tional investigations are necessary. Recently Chen and Abraham[18] have found that the addition of lithium to MgO results in a significant suppression of radiation damage in this material, and in view of the interest in using MgO as an electrical insulator in high-radiation environments, the problem of understanding the solid state processes in the lithium magnesium oxide system assumes new importance.

*Research sponsored by the U. S. Energy Research and Development Administration under contract with Union Carbide Corporation.

[1]For a recent review of the properties of trapped-hole centers in MgO see Y. Chen and M. M. Abraham, New Phys. (Korean Phys. Soc.) 15, 47 (1975).

[2]A. E. Hughes and B. Henderson, *Defects in Crystalline Solids*, edited by J. H. Crawford, Jr., and L. M. Slifkin (Plenum, New York, 1972).

[3]B. Henderson and J. E. Wertz, Adv. Phys. 17, 749 (1968).

[4]G. Rius, R. Cox, R. Picard, and C. Santier, C. R. Acad. Sci. 271, 724 (1970).

[5]O. F. Schirmer, J. Phys. Chem. Solids 32, 499 (1971).

[6]H. T. Tohver, B. Henderson, Y. Chen, and M. M. Abraham, Phys. Rev. B 5, 3276 (1972).

[7]M. M. Abraham, Y. Chen, J. L. Kolopus, and H. T. Tohver, Phys. Rev. B 5, 4945 (1972).

[8]M. M. Abraham, Y. Chen, J. T. Lewis, and F. A. Modine, Phys. Rev. B 7, 2732 (1972).

[9]M. M. Abraham, W. P. Unruh, and Y. Chen, Phys. Rev. B 10, 3540 (1974).

[10]M. M. Abraham, C. T. Butler, and Y. Chen, J. Chem. Phys. 55, 3752 (1971).

[11]G. Rius and A. Hervé, Solid State Commun. 15, 399 (1974).

[12]L. E. Halliburton, L. A. Kappers, D. W. Cowan, F. Dravniekds, and J. E. Wertz, Phys. Rev. Lett. 30, 607 (1973).

[13]M. M. Abraham, Y. Chen, L. A. Boatner, and R. W. Reynolds, Solid State Commun. 16, 1209 (1975), and references therein.

[14]J. Rubio, Y. Chen, and M. M. Abraham, J. Chem. Phys. 64, 4804 (1976).

[15]G. Rius and A. Hervé, Solid State Commun. 15, 421 (1974).

[16]G. Rius, A. Hervé, R. Picard, and C. Santier, J. Phys. (Paris) 37, 129 (1976).

[17]F. A. Modine, to be published.

[18]Y. Chen and M. M. Abraham, J. Am. Ceram. Soc. 59, 101 (1976).

Phonon Echoes in Glass

Brage Golding and John E. Graebner
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 2 August 1976)

Phonon echoes, the acoustic analog of spin and photon echoes, are observed in fused silica glass at ultralow temperatures. From the phonon echo decay, we infer a homogeneous transverse lifetime of 14×10^{-6} sec and a longitudinal relaxation time of 200×10^{-6} sec for tunneling states at 0.68 GHz at a temperature of 20 mK. The coupling between the two-level systems and phonons is estimated to be 1.6 eV.

We have observed for the first time the existence of coherent phonon echoes in a structurally disordered solid, fused silica glass. This echo phenomenon shares many features in common with magnetic spin echoes,[1] photon echoes,[2,3] and ultrasonic spin echoes,[4] because in a phonon echo an intense pulse of acoustic energy is observed following the preparation of a resonant system by two appropriately dimensioned acoustic pulses. Unlike the nuclear spin[1] or the electronic spin[2] systems in which echoes have been observed previously, the resonant "spin" system in glass is the broadly distributed two-level atomic tunneling-state system which is believed to be an intrinsic feature of the amorphous phase.[5] The observation of a coherent resonance phenomenon arising from the inherent disorder of a solid is unique and provides a powerful method for detailed study of the decay processes of the glass tunneling states.

Photographs of oscilloscope traces of the phonon echoes appearing in Suprasil W glass at a temperature of ~20 mK are shown in Fig. 1. The first trace shows the decay of a single excitation pulse, R_{10}, at time $t=0$, followed by two acoustic reflections R_{11} and R_{12} separated by $t_d=2.2$ μsec, the round trip delay time, $v_l/2L$, of the 0.68-GHz, 100-nsec duration, longitudinal acoustic pulse. If two excitation pulses, R_{10} and R_{20}, are now applied separated by a time τ_s, in addition to

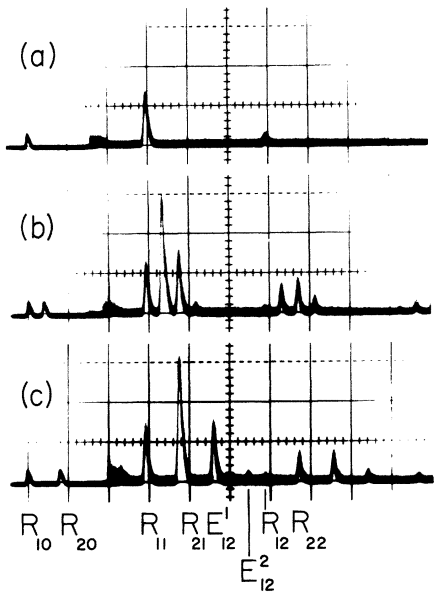

FIG. 1. Decay of 100-nsec, 0.68-GHz acoustic pulses in Suprasil W fused silica at 20 mK. Time scale is 0.75 μsec per division. Weak pulse(s) at left of oscilloscope photographs originate in attenuated leakage from excitation pulse(s) applied to transducer (switching transient observed ~ 2 divisions from left). (a) Decay after single pulse with reflections R_{11} and R_{12} visible separated by delay $t_d = 2.2$ μsec. (b) Two-pulse sequence with separation $\tau_s = 0.3$ μsec. Phonon echo E_{12}^{1} appears at τ_s after reflection of second pulse R_{21}. (c) Two-pulse sequence with separation $\tau_s = 0.6$ μsec.

the extra acoustic reflections R_{1n} and R_{2n}, appearing at nt_d and $nt_d + \tau_s$, additional echoes E_{12}^{m} ($m \geq 1$), the phonon echoes, appear at times $nt_d + (m+1)\tau_s$. In Fig. 1(b), $\tau_s = 300$ nsec, whereas in Fig. 1(c), $\tau_s = 600$ nsec. We note that the first acoustic reflection always occurs a time t_d after its initiating pulse is applied to the transducer but that the primary phonon echo ($m = 1$) appears at a time $t_d + 2\tau_s$ after the first pulse is applied. The reason is that the excited states radiate coherently in a direction collinear to the excitation pulses a time τ_s after the second rephasing pulse re-excites them. The signals for which $m > 1$ are higher-order phonon echoes, similar to those observed in photon echo experiments[2] (e.g., E_{12}^{2} is generated by R_{21} and E_{12}^{1}, an acoustic pulse and a phonon echo).

The echoes shown in Fig. 1 were generated by injecting into the glass sample two identical acoustic pulses of energy $\mathcal{E} = 2.9 \times 10^{-6}$ erg cm^{-2}, with a ZnO transducer area $\mathcal{A} = 5.5 \times 10^{-3}$ cm^2. Phonon echoes are observed in a range $\pm$ 10 dB about this energy for pulse durations τ of 100 nsec. The energy of maximum echo amplitude formation is

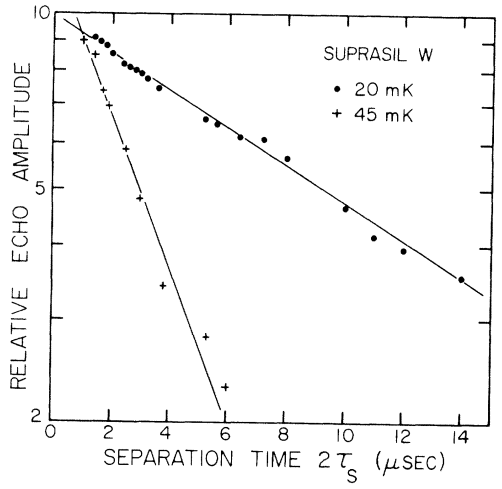

FIG. 2. Decay of the phonon echo E_{12}^{1} as a function of $2\pi_s$. Decay time T_2' is 14 μsec at 20 mK whereas T_2' is 3 μsec at 45 mK.

estimated as $\mathcal{E}_{max} \simeq 1.8 \times 10^{-6}$ erg cm^{-2}. The large uncertainty in this estimate is due to an interesting feature of this system: Echo formation is observed in the presence of significant saturation, or incoherent excitation, of the tunneling states. The unsaturated absorption coefficient α_0 ($\mathcal{E} < 10^{-7}$ erg cm^{-2}) at 20 mK is ≈ 3.4 cm^{-1}, whereas the effective absorption coefficient for the first pulse is roughly 2.3 cm^{-1} at $\mathcal{E}_{max}$. In a two-pulse sequence, the first pulse partially saturates the medium so that the second pulse propagates with an effective absorption some 6 dB less. Thus the pulse energies are functions of $\mathcal{E}$ and z, the position in the glass. Since the phonon echo propagates in a region partially saturated by the first and second pulses it can have an amplitude greater than the first pulse at $z = 2L$, as shown in Fig. 1. The low effective absorption makes it possible to see many high-order reflections and we can easily detect E_{12}^{3}, the phonon echo generated by the two preceding phonon echoes E_{12}^{1} and E_{12}^{2} (as well as by R_{11} and E_{12}^{1}).

The observation of the phonon echo requires a transverse homogeneous lifetime $T_2' \gtrsim \tau_s$. T_2' can be measured by observing the echo amplitude as a function of τ_s, which should decay as $\exp(-2\tau_s/T_2')$. Figure 2 shows the relative echo amplitude versus $2\tau_s$ for fused silica under the same conditions as Fig. 1. The decay is exponential and yields $T_2' = 14$ μsec at 20 mK, and $T_2' = 3$ μsec at 45 mK. The width of the phonon echo is the same as the excitation pulse width at these temperatures. This result is consistent with our observa-

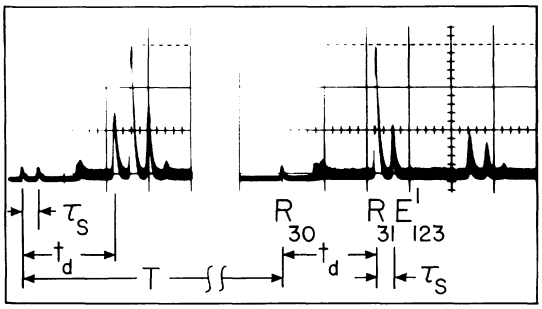

FIG. 3. Composite photograph demonstrating the stimulated phonon echo following a three-pulse sequence, with 100-nsec, 0.68-GHz pulses in Suprasil W fused silica at 20 mK. Scale is 1 μsec per division. Second pulse occurs at $\tau_s = 0.4$ μsec; third pulse occurs at $T = 12.3$ μsec. The stimulated echo $E_{123}{}^1$ occurs at a time $t_d + \tau_s = 2.6$ μsec after T. Measurement of the decay of $E_{123}{}^1$ as a function of T yields $T_1 \approx 200$ μsec.

tion in "hole-burning" experiments (wherein the spectral width of the hole produced by a partially saturating first pulse at ω_1 is probed by a weak test pulse at ω_2) for which at 20 mK and 0.6 to 0.8 GHz the spectral width is $\sim \tau^{-1} = 3$ MHz. Thus, the broadening mechanism to which was ascribed[5] the large 50-MHz widths at 0.5 K must be considerably smaller here at 20 mK and, indeed, may be responsible for the magnitude of T_2'.

If the glass is subjected to a three-pulse excitation sequence, the separation of the first two being τ_s as before, but the first- and third-pulse separation being T, with $T > 2\tau_s$, a phonon echo is observed at time $T + t_d + \tau_s$. This is usually termed a stimulated echo.[1] Figure 3 shows a three-pulse sequence, with $\tau_s = 400$ nsec, in which the third pulse R_{30}, identical to the preceding two, occurs at $T = 12.3$ μsec and produces a stimulated echo $E_{123}{}^1$. The lifetime of the stimulated echo provides a measure of the longitudinal relaxation time T_1. We have observed an exponential decay of $E_{123}{}^1$ for $12 < T < 300$ μsec with a characteristic time $T_1 \cong 200$ μsec at 20 mK. This result is in good agreement with $T_1 \cong 240$ μsec inferred from our previous "hole-burning" experiments, with $\omega_1 = \omega_2$, at 20 mK for similar values of $\mathcal{E}$.

The average linear coupling coefficient γ_l between the longitudinal acoustic strain and the two-level systems for those states contributing to the phonon echo can be easily estimated from the area relation[4] $\theta = (\gamma/\hbar)e\tau$, where $e = [2\mathcal{E}/\rho v_l{}^3\tau]^{1/2}$ is the strain and θ is the pulse area in radians. If we assume that echo production will occur with maximum efficiency when $\theta_1 = \pi/2$ and $\theta_2 = \pi$ over the largest spatial interaction region we are led to associate $\mathcal{E}_{\max}$ with the energy of a $\theta_2 = \pi$ pulse, since the first pulse, initially of area π at $z = 0$, rapidly attenuates to $\sim \pi/2$ after a short propagation distance. We thus find $e_{\max} = 1.3 \times 10^{-8}$ and $\gamma_l = 1.6$ eV. Previous estimates of γ_l have ranged from 0.3 to 4 eV,[5,6] with the lower value evaluated under the assumption that the density of two-level states was that obtained from specific-heat measurements, n_0. Since it is expected that only a fraction r of states at energy $\hbar\omega$ will strongly scatter phonons,[6] $r \equiv \tilde{n}/n_0$, the present independent determination of γ_l allows us to infer $r \approx 0.04$, or $\tilde{n} = 3 \times 10^{31}$ states/erg $\cdot$ cm^3. The unsaturated absorption coefficient $\alpha = l^{-1} = \pi\tilde{n}\gamma_l{}^2\omega \tanh(\hbar\omega/2kT)/\rho v_l{}^3$ calculated with the above values for γ_l and $\tilde{n}$ yields 4.3 cm^{-1} at 0.68 GHz and 20 mK in good agreement with our observations. More signficantly, for the saturation energy, calculated approximately as $\mathcal{E}_{\text{sat}} \simeq \frac{1}{2}\tilde{n}\hbar\omega(\hbar\Delta\omega)\tanh(\hbar\omega/2kT)L$, where $\Delta\omega$ is the frequency width of the states excited by the pulse, we find $\mathcal{E}_{\text{sat}} \approx 1 \times 10^{-6}$ erg/cm^2, which is the experimentally observed saturation threshold. It is also within a factor of 2 of the energy necessary to generate a π pulse, as inferred above from the maximum phonon echo production. Since the number of states in resonance with the pulse is $\propto \tau^{-1}$ in these experiments, the threshold for coherent or incoherent excitation should be the same, since it is then only a question of the ratio T_2'/τ which determines the degree of coherency of the process. The longitudinal relaxation time T_1 due to single-phonon emission can be calculated from[7] $T_1{}^{-1} = (\gamma_l{}^2/v_l{}^5 + 2\gamma_t{}^2/v_t{}^5)\omega^3 \times \coth(\hbar\omega/2kT)/2\pi\rho\hbar$, and since[5,8] $\gamma_l{}^2 = 2\gamma_t{}^2$, we find $T_1 = 65$ μsec at 0.68 GHz and 20 mK in reasonable agreement with our measurements.[9]

We have shown that the observation of echoes due to coherent phonon emission by states associated with atomic tunneling in a glass can be used to obtain relatively detailed information on the decay rates and coupling constants of these levels. The tunneling levels exist as a result of the atomic disorder in the amorphous phase and have a continuous, and nearly uniform, distribution of energies below a few kelvin, with $n_0 \sim 10^{21}$ states/eV $\cdot$ cm^3. Nevertheless, we are dealing with a relatively dilute system if only those states in contact with the phonon pulse are considered, since $n_0 r h \tau^{-1} \sim 5 \times 10^{12}$ states/cm^3. This corresponds to a mean spatial separation of ~ 0.5 μm, which is 1/20 of a wavelength between like states at 0.6 GHz.

In conclusion, it is remarkable that certain

atoms in a cold glass can remember their previous atomic coordinates for a time duration of hundreds of microseconds, whereupon on signal, they cooperatively return to their initial positions. It is somewhat paradoxical that these coherent effects should occur in a completely disordered solid system but, in fact, not in the perfectly ordered crystalline state.

We thank B. I. Halperin and S. L. McCall for helpful discussions.

[1]E. L. Hahn, Phys. Rev. 80, 580 (1950).
[2]I. D. Abella, N. A. Kurnit, and S. R. Hartmann, Phys. Rev. 141, 391 (1966).
[3]C. K. N. Patel and R. E. Slusher, Phys. Rev. Lett. 20, 1087 (1968).
[4]N. S. Shiren and T. G. Kazyaka, Phys. Rev. Lett. 28, 1304 (1972), and Phys. Rev. B 2, 2471 (1970).
[5]S. Hunklinger and W. Arnold, in "Physical Acoustics," edited by R. N. Thurston and W. P. Mason (Academic, to be published), Vol. 12.
[6]B. Golding, J. E. Graebner, B. I. Halperin, and R. J. Schutz, Phys. Rev. Lett. 30, 223 (1973).
[7]J. Jäckle, L. Piché, W. Arnold, and S. Hunklinger, J. Non-Cryst. Solids 20, 365 (1976).
[8]B. Golding, J. E. Graebner, and R. J. Schutz, Phys. Rev. B 14, 1660 (1976).
[9]The discrepancy between the measured and calculated T_1 may be significant in view of the substantially shorter relaxation times observed near 0.5 K, $T_1 \approx 0.5$ μsec from which was inferred $\gamma_t \approx 3$ eV[5]. These times would extrapolate to roughly ≈ 10 μsec at 20 mK. However, in previous unpublished experiments in this laboratory, we have observed an effective relaxation time at temperatures below 50 mK, which increased rapidly with acoustic power. The suggestion that the phonons emitted by the decaying states do not leave the acoustic beam region (B. I. Halperin, private communication) may be a possibility, or that other phonon "bottleneck" phenomena may be responsible for the anomaly.

Spin-Wave Damping in a Heisenberg Antiferromagnet

C. G. Windsor and D. H. Saunderson
Atomic Energy Research Establishment, Harwell, Oxon OX11 0RA, United Kingdom

and

E. Schedler*
Institute Laue-Langevin, 38042 Grenoble Cedex, France
(Received 16 August 1976)

Neutron scattering measurements are reported on the linewidth Γ of spin waves in the simple cubic antiferromagnet $RbMnF_3$ at relatively low temperatures T and spin-wave energies E_q. The results are well fitted by $\Gamma = AE_q^{\alpha}T^{\beta}$, where $\alpha = 2.13 \pm 0.18$, consistent with the scaling law prediction $\alpha = 2$ of Halperin and Hohenberg, and $\beta = 3.29 \pm 0.39$, in agreement with the prediction $\beta = 3$ of two regimes considered by Harris, Kumar, Halperin, and Hohenberg, although the magnitude A is not in agreement with theory.

Interactions between spin waves give rise to a linewidth or damping,[1-4] and the extensive theoretical work on the damping of spin waves in Heisenberg magnets reflects its importance as an illustrative case of the general problem of interacting bosons. Study of the Heisenberg anti-ferromagnet in this connection has the attraction that a realistic comparison with experiment is possible, since crystals exist whose Hamiltonians mirror closely that assumed in the theoretical studies. Thus $RbMnF_3$ is known to correspond closely to a simple cubic antiferromagnet with spin $S = \frac{5}{2}$, negligible anisotropy,[5] and exchange interactions essentially limited to the nearest-neighbor shell having $J = 0.068$ THz and $z = 6$ nearest neighbors.[6,7] A few experimental studies of spin-wave linewidths using neutron scattering techniques have already been made[7,8] but considerations of resolution have meant that these studies have been largely confined to the temperature range above half the Néel temperature T_N and the larger wave vectors where the widths are most easily observed. In contrast, theoretical work, with some exceptions,[4] has tended to concentrate on low temperatures and wave vectors where analytic methods may be used. The present experimental study examines $RbMnF_3$ in the temperature range from $0.2T_N$ to $0.6T_N$ and the wave-vector range up to 0.4 times the zone-boundary wave vector along the [111] direction (defined as a reduced wave vector $q^* = 0.4$). In terms of the reduced temperature $\tau = kT/zJS$ and reduced energy