58°K and $1.65\times10^{-2}$, respectively. The coexistence of two types of magnetism in the same specimen would seem to be consistent with the existence of a partial state of order that has been proposed to explain the resistivity anomaly around 230°C. We are planning to investigate these and other alloys in the same composition range at temperatures in the liquid helium range.

[1] F. A. Otter, Jr., Phys. Rev. **98**, 1552(A) (1955).

[2] A. L. Norbury and K. Kuwada, Phil. Mag. **4**, 1338 (1927); A. N. Gerritson and J. O. Linde, Physica **17**, 573 (1951).

[3] R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Company, Inc., New York, 1951), p. 763.

[4] F. J. Donahoe, Acta Metallurgia (to be published).

[5] $Au_2Mn$ was reported ferromagnetic by Roub, Zwicker, and Baur, Z. Metallkunde **44**, 312 (1953).

---

## Spin Echoes with Four Pulses

G. J. B. Crawford

*Radiation Laboratory, McGill University, Montreal, Canada*

(Received May 23, 1955)

RECENTLY, Das and Roy,[1] in extending previous analyses of the spin echo experiments[2,3] to the case of four pulses, have drawn attention to an unexplained echo (occurring at $t=2\tau_3-\tau_2+\tau_1$) specially characteristic of such a pulse sequence. Figure 1 shows a typical pattern of four pulses and their echoes obtained two years ago in this Laboratory. The echo spacing suggests that the echo in question arises in the normal manner by the action of the fourth pulse (at $\tau_3$) on what may be called a "virtual" stimulated echo at $\tau_2-\tau_1$. Vector considerations[4] and a detailed analysis do in fact make it clear that at any time after $\tau_2$ the spin ensemble is oriented as if it had given a signal at $\tau_2-\tau_1$ in exactly the same way as the stimulated echo at $\tau_2+\tau_1$ was produced. The analysis also shows that this "virtual" echo is the one transformed by the fourth pulse into the real signal at $2\tau_3-\tau_2+\tau_1$, in accord with the "mechanism" outlined in paragraph (e), Sec. III, of reference 1. In a similar way, the four "pentanary" echoes (in the case of five pulses) are due to the "mirror images" of the stimulated echoes at $\tau_3+\tau_1$, $\tau_3+\tau_2-2\tau_1$, $\tau_3+\tau_2-\tau_1$, and $\tau_3+\tau_2$ about the pulse at $\tau_3$.

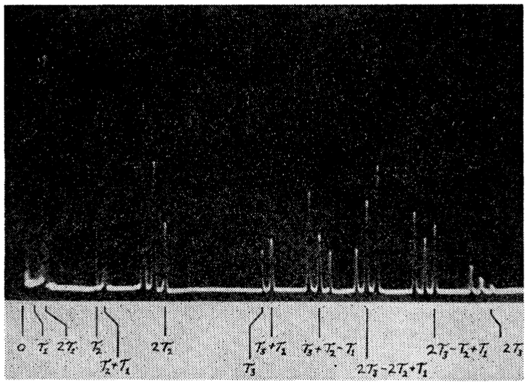

FIG. 1. A typical sequence of four pulses (at 0, $\tau_1$, $\tau_2$, and $\tau_3$) and their echoes. The separation between the echoes in any particular group of three is $\tau_1$. The pulses are all approximately 120°.

The use of the stimulated echoes generated by the fourth or reading pulse has been suggested[4] as the basis of a memory device in which the amplitude, width, and spacing of the first three pulses would form the coding mechanism. The possibilities of a somewhat simpler system have already been explored at Stanford University.[5]

The author gratefully acknowledges discussions on this problem with Professor J. S. Foster and Professor J. D. Jackson of this Laboratory.

[1] T. P. Das and D. K. Roy, Phys. Rev. **98**, 525 (1955).

[2] E. L. Hahn, Phys. Rev. **80**, 580 (1950).

[3] T. P. Das and A. K. Saha, Phys. Rev. **93**, 749 (1954).

[4] G. J. B. Crawford, Ph.D. thesis, McGill University, 1954 (unpublished).

[5] S. Fernbach and W. G. Proctor, J. Appl. Phys. **26**, 170 (1955).

---

## Effect of Screening on Solute Diffusion*

F. J. Blatt

*Physics Department, University of Illinois, Urbana, Illinois*

(Received May 13, 1955)

RECENT experiments[1,2] on the diffusion of cadmium, indium, tin, and antimony into silver have shown that the activation energy for diffusion decreases as $Z$, the valence difference between solute and solvent atoms, increases. Lazarus[3] proposed an explanation of these results, invoking the electrostatic interaction between solvent and solute ions in the metallic lattice. A critical parameter of his theory is the screening radius $r_s$ of the screened Coulomb potential used to represent the solute ion. Lazarus used a screening radius derived from the Fermi-Thomas model and obtained good agreement between theory and experiment. Since in the Fermi-Thomas approximation $r_s$ is independent of the valence of the solute atom, the theory predicted that $H$, the activation energy for solute diffusion, is given by

$$H=H_0-H_1Z,$$

where $H_0$ is the activation energy for self-diffusion of the solvent, and $H_1$ is a function only of the properties of the solvent, and not of the solute.

Now it is well known that in some instances, for example a calculation of the resistivity of dilute alloys,[4] the Fermi-Thomas model gives incorrect numerical results. Recently, Friedel has shown[5] that the Fermi-Thomas model is only a first approximation in an evaluation of the appropriate screening radius; if this parameter is determined by satisfying the quasi self-consistent condition that the total screening charge

TABLE I. Screening radius as a function of valence difference for impurities in silver.

| $Z$ | $-3$ | $-2$ | $-1$ | $+1$ | $+2$ | $+3$ | $+4$ |
|---|---|---|---|---|---|---|---|
| $r_s$ (A) | 0.73 | 0.7 | 0.665 | 0.5 | 0.485 | 0.473 | 0.468 |

equal the valence difference (Friedel sum rule), one then finds the $r_s$ is, for a given solvent metal, also a function of $Z$.

The correct screening radii for fulfilling the Friedel condition have been evaluated for impurities in silver. The results are listed in Table I. The form of the potential, namely $(Z/r)\exp(-r/r_s)$, was assumed *a priori*, and $r_s$ was treated as an adjustable parameter. In Fig. 1 are shown the activation energies for solute diffusion calculated from these screening radii using the formula derived by Lazarus, as well as the experimental activation energies and those obtained by using the screening radius predicted by the Fermi-Thomas model.

There may be a number of reasons for the discrepancy between the calculated and experimental results. The theory proposed by Lazarus is admittedly only semiquantitative. Also, the assumption of a screened Coulomb potential neglects all effects due to the size of the ion core, although this may play a significant role.

In any case, a significant feature of the results is the marked asymmetry of the calculated activation energies about the point $Z=0$. This asymmetry is a consequence of the dependence of $r_s$ on $Z$, shown in Table I, which gives rise to much larger screening radii for negative than for positive $Z$ values. One may, therefore, predict from this dependence of $r_s$ on $Z$ that the absolute magnitude of the difference in activation energies for solute and self-diffusion should be significantly larger for solutes which are electropositive relative to the solvent than for the corresponding electronegative solutes. This conclusion appears to be confirmed by preliminary measurements on the diffusion of ruthenium in silver.[6]

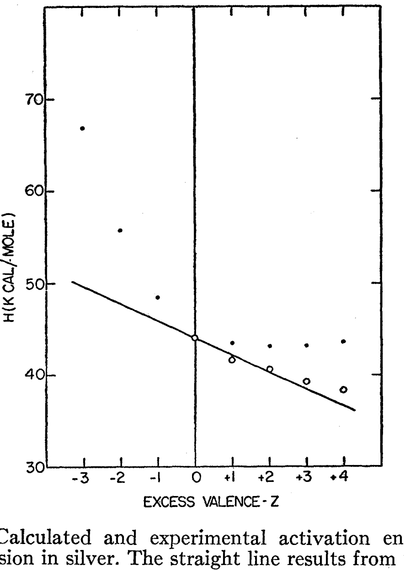

FIG. 1. Calculated and experimental activation energies for solute diffusion in silver. The straight line results from the use of a constant screening radius given by the Fermi-Thomas model. The solid points were calculated with the screening radii listed in Table I. The circles show the experimental results.

The author is grateful to Professor D. Lazarus, Professor L. Slifkin, and Dr. C. T. Tomizuka for several stimulating conversations, and to Dr. S. Machlup for his generous help in preparing the numerical work for machine computation by the ILLIAC.

---

[*] Supported by the Office of Naval Research.

[1] Sonder, Slifkin, and Tomizuka, Phys. Rev. **93**, 970 (1954).

[2] C. T. Tomizuka and L. Slifkin, Phys. Rev. **96**, 610 (1954).

[3] D. Lazarus, Phys. Rev. **93**, 973 (1954).

[4] N. F. Mott, Proc. Cambridge Phil. Soc. **32**, 281 (1936).

[5] J. Friedel, Advances in Phys. **3**, 446 (1954).

[6] C. T. Tomizuka (private communication).

---

# Energy Distribution of Neutrons Scattered by Paramagnetic Substances

B. N. BROCKHOUSE
*Physics Division, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada*

(Received April 26, 1955)

SLOW neutrons, when scattered magnetically by a paramagnetic material, undergo an energy change which depends on the degree of coupling of the magnetic ions. Van Vleck[1] has calculated the energy changes expected for paramagnetic substances in which the coupling arises from exchange forces. In a high-temperature approximation he finds that the rms energy change

$$(\delta E)_{\mathrm{rms}}=k_B|\Delta|[6/ZS(S+1)]^{\frac{1}{2}}, \qquad (1)$$

where $k_B$ is Boltzmann's constant, $Z$ is the number of interacting neighbors, $S$ is the spin of the ion and $\Delta$ is the Weiss constant determined from the measured susceptibility by fitting to the Curie Weiss law $\chi=C/(T-\Delta)$. Van Vleck was not able to obtain a detailed energy distribution but a calculation of the fourth moment suggested that a Gaussian might be a fair approximation.

By using the apparatus shown in Fig. 1, the energy distribution of neutrons scattered by a number of paramagnetic substances has been measured. Neutrons of wavelength $\lambda_0$ in the region of 1.3 angstroms (energy 0.05 ev) are selected from the *NRX* reactor spectrum by a crystal ($X1$). A small fraction (usually about 10 percent) of the resulting monoenergetic neutrons is scattered by the specimen, and the energy distribution of those scattered at some particular angle $\phi$ is examined by means of an analzying crystal spectrometer ($X2$). Background is obtained by turning the crystal ($X2$) by an amount such that the Bragg law can no longer be satisfied for any neutron energy. This is done automatically at intervals during a run. A background so