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Magnetic field dependence and bottlenecklike behavior of the ESR spectra in $YbRh_2Si_2$

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Electron spin resonance (ESR) experiments at different fields or frequencies ($4.1 \lesssim \nu \lesssim 34.4$ GHz) in the Kondo lattice ($T_K \simeq 25$ K) $YbRh_2Si_2$ single-crystal compounds confirmed the observation of a single anisotropic Dysonian resonance with $g_{\perp c} \cong 3.55$ and no hyperfine components for $4.2 \lesssim T \lesssim 20$ K. However, our studies differently reveal that (i) the ESR spectra for $H_{\perp c}$ show strong-field-dependent spin-lattice relaxation, (ii) a weak-field and temperature-dependent *effective g* value, (iii) a dramatic suppression of the ESR intensity beyond 15% of Lu doping, and (iv) a strong sample and Lu-doping ($\lesssim 15\%$) dependence of the ESR data. These results suggest a different scenario where the ESR signal may be associated to a coupled Yb^{3+}-conduction electron *resonant collective mode* with a strong bottleneck and dynamiclike behavior.

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I. INTRODUCTION

The metallic antiferrromagnetic [(AF) $T_N = 70$ mK] tetragonal ($I4/mmm$) heavy-fermion (HF) Kondo lattice ($T_K \simeq 25$ K) $YbRh_2Si_2$ is a peculiar system that has attracted great attention of the scientific community interested in strongly correlated electron systems. At high-T ($T \gtrsim 200$ K) its magnetic susceptibility follows an anisotropic Curie-Weiss law with a full Yb^{3+} magnetic moment ($\mu_{\text{eff}} \simeq 4.5\mu_B$), but at low T ($T \lesssim T_K$) HF behavior is found.[1,3,34] The AF ordering[2] of $YbRh_2Si_2$ can be suppressed by a weak magnetic field of $H_{\perp c} \sim 650$ Oe and when this AF state is H tuned toward a quantum critical point (QCP), pronounced non-Fermi-liquid (NFL) behavior is found.[1,34] These properties made $YbRh_2Si_2$ a special system for studying quantum criticality and NFL behavior in connection to other systems near a QCP.[4,5]

Other unexpected and interesting aspect of $YbRh_2Si_2$ was revealed by electron spin resonance (ESR) studies.[6] Narrow (100–200 Oe) single Dysonian resonance with no hyperfine components, T dependence of the linewidth, ΔH, and a g-value anisotropy consistent with Yb^{3+} in a metallic host of tetragonal symmetry was found for $T \lesssim 20$ K. However, despite its H-tunable ground state, no H-dependent ESR parameters were reported for $H \lesssim 10$ kOe.[6] Moreover, a narrow Yb^{3+} ESR in a dense Kondo system as $YbRh_2Si_2$ below T_K was totally unexpected. Since its first observation[6] various reports were published on the ESR of Yb^{3+} in stoichiometric $YbRh_2Si_2$,[7] $YbIr_2Si_2$,[8] and $YbRh_2Si_2$ doped with nonmagnetic impurities as Ge (Ref. 9) and La.[10] Recently, the ESR of Ce^{3+} in dense Kondo systems was also communicated.[11] Nevertheless, there is still no clear understanding of the microscopic mechanism that allows the observation of such a narrow Yb^{3+} ESR line characteristic of a local moment in a metallic host.

In this work, our main report is on the H-dependent ESR experiments in the NFL phase of $YbRh_2Si_2$ ($4.2 \lesssim T \lesssim 10$ K; $0 < H \lesssim 10$ kOe). Our results reveal an unconventional H dependence and bottlenecklike behavior of the Yb^{3+} resonance in this system that may help to shed light on the origin of such unexpected ESR signal.

II. EXPERIMENT

Single crystals of $Yb_{1-x}Lu_xRh_2Si_2$ ($0 \leq x \lesssim 1.00$) were grown from In and Zn fluxes as reported.[12–14] The structure and phase purity were checked by x-ray powder diffraction. The high quality of our undoped crystals was confirmed by x-rays rocking curves [(0,0,4) Bragg peak] for various crystals which revealed a mosaic structure of maximum c-axis angular spread of $\lesssim 0.015°$ and a correlation length of ~ 650 nm (grain size). The electrical residual resistivity ratio $\rho_{300\text{ K}}/\rho_{1.9\text{ K}}$ for the In and Zn-flux-grown crystals were 35 and 10, respectively.[12–14] The ESR spectra were taken in $\sim 2 \times 2 \times 0.5$ mm^3 single crystals in a Bruker S, X, and Q bands (4.1, 9.5, and 33.8 GHz) spectrometer using appropriated resonators and T-controller systems.

Single resonance of a Kramers doublet ground state with no hyperfine components was observed at all bands. The Dysonian line shape ($A/B \approx 2.5$) corresponds to a microwave skin depth smaller than the size of the crystals.[15]

III. RESULTS AND DISCUSSION

Figure 1 presents at $T = 4.2$ K (a) the Yb^{3+} ESR θ dependence of the field for resonance $H_r(\theta)$ and (b) linewidth $\Delta H(\theta)$ in a plane perpendicular to the ab plane for the In-flux $YbRh_2Si_2$ at S, X, and Q bands. The θ dependence of the *effective g* value can be inferred from $H_r(\theta)$ and it is given by $h\nu/\mu_B H_r(\theta) = g(\theta) = [g_{\perp c}^2 \cos^2\theta + g_{\parallel c}^2 \sin^2\theta]^{1/2}$. The solid

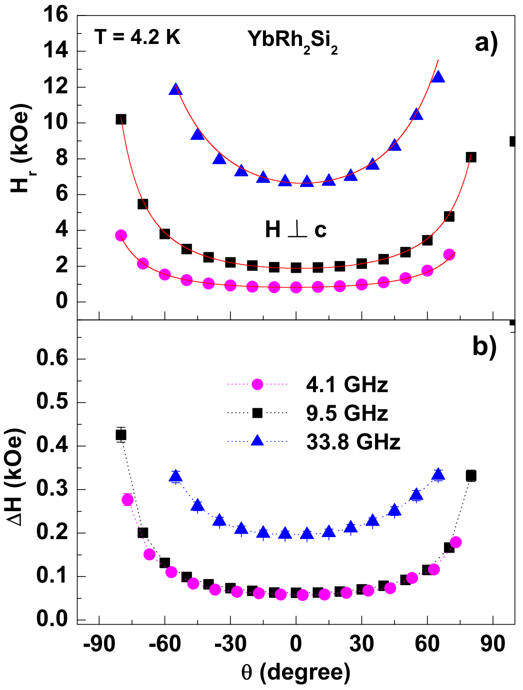

FIG. 1. (Color online) X, S, and Q-band angular dependences of the Yb^{3+} ESR at 4.2 K in a plane perpendicular to the ab plane: (a) $H_r(\theta)$ (solid lines, see text) and (b) $\Delta H(\theta)$ (dashed lines are guides for the eyes).

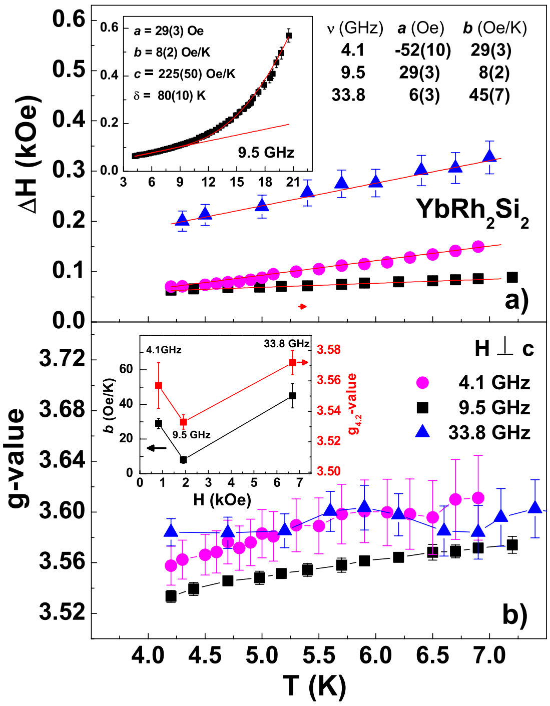

FIG. 2. (Color online) X, S, and Q-band low-T dependences of the Yb^{3+} ESR for $H_{\perp c}$ (a) $\Delta H(T)$ and (b) effective $g(T)$ value. Inset of (a): X-band $\Delta H(T)$ for $4.2 \leq T \leq 21$ K and fitting parameters to $\Delta H(T) = a + bT + c\delta/[\exp(\delta/T) - 1]$. Inset of (b): H dependence of b and effective $g_{4.2}$ value.

lines in Fig. 1(a) are simultaneous fittings for the three bands of the $H_r(\theta)$ data to $h\nu/\mu_B g(\theta)$. These fittings give $g_{\parallel c} \lesssim 0.6(4)$ and $g_{\perp c} = 3.60(7)$. Figure 1(b) shows that $\Delta H(\theta)$ for the S and X bands are about the same, indicating the absence of appreciable low H-dependent inhomogeneous broadening. At Q band, in contrast, $\Delta H(\theta)$ is significantly broader, suggesting the presence of a H-dependent broadening mechanism (see below). Furthermore, for the three bands and away from the ab plane, ΔH broadens by ≈ 200 Oe. The $g_{\parallel c}$-value distribution due to an angle spread of $\approx 0.015°$ for the c axis (mosaic effect) would only contribute to an inhomogeneous broadening of $\lesssim 5$ Oe and cannot account for the broadening of ≈ 200 Oe.

Figures 2(a) and 2(b) show, respectively, the low-T dependences of ΔH and effective g value of the Yb^{3+} ESR in In-flux-grown $YbRh_2Si_2$ measured at the three bands for $H_{\perp c}$. In this T interval and within the error bars, it is found $\Delta H = a + bT$ for the three bands. This suggests a Korringa type of mechanism for the Yb^{3+} spin-lattice relaxation (SLR), i.e., the Yb^{3+} local moment is exchange coupled to the conduction electrons (ces).[16] The residual linewidth a and relaxation rate $b = \Delta H/\Delta T$ are given in Fig. 2(a). The actual determination of the residual linewidth $a = \Delta H(T=0)$ would require measurements at lower T; therefore, the obtained values should be considered just as fitting parameters. However, the large $\Delta H(\theta)$ measured at Q band and at $T = 4.2$ K, relative to those in S and X bands [see Fig. 1(b)], is probably associated to a homogeneous (H-induced) increase in the SLR rate b and to a weak H-dependent inhomogeneous broadening of the residual linewidth. A H-dependent SLR rate b is not expected for a normal local magnetic moment-ce exchange-coupled system, where the Korringa rate is frequency and field independent.[17] However, since the Yb^{3+} and ce magnetic moments carry unlike spins and g values, the H dependence of b, having a minimum value at the X-band field $H \simeq 1900$ Oe [see inset of Fig. 2(b)], may be an anomalous manifestation of a bottlenecklike behavior. Figure 2(b) shows that the T dependence of the effective g values is slightly different in the three bands, with minimum effective $g_{4.2}$ values also at the X band. The effective g-value accuracy is much higher than that obtained from $g(\theta)$ of Fig. 1 because proper experimental conditions were chosen for these $H_{\perp c}$ measurements. The inset of Fig. 2(a) shows the X-band $\Delta H(T)$ for $4.2 \leq T \leq 21$ K. The data were fitted to $\Delta H(T) = a + bT + c\delta/[\exp(\delta/T) - 1]$ taking into consideration all the contributions to ΔH in a metallic host. The first and second terms are the same as above. The third is the relaxation, also via an exchange interaction with the (ce), of a thermally populated Yb^{3+} excited crystal-field state at δ K above the ground state.[18] The fitting parameters are in the inset of Fig. 2(a). This analysis does not consider any direct Yb^{3+} spin-phonon contribution.[18] The S and Q-band $\Delta H(T)$ data for $7 \lesssim T \lesssim 20$ K also show exponential behaviors with $c \approx 200(70)$Oe/K and $\delta \approx 75(20)$ K.

Figure 3 shows the X-band low-T Yb^{3+} ESR in $Yb_{1-x}Lu_xRh_2Si_2$: (a) $\Delta H(T)$ for $x=0$ at different θ between $H_{\perp c}$ and $H_{\parallel c}$, (b) $\Delta H(T)$ for $0 \leq x \leq 0.15$ and $H_{\perp c}$, and (c) the effective $g(x,T)$ for $0 \leq x \leq 0.10$. $\Delta H(T)$ was fitted to $\Delta H(T) = a + bT$ with parameters given in the insets of Figs. 3(a), 3(b), and 5(a). For 7 K $\lesssim T \lesssim 20$ K, $\Delta H(T)$ also shows exponential behaviors with parameters $c \approx 200(80)$Oe/K and

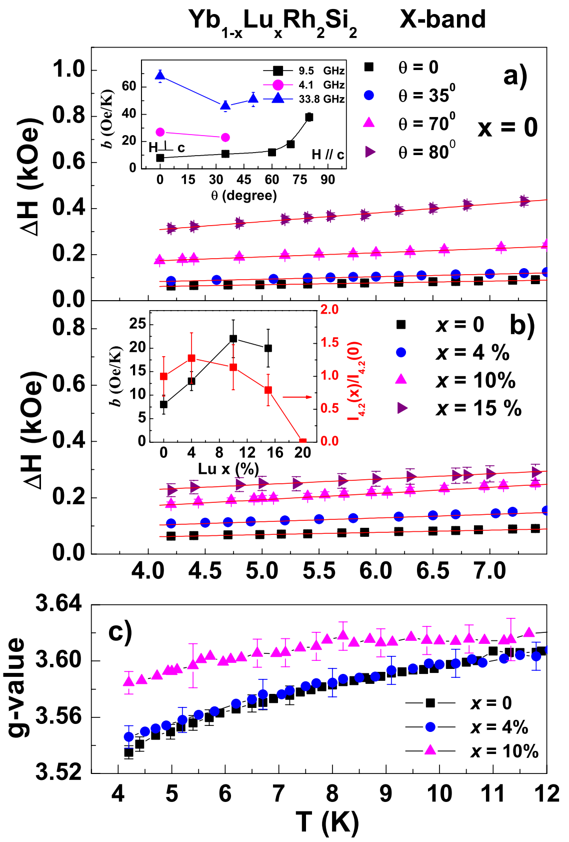

FIG. 3. (Color online) X-band low-T Yb^{3+} ESR data for $\mathrm{Yb}_{1-x}\mathrm{Lu}_x\mathrm{Rh}_2\mathrm{Si}_2$: (a) $\Delta H(T)$ for θ between $H_{\perp c}$ and $H_{\parallel c}$ and $x=0$, (b) $\Delta H(T,x)$, and (c) effective $g(x,T)$ for various Lu concentrations and $H_{\perp c}$. The parameters of $\Delta H(T)=a+bT$ are in the insets of (a) and (b) and in Fig. 5(a). Inset of (a): $b(\theta)$ for the S and Q bands. Inset of (b): relative normalized ESR integrated intensities at 4.2 K, $I_{4.2}(x)/I_{4.2}(0)$.

$\delta \approx 65(30)$ K.[18] The inset of Fig. 3(a) includes $b(\theta)$ for the S and Q bands and inset of Fig. 3(b) presents the relative normalized X-band ESR integrated intensities at 4.2 K as a function of x, $I_{4.2}(x)/I_{4.2}(0)$. The ESR intensities were determined taking into consideration the crystal exposed area, skin depth, and spectrometer conditions. The X-band data show that b increases as H gets close to $H_{\parallel c}$ and as x increases. $g(x,T)$ and $g(0,T)$ are similar but with higher values as x increases. Again, the θ and x dependences of b and T dependences of the effective g values resemble a bottleneck and/or dynamiclike behavior.[19] Furthermore, the inset of Fig. 3(b) shows that while for $x \leq 0.15$ there is nearly no decrease in the Yb^{3+} ESR intensity, for $0.15 < x \lesssim 1.00$ the intensity drops dramatically and no ESR could be detected; although, interestingly, for $x > 0.15$ and $T \gtrsim 200$ K, $\chi_{\perp c}(T)$ follows a Curie-Weiss law with a full Yb^{3+} magnetic moment. We should mention that for $x \leq 0.15$ there is no appreciable changes in the thermodynamic properties of these compounds.[12,13] The absence of resonance for $x > 0.15$ strongly suggests that the observed ESR for $x < 0.15$ cannot be associated to a single Yb^{3+} ion resonance but rather to a *resonant collective mode* of exchange-coupled Yb^{3+}-ce magnetic moments. We argue that a strong Yb^{3+}-ce exchange coupling may broaden and shift the ce resonance toward the Yb^{3+} resonance, building up a Yb^{3+}-ce coupled mode with bottleneck and/or dynamiclike features. An internal field caused by the Yb^{3+} local moments may be responsible for the shift of the ce resonance.[20] Moreover, the Lu doping may disrupt the collective-mode coherence and open the bottleneck and/or dynamic regime.[19]

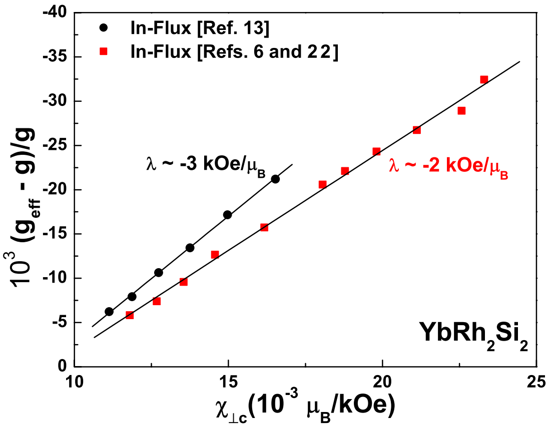

FIG. 4. (Color online) Effective g shift and magnetic-susceptibility correlation, $(g_{\mathrm{eff}}-g)/g \propto \lambda \chi_{\perp c}(T)$, for $T \leq 15$ K and X band for $x=0$ crystals (see text).

Moreover, within a molecular-field approximation the effective $g(x,T)$ may be written as $g_{\mathrm{eff}}=g[1+\lambda \chi_{\perp c}(T)]$. Figure 4 presents a plot of $\Delta g/g=(g_{\mathrm{eff}}-g)/g \propto \lambda \chi_{\perp c}(T)$ for $T \leq 15$ K and X band for our $x=0$ crystals[13] and that from Refs. 6 and 22. A linear correlation is obtained with λ values in the interval $-2\ \mathrm{kOe}/\mu_B > \lambda > -3\ \mathrm{kOe}/\mu_B$ which corresponds to a Yb^{3+}-Yb^{3+} exchange interaction of $J_{ff} \sim -200$ mK (~ -0.02 meV) within a first-neighbor mean-field approximation.[21] A Néel temperature of $T_N \cong J_{ff}(g/2)^2 \sim 500$ mK can be roughly estimated from these values. Therefore, these results definitely indicate that the T dependence of the effective $g(x,T)$ is nothing but a consequence of the shift of the field for resonance toward higher fields due to an AF internal molecular field and has nothing to do with a $\Delta g = c/ln(T_K/T)$ divergence.[6] Moreover, the expected g shift caused by the exchange interaction between the Yb^{3+} and ce local moments J_{fce} can be estimated from the largest measured Korringa-rate value (unbottleneck), $b \cong 40$ Oe/K. Within a single band approximation[18] and absence of q dependence of the Yb^{3+}-ce exchange interaction $J_{fce}(\mathbf{q}) \cong J_{fce}(\mathbf{0})$,[23] one can write $(\Delta g/g)^2 = \mu_B b/\pi g k_B$, which gives $|\Delta g/g| \lesssim 2\%$. This value is far much smaller than that estimated in Ref. 6 using as a reference the ESR of Yb^{3+} in the insulator PbMoO_4. On the other hand, from the Korringa relation[18] using $b \cong 40$ Oe/K and assuming a maximum *bare* density of state per one spin direction at the Fermi level η_F given by the Somerfield coefficient of the specific-heat measurements ($\gamma \cong 900$ mJ/mol K^2) (Ref. 24), we extract a lower limit for $|J_{fce}| \gtrsim 3$ meV, which is about 2 orders of magnitude larger than the value found for the Yb^{3+}-Yb^{3+} exchange interaction $|J_{ff}|$ (see above).

The behavior of the effective $g(x,T)$ shown in Fig. 3(c) is also qualitatively consistent with a collective-mode interpretation in that the effective g factors lie between the Yb^{3+} value of $g \approx 3.6$ and the ce value of $g \approx 2$. The effective g

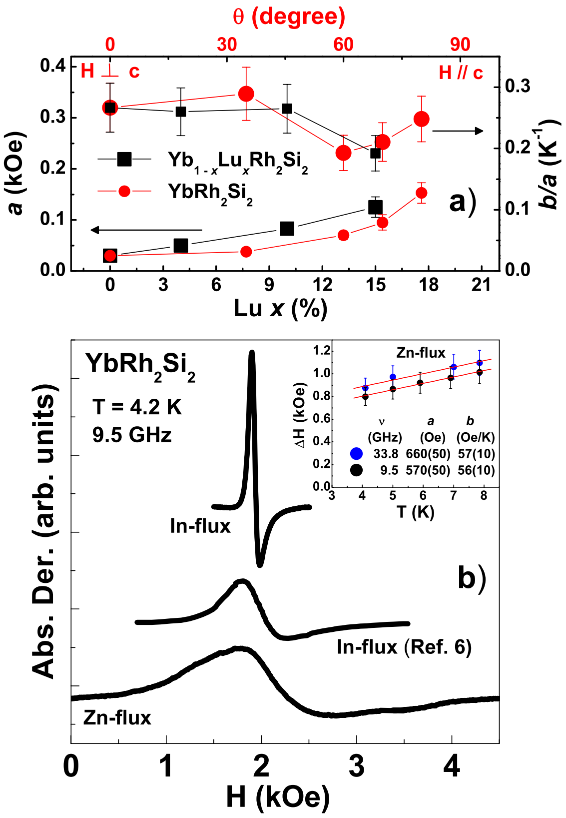

FIG. 5. (Color online) (a) X-band Yb^{3+} ESR: $a(x)$, $a(\theta)$, $b(x)/a(x)$, and $b(\theta)/a(\theta)$ for θ between $H_{\perp c}$ and $H_{\parallel c}$ and $0 \leq x \leq 0.15$ for $H_{\perp c}$; (b) for comparison, ESR spectra at 4.2 K and $H_{\perp c}$ for single crystals grown in In and Zn fluxes and for the In-flux crystals of Ref. 6. Inset: $\Delta H(T) = a + bT$ for Zn-flux crystals and $H_{\perp c}$ at X and Q bands.

values increase with increasing x for $T < 12$ K. At higher T, the effective g values are asymptotically T independent with a value of ≈ 3.6. In the collective-mode description, the limiting value of g is identified with the Yb^{3+} Kramers doublet g factor, and the onset of the mode is associated with the decrease in the effective g value below 12 K to a value that lies between the ce and the Yb^{3+}. This decrease is less for $x > 0$, indicating that the disorder weakens the effect of the Yb-ce correlations that give rise to the shift. General theoretical arguments[25] show that the effective g value of the collective mode is the weighted average of the g values of the ce and the Yb^{3+} ions. If one treats the interaction between the ce and the ions in a molecular-field approximation with interaction parameter γ, one obtains an expression for $g_{\mathrm{eff}} - g_{\mathrm{Yb}}$ of the form $g_{\mathrm{eff}} - g_{\mathrm{Yb}} = -(g_{Yb} - g_{\mathrm{ce}})(g_{\mathrm{Yb}}/g_{\mathrm{ce}})\gamma\chi_{\mathrm{ce}}$, where χ_{ce} denotes the susceptibility of the ce. Since it is unlikely that χ_{ce} has the same temperature dependence as the measured susceptibility $\chi_{\perp c}(T)$, which is dominated by the contribution from the Yb^{3+} ions, we conclude that the interpretation of the observed g shift as arising from Yb^{3+}-Yb^{3+} interactions is correct.

Figure 5(a) shows the $a(x,\theta)$ data from Fig. 3. Usually, nonmagnetic impurities cause an inhomogeneous broadening of the ESR line ($a \propto x$), which is in general attributed to a crystal-field distribution (CFD).[17,26] Natural impurities and/or crystal defects also contribute to a CFD. As we mentioned, the broadening due to a c-axis misorientation of $\lesssim 0.015°$ cannot account for the observed increase in a near $H_{\parallel c}$. Therefore, we attribute this to an inhomogeneous broadening described by a distribution of g values $\sigma_g(x) = \sigma_g(0) + \sigma_g'(x)x$ caused by a CFD. Then, we can write $a(x) = a(0) + \sigma_g'(x)xH_{r\perp c}/g_{\perp c}$ and $a(\theta) = a(0) + \sigma_g(0)H_r(\theta)/g(\theta)$. From our data we obtain $a(0) \approx 29$ Oe, $\sigma_g'(x) \approx 0.0114/\%_{\mathrm{Lu}}$, and $\sigma_g(0) \approx 0.0137$. Notice that for $\theta \cong 80°$ and $x \cong 0.15$ these broadenings are comparable. Figure 5(b) presents a comparison between the Yb^{3+} ESR X-band spectra at 4.2 K and $H_{\perp c}$ for single crystals grown in In and Zn fluxes. The inset displays $\Delta H(T) = a + bT$ and the fitting parameters for the crystal grown in Zn flux at X and Q bands and $H_{\perp c}$. The large a and b values are indications that Zn impurities were incorporated in the crystals. X-ray fluorescence measurements yield Zn concentrations of about 1%.

Our experiments confirm an ESR in YbRh$_2$Si$_2$ below $T_K \simeq 25$ K.[6] However, our results suggest that this ESR corresponds to a strong exchange-coupled Yb^{3+}-ce *resonant collective mode*. The features of this *resonant collective mode* resemble the bottleneck and/or dynamic scenario for diluted magnetic moments exchange coupled to the ce, both with $g \cong 2$, where in a normal metal the SLR rate b and g value depend on the competition between the Korringa and Overhauser relaxation and the ce SLR.[16,17,26,27] Then, the increase in b by the addition of nonmagnetic impurities to YbRh$_2$Si$_2$ (Lu and Zn in Figs. 3(b), 5(a), and 5(b) and La in Ref. 10) may be associated to "opening" the bottleneck regime due to the increase in the ce spin-flip scattering. Hence, we can write $b(x) = b(0) + b'(x)x$.[17,26] From our data, we estimate $b(0) \approx 8$ Oe/K and a ce spin-flip scattering cross section $b'(x) \approx 1.4(\mathrm{Oe/K})/\%_{\mathrm{Lu}}$. Moreover, the θ dependence of b [see Fig. 3(a)] may be another manifestation of the bottleneck effect. We argue that associated to the increase in $a \propto \sigma_g(0)H_r(\theta)/g(\theta)$ there will be a significant number of *detuned* Yb^{3+} ions that may slow down the Overhauser relaxation and contribute to open the bottleneck regime. Assuming $b(\theta) = b(0) + b'(\theta)\sigma_g(0)H_r(\theta)/g(\theta)$ we estimate $b(0) \approx 7.5$ Oe and $b'(\theta)\sigma_g(0) \approx 0.0032$ Oe^{-1}. We should mention that to *open* the bottleneck via *detuned* Yb^{3+} ions $[\propto \sigma_g(0)H_r(\theta)/g(\theta)]$ is only possible when the g value of the Kramers doublet is strongly anisotropic. Notice that in our case, this effect becomes important for $\theta \gtrsim 60°$. Figure 5(a) shows, as expected, that $b(x)/a(x) \approx b(\theta)/a(\theta) \approx 0.26(4)$ for our data, confirming that a g-value distribution $\sigma_g(x)$ due to a CFD is responsible for the increase in b and a in YbRh$_2$Si$_2$.

Another striking result reported in Fig. 2 is the *non*monotonic H dependence of b, a, and effective g value of the Yb^{3+}-ce *resonant collective mode*. The main difference with the bottleneck scenario given above is that the increase in b at S and Q bands is not followed by a systematic increase in a. Admixtures via Van Vleck terms[28] may be disregarded because this contribution should scale with H. Therefore, we believe that the low H tunability[1,3,34] of the ESR parameters in YbRh$_2$Si$_2$ is an "intrinsic" property of the NFL state near a QCP, where the strength of the Yb^{3+}-ce magnetic coupling may subtly tune and allows the formation of the *resonant collective mode*. We attribute the absence of low H-dependent ESR results in previous reports[6] to the presence of "extrinsic" impurities and/or Rh/Si defects[13,29] that increase the SLR (b) broadening the resonance and hiding the low H dependence of the ESR parameters in the NFL phase (such as for our Zn-flux crystals).

For this material, the Yb^{3+}-ce *resonant collective mode* presents the strongest bottleneck regime (smallest b) at $H \approx 1900$ Oe. However, due to the subtle details of the coupling between the Kondo ions and the ce in a Kondo lattice and to strong impurity effects, these *resonant collective modes* may not be always observable, unless extreme bottleneck regime is achieved. The proximity to a QCP and/or the presence of enhanced spin susceptibility may favor this condition.[11,30] Recent calculations by Abrahams and Wölfle[31] suggested that the ESR linewidth may be strongly reduced by a factor involving the heavy-fermion mass and quasiparticle ferromagnetic (FM) exchange interactions $(m/m^*)[1-\tilde{U}\chi^{+-}_{ff,H}(0)]$. These results indicate that the estimation of the linewidth from the Kondo temperature T_K is an overestimation. However, these calculations may not be contemplating all the possibilities and have to be taken with care when applied to the dynamic of the ESR of $YbRh_2Si_2$ compound because (i) it presents an AF Yb^{3+}-Yb^{3+} exchange interaction [although other works in literature have claimed in favor of the existence of FM fluctuation in $YbRh_2Si_2$ (Refs. 34 and 33)] and (ii) samples with the same thermodynamic properties present quite different linewidths [see Fig. 5(b)]. Furthermore, the anisotropy in the ESR in $YbRh_2Si_2$ reflects both single-ion crystal-field effects and the Yb^{3+}-Yb^{3+} and Yb^{3+}-ce interactions. In principle, the analysis of crystal-field effects is straightforward although somewhat hindered by the inability to detect a signal when the field is along the c axis. The anisotropy of the Yb^{3+}-Yb^{3+} and Yb^{3+}-ce is more difficult to determine and in the latter case more critical. The application of the *resonant collective-mode* model is based on the assumption that the Yb^{3+}-ce coupling is dominated by a scalar interaction between the Yb^{3+} ground-state doublet pseudospins S_{ps} and the spins of the conduction electrons s with the consequence that the total spin $s+S_{ps}$ is approximately constant of the motion.[25,32] In the presence of uniaxial anisotropy, only the component of the total spin along the symmetry axis is a constant of the motion. How the lower symmetry affects the formation of the collective mode is an unsolved problem requiring further study.[31] The bottleneck scenario for the Yb^{3+}-ce *resonant collective mode* may also explain the absence of Yb^{3+} hyperfine ESR structure.[35] Finally, we hope that our results will motivate further theoretical approaches to understand the dynamics of strong exchange-coupled magnetic moments of unlike spins and g values, as Yb^{3+} and ce, and explore the general existence of a *resonant collective mode* with a bottleneck and/or dynamiclike behavior.

IV. SUMMARY

In summary, this work reports low H-dependent ESR, below $T_K \simeq 25$ K, in the NFL phase of $YbRh_2Si_2$ ($T \lesssim 10$ K). It is suggested that the observed ESR in $YbRh_2Si_2$ corresponds to a Yb^{3+}-ce *resonant collective mode* in a strong bottlenecklike regime, which is highly affected by the presence of impurities, defects, and CFD. The analysis of our data allowed us to give estimations for the Yb^{3+}-Yb^{3+} exchange parameter J_{ff} and a lower limit for the Yb^{3+}-ce exchange parameter $|J_{fce}|$.

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