

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 ($4.1 \leq \nu \leq 34.4$ GHz) in the Kondo lattice ($T_K \approx 25$ K) YbRh_2Si_2 single-crystal compounds confirmed the observation of a single anisotropic Dysonian resonance with $g_{\perp c} \approx 3.55$ and no hyperfine components for $4.2 \leq T \leq 20$ 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 ($\leq 15\%$) 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 antiferromagnetic [(AF) $T_N = 70$ mK] tetragonal ($I4/mmm$) heavy-fermion (HF) Kondo lattice ($T_K \approx 25$ 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 ($T \geq 200$ K) its magnetic susceptibility follows an anisotropic Curie-Weiss law with a full Yb^{3+} magnetic moment ($\mu_{\text{eff}} \approx 4.5\mu_B$), but at low T ($T \leq T_K$) HF behavior is found.^{1,3,34} The AF ordering² 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 $T \leq 20$ K. However, despite its H -tunable ground state, no H -dependent ESR parameters were reported for $H \leq 10$ 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 observation⁶ 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 non-magnetic 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 ($4.2 \leq T \leq 10$ K; $0 < H \leq 10$ 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 $\text{Yb}_{1-x}\text{Lu}_x\text{Rh}_2\text{Si}_2$ ($0 \leq x \leq 1.00$) 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 $\leq 0.015^\circ$ 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 $\sim 2 \times 2 \times 0.5$ mm³ 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

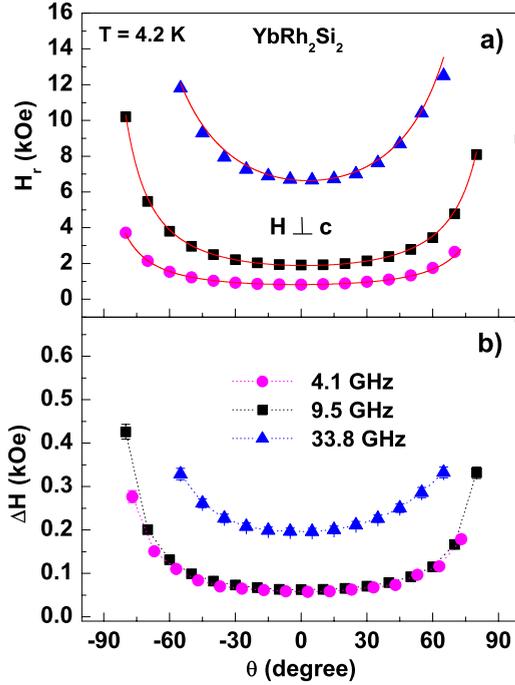


FIG. 1. (Color online) X, S, and Q-band angular dependences of the Yb^{3+} ESR at 4.2 K in a plane perpendicular to the ab plane: (a) $H_r(\theta)$ (solid lines, see text) and (b) $\Delta H(\theta)$ (dashed lines are guides for the eyes).

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 $g_{\parallel c} \leq 0.6(4)$ 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 $\approx 0.015^\circ$ for the c axis (mosaic effect) would only contribute to an inhomogeneous broadening of ≤ 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

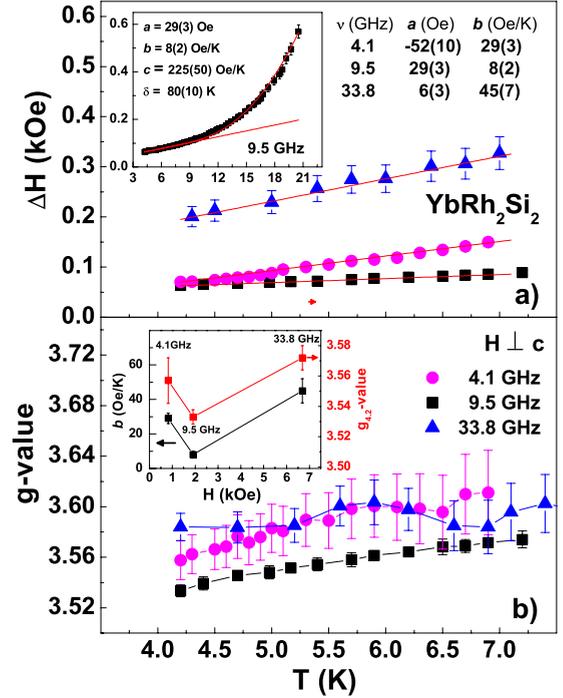


FIG. 2. (Color online) X, S, and Q-band low- T dependences of the Yb^{3+} ESR for $H_{\perp c}$ (a) $\Delta H(T)$ and (b) effective $g(T)$ value. Inset of (a): X-band $\Delta H(T)$ for $4.2 \leq T \leq 21$ K and fitting parameters to $\Delta H(T) = a + bT + c\delta/[\exp(\delta/T) - 1]$. Inset of (b):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

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 $H \approx 1900$ 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 $7 \leq T \leq 20$ 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 $\text{Yb}_{1-x}\text{Lu}_x\text{Rh}_2\text{Si}_2$: (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 $7 \text{ K} \leq T \leq 20 \text{ K}$, $\Delta H(T)$ also shows exponential behaviors with parameters $c \approx 200(80)$ Oe/K and

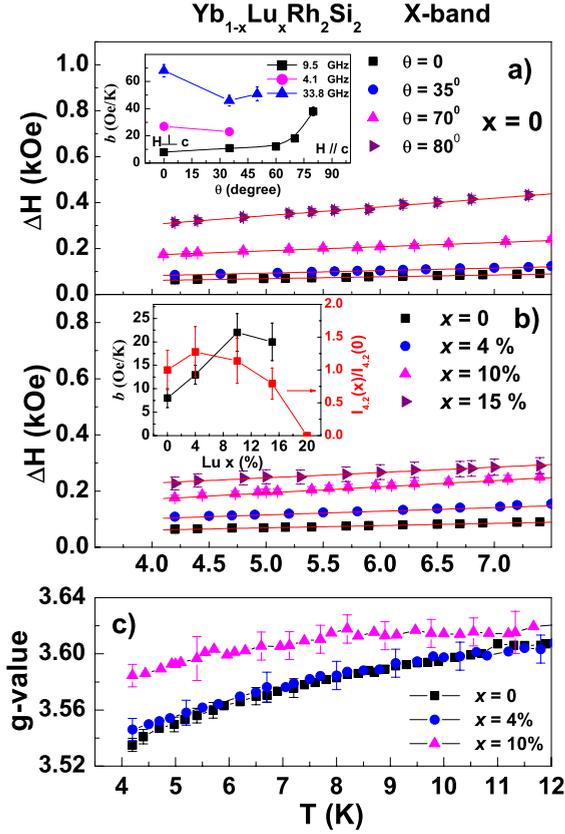


FIG. 3. (Color online) X-band low- T Yb^{3+} ESR data for $\text{Yb}_{1-x}\text{Lu}_x\text{Rh}_2\text{Si}_2$: (a) $\Delta H(T)$ for θ between $H_{\perp c}$ and $H_{\parallel c}$ and $x=0$, (b) $\Delta H(T, x)$, and (c) effective $g(x, T)$ for various Lu concentrations and $H_{\perp c}$. The parameters 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 $0.15 < x \leq 1.00$ the intensity drops dramatically and no ESR could be detected; although, interestingly, for $x > 0.15$ and $T \geq 200$ 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

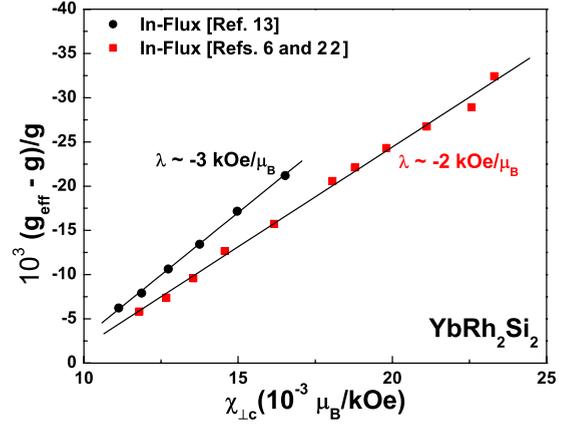


FIG. 4. (Color online) Effective g shift and magnetic-susceptibility correlation, $(g_{\text{eff}} - g)/g \propto \lambda \chi_{\perp c}(T)$, for $T \leq 15$ K and X band for $x=0$ crystals (see text).

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

Moreover, within a molecular-field approximation the effective $g(x, T)$ may be written as $g_{\text{eff}} = g[1 + \lambda \chi_{\perp c}(T)]$. Figure 4 presents a plot of $\Delta g/g = (g_{\text{eff}} - g)/g \propto \lambda \chi_{\perp c}(T)$ for $T \leq 15$ K and X band for our $x=0$ crystals¹³ and that from Refs. 6 and 22. A linear correlation is obtained with λ values in the interval $-2 \text{ kOe}/\mu_B > \lambda > -3 \text{ kOe}/\mu_B$ 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 $T_N \equiv J_{ff}(g/2)^2 \sim 500$ 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), $b \approx 40$ Oe/K. Within a single band approximation¹⁸ and absence of q dependence of the Yb^{3+} -ce exchange interaction $J_{fce}(\mathbf{q}) \equiv J_{fce}(\mathbf{0})$,²³ one can write $(\Delta g/g)^2 = \mu_B b / \pi g k_B$, which gives $|\Delta g/g| \approx 2\%$. 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 relation¹⁸ using $b \approx 40$ Oe/K and assuming a maximum *bare* density of state per one spin direction at the Fermi level η_F given by the Sommerfeld coefficient of the specific-heat measurements ($\gamma \approx 900$ mJ/mol K²) (Ref. 24), we extract a lower limit for $|J_{fce}| \geq 3$ 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

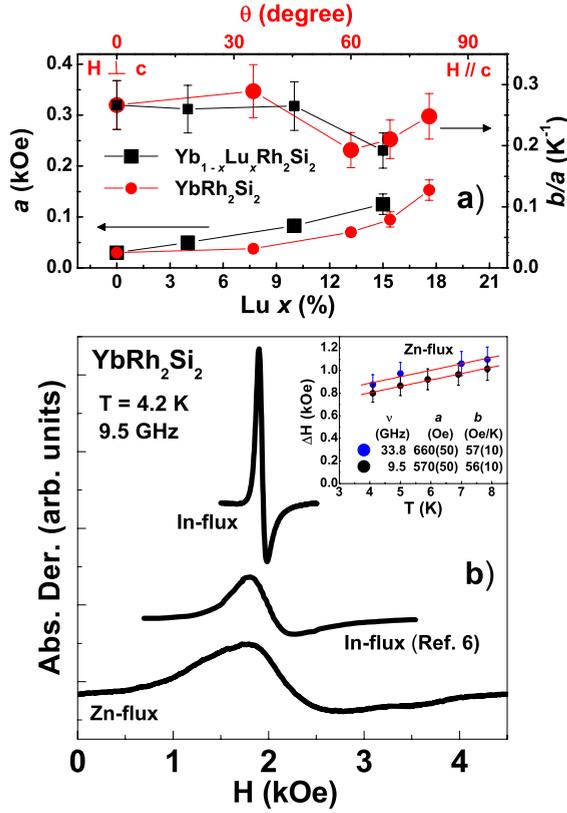


FIG. 5. (Color online) (a) X-band Yb^{3+} ESR: $a(x)$, $a(\theta)$, $b(x)/a(x)$, and $b(\theta)/a(\theta)$ for θ between $H_{\perp c}$ and $H_{\parallel c}$ and $0 \leq x \leq 0.15$ for $H_{\perp c}$; (b) for comparison, ESR spectra at 4.2 K and $H_{\perp c}$ for single crystals grown in In and Zn fluxes 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 arguments²⁵ 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 $g_{\text{eff}} - g_{\text{Yb}}$ of the form $g_{\text{eff}} - g_{\text{Yb}} = -(g_{\text{Yb}} - g_{\text{ce}})(g_{\text{Yb}}/g_{\text{ce}})\gamma\chi_{\text{ce}}$, 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 $\leq 0.015^\circ$ 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, $\sigma'_g(x) \approx 0.0114/\%_{\text{Lu}}$, and $\sigma_g(0) \approx 0.0137$. Notice that for $\theta \approx 80^\circ$ and $x \approx 0.15$ 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_2Si_2 below $T_K \approx 25$ 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 $g \approx 2$, 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_2Si_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 $b'(x) \approx 1.4(\text{Oe}/\text{K})/\%_{\text{Lu}}$. 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 $\theta \geq 60^\circ$. 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_2Si_2 .

Another striking result reported in Fig. 2 is the nonmonotonic 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 terms²⁸ 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_2Si_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 reports⁶ 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 Wölfle³¹ 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 $s+S_{\text{ps}}$ 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 $T_K \approx 25$ 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 $|J_{fcl}|$.

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