

I. Magnetic, thermal and transport properties of $\text{YbCu}_{5-x}\text{Zn}_x$ alloys

I. Čurlik,¹ F. Akbar,² S. Gabani,³ M. Giovannini,⁴ and J.G. Sereni⁵

¹*Faculty of Sciences, University of Prešov, 17. novembra 1, SK - 080 78 Prešov, Slovakia*

²*UMR7140-CMC, Univ. Strasbourg, 4 B. Pascal, CS 90032, 67081 Strasbourg, France*

³*Institute of Experimental Physics, SAS, Watsonova 47, SK - 040 01 Košice, Slovakia*

⁴*Department of Chemistry, University of Genova, Via Dodecaneso 31, Genova, Italy*

⁵*Low Temperature Division, CAB-CNEA, CONICET, IB-UNCuyo, 8400 Bariloche, Argentina**

(Dated: November 4, 2025)

Within the family of cubic YbCu_4X compounds ($\text{X} = \text{Ni}, \text{Au}$ and Zn), we have investigated the $\text{YbCu}_{5-x}\text{Zn}_x$ ($1 \geq x \geq 0.7$) alloys by means of structural, magnetic, thermal and transport measurements. In the $\tau 1$ - $\text{YbCu}_{5-x}\text{Zn}_x$ (cubic AuBe_5 type, $0.7 \leq x \leq 1.5$) structural phase, Yb ion is in its Yb^{3+} magnetic configuration. However, by increasing Zn content the unit cell grows faster than a reference computed as a Cu by Zn atoms substitution, which indicates a shift of Yb ions towards the larger Yb^{2+} configuration. The magnetic behavior confirms such tendency with a clear decrease of the saturation magnetization and effective moment between $x = 0.7$ and $x = 1$. The specific heat at low temperature shows a logarithmic dependence characteristic for a non-fermi-liquid behavior. The characteristic energies of all studied parameters, including magneto resistivity, show notably low values as an indication that these alloys are close to a quantum critical point, which is approached from the non-magnetic side as the Zn content decreases.

I. INTRODUCTION

The family of Yb-based ternary intermetallic compounds YbCu_4X , with $\text{X} = \text{Ag}, \text{Au}, \text{Cd}, \text{Mg}, \text{Tl}$ and Zn , is known since more than two decades [1]. It exhibits a cubic crystalline structure derivative of AuBe_5 , sp. gr. F43m one [2]. This fcc lattice can be viewed as a network of edge-sharing tetrahedra with Yb magnetic ions located at the vertices, being a 3D analog of a triangular lattice [3]. The composition phase diagram shows the formation of solid solutions [4] among which $\text{X} = \text{Au}, \text{Ag}$ were intensively studied [5–7]. Particularly, $\text{YbCu}_{5-x}\text{Au}_x$ alloys have shown very interesting properties because of the lack of magnetic order even at very low temperature ($T \leq 40 \text{ mK}$) [8] and its proximity to a quantum critical point (QCP).

In $\text{YbCu}_{5-x}\text{Au}_x$ allows the magnetic behavior is driven by the change in the chemical potential produced by the substitution of larger Au by smaller Cu rather than by their equivalent electronic structure, the question arises about which is the effect of the alternative experimental parameter like the change of electronic concentration. The recently synthesized $\text{YbCu}_{5-x}\text{Zn}_x$ solid solution [9] allows to investigate such effect.

In this work we present a detailed study of the physical properties of $\text{YbCu}_{5-x}\text{Zn}_x$ within the $0.7 \leq x \leq 1$ range of concentration obtained from structural, magnetic, thermal and transport properties.

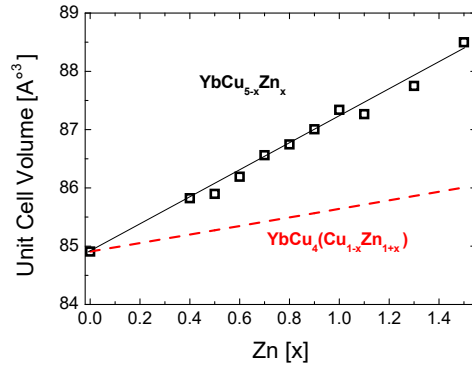


FIG. 1. (Color online) Comparison of the formula unit (f.u.) volume dependence with an hypothetical Vegard's law reference, where one (of five) Cu atoms is progressively substituted by one Zn. The $\text{Zn}(x=0)$ origin is taken from [10]. Notice that there are four f.u. in each cell volume [9].

II. EXPERIMENTAL

A. Structural properties

In most of these intermetallic compounds Yb atoms are in their Yb^{3+} electronic configuration, they may enter into the range of valence instability when the energy of the $4f$ level (E_{4f}) is close to the conduction band Fermi energy (E_F) through the $4f$ – $band$ hybridization [12, 13]. In that case, due to the larger size of Yb^{2+} ions a supplementary expansion to the expected Vegard's law occurs. Due to the lack of a reference for such

* jsereni@yahoo.com

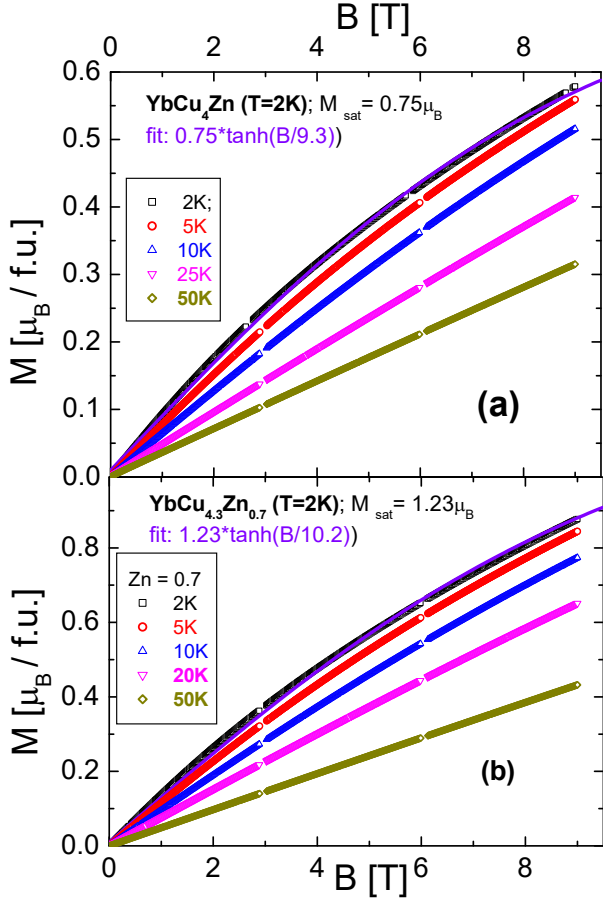


FIG. 2. (Color online) field dependent magnetization $M(B)$ for (a) YbCu_4Zn and (b) $\text{YbCu}_{4.3}\text{Zn}_{0.7}$, up to 9T in the range of 2 K to 50 K. Continuous curves in the 2 K isotherms are the fits to extract the saturation magnetization.

a Vegard's law volume evolution (e.g. a $\text{LuCu}_{5-x}\text{Zn}_x$ compound), we compare in Fig. 1 the measured unit cell volume $V(x)$ increase as a function of Zn content with an 'ad hoc' Vegard's reference. There, one (on five) Cu atoms are progressively substituted by one Zn. For this purpose the metallic radio of pure Cu and Zn elements is used and the $\text{Zn}(x=0)$ origin is extracted from [10].

One can see that $V(x)$ of $\text{YbCu}_{5-x}\text{Zn}_x$ increases quite faster than the expected from the size difference between Cu and Zn atoms, that is represented by the proposed Vegard's law for the pseudo $\text{YbCu}_4(\text{Cu}_{1-x}\text{Zn}_x)$ alloy. This evidence reveals the effect of mean sizes increase of Yb atoms towards the larger Yb^{2+} configuration due to valance instability [11] or valance fluctuations [12, 13].

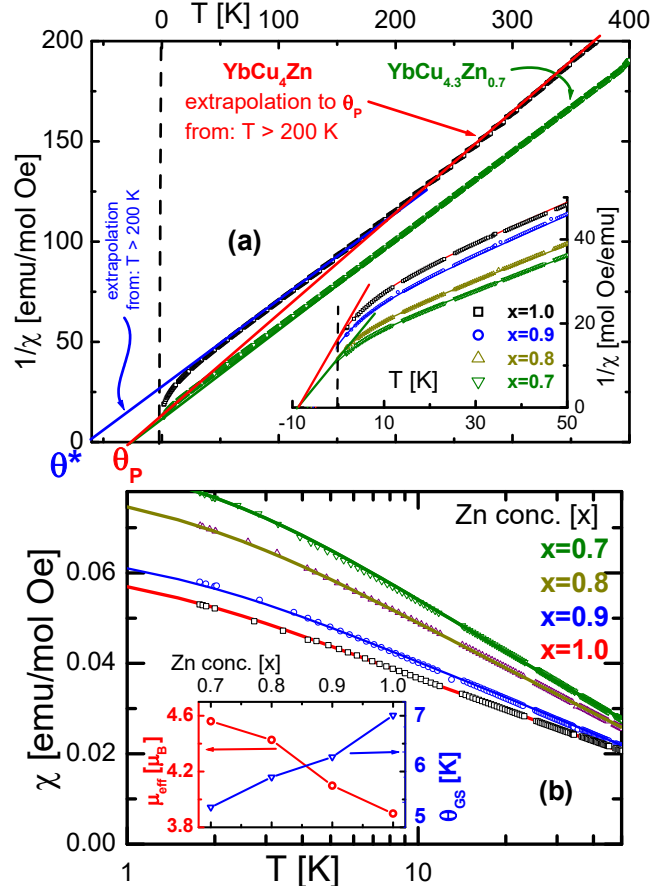


FIG. 3. (Color online) a) High temperature inverse susceptibility of $\text{YbCu}_{5-x}\text{Zn}_x$ ($x=1$ and $x=0.7$) alloys, up to room temperature, measured at $B = 1$ T (after [9]) where different extrapolations to θ_P^{ht} are discussed. Inset: detail of the inverse susceptibility at low temperature for all studied concentrations. b) Low temperature susceptibility in a semi-logarithmic representation, showing respective fittings. Inset: main extracted parameters: μ_{eff} (left blue axis) and θ_P^{lt} (right red axis). The left red arrow indicates the theoretic $\mu_{eff}(x) = 4.54 \mu_B$ value.

B. Magnetic properties

1. Magnetization

In Fig. 2 we show the field dependent magnetization $M(B)$ for YbCu_4Zn (a) and $\text{YbCu}_{4.3}\text{Zn}_{0.7}$ (b), between 2 and 50 K and up to $B = 9$ T. The respective isotherms at 2 K are properly fitted with a Brillouin function $B_{1/2}(y)$ (continuous curves), where $y = g_{eff}\mu_B JB/k_B T$ [14] for the present doublet GS. These functions are normalized to a saturation value of $M_{sat} = 0.75 \mu_B$ for $x = 1$ and $1.23 \mu_B$ for $x = 0.7$.

We can compare the highest saturation value (ob-

served for the $x = 0.7$ alloy) with those of the two possible GS doublets: Γ_6 and Γ_7 , with respective $M_{sat}(\Gamma_6) = 1.33\mu_B$ and $M_{sat}(\Gamma_7) = 1.72\mu_B$. It is evident that Γ_6 is the most likely GS. The significant decrease of $M_{sat}(x)$ indicate a weakening of the magnetic character of these alloys by increasing the Zn content because this system is located on the non-magnetic side of a quantum critical point (QCP), with the tendency to a fermi liquid behavior.

2. Magnetic susceptibility

The magnetic susceptibility $\chi(T)$ of the $\text{YbCu}_{5-x}\text{Zn}_x$ alloys was measured up to room temperature with $B = 1$ T and the results are presented in Fig. 3a (for $x=1$ and $x=0.7$) as the inverse $1/\chi(T)$, after [9]. In a detailed analysis of the crystal electric field CEF effect, one can see that it does not strictly follow a straight line: $1/\chi(T) = (T + \theta_P)/C_C$ as expected for the pure Curie-Weiss model. With θ_P being the paramagnetic temperature and C_C the Curie constant $\propto \mu_{eff}^2$. This is because the GS degeneracy is broken by the lower symmetry of the CEF. Fig. 3a shows a moderate up-turn of measured $1/\chi(T)$ for YbCu_4Zn , which is related to the progressive depopulation of the excited CEF levels by cooling, see red straight line which extrapolates to θ_P . This feature is less pronounced for $\text{YbCu}_{4.3}\text{Zn}_{0.7}$ because of the atomic disorder at the 4c Wyckoff site [9] introduced by the random occupation of Cu and Zn by alloying. Therefore, for a precise evaluation of θ_P the high temperature extrapolation has to be done from $T \geq 200$ K in this case, because a lower temperature e.g. $T \leq 200$ K (see blue line in Fig. 3a) extrapolation would result in an artificial over-evaluation of $\theta^* \approx 60$ K. The value $\theta_P = 26 \pm 2$ K coincides for all Zn concentrations. From the Kondo temperature evaluation: $T_K = \theta_P/\sqrt{2}$ [16], one extracts for high temperature $T_K = 15$ K that starts to affect the contribution of the excited CEF levels [17].

To analyze the GS properties of these compounds, in the inset of Fig. 3 we include more details on the $T \leq 50$ K data for all the Zn concentrations. In order to better compare their characteristic parameters, we applied in the inset of Fig. 3a an heuristic equation:

$$1/\chi(T, x) = [T + \theta_{GS}]/C_C e^{-\Delta/[T+\theta_P]}$$

where $\theta_{GS}(x)$ characterizes the GS paramagnetic temperature, $C_C(x)$ are the respective Curie constants and $\Delta(x)$ proportional to the CEF splitting. In Fig. 3b the $\chi(T)$ is also presented to show the quality of the fit at low temperature.

Another check for these results can be done by comparing the $\mu_{eff}(GS)$ extracted from $1/\chi$ at $T \approx 2$ K

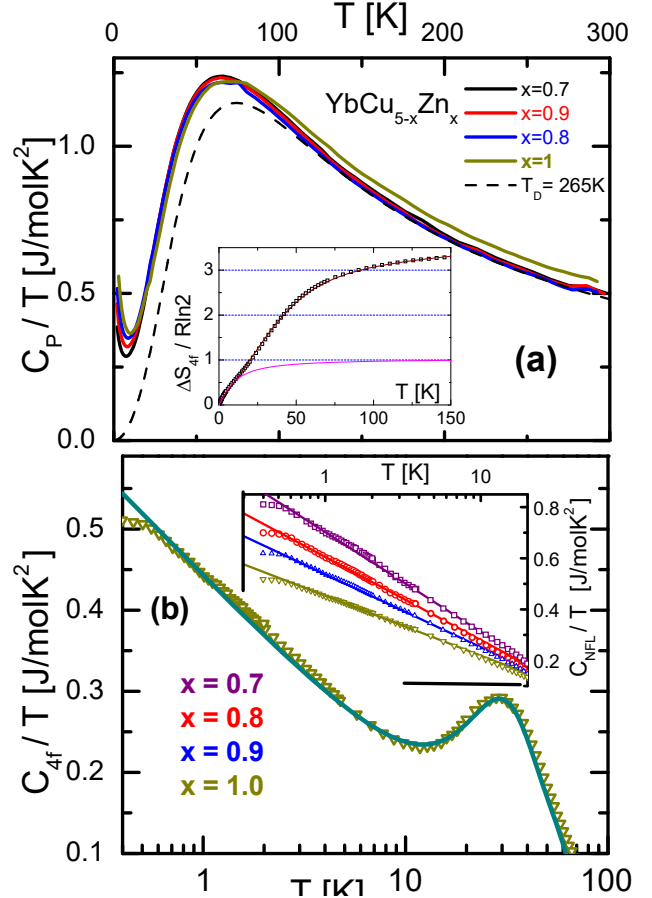


FIG. 4. (Color online) a) High temperature specific heat of $\text{YbCu}_{5-x}\text{Zn}_x$ alloys up to room temperature in a C_P/T representation, compared with a Debye function of $T_D = 265$ K (dashed curve). Inset: Entropy of the 4f electrons after phonon subtraction. Continuous curves indicate the increase to the entropy of respective CEF levels: excited doublet (magnet) and Γ_8 quartet (dark yellow). b) Specific heat contribution divided temperature of the 4f electrons in a semi-logarithmic representation indicating the NFL behavior of the GS doublet for the YbCu_4Zn_1 compound from $T \geq 0.4$ K up to 10 K. Continuous curve: fit between 0.4 and 70 K (see the text) including the CEF contribution. Inset: Comparison of the C_{NFL}/T dependencies of the $\text{YbCu}_{5-x}\text{Zn}_x$ alloys.

with the magnetic saturation at that temperature because $\mu_{eff}(GS)/M_{sat}(2\text{ K}) = 2.13\mu_B/1.23\mu_B \approx \sqrt{3}$, as expected for a doublet ($S = 1/2$) ground state.

The effective magnetic moments $\mu_{eff}(x)$ depend on Zn concentration as displayed in the inset of Fig. 3b and range between $\mu_{eff}(0.7) = 4.57\mu_B$ and $\mu_{eff}(1.0) = 3.95\mu_B$. Notice that the theoretic effective moment for $\vec{J} = 7/2, \vec{S} = 1/2, \vec{L} = 3$ of Yb atoms is $\mu_{eff} = g_J[J(J+1)]^{1/2} = 4.54\mu_B$, see dashed (red) line in the inset of

Fig. 3b, with a Landé factor $g_J = 7/6$.

The inset also contains the values of θ_{GS} obtained by extrapolating the $1/\chi(T \approx 2K)$ curves to zero. These parameter ranges between $\theta_{GS}(0.7) = 4.7K$ and $\theta_{GS}(1.0) = 7K$. The CEF splitting slightly change from $\Delta(0.7) = 42K$ to $\Delta(1.0) = 38K$, like θ_P between 23 and 26 K.

C. Specific heat

1. High temperature specific heat

The specific heat of $\text{YbCu}_{5-x}\text{Zn}_x$ alloys are shown in Fig. 4a also up to room temperature, in a C_P/T representation and compared with a pure phonon-Debye function (C_D) with $T_D = 265K$ (dashed curve). The T_D value was determined by the temperature of the maximum of $C_D/T = 0.28T_D$ [15], that is in good agreement with the value obtained for $\text{LuCu}_{5-x}\text{Ag}_x$ [18]. As expected, no significant variation in the phonon spectrum is observed as a function of Zn concentration because of its similar weight as Cu.

From the difference: $C_{4f}/T = C_P/T - C_D/T$ the 4f electronic contribution of the crystal electric field CEF is extracted. This procedure is checked by computing the 4f entropy $\Delta_{4f}/R \ln 2$ accumulated up to 150 K, see the inset in Fig. 4a, where the continuous curves represent the entropy variation related to the excited doublet (magenta) and the total entropy including the Γ_8 quartet. The excess of entropy at high temperature is originated in the band electrons and corresponds to a low Sommerfeld coefficient $\gamma \approx 5 \text{ mJ/mol K}^2$, which for $\text{LuCu}_{5-x}\text{Ag}_x$ [18] was reported to be $\gamma \approx 9 \text{ mJ/mol K}^2$.

2. Intermediate and low temperature specific heat

In Fig. 4b we present the C_{4f}/T contribution to specific heat for YbCu_4Zn in a semi-logarithmic representation, covering more than two orders of magnitude in temperature. There, it is evident the dominant NFL behavior of the GS doublet between $T \geq 0.4K$ up to 10 K, followed by a the CEF excited levels contribution. The $10 \leq T \leq 100K$ anomaly cannot be properly fitted by a standard Schottky one because those levels are affected by Kondo interaction that induces a level broadening. Such effect is described using a Gaussian function centered on the CEF level energy and a dispersion factor. The used function to fit C_{4f}/T is the following:

$$a + b \log(T_q/T) + \sum_{i=1}^2 c_i e^{[-(T-\Delta_i)^2/(2*T_{K_i}^2)]} \quad (1)$$

This equation is composed by terms with different physical meaning. The constant value $a = 0.15 \text{ J/molK}^2$ is

originated in the electronic band contribution. At low temperature $C_{4f}/T = 0.26 \log(T_q/T)$ is characteristic of a NFL behavior for the GS doublet, with a quantum fluctuation energy of $T_q = 7.5K$.

The third term in eq.(1) includes two Lorentzian functions that account for the excited CEF levels. From this fit we extract the CEF levels splitting of $\Delta_1 = 30 \pm 2K$ to the first excited doublet and a width $T_{K1} = 15 \pm 1K$, in good agreement with the $T \leq 30K$ curvature of $1/\chi(T)$ in Fig. 3. The values for the upper level are $\Delta_2 = 46 \pm 3K$ and a width $T_{K2} = 40 \pm 2K$. The c_i prefactor is related to the degeneracy of each level, where the quartet doubles the first excited doublet as expected. The full fit is presented in Fig. 4b as a continuous (green) function in the range between 0.4 and 70 K.

The CEF levels splitting is relatively low in comparison to some other Yb-based compounds. Nevertheless, in this case the cubic crystalline structure and the similar electronic structure of Cu and Zn provides a quite symmetric environment to Yb ions. Both features provide highly symmetric environment to Yb ions. These values extracted from $C_{4f}(T)$ measurements can be compared with those from $\chi(T)$ results, but taking into account that the former are more precise because they are related to the derivative of the internal energy of the system (e.g. $C_{4f} = \partial U_{4f}/\partial T$).

Concerning the GS behavior, in the inset of Fig. 4b we compare the C_{NFL}/T dependencies of the $\text{YbCu}_{5-x}\text{Zn}_x$ alloys for $1 \geq x \geq 0.7$. These measurements were performed in two different calorimeters, those at $T < 3K$ in a He3 insert of PPMS (Quantum Design) and those at $T > 2K$ in an He4 pumped system. Therefore respective results were matched between 2 and 3 K adding a small correction at the $T > 3K$ data. Notice that for the $C_{NFL}/T = b \log(T_Q/T)$ function, the characteristic energy of quantum fluctuations $T_Q = 9K$ do not change with concentration. Nevertheless, the intensity of the C_{NFL}/T contribution increases by reducing Zn content, i.e. increasing the magnetic character of the alloys that suggests an increasing proximity to a QCP.

D. Electrical resistivity and Magnetoresistivity

The electrical resistivity of some selected Zn alloys was measured between 2K and room temperature. In the stoichiometric compound it was measured in magnetic field up to $B = 9T$ and presented in a semi-logarithmic representation with the resistivity values normalized to room temperature R/R_{300K} , see Fig. 5a. The general behavior resembles that of a single impurity system. There one can appreciate how the electronic scattering tends to saturation at low temperature, but without any evidence of coherency at $T \rightarrow 0$.

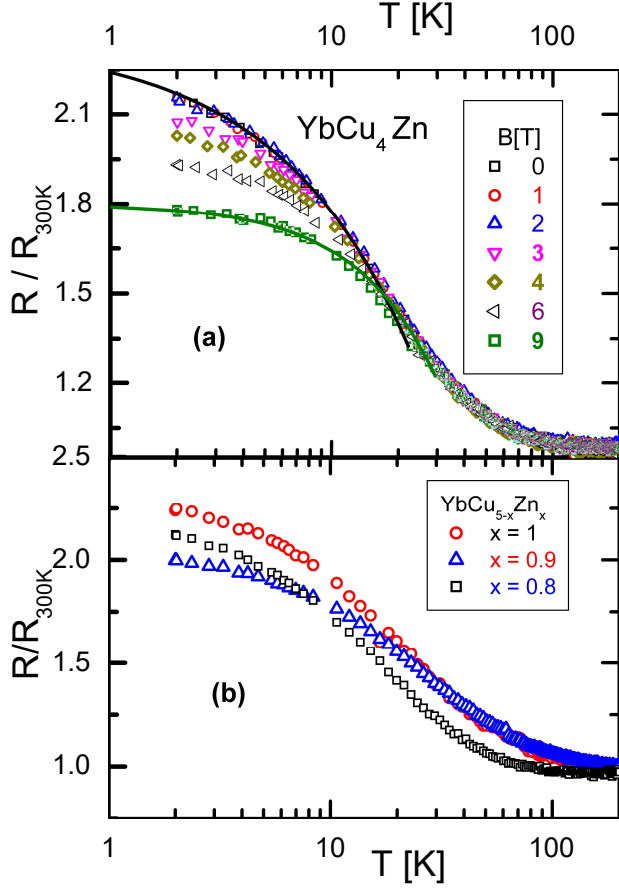


FIG. 5. (Color online) Temperature dependence of the electrical resistivity of YbCu_4Zn , normalized to room temperature in a semi-logarithmic representation. a) YbCu_4Zn compound at different applied fields. Continuous curves are fits to describe the curvature evolution at low temperature, see the text. b) Substitution of Cu by Zn in $\text{YbCu}_{5-x}\text{Zn}_x$.

The resistivity for different Zn concentrations are collected in Fig. 5b. Despite of the values dispersion between different alloys, one can see a similar qualitative temperature dependence.

The reduced magnetoresistivity $r(B) = \Delta R(B)/R(0)$ of YbCu_4Zn in magnetic field up to 9 T is presented in Fig. 6a, showing a negative tendency as a function of field. From the curves at $T = 2, 5, 10$ K a scaling procedure proposed by Schlottmann [21] can be performed. In Fig. 6b we show the unified curve of $r(T, B)$ dependence on $\zeta = B/(T + T^*)$ from where the characteristic temperature $T^* = 7$ K is extracted. The scaling function is described as: $r(B, T) = -2\zeta \exp(-0.3/\zeta)$.

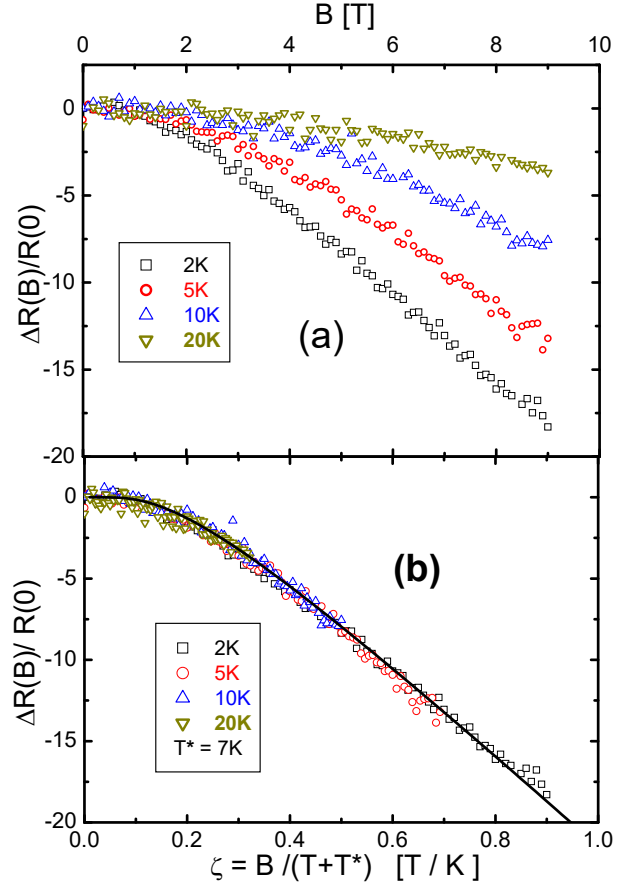


FIG. 6. (Color online) a) Magnetoresistivity measurements on YbCu_4Zn at different temperatures. b) Scaling procedure with a characteristic temperature scale $T^* = 7$ K using curves at $T = 2, 5, 10$ and 20 K (see text). Continuous curve: fit with $r(B, T) = -29\zeta \exp(-0.3/\zeta)$.

III. CONCLUSIONS

From these four experimental parameters: magnetic susceptibility, specific heat, entropy and magnetoresistivity, it is evident that the doublet GS of YbCu_4Zn has a significantly low characteristic energy scale, between 7 and 8.7 K. This may occur because of the lack of long range collective interactions, topologically prevented by magnetic frustration

As a function of Zn concentration, we have determined that: i) the lattice expansion exceeds the expected from a sort of Vegard's law reference, that corresponds to a shift towards the larger size Yb^{2+} electronic configuration. ii) the effective moment decreases from $x=0.7$ towards 1 indicating the weakening of magnetism. iii) Coincidentally, the paramagnetic temperature slightly increases that may indicate an increase

of the Kondo interaction. iv) also the low temperature specific heat intensity decreases suggesting a departure from an eventual QCP as the electronic concentration increases driving the Yb ions towards the less magnetic configuration. v) Furthermore, the entropy of the GS doublet reaches the value of $1/2R\ln(2)$ at 8.7 K which is also considered a measure of the Kondo energy. Altogether one can conclude that $\text{YbCu}_{5-x}\text{Zn}_x$ is an ap-

propriate system for the study of the environment of a QCP.

ACKNOWLEDGEMENTS

We acknowledge the support from APVV-23-0226 and VEGA 2/0034/24 projects.

-
- [1] J. L. Sarrao, C. D. Immer, Z. Fisk, C. H. Booth, E. Figueroa, J. M. Lawrence, R. Modler, A. L. Cornelius, M. F. Hundley, G. H. Kwei, J. D. Thompson, F. Bridges, *Physical properties of YbXCu_4X ($\text{X} = \text{Ag}, \text{Au}, \text{Cd}, \text{Mg}, \text{Tl}, \text{and Zn}$) compounds*, Phys. Rev. B **59** (1999) 6855.
 - [2] C. Rossel, K.N. Yang, M.B. Maple, Z. Fisk, E. Zirngiebl, J.D. Thompson, *Strong electronic correlations in a new class of Yb-based compounds: YbXCu_4 ($\text{X} = \text{Ag}, \text{Au}, \text{Pd}$)*, Phys. Rev. B **35** (1987) 1914, <https://doi.org/10.1103/PhysRevB.35.1914>.
 - [3] I. Čurlík, M. Reiffers, and M. Giovannini, *Study of magnetic contribution to the heat capacity of YbCu_4Ni* , Acta Phys. Polonica A **122**, 3 (2012).
 - [4] M. Giovannini, I. Čurlík, F. Gastaldo, M. Reiffers, J. G. Sereni, *The role of crystal chemistry in $\text{YbCu}_{5-x}\text{Au}_x$* , J. Alloys Compd. **627**, 20 (2015).
 - [5] I. Čurlík, M. Giovannini, J. G. Sereni, *Extremely high density of magnetic excitations at $T = 0$ in $\text{YbCu}_{5-x}\text{Au}_x$* , Phys. Rev. B **90** (2014).
 - [6] K. Yoshimura, N. Tsujii, J. He, M. Kato, K. Kosuge, H. Michor, K. Kreiner, G. Hilscher, T. Goto, *Synthesis and dense kondo behavior of cubic AuBe_5 -type YbCu_5 compound-systematic change of physical properties in the $\text{YbCu}_{5-x}\text{Ag}_x$ ($0 \leq x \leq 1$) system*; JALCO **262** (1997) 118–123, [https://doi.org/10.1016/S0925-8388\(97\)00340-X](https://doi.org/10.1016/S0925-8388(97)00340-X).
 - [7] J. He, N. Tsujii, K. Yoshimura, K. Kosuge, T. Goto, *Crossover from first-order valence transition to kondo behavior in C15b -type $\text{YbCu}_{5-x}\text{In}_x$ System*; J. Phys. Soc. Jpn. **66** (1997) 2481–2486, <https://doi.org/10.1143/JPSJ.66.2481>.
 - [8] J. Banda, D. Hafner, J.F. Landacta, E. Hassinger, K. Mutsimoto, M. Giovannini, J.G. Sereni, C. Geibel, M. Brando; *Electronuclear Quantum Criticality*, arXiv:2308.15294 [cond-mat.str-el] 29 Aug 2023.
 - [9] F. Akbar, I. Čurlík, M. Reiffers, M. Giovannini; *Phase equilibria and crystal structures in the ytterbium-copper-zinc system*, Jour. of Alloys and Compounds **976** (2024) 173195.
 - [10] N. Tsujii, J. He, F. Amita, K. Yoshimura, K. Kosuge, H. Michor, G. Hilscher, T. Goto; *Kondo-lattice formation in cubic-phase YbCu_5* ; Phys. Rev. B **56** (1997).
 - [11] R. D. Parks *Valence instabilities and related narrow-band phenomena*; Plenum Press, New York, ©1977
 - [12] D. Wohlleben, B. Wittershagen; *An empirical selection rule for valence fluctuations*; Jour. Mag. Magn. Mat. **52** (1985) 32–36
 - [13] M. Peters, K. Kliemt, M. Ocker, B. Wolf, P. Puphal, M. Le Tacon, M. Merz, M. Lang, C. Krellner *From valence fluctuations to long-range magnetic order in $\text{EuPd}_2(\text{Si}_{2-x}\text{Ge}_x)$ single crystals*; Phys. Rev. Materials **7** (2023) 064405; DOI: <https://doi.org/10.1103/PhysRevMaterials.7.064405>.
 - [14] See for example: S. Blundell; *Magnetism in Condensed Matter*, Oxford, University Press (N.Y.), 2001.
 - [15] J.G. Sereni; *Magnetic Systems: Specific Heat*; in Saleem Hashmi (editor-in-chief), Reference Module in Materials Science and Materials Engineering. Oxford: Elsevier; 2016. pp. 1-13; ISBN: 978-0-12-803581-8.
 - [16] A.A. Katanin, *Extracting Kondo temperature of strongly- correlated systems from the inverse local magnetic susceptibility*, Nat. Comm. **12** (2021) 1433.
 - [17] H.-U Desgranges and J.W. Rasul, *Specific heat of the degenerate Kondo model: Exact results in the presence of crystal fields*, Phys. Rev. B **36** (1987) 328.
 - [18] H. Mocho, K. Kreiner, N. Tsujii, K. Yoshimura, K. Kosuge, G. Gilsher; *Crystalline electric field and Kondo energy scales in $\text{YbCu}_{5-x}\text{Ag}_x$* ; Physica B **319** (2002) 277.
 - [19] J.G. Sereni, I. Čurlík, M. Giovannini, A. Strydom, M. Reiffers, *Physical properties of the very heavy fermion YbCu_4Ni* ; Phys. Rev. B **98** (2018) 094420.
 - [20] S. Gabani, I. Čurlík, F. Akbar, M. Giovannini; J.G. Sereni; *Hyperfine electro-nuclear coupling at the quantum criticality of YbCu_4Zn* ; arXiv:2506.18192v1 [cond-mat.str-el] 22 Jun 2025.
 - [21] P. Schlottmann, Z. Phys. B, Cond. Mat. **51** (1983) 233.