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Temperature dependence of the magnetic hyperfine field at cerium impurity in Co

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Abstract Perturbed gamma-gamma angular correlation (PAC) technique was used to measure the magnetic hyperfine field (B_{hf}) at Ce impurity in Co using ^{140}La→ ^{140}Ce probe. The radioactive ^{140}La produced by neutron irradiation of lanthanum metal with thermal neutrons was introduced in Co by arc melting in argon atmosphere. The present measurements cover the temperature range from 4.2–1300 K. Two pure magnetic interactions were observed at impurity sites, corresponding to a ferromagnetic ordering of Co moments in hcp and fcc phases. The temperature dependence of B_{hf} for both phases, however, shows a sharp deviation from an expected standard Brillouin-like behavior for the host magnetization. The results are discussed in terms of a simple molecular-field model where the localized moment at impurity ions as well as the conduction electron contributions to the hyperfine field are taken into account.

Keywords Cobalt · Magnetism · PAC spectroscopy · Magnetic hyperfine field

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1 Introduction

The magnetic hyperfine field (mhf) at rare earth impurities in magnetic hosts is a very interesting subject not yet totally understood . In particular, the exchange interaction between the localized moments of the impurity and the host, which may be different from the host-host exchange interaction, is not well described so far. In this work, the

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temperature dependence of mhf at ^{140}Ce probes diluted in Co are reported for the first time.

It is well known that metallic Co exists in two different crystallographic phases: at low temperatures Co crystallizes in almost an ideal hexagonal-close-packed (hcp)lattice. At room temperature and below the Co moments are parallel to the direction of c-axis. The spin orientation changes from parallel to perpendicular in the temperature range of 500–600 K. At about 700 K, Co undergoes a phase transition to face-centered cubic(fcc)lattice. The phase transition is however not sharp and usually both fcc and hcp phase co-exist below 700 K In the fcc phase Co orders ferromagnetically below $T_C = 1394$ K.

In the present work, perturbed gamma-gamma angular correlation (PAC) technique was used to measure the magnetic hyperfine field at Ce impurity in Co using ^{140}La→ ^{140}Ce probe. The measurements cover a temperature range from 4.2–1300 K. A major and well-defined magnetic interaction is observed at impurity sites, corresponding to a ferromagnetic ordering of Co moments. The temperature dependence of mhf, however, shows a sharp deviation from an expected Brillouin-like behavior. The results are discussed in terms of a simple molecular-field model model where the localized moment at impurities ions as well as the conduction electron contributions to the hyperfine field are taken into account.

2 Experimental procedure

Samples were prepared by repeatedly melting very pure metallic Co (99.999%) along with 0.1 % (atomic) of natural La (99.9%), which was previously irradiated with thermal neutrons in the IEA-R1 nuclear reactor at IPEN to produce ^{140}La, in an arc furnace under argon atmosphere purified with a hot titanium getterer followed by an annealing at 800 °C in vacuum for 24 h.

The hyperfine magnetic field was measured with PAC technique using ^{140}Ce probe nuclei, which are formed in the beta decay of ^{140}La. Details of PAC method as well as data acquisition and analysis of magnetic interaction in a polycrystalline sample are described in references [1] and [2]. The PAC measurements were carried out in the temperature range of 4 K to 1300 K with a conventional fast-slow coincidence set-up with four conical BaF_2 detectors. A small tubular furnace was used for heating the sample above room temperature and the temperature was controlled to within 1 K. For low temperature measurements the sample was attached to the cold finger of a closed-cycle-helium refrigerator with temperature controlled to better than 0.1 K. The 4 K measurement was taken with the sample in liquid He.

3 Results and discussion

PAC spectra at ^{140}Ce in Co at selected temperatures are shown in Fig. 1. The fitting results for pure magnetic dipole interaction to the experimental spectra (solid lines in Fig. 1) indicate a unique interaction at temperatures higher than ~700 K and a major fraction, at temperatures below ~700 K. These interactions were identified as Co in fcc and hcp structures, respectively. A very small second fraction is observed at temperatures below ~700 K. The frequency associated with this fraction however

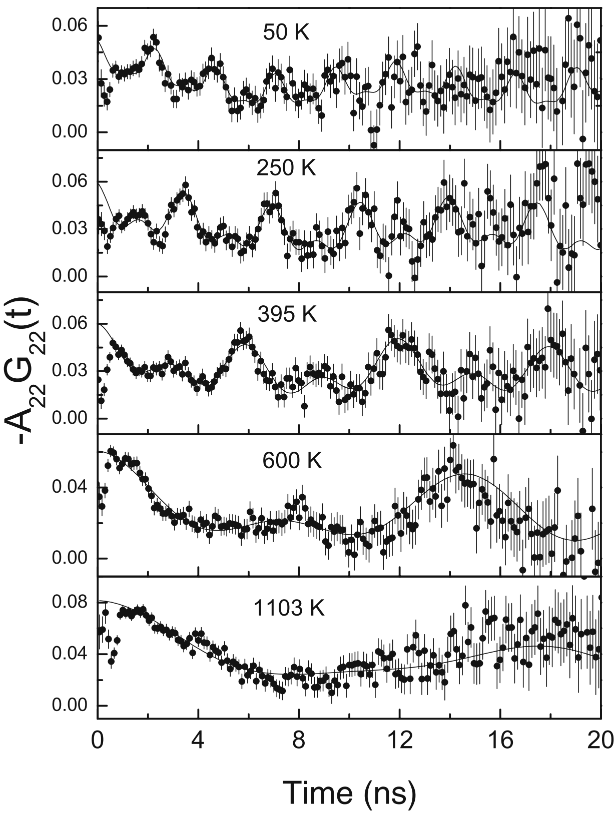

Fig. 1 PAC spectra for magnetic dipole interaction at ^{140}Ce in Co measured at indicated temperatures. *Solid lines* are least-squares fits of the theoretical perturbation functions to the experimental data

does not change with temperature, thus ruling out the possibility that it may be due to some of the fcc phase still coexisting with the predominantly hcp phase. We do not yet know the origin of this fraction. Figures 2 and 3 show the temperature dependence of the hyperfine field B_{hf} at ^{140}Ce for each fraction. The observed magnetic interaction corresponds to the ferromagnetic ordering of the Co moments in hcp and fcc phases, respectively.

The measurements for both phases, however, show a sharp deviation from the expected normal behavior for a standard ferromagnetic ordering. Results of the magnetic hyperfine fields at other impurity probes in Co [3–5] have reported that the sign of B_{hf} for both phases are negative. The sign of B_{hf} was not measured in this work but, in order to explain the temperature dependence of B_{hf} in the case for fcc phase, it was assumed that the sign changes for temperatures greater than 700 K .

The temperature dependence of B_{hf} at ^{140}Ce in both hcp and fcc phases of Co compounds was explained by a molecular field calculation based on a model proposed by Jaccarino et al. [6] and adapted to ^{140}Ce diluted in magnetic rare-earth hosts [7, 8]. In this model the effective hyperfine field, B_{hf}, at the probe site is given by the sum of the contributions from the probe ion itself, B^i_{hf} and the conduction electron polarization, B_{ce}, which scales with the host reduced magnetization $\sigma(T)$. B^i_{hf} is proportional to the thermal average of the impurity moment $\langle J^i \rangle$, which is localized and independent of temperature. In this calculation, which is described in

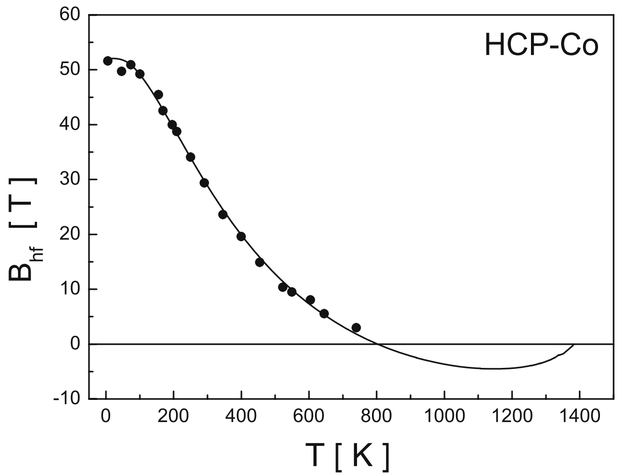

Fig. 2 Temperature dependence of B_{hf} in Co at HCP phase measured with ^{140}Ce. The *solid lines* represent the fitting of experimental data to a molecular field model described in the text

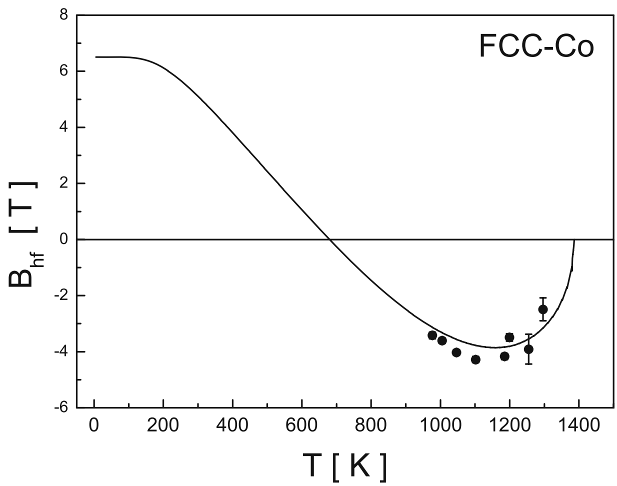

Fig. 3 Temperature dependence of B_{hf} in Co at FCC phase measured with ^{140}Ce. The *solid lines* represent the fitting of experimental data to a molecular field model described in the text

detail in reference [9], the parameter ξ takes into account the fact that the host-impurity exchange may be different form the host-host exchange.

The solid lines in Figs. 2 and 3 show the modified Brillouin function described in the molecular field model above fitted to the experimental data. For hcp phase the fitting yields $B_{ce}(0) = -28$ T, B^{i}_{hf} (0) = −80 T and $\xi = 0.23$. The fitted curve shows an inversion of the B_{hf} sign for temperatures above ~800 K. It is worth while to compare this temperature with temperature of 975 K (far below the Curie temperature for hcp phase) reported by Bedi and Forker [5] from the extrapolation of a Brillouin curve fitted to experimental data of B_{hf} at ^{181}Ta in hcp Co. As the application of the model to the experimental data shows this sign inversion we have assumed that a similar inversion may occur in fcc phase and have considered that the B_{hf} values above 800 K have an opposite sign. The application of the model to fcc experimental data agrees quite well to the values with inverted sign above 800 K as shown in Fig. 3. The results of the fitting gives $B_{ce}(0) = -37.5$ T, B^{i}_{hf} (0) = −44 T and $\xi = 0.69$ for fcc phase. The results for B_{hf} in fcc Co measured with ^{119}Sn also show a sign inversion. In order to explain this behavior Huffman and Dunmyre [3] have assumed that the Sn atom respond to temperature as a spin polarized unit with the exchange coupling being different from that of the host Co.

The Curie temperatures for hcp and fcc phases of Co obtained in the fitting, respectively are 1360 K and 1390 K, which agree with the values of 1350 K [10] and 1388 K [11] found in literature.

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