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Effect of Low-Level Radiation on the Low Temperature Acoustic Behavior of *a*-SiO$_2$

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We report on the mechanical behavior of an *a*-SiO$_2$ 84 kHz torsional oscillator operated between $100 \geq T \geq 1.0$ mK. Below 10 mK we observed well-differentiated transient responses which we attribute to the interaction with low-level background radiation (γ quanta and cosmic ray μ) and which can be modeled in terms of a change in the spring constant.

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Understanding the low temperature behavior of glassy systems is important since it pertains to a large class of amorphous (or highly disordered crystalline) matter that displays nearly universal properties [1,2]. In a recent study [3] to examine whether the elastic properties of amorphous solids at low temperatures are consistent with predictions of the "tunneling model" [4,5] we reported briefly on the observation of a stochastic response of the amorphous SiO$_2$ oscillator observed below 10 mK, which we referred to as "noise."

In this Letter, we trace this phenomenon to ubiquitous low-level background radiation. The γ quanta emitted due to the decay of radioactive nuclei in building materials can be shielded from the low temperature environment, but the remainder, which we take to be μ (decay products of cosmic rays) cannot be shielded out and have a surprisingly large effect on the acoustic properties of amorphous solids at low temperatures. We provide a simple model that accounts for the observed response. The phenomenon has implications for measurements on macroscopic insulating solids below 10 mK, as well as for future ultralow temperature experiments.

The Suprasil W sample [3] mounted on its quartz driver comprised a composite torsional oscillator [6] and was installed on our cryostat together with its Nb shield. A number of improvements were incorporated including a thermal shield anchored to the low temperature stage (to intercept suprathermal atoms) and improved signal to noise (to allow measurements without self-heating). In contrast to the results in [3] where data were taken at discrete frequencies, here the drive frequency was either swept through the 84 kHz resonance in ~2000 s, or the oscillator was operated at a fixed drive frequency while recording the response continuously with a lock-in amplifier. We maintained the temperature constant to within a fraction of a μK during data acquisition.

We start by describing our investigation of the characteristics of this unusual phenomenon. The apparently random "transients" superposed on a resonant response (see Fig. 1) could arise from a variety of instrumental or physical sources. After testing for other origins we found that the transients' number could be reduced only by introducing a 5 cm thick lead shielding with 98.5% solid angle coverage around the cryostat. A comparison of the results at 3 mK with and without shielding is shown in the upper two panels of Fig. 1. Examination of the resonances reveals that the transients' occurrence is reduced by approximately a factor of 3 after the introduction of shielding. We show the response of a similar quartz-on-quartz oscillator under the same conditions with shielding in place in the third from the top panel of Fig. 1. No transients are seen in the quartz oscillator's response.

When we examined the response of the oscillator with shielding in place at temperatures between 2.4 and 21 mK (Fig. 1), we found that the Lorentzian response was free of these transients above 10 mK. They were well resolved below 10 mK, displaying ringing that became more long lived as the temperature was lowered. Larger transients are seen near f_0, the resonant frequency, and transients are still visible far from resonance, especially for $f > f_0$. For $f < f_0$, following a transient, the amplitude initially decreases below the expected Lorentzian line, while the excursion is positive for $f > f_0$. The simplest explanation for the transients' origin is an interaction that transfers energy (heat) to the oscillator. Since the sound velocity of a glass (related to the spring constant) increases with temperature due to the presence of two level systems (TLS) [3–5], any temperature rise would stiffen the *a*-SiO$_2$, consistent with these observations. We will argue that the shift manifests a nonequilibrium elevation of the oscillator's temperature.

To explore the nature of the transients we maintained the cryostat at 1.1 mK, and drove the oscillator at two frequencies, f_D, with $\Delta f = f_D - f_0$ set at 0.2 and 0.4 Hz. The lower panel in Fig. 2 shows transients of different sizes followed by ringing at frequency Δf that decay exponentially to the quiescent response at f_D with characteristic time τ_r, independent of the size of the transient. The decay envelope (aside from the initial excursion) is symmetric about equilibrium. In the upper panels we show data acquired during frequency sweeps similar (or identical) to those shown in Fig. 1, at approximately 0.2 Hz from f_0. The values of $\tau_r = 8$ s (7 mK), 12.5 s (3 mK), and 13 s (1.1 mK) are comparable to the τ from the temperature dependent Q's (see Fig. 1).

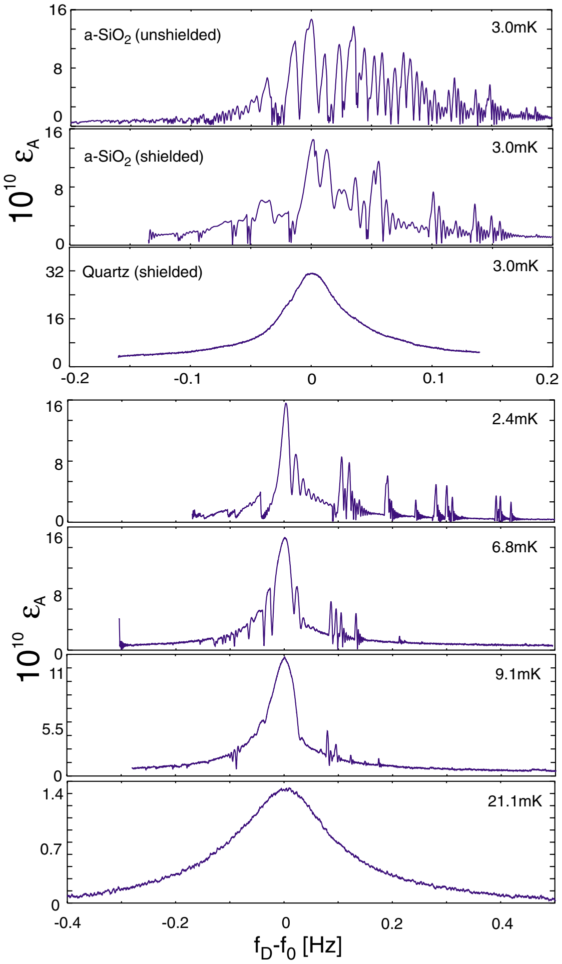

FIG. 1 (color online). The response of the a-SiO$_2$ oscillator without and with lead shielding (top panel and next) as the drive frequency, f_D, is swept through resonance, f_0, at 3 mK. The third panel shows the transient-free shielded quartz oscillator's response at 3 mK. The lower four panels show that noise in the shielded a-SiO$_2$ oscillator's response diminishes with increasing temperature and vanishes above 10 mK. The transients' ringing at low temperatures persists for longer times, and their occurrence is more frequent at $f_D > f_0$. The amplitude at f_0 does not reflect the increased low temperature Q because of interference from transients (e.g., at 2.4 mK).

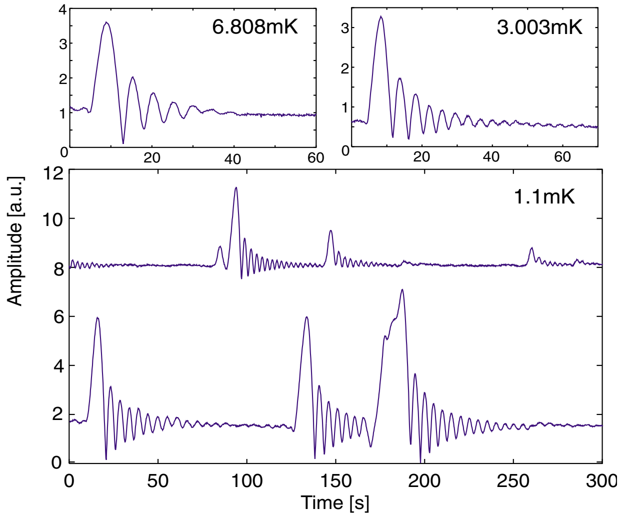

FIG. 2 (color online). Lower panel: Transients observed with the a-SiO$_2$ oscillator driven at $f_D = f_0 + \Delta f$, and $\Delta f =$ 0.2 Hz (lower trace) and 0.4 Hz (upper trace) at 1.1 mK. The upper panels show transients from Fig. 1 with beat frequencies $\simeq \Delta f$. The recovery times, τ_r, are comparable to τ's from the temperature dependent Q's (see Fig. 1).

We decided to characterize the γ background in order to quantify the laboratory radiation. The ambient γ flux between 0.05 and 2.6 MeV ($0.7\gamma/\mathrm{cm}^2\,\mathrm{s}$ after corrections [7]), measured with a 52.6 mm diam × 57.6 mm long Ge detector, is comparable to the $\sim 0.33\gamma/\mathrm{cm}^2\,\mathrm{s}$ recorded with a 25.4 cm diam × 25 cm long NaI detector at Heidelberg over the same energies [8]. We resolved peaks associated with radioactivity in building materials (^{40}K, ^{228}Ac, and ^{208}Tl, the latter two being the daughter nuclei of ^{232}Th) [9,10], and peaks associated with ^{214}Bi, a daughter nucleus of ^{226}Ra. Enclosing the detector in 5 cm thick lead reduced the counts over this energy range by $\sim 30\times$, much larger than the $3\times$ reduction of the transients' in Fig. 1. The discrepancy is due to cosmic ray μ whose deposited energy is ≥ 2.6 MeV (outside our measurement range) and which are not shielded by the lead [11]. We estimate that they strike the oscillator at a rate $\sim 0.024\ \mathrm{s}^{-1}$ [11], comparable to the shielded cryostat value, $0.025\ \mathrm{s}^{-1}$ [12].

The mechanism by which radiation induces acoustic transients in the silica must also account for the absence of transients in the crystalline analog of a-SiO$_2$ quartz. Direct momentum transfer is ruled out because it would superpose a transient response at f_0, the resonant frequency (much like an impact on a bell) on the driven response at f_D, following an interaction with a γ or μ. The lock-in detector referenced to f_D should register the decay of the transient (due to dissipation) with a beat frequency $= | f_0 - f_D |$, consistent with Figs. 1 and 2. Since quartz and a-SiO$_2$ have nearly identical densities (hence scattering cross sections and energy deposited/event) and low temperature Q's (Fig. 1), this mechanism would predict identical responses in the crystalline and amorphous analogs.

An alternative scenario is the photoacoustic effect, in which absorbed radiation creates stress via the expansion coefficient [13]. The main difference between a-SiO$_2$ and quartz is that the former is glassy and, as a consequence of the distribution of TLS, exhibits a sound velocity that varies as $\log T$, while the quartz sound velocity is constant (corresponding to a negligible expansion coefficient [14–16]). Thus the absorption of energy would not create significant stress in the quartz and account for the lack of transients in this material. However, in this scenario, the relative amplitude of the transient response in the a-SiO$_2$ would diminish at larger drive amplitudes since the stored energy is greater, and the stress induced by any absorption event would be identical. Figure 3 reveals no

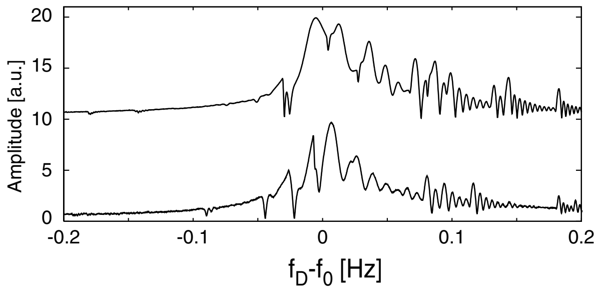

FIG. 3. The normalized (top ×1/4) response at 5.9 mK and 40 mV (upper), 10 mV (lower) drive. The transients do not diminish at higher drive.

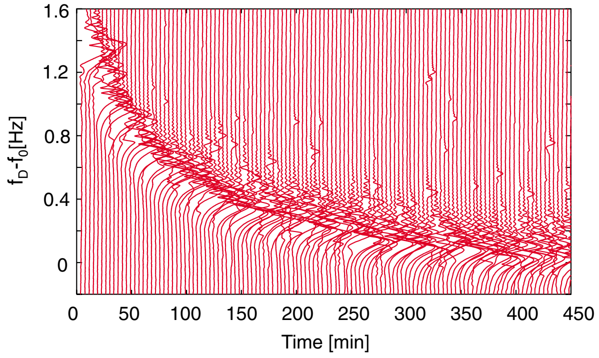

FIG. 4 (color online). A record showing the several hour relaxation time of the oscillator's resonant frequency following long-time exposure of the oscillator to a ^{22}Na γ source at 1.5 mK.

such diminution, eliminating the *conventional* photoacoustic effect as the transients' origin.

We concentrate below on the photoacoustic coupling via the temperature rise that stiffens the elastic modulus after the absorption of energy from the passage of a μ. Assuming as an upper limit that all tunneling states couple to the lattice on the short experimental time scale we use an extrapolation of the linear specific heat measured above 20 mK [17] to estimate the temperature excursion. At 3 mK, the sample heat capacity is $C = 1.9 \times 10^{-9}$ J/K. The energy transferred to the sample is $\sim$2 MeV cm^2/g per charged particle [18], the density of a-SiO$_2$ and quartz is $\sim$2.1 g/cm^3, and the mean track length is $\simeq 1$ cm. Thus, the energy deposited/event is $\sim 10^{-12}$ J producing a temperature rise of 0.5 mK/event. The temperature dependence of the resonance frequency at 3 mK is $\sim$0.4 Hz/mK [19], so the resonant frequency could increase by ≈ 0.2 Hz, comparable to (but smaller than) the range of Δf at which the transients appear in Fig. 1. However, the relaxation of the resonant frequency after heating the oscillator (by over driving or exposure to a γ source) displays a time constant of several hours below 3 mK (see Fig. 4), incompatible with the response seen in Figs. 1 and 2. We conclude that the TLS that are responsible for the temperature dependent behavior must be only weakly coupled to the phonons and are not in thermal equilibrium with the phonon bath following the passage of a charged particle.

Using the phonon (Debye) specific heats for the 0.64 g a-SiO$_2$ ($8.7 \times 10^{-7} T^3$J/gK^4) and quartz actuator ($5.7 \times 10^{-7} T^3$J/gK^4) [1], the temperature rise inferred for the combined phonon bath is $\simeq 40$ mK at 3 mK corresponding to the creation of a "phonon fireball." The phonon bath's recovery time is estimated from the heat capacity at the mean temperature (25 mK) (1.34×10^{-11} J/K) and the thermal resistance 5×10^7 K/W [3] to be 6.5 ms, much shorter than the temperature dependent transient recovery times $\tau_r \sim 10$ s in Fig. 2. We suggest that the latter is related to the oscillator Q, which, at 1 mK is on the order of 4×10^6 [19]. For this frequency (84 kHz), this Q corresponds to a time constant of $\sim$15 s.

Thus we propose the following sequence. A charged particle's passage initiates the release of electrons, depositing energy in the material. This energy is coupled via the electron-phonon interaction into phonons, whose temperature rapidly rises. The thermal expansion coefficient (corresponding to the presence of TLS in a-SiO$_2$) leads to a strain that affects the TLS that are responsible for the temperature dependence of the elastic properties of the a-SiO$_2$, while the temperature independent elastic properties (and negligible expansion coefficient) lead to no transients in quartz. In turn, the TLS are coupled to the strain that would result from an elevated phonon temperature. Only a few TLS with a rapid response would couple and absorb energy leading to a nonequilibrium temperature distribution; however, any temperature rise would produce stiffening and result in transients. Above $\sim$ 20 mK, the a-SiO$_2$ oscillator's Q is low, and the phonon heat capacity is high, reducing the thermal signature on the phonons, along with the strain coupled to the TLS, and leading to a negligible transient. There are parallels to the case of the A-B transition in superfluid ^{3}He, where the deposition of energy can elevate the temperature locally by several mK [20,21].

To model the transients, we simulated the effect of a sudden fractional change, ϵ, in the oscillator spring constant, κ, where $\epsilon = \Delta\kappa/\kappa$ followed by an exponential relaxation with characteristic time τ_κ to its original value, while the oscillator is driven at a frequency f_D:

$$\ddot{x} + \frac{2\pi f_0}{Q}\dot{x} + (2\pi f_0)^2[1 + \epsilon e^{-t/\tau_\kappa}]x = \cos 2\pi f_D t. \quad (1)$$

The model produces a response envelope that decays exponentially with beats whose characteristics depend on the relative magnitudes of τ_κ and $\tau = Q/(\pi f_0) \simeq$ 15 s, the oscillator's decay time at 1.1 mK (corresponding to a $Q = 4 \times 10^6$). In Fig. 5, we show the results of the model which can be compared to the experimental results at 1.1 mK shown in Fig. 2. Figure 5(a)–5(c) show the modeled response for $\tau_\kappa = 5\tau$, $\tau_\kappa = \tau$, and $\tau_\kappa = 0.2\tau$.

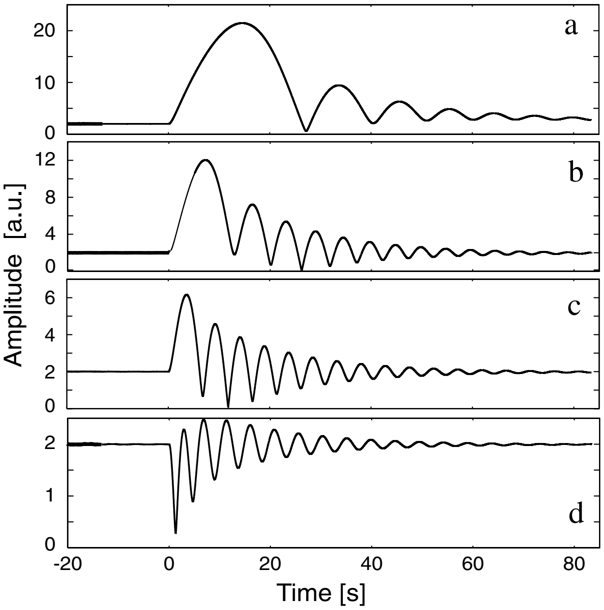

FIG. 5. Simulations of Eq. (1) with the oscillator driven at $f_D > f_0$ and $\tau_\kappa = 5\tau$ (a), $\tau_\kappa = \tau$ (b), and $\tau_\kappa = 0.2\tau$ (c). The observed transients in Figs. 1 and 2 correspond closely to (c) for $f_D > f_0$. The result (d) with $\tau_\kappa = 0.2\tau$ and $f_D < f_0$ corresponds to transients seen in Fig. 1 for $f_D < f_0$.

These simulations were obtained with realistic parameters, $f_D = 1.000\,002\,5 f_0$ (i.e., $\Delta f = 0.2$ Hz), $Q = 4 \times 10^6$ (the fitted value at 1.1 mK), and $\epsilon = 5 \times 10^{-6}$ (chosen to obtain a good fit for the initial excursion). For Figs. 5(a) and 5(b), the beat frequency varies and the transient displays a pronounced asymmetry to above the undisturbed response, while for $\tau_\kappa = 0.2\tau$ [Fig. 5(c)] the beat frequency is $\simeq (f_D - f_0)$ [22]. We rule out the first two cases on account of the nearly symmetric ringing about the equilibrium response seen in Fig. 2. This picture is clearly inconsistent with $\tau_\kappa = \tau$ and $\tau_\kappa = 5\tau$, and we conclude that $\tau_\kappa < \tau$. This is reinforced by the simulation with $\tau_\kappa = 0.2\tau$ and $f_D = 0.999\,997\,5 f_0$ [Fig. 5(d)] that exhibits a *negative* initial excursion identical to the response observed for $f_D < f_0$ in Fig. 1

The presence of cosmic ray by-products invoked to explain the residual heat leak to large nuclear cryostats [23] and the nucleation of the *A*-*B* transition have been graphically observed in this experiment. Besides the obvious heat deposition by γ radiation and μ the potential for other significant effects (such as those seen in this experiment) must be considered in the future.

To summarize, we conclusively show that transients observed in measurements of acoustic properties of a-SiO$_2$ are caused by interactions with low-level radioactivity and high energy charged particles whose passage causes a rapid heating of the lattice creating a phonon fireball. Some of this energy is transferred via strain and without thermal equilibration to the tunneling states, stiffening the elastic modulus. We provide a simple model that calls for a rapid increase (followed by decrease) of the elastic modulus and accurately reproduces the transients in phase, magnitude, and beat frequency. These observations demonstrate potential problems from background radiation in insulating solids at mK temperatures.

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