

Internal-friction anomalies in crystalline hydrogen

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Anomalous features have been detected in the low-frequency internal friction in crystalline $n\text{-H}_2$ at low temperatures. These features are peaks at $T \approx 5.5$ and 9 K, an increase in the internal-friction background at $T < 8$ K with decreasing temperature, and a low and relatively constant shear modulus in the interval 2–12.5 K. The features seen in the low-frequency internal friction in hydrogen which are also seen in solid argon are attributed to an increase in the mobility of defects at low temperatures.

The method of the low-frequency internal friction, which provides extensive information on plastic deformation, phase transitions, diffusion, and structural defects of crystals, has previously been used to study internal friction only in crystalline argon.^{1,2} For quantum cryogenic crystals such as solid hydrogen, the literature reveals no such information. Studies of the creep^{3–5} of solid $n\text{-H}_2$ ($T_m = 13.96$ K) have shown that quantum fluctuations play an important role in the plastic deformation of this cryogenic crystal. In the present letter we report a study of the low-frequency internal friction of solid $n\text{-H}_2$ over the temperature interval 2–12.5 K. The samples are free-standing polycrystalline samples of 99.99%-pure hydrogen whose grains have linear dimensions of 0.5–2 mm. The samples are synthesized at a crystallization rate of 0.3–0.5 mm/min. After growth at 11–12 K, a sample is peeled from the cell wall by evacuation and then annealed for ≈ 1 h. According to Ref. 2, this procedure is sufficient to remove the internal stress and defects resulting from the crystal growth. The low-frequency internal friction of $n\text{-H}_2$ is studied by the method of an inverted torsional pendulum, described in Ref. 2, with free samples. The length of the working region is 30 mm, the diameter is 4 mm, and the strain amplitude is 5×10^{-5} .

Our results show that there is no amplitude dependence of the low-frequency internal friction in solid hydrogen anywhere in the temperature region studied. On the temperature curve of the internal friction, $Q^{-1}(T)$, in solid hydrogen (Fig. 1), we see some characteristic peaks in the interval $(0.14\text{--}0.93)T_m$, at $T_1 \approx 5.5$ K ($\approx 0.4T_m$) and $T_2 \approx 9$ K ($\approx 0.64T_m$).

Figure 2 shows the temperature dependence of the square of the frequency, $f^2(T)$, which is known to be proportional to the shear modulus $G(T)$. We see that in the temperature interval 2–12.5 K the square frequency f^2 varies only slightly. As the temperature is lowered in the interval 12.5–7 K, f^2 increases by 13%, while below 5 K it decreases by 10%. On the curves of $f^2(T)$ there are inflection points corresponding to peaks in the low-frequency internal friction.

To explain the structural features in the low-frequency internal friction in H_2 , we compare it with argon^{1,2} ($T_m = 83.75$ K), which is known to be a "classical" cryogen-

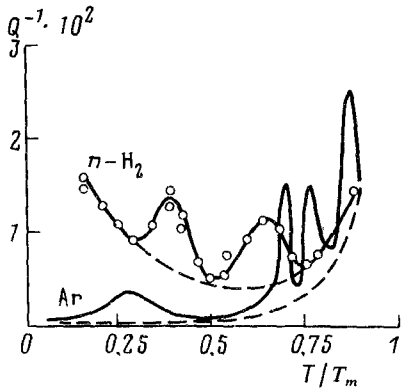


FIG. 1. The low-frequency internal friction of crystalline Ar and $n\text{-H}_2$ versus the reduced temperature T/T_m .

ic crystal. Figures 1 and 2 also show data on the temperature dependence of the low-frequency internal friction and the square frequency $f^2(T/T_m)$ for argon. On the temperature curve of the internal friction in Ar and H_2 there are two regions, below and above $0.5T_m$. In the high-temperature region, hydrogen behaves in the same way as argon; the background level of the low-frequency internal friction increases as the temperature is raised to $0.9T_m$. The activation energies of the high-temperature peaks in H_2 and Ar, estimated by the method described in Ref. 2, are $U \approx 200$ K and 1500 K, respectively, close to the activation energies for self-diffusion in H_2 and Ar. In the low-temperature region ($0.5T_m$), on the other hand, there are several features in the behavior of $n\text{-H}_2$, which distinguishes it from the Ar. In the first place, the background of the low-frequency internal friction in $n\text{-H}_2$ increases as the temperature is lowered, from 4×10^{-3} at 7 K to 1.5×10^{-2} at $T = 2$ K, whereas for argon the internal-friction background remains essentially constant over the temperature and comparatively low (below 10^{-3} ; Fig. 1). As was mentioned in Ref. 2, the low-temperature peak in argon corresponds to the temperature at which the Peierls mechanism for plastic deformation begins to operate intensely ($U = 0.1E_c$). The activation energy of the low-temperature peak in hydrogen is $0.3E_c$, close to the results on stress relaxation in hydrogen.⁸ It follows from those results that at $T < 5$ K the mechanism for plastic

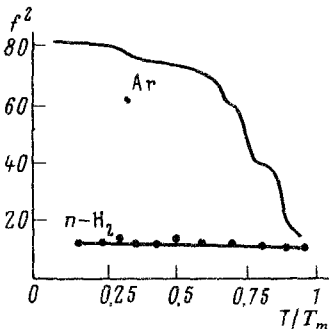


FIG. 2. The dependence $f^2(T/T_m) \sim G(T/T_m)$ for crystalline $n\text{-H}_2$ and Ar.

deformation changes, and the plasticity of normal hydrogen decreases. However, the increase in the background of the low-frequency internal friction at low temperatures, which was described above, conflicts with this suggestion regarding the decrease in the plasticity of hydrogen. In argon at $T < 0.5T_m$, one observed a sharp decrease in plasticity due to an "absolute" brittleness,⁹ which causes a decrease in the internal-friction background. A characteristic feature of the internal friction of hydrogen is that the average relaxation time τ_{av} is essentially the same for the low-temperature and high-temperature peaks, whereas in Ar this time increases with decreasing temperature of the peak. The large height of the low-temperature peak, its large degree of relaxation in comparison with that of the high-temperature peak (a factor of 1.3), the increase in its half-width (by a factor of 2), and the increase in the internal-friction background imply an increase in the intensity of relaxation processes with decreasing temperature in the crystalline hydrogen, in contrast with the situation in Ar, where the degree of relaxation and the magnitude of the internal-friction background decrease sharply with decreasing temperature and are considerably lower than in hydrogen. Yet another important systematic feature of hydrogen is the anomalous behavior of the shear modulus, $G(T) \sim f^2$, in the temperature interval $(0.15-0.95)T_m$. Figure 2 shows, in reduced coordinates, the temperature dependence of the average values of f^2 for hydrogen and argon. The values found for G_0 by extrapolating to $T = 0$ the temperature dependence of the shear modulus $G = \rho v_t^2$ according to the data of Ref. 10 differ in the same way as the values of $f^2(0)$ for these cryogenic crystals.

Interestingly, the values of $f^2(T)$ for hydrogen remain essentially constant as the temperature is varied (in contrast with the behavior in argon), remaining at a constant level of about $f^2(0)$. The absolute values of f^2 in hydrogen are an order of magnitude lower than in argon. The anomalies found in the low-frequency internal friction in crystalline hydrogen in these experiments appear to be caused by a delocalization of defects, which intensifies the internal friction in quantum crystals, as was shown in Refs. 11 and 12.

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