ESR study of spin dynamics in the ternary phosphide YbRh₆P₄

V A Ivanshin¹, E M Gataullin¹ and A A Sukhanov²

¹Kazan (Volga region) Federal University, Kremlevskaya str. 18, 420008 Kazan, Russia
²Zavoisky Physical-Technical Institute, Sibirsky trakt 10/7, 420029 Kazan, Russia

E-mail: Vladimir.Ivanshin@ksu.ru

Abstract. We have used electron spin resonance (ESR) to investigate the YbRh₆P₄ powder samples. It is shown that the exotic ESR absorption is caused here by hybridization effects between the Yb ⁴f-orbitals and the wave functions of the conduction electrons (CE) of the outer electronic shells. A broadening and disappearance of the ESR line at temperatures above 10 K can be explained by the processes of the spin-lattice relaxation of the Yb³⁺ ions through the first excited Stark sublevel with an activation energy Δ ≈ 82.1 K.

1. Introduction
The explanation of transformation of localized electrons at high temperatures into itinerant quasi-particles with an enhanced mass at lower temperatures belongs to the most important challenges in the physics of the solid state. The mechanism of this evolution depends on the Kondo interactions between the CE and the localized d or f electrons. ESR probes microscopically both the local moment (LM) spins and CE in different strongly correlated electron systems (SCES) such as high-temperature superconductors, pnictides, heavy fermion systems. As a rule, LM ESR is studied in compounds with doped paramagnetic ions and localized electrons. ESR from CE can be detected in metallic systems with an enhanced Pauli susceptibility. Surprisingly, ESR could be also observed in some dense SCES without any kind of paramagnetic doping (s. [1] and references therein). According to several recent theories [2-5], a measurable ESR signals in these experiments are caused by an effective hybridization between localized f electrons and conduction bands in conjunction with ferromagnetic (FM) correlations which reduce usually a very fast spin-lattice relaxation. In the present contribution, we report the temperature-dependent ESR spectra in the recently synthesized phosphide YbRh₆P₄.

2. Experimental
YbRh₆P₄ belongs to the large number of metal-rich compounds with a metal-to-phosphorus ratio near 2:1. The twinned crystal YbRh₆P₄ samples were prepared by the bismuth flux technique and were refined using X-ray diffractometer [6]. ESR spectra were recorded on an X-band EMX/plus spectrometer (Bruker BioSpin GmbH, Germany) in the temperature range between 4.2 and 20 K. Figure 1 presents the temperature evolution of the ESR spectrum with \( g_{\text{eff}} \approx 3.34 \) (at \( T = 6 \) K) in the YbRh₆P₄ powder samples which shows typical properties of the Yb³⁺-ESR similar to YbRh₂Si₂ [7], Ybl₃Si₂ [8], and YbRh₂Pb [9].

Published under licence by IOP Publishing Ltd
3. Discussion
The twinned sample structure has prevented the detailed investigation of the anisotropy of the LM centers. The nature of the relaxation mechanism of the ESR-active spins has been analyzed using the temperature dependence of the ESR peak-to-peak linewidth $\Delta H$ which is shown in Figure 2. These data can be well described by the dashed line which displays the behaviour for the LM relaxation in metallic environment [7-9]:

$$\Delta H = A + BT + C \exp(-\Delta/T),$$

where $A \approx 348.7$ Oe, $B \approx 5$ Oe/K, $C \approx 5.6$ kOe, and $\Delta \approx 82.1$ K. The parameter $A$ is caused by spin–spin interactions and inhomogeneous ESR line broadening. The term $BT$ belongs to the contribution to the ESR linewidth from Korringa relaxation. The third term in Eq. (1) is the result of thermal fluctuations of the electronic states of the Yb$^{3+}$ ions proposed in [10] for YbRh$_2$Si$_2$.

This spin-lattice relaxation mechanism which stimulates random transitions of the Yb$^{3+}$ ions from the ground state to the first excited Kramers doublet with an activation energy $\Delta \approx 82.1$ K can be also responsible for the temperature dependence of the effective ESR $g$-factor in YbRh$_6$P$_4$ at $T > 10$ K (figure 3):

$$g(T) = g_0 + \Delta g_0 \exp(-\Delta/T),$$

$$\Delta g_0 = g_{exc} - g_0,$$

(2)
where \( g_0 \approx 3.34 \) and \( g_{\text{exc}} \approx -25.66 \) are the effective \( g \) factors of the ground and the first excited Stark sublevels of the Yb\(^{3+}\) ion, respectively.

![Figure 2. Temperature dependence of the ESR linewidth in YbRh\(_6\)P\(_4\). The dashed line presents the equation (1) with the parameters \( A \approx 348.7 \) Oe, \( B \approx 5 \) Oe/K, \( C \approx 5.6 \) kOe, and \( \Delta \approx 82.1 \) K.](image1)

\[ g_{\text{exc}} \approx -25.66 \]

\[ g_0 \approx 3.34 \]

![Figure 3. Temperature dependence of the ESR \( g \)-factor measured at a frequency 9.4 GHz. The solid line is the theoretical fit using equation (2).](image2)

Functional dependence (2) which is shown as a solid line in figure 3 illustrates a transition from the mixed correlated state of localized \( 4f \) states of ytterbium and collectivized electrons from the unfilled outer \( d \) and \( p \) shells of rhodium and phosphorus below 10 K to a paramagnet with the magnetic moments of the \( 4f \) shells close to the magnetic moments of free Yb\(^{3+}\) ions at higher temperatures. Although a very similar behaviour has been observed in YbRh\(_2\)Si\(_2\) and YbIr\(_2\)Si\(_2\), the ESR signal intensity in YbRh\(_6\)P\(_4\) was significantly smaller demonstrating a weaker hybridization effects in the phosphide in contrast to the both these silicides. Most likely, a weak extent of hybridization results
also in the small value of an indirect interspin Rudermann-Kittel-Kasuya-Yosida (RKKY) interaction and the corresponding FM correlations [11] as it also has been detected in the EPR experiments on the hybridized electronic states in the Heusler alloy \( \text{YbRh}_2\text{Pb} \) [9]. It means that the replacement of Si (\([\text{Ne}]3s^23p^2\)) by Pb (\([\text{Hg}]6p^2\)) or by P (\([\text{Ne}]3s^23p^3\)) does not lead to a significant qualitative change of the ESR behaviour but dramatically reduces the \( f-p \) hybridization in \( \text{YbRh}_6\text{P}_4 \) and \( \text{YbRh}_2\text{Pb} \) as compared to \( \text{YbRh}_2\text{Si}_2 \). Thus, a comparison of spin dynamics in all \( \text{Yb}-\text{Rh}\)-based systems investigated by ESR method [7-10] allows us to suggest that the \( f-d \) hybridization is mainly responsible for the contribution of CE in the collective spin mode of LM and CE. The strength of the \( f-p \) hybridization which determines the intensity of ESR absorption is essentially more in the both Si-containing intermetallics (\( \text{YbRh}_2\text{Si}_2 \) and \( \text{YbIr}_2\text{Si}_2 \)) than in \( \text{YbRh}_6\text{P}_4 \) or \( \text{YbRh}_2\text{Pb} \).

In conclusion, the low temperature ESR absorption has been found out in the new phosphide \( \text{YbRh}_6\text{P}_4 \). Electronic spin-lattice relaxation processes with an involvement of the first excited Stark sublevel of the \( \text{Yb}^{3+} \) ion with an energy \( \Delta \approx 82.1 \text{ K} \) describe quite well a drastic broadening and vanishing of the ESR signal above 10 K. The observed ESR behavior provides evidence for the relatively weak \( f-p \) hybridization effects in \( \text{YbRh}_6\text{P}_4 \) in contrast to silicides \( \text{YbRh}_2\text{Si}_2 \) and \( \text{YbIr}_2\text{Si}_2 \).

We would like to thank U. Pfannenschmidt and R. Pöttgen for sample preparation.

References
[1] Ivanshin V A, Litvinova T O, Sukhanov A A, Ivanshin N A and Enderward B 2011 Solid State Phenomena 170 170
[2] Abrahams E and Wölfle P 2008 Phys. Rev. B 78 104423
[3] Schlottmann P 2009 Phys. Rev. B 79 045104
[4] Huber D L 2009 J. Phys.: Condens. Matter 21 322203
[5] Wölfle P and Abrahams E 2009 Phys. Rev. B 80 235112
[6] Pfannenschmidt U, Rodewald U C and Pöttgen R 2011 Monatsh. Chem. 142 219
[7] Sichelschmidt J, Ivanshin V A, Ferstl J, Geibel C and Steglich F 2003 Phys. Rev. Lett. 91 156401
[8] Sichelschmidt J, Wykhoff J, Krug von Nidda H-A, Fazlishanov I I, Hossain Z, Krellner C, Geibel C and Steglich F 2007 J. Phys.: Condens. Matter 19 016211
[9] Ivanshin V A, Litvinova T O, Sukhanov A A, Sokolov D A and Aronson M C 2009 JETP Lett. 90 116
[10] Ivanshin V A, Aminov L K, Kurkin I N, Sichelschmidt J, Stockert O, Ferstl J and Geibel C 2003 JETP Lett. 77 526.
[11] Krellner C, Förster T, Jeevan H, Geibel C and Sichelschmidt J 2008 Phys. Rev. Lett. 100 066401