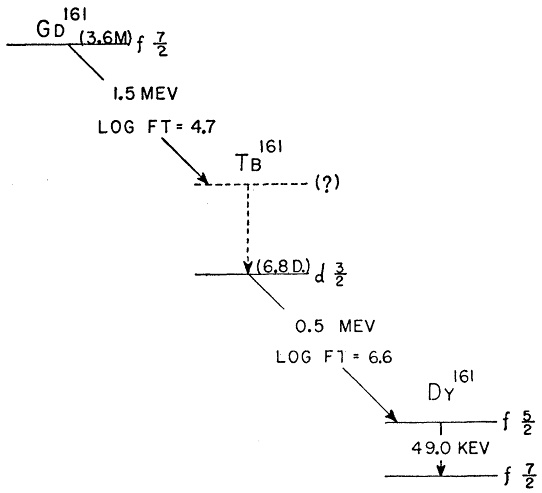

FIG. 2. Energy levels associated with Gd^{161} (from shell theory).

others has been observed in the beta-decay of Sm^{153}. It must follow in the ordering of the levels of Eu^{153} that the 103.7-kev transition leads directly to the ground state of the nucleus. It has been noted[5] that the measured parity of this ground state ($f_{5/2}$) is not in agreement with the value expected from shell theory ($d_{5/2}$).

In the Dy^{161} nucleus a single gamma-ray of energy 49.0 kev is found. At the low energy no K conversion electron line could occur. The L/M conversion ratio is found to be 3.7 ± 0.8. Since conversion occurred mainly in the L_1 level, the radiation[6] is quite probably $M1$. The half-life of the Tb^{161} activity was followed through six octaves and was found to be 6.8 ± 0.1 days. The beta-energies and the gamma-energy in Gd^{161} have not been re-evaluated in this investigation.

From shell theory for odd-even nuclei it is possible to assign spin and parity values to the observed levels of the isobar 161, with one exception. The $\log ft$ value for the beta-decay in Gd^{161} is 4.8. This indicates an allowed transition with no parity change. Shell theory indicates the ground state of Gd^{161} to be $f_{7/2}$ and the only low-lying excited state of Tb^{161} of the same parity is an $h_{11/2}$ state, which would require a spin change of two. It may be that the data leading to the ft value are inaccurate. Otherwise, this particular transition cannot be regarded as in satisfactory agreement with the extreme single particle theory. The complete data are shown graphically in Fig. 1 for Gd^{153} and in Fig. 2 for Gd^{161}.

† This investigation received the joint support of the ONR and AEC.
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Total Cross Sections for 14-Mev Neutrons*

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(Received August 18, 1952)

TOTAL cross sections for 14-Mev, $T(d, n)He$ neutrons were measured for several elements. The deuterium ions were accelerated through a 130-kv potential drop against a tritiated zirconium target.

Detection of the neutrons was accomplished with an anthracene crystal and an RCA 5819 photomultiplier tube. The signal, after amplification, was biased so that recoil protons (in the anthracene crystal) of energy less than 12 Mev were not detected.

The usual corrections for background and room scattering were made. In-scattering corrections were made according to the method of McMillan and Sewell.[1] The results listed in Table I are, within statistical counting errors, in reasonable agreement with more accurate data by Coon, Graves, and Barschall.[2]

TABLE I. Total cross sections for 14-Mev neutrons (in units of 10^{-24} cm^2).

H	0.69 ± 0.06	Ti	2.2 ± 0.2	Zr	3.6 ± 0.2
D	0.82 ± 0.08	V	2.4 ± 0.1	Mo	3.6 ± 0.3
Be	$1.4\ \pm0.1$	Cr	2.3 ± 0.2	Sn	4.0 ± 0.4
C	1.20 ± 0.04	Fe	2.4 ± 0.2	Sb	4.6 ± 0.3
O	$1.5\ \pm0.1$	Ni	2.5 ± 0.1	W	4.8 ± 0.3
Mg	$1.8\ \pm0.2$	Cu	2.5 ± 0.1	Pb	5.1 ± 0.4
Al	$1.8\ \pm0.1$	Zn	3.0 ± 0.2	Bi	5.2 ± 0.5

The author wishes to express his gratitude to Professor Samuel K. Allison, representing the University of Chicago Physics Department, for his considerate interest and assistance throughout the progress of the experiment.

We would like to thank Dr. J. H. Coon for the privilege of seeing his report before it appeared in print.

* These data are part of a paper which was written to fulfill a partial requirement for a Ph.D. degree at the University of Chicago.
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Spin-Spin Relaxation in Ferromagnetic Resonance*

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(Received September 15, 1952)

WE demonstrate here the theoretical possibility of a non-vanishing line width in ferromagnetic resonance at 0°K arising from zero-point fluctuations of spin-spin magnetic dipole fields.

The Hamiltonian of the spin system is

$$\mathcal{H}=\mathcal{H}^0+\mathcal{H}^{++}+\mathcal{H}^{--}+\mathcal{H}^{+}+\mathcal{H}^{-}, \tag{1}$$

with

$$\mathcal{H}^0=-Hg\beta\Sigma_j S_j^z+\Sigma_{k>j}(A_{jk}\mathbf{S}_j\cdot\mathbf{S}_k+B_{jk}S_j^zS_k^z),$$
$$\mathcal{H}^{++}=\Sigma_{k>j}E_{jk}S_j^+S_k^+;\quad \mathcal{H}^{--}=\Sigma_{k>j}E_{jk}^*S_j^-S_k^-,$$
$$\mathcal{H}^{+}=\Sigma_{k\neq j}F_{jk}S_j^+S_k^z;\quad \mathcal{H}^{-}=\Sigma_{k\neq j}F_{jk}^*S_j^-S_k^z,$$

where

$$A_{jk}=-2J_{jk}+\tfrac{1}{2}D_{jk}(3\gamma_{jk}^2-1),$$
$$B_{jk}=-\tfrac{3}{2}D_{jk}(3\gamma_{jk}^2-1),$$
$$E_{jk}=\tfrac{3}{4}D_{jk}[\beta_{jk}^2-\alpha_{jk}^2+2i\alpha_{jk}\beta_{jk}],$$
$$F_{jk}=-\tfrac{3}{2}D_{jk}\gamma_{jk}(\alpha_{jk}-i\beta_{jk}).$$

In the above J_{jk} is the exchange integral between spins j and k; $D_{jk}=g^2\beta^2/r_{jk}^{-3}$ if purely magnetic dipole forces are operative; and α_{jk}, β_{jk}, γ_{jk} are direction cosines of r_{jk} taken with respect to the crystal axes. We shall assume for simplicity that the applied field H lies along a crystal axis.

The only part of $\mathcal{H}$ commuting with S^z is $\mathcal{H}^0$. The remainder of $\mathcal{H}$ breaks down the selection rules $\Delta M=\pm1$ in a resonance experiment, causing weak satellite lines to appear at $\Delta M=0, \pm2, \pm3$. In evaluating the second and fourth moments of the principal ($\Delta M=\pm1$) resonance line for a paramagnetic sample, therefore, Van Vleck[1] used the ingenious trick of limiting the Hamiltonian to $\mathcal{H}^0$.

If, however, $J>Hg\beta$, the energies of the many states of a given S^z are spread over a spin-wave spectrum larger than the Zeeman splitting of states of different S^z. States of different S^z are then nearly degenerate and are strongly mixed by the dipole terms. Thus M ceases to be even approximately a good quantum number, and the satellite picture breaks down. In paramagnetic resonance in a sample with large exchange forces, therefore, the moments should be evaluated by use of the entire Hamiltonian. This has the effect of multiplying Van Vleck's second moment by 10/3; and from general considerations it can be seen that the line width, as estimated by Van Vleck from "exchange narrowing," should also be multiplied by 10/3.

In the case of ferromagnetic resonance, as Van Vleck has shown,[2] use of the truncated $\mathcal{H}^0$ leads to a second moment which goes rapidly to zero below the Curie point. Here in order to justify use of the entire Hamiltonian we must show a strong mixing of the ground (saturated) state with the next highest state. This can be produced by pseudodipole forces of magnitude sufficient to account for anisotropy and magnetostriction, i.e., of the order of 10^4 to 10^5 oersteds.

Using the entire Hamiltonian, we find[3] at 0°K for a spherical face-centered cubic crystal with individual spin quantum number S:

$$\begin{aligned} \hbar\langle\omega\rangle_{\mathrm{Av}} &= g\beta H, \\ \hbar^2\langle\omega^2\rangle_{\mathrm{Av}} &= g^2\beta^2H^2+4S\Sigma_j|F_{jk}|^2, \\ \hbar^3\langle\omega^3\rangle_{\mathrm{Av}} &\cong 8JS(24S-1)\Sigma_j|F_{jk}|^2, \\ \hbar^4\langle\omega^4\rangle_{\mathrm{Av}} &\cong 16J^2S(24S-1)^2\Sigma_j|F_{jk}|^2. \end{aligned} \tag{2}$$

Here we have given only the leading exchange terms of the third and fourth moments and have limited the exchange integral J to nearest neighbors. From magnetic dipole forces alone we obtain for a f.c.c. crystal and lattice constant a:

$$\Sigma_j|J_{jk}|^2 \cong 36g^4\beta^4a^{-6} = (3g\beta M_s/2S)^2, \tag{3}$$

where M_s is the saturation magnetization.

If the resonance curve were Gaussian, the half-width would be[1]

$$(\Delta H)_{\frac{1}{2}} = 2.35(\hbar/g\beta)[\langle\Delta\omega^2\rangle_{\mathrm{Av}}]^{\frac{1}{2}} \cong 7M_s/S^{\frac{1}{2}}. \tag{4}$$

This is increased by $\sim$50 times when pseudodipole forces are introduced. However, since the third and fourth moments involve J, the line must be much more sharply peaked than a Gaussian. Van Vleck[1] suggests that this "exchange narrowing" might reduce the line width by a factor $\sim D/J$. Again introducing pseudodipole forces to determine D, we are left with a line width of the reasonable order of hundreds of oersteds.

From Eq. (4) we note that if $S\rightarrow\infty$ with M_s held constant (classical limit), the width disappears. We are thus dealing with a zero-point quantum effect.

As can be seen from Eq. (2), the only part of the Hamiltonian contributing to the moments, apart from the Zeeman and exchange terms, is $\mathcal{H}^+ + \mathcal{H}^-$. This is in agreement with the results of spin-wave theory. In the approximation used by Holstein and Primakoff[4] $\mathcal{H}^+ + \mathcal{H}^-$ is effectively dropped, whereas $\mathcal{H}^0 + \mathcal{H}^{++} + \mathcal{H}^{--}$ is retained; this introduces demagnetizing fields but leads to no mixing of spin waves of different wave number k. On using the $\mathcal{H}^+ + \mathcal{H}^-$ term, Akhieser[5] finds a mixing of spin waves and hence a spin-spin relaxation. Further progress on the spin-spin relaxation problem might well come from using pseudodipole forces and otherwise improving Akhieser's calculation.

I wish to thank Professor C. Kittel, Professor J. H. Van Vleck, and Dr. M. H. Cohen for many enlightening discussions of this problem.

* This work was supported in part by the ONR.

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