Search for superfluidity in hcp ^{4}He

D. J. Bishop and M. A. Paalanen
Bell Telephone Laboratories, Murray Hill, New Jersey 07974

J. D. Reppy
Department of Physics, Cornell University, Ithaca, New York, 14853

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We have measured the moment of inertia of hcp ^{4}He crystals from 25 mK to 2 K. With a precision of five parts in 10^6 we find no evidence for a nonclassical rotational inertia. This indicates that if a supersolid exists, it has a ρ_s/ρ of less than 5×10^{-6}, a transition temperature of less than 25 mK, or a critical velocity of less than 5 μm/sec.

The last decade has seen considerable theoretical speculation on the existence of a supersolid phase in a quantum solid.[1–17] However to date there has been no experimental observation of such a phase.[18–21] This report describes another search for a supersolid phase in hcp ^{4}He using a high-Q mechanical oscillator to measure the density of a single helium crystal. This search differs from previous attempts in that it directly measures the moment of inertia of the helium crystal. Earlier investigations have looked at the movement of an iron mass[18,19] through solid ^{4}He or looked for mass flow between two chambers filled with solid connected by a superleak.[21] Leggett has argued[4] that a supersolid will have the property of a nonclassical rotational inertia (NCRI). Our experiment directly measures the inertia of a helium crystal and is the first one to provide a direct way to observe any NCRI if it exists. The fact that we see no evidence for NCRI indicates that if a supersolid phase exists it has a superfluid density ρ_s/ρ of less than 5×10^{-6}, a T_c of less than 25 mK or a critical velocity of less than 5 μm/sec. This experiment defines the sensitivity and temperatures required for any future search for the supersolid phase in hcp ^{4}He crystals.

The measurement used the high-Q torsional oscillator technique developed by Reppy and coworkers at Cornell.[22] The cell (shown in the insert in Fig. 1) consists of a hollow spherical ball connected to a mounting base by a small-diameter hollow torsion rod. The base, torsion rod, and cell bottom are machined from a solid piece of BeCu and then heat treated to achieve the maximum Q. A cap is then soldered into place to form the spherical ^{4}He chamber. The cell was driven and its amplitude detected electrostatically using the electrode structure mounted on its top. The cell oscillated in its fundamental torsional mode. The cell was run in a feedback loop at its resonant frequency and the system had a frequency stability of one part in 10^8 and a Q of $\sim 10^5$. The empty cell had a resonant period of 1480 μsec. The torsion rod had an inside diameter of 0.41 mm, and outside diameter of 1.02 mm and a length of 9.5 mm. The spherical cavity had an inner diameter of 9.5 mm. Crystals of hcp ^{4}He were grown using the blocked capillary method in the cell and were carefully annealed just below the melting temperature for several hours to assure that we had large single-crystal regions for our measurements.

An example of the data we have obtained is shown in Fig. 1. We show the empty-to-full-cell period shift $\Delta\tau$ for a solid hcp ^{4}He crystal at 30 bars. Shown are data for two different average cavity velocities, 50 μm/sec(0) and 5 μm/sec(Δ). The ^{4}He used in the experiment was later analyzed and found to contain

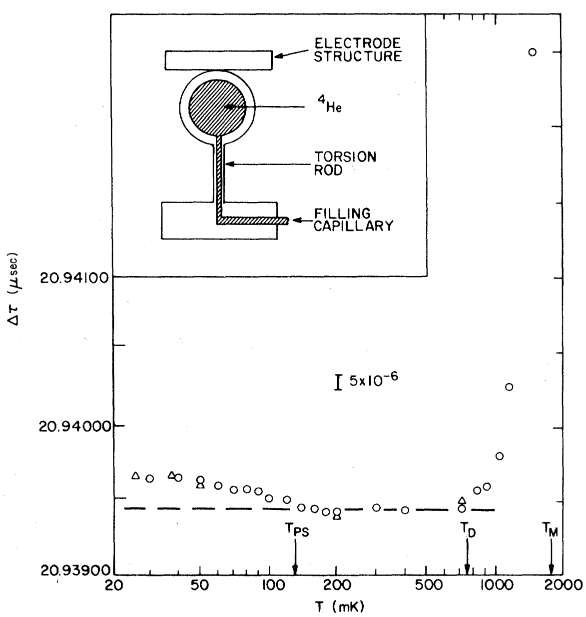

FIG. 1. The experimental cell is shown (insert) and the period shift $\Delta\tau$ as a function of temperature. The measurements were performed at an average cell velocity of 50 μm/sec (0) and 5 μm/sec (Δ).

411 ppm ^{3}He. The temperature marked T_{PS} is where phase separation should occur for a solid mixture of this concentration. The phase-separated mixture has a somewhat higher pressure than the fully mixed phase. This causes an elastic expansion of the spherical cell and the higher moment of inertia. The point labeled T_M is where the crystal melts. Also labeled in the figure is T_D. At this temperature the ^{3}He impurities boil off the dislocation lines which unpin the lines. The lines are then free to bend and this elastic dislocation motion can reduce the shear modulus up to 40%. This reduction of the shear modulus of the ^{4}He in the torsion rod itself causes an increase in the resonant frequency of the cell. This phenomenon is not related to density changes of the ^{4}He in the spherical chamber. Using a cell in which ^{4}He is contained only in the torsion rod we have studied at length this dislocation motion in hcp ^{4}He and our results are presented elsewhere.[23]

The key result to be obtained from data such as shown in Fig. 1 is that to within an accuracy of five parts in 10^6 we see no evidence for any nonclassical rotational inertia. We can see phase separation of the solid, dislocation motion and finally melting of the crystal but we see no NCRI. We have studied other ^{4}He crystals at different pressures (25–48 bars) and other ^{3}He concentrations (down to 0.3 ppm) and have seen no evidence for a supersolid phase.

One may draw one of several conclusions from our results. A supersolid, if it exists in ^{4}He might have a T_c or less than 25 mK, a ρ_s/ρ of less than 5×10^{-6}, or a critical velocity of less than 5 μm/sec. A fourth possibility is that a supersolid may exist in regions of the PT plane already examined but that it is not accompanied by any anomalous mass flow or NCRI. For example, Cheng[17] has suggested that neutron scattering might be used to probe for the existence of a supersolid. Thus experiments performed to date might not have been sensitive to this phase while future neutron scattering or other probes might still discover a supersolid.

In conclusion we have measured the rotational inertia of solid ^{4}He crystals with a precision of five parts in 10^6 down to a temperature of 25 mK. We have failed to observe any NCRI which might indicate the existence of a supersolid. Despite the null result we feel that this measurement provides a useful piece of information in that it places severe constraints on the regions where a supersolid might be found to exist.

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