where $E_p = \frac{1}{2}(g_1 - g_2)\beta H$, the oscillatory part of the tunneling current is given by

$$\frac{j(H) - j_{av}(H)}{j_{av}(H)} = \left[\lambda_0 + \left(\frac{\hbar\omega}{2}\frac{\partial\lambda_0}{\partial\epsilon}\right)\coth\left(\frac{\hbar\omega}{2}\frac{\partial\lambda_0}{\partial\epsilon}\right) - \left(E_p\frac{\partial\lambda_0}{\partial\epsilon}\right)\tanh\left(E_p\frac{\partial\lambda_0}{\partial\epsilon}\right)\right] \times \left(\frac{\alpha - 1}{\alpha}\right)\left(\frac{\mu_1}{\mu_1 + \mu_2 + \epsilon}\right)\left(\frac{\Delta\mu_1}{\mu_1}\right). \quad (7)$$

Here $\Delta\mu_1/\mu_1$ is to be obtained from (2), and $j_{av}(H)$ is obtained from (6) with λ replaced by λ_0.

Under normal conditions for observation of oscillations, the coth and tanh terms are negligible and we find for InSb (with $\alpha = 2$)

$$\frac{j(H) - j_{av}(H)}{j_{av}(H)} \simeq \frac{\lambda_0}{12}\left(\frac{\mu_1}{\mu_1 + \mu_2 + \epsilon}\right)\left(\frac{\hbar\omega_1}{\mu_1}\right)^{3/2} \times \left[E\left(\frac{\mu_1}{\hbar\omega_1} - 0.32\right) + E\left(\frac{\mu_1}{\hbar\omega_1} - 0.68\right)\right]. \quad (8)$$

For $\mu_1/\hbar\omega_1 \sim 1.5$, $\lambda_0 \sim 30$, $\mu_1/(\mu_1 + \mu_2 + \epsilon) \simeq \frac{1}{4}$, the oscillations are therefore ~30% of the average current. For smaller fields the relative importance of the oscillations is seen to decrease like $H^{3/2}$. Temperature and collision broadening of the sharp peaks in Fig. 1 are ignored in this estimate, which would tend to reduce the amplitudes. This damping effect also accounts for the appearance of only one current peak per cycle. The observations of Chynoweth et al.[1] are in good agreement with the above results.

It should be noted that the above effect is not to be expected for a transverse magnetic field. In this case the discontinuities in the density of electron states for states whose orbit center lies less than one orbit radius from the junction no longer occur at particular values of the magnetic field, but are distributed more or less continuously and hence the average junction field remains unaltered. Density of states fluctuations due to states whose orbit center is far from the junction do result in the appearance of a weak space-charge region on the n side. However, this space-charge region is not in the vicinity of the junction and hence does not affect the junction field.

In previous theories it was customary to ignore the shift of the Fermi level with magnetic field.[2,4] The present analysis indicates that although this shift is small, it plays an important role in the tunneling process.

The authors would like to thank Dr. E. N. Adams for several helpful discussions.

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STIMULATED SPIN-ECHO MEASUREMENT OF CROSS-RELAXATION IN NEUTRON-IRRADIATED CALCITE*

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(Received December 19, 1960; revised manuscript received February 9, 1961)

In recent years, possibly due to the advent of microwave spectroscopy and maser applications, a great deal of research has been conducted on the relaxation times of spin systems. Presently there is a large amount of work being conducted on cross-relaxation decay[1] and its subsequent effects. The majority of these experimental measurements have been conducted by saturation methods or pulse modifications of them, which lead to exponential decay with two or more time constants. The study of electron spin echo as an information storage medium for high-speed carrier-type microwave computers has led the authors to some interesting measurements of relaxation times in neutron-irradiated calcite. Of more significant interest, however, is the use of the stimulated spin-echo technique in cross-relaxation measurements. This method, in cases where the T_1 relaxation time is somewhat larger in magnitude than the cross-relaxation time,

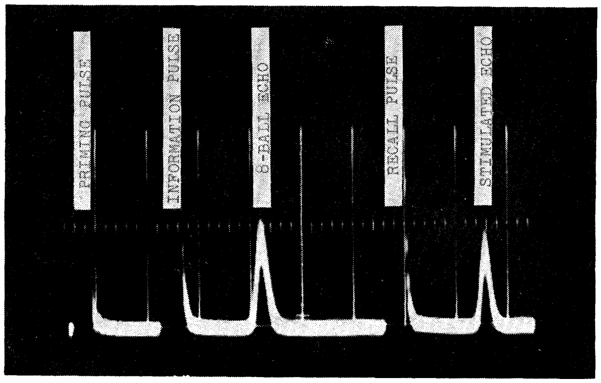

FIG. 1. Oscilloscope photograph of a stimulated spin echo, Horizontal scale 5 μsec/cm, vertical 0.01 v/cm, temperature = 1.5°K. The pulses from the klystron show as breaks in the base line.

gives a single exponential decay curve due only to the T_{21} time constant.

The experimental arrangement used is very similar to that of Gordon and Bowers,[2] consisting of an X-band heterodyne spectrometer and a programmed pulse generator. The pulsing system was made up of six Tektronix pulse generators connected into a single General Radio pulse amplifier. The latter supplied negative pulses to the klystron repeller. The pulses were variable in width, separation, and also in repetition rate of the entire pulse group. The narrowest pulses obtainable from the programmed pulse generator were 1 μsec long. This hindered the measurements to some extent, but in our case versatility was felt to be more important. The local oscillator was used in the early studies of the spin-spin and spin-lattice relaxation times, but was later eliminated for some of the tests.

The stimulated echos obtained here at a frequency of 8807 Mc/sec are a paramagnetic analog of those obtained at nuclear frequencies by Hahn.[3] Figure 1 is a typical oscilloscope photograph of the stimulated spin-echo signals. The microwave pulses from the klystron drive the oscilloscope off scale, and are therefore merely indicated by breaks in the base line of the trace. All of these pulses were 1 μsec long and of an intensity to give the spin system a rotation through an angle of approximately $\pi/2$ radians. The first echo is the familiar 8-ball echo (so called because of the pattern of the spin vectors on a sphere[3]). This echo relaxes in a time characterized by spin-spin relaxation or T_2. In our radiation-damaged calcite sample, this was approximately 18 μsec at 1.5°K.[4] However, the stimulated echo following the recollection pulse is of much greater interest. As pointed out by Fernbach and Proctor,[5] this signal is due to storage parallel to the direction of the Z axis and, consequently, its decay normally depends only on spin-lattice relaxation. In our case, the spin-lattice relaxation time of the calcite sample was measured both by adiabatic fast passage and by saturation methods, giving a time constant of $T_1 = 5 \pm 2$ seconds at 1.5°K.[4] However, the stimulated echo decayed with a time constant of approximately $T = 600$ μsec or nearly 8000 times faster than predicted by T_1. This rapid relaxation is undoubtedly due to cross-relaxation,[1] since the calcite spectrum consists of three spectral lines with a separation of about three gauss, when equally spaced. Figure 2 shows a decay curve obtained by means of the stimulated spin-echo technique. The solid

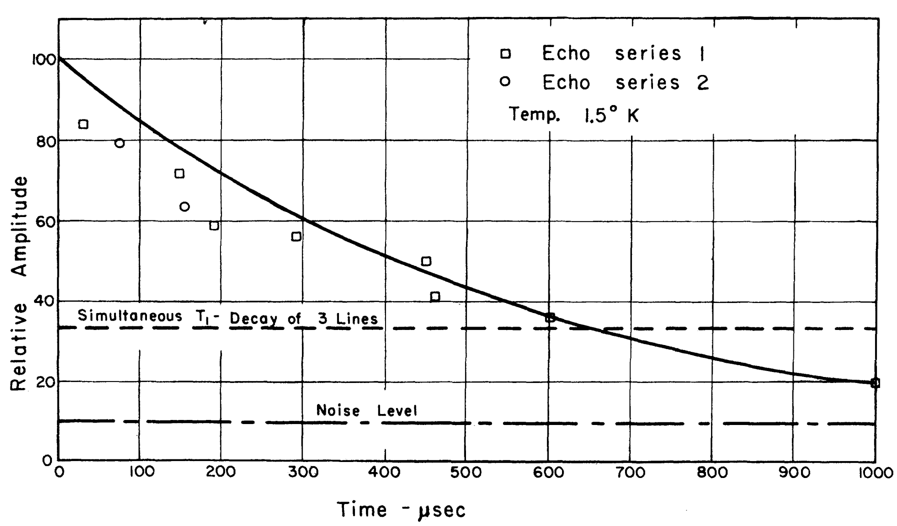

FIG. 2. Cross-relaxation decay curve of stimulated spin echos in radiation-damaged calcite. No attempt was made to form a best fit to the experimental points. The solid line is a plot of an $\exp(-t/6\times10^{-4})$ decay from the normalized amplitude. The dashed line is the level to which the energy decays by cross-relaxation.

line is a theoretical plot of an exponential decay $\exp(-t/6\times10^{-4})$, while the dashed curve represents the level to which the energy stored in the line under observation decays by cross-relaxation. The energy of the three lines then decays simultaneously from this level with a time constant equal to T_1. No attempt was made to fit a curve to the experimental points of the echo signal amplitudes, but the smaller values obtained at the start of the decay can be justified by the method used to measure the echos.

It is of importance to note that the spin-echo decay continues at the cross-relaxation rate even after the three lines of calcite have come to energy equilibrium. This is to be expected on the basis of the model proposed by Bloembergen et al.[1] Since the balance of energy between the three lines has the characteristics of a dynamic equilibrium and the very nature of cross-relaxation allows mutual spin flips between electrons with somewhat different resonant frequencies to transfer energy between spectral lines, the frequency storage of the spins is destroyed by the cross-relaxation process. The stimulated echo depends on the Z-axis storage of this frequency dependence and the echo signal consequently decays exponentially to zero with the cross-relaxation time constant.

This same process can occur within a single inhomogeneously broadened line and might make a very interesting study, since the stimulated spin-echo technique effectively separates the decay due to cross-relaxation from that due to spin-lattice relaxation when the time constants are not comparable.

The authors would especially like to thank Professor J. R. Singer for suggesting this project and for his continuing support and helpful guidance. Thanks are also due to Professor E. L. Hahn as well as Dr. J. Kemp, S. Hartmann, and M. Weger for helpful discussions.

*This research was supported in part by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.

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DISLOCATION RELAXATION SPECTRA OF COLD-WORKED BODY-CENTERED CUBIC TRANSITION METALS*

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During the course of a low-temperature acoustical study of the defect structure introduced into bcc transition metals by cold work, peaks have been found in the internal friction vs temperature curves of Nb, Ta, Mo, and W. The peaks appear only with prior plastic deformation and have a detailed shape which is controlled by the annealing history of the specimen.

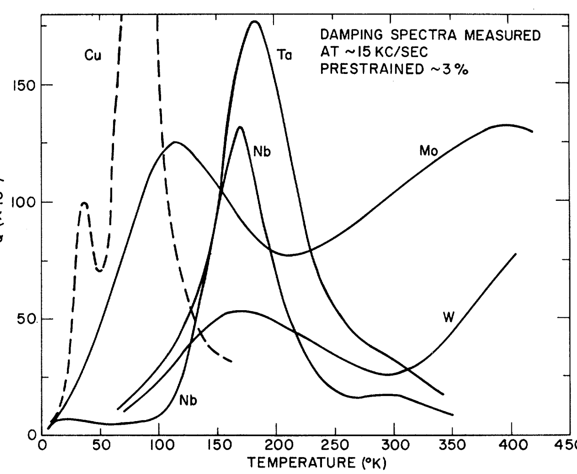

FIG. 1. Damping spectra of polycrystalline Cu, Nb, Ta, Mo, and W measured at ~15 kc/sec. All specimens were given ~3% tensile prestrain at 300°K (~600°K for W).

Figure 1 shows the internal friction vs temperature curves for fine-grained vacuum-melted Nb, Ta, Mo, and W specimens given a 3% tensile prestrain at 300°K (~600°K for W). An internal friction spectrum of a typical fcc metal (Cu) prestrained 3% is included for comparison. Most of the acoustical measurements were made by the longitudinal resonant bar method at 15 kc/sec and oscillating strain amplitudes of $\sim10^{-7}$; several measurements on Mo were made at 6 cps, at a strain amplitude of 2×10^{-7} in a torsion

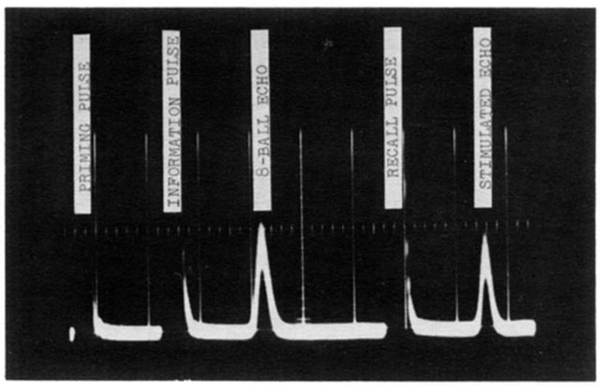

FIG. 1. Oscilloscope photograph of a stimulated spin echo, Horizontal scale 5 μsec/cm, vertical 0.01 v/cm, temperature = 1.5°K. The pulses from the klystron show as breaks in the base line.