La-dilution effects in TbRhIn$_5$ antiferromagnet

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We report measurements of temperature dependent magnetic susceptibility, resonant x-ray magnetic scattering (XRMS) and heat capacity on single crystals of Tb$_{1-x}$La$_x$RhIn$_5$ for nominal concentrations in the range $0 \leq x \leq 1.0$. TbRhIn$_5$ is an antiferromagnetic (AFM) compound with $T_N \approx 46$ K, which is the highest $T_N$ values along the RRhIn$_5$ series. We explore the suppression of the antiferromagnetic (AFM) state as a function of La-doping considering the effects of La-induced dilution and perturbations to the tetragonal crystalline electrical field (CEF) on the long range magnetic interaction between the Tb$^{3+}$ ions. Additionally, we also discuss the role of disorder. Our results and analysis are compared to the properties of the undoped compound and of other members of the RRhIn$_5$ family and structurally related compounds ($R_2$RhIn$_3$ and $R$In$_3$). The XRMS measurements reveal that the commensurate magnetic structure with the magnetic wave-vector $(0, \frac{1}{2}, \frac{1}{2})$ observed for the undoped compound is robust against doping perturbations in Tb$_{0.6}$La$_{0.4}$RhIn$_5$ compound.

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I. INTRODUCTION

The magnetic dilution and percolation problems are directly connected to each other and continue to be attractive subjects in the field of magnetism and strongly correlated electrons systems (SCES). This is because different and interesting ground states (GS) can be generally tuned by chemical substitution in the these systems. In particular, for heavy-fermions compounds, chemical substitution is a very important tuning parameter as it may strongly affects the interplay between the intra-site Kondo effect and the inter-site long range Ruderman-Kittel-Kasuya-Yoshida (RKKY) magnetic interaction, driving the system from a magnetic ordered state (for instance, antiferromagnetic (AFM) to a non-magnetic heavy-electron paramagnetic metal). Interestingly, in the vicinity of the magnetic phase, unconventional superconductivity (USC) and non-fermi-liquid behavior (NFL) may be found in many cases. In terms of dilution at the heavy fermions ion site, a non-obvious evolution from a magnetic or non-magnetic dense Kondo lattice state to a Kondo single impurity regime in the very diluted regime is expected.

The family of heavy fermions Ce$_m$M$_n$In$_{3m+2n}$ ($M$ = Co, Rh or Ir, $m = 1, 2$; $n = 1$) have been proving to be a great series to explore the role of doping in tuning a variety of ground states such as AFM, USC, NFL and Fermi Liquid (FL) behavior in high-quality single-crystals. All these interesting GS have been found in these systems in specific regions of their rich phases diagrams.

Dilution studies in the above series were performed for both ambient pressure AFM (CeRhIn$_5$) and USC (CeCoIn$_5$) heavy-fermion compounds. In terms of suppression of AFM, a critical La-concentration of about $x_c \approx 0.4$ was obtained from the extrapolation of $dT_N/dx$ slope to $T \to 0$ for La-doped Ce$_{1-x}$La$_x$RhIn$_5$. This is consistent with the theoretical percolation threshold for a 2D-spin system. On the other hand, measurements of thermal expansion and magnetostriction in Ce$_{0.9}$La$_{0.1}$RhIn$_5$ single crystals suggested the evolution of the crystalline electrical field (CEF) ground state as a function of La-concentration and revealed the presence of remaining anisotropic short-range magnetic correlations, which was consistent with earlier reported heat capacity data.

In terms of La-doping induced changes in the electronic structure, recent de Haas-Van Alphen (dHvA) measurements in Ce$_{1-x}$La$_x$RhIn$_5$ has shown a near insensitivity of the Fermi surface topology to $x$ implying almost entirely localized $f$-electron behavior. The magnetic structure of the CeRhIn$_5$ is also nearly unaffected by 10% of La substitution.

More recently, studies of Ce$_{0.9}$La$_{0.1}$RhIn$_5$ under pressure have revealed that the La-doping shifts the pressure induced superconducting phase to higher pressures, indicating that the main effect of the La-doping in CeRhIn$_5$ in this range of La concentration is the decreasing of the Kondo coupling.

Regarding the effect of La-dilution in the properties of the superconducting and dense Kondo lattice CeCoIn$_5$, the pair-breaking by non-magnetic La results in a depression of $T_c$ that extrapolates to zero for a critical La-concentration $x_c \approx 0.18$ indicating a strong gap anisotropy. Further, thermal conductivity and specific heat experiments at low temperature revealed that the suppression of $T_c$ is followed by the increase in the residual electronic specific heat but along with the decrease in the residual electronic thermal conductivity. This contrasting result suggests a coexistence between unpaired electrons and nodal quasiparticles. Still in the Ce$_{1-x}$La$_x$CoIn$_5$ series, an interesting evolution of the normal state properties was also verified through the finding of scalings laws for the specific heat and magnetic susceptibility data suggesting two separated energy scales: one from a single-impurity Kondo temperature $T_K$ and the other from a larger inter-site spin-liquid
temperature \( T^* \) which involves the inter-site antiferromagnetic correlations. From their high-\( T \) heat capacity data, they claimed that the CEF scheme remains unchanged as a function of La-concentration.

However, to achieve a complete microscopic understanding of the evolution of physical properties induced by La-doping in CeRhIn\(_5\) and CeCoIn\(_5\) is a very difficult task as the doping may affect simultaneously, and in a combined way, the in-site Kondo effect, the inter-site RKKY interaction, the CEF effects, the electronic structure and also introducing disorder. In this sense, the study of structurally-related compounds within the \( R_m M_n In_{3m+2n} \) family have been successfully used to understand the evolution of 4f-electrons magnetism for many members of the series in situations where some of the contributions above can be negligible. For instance, in the Gd\(_m M_n In_{3m+2n} \) (\( M = \) Rh and Ir) compounds, as Gd\(^{3+}\) is a pure \( (S = 7/2, L = 0) \) spin ion, the RKKY interaction and its dependence with electronic structure is the main contribution. For the Nd- and Tb-based members of the \( R_m M_n In_{3m+2n} \) family, both RKKY interaction and CEF effects are present, and the CEF contribution can be evaluated for Krammers (Nd\(^{3+}\), \( J = 9/2 \)) and non-Krammer ions (Tb\(^{3+}\), \( J = 6 \)) without the complexity of the Kondo lattice behavior of the Ce-based compounds.

Nonetheless, to the best of our knowledge, none of these isostructural magnetic relatives of CeM\(_n\)In\(_5\) had their properties systematically investigated as a function of dilution.

In this work, we have studied dilution effects on TbRhIn\(_5\) as the Tb\(^{3+}\) ions are substituted by non-magnetic La\(^{3+}\) ions for \( 0 \leq x \leq 1.0 \). The TbRhIn\(_5\) intermetallic compound orders antiferromagnetically with a commensurate magnetic structure \((0, 1, 0)\) below \( T_N \sim 46 \text{ K} \), which is the highest \( T_N \) among the \( RRhIn_5 \) compounds. Results from magnetic susceptibility and specific heat data taken below \( \sim 150 \text{ K} \) down to 2 K in Tb\(_{1-x}\)La\(_x\)RhIn\(_5\) \((x = 0.15, 0.4 \) and 0.5) as well as the magnetic structure determination for the Tb\(_{0.6}\)La\(_{0.4}\)RhIn\(_5\) compound using resonant x-ray magnetic scattering (XRMS) are reported. From the analysis of the evolution of magnetic properties of the studied samples as a function of La-concentration, we evaluate the role of the different mechanisms for the suppression of the long-range AFM coupling by considering dilution, changes in the CEF scheme and the introduction of disorder. Additionally, the XRMS measurements has shown that the commensurate magnetic structure \((0, 1, 0)\) observed for the undoped compound is robust against doping perturbations, indicating that no changes in the relative spin interaction of neighboring Tb-spins are taking place. These results are discussed in a broader prospective considering others members of the \( R_m M_n In_{3m+2n} \) family.

![FIG. 1: Lattice cell parameters \( a \) and \( c \) vs. lanthanum concentration \( x \) for the Tb\(_{1-x}\)La\(_x\)RhIn\(_5\) system. The dotted line is a linear fit to both datasets.](image)

**II. EXPERIMENTAL**

All measurements were taken on single-crystalline samples grown by the Indium excess flux. Typical crystal sizes were 0.5 cm x 0.5 cm x few mms. The tetragonal HoCoGa\(_5\)-type structure and crystals phase purity were confirmed at ambient temperature by X-ray powder diffraction. Magnetization measurements were performed as a function of temperature in a commercial superconducting quantum interference device (SQUID) magnetometer. Specific heat data was taken using a commercial physical property measurement system (PPMS) using the adiabatic relaxation method in the temperature range between 1.9 - 150 K. The x-ray resonant magnetic scattering (XRMS) experiments were performed at the XRD2 beamline of the Laboratório Nacional de Luz Síncrotron (LNLS), Brazil, and the description of the experimental setup used can be found on Refs. 22, 25, 31.

**III. RESULTS AND DISCUSSION**

Fig. 1 displays the cell parameters for \( x = 0, 0.15, 0.3, 0.4, 0.5, 0.6, 0.7 \) and 0.9 Lanthanum concentration. Both parameters expand linearly with concentration \( x \) (taking \( x \) as the nominal concentration given by the Ce/La ratio in the starting materials) as the larger La\(^{3+}\) ion is substituted into the Tb\(^{3+}\) site, in agreement with the Vegard’s law. The cell parameters \( a \) and \( c \) were determined from least-squares fits of the Bragg peak positions. (29)

Fig. 2 shows the magnetic susceptibility, \( \chi (T) \), and heat capacity, \( C(T)/T \), data for representative samples of Tb\(_{1-x}\)La\(_x\)RhIn\(_5\). \( \chi (T) \) data [Fig. 2(a–c)] were taken at a magnetic field \( H = 1 \text{ kOe} \) applied parallel to the
nominal concentration within concentrations were found to be in agreement with the increases. These temperatures taken from both measurements (horizontal error bars in Fig. 1). Therefore, we have from this consideration we define the tetragonal crystal field terms into the hamiltonian.

The actual La-concentration in our samples was estimated from linear fits to the inverse of the magnetic susceptibility at high-T (T > 200 K) assuming the full moment of 9.72 µB for the free Tb3+ ion. The obtained concentrations were found to be in agreement with the nominal concentration within ~ 4% for all doped samples (horizontal error bars in Fig. 1). Therefore, we have used the nominal concentrations, x, in this work.

The Fig. 2 demonstrate the shift to lower values of the temperatures at which the maximum in the susceptibility occurs, and the specific heat has a peak, as the La-content increases. These temperatures taken from both measurements coincides reasonably well, therefore we take this temperature as the Néel temperature, T_N, for all samples. From this consideration we define T_N for the two doped samples x = 0.15 and 0.40 as being 43 and 34 K, respectively. The shift of T_N to lower values is a signature from the expected suppression of the long-range-ordered AFM state. For all cases, the susceptibility is anisotropic but the ratio χ///χ⊥, defined at the maximum of the χ// data, remains almost the same (roughly 2.12, 2.06 and 1.91 for x = 0, 0.15 and 0.4, respectively). Additionally, the transitions in the specific heat data become evidently broader as a function of La-doping.

Fig. 3 displays the T_N behavior for the studied compounds normalized by the T_N value of the TbRhIn5 compound (T_N(x)/T_N(x=0)) - filled symbols. Similar data obtained for Ce1−xLa_xRhIn5 (open symbols) is included for comparison. Interestingly, the suppression of T_N as a function of La-doping is less dramatic in Tb1−xLa_xRhIn5 when compared to Ce1−xLa_xRhIn5, and its behavior follows approximately a power-law decrease, differently from the Ce-based series, where a linear decrease of T_N was observed. The critical concentration for which T_N → 0 was found to be x_c ≈ 0.7 for Tb1−xLa_xRhIn5 in contrast to the x_c ≈ 0.4 found for Ce1−xLa_xRhIn5.

La-doping perturbations in the AFM state of TbRhIn5 was further explored through x-ray magnetic diffraction experiments in a crystal of Tb0.6La0.4RhIn5 from the same batch used for the macroscopic measurements above. These measurements were performed with the incident photon energy at both L2 and L3 Tb absorption edges (resonant condition) in order to enhance the small signal from the AFM order of Tb ions below T_N. We found satellite peaks at reciprocal space positions corresponding to the same reciprocal propagation vector found in the undoped TbRhIn5, i.e. (0, 1/2, 1/2) indicating that Tb0.6La0.4RhIn5 orders in a commensurate AFM single k structure (k - propagation vector). Above T_N we only found charge Bragg peaks from the tetragonal HoCoGa5-type structure. Other magnetic peaks, representing twinned AFM domains, were also observed at (1/2, 0, 1/2), (1/2, 0, 1/2) and (1/2, 0, 1/2) reciprocal space positions (not shown). A comparison between the intensities...
of the symmetrically-equivalent reflections \((\frac{1}{2},0,\frac{1}{2})\) and \((0,\frac{3}{2},\frac{1}{2})\) reveals a higher \((0,\frac{3}{2},\frac{1}{2})\) domain population over the \((\frac{1}{2},0,\frac{1}{2})\) ones \([h, k, l\text{ integers}]\), the later representing roughly 75% of the former.

Open circles in Fig. 4(a) and (b) represent the resonance profiles of the superlattice diffraction peak \((0,\frac{1}{2},\frac{1}{2})\) around the \(L_2\) (8.253 keV) and \(L_3\) (7.514 keV) Tb absorption edges, respectively, taken at 11 K. The spectral shapes are typical of magnetic scattering from the ordered moments of the Tb ion sublattices and the peak maxima coincides with the inflection point of the fluorescence spectrum (not shown), revealing the E1 electric dipole-type resonance involving electronic transitions \(2p_{1/2} \rightarrow 5d\) and \(2p_{3/2} \rightarrow 5d\). Therefore, we used the energy where maxima in Figs. 4 take place as incident energies for all our measurements of magnetic peaks. Full lines are single-Lorentzian fits from which we were able to get the resonance width, as being 8.4 eV for \(L_2\) and 6.7 eV for \(L_3\). This width is inversely proportional to the resonance core-hole lifetime. The photon energy variation profile at a fixed reciprocal point has proved to be higher \((I(L_{111})/I(L_{111}) \approx 3\text{ eV})\) and narrower at the \(L_3\) Tb edge, which confirms the \(L\)-edge resonances behavior of the \(Tb^{3+}\) ion previously suggested in Refs. 33 and observed for other rare-earth-based compounds.

Fig. 5 displays the temperature dependence of the \((0,\frac{1}{2},\frac{1}{2})\) magnetic Bragg peak intensities, which is proportional to the Tb magnetization sublattice, obtained from numerical integrations to \(\theta - 2\theta\) scans (using a Pseudo-Voigt function). The data was taken between \(T = 11–37\) K with a \(T\)-step of 1 K while warming the sample. The inset shows the experimental (filled circles at \(T = 15\) K and open ones at \(T = 37\) K) and calculated curves (continuous line) together. Error bars in the main panel represent statistical standard deviation from the fits. The decrease of the Bragg intensities as the temperature is increased toward the bulk \(T_N\) denotes also the magnetic character of this reflection. It smoothness is a signature of a second order-type transition.

The XRMS results, together with the properties shown in Fig. 2, demonstrate the existence of long-range AFM correlations for the \(x = 0.4\) doped sample. From the point of view of magnetic diffraction, it seems that the AFM propagation vector does not change as function of La-doping up to \(x = 0.4\). As such, we may argue that the relative spin orientation of neighboring \(Tb^{3+}\) ions is not strongly modified by dilution in the \(x = 0.4\) sample, re-enforcing the long range character of the RKKY interaction between the \(Tb^{3+}\) ions. Further, this result may be indicative that the balance between the Tb first and second-neighbors interactions \((J_1 \text{ and } J_2, \text{ respectively})\) is the same as for the undoped \(TbRhIn_5\) compound.

Nonetheless, from our recent data we can not determine the direction of magnetic moments in the Tb sublattice through the comparison between observed and calculated integrated intensities of magnetic peaks because only three reflections from the same AFM domains were reached with our experimental setup. Therefore, new data in the resonant condition are required to know the moments orientation for this La-doped sample. Particularly, it should be interesting to includes azymuthal...
Table I: $T_N$ and CEF parameters for $\text{Tb}_{1-x}\text{La}_x\text{RhIn}_5$

|        | $T_N$(K) | $B_{20}$(K) | $B_{40}$(K) | $B_{44}$(K) | $B_{60}$(K) | $B_{64}$(K) |
|--------|----------|-------------|-------------|-------------|-------------|-------------|
| $\text{TbRhIn}_5$ | 45.6     | -1.9        | -2.2        | $6.4 \times 10^{-3}$ | $-4.5 \times 10^{-5}$ | $2.7 \times 10^{-3}$ |
| $\text{Tb}_{0.85}\text{La}_{0.15}\text{RhIn}_5$ | 42.8     | 1.8         | -1.8        | $6.8 \times 10^{-3}$ | $5.6 \times 10^{-2}$ | $7.5 \times 10^{-5}$ | $2.3 \times 10^{-3}$ |
| $\text{Tb}_{0.4}\text{La}_{0.6}\text{RhIn}_5$ | 32       | 1.6         | -1.8        | $1.1 \times 10^{-2}$ | $-3.6 \times 10^{-3}$ | $-1.0 \times 10^{-4}$ | $-2.6 \times 10^{-3}$ |

dependence of magnetic peaks intensity combined with polarization analysis.

We now discuss the effects of La-doping in the antiferromagnetic interaction between the Tb$^{3+}$ ions in $\text{TbRhIn}_5$. The first obvious effect is dilution. As La$^{3+}$ replaces the Tb$^{3+}$, the average distance between the remaining Tb$^{3+}$ increases and consequently the RKKY magnetic exchange between them decreases. Secondly, there is the chemical pressure effect induced by the difference in ionic size between La$^{3+}$ and Tb$^{3+}$. This can affect the CEF effects at the Tb$^{3+}$ site. These effects maybe subtle but are not straightforward. Slight modifications in the CEF scheme and/or wave-functions can cause significant changes in $T_N$ and in the magnetic anisotropy of the ordered state for low-symmetry systems. Last, there could exist the effect of chemical disorder caused by a not perfectly homogeneous La-distribution through the sample. This may cause competing magnetic interaction between Tb$^{3+}$ ions in different grains, creating multiple spin configuration and/or distribution of $T_N$, leading to the suppression of the long range ordered state.

In order to account for the evolution of the first and second effects above we have used our MF model from Ref. 27 to fit concomitantly the whole set of data of Fig. 2. In Fig. 6 we show the CEF schemes obtained from the best fits to the data of the representative samples shown in Fig. 2.

Before we proceed with the analysis of the results presented in Fig. 6, it is important to discuss the reliability of these results because CEF parameters obtained from fits to macroscopic measurements data could be mistaken and not unique. Is is known that, in general, a given set of parameters can describe very nicely a set of experimental macroscopic results and completely fail in describe others and that a definitive determination of CEF schemes and/or parameters usually requires direct measurements by inelastic neutron scattering (INS).

In an earlier report, we proposed a CEF scheme for pure $\text{TbRhIn}_5$ obtained from fits to magnetic susceptibility and specific heat data. This CEF scheme was based on a $\Gamma_5^{(1)}$ doublet ground state and an overall splitting of $310 \text{ K}$. Later, low temperature magnetization experiments shown that this scheme is incompatible with the high field ($H > 10 \text{ T}$) magnetization data taken at $T = 2 \text{ K}$ for a magnetic field applied along the $c$-axis. As such, in Ref. 25, the authors proposed an alternative scheme of levels with a singlet ground state and overall splitting of about $220 \text{ K}$. This alternative scheme agrees qualitatively with the high field behavior of their $T = 2 \text{ K}$ magnetization data but it does not give a better fit to the $\chi(T)$ and zero field $C_p(T)$ data than that obtained with the CEF scheme of Ref. 25.
Taking into account all the above, we have re-analyzed our $\chi(T)$ and zero field $C_p(T)$ and the high field magnetization data of Ref. [35] and obtained the new CEF scheme of levels present in Fig. 8 for pure TbRhIn$_5$. The new scheme has a singlet ground-state with a first excited singlet at 10 K and an overall splitting of $\sim 350$ K (see Fig. 8 left scheme). Although both present a singlet ground state, the TbRhIn$_5$ CEF scheme of Fig. 8 and the one from Ref. [35] display appreciable differences in terms of energy level and wave functions. These level of controversy usually requires direct measurements by INS to be completely solved, however our preliminary CEF parameters determination and data fits proceeding allow us to follow the La-doping induced changes in the crystal field and the modifications on the AFM state of TbRhIn$_5$. Further, it is important to emphasized that the qualitative evolution of the CEF scheme and parameters as a function of La-doping was found to be nearly independent of the details of a particular choice of CEF parameters (and scheme) for pure TbRhIn$_5$ (Fig. 4 or Ref. [35]).

Analyzing the La-doping evolution of the CEF energy level schemes in Fig. 8 we observe that for $x \lesssim 0.4$ the best fits yield ground-state singlets and a non-monotonic evolution of the overall CEF splitting as a function of La-doping. However, one can clearly observes a trend in the low-$T$ energy levels ($T < 200$ K), showing a compression to lower temperature ranges. This effect causes the increase of the low-$T$ magnetic entropy and may certainly affect $T_N$ and the ordered state\textsuperscript{22}. Additionally, the set of CEF parameters giving place to the fits of Fig. 2 and to the schemes of Fig. 8 show systematic changes as the La-concentration is increased, see Table 1 and Fig. 7.

From Fig. 7 one can obviously notice the effect of dilution by decreasing the effective Tb$^{3+}$-Tb$^{3+}$ exchange interaction, $J_{\text{RKKY}}$, as well as the modification of the crystal field parameters due the Lattice expansion caused by La-doping. Although these two effects are maybe expected, it is not obvious how they are combined to suppress $T_N$ and to affect the details of the ordered state of complex magnetic systems in dilution studies.

In order to explore separately the two effects above, we used our MF model to simulate the evolution of $T_N$ while changing the CEF parameters values of Table 1 for a fixed $J_{\text{RKKY}} = 0.2$ meV (obtained for the undoped TbRhIn$_5$). Alternatively, we study the $T_N$ suppression with the La-doping solely due to the decrease of $J_{\text{RKKY}}$ and keeping unchanged the CEF scheme of the TbRhIn$_5$ compound. The results of these procedures can be seen in Fig. 8. From this plot it is evident that the CEF changes and the decrease of $J_{\text{RKKY}}$ have comparable effects on the $T_N$ suppression. The $T_N$ shift due the changes of the CEF parameters by La-doping, $|\Delta T_N - \text{CEF}|$, is nearly the same as the $T_N$ shift resulting from the increase of the Tb$^{3+}$-Tb$^{3+}$ average distance changes by dilution, $|\Delta T_N - \text{RKKY}|$. However, both effects had to be taken into account to best reproduce the data of Fig. 2 and the experimental $T_N$ suppression of Fig. 8 (what we called modeled $|\Delta T_N|$). The significant decrease of $T_N$ induced by CEF is a non-trivial and important result that indicates that the effects of CEF changes should be generally taken into account when important temperatures scales are mapped and analyzed as function of doping in the RRhIn$_5$ family and related compounds.\textsuperscript{2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17}

Another important aspect of our results for Tb$_{1-x}$La$_x$RhIn$_5$ is the role of disorder on the properties of this series. Our theoretical model does not include any kind of disorder (for instance, a random distribution of $T_N$ and/or CEF parameters) and this is probably the reason why the fittings curves cannot reproduce the width of the AFM transition in the $C/T$ data of Fig. 2 for samples with higher La-concentration. This also prevents our models to achieve better fits to our data for $x = 0.4$. On the other hand, it interesting to notice that we do not see a clear contribution of the disorder in the suppression of the $T_N$ for $x \lesssim 0.4$, as we were able to simulate the experimental data and the $T_N$ behavior only by considering dilution and CEF tuning effects (see Figs. 2 and 8).

Finally, the last interesting point to be addressed is the comparison between the $T_N$ suppression in Tb$_{1-x}$La$_x$RhIn$_5$ and in its HF counterpart Ce$_{1-x}$La$_x$RhIn$_5$ given in Fig. 8. It is evident that the critical concentration $x_c \approx 0.7$ for Tb$_{1-x}$La$_x$RhIn$_5$ is much higher than the $x_c \approx 0.4$ found for Ce$_{1-x}$La$_x$RhIn$_5$. While the $x_c \approx 0.4$ for Ce$_{1-x}$La$_x$RhIn$_5$ is close to the 2D percolation threshold for a Heisenberg square lattice,\textsuperscript{9,18} the $x_c \approx 0.7$ for Tb$_{1-x}$La$_x$RhIn$_5$ is the same as for a 3D lattice. Thus, a simple argument to understand the increase in $x_c$ for...
Tb$_{1-x}$La$_x$RhIn$_5$ may be given by its more 3D character, as the tetragonal lattice parameters ratio $c/a$ decreases along the $RR$RhIn$_5$ series.$^{21,25}$ On the other hand, it is clear that the non-linear suppression of $T_N$ is in obvious contrast to the linear behavior found for Ce$_{1-x}$La$_x$RhIn$_5$ and even for cubic Ce$_{1-x}$La$_x$In$_3$ ($x_c \approx 0.7$). In this regard, it is interesting to notice that for Tb$_{1-x}$La$_x$RhIn$_5$ we found a roughly linear decrease of $T_N$ as a function of $x$ up to $x \sim 0.4$ (see Fig. 3). This linear behavior of the $T_N$ decrease could be successfully understood by monotonic evolution of $J_{RKKY}$ and the CEF parameters as a function of $x$ (see Figs. 7 and 8). However, for $0.4 < x \lesssim 0.7$, the $T_N$ decrease becomes more abrupt and we were no longer able to fit the data using our model in this range of concentration, presumably due to the role of disorder. Therefore, we speculate that the non-trivial $T_N$ suppression for $0.4 < x \lesssim 0.7$ in Tb$_{1-x}$La$_x$RhIn$_5$ may be related to the details of the disorder effects near the percolation threshold. This effect has not been observed in Ce$_{1-x}$La$_x$RhIn$_5$ and cubic Ce$_{1-x}$La$_x$In$_3$ because the difference in ionic size between Tb$^{3+}$ and La$^{3+}$ ions is much larger than between Ce$^{3+}$ and La$^{3+}$. In addition, the percolation problem including an exchange interaction with long range character, as the RKKY interaction, have not been completely understood even in a perfectly ordered system.$^{26}$ In fact, our XRRS results for $x=0.4$ indicate that the relative exchange interaction between neighboring Tb$^{3+}$ ions is very robust against La-doping which suggests that, due to the long range character of the RKKY interaction, the dilution-induced $J_{RKKY}$ decrease may be much smaller than that expected for a Heisenberg square lattice$^{9,18}$ specially for a more 3D-system.

### IV. CONCLUSIONS

In summary, we have performed magnetic susceptibility and specific heat measurements for the Tb$_{1-x}$La$_x$RhIn$_5$ ($x = 0.15$, 0.3, 0.4 and 0.5) diluted compounds. We also presented preliminary results of resonant x-ray magnetic scattering experiments in Tb$_{0.6}$La$_{0.4}$RhIn$_5$. The AFM structure revealed is commensurate with the same propagation vector $(0 \frac{1}{2} \frac{1}{2})$ of the undoped compound, which indicates the same relative interaction $J_1/J_2$ between Tb$^{3+}$-neighbors. Néel temperature decreases with a non-linear behavior as a function of Lanthanum concentration and extrapolates to zero at roughly 70% of La content, which demonstrates that for TbRhIn$_5$ the non-magnetic La-substitution shifts the dilution limit differently to the $x_c \sim 40$% observed for Ce$_{1-x}$La$_x$RhIn$_5$ and (Ce$_{1-x}$La$_x$)$_2$RhIn$_5$ families. Furthermore, our mean field model simulation for Tb$_{1-x}$La$_x$RhIn$_5$ ($x \lesssim 0.4$) reveals that the crystal field scheme evolves as a function of doping and that this evolution affects $T_N$ as much as the decreasing in $J_{RKKY}$ due to dilution. This effect may be of great importance in phase diagrams of complex magnetic systems where the AFM is tuned to zero temperature by chemical substitution.

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