is mapped in the inset of fig. 4(b). It is clear that the extrapolated FM saturation field decreases monotonously from 4.29 tesla ($x = 0.5$) to 0.85 tesla ($x = 1$). This is consistent with the susceptibility upturn shown in fig. 3 that the FM coupling between Ce$^{3+}$ ions is enhanced by Ru substitution significantly.

Figure 5 shows the results of low-temperature specific-heat measurements for CeFe$_{1-x}$Ru$_x$AsO ($x = 0.5, 0.8, 1.0$) in a fixed magnetic field (0 T, 8 T). For $x = 0.5$ at 0 T, the specific heat increases rapidly upon cooling. When a static magnetic field of 8 T is applied to the sample, the upturn at low temperature is suppressed, followed by the emergence of a broad peak at around 3.8 K. This indicates that the specific-heat upturn in zero field should be mostly contributed by magnetic instability rather than Kondo screening effects. For the samples with $x = 0.8$ and 1.0, the broad peaks of 8 T shift to 4.3 K and 5.4 K, respectively. This suggest that the FM correlation is strengthened by
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Fig. 5: (Color online) Temperature dependence of specific heat for CeFe$_{1-x}$Ru$_x$AsO ($x = 0.5, 0.8, 1.0$) under a magnetic field of 0 T and 8 T, respectively.

Fig. 6: (Color online) Electronic phase diagram of CeFe$_{1-x}$Ru$_x$AsO ($0 \leq x \leq 1$). $T_{Nd}$ and $T_{Nf}$ represent the respective Néel temperatures of $d$ and $f$ electrons. $T_{Nd}$ is derived from the resistivity anomaly using the method proposed by Klaus et al. [40], and $T_{Nf}$ is denoted by the peak in the susceptibility.

Ru substitution, which is consistent with both $M$-$T$ and $M$-$H$ measurement. It is noted that there is one (two) small peak on the zero-field curve of $x = 0.8$ ($x = 1$). We ascribe this phenomenon to trace the amount of Ce$_2$O$_3$ impurity which undergoes AFM transition between 5.7 K to 8.6 K [41].

We summarize the experimental results by suggesting the electronic phase diagram shown in fig. 6. As far as the $d$ electrons are concerned, the phase diagram can be divided into two parts: For $x \leq 0.6$, the $d$ electrons show AFM spin density wave at low temperature, while for $x \geq 0.7$, the $d$ electrons exhibit Pauli PM behavior over the entire temperature range. It is well known that a similar AFM-PM transition followed by superconductivity is observed in phosphorus-doped “1111” and “122” systems, which is acribed to quantum critical behavior induced by the enhanced itinerancy of $d$ electrons [15,20]. Similarly, the enhanced itinerancy of $d$ electrons is also observed in Ru-doped “122” phases [23,24], which may explain the origin of the resulting superconductivity [19]. In Ru-doped “1111” phases however, no superconductivity above 2 K has been reported so far. Meanwhile, nearly twice as much Ru substitution as in “122” phases is required to suppress the AFM order of $d$ electrons. This may suggest that Ru substitution in “1111” compounds does not enhance the itinerancy of $d$ orbitals as much as it does in the “122” system. Nevertheless, more direct evidence is required to clarify this question. As for the $4f$ electrons, the $T_{Nf}$ gradually decreases from 4.1 K ($x = 0$) to 2.6 K ($x = 0.2$). Higher doping leads to a further suppression of the $T_{Nf}$ that cannot be observed directly down to 2 K. At the same time, The FM correlation is gradually strengthened by Ru substitution, suggesting the strong $d$-$f$ coupling in the CeFe$_{1-x}$Ru$_x$AsO system.

To clarify the relationship between the crystal structure and the ground state of $4f$ orbital, we map the four quaternary compounds CeM$X$O($M$ = Fe, Ru; $X$ = P, As) in fig. 7 according to their different $D_{Ce-Fe/Ru}$ and $D_{Ce-Ce}$. It is now known that the $d$-$f$ coupling determines the properties of Ce-based “1111” compounds, which is very different from other lanthanide analog. The ground state of $4f$ electrons is mainly controlled by two kinds of interactions, including i) the direct Kondo coupling ($J_{Kondo}$) between localized $4f$ electrons and itinerate $d$ electrons, and ii) the indirect RKKY coupling ($J_{RKKY}$) between two separate Ce atoms. While $J_{Kondo}$ is negatively correlated with $D_{Ce-Fe/Ru}$ [29], the dependence on $D_{Ce-Ce}$ of $J_{RKKY}$ is a Friedel oscillation following the equation: $J_{RKKY}(r) \sim -J^2_{Kondo}(N_F^2 \times \cos(2k_Fr)/k_F^2r)$, where $N_F$ is the density of states (DOS) at the Fermi level, $k_F$ is the Fermi momentum and $r$ is the distance between two Ce

Fig. 7: (Color online) Schematic diagram of the quaternary compounds CeM$X$O($M$ = Fe, Ru; $X$ = P, As). The red and blue arrows indicate the direction of increasing $J_{RKKY}$ and $J_{Kondo}$, respectively.
atoms. In the case of CeFeAs$_{1-x}$P$_x$O, the shrinkage of $D_{\text{Ce-Fe}}$ is 0.202 Å, which greatly strengthens $J_{\text{Kondo}}$ and finally induces heavy-fermion behavior for $x \geq 0.95$ [29]. In the case of CeFe$_{1-x}$Ru$_x$As, on the other hand, the total shrinkage of $D_{\text{Ce-Fe/Ru}}$ is 0.089 Å, equivalent to that of ~45% P substitution in CeFeAs$_{1-x}$P$_x$O. This quantitative analysis is consistent with the similarity of the two phase diagrams, so that the role of the end member CeRuAsO in the CeFe$_{1-x}$Ru$_x$As system is rather similar to that of the CeFeAs$_{0.55}$P$_{0.45}$O in CeFeAs$_{1-x}$P$_x$O, where the FM state has just been stabilized. In addition, the $D_{\text{Ce-Ru}}$ value in CeRuPO is 2.913 Å, equivalent to that of ~94% P doping in CeFeAs$_{1-x}$P$_x$O where the heavy-fermion behavior is about to dominate. This is also consistent with the incomplete Kondo screening of the 4f local moments in CeRuPO [27].

As for the $J_{\text{RKKY}}$ which is dependent on both $J_{\text{Kondo}}$ and $D_{\text{Ce-Ce}}$, the situation is more complex. However, we can still estimate the trend of $J_{\text{RKKY}}$ by comparing the FM ordering temperature. As is shown in fig. 7, the Curie temperature of CeRuPO and CeFeAs$_{0.55}$P$_{0.45}$O are 15 K and 8 K respectively [27,29]. Thus considering the PM state with strong FM instability in CeRuPO, it is reasonable to believe there should be a maximum of $J_{\text{RKKY}}$ hovering around CeRuPO. This speculation is consistent with the heavy-fermion behavior of CeFePO, where $J_{\text{Kondo}}$ rules the ground state of 4f electrons. Meanwhile, the high-pressure experiment in CeFePO [42] can also be understood easily, that the Kondo screening of Ce 4f moments is further stabilized by the pressure-induced shrinkage of both $D_{\text{Ce-Fe/Ru}}$ and $D_{\text{Ce-Ce}}$.

**Concluding remarks.** – To conclude, our experiment results of CeFe$_{1-x}$Ru$_x$AsO ($0 \leq x \leq 1$) show that strong FM instability emerges after AFM states of both d and 4f electrons are killed by Ru substitution. Combined with structural refinement data and other published works, we provide a picture of the relationship between the ground state of 4f electrons and the crystal structure in CeM$_2$O$_3$($M = \text{Fe, Ru;}$ $X = \text{P, As}$) compounds. The combined effects of $J_{\text{Kondo}}$ and $J_{\text{RKKY}}$ determine the ground state of 4f electrons, ranging from localized AFM ordering to an FM Kondo lattice and an itinerant heavy-fermion metal. In addition, this also leads to a prediction that heavy-fermion behavior may be introduced into both CeRuAsO and CeRuPO by applying an adequate physical or chemical pressure.

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