

Van Vleck⁵ has proposed a theory of antiferromagnetism in which the exchange forces between neighboring atoms give rise to a Curie temperature and a maximum in the powder susceptibility. However, although the exchange forces align the spins with respect to one another, they cannot lead to an anisotropy since the energy is invariant under rotation with respect to the crystal axes.⁶ The small anisotropy of MnF_2 observed at high temperatures is comparable to that observed in more dilute manganous salts,⁷ which is explained by Van Vleck and Penney⁸ as due to a slight splitting of the 6S level of the free Mn^{++} ion by the crystalline electrostatic fields. In the case of MnF_2 the susceptibility parallel to the c -axis is the greater at high temperatures indicating that the alignment of spins parallel to this axis is energetically more stable by a few tenths of a wave number.

The cooperative phenomenon at temperatures below $70^\circ K$ is presumably due to the strong exchange coupling between the Mn^{++} ions. The deviation of the powder susceptibility at high temperatures from the free ion value is also caused by the exchange forces. The large anisotropy at temperatures below $70^\circ K$, where the spins are presumed cooperatively coupled antiparallel, occurs because the forces which at high temperatures can produce only a very small anisotropy become, when acting on a large group of coupled spins, energetically important compared to kT . These forces would serve to align the coupled spin system parallel to the c -axis and the anisotropy calculated from Van Vleck's theory of antiferromagnetism would then be in good qualitative agreement with our observations.

Magnetic dipole-dipole interactions could also, through a similar mechanism, produce an anisotropy. However, if the spins of the nearest neighboring Mn^{++} ions, which lie in chains parallel to the c -axis, are coupled antiparallel the dipole forces would favor an alignment of the spin system perpendicular to the c -axis.

A detailed account of this investigation will be published elsewhere.

* Atomic Energy Commission Fellow 1948-49.

¹ H. Bizette and B. Tsai, *Comptes Rendus* **209**, 205 (1939).

² de Haas, Schultz and Koolhaas, *Physica* **7**, 57 (1940).

³ J. W. Stout and H. E. Adams, *J. Am. Chem. Soc.* **64**, 1535 (1942).

⁴ *Strukturbericht* (Leipzig, 1931), Vol. I, p. 192.

⁵ J. H. Van Vleck, *J. Chem. Phys.* **9**, 85 (1941).

⁶ See J. H. Van Vleck, *Phys. Rev.* **52**, 1178 (1937).

⁷ K. S. Krishnan and S. Banerjee, *Trans. Roy. Soc. A235*, 343 (1936).

⁸ J. H. Van Vleck and W. G. Penney, *Phil. Mag.* **17**, 961 (1934).

An Accurate Nuclear Magnetic Resonance Method for Measuring Spin-Lattice Relaxation Times*

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THE bridge method¹ for obtaining nuclear magnetic resonance has been applied in conjunction with an electronic technique² which permits accurate measurements of spin-lattice relaxation times T_1 . The recovery in time of a non-equilibrium value of the energetic component of nuclear magnetization, $M_z(t)$, toward thermal equilibrium M_0 is observed by measurement of resonance absorption and emission signal amplitudes on the oscilloscope which are proportional to $M_z(t)$. When an ensemble of spins, such as protons in H_2O , is subjected to a perturbing r-f field H_1 in a large d.c. magnetic field H_0 perpendicular to H_1 , the excess population of spins n_0 in the ground state is reduced to a smaller value n_i . In general $n = N_{+\frac{1}{2}} - N_{-\frac{1}{2}}$ where $N_{+\frac{1}{2}}$ and $N_{-\frac{1}{2}}$ are the number of spins parallel and antiparallel to H_0 respectively, and n is proportional to $M_z(t)$. Upon removal of H_1 the recovery of n is given by

$$n = n_0[1 + (n_i - n_0/n_0)e^{-t/T_1}].$$

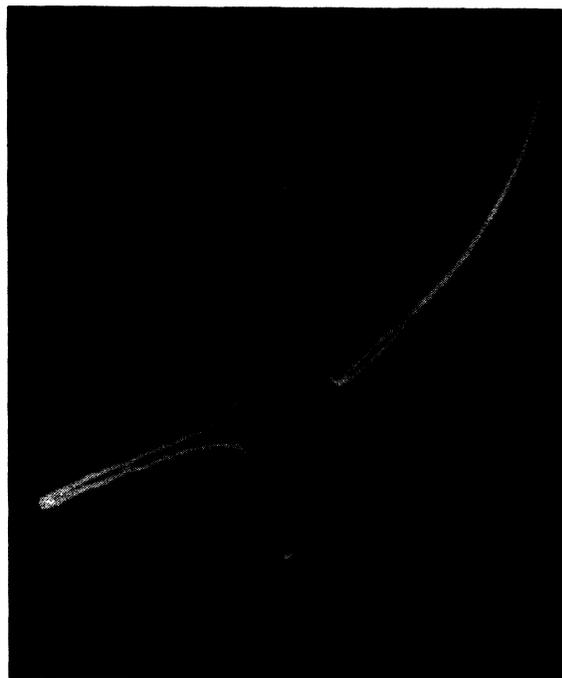


FIG. 1. The positive (n_0) and negative (n) signals represent slow passage resonance absorption and emission respectively. The emission signal occurs for $t = 1/30$ sec. For t sufficiently large the n signal is positive, and coincides with the fixed n_0 absorption signal for t infinite.

A conventional Higginbotham array of scalar units provides interval timing between a single r-f pulse of large amplitude which inverts** M_0 to a negative value M_i (i.e. $N_{-\frac{1}{2}} > N_{+\frac{1}{2}}$ at $t=0$) and a later single r-f pulse, also of large amplitude, which inspects the amplitude and sign of M_z at a known time t . 30 c.p.s. modulation of the d.c. field H_0 is used to synchronize the interval times with passage through resonance, but no r-f field is applied to the sample between pulses. The operator arbitrarily initiates the first r-f square wave pulse which is adjusted to center automatically upon a resonance; the inspecting pulse, identical to the first one, automatically follows at a specified time t later. Combinations of scalar units are preset according to time intervals desired. In order to repeat data for a particular time interval, reset switches permit the process to be repeated. In order to inspect various points in time t on the exponential recovery of M_z toward thermal equilibrium, one needs simply to preset the proper

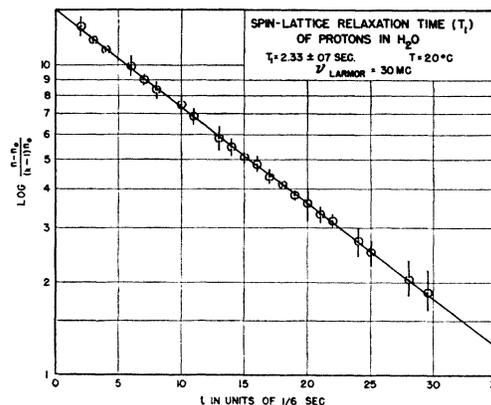


FIG. 2.

scalar units in desired combinations. The H_1 intensity of the square wave is constant throughout a T_1 measurement, giving $n_i = k(H_1)n_0$ where $k(H_1)$ is a proportionality factor which is constant for H_1 constant. In Fig. 1, n corresponds to the measured height of the inverted signal occurring at the time t chosen; n_0 corresponds to the measured height of the positive signal at $t=0$. For distilled water (not in vacuum) the data illustrated in Fig. 2 give $T_1 = 2.33 \pm 0.07$ sec. as compared with 2.3 ± 0.5 sec. measured by Purcell *et al.*¹ For this particular case, five measurements were made per point. The method permits even higher accuracy if more measurements per point are taken. The single signals seen here are much larger than ordinary periodic resonance signals, and signal to noise ratio is high. Shorter values of T_1 can also be measured by subjecting the sample to higher frequency H_0 field modulation.

* This work was supported in part by ONR contract N6-ori-71.
¹ Bloembergen, Pound, and Purcell, Phys. Rev. **71**, 466 (1947).
² This method appears to be similar to one reported by H. C. Torrey, Phys. Rev. **75**, 1326 (1949).
 ** This effect will be discussed in a paper to be published on the nutation of the nuclear magnetic moment.

An Error in a Paper by Landau on Coulomb Interactions in a Plasma*

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LANDAU¹ attempts to show that the Coulomb interactions of electrons and ions in a plasma can be represented as the divergence of a flow vector in momentum space. To obtain this result he expands the probability w of scattering through a small angle in powers of that angle without properly taking into account the singularity of w at zero deflection. Fortunately this expansion is avoided by reversing the integration by parts. Landau's Eq. (1) is

$$\int [n(p)n'(p') - n(p+\Delta)n'(p'-\Delta)]w(p-p', \Delta) d\tau' d\tau_\Delta. \quad (1)$$

The distributions n, n' are continuous and can be expanded in powers of Δ

$$n(p+\Delta) = n(p) + \frac{\partial n}{\partial p_i} \Delta_i + \frac{1}{2} \frac{\partial^2 n}{\partial p_i \partial p_k} \Delta_i \Delta_k,$$

$$n'(p'-\Delta) = n'(p') - \frac{\partial n'}{\partial p'_i} \Delta_i + \frac{1}{2} \frac{\partial^2 n'}{\partial p'_i \partial p'_k} \Delta_i \Delta_k.$$

Substituting in (1) the zero order terms cancel and the first order terms vanish on integration, leaving

$$\int \left[\frac{\partial n}{\partial p_i} \frac{\partial n'}{\partial p'_k} - n' \frac{\partial^2 n}{\partial p_i \partial p_k} + \frac{\partial n}{\partial p_i} \frac{\partial n'}{\partial p'_k} - n \frac{\partial^2 n'}{\partial p'_i \partial p'_k} \right] w \frac{\Delta_i \Delta_k}{2} d\tau' d\tau_\Delta. \quad (2)$$

This expression is correct. The last two terms are now integrated by parts, and use made of the relation

$$\partial w / \partial p'_k = -\partial w / \partial p_k,$$

giving

$$\int \left[\left(\frac{\partial n}{\partial p_i} \frac{\partial n'}{\partial p'_k} - n' \frac{\partial^2 n}{\partial p_i \partial p_k} \right) w + \left(n' \frac{\partial n}{\partial p_i} - n \frac{\partial n'}{\partial p'_i} \right) \frac{\partial w}{\partial p_k} \right] \Delta_i \Delta_k d\tau' d\tau_\Delta. \quad (3)$$

This is Landau's result on page 156 *except for the sign before the second parenthesis*. Unfortunately this expression does not reduce to a divergence.

There is a further error in Landau's method, which I have followed in going from (2) to (3) in order to point out the error in sign. The vector $(\mathbf{p} + \mathbf{p}')/2 = \mathbf{g}$ represents the motion of the center of gravity and the conservation laws require $\mathbf{p}, \mathbf{p}', \mathbf{p} + \Delta,$ and $\mathbf{p}' - \Delta$ to terminate on a sphere about \mathbf{g} . The integration by

parts was done holding \mathbf{p} and Δ constant. This obviously restricts \mathbf{p}' . To be correct the integration should be at constant scattering angle, in which case the quantity $\Delta_i \Delta_k$ occurs with w in the derivative $\partial(w \Delta_i \Delta_k) / \partial p_k$.

Unless the second half of (3) can be shown to be small, these errors will affect the results of Cahn² in two recent papers on the velocity distribution in a plasma.

* This work has been supported in part by the Signal Corps, the Air Materiel Command, and ONR.
¹ E. Landau, Physik Zeits. Sowjetunion **10**, 154 (1936).
² J. H. Cahn, Phys. Rev. **75**, 293, 838 (1949).

Proton Range-Energy Relation

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RECENT experiments have provided several points for the proton range-energy relation at low energies. We wish to report two more points and review the available data. The review is limited to data from cloud chambers since these experiments give mean ranges directly. The results of these determinations are shown in Fig. 1. The experimental points are numbered to correspond to paragraphs in the text. The Livingston and Bethe¹ (hereafter L & B) and the Cornell revised 1938² range-energy curves are included for comparison. All data are at S.T.P. (15°C, 76 cm Hg).

Point I: Twenty-eight tracks, equivalent in weight to fourteen tracks of good quality were obtained from the $H^2(\gamma, n)H^1$ reaction using Ga^{72} γ -rays in a cloud chamber filled with D_2 and D_2O vapor.* The expansion ratio was 1.36, the average temperature was 26.2°C and the total pressure was 65.1 cm before expansion. The mean range in deuterium was 0.53 ± 0.03 cm which, using the differential stopping powers of Blackett and Lees,³ is equivalent to 0.18 ± 0.01 cm in air. Using $E_\gamma = 2.250 \pm 0.05$ Mev⁴ and a deuterium binding energy of 2.237 ± 0.005 Mev⁵ E_p becomes 0.13 ± 0.03 Mev.

Point II: A similar experiment was performed using the γ -rays from ThC'' . Thirty-five tracks of good quality were obtained at an expansion ratio of 1.33 at an average temperature of 21°C and

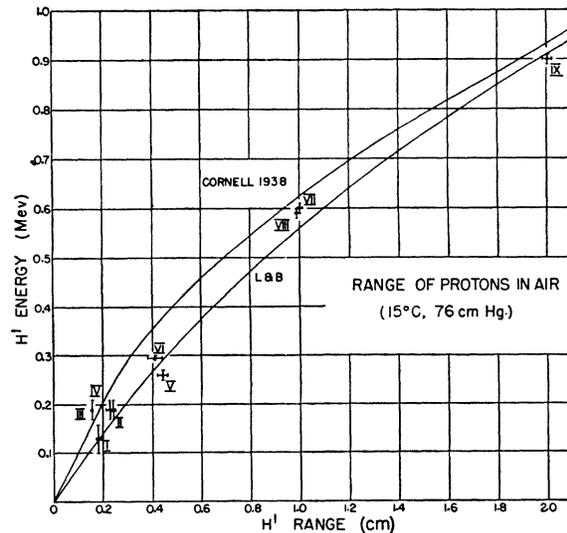


FIG. 1. Range of protons in air (15°C, 76 cm Hg).

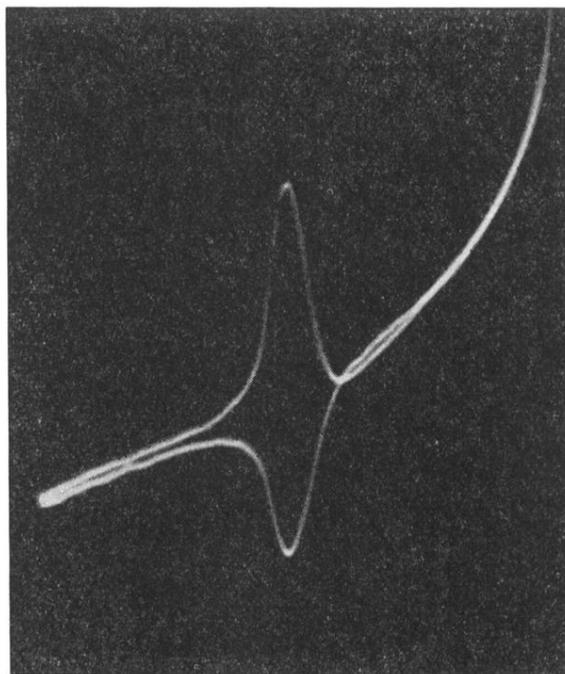


FIG. 1. The positive (n_0) and negative (n) signals represent slow passage resonance absorption and emission respectively. The emission signal occurs for $t=1/30$ sec. For t sufficiently large the n signal is positive, and coincides with the fixed n_0 absorption signal for t infinite.