COMMENTS AND ADDENDA

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Nuclear Magnetic Resonance of ^{61}Ni in Nickel Metal–Rotary Saturation

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In 1965 we reported rotary-saturation data on ^{61}Ni in nickel metal. We reinterpret these rotary-saturation data on ^{61}Ni in pure-nickel metal with the following results: The rotary-saturation data imply a distribution of enhancement factors. At room temperature the maximum value of the enhancement factor in our pure-nickel sample is ~ 5000.

In 1965 we reported room-temperature measurements on the rotary saturation of the nuclear-magnetic-resonance (NMR) signal from ^{61}Ni in pure-nickel metal.[1] Recently Mendis and Anderson have reported a study of the rotary saturation of ^{57}Fe in pure-iron metal.[2] In this comment to Ref. 1 we wish to reinterpret our previous rotary-saturation data on ^{61}Ni in pure-nickel metal. Redfield was the first person to describe the experimental observation and the theoretical interpretation of rotary saturation.[3] His description of rotary saturation was based on the fact that if a spin system is in an intense rf magnetic field, then the nuclear magnetization will orient itself along the effective magnetic field in the rotating frame, H_e. If $\omega=\omega_0$, i.e., at resonance in the stationary frame, then H_e is equal to H_1, the applied rf field. If an audio magnetic field is applied perpendicular to H_e, then transitions are induced in the nuclear-spin system and the nuclear magnetization along H_e will be decreased. If rotary saturation is carried out when $\omega=\omega_0$, then the audio frequency ω_a required to induce transitions in the nuclear-spin system is $\omega_a=\gamma H_1$. Thus if ω_a is observed and γ is known, then H_1 can be found. Portis and Gossard[4] first observed NMR in a ferromagnetic material (Co metal). They found that the actual rf magnetic field acting on a spin in a ferromagnetic material is enhanced over the applied rf field because of the motion of the domain walls. Thus we can write $H_1=\frac{1}{2}\eta H_x$, where H_1 is the actual rotating rf field at the nucleus, $\frac{1}{2}H_x$ is the magnitude of the correctly rotating component of the applied rf field, and η is the enhancement factor. Thus if we measure H_1 by rotary saturation and know H_x from other measurements, we can obtain η. Although Portis and Gossard's original experiments were on metallic Co, later experiments have shown that the rf field in nickel metal is also enhanced due to domain-wall motion.[1,5,6]

In Fig. 1 of Ref. 1 we presented rotary-saturation data on ^{61}Ni in nickel metal. The curve labeled "3V peak-to-peak rf level" in Fig. 1 of Ref. 1 was used to determine the enhancement factor η. This curve corresponded to $H_x=42$ mG. In Ref. 1 we simply assumed that the maximum of the rotary-saturation curve could be used to determine η. Using the value of $\gamma=2.3\times10^3$ sec^{-1}G^{-1} for the gyromagnetic ratio for ^{61}Ni, we concluded that $\eta=1600$ for Ni.[7] In Ref. 1 we attributed the slow fall of the rotary saturation to zero, as the audio frequency ω_a increases above the value necessary for the maximum rotary-saturation signal, to the inhomogeneous linewidth of the Ni resonance. Mendis and Anderson[2] have shown that the slow fall in the rotary-saturation signal as the audio

frequency ω_a increases cannot be due to the inhomogeneous linewidth and is instead due to a distribution of enhancement factors. Utilizing the same analysis as Mendis and Anderson,[2] we find that the room-temperature rotary-saturation data presented in Ref. 1 are consistent with a distribution of enhancement factors having a maximum enhancement factor of $\eta_{max} \simeq 5000$. The uncertainty in the value of η_{max} is not more than $\pm 20\%$.

The average value of the enhancement factor (as defined in Ref. 2) is $\eta_{av} = 1600$.

Stearns[8] has recently measured the enhancement factor for nickel metal and finds $\eta = 4000 \pm 500$ independent of temperature over the temperature range from 1.3 to 77 °K. We believe our room-temperature result combined with the low-temperature results of Stearns indicates that η is independent of the temperature from 1.3 to 300 °K. In addition to the measurements on η Stearns found that T_1 as a function of temperature obeys an equation $T_1 T^{0.8} = 6.5 \pm 1.5$ msec °K in the range of temperatures from 1.3 to 77 °K. Using Stearn's formula for T_1 to extrapolate to $T = 300$ °K, one obtains a value for T_1 that is about half the value $T_1 = 0.16$ msec which we reported in Ref. 1. This seems reasonable since Stearns actually determines the value of T_1 at the center of the domain wall whereas we measure a complicated average over the various spins in the domain wall.

[1]D. L. Cowan and L. W. Anderson, Phys. Rev. 139, A424 (1965).
[2]E. F. Mendis and L. W. Anderson, Phys. Rev. B 2, 569 (1970).
[3]A. G. Redfield, Phys. Rev. 98, 1787 (1955).
[4]A. M. Portis and A. C. Gossard, Phys. Rev. Letters 3, 164 (1959); J. Appl. Phys. 31, 2055 (1960).
[5]L. H. Bruner, J. I. Budnik, and R. J. Blume, Phys. Rev. 121, 83 (1961).
[6]R. L. Streever and L. H. Bennet, Phys. Rev. 131, 2000 (1963).
[7]P. R. Locher and S. Geschwind, Phys. Rev. Letters 11, 333 (1963).
[8]M. B. Stearns, Bull. Am. Phys. Soc. 16, 403 (1971).

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Ising Model with Four-Spin Interactions*

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It is shown that Baxter's recent results on a lattice-statistical model lead to the solution of an Ising model with two- and four-spin interactions. Critical properties of this Ising model in various regions of the parameter space are given. It is argued that four-spin or crossing interactions in a two-dimensional Ising model would in general lead to a critical exponent $\alpha' \neq 0$.

The recent exact solution by Baxter[1] of a lattice-statistical model[2] constitutes a breakthrough in the study of phase transitions. The most striking feature of Baxter's solution is that the nature of the phase transition is dependent on the energy parameters of the model. While it has been known for some time that the behavior of this lattice model is quite different in the isolated soluble cases of Ising, F, and potassium dihydrogen phosphate (KDP) models, it is for the first time that a phase transition is shown to exhibit a continuously variable exponent. Baxter's solution is given in the language of a ferroelectric model. To those who are accustomed to the "magnetic" language of phase transitions, the implications of his results are perhaps not very transparent. Therefore, we wish to point out in this note the conclusions on the more familiar Ising model that can be deduced from Baxter's solution.

It can be shown[3] that the ferroelectric problem considered in Refs. 1 and 2 is equivalent to an Ising model in zero magnetic field with *finite* two- and four-spin interactions.[4] The equivalent Ising lattice, shown in Fig. 1, has first-neighbor interactions $-J_1$ and $-J_2$, second-neighbor interactions $-J$ and $-J'$, and a four-spin interaction $-J_4$ between any four spins surrounding a unit square. The Hamiltonian reads, in obvious summation notations,

$$H = -J_1 \sum \sigma\sigma' - J_2 \sum \sigma\sigma' - J \sum \sigma\sigma' - J' \sum \sigma\sigma' - J_4 \sum \sigma\sigma'\sigma''\sigma''' \quad . \qquad (1)$$

The energy parameters of the ferroelectric problem turn out to be, using Baxter's notation,[5]