Measurements of the Collective Nuclear Spin Dynamics of ^{59}Co in hcp and fcc Co at Temperatures below 100 mK by Calorimetric Detection of NMR ◇

G. Seewald, E. Hagn, and E. Zech

1. Introduction

In magnetically ordered solids an indirect coupling between like nuclear spins I exists via the hyperfine interaction $A\vec{I}\vec{s}$ and the virtual excitation and absorption of electronic spin waves – the Suhl-Nakamura (SN) interaction. With increasing longitudinal nuclear polarization, obtained e.g. by cooling to low temperatures, there is a continuous change from single-spin flip to collective behaviour, i.e. the excitation of nuclear magnons. It gives rise to a displacement of the nuclear magnetic resonance (NMR) frequency, the so-called frequency pulling. This frequency pulling has been observed for several antiferromagnets, but not for ferromagnetic metals until now.

Due to the coupling of the nuclear spins via the long-range SN interaction, the excitation modes of the coupled nuclear spin system are nuclear spin waves. Resonant radio-frequency absorption senses the $k = 0$ component of the nuclear spin wave spectrum. The resonance frequency is given by

$$\begin{aligned} \nu_{\mathrm{p}}^2 &= \nu_\circ^2 \times R_x \times R_y \qquad (1)\\ R_{x,y} &= \left(1 - \eta_{x,y} \times \frac{m_\circ}{M_\circ} \times \frac{<I_z>}{I}\right) \end{aligned}$$

where $\nu_\circ$ is the resonance frequency in absence of collective effects, η_x and η_y are the enhancement factors in x and y direction – the orientation axis is in z direction –, respectively, $m_\circ$ and $M_\circ$ are the saturation values of the nuclear magnetization and electronic magnetization, respectively, and $<I_z>/I$ represents the degree of nuclear orientation. The maximum shift is obtained for $<I_z>/I = 1$ (i.e. T $\rightarrow$ 0). For hcp-Co, the maximum shift for zero external magnetic field is

$$\delta\nu_{\mathrm{p}}^{(\max)} = -6.65 \text{ MHz}.$$

This is much larger than the quadrupole splitting of the nuclear spin system, $\Delta\nu_{\mathrm{Q}} = -0.2$ MHz. This means that, for low temperatures, the quadrupole substructure is wiped out. However, the quadrupole interaction causes an additional resonance shift $\delta\nu_{\mathrm{Q}}$ which is given by

$$\delta\nu_{\mathrm{Q}} = -(I - \frac{1}{2}) \times \Delta\nu_{\mathrm{Q}} \times \frac{<I_z>}{I} \qquad (2)$$

The maximum value for the quadrupole shift is

$$\delta\nu_{\mathrm{Q}}^{(\max)} = +0.6 \text{ MHz}.$$

It is evident that the resonance frequency ν_{p} depends on the temperature via $<I_z>/I$, on the external magnetic field via the enhancement factor $\eta_{x,y}$ and on the sample geometry, which also has an influence on $\eta_{x,y}$ via the demagnetization fields in the different directions.

2. Experiments and Results

Several thin hcp-Co single crystals were neutron-irradiated at the Munich research reactor FRM to produce radioactive ^{60}Co which served as nuclear orientation thermometer. The samples were cooled to milli-Kelvin temperatures with a ^{3}He-^{4}He-dilution refrigerator. A radio frequency field was applied and NMR was detected calorimetrically, i.e. via the resonant temperature increase which was measured via the low-temperature γ-anisotropy of ^{60}Co. As example, the dependence of the resonance frequency of ^{59}Co in hcp-Co is shown in Fig. 1 for the so-called 90° geometry. Here the external magnetic field is applied perpendicular to the the c-axis of the single crystal. Then, the enhancement factor depends resonance-like on the external magnetic field.

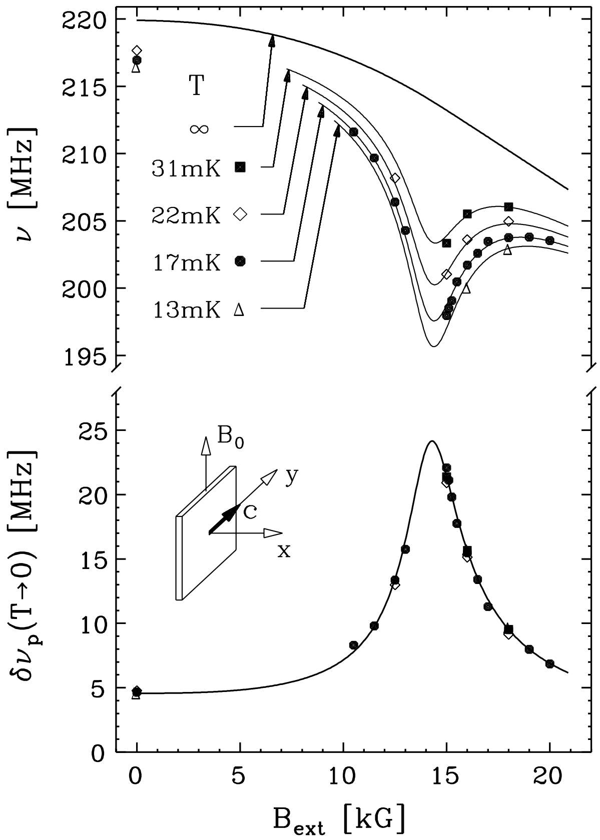

Fig. 1: Top: Resonance frequencies for ^{59}Co in hcp-Co in 90°-geometry as function of the external magnetic field for different temperatures. Bottom: Frequency pulling effect extrapolated to $T = 0$.

A more detailed description is given in ref. [1].

References

[1] G. Seewald et al., Hyp.Interactions (C) **1** (1996) 29

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