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ORIGIN OF HYPERFINE FIELDS ACTING ON $^{155}$Gd IN $(Gd_{1-x}R_x)(Co_{1-y}M_y)_5$ ($R =$ RARE EARTH, $M =$ Cu, Ni, Pd)

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The study of hyperfine fields acting on 'lossbauer probes in magnetic materials may yield useful information on the magnetic structure, local magnetism, conduction electron polarization and exchange interactions. As a first step one has to understand the various origins of the hyperfine field acting on the 'lossbauer probe. Here we present studies of the hard magnetic materials $(Gd_1-xR_x)(Co_{1-y}M_y)_5$ where we have chosen for a probe the isotope $^{155}$Gd. Gd$^{3+}$ is a $S$ state ion ($^6S^\frac{7}{2}$), its hyperfine field is small, contributed by the core polarization mechanism ($\sim 340$ kOe). This enables a detailed study of the origins of other contributions to the hyperfine field, in a similar manner as has previously been done with Eu$^{2+}$ in europium intermetallics [1].

Since Eu$^{2+}$ is equivalent to Gd$^{3+}$ all the discussion given in [1] for Eu$^{2+}$ is also relevant for Gd$^{3+}$.

The hyperfine field acting on the Gd nuclei in $(Gd_1-xR_x)(Co_{1-y}M_y)_5$ should be composed of four contributions: $H_{\text{eff}} = H_{\text{core}} + H_0 + H_R + H_N$.

$H_{\text{core}}$ is the core polarization, $H_0$ is the contribution of the conduction electrons polarized by the Gd ion itself, $H_R$ and $H_N$ are the contributions of the conduction electrons polarized by the rare earth and cobalt sublattices respectively. We were able to determine the various contributions to $H_{\text{eff}}$ through Mössbauer studies of the 86.5 keV transition of $^{155}$Gd.

The samples were prepared by melting the appropriate amounts of the elements in an induction furnace. They were studied by X rays and were found to be of single phase, their lattice parameters are given in Table 1. Some of the obtained experimental Mössbauer spectra are shown in fig. 1. The detailed analysis of the spectra, by diagonalization of the full Hyperfine Hamiltonian and a least squares fit procedure leads to the parameters given in Table 1. One observes that in addition to the isomer shift, quadrupole interaction and hyperfine field, one is able to determine also $\theta$, the angle between $H_{\text{eff}}$ and the c-axis. Observing the data in Table 1 we notice the electric field gradient acting on the Gd nuclei is almost the same in all samples. This tends to indicate that $M$ con-

<table>
<thead>
<tr>
<th>Compound</th>
<th>Isomer Shift (meV)</th>
<th>Quadrupole Interaction (mm/s)</th>
<th>Hyperfine Field (kOe)</th>
<th>Angle ($\theta$, deg)</th>
<th>Electric Field Gradient (10$^{-10}$ cm$^2$/Vs$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd,Co5</td>
<td>152.2</td>
<td>0.5</td>
<td>340</td>
<td>90</td>
<td>2.1</td>
</tr>
<tr>
<td>Gd,Ni4</td>
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</table>

Fig. 1 Spectra of Gd$^{155}$ in $(Co_{1-y}M_y)_5$ at 4.1 K.
Fig. 2 Fields acting on Gd$^{155}$ in $(\text{Gd}_{1-x}\text{La}_x)(\text{Co}_{1-y}\text{Cu}_y)_5$ contribute very little to the electric field gradient at the Gd site. This conclusion is confirmed by a point charge calculation which agrees with the experimental results if it is assumed that the M ion is neutral (Table 1). The origins of the magnetic hyperfine field can be found by plotting $H_{\text{eff}}$ as a function of $x$ for Gd$_{1-x}$La$ _x$Co$_5$ and as a function of $y$ for Gd(Co$_{1-y}$Cu$_y$)$_5$ (fig. 2). If we assume that the contributions of magnetic neighbors are additive, then the average hyperfine field should be linear in $x$ and $y$. The dependence of $H_{\text{eff}}$ on $x$ and $y$ can be expressed as:

\begin{equation}
H_{\text{eff}} = (H_{\text{core}} + H_0) + H_n^{\text{Co}}(1-y) + H_n^{\text{Gd}}(1-x) + H_{\text{mm}}^{\text{Gd}}.
\end{equation}

The slopes of the two lines shown in fig. 2 yield the values $H_n^{\text{Co}} = 220 \pm 5$ kOe and $H_n^{\text{Gd}} = 70 \pm 5$ kOe. Since $H_{\text{core}}$ is about $-340$ kOe we obtain for $H_0$ the small value of $\sim 10$ kOe. If we assume that all parameters in eq (1) are independent of magnetization orientation and that $H_0$, $H_n^{\text{Co}}$ and $H_n^{\text{Gd}}$ in (Gd$_{1-x}$La$_x$)(Co$_{1-y}$Cu$_y$)$_5$ are the same as in $(\text{Gd}_{1-x}\text{La}_x)(\text{Co}_{1-y}\text{Cu}_y)_5$ then $H_n^{\text{R}}$ is given by:

\begin{equation}
H_n^{\text{R}} = \frac{-H_{\text{eff}} - (H_{\text{core}} + H_0 + H_n^{\text{Co}} + 0.1H_n^{\text{Gd}})}{0.9}.
\end{equation}

The positive sign is for the heavy rare earths whose moments are parallel to that of Gd, the negative sign is for the light rare earths whose moments coupled to the Co sublattice ferromagnetically are antiparallel to the Gd moment. In fig. 3 we show the experimental values of $H_n^{\text{R}}$ against $R$ and the expected values if we assume that $H_n^{\text{R}}$ is linear in the expectations value of the rare earth spin [2]. We observe no agreement between the ex-

Fig. 3 The variation of $H_n^{\text{R}}$ in Gd$_{1-R}$Co$_5$. experimental and simple theory results. This may indicate the presence of strong orbital effects [2]. But even if these are considered, it is still difficult to obtain full agreement between theory and experiment. This may indicate that our assumptions about the stability of $H_0$, $H_n^{\text{Co}}$ and $H_n^{\text{Gd}}$ under change of magnetization orientation and exchange of Gd by R are not completely justified. All parameters may depend on orientation of magnetization as in the case of Gd metal itself [3].

Our experimental results lead us to the following conclusions; The contributions to the hyperfine field acting on Gd in $(\text{Gd}_{1-x}\text{R}_x)(\text{Co}_{1-y}\text{M}_y)_5$ are additive and follow eq. 1. The hyperfine field and electric field gradient are little affected by the nature of the M component. The hyperfine field parameters are sensitive to magnetization orientation [3] and possibly to orbital effects [2].

References