Co^{59} INDIRECT SPIN-SPIN INTERACTION IN FERROMAGNETIC Co METAL*

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We discuss a new approach to the study of the Suhl-Nakamura interaction in ferromagnets. The method, which consists of varying the Suhl-Nakamura range function by applying an external magnetic field and observing its effects on the nuclear $1/T_2$, was utilized to study the Suhl-Nakamura interaction in ferromagnetic Co.

In this report we describe a new approach to the study of the indirect nuclear spin-spin interaction in ferromagnets, first predicted by Suhl[1] and Nakamura.[2] Attempts to study the Suhl-Nakamura (SN) interaction in the past have almost invariably suffered from the fact that the NMR lines so far studied are subjected to static broadening, part of which occurs on a local scale. This broadening detunes nuclei from each other and reduces the effectiveness of the SN interaction, while the original SN theory treats only homogeneous nuclear systems.

Very recently,[3] the SN theory, as well as the theory of dipolar broadening, was extended to include the effects of static local broadening on the dynamic line shape. Consider a locally broadened NMR line in a ferro- or antiferromagnet with small anisotropy energy $K/2J \ll 1$. The contribution of the SN interaction to the dynamic linewidth, as manifested by the transverse relaxation rate $1/T_2 = \delta\omega$, can be written as[3]

$$\hbar^2(1/T_2)^{\mathrm{SN}} = \frac{\pi\sqrt{3}}{6} g(\omega)\left(\frac{A^2}{2Jz}\right)^2 \frac{(\sum_l f_l^3)^{3/2}}{(\sum_l f_l^5)^{1/2}} \times [\tfrac{1}{3}I(I+1)]^{1/2}\left[8 - \frac{3}{2I(I+1)}\right]^{-1/2}, \quad (1)$$

where $g(\omega)$ is the normalized shape function describing the local broadening, and it is assumed that the width of $g(\omega)$ exceeds the linewidth that would have resulted in the absence of the static broadening. The SN range function f_l is given by[1,3]

$$f_l = \frac{1}{4\pi\alpha} \frac{e^{-(K/Jz\alpha)^{1/2} r_l/a_0}}{r_l/a_0}, \quad (2)$$

where α is a geometric structure factor of order unity. The summation is over all occupied lattice points $\vec{r}_l$ around a given atom. Similarly, the dipolar contribution to $1/T_2$ can be written[3] as

$$\hbar^2(1/T_2)^{\mathrm{dip}} = \frac{\pi\sqrt{3}}{6} g(\omega) \frac{(\sum_l |d_l^3|)^{3/2}}{(\sum_l |d^5|)^{1/2}} \times [\tfrac{1}{3}I(I+1)]^{1/2}\left[\frac{7}{5} - \frac{3}{10I(I+1)}\right]^{-1/2}, \quad (3)$$

where the dipolar range function is defined as

$$d_l = \tfrac{3}{2}\gamma^2 h^2 (1 - 3\cos^2\theta_l)/r_l^3 \quad (4)$$

and θ_l is the angle between $\vec{r}_l$ and the magnetic field. Dividing Eq. (1) by Eq. (3), one obtains readily an estimate as to the relative importance of the SN and the dipolar contributions to the observed $1/T_2$. Substituting the appropriate constants in (1) and (3), it is concluded[3] that, with perhaps one exception,[4] the calculated SN contribution to $1/T_2$ in all of the NMR lines so far examined in antiferromagnets is negligible compared with the dipolar one. What is perhaps more distressing is the fact that even for cases where calculation gives $(1/T_2)^{\mathrm{SN}}/(1/T_2)^{\mathrm{dip}} \geq 1$, the mere measurement of $1/T_2$ by the standard procedure would yield no information on the SN interaction[5] since $g(\omega)$ cannot be measured independently.

The present experiment, which is very simple in concept, was motivated by the difficulties mentioned above. The idea is to find a material in which calculation predicts $(1/T_2)^{\mathrm{SN}}$ to be at least comparable with $(1/T_2)^{\mathrm{dip}}$, and then measure $1/T_2$ as function of the range function f_l. For example, it is possible to control f_l in a ferromagnet with the help of a large external magnetic field H_{app}. Provided that $K \ll g\beta H_{\mathrm{app}} \ll 2Jz$, the term K in Eq. (2), which represents crystalline and/or shape anisotropy, can be replaced by $g\beta H_{\mathrm{app}}$, and thus one can vary f_l in a controlled manner. Qualitatively, the effect of H_{app} on the SN interaction in a ferromagnet comes about in the following way: The interaction is essentially a second-order indirect process in which two nuclei interact through the virtual emission and absorption of spin waves. The long-wavelength, or small-wave-number q, magnons are particularly important since these are the ones responsible for the long range of the SN interaction. The dispersion of spin waves in ferromagnets is given by $E_q = g\beta H_{\mathrm{app}} + cq^2$ and therefore application of external field will change most drastically the density of states of small-q magnons. This in turn should be reflected as changes in the SN interaction. It should be noted that because of the interplay between exchange and anisotropy in a two-sublattice system, a similar effect does not take place, to first order, in antiferromagnets.

All things considered, metallic powder of fcc Co was selected for the experiment. The sample consisted of 99.999% pure Co "sponge," with average particle size of ~30 μ. The Co^{59} NMR spin decay rate, following a double rf pulse sequence, was measured at 4.2°K in a superconducting magnet with H_{app} varied between 20 and 60 kG. The echo decay was followed across a dynamic range of two decades. A typical decay curve is shown in the inset to Fig. 1, and it is clear that the decay is not purely exponential, the magnitude of the slope decreasing slowly as t increases. Because of this behavior, we can use only an operational definition for the experimental transverse relaxation rate:

$$\frac{1}{T_2(t)} = -\frac{1}{m(t)}\frac{dm(t)}{dt},$$

where m is the transverse nuclear magnetization. One set of $1/T_2(t)$ values as function of H_{app}, obtained by best fitting an exponential decay to the experimental points in the range 75-250 μ_{sec}, is plotted in Fig. 1 (left scale). These values are 2 to 3 times smaller than $1/T_2$ at zero field.[5] The error bar on each point is the computed standard error and its value is somewhat exaggerated since the sections fitted are not strictly exponential. Sets of points with similar dependence on H_{app} were obtained for other sections of the decay curves.

Analyzing the results, we first examine processes that could affect $1/T_2$ without being relevant to the present study. First, we can rule out effects of domains and walls on T_2, since with H_{app} being always well above $4\pi M$, no walls could exist in the sample during the measurements. Similarly, no changes could be induced on $g(\omega)$ as function of H_{app} (such changes would have been detrimental if at all existed) since for $H_{app} > 4\pi M$ all the fcc particles are completely magnetized parallel to H_{app} and further change of H_{app} cannot change the macroscopic <u>or</u> microscopic broadening. Lastly, we can rule out contribution of spin-lattice processes to $1/T_2$, this contribution being negligible at 4.2°K.[6] We can now analyze the data in accordance with the theory[1-3] outlined in the introductory sections.

As noted, the experimental decay curves are

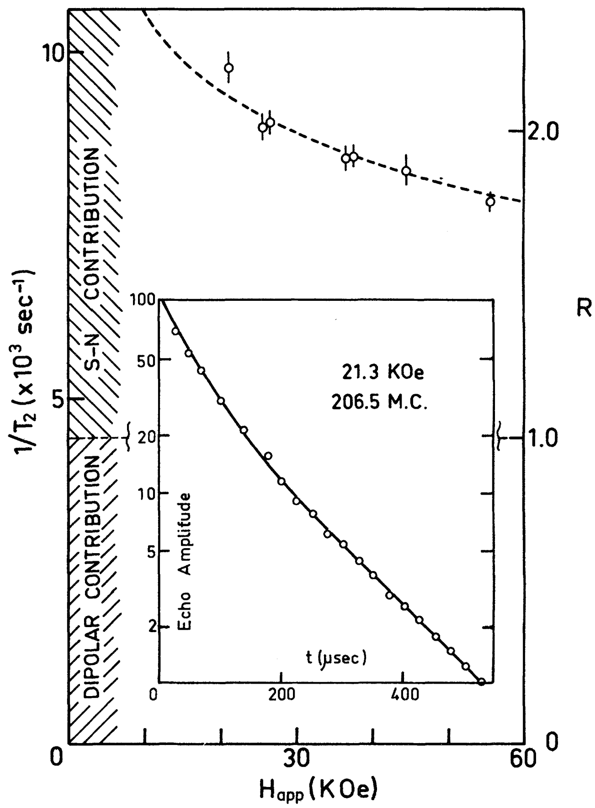

FIG. 1. Points with error bars represent experimental relaxation rates (left-hand scale). The dashed curve is a plot of the theoretical ratio $R = [(1/T_2)^{SN} + (1/T_2)^{dip}][(1/T_2)^{dip}]^{-1}$. The R scale is adjusted to fit the curve to the points. The inset is a decay curve for $H_{app} = 21.3$ KOe.

not purely exponential. This is to be expected if the dipolar contribution to $1/T_2$ is not negligible, since different crystallites in the sample have different orientations. Indeed, computing Eq. (3) for fcc lattice, we find $(1/T_2)_{(100)}{}^{dip}:(1/T_2)_{(110)}{}^{dip}:(1/T_2)_{(111)}{}^{dip} = 1:1.43:1.80$, the subscripts (100), etc. standing for the direction of $\vec{M}$. Thus, we can assert roughly that the slopes in the "middle" of the decay curves, e.g., values plotted in Fig. 1, represent regions in the sample where $(1/T_2)^{dip}$ is of the order of $(1/T_2)_{(110)}{}^{dip}$. Substituting in Eqs. (1) and (3) the values appropriate for Co [$2Jz = 4.2\times10^{-13}$ erg, $A = 1.3\times10^{-18}$ erg, $I = \frac{7}{2}$, a_0(fcc Co) = 3.54 Å, $\gamma^{59}/2\pi = 1.01\times10^3$ cps/G, α(fcc) $= \frac{1}{6}$], the ratio $(1/T_2)^{SN}$: $(1/T_2)_{(110)}{}^{dip}$ was computed for the fcc Co lattice as function of H_{app}. Assuming that $1/T_2 = (1/T_2)^{SN} + (1/T_2)^{dip}$, and remembering that $(1/T_2)^{dip}$ is independent of field, the theoretical relaxation rate can be written apart from a scaling factor as

$$R = \frac{(1/T_2)^{SN} + (1/T_2)^{dip}}{(1/T_2)^{dip}}.$$

The ratio R is plotted in Fig. 1 (right scale), scaled to obtain a good fit to the experimental points. It is seen from the theoretical curve that the dipolar and the SN contribution to $1/T_2$ are equal in magnitude. The agreement between the theoretical curve and the experimental points is satisfying although the experimental accuracy is not quite good enough to test in a critical manner the exact functional form predicted by the theory.

We conclude that there exists SN interaction in ferromagnetic Co metal, and that the relative magnitude and the external-field dependence of this interaction is in accordance with existing theory. It should be pointed out, however, that Co is an itinerant-electron ferromagnet, whereas the SN theory[1,2] with its extension[3] has been worked out formally only for a Heisenberg ferromagnet. It seems therefore worthwhile to repeat a similar experiment in an insulating ferromagnet, and work in this direction is now under way.

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Note added in proof.—We are informed that the preliminary results of similar study performed very recently in the low-field limit are also consistent with the SN theory.[7]

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EXPERIMENTAL TEST OF QUANTUM ELECTRODYNAMICS BY PHOTOPRODUCTION OF WIDE-ANGLE ELECTRON PAIRS FROM HYDROGEN

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The photoproduction of wide-angle electron pairs from hydrogen and carbon has been measured as a test of quantum electrodynamics (QED), using the 5-GeV electron synchrotron NINA. The results are consistent with the predictions of QED up to an invariant mass of the electron-positron pair of 500 MeV/c^2.

In an experiment performed at the 5-GeV electron synchrotron NINA, we have measured the yields of wide-angle electron pairs produced in the reactions

$$\gamma + p \rightarrow p + e^+ + e^-$$

and

$$\gamma + \mathrm{C} \rightarrow \mathrm{C} + e^+ + e^-.$$

Our results are in agreement with the predictions of quantum electrodynamics (QED) up to an electron-pair invariant mass of 500 MeV/c^2. They also agree with previous measurements on carbon in this energy range at DESY[1] and at the Cambridge Electron Accelerator (CEA),[2] and do not agree with an earlier measurement at CEA.[3]

Both hydrogen and carbon targets were used in order to identify the cause of any possible deviation from QED, e.g., nuclear or Compton effects.

The photoproduction of high energy electron pairs as a test of QED was proposed by Bjorken, Drell, and Frautschi[4] (BDF), who calculated the cross section for the Bethe-Heitler process. The contribution of the virtual Compton process was shown to be small. It was pointed out that under symmetric conditions of e^+e^- detection, the interference between the Bethe-Heitler and Compton diagrams vanishes, due to charge-conjugation invariance.

The experimental apparatus is shown in Fig. 1. The photon beam was produced by steering the NINA circulating electrons onto an internal target of tungsten 0.15 radiation length thick. The beam was then collimated to produce a spot 15 $\times 15$ mm^2 at the target. Charged particles were removed from the photon beam by two dipole magnets bending horizontally and vertically. A quantameter, calibrated in an electron beam