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Gas Dynamics of Pulsed Low Energy Helium Beams

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We report data on pulsed atomic helium beams for use in an experiment on atomic reemission of atoms incident on a superfluid helium four sample. We used a gas dynamics code to model these pulsed low energy helium beams and found a good fit with the experimental results at low source power. The fit implies that significant collisional effects occur in these beams. Using the model for the incident pulsed beam which we obtained, we produced simulated signals from the reemitted atoms which we expect to see in the experiment in which we monitor reemission from the sample when these atomic pulses are fired at it. We find that the present experiment could detect the proposed condensate mediated transmission process but that a larger superfluid sample would give a more definitive result.

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1. INTRODUCTION

We are engaged in a program to test the proposal[1,2] 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[3] have carried out experiments in which the superfluid is moving in the laboratory and the atomic helium vapor is stationary. (In those experiments the incident atomic energy was too high to see the anticipated effects.) In our realization of the experiment, we are producing helium vapor pulses which will strike a target of superfluid suspended over a small ($\approx 100\ \mu$m) hole coated with cesium.[4,5] Here we report experimental detection and characterization

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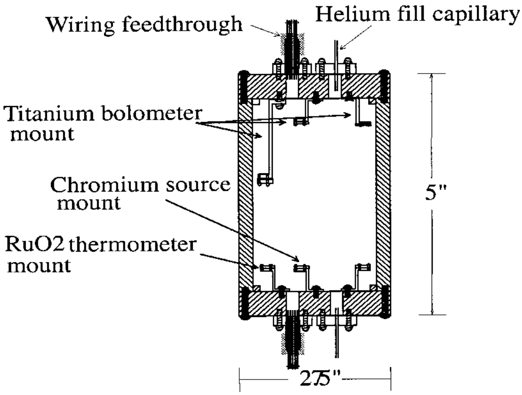

Fig. 1. Experimental cell used in the dilution refrigerator for vapor propagation experiments in the absence of a suspended film.

of vapor pulses in the apparatus in which the transmission experiment will be carried out. We use gas dynamics simulations, similar to those used by Hjort *et al.*[6] but germane to our experimental system, to characterize details of the vapor pulse velocity and density distribution. These distributions are not directly accessible from experiment. We may use them to make more detailed predictions of the expected signal from the transmission experiment than have hitherto been possible.

2. EXPERIMENT AND PULSE PROFILES

We show a diagram of the cell in which the atomic pulsed beams have been made and detected in Fig. 1. The cell resides in a dilution refrigerator and the experiments were carried out at ambient temperatures of 0.3 K. The sources are thin film chromium heaters covered with a film of superfluid helium and the detectors are titanium film bolometers held at their superconducting transition temperature.

We show a detected pulse in Fig. 2. We also show results of some simulations in Fig. 2 as described below.

3. GAS DYNAMICS SIMULATIONS

To model the pulse shapes observed in the experiments, we have carried out gas dynamics simulations using the Boltzmann equation. The creation of the pulse is modeled as quantum evaporation of quasiparticles at the surface of the helium as a one-to-one process.[7] The velocity distribution of emitted particles is determined from time-dependent temperatures arising

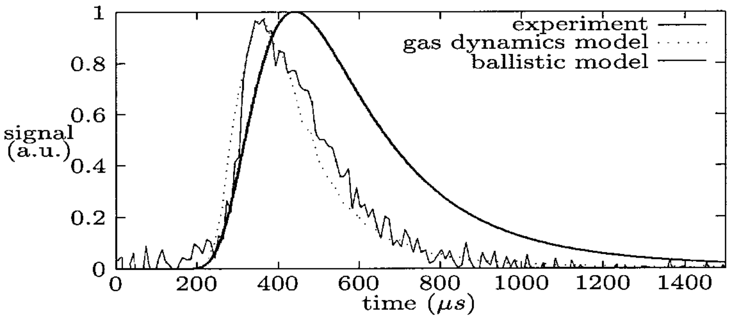

Fig. 2. Detected vapor pulse signal compared with simulations.

from a model of the resistive source heated by varying applied voltage pulses. Atoms in the pulse collide elastically at rates determined from a cross section calculated from an accurate helium atom interaction potential[8] (This cross-section grows very large when the relative velocity between the atoms is small). Total momentum is conserved in the simulated collisions. The code is made more efficient by various methods which we describe elsewhere.[9] With periodic boundary conditions in the directions normal to the beam propagation direction, we use this code to simulate a characteristic portion of the real experimental helium pulses which are being created in the laboratory by means of computations on about 10^4 helium atoms in pulses created over 1 microsecond. As time goes on, the collisions die off as the pulse spreads. Thus, at a certain point, the beam can be treated ballistically. To make fits to observed beam signals we have also taken account of effective beam collimation and of some particle losses in the directions normal to the propagation directions.

Both the experiments and the simulations show evidence of cooling due to two different effects, distinguishable in principle, arising from collisions and from geometrical effects of expansion and collimation. This is consistent as well with previous theories[10,11] and experiments.[12,13] Some results of these simulations are shown in Fig. 2 . In Fig. 2, all the signals have been normalized to one and the source-to-detector distance was taken to be the experimental value of 4.7 cm. In the gas dynamics fit we assumed that 5% of atoms traversing a transverse boundary of the simulation cell leave the simulation. The detected beam is assumed to only include those particles that are collimated such that they reach the detector. For the fit in Fig. 2, the collimation was about a factor of 5 less than that suggested by the geometry of the experiment. Possibly this was necessary because we did not take account of slower particles originating from the source outside the transverse boundaries which reenter the beam. This collimation does not effect the time of flight for the beam or the profile of the front edge of the beam, but increased collimation does cause a faster decay of the tail of the detected pulse (thereby narrowing the pulse). In the curve labeled 'ballistic model', collisions were omitted, but in all other respects the same parameters (source temperature, collimation ratio, experimental geometry, etc.) were used to characterize the pulse. From the fit of the experiments to the simulation we are able to infer considerable information about the composition of the pulse which is not directly accessible from the experiment.

4. SIMULATIONS OF THE PREDICTED TRANSMISSION SIGNALS

We have used these pulse simulations together with known features of the excitation spectrum of superfluid helium to predict the shape of expected transmission pulses due to phonon, roton and condensate processes. We assumed a one-to-one process for the excitation of quasiparticles at the helium surface and the subsequent excitation of a helium atom by a quasiparticle at the opposite surface of the helium, yielding a time delay for transmission which we obtained from the quasiparticle group velocity. For the condensate mediated process, the predicted[2] time delay is so small that it may be treated as zero for the relevant time scales. A result for a 2mm slab of superfluid helium (expected in the presently planned experiment) is shown in Fig. 3. We present results for several values of the relative probability of condensate mediated to quasiparticle mediated transmission events. Thus 10% in Fig. 3 means that 10% of the reemitted atoms were assumed to arise from the condensate process. The theoretical calculations[2] give a large value for this fraction but because the calculations depend on a choice of variational function and take no account of dissipation due to ripplons, we present results for a range of values. (The three sharp peaks in Fig. 3 correspond to quasiparticle mediated processes. We assumed the same probability of transmission for R^- rotons as for R^+ rotons and phonons since we did not find definite values[14–16] for the R^- roton branch amplitude. We have also taken into account phonon decay of lower energy excited phonons.) One sees from these simulations that a condensate mediated signal may be detectable in our planned experiment, given the temporal resolution of our detector of about a microsecond.

From Fig. 3, one can see that the temporal resolution constraints on the experiment would be reduced if one could extend the length of the path between the surface at which the atoms are incident and the surface at which atoms emerge. We have suggested that a way to do this would be to suspend a very large sphere of superfluid helium in microgravity. To see the effects

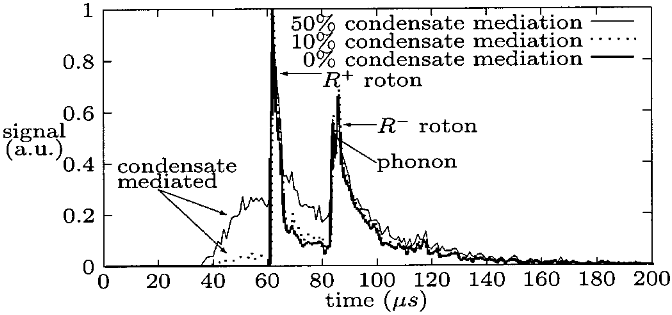

Fig. 3. Simulations of the transmitted signal anticipated in the superfluid experiment for a film thickness of 2 mm.

of this on the proposed experiment we repeated the calculation leading to Fig. 3 for a much thicker slab (1m). When we increase the slab width to one meter, we need to consider the temperature dependence of the roton and phonon mean free paths.[17] We show results at three temperatures in Fig. 4. In Fig. 4, the simulated condensate mediated signal is now separated from the phonon-roton signals by an easily resolved millisecond or more.

5. DISCUSSION AND CONCLUSIONS

We have detected vapor pulses in our apparatus of the right energy range and shape to carry out the proposed experiment. By carrying out gas dynamics calculations, we showed that these pulses have undergone cooling during expansion from the source and that the atoms do not propagate purely ballistically. (The mean free path of atoms in the simulations is around 1000 angstroms.) Using the gas dynamics calculations to characterize the pulse, we have simulated signal shapes expected for the proposed transmission experiment and have shown that, while the presently planned experiment can detect a signal, increasing the path length between incident and emitted atoms within the superfluid would permit much better temporal resolution of the expected effect.

It is interesting that, at higher source powers, we see signals at the detector which are much more complex than those shown in Fig. 2. We are actively exploring various explanations for the origins of these complex signals, which have also been observed in another laboratory.[18]

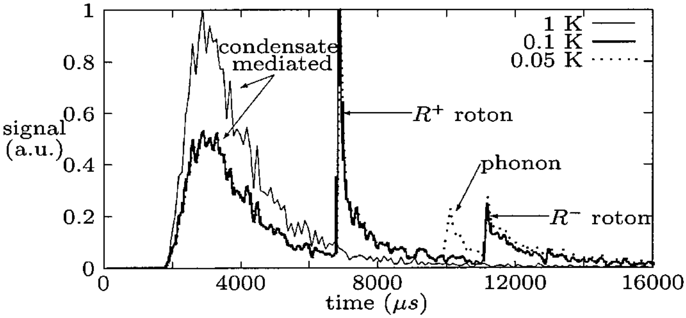

Fig. 4. Simulations of the transmitted signal anticipated in the superfluid experiment for a 1 m slab of helium.

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