Microwave tunnel echo in glass

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A microwave echo was observed for the first time in glass without magnetic impurities. A dependence of the echo signal on the magnetic field was obtained in glass with rare-earth impurities. It was found that the relaxation times decrease as a result of application of the field. It is assumed that the observed signals are due to the spectrum of low-frequency excitations caused by tunneling.

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An anomalous behavior of the specific heat and absorption of sound, dependence of the attenuation of sound pulses on their intensity, phonon echo, etc. have been detected in glass at low temperatures by using different physical methods.[1,2] These effects can be accounted for by the spectrum of elementary excitations in amorphous media, which are produced by tunneling. Kopvillem *et al.*[3] were first to observe the analogs of the electron-spin echo in glass, whose signals rapidly attenuated with increasing magnetic field. The physical nature of echo signals in glass was not explained

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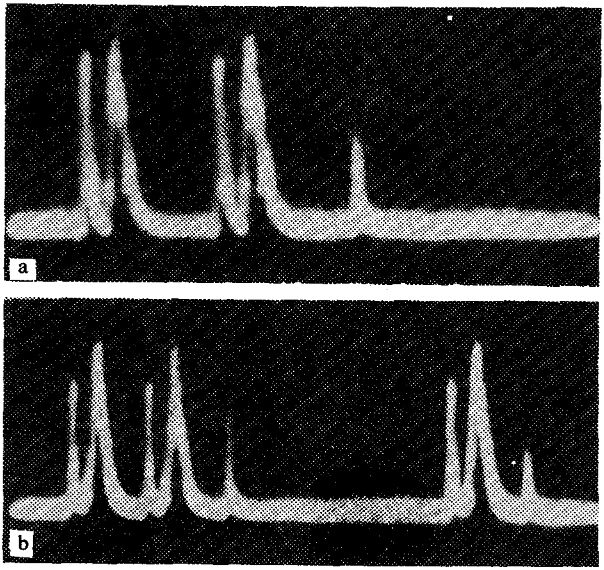

FIG. 1. (a) A two-pulse echo in glass without impurities. (b) A two- and three-pulse (stimulated) echo in glass with Nd^{3+} ion impurities.

at that time. Kopvillem[4] explained the indicated experiment as a photon echo in glass, which is produced by tunneling. However, the anomalies in glass due to tunneling, which were investigated by other methods, showed that the introduction of impurities does not significantly change the character of the effects.[5] Therefore, the suppression of the echo signal by the magnetic field required additional experiments for detection of the echo independent of the field.

In this paper, we report the first observation of a microwave echo in glass, which is independent of the constant magnetic field H (Fig. 1a). The field-independence indicates that the observed effect, which can be called a microwave tunnel echo, is most likely due to the low-energy excitations. Echo signals at $H = 0$ and in > 8-kG fields were detected in a glass with paramagnetic impurities. Whereupon the times T_1 and T_2 decreased as a result of application of the field.

The experiments were carried out in the temperature range of 4.2 to 1.8 K at 9.5 GHz. The investigated glass samples were placed in the peak uhf electric field of the cavity. The echo signals were excited by the uhf pulses of 3×10^{-8} sec duration with a maximum pulse power of $\sim 3 \times 10^{3}$ W and an adjustable 10^{-7} to 10^{-4} sec spacing between the pulses. The echo signals were recorded by a wide-band traveling wave tube with a sensitivity of 10^{-12} W. During a two-pulse excitation in a lithium-alumo-silicate glass devoid of paramagnetic impurities, we detected an echo signal (Fig. 1a) at 1.8 K with the characteristic relaxation time $T_2 = 0.5 \times 10^{-6}$ sec. Special attention was focused on the effect of the external magnetic field on the echo signals. The echo signal was gated, fed to the integrator, and then recorded on an X-Y recorder as a fucntion of the linearly varying magnetic field in the range of 0 to 13.5 kG. The effect of the

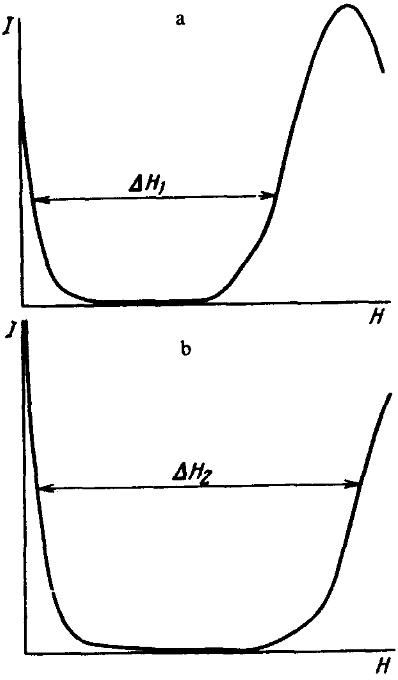

FIG. 2. (a) Dependence of the intensity of the two-pulse echo signals in glass with Ce^{3+} on the magnetic field H at maximum power of the exciting pulses and minimum interval between them. $\Delta H_1 = 9.25$ kG. (b) Corresponding dependence for the minimum power and maximum interval. $\Delta H_2 = 12.9$ kG.

magnetic field on the echo signals was not detected in the sample under consideration. We also investigated the sodium-calcium-silicate glass with Ce^{3+} and Nd^{3+} ion impurities. As a result of the measurements we detected a strong dependence of the echo signal on the magnetic field H (Fig. 2).

In the sample with the Ce^{3+} ions at 4.2 K in the field $H = 0$ we observed two- and three-pulse echo signals with characteristic relaxation times $T_2 = 10^{-6}$ sec and $T_1 = 10^{-5}$ sec. In the field of ~ 100 G both echo signals vanish abruptly and a two-pulse echo appears in the field $H > 8$ kG. At $T = 1.8$ K in the field $H = 0$ T_2 and T_1 increase to 5×10^{-6} sec and 5×10^{-5} sec, respectively, and the amplitude of the echo increases by an order of magnitude.

As a result of application of the magnetic field both echo signals also vanish abruptly. A two- and three-pulse echos appear again with further increase of the field, but with different relaxation times $T_2 = 0.5 \times 10^{-6}$ sec and $T_1 = 0.5 \times 10^{-5}$ sec.

Analogous results were obtained in Pyrex and in a lithium-alumo-silicate glass with Nd^{3+} ions. The signals of the two- and three-pulse echos were also observed in crystallized (heat treated) and in uncrystallized samples of gemmanate glass with Ce^{3+} ions. It is characteristic that the intensity of the echo in a crystallized sample is lower than that in an uncrystallized sample, which is attributable to a decrease in the amount of matter in the glass phase which leads to tunneling. It is interesting to note that the echo signals were observed at such fields H for which the EPR lines were missing.

Moreover, the experiments showed that ΔH (Fig. 2) increases with increasing spacing between the exciting pulses. There is also a weaker dependence of increase of ΔH with decreasing power supply.

The results can be interpreted on the basis of the spectrum of the localized, two-level excitations produced as a result of tunneling transitions. Such a spectrum can be described by using the pseudospin $\hat{T} = 1/2$.[6] In the simplest case of double symmetric potential well the Hamiltonian has the form:

$$\hat{\mathcal{H}} = \Delta \hat{T}_x + a E(t) \hat{T}_z , \tag{1}$$

where Δ is tunnel splitting, $E(t)$ is the transient electric field, and α is the coupling coefficient. For the average values of $\langle T \rangle$ we can use the Bloch equations with T_1 and T_2 corresponding to the longitudinal and transverse relaxation. A Zeeman and spin-phonon interaction occurs in a glass with paramagnetic impurities. It is known that pseudospins do not interact directly with the magnetic field, but a pseudospin-phonon interaction exists. Taking into account all these interactions together with the Hamiltonian (1) for the one-dimensional chain in the long-wave approximation, we obtain an equation for coupled-oscillation frequencies:

$$(\omega^2 - \omega_\phi^2) - \frac{4\epsilon^2 \langle \hat{S}_z \rangle \omega_0 \omega_\phi^2}{K(\omega_0^2 - \omega^2)} - \frac{4\gamma^2 \langle \hat{T}_x \rangle \Delta \omega_\phi^2}{K(\Delta^2 - \omega^2)} = 0 , \tag{2}$$

where $\omega_0 = gBH$, K is the force constant, ϵ and γ are the spin-phonon and pseudospin-phonon coupling coefficients and ω_ϕ is the natural frequency of the lattice mode. It can be seen from Eq. (2) that we have a dependence of the field H and the term containing ω_0 changes its sign at $\omega_0 = \omega$, which corresponds to a complex dependence of the intensity of the echo signal on H (Fig. 2). The damping of the coupled waves differs from pure pseudospin oscillations, which apparently accounts for the observed different relaxation times at $H = 0$ and $H \neq 0$.

In conclusion, we note that the much simpler method of investigation of tunneling in glass, which is based on the use of a microwave echo rather then an acoustical echo, will be used widely in the future in the investigation of amorphous solids.

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