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Phonon Mediated Helium Atom Transmission through Superfluid Helium Four

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We report results of experiments in which pulses of helium vapor with translational energies of 3 K are directed at a thin film of superfluid helium at a temperature of about 0.2 K suspended over a cesium covered orifice in a platinum film. The response of the superfluid film was detected by a superconducting titanium bolometer placed on the side of the film opposite to that of the source. For films of approximately 1 mm in thickness we find no response of the bolometer within the limits of our detector. However, for films of less than 100 μ thickness, we find a response which is of the same temporal shape, but smaller in amplitude, than that of the orifice when it is not covered with superfluid helium. We interpret these results to mean that we are seeing phonon mediated transmission in the thin films. Roton and condensate mediated transmission amplitudes for these conditions are apparently too small for us to detect in any of the films. This result is consistent with the theoretical results of Sobnack and Inkson [M. B. Sobnack, J. C. Inkson, and J. C. H. Fung, Phys. Rev. B 60, 3465 (1999)] concerning the amplitude of roton to atom and photon to atom conversion as a function of the atomic energy.

***KEY WORDS*:** Superfluid; suspension; transmission; phonons.

1. INTRODUCTION

We are engaged in a program to test the proposal[1–4] that Bose Einstein condensation in superfluid helium permits anomalously fast reemission of atomic helium particles incident on the superfluid surface, at superfluid surfaces far from the point of impact of the incident particles. Others[5] have carried out experiments in which the superfluid is moving in the laboratory and the atomic helium vapor is stationary. Here we report results from an experiment in which the superfluid is stationary in the laboratory and the translational kinetic energy of the vapor is substantially less, relative to the superfluid, than it was in the experiments of Ref. 5. (Williams and Wyatt[6] have recently reported experiments somewhat similar to ours in which multiple samples of superfluid suspended by a different method were used. We discuss these below.) We find reemission of atoms from a surface of the superfluid which is a macroscopic distance away from the surface on which the atoms are incident on the superfluid. However, the remission was observed when the distance was estimated to be of the order of $10^2\,\mu$ and disappeared when that distance was increased to about a millimeter. We will suggest that these results are consistent with a phonon mediated transmission mechanism. The amplitudes for roton and condensate mediated transmission were apparently below our detection limits. With regard to rotons, these results appear to be consistent with recent calculations[7] of the roton-atom amplitude as a function of energy, as we will discuss.

The next section describes the experiments, the third section presents an analysis and the last section contains conclusions and discussion.

2. EXPERIMENTS

We show a diagram of the cell in which the experiments have been carried out in Fig. 1. It is similar to the cell in which atomic pulsed beam experiments reported previously[8] were done except that an "inner can" has been added with a small $(50\,\mu)$ orifice in the bottom and equipped with a pair of capacitors for measuring the depth of liquid helium in the bottom of the inner can. The two capacitors have similar capacitances, and are used in a bridge formation with the upper capacitor used as a reference for the lower liquid helium level measuring capacitor. As in our previously reported suspension experiments,[9] we made use of the property that superfluid helium does not wet cesium. By covering the region around the orifice in the platinum disc with cesium, the superfluid helium film at the bottom of the inner can could form a meniscus across the orifice that suspends a film through surface tension. A full analysis of this phenomenon and experimental proof that it occurs is reported in Ref. 9. In the experiment reported here, "boats" containing a cesium salt were mounted below the orifice so that cesium could be deposited on the surfaces around the orifice after the cell was cooled. As in our previous atomic pulsed beam experiments[8, 10] there is a source of helium vapor pulses and a bolometric detector capable of detecting them. In the apparatus used in the experiments reported here, the source was mounted below the orifice at the bottom of the inner can on a shield designed to protect the source

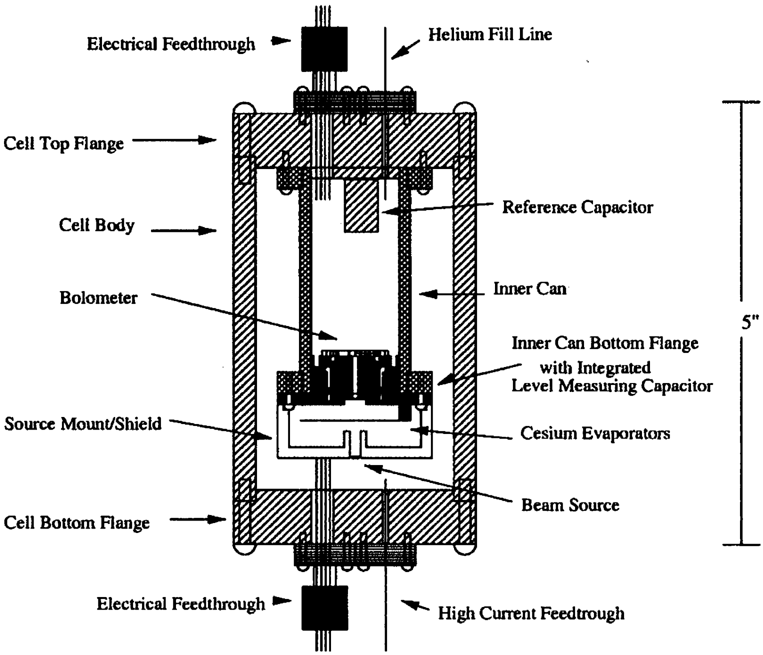

Fig. 1. The experimental cell.

from Cesium contamination, and the detector mounted inside the inner can above the orifice and level measuring capacitor.

2.1. Setup

2.1.1. Inner Can and Level Capacitor

The cell is divided into two regions (Fig. 1) separated by an inner can. At the center of the bottom of the inner can, a $100\,\mu$ thick Platinum–Iridium disc with a small $50\,\mu$ orifice at its center is mounted. Most of the bottom of the inner can is filled with the superfluid helium level measuring capacitor shown in Fig. 2. The space at the bottom of the inner can was configured to minimize the volume available to superfluid in order to maximize the vertical fill rate and make it approach the effective vertical fill rate achieved in our previous 1 K suspension experiment[9] even though we had substantially less cooling power in the dilution refrigerator. The bolometer used for detection was mounted just above the level measuring capacitor.

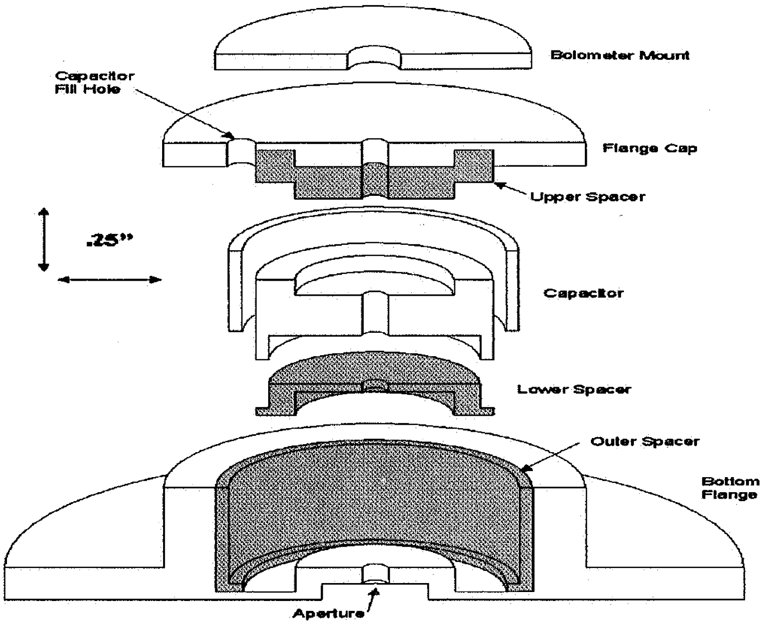

Fig. 2. Helium suspension and level-measuring apparatus. For clarity only holes relevant to fluid flow are shown.

2.1.2. Superconducting Bolometer Detectors

We used superconducting titanium thin film bolometers like those used in our previously reported pulsed beam experiments[8]. However, the titanium films used to obtain the results reported here were made with an e-beam evaporator system at the Microelectronics Technology Laboratory at the University of Minnesota. The temperature resistance characteristic for one of these titanium bolometers is shown in Fig. 3.

As a result of our earlier pulsed beam experiments[8] we discovered that the dynamics of the atomic pulses are significantly affected by the ambient gas density gradient which results in the cell if the operating temperature of the bolometer is significantly different from the operating temperature of the cell. Because the superconducting transition temperatures of the titanium films produced by e-beam evaporation (Fig. 3) were around 0.5 K, substantially different from the ambient cell temperature of around 0.2 K, we sought a way to reduce the transition temperature and found that this could be achieved by annealing the films. We show the resistivity of an annealed film in Fig. 4. The transition temperature has been reduced to a value of about 0.36 K, closer to the ambient

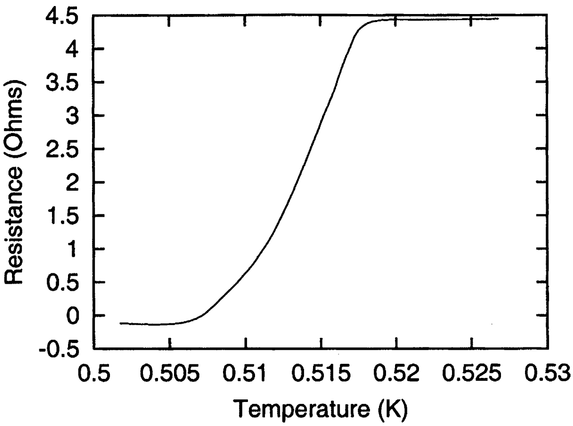

Fig. 3. Resistivity of a titanium thin film bolometer prepared by e-beam deposition, before annealing.

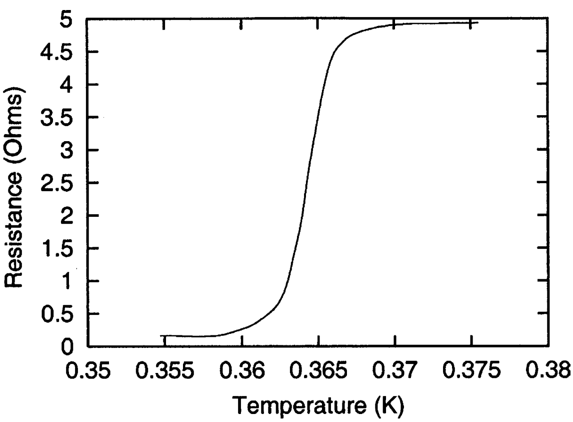

Fig. 4. Resistivity of a titanium thin film bolometer prepared by e-beam evaporation, after annealing.

temperature. (The target ambient temperature for the cell is fixed by the need to keep the equilibrium vapor density low enough to permit ballistic passage of the vapor pulse from the source to the superfluid target). The bolometers are in weak thermal contact with the cell and thus can be held in the middle of their transition by a feedback circuit.[11] The feedback voltage of the bolometer circuit is amplified and measured with a digital oscilloscope to determine the energy imparted to the detector. We find that these bolometers have a rise time of the order of 1 μs and a recovery time of the order of 10's of μs. This is consistent with other reported work.[12]

2.1.3. Source of Pulsed Vapor Beams

The source creates pulsed helium vapor beams by evaporation from the adsorbed helium film on small resistive elements consisting of a thin film of chromium on a thin 1.6 mm diameter sapphire disc. Current pulses heat the chromium film and thereby the sapphire and helium, evaporating atoms. (Simulations[8] indicate that the evaporating atoms impinging on the orifice come mainly from above the chromium film which faces the orifice.) When there is a superfluid film suspended above or in the orifice, the evaporated atoms hit the superfluid surface and in response, the bolometer can only detect atoms which are emitted from the opposite (top) surface of the suspended film.

A simulation using the method of Ref. 8 given the source-detector distance of 30 mm (used later in the transmission analysis section) calculates a beam energy of 3 K with an internal temperature of only a few milliKelvin. This is consistent with previously reported beam sources[13] that use similar power pulses and also with time of flight measurements which we carried out earlier.[8]

2.2. Methods

2.2.1. Cesium Deposition

In order to obtain superfluid suspension through the formation of a meniscus in the orifice in the Pt-Ir film, we had to deposit Cs on the surfaces of the orifice so that superfluid helium would not wet it. Because of the complications associated with depositing cesium at low temperatures in the dilution refrigerator, we first attempted to deposit cesium at room temperature. However, we failed to observe superfluid film suspension when we deposited Cs at room temperature, presumably because of the presence of impurities. To avoid this problem we deposited Cs at lower pressures and temperatures. Before the cesium deposition, the cell was evacuated using a turbo pump to about 10^{-6} torr at room temperature and then cooled to 4 K. The cell was never allowed to reach a temperature of more than 20 K (at the end of the cesium deposition) for the remainder of the experiment.

During the cesium deposition, a large current (8 amps) had to be passed through the “boats” which we used as sources of Cs vapor. The large current produced a heat load which was managed by filling the vacuum can surrounding the cell with several torr of helium gas to provide a heat exchange mechanism to the surrounding helium bath. With this gas in place, the cell quickly returned to 4 K after deposition was complete. After completing deposition, the cell could not be cooled to the operating temperature of 0.2 K with the wires that carried the 8 amps of current to cesium sources in place because they provided a large heat leak. To sever these wires without heating up the cell, "fuses" consisting of about 2 cm of 0.009 inch diameter manganin wire had been inserted into the wires, just before they entered the cell. After the deposition, these manganin fuses were melted with a discharge from a large capacitor. Finally, the vacuum can was evacuated with a turbo pump while the helium in the bath space was allowed to boil-off. The pressure in the vacuum can was reduced to less than 10^{-6} torr and when the cell warmed to 10 K, liquid helium was reintroduced into the bath space, and the cell was allowed to cool overnight to 4 K before operation of the dilution refrigerator began.

2.2.2. Transmission Experiments

The suspension of the helium above the cesium coated orifice began by cooling the cell to the operating temperature of around 0.2 K. In each experimental run, helium was allowed into the cell in controlled amounts from a 20 l gas ballast. The cell temperature, the lock-in voltage representing the superfluid level in the capacitor and the pressure in the gas ballast were recorded once per second. The beam source was run continuously with a pulse repetition rate of 10 Hz. We used a $t^{0.7}$ power law pulse with a maximum of 3 Volts applied across the beam source and lead resistance. (Empirically, we had found earlier[8] that this pulse shape resulted in sharp leading edge pulses at the detector.) A digital storage oscilloscope that was triggered by each source pulse collected and averaged the bolometer response. A computer retrieved the pulse shape data averaged over 128 vapor pulses from the oscilloscope approximately every 30 s. The pulse shape data from each average over 128 pulses was saved to a file. Signal averaging over selected regions of time or experimental conditions were done later by averaging the appropriate sets of data in these files. In the case of the data discussed below (Fig. 8) data were averaged for an hour so that each curve in Fig. 8 corresponds to averages over approximately $120 \times 128 = 15360$ pulses.

3. RESULTS

We first present results demonstrating superfluid suspension in this apparatus. In fact, we found it much more difficult to achieve superfluid suspension in this apparatus than in the apparatus used for the suspension experiments at 1 K which we previously reported.[9] As discussed in the previous section, the reasons for this included the need to cut the cables to the cesium boats remotely and the reduced helium fill rate to the inner cell. In Fig. 5 we show the result of a successful suspension in this

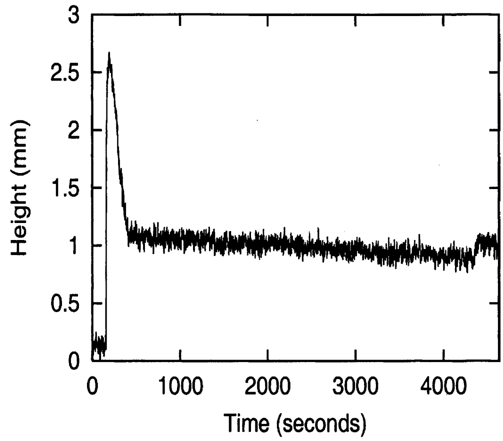

Fig. 5. Measured superfluid helium depth as a function of time for a successful film suspension experiment.

apparatus. (No transmission experiments were carried out during this particular run).

On this run, 3 Torr of the 20 l gas ballast was allowed into the cell. During the first few hundred seconds, there was a rapid level rise (as measured by the capacitance bridge) followed by a rapid level drop. From the data in Fig. 5 and the known geometry of the cell we calculate that the flow velocity out of the inner can during this rapid level drop was about 15 cm/s, consistent with reported values of superfluid critical velocities through similar orifices.[14] After the rapid level drop, the level attained an almost steady state level of about 1 mm height. Applying our previous analysis[9] we predict a suspension level of about 1 mm for this orifice, so we interpret the nearly constant level of around 1 mm sustained for more than an hour as arising from suspension. During this period, however, there is a slow decline in the level, which we did not observe in the experiments reported in Ref. 9. It corresponds to a level drop rate of about 0.5×10^{-5} cm/s. We do not know the origin of this slow level decline, which is much too small to correspond to superfluid flow through the orifice and it is possible that is only due to drift in the level measuring capacitance bridge electronics.

We have made two experimental runs using the same Cs covered orifice in the Pt-Ir disc in order to study transmission through superfluid slabs. In the first run, data was taken to detect transmission through a superfluid slab that changed thickness with time and was as thick as 0.8 mm during the experiment. In that run we saw no definitive evidence of transmission when superfluid was present, but an atomic beam signal was seen when there was no superfluid slab present. We will assume in our analysis that the atomic beam signal seen in this run when there was no indication of superfluid present represented 100% transmission. The failure to observe any transmission at finite thicknesses in this experiment was unexpected, because we had anticipated that at least a roton mediated signal would be observed. This is discussed further in the next section. In the second run, data was taken for transmission through films when the level capacitor showed zero superfluid depth within its resolution. We interpret this data as evidence of transmission through a film of thickness 100 μm or less suspended entirely within the orifice in the Pt–Ir disc, where it could not be measured with the capacitance bridge.

In Fig. 6 we show the capacitor readings taken during the second run, expressed as measured depth of suspended superfluid. Two Torr of helium from the 20 l gas ballast was allowed into the cell. The measured level height dropped linearly to zero in about 20 minutes. The measured depth remained zero within the resolution of the capacitance bridge measurement for the remainder of the run. However, as explained in more detail below, we believe that there was a film inside the orifice in the Pt–Ir disc during some of the time when the capacitors measured zero depth. This is possible because the capacitive measurement can only detect a superfluid helium level above the top surface of the Pt–Ir disc. A small leak from the cell into the surrounding vacuum space compromised thermal isolation

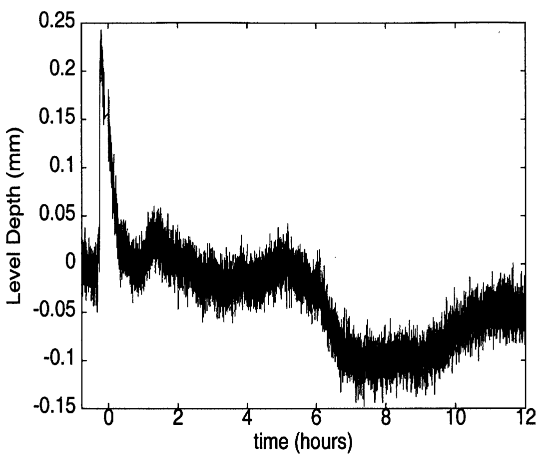

Fig. 6. Helium level depth of the cell during thin film run. The negative values after 6 hours are believed to result from a drift in the zero of the capacitor bridge.

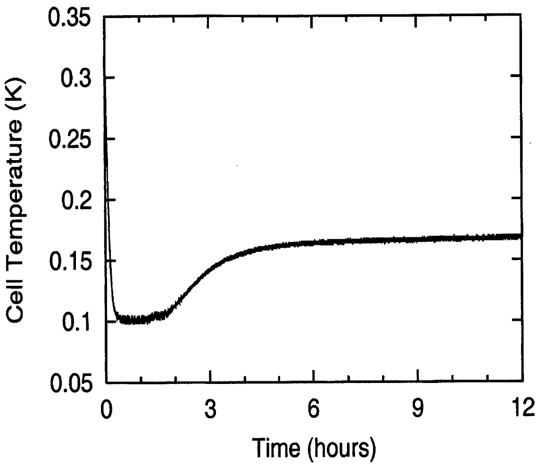

Fig. 7. Temperature of the cell during thin film run.

and the minimum achievable temperature increases over time. The temperature of the cell during the run is shown in Fig. 7.

The bolometer response was averaged over 1 hour periods starting at the beginning of the run and the results are shown in Fig. 8 and compared to the open orifice signal in Fig. 9. As noted above, the data in each curve are the result of averaging over approximately 15,360 pulses. The signal intensity is seen to increase from no apparent transmission up to a maximum value. The maximum value is reached after about 8 hours. The signal then remains constant until the end of the run. This signal observed in the second run after 8 hours was, however, about 5 times lower in intensity than the open orifice signal observed in the first run, when we had no indication of the presence of superfluid in the orifice.

Unfortunately, in these experiments, the thickness of the superfluid helium slab through which a transmitted beam could be detected was so small that it could not be measured by the level measuring capacitors. Nevertheless, attenuation of the detected pulse strongly suggests that superfluid was in the beam's path and we will assume a finite thickness of superfluid was suspended over the cell orifice. This thickness could be as large as 100 μm because, according to our previous analysis,[9] the lower surface of the suspended superfluid will be at the bottom of the orifice in the Pt–Ir film, whose thickness is approximately 100 μm, whereas the capacitor will not detect any superfluid when the upper level of the superfluid drops below the top of the orifice in the Pt–Ir film. Thus the data are consistent with the hypothesis that the film was present, and blocked the orifice, but that it was confined entirely to the orifice. Taking the baseline

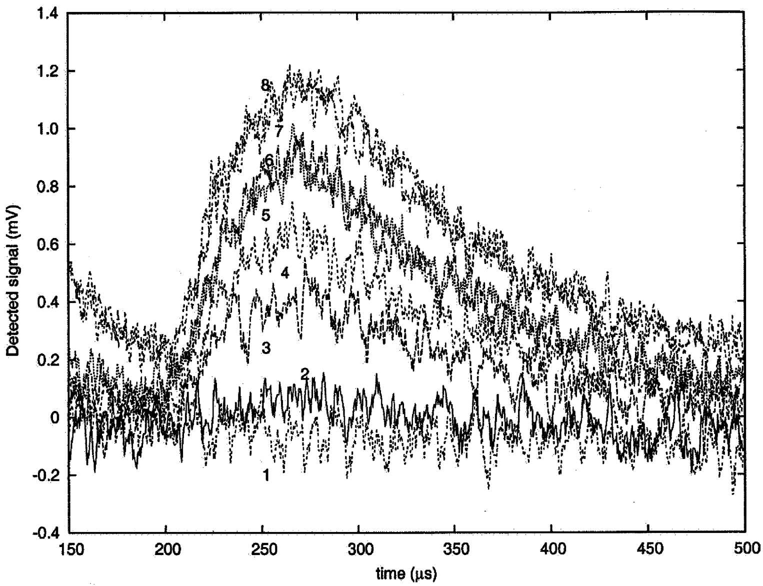

Fig. 8. The detected transmitted pulses averaged over 1 hour periods for a 3 V, 50 μs. 0.7 power law source pulse. "1" corresponds to the pulse signals averaged over the first hour of the experimental run, "2" the second hour, and so on.

as the transmission signal with no superfluid present in the first run, the data marked 2, 3, 4, 5, 6, 7, 8 in Fig. 8 is correspondingly attributed to transmission through a progressively thinner suspended film.

4. ANALYSIS

4.1. Other Mechanisms

In the detailed analysis described in Section 4.2 below, we will assume that the data in Figs. 8 and 9 were taken when the orifice was covered with a slowly thinning superfluid film of thickness too small to be detected by our capacitor. However, because we have not definitively measured the film thickness we will first consider other scenarios, which might be thought to account for the data in Figs. 8 and 9.

4.1.1. Partial Blockage

A slowly increasing signal might result if a small opening formed in the superfluid film and subsequently grew larger, allowing an increasing

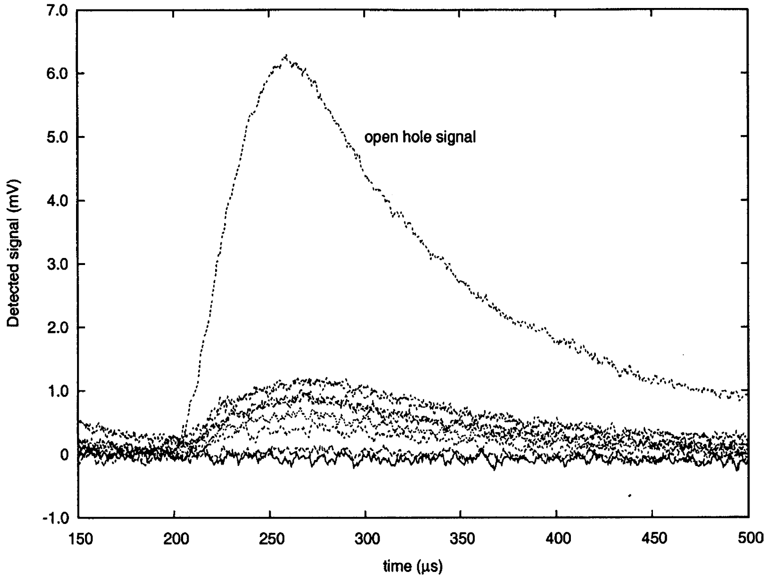

Fig. 9. The same detected transmitted pulses averaged over 1 hour periods from Fig. 8 along with the open orifice signal.

portion of the source beam to travel unobstructed to the detector. In the scenario suggested by the results in Fig. 5, the superfluid in the inner can is very slowly leaking out and so may on intermediate time scales be regarded as trapped in the inner can. If this is still true in the experiments showing transmission, then for a fixed level in the inner can, it is easy to show that a superfluid configuration in which a circular orifice is partially blocked involves substantially more surface energy than one in which the orifice is covered. For this reason, one would expect partial blockage to be energetically unfavorable. This conclusion would be modified if the orifice were very rough and not at all cylindrical but microscopic inspection of the orifice does not suggest this.

4.1.2. Opening and Closing of the Orifice

We evaluated the possiblity that the orifice was opening and closing by a statistical study of the temporal fluctuations in the transmission data. If the orifice is rapidly opening and closing, these data will be characteristic of those generated from a random binary distribution, whereas if the fluctuations in the data arise from a continuous random distribution then

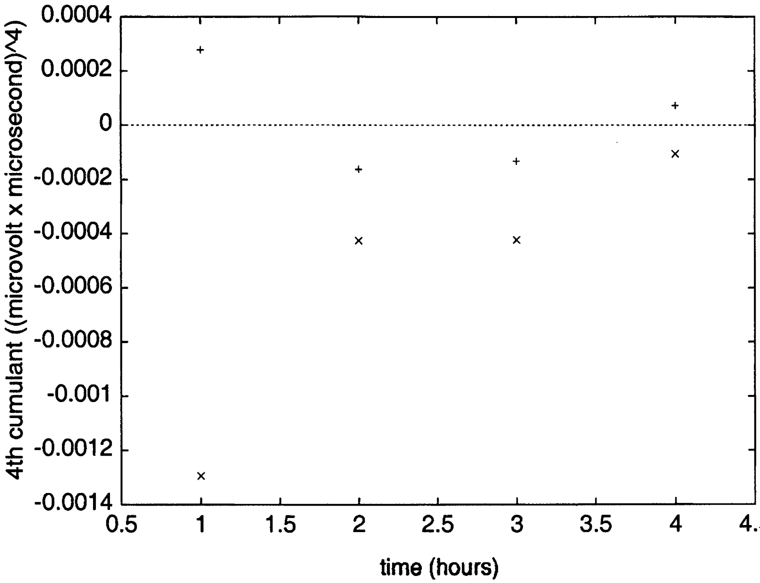

Fig. 10. Results of statistical analysis. Plusses are fourth cumulants of the data whereas x's show the value which the fourth cumulant would have if the data conformed were drawn from a binary distribution. The cumulants were calculated in each case by averaging over the data taken for an hour preceding the time on the horizontal axis.

the distribution will be Gaussian. To distinguish between these possibilities we calculated the fourth order cumulant of the time series:

$$\kappa_4 = \mu_4 - 3\mu_2^2, \tag{1}$$

where the averages $\mu_4 = (1/N)\sum_i S_i^4$ and $\mu_2 = (1/N)\sum_i S_i^2$ are taken over N stored data points S_i each of which is the voltage bolometer signal integrated over 128 pulses. κ_4 is zero for a Gaussian distribution, and is $-2\sigma^4$ binary distribution where σ is half the distance between the points of the binary distribution. We show results for κ_4 in (Fig. 10). The distribution of the pulse data can be seen to be significantly more Gaussian-like than binary. We conclude that the variations in the individual signal data arose from random noise rather than because the orifice was opening and closing (at least on any time scale slower than about 30 s and faster than 1 hour).

One may also be concerned that the orifice may be partially opening on a time scale slower than 1 hour. We cannot totally exclude this possibility but consider the following scenario: If the orifice remains blocked by the superfluid and the thickness of the level continues to decrease

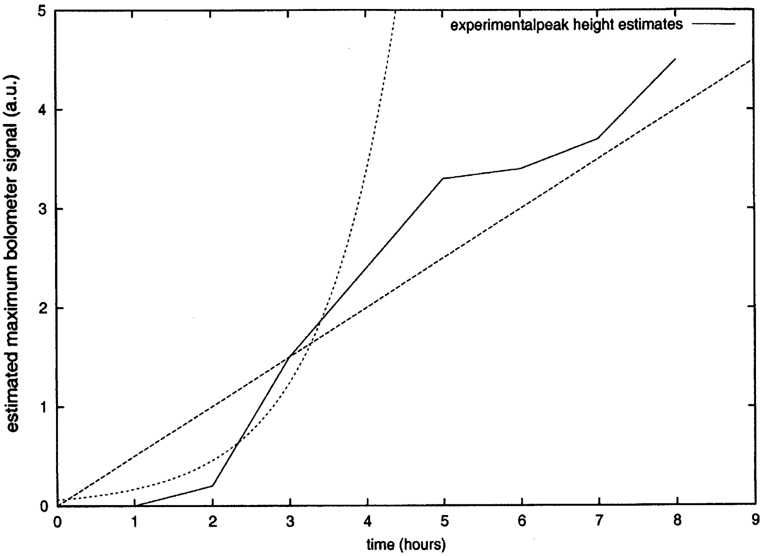

Fig. 11. Estimates of pulse peak heights as a function of time, compared with exponential and linear functions.

approximately linearly in time, as it did at larger film thicknesses, then one would expect an exponential increase of the bolometer signal with time in Fig. 8. On the other hand, if the system finds a stable configuration in which it is partially open, then the transmission might be less sharply dependent on time. We show rough estimates of the maximum bolometer signal as a function of time in Fig. 11 and an exponential and linear function for comparison. For the first 3–4 hours, the signal appears to roughly follow the exponential prediction but from 5 to 7 hours it approximately saturates. Whether this saturation arises because the superfluid film thickness stabilizes at this thickness, or whether on the other hand, the saturation occurs because a partially open configuration stabilizes during that time is difficult to determine from Fig. 11 (though we have noted above that such a partial opening is likely to be energetically unfavorable). In fact, the hypothesis of continued linear decrease of the thickness with time is questionable, because as the thickness declines, the pressure driving the fluid through the orifice decreases. We conclude that a partial opening of the orifice during hours 5–7 cannot be excluded from the data of Fig. 11 alone, but that on the other hand it does not exclude the existence of a film during that period either, and we think partial stable opening is unlikely on energetic grounds. In the rest of this discussion, we will hypothesize that a film continues to block the orifice during this time, and will explore whether such a hypothesis can account for other features of the data.

4.1.3. Ripplon Creation

Since the attenuation of the transmitted signals must result from scattering effects at the surface of the superfluid or scattering within the fluid itself, we considered the hypothesis that the dependence on orifice size of the effects of dissipation at the surface resulting from ripplon production might account for the dependence of the signal on time. This effect could arise as the top surface of the thin film changes area from about 1.6 mm to 50 μm as it enters the orifice, giving differing probabilities of ripplon production. The Edwards group,[15,16] used a path-integral method for the scattering of a helium atom near the free surface of liquid helium to determine an amplitude for ripplon generation during scattering. Employing a realistic atom–ripplon interaction outside the liquid, they calculated the amplitude γ of an atom reaching the surface without exciting a ripplon to be

$$\gamma = \exp\left[-l^{3/2}\left(q_{\mathrm{sw}}^{3/2} - q_{\mathrm{lw}}^{3/2}\right)\right], \tag{2}$$

where q_{sw} is a wave vector corresponding to the ripplon short wavelength cut-off, q_{lw} corresponds to the ripplon long wavelength cut-off, and l is a characteristic length given by

$$l^{3/2} = \frac{\hbar^3}{24\pi m^2 v_z^2}\frac{(\beta + \beta'^2)}{\rho_0^{1/2}\sigma^{1/2}} = 8.4\times 10^{-15} m^{3/2}. \tag{3}$$

β and β' are parameters defining how the density of the superfluid changes at the surface and are on the order of an angstrom, ρ_0 is the density of the superfluid, σ is the surface tension of the superfluid, and v_z is the velocity of the incident helium atom normal to the surface which is about 60 m/s for a 1 K beam. Because of the geometry the experiment, when the top surface of the superfluid is above the orifice, there is a greater probability for ripplon creation since there is a broader spectrum of ripplons which can be created than there is when the top surface lies within the orifice. When the superfluid surface descends into the orifice, the long wavelength cut-off wave vector q_{lw} becomes larger which reduces the amplitude for ripplon creation (Eq. (2)). The relative amplitudes of not generating ripplons when the surface lies above the orifice compared to when it lies within the orifice is given by

$$\frac{\gamma(L_{\rm ah})}{\gamma(D_{\rm h})} = \exp\left[l^{3/2}\left(\left(\frac{\pi}{L_{\rm ah}}\right)^{3/2} - \left(\frac{\pi}{D_{\rm h}}\right)^{3/2}\right)\right], \tag{4}$$

where $L_{\rm ah}$ is the diameter of the open space above the orifice in the cell and $D_{\rm h}$ is the diameter of the orifice. In the experiment, $L_{\rm ah}$ is about 1.6 mm and $D_{\rm h}$ is about 50 μm, so that

$$\frac{\gamma(L_{\rm ah})}{\gamma(D_{\rm h})} \approx 1 - 10^{-5}. \tag{5}$$

Therefore, the relative amplitude for not producing ripplons, although smaller when the superfluid surface is above the orifice, is only very slightly different and this difference cannot account for the change of the signal with time shown in Fig. 8. This calculation assumes that the theoretical work[15,16] is correct and applicable to our system.

4.1.4. Temperature Changes

We also considered the possibility that the changing pulse heights in Fig. 8 might be correlated with the change in cell temperature from about 0.15 to 0.2 K which took place over 3 hours while the pulse height changes took place over 6–7 hours, a roughly similar time scale. We know of no causal mechanism which would lead to such a correlation. The slight increase in ambient gas density associated with the temperature rise is too small to lead to a significant increase in shock wave formation in the vapor, if any such shock wave formation were occurring. However, shock wave formation would lead to multiple peaks in the signals which are not observed in Fig. 8 and estimates based on our simulations show that shock wave formation is not expected under the conditions of this experiment, because the vapor density, even with an open orifice, would be too low.

4.2. Transmission Analysis

The transmitted signal may also be attenuated due to the effects of scattering from quasiparticles within the superfluid. Since the coefficient of reflection of atoms from the surface is very small,[17] it is expected that the atoms either excite ripplons or rotons and phonons at the surface. Experiments[18] have shown evidence of phonon and roton creation during atomic scattering at a superfluid surface, but the amplitudes of these processes are not well known. Nevertheless, since there is a finite probability for exciting these quasiparticles, and likewise, quasiparticles can in turn eject atoms

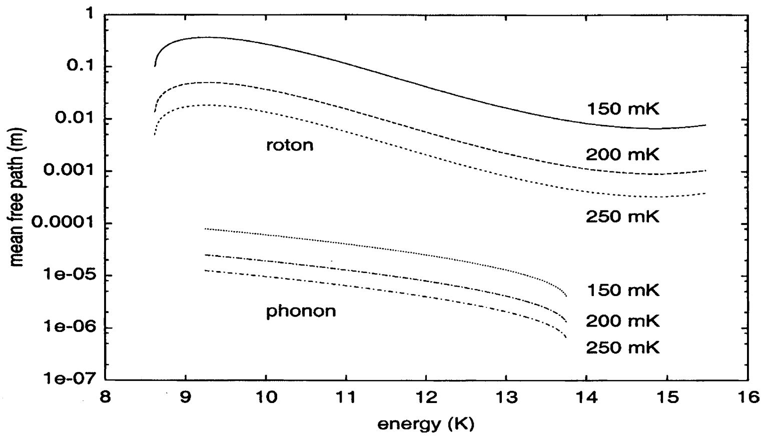

Fig. 12. The mean free paths of phonons and rotons in the superfluid as a function of quasiparticle energy and superfluid temperature from Refs. 16–18.

at the opposite surface, an atomic beam mediated by the quasiparticles should be observable.

Once the quasiparticles are created, they may traverse the superfluid film to eject atoms from the opposite surface. Propagation of the quasiparticles may be hindered by scattering from thermally excited phonons within the film. Since the population of the background thermal phonons is a strong function of temperature, the mean free paths[19–21] of the propagating quasiparticles likewise are highly dependent on the temperature of the superfluid film (see Fig. 12). The mean free paths of rotons are much longer than those of phonons, and as illustrated in Fig. 12, the probability of a phonon traversing a 1 mm sample with a temperature of 0.2 K (approximately the ambient temperature in the transmission experiments) is rather small.

If one were to assume that the probability of roton and phonon creation is energy independent and the same for rotons and phonons, then one could predict the form of the quasiparticle mediated signal using the data of Fig. 12, as we did Ref. 10. However, the calculation reported in Ref. 10 predicted a very substantial roton mediated signal through a 1 mm film which we did not observe in the set of experiments reported here. To understand the experimental results in Fig. 8, we modified the hypothesis that the probabilities of phonon and roton creation are energy independent and equal. Instead we use the calculations of Ref. 7 to model the probability of phonon and roton creation probabilities as a function of energy and a detailed simulation[8] of the pulse properties to simulate

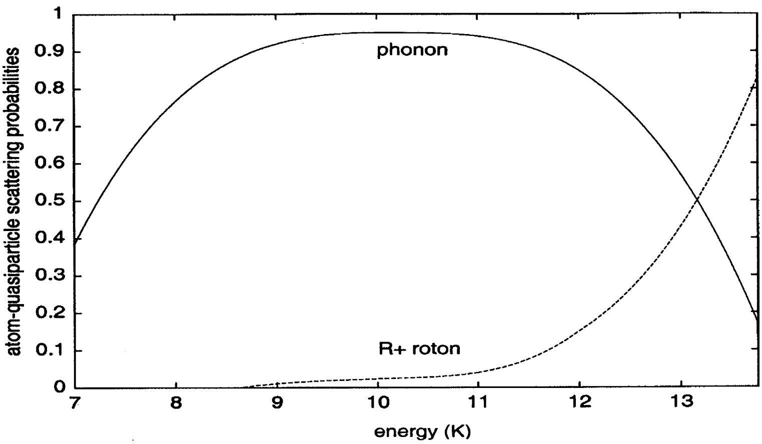

Fig. 13. The probabilities of phonon and roton excitation for an atom incident on the surface of liquid helium from Ref. 5. Energies on the horizontal axis are relative to the ground state of the superfluid.

the signal. The results of Ref. 7 are shown in Fig. 13. According to these calculations, lower energy atoms predominantly excite phonons. For atoms with energies near the maxon (bearing in mind the chemical potential of -7.15 k), the probability of creating rotons increases. When the energy of the atom is greater than the maxon, the phonon channel is closed so that only R^+ rotons can be excited. These calculations neglect ripplons and assume that all the scattering processes are one to one. Nevertheless, as will be demonstrated, our experimental pulses can be explained reasonably well using these results.

Using these hypotheses and the probabilities for quasiparticle excitation in Fig. 13 and the quasiparticle mean free paths in Fig. 12, we simulated the detected signal for a transmitted pulse. The incident pulse of atoms on the film was generated using our gas dynamics model,[10] and the propagation of the pulse was handled by a hybrid gas dynamics–hydrodynamic simulation described in Ref. 8 which, given our experimental parameters, produced a beam with 3 K translational energy and internal temperatures of only a few milliKelvin. Time delays corresponding to the energy of the quasiparticle excitations created by the incoming particles according to the probabilities of Ref. 7 were calculated. Finally, the energy and temperature dependent mean free paths were used to determine the attenuation of the quasiparticles for a given film thickness. Results of a simulation for a 0.2 K helium slab are shown for different film thicknesses in Fig. 14.

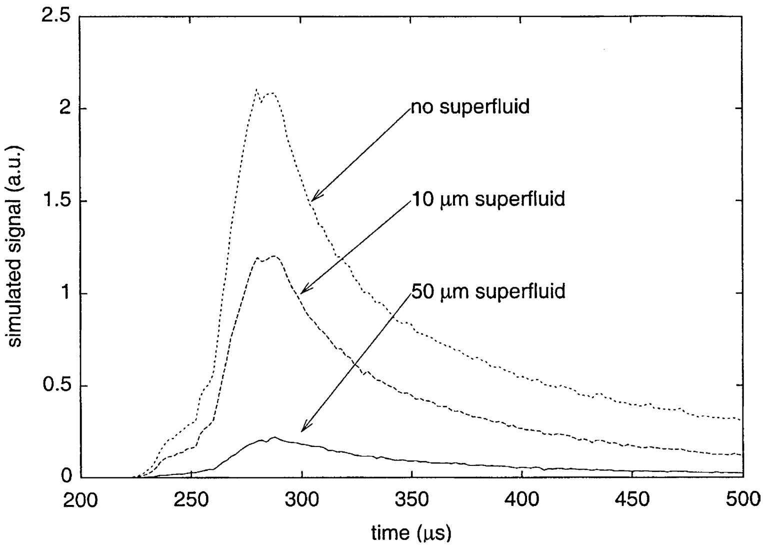

Fig. 14. Detected signals of simulated pulse transmission across helium films of various thicknesses at a temperature of 0.2 K.

We note that the experimental data in Fig. 8 is very similar to the calculated results Fig. 14. The shape of the pulse is independent of the amount of attenuation, for both the experimental data and the simulated pulse. From the simulated pulse, we see that the attenuation is heavily dependent on the helium film thickness, since at this temperature the mean free path for phonons is on the order of tens of microns. The attenuation of the simulated pulse is consistent with that of an experiment in which the helium is slowly flowing out of the orifice. We note that in the calculational results, the amplitude for roton mediated transmission is small both because we used the small amplitudes of Ref. 7 for roton creation at low energies and also because our detailed pulse simulation[8] gave a lower population for atoms of sufficient energy to excite rotons than did the pulse simulation used in Ref. 10.

5. DISCUSSION AND CONCLUSION

We have presented data indicating effective transmission of a helium vapor pulse through a very thin suspended film of superfluid helium. We also presented results of a simple model in which the transmission is attributed to phonon mediation. The model seems to account for our experimental signals quite well. However, this analysis cannot be regarded as completely conclusive because the film thicknesses were not explicitly measured during the experiment, though we believe that the helium depth is changing over time and is on the order of tens of microns thick when we detect the signals.

We do not attribute the observed signals to the condensate mediated transmission process which it is our ultimate objective to observe, because such signals are expected to arrive earlier than quasiparticle mediated ones, and to have a sharper temporal structure.[10] However, we are interpreting the experiments reported here to be indications of transmission when the films are very thin and the time delays associated with phonon mediated transmission will be less than a microsecond. Under such circumstances, distinguishing a phonon mediated signal from a condensated mediated one on the basis of a difference in time delay would be beyond the capabilities of our time resolution. Thus we cannot exclude the possibility that a part of the thin film signal could be condensate mediated. On the other hand the failure to observe any transmission signal in the thicker (≈ 1 mm) films could mean that there is an unidentified damping mechanism for a condensated mediated signal, or that the existing theoretical estimates of the transmission amplitude are too high.

Recently, Williams and Sobnack[22] reported experiments suggesting a weaker energy dependence of the roton production amplitude than the theoretical energy dependence reported in Ref. 7, shown in Fig. 13 and used in our analysis here. We also note that Williams and Wyatt[6] have recently also reported transmission events through distances up to 190 μm of superfluid, which they attribute to roton mediated transmission. The experiments of Ref. 6 can observe lower transmission amplitude events because there are multiple (we estimate 5000) orifices in that experiment. Ref. 6 reports attenuation of a factor of roughly 15 for a path length of 190 μm. Though our sensitivity is lower, it appears that we should have observed such events if they were present in our data. One possibility is that the energy distribution in the pulses used in the experiment reported in Ref. 6 is different than ours. Reference 6 reports peak transmission at incident energy of 4.5 K relative to vacuum. Ana1ysis of our pulses indicates that our pulses have very few atoms in that energy range.

We are currently repeating the experiments reported here. We are also developing a new source, which will permit the production or pulses with higher energy per particle permitting higher rates of roton production.

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