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Effect of Superconductivity on Spin Dynamics in $(Y_{1-x}RE_x)Rh_4B_4$*

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**On leave from the Department of Materials Physics, Faculty of Engineering Science, Osaka University, Osaka, Japan.

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Effect of Superconductivity on Spin Dynamics in $(Y_{1-x}RE_x)Rh_4B_4$*

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ABSTRACT

An adiabatic field-cycle method has been used to study spin dynamics of RE ions in $(Y_{1-x}RE_x)Rh_4B_4$. Longitudinal dipolar fluctuations of RE moments are found to be the main source of the nuclear spin-lattice relaxation time of ^{11}B. The variation of T_1 in the superconducting state is attributed to the reduction of the electronic spin-relaxation time, τ_m, which is mainly determined by the RKKY type interaction mediated by the conduction electrons.

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There have been numerous experimental and theoretical investigations on ternary superconducting compounds to clarify the relation of superconductivity and magnetism [1]. The origin of magnetism in these compounds is associated with the unfilled 4f electron shell of the rare earth ions, and the dominant interaction between localized moments is considered to be the indirect RKKY interaction mediated by the conduction electrons, which are responsible for superconductivity. Although microscopic investigations such as NMR and ESR have been reported, the interesting problem of how superconductivity affects the spin dynamics of the localized moments is still open to question. In this paper, we report on the spin dynamics of RE ions using the ^{11}B nuclear magnetic relaxation time in dilute $(Y_{1-x}RE_x)Rh_4B_4$ (RE = Gd and Er). Because of the relatively small s-f exchange coupling and the small hyperfine coupling of ^{11}B in those compounds, the nuclear spin-lattice relaxation time of ^{11}B is long enough to study the relaxation behavior in various external fields with an adiabatic demagnetization/remagnetization field cycle method. The details of the experimental procedure and the sample preparation will be described elsewhere [2].

Fluctuations of the rare earth moment induce nuclear magnetic relaxation that is found to follow a square root dependence on time, indicating lack of spin diffusion between boron nuclei. The longitudinal nuclear magnetization is given by [3]

$$M_z(\infty) - M_z(t) = [M_z(\infty) - M_z(0)]\ \exp(-t/T_{1K})\ \exp\left[-\left(\frac{t}{T_1}\right)^{1/2}\right] \quad (1)$$

where T_{1K} is the Korringa relaxation time = 46 sec-K in the normal state and τ_1 is the localized moment induced nuclear relaxation time. The temperature dependence of τ_1 at various external fields is shown in Fig. 1 for $(Y_{1-x}Gd_x)Rh_4B_4$ and $(Y_{1-x}Er_x)Rh_4B_4$. τ_1^{-1}, in the normal state, is independent of external field and temperature and is proportional to the concentration of rare earth ions.

From numerical estimation and the lack of field dependence in the normal state, the largest contribution to τ_1 is found to be due to the longitudinal dipolar fluctuations described by [3],

$$\left.\frac{1}{\tau_1}\right)_{LD} = \frac{16}{9}\pi^3 \, (\gamma_n g_J \mu_B J N_o x)^2 \, \frac{\partial B_J(X)}{\partial X} \, \frac{\tau_m}{1+(\omega_n \tau_m)^2} \tag{2}$$

where γ_n is the nuclear gyromagnetic ratio, g_J is the Landê factor, μ_B is the Bohr magnetron, J is the total RE angular momentum, x is the concentration of the magnetic ions, N_o is the density of the rare-earth site, B(X) is the Brillouin function, τ_m is the longitudinal relaxation time of the paramagnetic ions and ω_n is the nuclear Larmor frequency. The dependence of τ_1 on temperature for Gd and Er doped compounds is due to the large reduction of the paramagnetic moment relaxation time τ_m in the superconducting state. The rapid fluctuation region ($\omega_n\tau_m \ll 1$) at higher temperatures is separated from the slow fluctuation region ($\omega_n\tau_m \gg 1$) at lower temperature in the superconducting state. The field dependence of τ_1 comes primarily from the $\omega_n^2 \propto H^2$ factor in the superconducting state.

In Fig. 2 we show τ_m^{-1} as a function of 1/T from the data in Fig. 1 and Eq. (2) using the full J value. (Crystal field effects will be discussed in an extended paper.) In the normal state, the relaxation time of the localized moment is found to be independent of T and H and proportional to concentration as expected for the RKKY interaction [3],

$$\frac{1}{\tau_m}\Big)_{RKKY} = \frac{2}{3}\pi^2 \left[\frac{\pi(g_J-1)^2 \; J(J+1)}{6}\right]^{1/2} \frac{E_F N_o \;\; [N(0)\mathcal{J}]^2}{\hbar k_F^3} \, x \qquad (3)$$

where N(0) is the density of state at the Fermi level, $\mathcal{J}$ is the s-f exchange interaction and E_F and k_F is the Fermi energy and momentum, respectively. The competing Korringa relaxation of the local moment via the exchange interaction with the conduction electron spins [4] is not important in the normal state at 11 K and would be expected to become much less effective in the superconducting state as the gap opens. Interestingly, from a comparison of τ_m in the normal state, we find from Eq. (3) that $N(0)\mathcal{J}$ is approximately equal to 3×10^{-3} for both Gd and Er doped compounds.

The most important observation is the striking effect of superconductivity on the spin dynamics of RE moments in the superconducting state. Although no theoretical study is presently available with which to compare to the present results, we would expect that the reduction of the RKKY interaction in the superconducting state can be attributed to the reduction of the conduction electron spin susceptibility $\chi(q)$ [5]. However, the importance of the electromagnetic interaction between moments through the superconducting persistent current has been proposed to explain the anomalous nature of magnetic superconductors [6]. Further investigations are now in progress to obtain detailed analyses of the spin dynamics of the local moments in the superconducting state.

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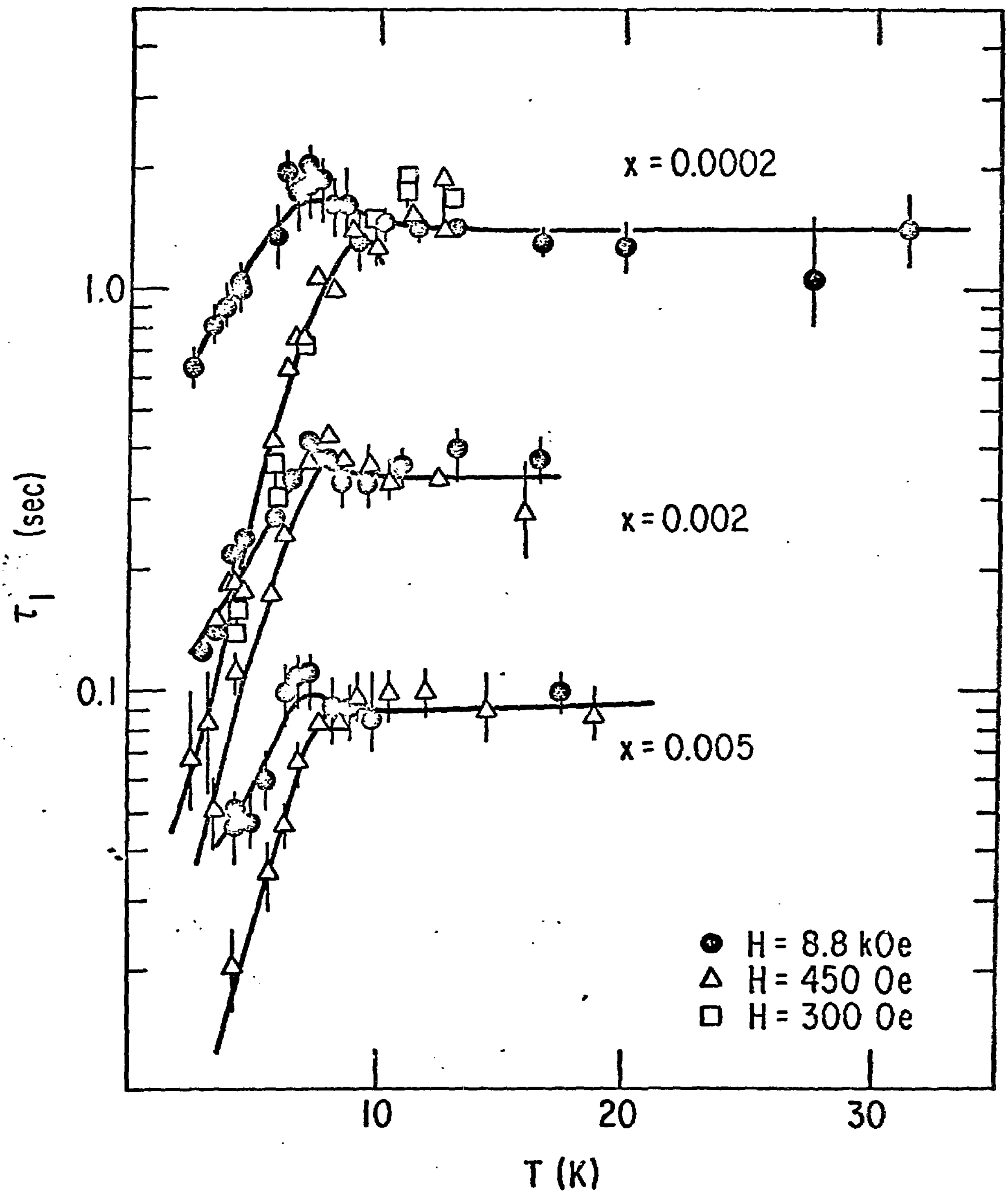
Figure Captions

Fig. 1. Temperature dependence of ^{11}B nuclear relaxation time τ_1 due to the fluctuation of the localized moment as a function of temperature in (a) $(Y_{1-x}Gd_x)Rh_4B_4$ and (b) $(Y_{0.9998}Er_{0.0002})Rh_4B_4$.

Fig. 2. Electronic spin relaxation time τ_m of Gd and Er versus reciprocal temperature for various external fields.



x = 0.0002
x = 0.002
x = 0.005
1.0
0.1
τ_1 (sec)
10
20
30
T (K)
H = 8.8 kOe
H = 450 Oe
H = 300 Oe

Fig. 1: (a)

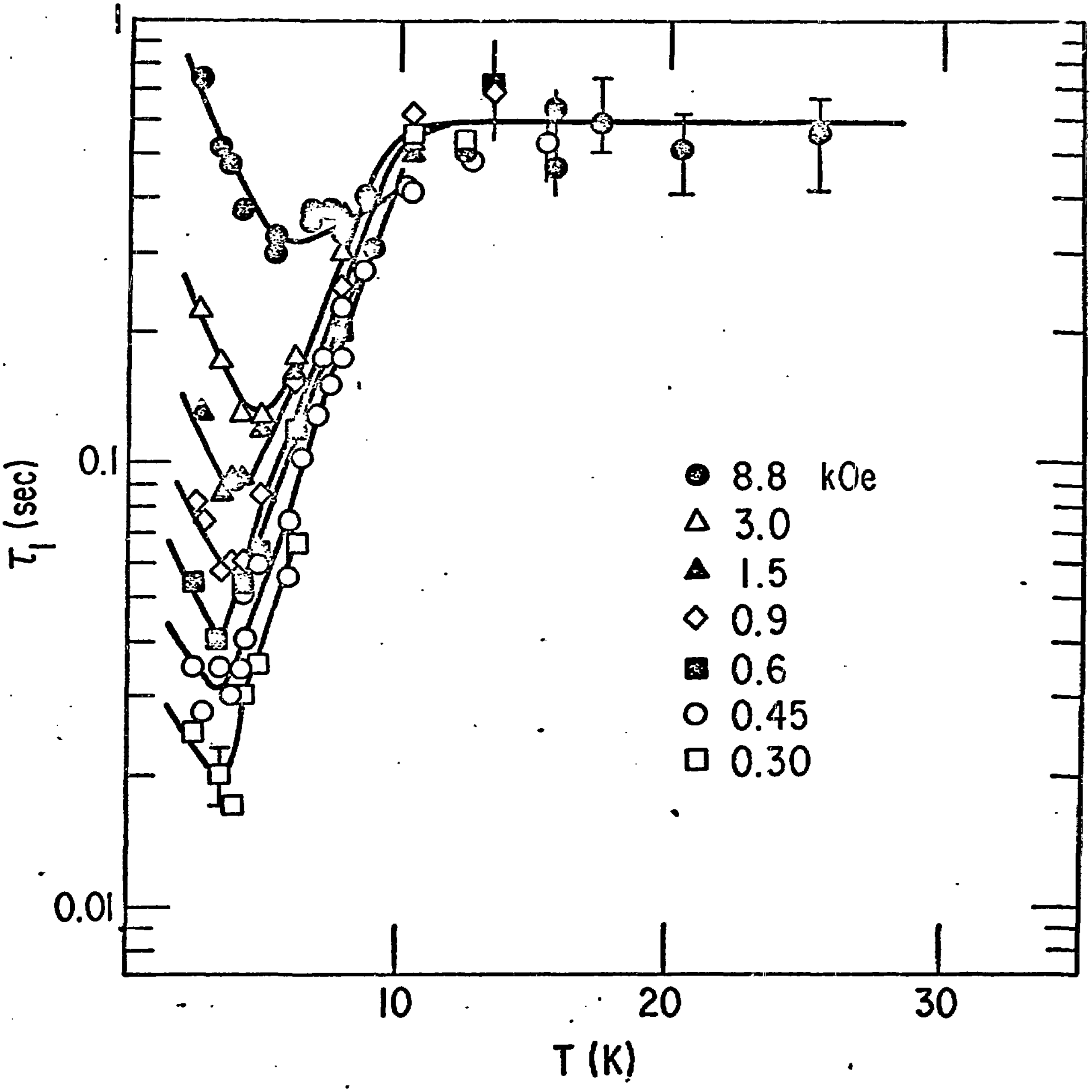
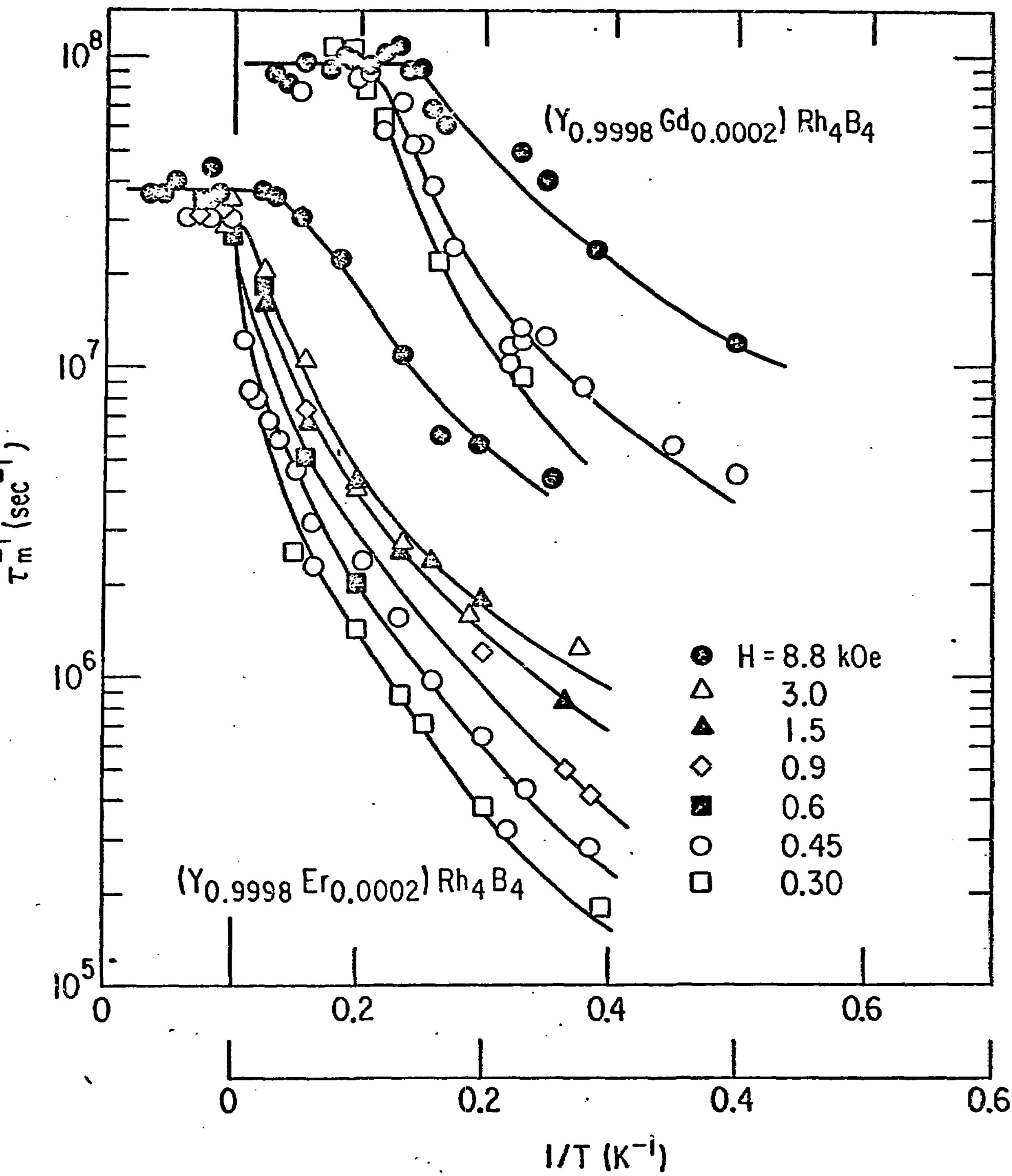


Fig. 1 (b)



$(Y_{0.9998}Gd_{0.0002})Rh_4B_4$
$(Y_{0.9998}Er_{0.0002})Rh_4B_4$
H = 8.8 kOe
3.0
1.5
0.9
0.6
0.45
0.30
τ_m^{-1} (sec^{-1})
10^8
10^7
10^6
10^5
0
0.2
0.4
0.6
1/T (K^{-1})

Fig. 2