Anomalous Temperature Dependence of the Sound Velocity of Amorphous Silica below 3 mK

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Abstract. The sound speed $\Delta V/V_0$ of amorphous silica between 1 and 30 mK was measured using a double paddle oscillator, cut with a laser from a 0.4 mm thick plate of vitreous silica. The oscillator was operated at four of its resonant modes between 610 Hz and 14 kHz. Above 3 mK and up to the maximum of $\Delta V/V_0$, the sound speed exhibits the logarithmic temperature dependence predicted by the tunneling model with the slope $C = 2.4 \times 10^{-4}$, varying by a few percent between the various modes. Below 3 mK, the sound speed departs from the logarithmic dependence and levels off. This can be explained either by a large heat input (>10^{-3} nW/g) of unknown origin or by a low energy cut off, E_{min}, in the density of tunneling states of 1.5 mK.

Keywords: glasses, tunneling model
PACS: 61.43.Fs, 62.65.+k

INTRODUCTION

The properties of glasses below 10 K are thought to be successfully explained by the Tunneling Model (TM). In this model, unknown entities tunnel between potential wells with nearly equal potential energy minima. The parameters describing the potential energy function are assumed to have a broad distribution since there are many possible configurations for the atoms of a glass. Furthermore, a constant density of tunneling states is assumed [1, 2].

Below 100 mK, several discrepancies between the TM and the observed behavior of glasses have been noted. In this paper, we describe a further discrepancy. While the TM predicts that the sound speed in glass should decrease logarithmically near absolute zero, a leveling off from the logarithmic dependence was observed below 3 mK.

RESULTS AND DISCUSSION

The sound speed in glass was measured using a double paddle oscillator nearly identical to the small oscillator described in [3]. One surface of the oscillator was coated with a silver film 1.1 μm thick. This aided in the cooling of the glass and also formed an electrically conductive surface for capacitive drive and detection. Four dominant modes of oscillation were identified at 0.61, 1.0, 3.7, and 14 kHz.

Figure 1 displays the sound speed $\Delta V/V_0$ versus the temperature of the nuclear stage for the 14 (○), 3.7 (□), 1.0(+), and 0.61(∗) kHz modes. Above 3 mK, each resonant frequency varies logarithmically with temperature, which agrees with the TM. Figure 1 also displays 14 and 1.0 kHz sound speed measurements made on a nearly identical oscillator as described in [3]. Contrary to Fig. 4 in [3], the slopes of the curves, C, from the present experiment show only slight variations with frequency above 3 mK. While the slope of the 14 kHz curve from [3] is the same as the slope of the 14 kHz curve from the present experiment between 3 mK and the maximum in $\Delta V/V_0$, the slopes of the 1.0 kHz curves from the two experiments are not the same in this temperature range.

A constant heat input can explain the leveling off displayed by our data below 3 mK from the logarithmic decrease in the sound speed predicted by the TM, $\Delta V/V_0 = C \ln(T/T_0)$, where C is the tunneling strength, T is the temperature of the oscillator, and T_0 is an arbitrary reference temperature. We measured the thermal resistance, $R_{th} = 5.62 \times 10^4/T^{1.54}$ [K/W] (T in K)

CP850, *Low Temperature Physics: 24th International Conference on Low Temperature Physics;*
edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirschfeld, and A. M. Goldman

using the heat deposited in the silica from a cobalt source placed outside the cryostat. Any heat deposited

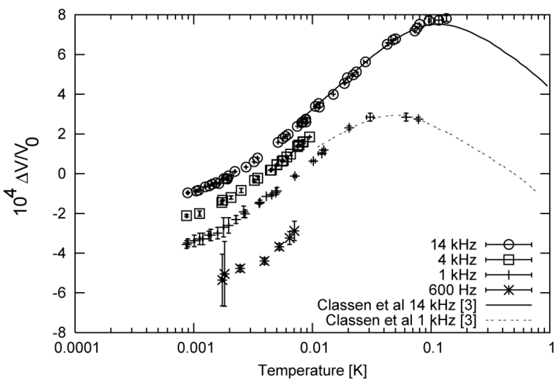

FIGURE 1. Sound speed in silica measured with a paddle oscillator at 14, 3.7, 1.0 and 0.61 kHz and with a nearly identical paddle oscillator [3] at 14 and 1.0 kHz. The temperature is that of the nuclear stage, T_s.

in the glass elevates the temperature of the oscillator (T) relative to the nuclear stage (T_s). To reconcile the TM with the data below 3 mK, we used the measured value of R_{th} to relate T_s to T for a heat input $\dot{Q}$. Thus, $\Delta V/V_0 = C\ln(T/T_0)$ can be written in terms of T_S as

$$\frac{\Delta V}{V_0} = C\ln\frac{\left(1.43\times10^5\,\dot{Q}+T_S^{2.54}\right)^{\frac{1}{2.54}}}{T_0}\,. \qquad (1)$$

A similar leveling off of the sound speed in silica observed in [4] was explained in terms of a $\dot{Q}$ of 10^{-4} nW/g (1000 h after cooling down to the mK range), only partially attributable, via the inverse time (t^{-1} behavior) to internal heat release. Eq. 1 also fits the data in Fig. 1 well, but requires a heat input $\dot{Q} > 3\times10^{-3}$ nW/g (Table 1), more than an order of magnitude too large to be ascribed to internal heat release. Scatter due to noise in the 610 Hz data precluded good fits. No strain heating was observed in the present experiment, and the heating due to radiation from building materials and cosmic rays [4] is negligible compared to the required $\dot{Q}$. Conceivably vibrations of the cryostat and sample could produce a $\dot{Q}$ of this magnitude but running the experiment with an empty 1 K pot (to reduce vibrations) did not significantly affect the sound speed. A new experiment in which a mechanical filter is introduced to further isolate the oscillator is currently underway.

A more likely explanation for the leveling off is a low energy cut off in the density of states, E_{min}. As in previous experiments [5], we assume that $\dot{Q}$ is so small

TABLE 1. Parameters required to obtain a satisfactory fit of the data measured (at 14, 3.7, and 1.0 kHz) with a silica paddle oscillator to the TM model [1].

Resonance Frequency	$\dot{Q}$ [nW/g]	E_{min} [mK]
1.0 kHz	3.1×10^{-3}	1.32
3.7 kHz	3.9×10^{-3}	1.43
14 kHz	5.9×10^{-3}	1.66

that there is no significant difference in temperature between the nuclear stage and the oscillator. A good fit to the data was then obtained using the expression given in [5] for sound speed in terms of a low energy cut off. The best fit values for the low energy cut off in the present experiment are given in Table 1 and are seen to be significantly less than the roughly 6 mK obtained in [5]. It has since been shown [4] that the leveling off due to a low energy cut off was probably masked in [4,5] by leveling off due to a $\dot{Q}$ and the large thermal resistance of that experimental arrangement. However, the decreased thermal resistance of the sample in the present experiment has reduced the possibility for thermal decoupling and has revealed evidence for a departure from the logarithmic behavior of the TM manifested as a low energy cut-off, $E_{min} \approx 1.5$ mK.

ACKNOWLEDGMENTS

We thank E. N. Smith, E. Nazaretski, and D. Finkelstein Shapiro for their help with this experiment. Support was provided by the NSF under DMR-0202113 and by the Cornell Center for Materials Research under DMR-0079992.

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