Physical properties and magnetic structure of TbRhIn₅ intermetallic compound.

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In this work we report the physical properties of the new intermetallic compound TbRhIn₅ investigated by means of temperature dependent magnetic susceptibility, electrical resistivity, heat-capacity and resonant x-ray magnetic diffraction experiments. TbRhIn₅ is an intermetallic compound that orders antiferromagnetically at \( T_N = 45.5 \text{ K} \), the highest ordering temperature among the existing RRhIn₅ \((1-1-5, \text{R = rare earth})\) materials. This result is in contrast to what is expected from a de Gennes scaling along the RRhIn₅ series. The X-ray resonant diffraction data below \( T_N \) reveal a commensurate antiferromagnetic (AFM) structure with a propagation vector \((\frac{1}{2} 0 \frac{1}{2})\) and the Tb moments oriented along the c-axis. Strong (over two order of magnitude) dipolar enhancements of the magnetic Bragg peaks were observed at both Tb absorption edges \( L_{II} \) and \( L_{III} \), indicating a fairly high polarization of the Tb 5d levels. Using a mean field model including an isotropic first-neighbors exchange interaction \((J_{R-R})\) and the tetragonal crystalline electrical field (CEF), we were able to fit our experimental data and to explain the direction of the ordered Tb-moments and the enhanced \( T_N \) of this compound. The evolution of the magnetic properties along the RRhIn₅ series and its relation to CEF effects for a given rare-earth is discussed.

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I. INTRODUCTION

The discovery of new series of structurally related compounds with novel physical behavior is an important approach to explore fundamental problems in the physics of highly correlated electron systems. Such problems include the interplay between superconductivity, magnetism and heavy fermion behavior in structurally related materials. Although the microscopic origin of this interplay remains a mystery, the search for new heavy fermion superconductors (HFS) is partially guided by the knowledge that certain structures favor the formation of this heavy electron ground state. Remarkable examples of amazing physical properties occurring in structurally related compounds are the series Ce₃MIn₃m+2 \((M = \text{Co, Rh or Ir}, \text{m} = 1,2,3,4,5,6,7)\) and their Pu-based analogs PuMGa₅ \((m = 8,9,10)\). These materials grow in a tetragonal variant of the Cu₃Au-type structure and can be viewed as layers of a cubic cell (CeIn₃ or PuGa₃) stacked sequentially along the c-axis with intervening layers of \( \text{M(In,Ga)}_2 \). The discovery of unconventional superconductivity (USC) in many of these compounds is an exciting opportunity to further explore the possibility of magnetically mediated superconductivity in strongly correlated electrons systems and its relationship with dimensionality and crystal structures. For instance, systematic alloying studies in \( \text{CeRh}_{1-x}\text{Ir}_x\text{In}_5 \) and \( \text{PuCo}_{1-x}\text{Rh}_x\text{Ga}_5 \) possess the highest superconducting transition temperature, \( T_c = 18 \text{ K} \), among the pure Pu-based compounds. This apparent contradiction is directly related to an open question in condensed matter physics regarding the details of the crossover between quasi-localized 4f electron magnetic behavior at high-T to a renormalized heavy-electron state at lower temperatures. However, if certain structures favor USC mediated by magnetic fluctuations, it is an important first step to understand how layered structures can affect CEF anisotropy, magnetic exchange and/or anisotropic transport properties (quasi-2D band-structure). In this regard, detailed studies of the 4f electrons magnetism along the series of rare-earth and actinides based 1-1-5 compounds may be very elucidative.

In the case of the Ce-based compounds, their Nd-, Sm- and Gd-based structurally related magnetic mate-
rials have been studied in detail. It has been found that the magnetic properties of these non-Ce analogs mainly depend on the interplay between CEF effects and exchange magnetic interaction. For example, among the Nd-based compounds NdMIn$_5$ and Nd$_2$MIn$_8$ analogs for M = Rh or Ir, it was found a systematic relationship between the AFM ordering temperature $T_N$ and the low-$T$ CEF splitting. Besides, when the magnetic properties of the tetragonal variants NdMIn$_5$ and Nd$_2$MIn$_8$ are compared to that for its cubic NdIn$_3$, $T_N$ is enhanced by a factor of two. In contrast, the tetragonal CeRhIn$_5$ and Ce$_2$RhIn$_8$ present a $T_N$ a factor of two smaller than that for CeIn$_3$ whereas for the Gd-based tetragonal materials the low temperature magnetic properties remain nearly unaltered compared to the GdIn$_3$. Finally, the resolved magnetic structures for some of these compounds have revealed that the rare-earth magnetic moments lie in the $ab$-plane for CeRhIn$_5$ and GdRhIn$_5$ compounds and point along the $c$-axis for NdRhIn$_5$ tetragonal materials.

To further explore the trends in the evolution of the magnetic properties within the series, particularly for the RRhIn$_5$ compounds, we have investigated the physical properties and magnetic structure of a new member of this series, TbRhIn$_5$. It was found to be an intermetallic compound that orders antiferromagnetically at $T_N \sim 46$ K, the highest ordering temperature among the existing RRhIn$_5$ materials. The magnetic structure of TbRhIn$_5$, resolved using Resonant X-ray Magnetic Diffraction (RXMD) experiments, is commensurate with propagation vector $\tau = (\frac{1}{2} \ 0 \ \frac{1}{2})$ and the Tb moments oriented along the $c$-axis. The direction of the ordering Tb-moments and the enhanced $T_N$ of this compound were successfully explained by a mean field model including an isotropic first-neighbors exchange interaction ($J_{R-R}$) and the tetragonal CEF, and was used to fit the magnetic susceptibility and specific heat experimental data.

Besides revealing the magnetic properties of this novel compound, the reported results confirm the CEF driven $T_N$ behavior and the direction of ordered moments observed in other members of the series. We discuss also the particular case where the rare-earth moments order out of the $c$-axis, for which $T_N$ can be reduced by tuning the CEF parameters. This fact represents an interesting frustration mechanism that may play some role in the origin of the relevant low-dimensional SF in complex classes of materials such as the Ce$_{m}$MIn$_{3m+2}$ (M = Rh, Ir and Co; $m = 1, 2$) HFS.

II. EXPERIMENT

Single crystals of TbRhIn$_5$ with dimensions up to 2 cm$^3$ approximately were grown from In-flux, as reported previously. Most of the crystals show columnar habit, with their long axis along the tetragonal $c$-axis. The tetragonal HoCoGa$_5$-type structure with cell parameters $a = 4.595(4)$ Å and $c = 7.418(4)$ Å were confirmed by x-ray powder diffraction and the crystal orientation was determined by the usual Laue method. Specific heat measurements were performed in a Quantum Design PPMS small-mass calorimeter that employs a quasi-adiabatic thermal relaxation technique. Magnetization measurements were made in a Quantum Design $dc$ Superconducting Quantum Interference Device and electrical resistivity was measured using the PPMS low-frequency $ac$ resistance bridge and four-contact configuration. The samples used in the electrical resistivity measurements were previously screened for In-free surface contamination.

RXMD measurements were carried out at the bending magnet beamline XRD2 of the Brazilian Synchrotron Light Source (LNLS), in Campinas, Brazil using a double-bounce Si (111) monochromator, with sagittal focusing. A Rh-coated mirror was used to vertically focus the beam and also to eliminate third and higher-order harmonics in the incident beam. The bending magnet source delivers photon beams with a flux of $\sim 3 \times 10^{10}$ photons/s around 8 keV at 100 mA in spot of $\sim 0.6$ mm (vertical) x $2.0$ mm (horizontal) at the sample, with an energy resolution from the source of $\Delta E \sim 10^{-4}$. Our experiments were performed in the vertical scattering plane, i.e., perpendicular to the linear polarization of the incident photons ($\sigma$ polarization).

Although neutron diffraction is the natural choice of experiments to resolve magnetic structures, RXMD offers the advantage that only very small samples are required. For the RXMD experiments the high resolution of the magnetic reflections is obtained as a natural consequence of the intrinsic collimation of the synchrotron x-ray source, and the small cross section ensures that even for strong magnetic Bragg peaks, the intensity is not extinction limited and a reliable measurement of the order parameter is possible. In our experiments high count rates were obtained, allowing a precise temperature dependence of the ordered Tb moments.

A platelet of TbRhIn$_5$, from the same batch as that used for macroscopic properties measurements, was mechanically polished perpendicular to $c$-axis ((0 0 1) flat surface) to eliminate surface contamination from the residual flux and to increase the reflectivity, which gives a mosaic spread characterized by the full width at half maximum (FWHM) of $\sim 0.04^\circ$. The sample was cut parallel to the $ab$-plane to have a final shape of a long block with dimensions of 4x3x1 mm$^3$ and to investigate reflections in the $[h \ 0 \ l]$ zone axis. The size of the sample was chosen to ensure that the beam completely reaches the crystal in the scattering plane for all angles of interest. The sample was mounted on the cold finger of a closed-cycle He cryostat (base temperature 11 K) with a cylindrical Be window.
III. RESULTS

The temperature dependence of the magnetic susceptibility measured for a magnetic field $H = 1$ kOe applied parallel $\chi_{//}$ and perpendicular $\chi_{\perp}$ to the $c$-axis is presented in Fig. 1(a). Fig. 1(b) shows the polycrystalline average of Fig. 1(a) data taken as $\chi_{\text{poly}} = (\chi_{//} + 2 \chi_{\perp})/3$.

![Figure 1](image)

**FIG. 1:** (a) Temperature dependence of the magnetic susceptibility for TbRhIn$_5$, for $H = 1$ kOe applied parallel (open squares) and perpendicular to the $c$-axis (open circles). The solid lines are best fits to the data for both directions using our mean field model (see below). (b) $\chi_{\text{poly}}(T)$ and the inverse $1/\chi_{\text{poly}}(T)$; the solid line is the best fit to the $1/\chi_{\text{poly}}$ data for $T > 140$ K. From this fit we extracted $\mu_{\text{eff}} = 9.4(1) \mu_B$ and $\theta = -47(1)$ K for TbRhIn$_5$.

From a linear fit to the inverse of $\chi_{\text{poly}}(T)$ for $T > 140$ K using a Curie-Weiss law, we have obtained a Curie-Weiss temperature $\theta = -47(1)$ K and the Tb$^{3+}$ effective magnetic moment $\mu_{\text{eff}} = 9.4(1) \mu_B$. As it can be seen in Fig. 1(a) the magnetic susceptibility of TbRhIn$_5$ is higher for the field applied along the $c$-axis, in agreement to what was found for all other non-S-R members of these series.$^{3,38,19}$ The ratio $\chi_{//}/\chi_{\perp} \sim 2.08$ taken at $T_N$ is mainly determined by the tetragonal CEF and it reflects the same order of magnetic anisotropy found for other members of these series.$^{3,38,19}$ The solid lines in Fig. 1(a) are the best fits to the data using a mean field model which includes an isotropic first-neighbors exchange interaction and the tetragonal CEF.$^{25}$ The best fit yields a $\Delta = 0.2$ meV ($\Delta = 0.2$ meV is equal to $\Delta$ in Ref. 25) for the exchange parameter and the CEF parameters $B_{20} =$ 1.4 x $10^{-3}$ meV, $B_{44} = 1.3 x 10^{-4}$ meV, $B_{44} = 5.3 x 10^{-4}$ meV, $B_{60} = 0.21 x 10^{-4}$ meV, $B_{64} = 1.5 x 10^{-4}$ meV. The CEF level scheme obtained from the splitting of the Tb$^{3+}$ ($J = 6$) multiplet by above parameters is built up of three doublets and seven singlets with an overall splitting of roughly 310 K. The calculated curves using our model reproduce very well the magnetic anisotropy and the peak of the magnetic susceptibility at $T_N \sim 45.5$ K for both directions (Fig. 1(a)). At lower-$T$ an intrinsic and anisotropic Curie-like tail can be seen in the magnetic susceptibility data and it is presumably associated with an additional magnetic transition with changes in the magnetic structure which happens within the ordered state (similarly to TbIn$_3$ cubic compound at higher temperatures$^{25,29}$).

![Figure 2](image)

**FIG. 2:** (a) Specific-heat data divided by temperature as a function of temperature for a single crystal of TbRhIn$_5$. The solid line is the best fit to this data using our mean field model. (b) The corresponding magnetic entropy in the temperature range 2°C< $T <$150 K for TbRhIn$_5$.

Fig. 2(a) shows the specific heat divided by temperature and the corresponding magnetic entropy (Fig. 2(b)) in the temperature range 0°C< $T <$150 K for TbRhIn$_5$. To calculate the magnetic entropy, the phonon contribution was estimated from the non-magnetic specific-heat data of YRhIn$_5$ and subtracted from the total specific heat of the magnetic compound. The recovery magnetic entropy at high-$T$ is close to its expected values for $J = 6$. An anomaly in the specific-heat data associated with the onset of AFM order can be seen at $T_N = 45.5$ K in good agreement with the temperatures where the maximum in the magnetic susceptibility occurs (see Fig. 1). Again, the solid line in Fig. 1(a) represents the best fit to the data using our mean field model for the same parameters used in the fit of the $\chi(T)$ data (the best set of parameters was obtained from simultaneous minimization process for both $\chi(T)$ and $C/T(T)$ data).

The temperature dependence of the electrical resistivity for TbRhIn$_5$ single crystals is plotted in Fig. 3. Among various measured crystals, the room temperature value of the resistivity ranges between 10 – 35 $\mu\Omega$ cm indicating the high quality of the crystals. At high temperature the data always showed a metallic behavior while, at low temperatures, a clear kink can be seen at the ordering temperature $T_N$.

The $c/a$ ratio and $T_N$ values for RRhIn$_5$ compounds are shown in Fig. 4. The solid line in Fig. 4(a) is the expected behavior for $T_N$ and $\theta$ according to de Gennes factor $(g J-1)^2 (J+1)$ for the ground-state multiplet $J$ of each rare earth normalized by their values for GdRhIn$_5$. 

As for \( R = \text{Ce and Nd} \), \( T_N \) of the TbRhIn\(_5\) does not follow the de Gennes scaling. Interestingly, \( T_N \) for TbRhIn\(_5\) is the highest among the existing RRhIn\(_5\) members.

The microscopic low-temperature magnetism of TbRhIn\(_5\) was further investigated by RXMD. For the sample orientation used in the experiments, with the zone axis \([h 0 l]\) parallel to the scattering plane, the resonant scattering cross section (the non-resonant scattering contribution was observed to be negligible) for the case of a dipolar resonance with a linear polarized incident beam perpendicular to the scattering plane may be written as:

\[
I \propto \left| \sum \hat{u}_n \cdot \hat{k}_f e^{iQ \cdot r_n} \right|^2
\]

where \( Q = k_f - k_i \) is the scattering vector, \( \hat{k}_f \) is the direction of the scattered wave vector \( k_f \), and \( \hat{u}_n \) is the moment direction at the \( n \)th site. The proportionality symbol \( \propto \) includes \( Q \)-independent resonant amplitudes, the Lorentz factor, arbitrary scale factors and an angular correction factor for asymmetric reflections. The summation is over all the \( n \)th resonant ions in the magnetic unit cell and \( r_n \) is the position of such an ion. Note that in the present geometry and in the absence of an in-plane \( \pi \) polarized component of the incident beam, the dipolar resonant cross section terms are not sensitive to the component of the ordered moment perpendicular to the scattering plane (i.e., along the \( b \) axis).

Below \( T_N \sim 46 \text{K} \), careful scans along \([h 0 l]\) direction revealed superstructure Bragg peaks of type \((\frac{2n+1}{2} \ 0 \ \frac{2m+1}{2})\) \((n, m \text{ integers})\), appearing as a result of the strong resonant enhancements of the magnetic peaks for both Tb \( L_{11} \) and \( L_{11} \) edges, and the high magnetic moment per Tb\(^{3+}\) ion of \( \mu = 9.5 \ \mu_B \). In the low temperature phase, magnetic peaks \((0 \ \frac{2n+1}{2} \ \frac{2m+1}{2})\) were also observed, revealing a twinned magnetic structure. The intensities of \((\frac{2n+1}{2} \ 0 \ \frac{2m+1}{2})\) and \((0 \ \frac{2n+1}{2} \ \frac{2m+1}{2})\) were comparable, suggesting approximately equal domain population. Therefore, our magnetic cell is duplicated in the \( a \) and \( c \) directions when compared to the chemical one. Above \( T_N \) only charge peaks consistent with the tetragonal HoCoGa\(_5\)-type structure were observed. The widths (FWHM) of magnetic peaks were the same as that for equivalent scans through a charge Bragg peak.

![FIG. 3: Temperature dependence of the electrical resistivity for TbRhIn\(_5\) single crystal. The current (I) has been applied parallel to the \( ab \)-plane. The solid arrow point out a kink at the Néel temperature for this compound.](image)

![FIG. 4: \( T_N \) (a) and \( c/a \) ratio (b) for the RRhIn\(_5\) compounds. The solid line in (a) represents the de Gennes factor \((g_J - 1)^2J(J+1)\) for the ground state multiplet \( J \) of the rare earth ions, normalized by the GdRhIn\(_5\). The dashed line in (b) is just a guide to the eye.](image)
of the ordered moments is determined within $\sim 10^9$ of the $c$-direction.

In Fig. 6 the magnetic unit cell of TbRhIn$_5$ is shown according to results depicted in Fig. 5. A half magnetic cell is shown with moment directions at the Tb$^{3+}$ ion crystallographic sites.

In order to use the resonant enhancement of the magnetic peaks, the primary beam energy was tuned to the $L_{II}$ and $L_{III}$ absorption edges of Tb$^{3+}$ ion (tabulated as being 8252 eV and 7514 eV, respectively). In Figs. 7(a) and (b) we plot the scattered intensity of the $(\frac{1}{2} 0 \frac{1}{2})$ magnetic Bragg peak as a function of the incident photon energy on tuning through the $L_{II}$ and $L_{III}$ edges, respectively. The data were corrected for absorption (coefficient $\mu(E)$ is showed with the solid line curve and the right side scale in Figs. 7) using the fluorescence emission. The inflection points of $\mu(E)$ curves (vertical dashed line) were used to define the absorption edges. In both cases, the maximum resonant enhancement is observed $\sim 2$ eV above the edges, which is a signature of the electric dipole ($E1$) resonance involving electronic $\mu(E)$ and $\beta$ with our observations. Intensity oscillations have been observed above the edges, and can be ascribed to magnetic DAFS oscillations (Diffraction Anomalous Fine Structure) which are oscillations of the anomalous scattering factors associated with the interference of the photoelectrons wave function with the surrounding atoms that bring a fine structure of oscillations in the energy line-shape spectrum.

The behavior of the ordered phase was measured as the temperature was raised at the $L_{II}$ edge. The measurements of the integrated intensities were performed on the $(\frac{1}{2} 0 \frac{1}{2})$ satellite reflection. In Fig. 8 the data of longitudinal scans along this reflection is displayed as function of the reduced temperature $T/T_N$. As the temperature increases, the peak intensity gradually decreases and disappears above $T_N$. This result, as well as the one obtained for the energy dependence described above, clearly confirm the magnetic nature of the observed peaks. Data were taken on two regimes: on warming (filled circles on Fig. 8) and cooling (open circles). A fitting to the usual power-law expression ($\sim (1 - T/T_N)^{2\beta}$) for a second order phase transition (denoted by a solid line in the inset) within the temperature range of approximately 3% below $T_N$ on the warming regime data gives a magnetic transition temperature $T_N = 45.56(2)$ K and a critical order exponent $\beta = 0.35(2)$ for the Tb sublattice magnetization. This value of $\beta$ is compatible with a three-dimensional Heisenberg system. No hysteresis was observed around the ordering temperature and the smooth decreasing in intensity in the crossover to the paramagnetic phase is consistent with a second order transition.

In Table 1 we summarize the experimental parameters obtained for TbRhIn$_5$ in this work.
IV. DISCUSSION

As discussed in the introduction, to follow the evolution of the 4f magnetism along the \( R_m \text{MIn}_{3m+2} \) series is a crucial first step to achieve a deeper understanding of the complex physical properties of these materials. Earlier comparative studies of the magnetic properties in this family have shown that for the Ce-based materials where the magnetic ordered moments are not aligned along the \( c \)-axis, \( T_N \) is suppressed to less than 0.5 of the CeIn\(_3\) value for CeRhIn\(_5\) where the Ce magnetic moments lie in the \( ab \)-plane within the AFM state. On the other hand, for NdRhIn\(_5\), where the ordered moments point along the \( c \)-axis materials, \( T_N \) is significantly enhanced when compared to that for their cubic NdIn\(_3\) parent compound. And lastly, for the Gd-based materials, where the CEF effects are small, the low temperature magnetic properties remain nearly unaltered compared to the GdIn\(_3\), suggesting that the low temperature CEF scheme configuration plays a fundamental role in the observed trends.

Regarding the influence of a given CEF scheme in the AFM ordering temperature, it is reasonable to assume that if a system orders in a given direction and CEF parameters are modified making it more magnetically susceptible in some other direction, but without actually changing the order, the system may experiment some kind of magnetic frustration or the energy barrier between these states should diminish. Therefore, the ordering temperature should decrease as well. Inversely, if the system orders in a certain direction and CEF parameters change favoring even more this state, the ordering temperature should increase.

We have shown that this new member of the RRhIn\(_5\), TbRhIn\(_5\), orders antiferromagnetically at \( T_N = 45.5 \) K, which is an enhanced ordering temperature when compared to \( T_N \sim 32 \) K of TbIn\(_3\). As TbRhIn\(_5\) is more magnetically susceptible for a field applied along the \( c \)-axis, according to the scenario above, the Tb moment must be ordered along the \( c \)-axis to explain the enhanced \( T_N \) of TbRhIn\(_5\).

Taking advantages of the higher \( Q \) resolution available with x-ray scattering techniques and using the RXMD cross section to determine moment directions in magnetic compounds 27,35, we resolved the magnetic structure of TbRhIn\(_5\). Recently, this technique has been also successfully used to determine the magnetic structure of two Gd members of the \( R_m \text{MIn}_{3m+2} \) \((m = 1, 2; \text{M} = \text{Rh, Ir}; n = 1)\) series 20,21.

As expected from the idea above, the solved magnetic structure of TbRhIn\(_5\) reveals a commensurate AFM structure with propagation vector \((\frac{1}{2} 0 \frac{1}{2})\) and the Tb moments oriented along the \( c \)-axis (see Fig. 6). The direction of the ordered moments was established by comparing the observed intensities of five magnetic Bragg reflections (Fig. 3) with a model based on the resonant cross section for the case of dipolar resonance with a linear polarized incident beam perpendicular to the scattering plane (Eq. 11). The model considers the possible orienta-

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**FIG. 7:** Energy dependence of the \((\frac{1}{2} 0 \frac{1}{2})\) magnetic peak (open squares) through the Tb \( L_{III}^1 \) (a) and \( L_{III}^2 \) (b) edges. The open symbols are gaussian fit to the elastic peak at each energy used in the scan. The data have been corrected for absorption. Solid line curve represents \( \mu(E) \) obtained from the fluorescent yield (scale on the right). From the \( \mu(E) \) inflection points we determine the absorption edges values (vertical dashed line) as being 8253 eV (\( L_{III} \)) and 7516 eV (\( L_{III}^2 \)).

**FIG. 8:** Temperature dependence of the magnetic Bragg integrated intensities for \((\frac{1}{2} 0 \frac{1}{2})\) magnetic peak. The inset shows in details the critical region around the transition at the Néel temperature for this compound. From a power law fit to this data within the temperature range of approximately 3% below \( T_N \) we obtain a \( T_N = 45.56(2) \) K and a critical parameter \( \beta = 0.35(2) \).
tion of the moments along the three tetragonal axis. In Fig. 3, it is obvious the agreement between experimental data and the model when the calculations were done assuming the moments along c-direction (solid line).

In addition, a proposed mean field model including an isotropic first-neighbors exchange interaction and the tetragonal CEF\cite{28} has shown that the enhancement of $T_N$ for tetragonal compounds that orders axially is a general trend for tetragonal materials when the CEF parameters tend to increase the fluctuations along the c-axis. We have used this model to fit our susceptibility and specific heat data, and we could successfully reproduce all the main features of our data, including the prediction of AFM ordering along the c-axis\cite{28} for the CEF and $J_{R-R}$ parameters given in Table 1.

Therefore, the reported magnetic properties of TbRhIn$_5$ compound is another experimental evidence of these general CEF induced trends along R$_m$MIn$_{3m+2}$ ($m=1,2$; $M=$ Rh, Ir). As such, with the CEF effects being very important in determining $T_N$, it is expected that the de Gennes scaling would fail to describe the behavior of $T_N$ along the RRhIn$_5$ series (see Fig. 1).

It is important to note that this mean field model has also predicted that, for $J=5/2$ and when the system spin is on the plane (for the Ce case) the Néel temperature approximately decreases when the CEF parameters increases fluctuations on c-axis, which is an effective measure of the system likeness to be in the c-direction. This prediction is consistent with the fact that the tetragonal CeRhIn$_5$ and Ce$_2$RhIn$_8$ present higher magnetic susceptibilities when magnetic field is applied along the c-axis and $T_N$ a factor of two smaller than that for CeIIn$_5$. It is obvious that the hybridization and Kondo effects are very important in the case of the Ce-based materials, but it is interesting to note that this CEF driven magnetic frustration mechanism combined to hybridization could create strong in-plane magnetic fluctuations that can mediate the quasi-2D unconventional superconductivity in these systems. It would be interesting to further test this model for others members of the R$_m$MIn$_{3m+2}$ that present decreasing of $T_N$ for tetragonal compounds. Although the effect is only about 20%, the tetragonal Sm-based compounds present smaller $T_N$ values than their cubic relatives SmI$_n$\cite{28}. Therefore, according to the present model, the Sm-ordered moment for these materials should be aligned out of the c-axis, most likely in the ab-plane.

V. CONCLUSION

In conclusion, we have presented the physical properties and magnetic structure of a new member of the R$_m$MIn$_{3m+2}$ series, TbRhIn$_5$. This intermetallic compound orders antiferromagnetically at $T_N = 45.5$ K, the highest ordering temperature among the existing RRhIn$_5$ materials. The solved magnetic structure of TbRhIn$_5$ is commensurate with propagation vector $\tau=(\frac{1}{4} \ 0 \ \frac{1}{2})$ and the Tb moments oriented along the c-axis. The direction of the ordering Tb-moments and the enhanced $T_N$ of this compound was successfully explained by a mean field model including an isotropic first-neighbors exchange interaction and the tetragonal CEF. Also, the model reproduces all interesting features of our susceptibility and specific heat experimental data for the set of CEF parameters given in Table 1. We argue that reported magnetic properties of TbRhIn$_5$ compound is another experimental evidence of a more general CEF induced trend along the R$_m$MIn$_{3m+2}$ ($m=1,2$; $M=$ Rh, Ir). The particular case where the rare-earth moments ordered out of the c-axis and the $T_N$ can be reduced by tuning the CEF parameters reveals a frustration mechanism that may play some role in producing in-plane magnetic fluctuations relevant to the physical properties of complex classes of materials such as the Ce$_m$MIn$_{3m+2}$ (M = Rh, Ir and Co; $m=1,2$) HFS.

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\begin{table}
\centering
\begin{tabular}{cccccccc}
\hline
$a$(Å) & c(Å) & $T_N$(K) & $J_{R-R}$(meV) & $\frac{T_{N,RRhIn_5}}{T_{N,RIn_3}}$ & $B_{20}$(meV) & $B_{40}$(meV) & $B_{60}$(meV) & $B_{64}$(meV)
\hline
4.595(3) & 7.418(3) & 45.5 & 0.2 & 1.39 & -1.4x10^{-4} & 1.3x10^{-4} & -5.3x10^{-5} & 0.2x10^{-4} & 1.5x10^{-4}
\hline
\end{tabular}
\caption{Experimental parameters for TbRhIn$_5$.}
\end{table}

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1 Z. Fisk, J. L. Sarrao, J. L. Smith, and J. D. Thompson, Proc. Natl. Acad. Sci. USA 92, 6663 (1995).
2 T. Moriya and K. Ueda, Rep. Prog. Phys. 66, 1299 (2003).
3 H. Hegger, C. Petrovic, E. G. Moshopoulou, M. F. Hundley, J. L. Sarrao, J. D. Thompson, and Z. Fisk, Europhys. Lett. 354-359, 4986 (2001).
4 C. Petrovic, R. Movshovich, M. Jaime, P. G. Pagliuso, M. F. Hundley, J. L. Sarrao, J. D. Thompson, and Z. Fisk, Europhys. Lett. 54-55, 4986 (2000).
