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Acoustic Properties of an Amorphous Silica Oscillator at mK Temperatures

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We have studied the acoustic behavior of an a-SiO_2 composite torsional oscillator in the temperature range between 1 and 100mK. At higher temperatures, the acoustic properties of amorphous solids are well described by the 'tunneling model'. However, below 10mK it was found that the resonance exhibited a non-Lorentzian shape and was highly distorted by random 'noise'. We attribute this stochastic noise - 'transients' to interactions of a-SiO_2 with ambient γ quanta present in the laboratory. By shielding the cryostat with a 5cm thick lead wall we were able to reduce the number of transients. On the other hand, a deliberately introduced 6.1μCi ^{22}Na source of γ radiation caused the opposite effect. We interpret the transients in the framework of local heating caused by the interaction between photons and amorphous SiO_2 which changes the elastic properties of the oscillator. Our findings have potential applications for particle detection.

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1. INTRODUCTION

The universal properties of amorphous solids at temperatures below 1K were first noted by Zeller and Pohl[1] and are well described by the phenomenological tunneling model (TM)[2,3]. In this model, it is assumed that atoms or groups of atoms have two nearly equivalent equilibrium positions and tunneling takes place between these two states. Tunneling states are characterized by the energy asymmetry Δ and the tunneling splitting Δ_0 and have a broad energy distribution in contrast to doped crystals[4].

In the recent publication of Thompson *et al.*[5] novel features were reported in the acoustic properties of amorphous silica at mK temperatures. From the sound velocity it was inferred that there is a low temperature cut-

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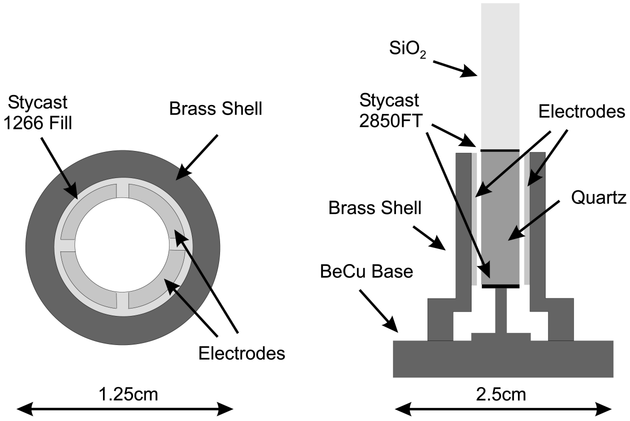

Fig. 1. View of the electrodes (left) and the torsional oscillator (right).

off, Δ_{0min} in the energy distribution of tunneling states. However, using the torsional oscillator technique[6], it was extremely difficult to carry out the measurements below 10mK since the resonator revealed an unexpectedly high level of 'noise' in the form of random variations in amplitude while operating the oscillator near resonance at fixed frequencies (to map out the resonance). We have re-installed the oscillator in our cryostat and in this paper, we report on the acoustic behavior of an amorphous SiO_2 torsional oscillator at temperatures down to 1mK.

2. EXPERIMENT

We have used a composite torsional oscillator identical to those described by Cahill and VanCleve[6] schematically shown in Fig.(1). The lower part is the cylindrical quartz actuator with its X axis oriented along the torsion axis. The upper part is an amorphous SiO_2 sample (Suprasil - W, $<$5ppm OH^- impurities). Both parts are 4mm in diameter and $\sim$22mm long and were glued together using Stycast 2850FT epoxy that was also used to attach the oscillator to the BeCu pedestal. Gold electrodes were evaporated on the quartz surface and alignment during assembly ensured that the electrodes on the quartz matched the electrodes on the brass shell. We used an AC bridge to drive and detect the resonant signal. The oscillator was installed on a $PrNi_5$ nuclear demagnetization cryostat whose temperature was varied between 1 and 100mK and monitored with a ^{3}He melting curve thermometer. A high stability programmable power supply allowed us to maintain the temperature within a fraction of a μK during a sweep.

3. RESULTS AND DISCUSSION

In contrast to the previous measurements where the data were taken at fixed frequencies[5], in our experiments the drive frequency (~84kHz) was swept through resonance. Sweeps at different temperatures are shown in Fig.2. At higher temperatures (21.1mK in Fig.2) the resonance is free of 'noise'. At lower temperatures, the resonance revealed more distortion by transients. In comparing between the a-SiO_2-on-quartz resonator, the quartz-on-quartz (pure crystalline) oscillator didn't show any transients at any temperature down to 1mK. The upper right panel in Fig.2 depicts a typical recovery from a transient.

After thorough analysis of various instrumental origins for these transients, we have found that the only way to reduce the level of 'noise' was to introduce a layer of 5cm thick lead shielding surrounding the cryostat. The introduction of lead shielding reduced the number of transients by a factor of three and suggested that the SiO_2 oscillator is sensitive to the ambient low energy γ radiation present in the laboratory. To verify the effect of γ radiation on the behavior of the oscillator, we introduced a variable thickness aperture in the lead shielding and irradiated the sample with a 6.5μCi ^{137}Cs (0.662MeV photons) source. Fig.3 shows the spectra before and during the irradiation.

Two effects of γ irradiation can be seen in Fig.3. Firstly, there is an overall increase of the resonant frequency consistent with the overall temperature increase of the sample[5]. Secondly, the number of transients increased significantly. To quantify the effect of γ radiation we operated the torsional oscillator as a radiation detector. At a fixed temperature we drove the resonator at a fixed frequency difference Δf=f_D-f_0, where f_0 is the center frequency obtained from a phase plot and f_D is the drive frequency. We used a 6.1μCi ^{22}Na source to irradiate the oscillator and changed the lead thickness intervening between ^{22}Na and the SiO_2 sample. During the experiment we maintained a fixed temperature of 5.9mK. The number of transients as a function of intervening lead thickness is shown in Fig.4.

^{22}Na decays emit 1.8 photons (on average) of 0.511MeV energy and 1 photon of 1.275MeV[7]. We measured the photon flux at room temperature with a Ge detector and found an exponential attenuation length in lead of 0.55cm for the low energy photons and ~1.5cm for the photons with higher energy. The frequency of transients observed, see Fig.4, revealed a characteristic attenuation length λ=1.8cm, close to the value measured by the Ge detector for 1.275MeV photons.

The most trivial mechanism responsible for the transients would be the direct transfer of incoming energy (γ radiation) to electrons and then

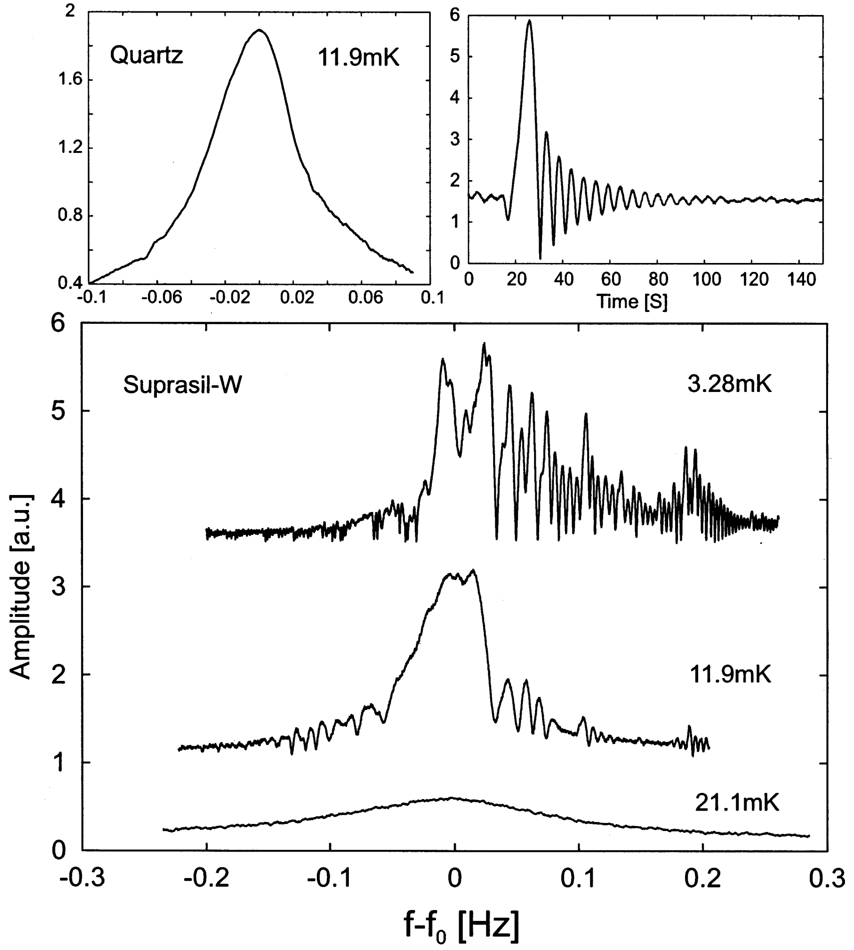

Fig. 2. The oscillator response as the drive frequency is swept through resonance in ∼2000s. The frequencies are offset by the temperature dependent resonant frequency, f_0. Three lower spectra show the resonance as a function of temperature. The amplitude scales with Q which is temperature dependent. The resonance at 21.1mK is free of 'noise'. As the temperature is decreased the effect of 'noise' became more significant. The upper left panel shows the quartz-on-quartz resonance which is free of 'noise'. The upper right panel depicts a typical recovery from a transient with a characteristic recovery time (decrease to 37% of maximal amplitude) of ∼15s. The X-axis units are the same for the main and the upper left figure. The Y-axis shows the amplitude of the response (in arbitrary units) in all three panels.

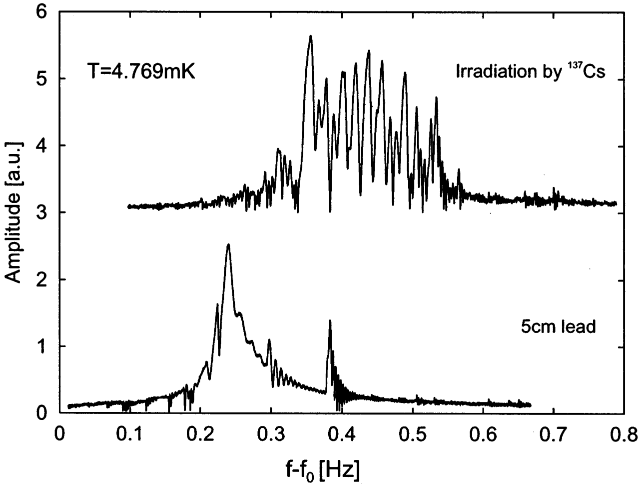

Fig. 3. The effect of γ radiation on the resonance. The lower trace was taken with lead shielding in place while the upper panel shows the resonance shape during irradiation with a 6.5μCi ^{137}Cs source. f_0=84058.1Hz.

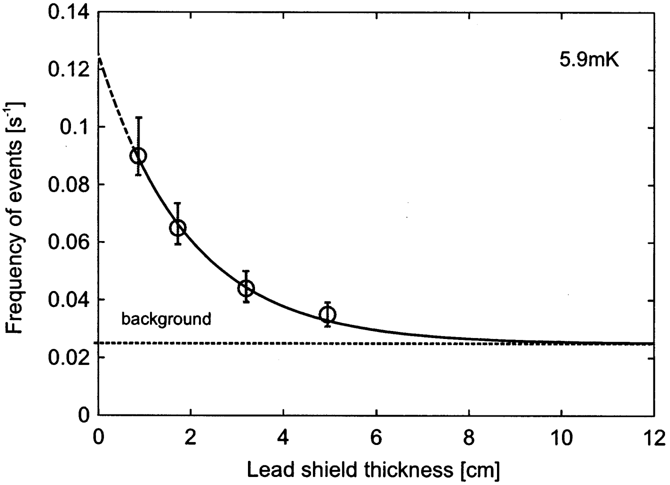

Fig. 4. The frequency of transients as a function of lead thickness in the aperture between the ^{22}Na source and the SiO_2 sample. The solid curve shows an exponential dependence with attenuation length, λ=1.8cm that merges the background rate of $0.025s^{-1}$ observed with no ^{22}Na. The point at zero thickness of lead and full exposure to the ^{22}Na source was not resolved accurately because the inverse frequency of transients exceeded their decay time.

to phonons in the amorphous silica, causing the heating of the sample and consequently increased resonant frequency. Using the Debye specific heats ($8.7\text{x}10^{-7}T^3$J/gK^4 for the 0.64g a-SiO_2 and $5.7\text{x}10^{-7}T^3$J/gK^4 for the quartz actuator[1]), the temperature rise for the entire phonon bath would correspond to ~20mK. The phonon bath's relaxation time, (~1.4ms) can be calculated from the specific heat and the thermal resistance values[5] and is four orders of magnitude smaller than the observed transient recovery times τ ~15s (see Fig 2). On the other hand, the actual thermal relaxation time following removal of the γ source is $\geq$1000s below 5mK. We believe that the recovery from transients is related to the oscillator quality factor Q, which, at 1mK is on the order of $8\text{x}10^6$ and corresponds to a time constant of ~30s. The two level systems (TLS) that are responsible for the temperature dependent behavior of an amorphous glass, are weakly coupled to the phonon bath and only part of the incoming energy is transferred to the tunneling states[8]. As a result, we infer that the spring constant of a composite oscillator changes locally giving rise to transients. This effect can be interpreted as a local heating of the sample.

In summary, we have operated a composite a-SiO_2-quartz torsional oscillator at temperatures down to 1mK. We find that stochastic noise visible at temperatures below 20mK originates from the interaction of energetic γ quanta with the a-SiO_2. We believe that the mechanism responsible for transients is the local change of the spring constant. Our observations demonstrate the potential application of amorphous materials for the detection of energetic particles.

ACKNOWLEDGMENTS

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