Hyperfine Interactions (2004) 158:125–129
DOI 10.1007/s10751-005-9020-8

Temperature Dependence of the Magnetic Hyperfine Field at ^{140}Ce on Gd Sites in GdAg Compound

F. H. M. CAVALCANTE, A. W. CARBONARI*, R. N. SAXENA and J. MESTNIK-FILHO
Instituto de Pesquisas energéticas e Nucleares - IPEN-CNEN/SP; e-mail: carbonar@ipen.br

Abstract. Perturbed gamma–gamma angular correlation technique was used to measure the magnetic hyperfine field at Gd sites in the intermetallic compound GdAg using the ^{140}La→^{140}Ce nuclear probe. A major and well-defined magnetic interaction is observed at ^{140}Ce substituting Gd sites in GdAg below 130 K, corresponding to a ferromagnetic ordering of Gd moments. The temperature dependence of magnetic hyperfine field, however, shows a sharp deviation from an expected Brillouin-like behavior for temperatures below 75 K. This additional magnetic interaction is believed to result from the polarization of Ce spin moments induced by the magnetic field from Gd atoms.

Key Words: ^{140}Ce, magnetic hyperfine field, PAC spectroscopy, rare earth magnetism.

1. Introduction

The magnetic hyperfine field (mhf) at rare earth atom sites in intermetallic compounds is still a very interesting subject specially if the probe nuclei are rare earth elements where the orbital contribution to the mhf can be important. For closed shell probe nuclei as impurity in rare earth intermetallic compounds, the magnetic hyperfine field is proportional to the conduction electron spin polarization (CEP) at the probe site, as has been shown in literature for several compounds using, for instance, ^{111}Cd. In the case of rare earth probe nuclei, the 4f electrons are expected to contribute significantly to the magnetic hyperfine field. However, there are only few experimental results available for rare earth probe nuclei in rare earth magnetic compounds to permit a systematic investigation of the mhf contribution due to 4f electrons. Moreover, it is not well understood yet whether the influence of 4f electrons of the probe on the magnetic hyperfine field in rare earth compounds is always present. In this work we have investigated the mhf at ^{140}Ce probe nuclei substituting Gd sites of the cubic intermetallic compound GdAg in order to quantify the 4f contribution and

* Author for correspondence.

compare the results with previous measurements of mhf on ^{140}Ce in other rare earth compounds.

The cubic rare-earth intermetallic compounds of the type RM where M is a noble metal have shown interesting magnetic properties. These compounds usually show antiferromagnetic behavior when *M* is a monovalent metal Cu or Ag, the exception being PrAg. The antiferromagnetic (π,π,0) structure in these compounds is built up by ferromagnetic (1,1,0) planes coupled antiferromagnetically. The presence of phenomena like quadrupole interactions and crystal field splitting, spin fluctuations and incommensurate magnetism can turn the magnetic behavior in these compounds very complex. The magnetism in GdAg is less complex, however. Quadrupolar and crystal field effects are absent in this compound which also has the highest Néel temperature in the family of compounds with T_N ~132.8 K [1].

2. Experimental

Samples of GdAg were prepared by repeatedly melting the constituent elements (Gd 99.99% and Ag 99.9985%) under argon atmosphere purified with a hot titanium getterer in an arc furnace. The samples used for TDPAC measurements were prepared in a similar way but with radioactive ^{140}La (obtained by neutron irradiation of lanthanum metal) substituting about 0.1% of Gd atoms. Samples were annealed under an atmosphere of ultra pure Ar for 48 h at 700 °C. The structure of the samples was checked by X-ray diffraction, which indicated a single phase and the cubic CsCl-type structure with the $Pm\bar{3}m$ space group. Magnetization measurements were carried out in the temperature range of 4.2–200 K using a superconductor quantum interference device (SQUID).

The TDPAC measurements were carried out with a conventional fast-slow coincidence set-up with four conical BaF_2 detectors. The gamma cascade of 329–487 keV populated from the decay of ^{140}La with an intermediate level with spin I = 4^+ at 2083 keV ($T_{1/2}$ = 3.45 ns) in ^{140}Ce was used to measure the magnetic hyperfine field at Gd sites. The samples were measured in the temperature range of 10–295 K by using a closed-cycle helium cryogenic device. The time resolution of the system was about 0.6 ns for the ^{140}Ce gamma cascade. A detailed description of the method can be found elsewhere [2, 3]. The experimental data for temperatures below T_N were analyzed for a pure magnetic dipole interaction.

3. Results and discussion

Some of the TDPAC spectra measured with ^{140}Ce probe nuclei are shown in Figure 1. The solid curves are the least squares fit of the experimental data to the appropriate function in each case. The quadrupole moment of the 2083 keV 4^+ state of ^{140}Ce is known to be very small [4], consequently one expects to observe

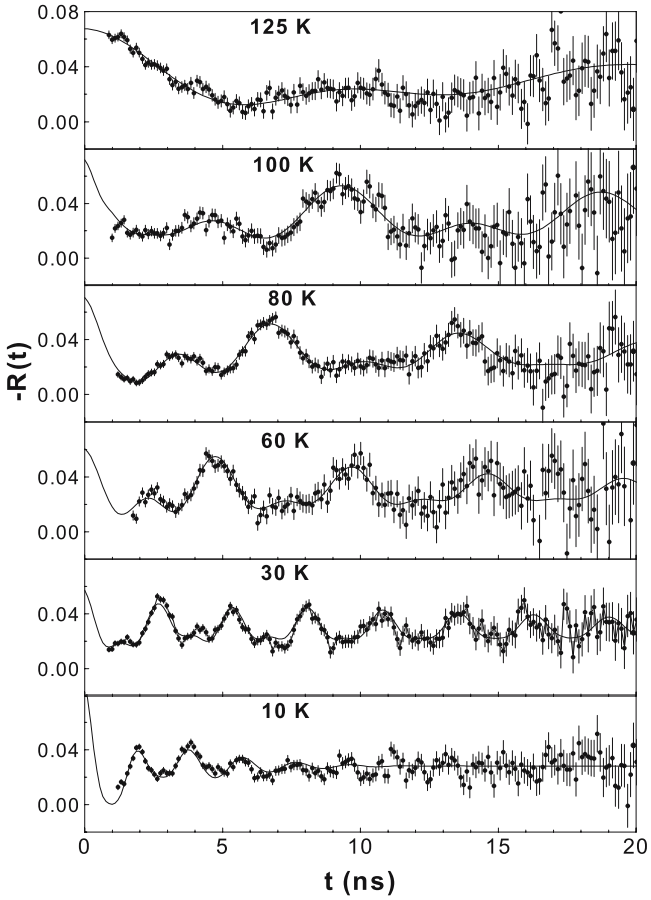

Figure 1. TDPAC spectra for ^{140}Ce at Gd sites in GdAg.

an almost pure magnetic dipole interaction in the antiferromagnetic phase of the sample. Below 130 K, a unique and well-resolved magnetic interaction is observed at ^{140}Ce in GdAg. The temperature dependence of B_{hf} is plotted in Figure 2. The observed magnetic interaction corresponds to the antiferromagnetic ordering of the Gd moments. The measurements below ~75 K, however, show a sharp deviation from the expected standard behavior for a simple antiferromagnetic ordering. The Ce hyperfine field, instead of approaching a saturation value, increases sharply at lower temperatures. The measured hyperfine field at 80 K is 20 T while at 10 K it is 73 T. The five points immediately below T_N in Figure 2 were least-square fitted to the modified Curie–Weiss law $B_{hf}(T) = B_{hf}(0)(1 - T/T_N)^{\beta}$. The results of this fitting yielded β = 0.41(2), B_{hf} (0) = 25(1)T, T_N = 131.5(3) K. The value of T_N is somewhat smaller while the value of β is higher than the values of 132.8(1) K and 0.33, respectively obtained from neutron diffraction measurements [1]. It is well known that neutron diffraction data for magnetic materials are affected by

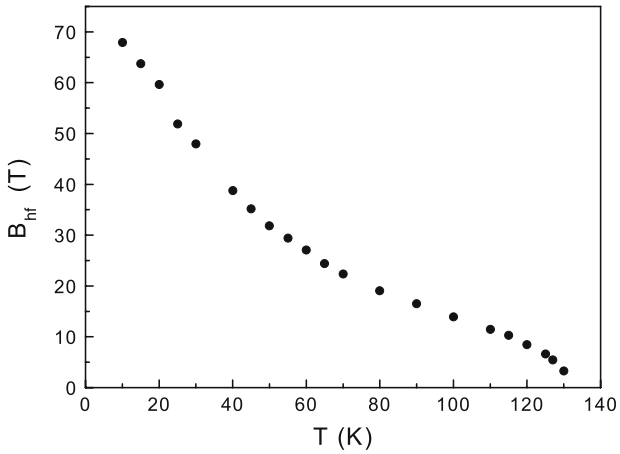

Figure 2. Temperature dependence of the magnetic hyperfine field at Gd sites.

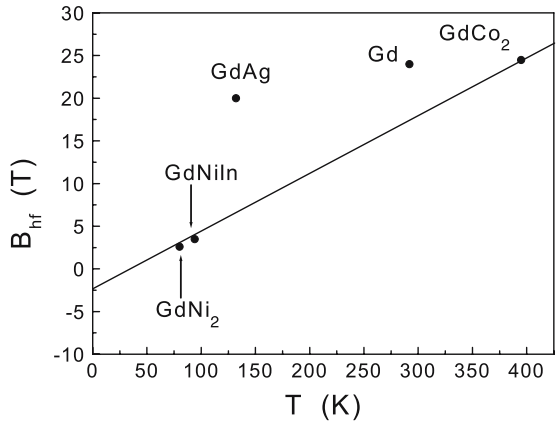

Figure 3. The extrapolated magnetic hyperfine field $B_{hf}(0)$ at ^{140}Ce in some Gd compounds as a function of the respective magnetic transition temperatures.

the temperature dependent extinction effects, which cause a reduction in the critical exponent value. The present value of β is higher than the theoretical value expected for a three-dimensional isotropic Heisenberg critical exponent (β ≈ 0.38).

The explanation for the additional magnetic interaction is similar to that given for the temperature dependence of the B_{hf} at ^{140}Ce in $CeMn_2Ge_2$ compound [5]. The additional field is believed to result from the polarization of Ce spin moments induced by the magnetic field from Gd moments. Previous measurements of the mhf at ^{140}Ce in Gd [6] also shows a similar behavior for the temperature dependence of B_{hf}, with a sharp deviation from the standard magnetization curve below a certain temperature.

In [7] the saturation values of B_{hf} measured with ^{140}Ce for some Gd compounds are compared to the respective magnetic transition temperature. The

linear dependence obtained shows that the main contribution to the B_{hf} comes from the conduction electron spin polarization via RKKY interaction. In order to insert the points for GdAg and Gd in such comparison, we have estimated the saturation values by visually extrapolating the B_{hf} curve from the points between the temperature where the deviation starts and the ordering temperature, e.g., we have disregarded the probe effect from the magnetization curve. The results are shown in Figure 3 and indicate that both GdAg and Gd do not follow the same proportionality. Therefore, we can assume that the B_{hf} for these compounds have additional contributions besides those from the conduction electrons spin polarization, even for the temperature region free of the probe effect.

Acknowledgements

Partial support for this research was provided by the Fundação de Amparo á Pesquisa do Estado de São Paulo (FAPESP). Authors FHMC and AWC thankfully acknowledge the support provided by CNPq in the form of research fellowships.

References

1. Chattopadhyay T., McIntyre G. J. and Kiiblerb U., *Solid State Comm.* **100** (1996), 117.
2. Pendl W. Jr., Saxena R. N., Carbonari A. W., Mestnik-Filho J. and Schaft J., *J. Phys. Condens. Matter.* **8** (1996), 11317.
3. Attili R. N., Saxena R. N., Carbonari A. W., Mestnik-Filho J., Uhrmacher M. and Lieb K. P., *Phys. Rev. B* **58** (1998), 2563.
4. Królas K., Wodniecka B. and Niewodniczanski H., Institute of Nuclear Physics, Kraków, Poland, Report No. 1644/OS-1993 (unpublished).
5. Carbonari A. W., Mestnik-Filho J., Saxena R. N. and Lalic M. V., *Phys. Rev. B* **69** (2004), 1444251.
6. Thiel T. A., Gerdau E. and Böttcher M., *Hyperfine Interact.* **9** (1981), 459.
7. Lapolli A., Carbonari A. W., Saxena R. N. and Mestnik-Filho J., this conference.