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# Use of calorimetry to study the energy decay of quantum turbulence

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**Abstract.** The promise of understanding turbulence through studies in superfluid helium have been frustrated by technical difficulties. We have used a superconducting motor to drive a mesh grid [1] which we believe produces near homogeneous, isotropic turbulence in liquid $^4$He at 90 mK. We have measured the thermal response of two separate 300 micrometer Germanium thermistors [2] after the stainless steel mesh grid has been pulled through several different amounts of liquid helium at speeds up to 0.9 m/s. Various heating trends are observed, some of which are yet to be understood. Along with pulling the grid, we have also used a resistive heater to attempt to differentiate between sources of heat seen on the thermistors after a grid pull. The results from both the grid pull and the heat pulse have been used to determine both the response time of the thermistors and the boundary resistances in the system.

## 1. Introduction

Towed grid studies of turbulence in liquid helium near absolute zero have been made possible by the development of small sensitive thermistors and a super-conducting motor. The motor is able to drag an armature and a light grid a short distance to create a turbulent bundle of vorticity. Two separate grids have been successfully pulled though a bath of He$^4$ at sub-kelvin temperatures, constructed of spring and stainless steal. In all respects other than material the grids were designed to be identical. The attempt to create non-polarized, quasi-isotropic turbulence has verified that we can pull light grids through helium at low temperature at a variety of different speeds. Here we describe further steps to characterize our system as a whole. By continuing to develop our apparatus, we will further our quest to probe the fundamental question of turbulent energy decay in a superfluid. The experiments described in this report were conducted by observing temperature changes in the helium as a function of time.

Calorimetry is an important tool in studies of turbulent energy decay. Since ultimately the decay of turbulent energy must appear as heat, measuring the temperature change is fundamental to the understanding of the system. Along with energy content, we hope to explore the time scales of the energy cascades. In addition to the two properties listed above, we can also look at the effects of various system properties on the turbulent energy decay process, such as system size and grid velocity . To accomplish all of these goals, the apparatus must be able to consistently produce turbulence by reproducible methods, in our case pulling a grid through a bath of helium at millikelvin temperatures at constant velocity. The challenge is to create the turbulence while interacting as little as possible with the non helium environment around the experimental helium sample.

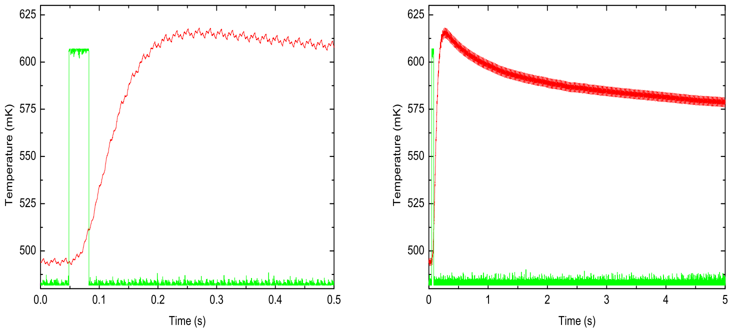

**Figure 1.** Heating as measured by one of our thermistors in the liquid helium after a 30 millisec wide current pulse is applied to the resistor in the liquid. Both graphs are from the same heat pulse: the left one is one tenth the time span of the right one. The current pulse (rectangular curve) shows the reaction time for the thermistor at this temperature, which results after heat has overcome the Kapitza boundary resistance of both the heater and thermometer.

The idea behind the experiment is a simple one: a grid is pulled through a helium bath and the temperature is measured as a function of time. However, even with such a simple design some subtleties must be considered. After the grid has been dragged through the helium, the temperature is expected to remain more or less constant until the energy has had time to cascade to the length scale in which it can efficiently decay to heat. Once this time period has elapsed, the temperature will begin to rise and to continue to do so for some time. The amount of time this process takes is dependent on both the classical Richardson and the quantum Kelvin wave cascade. After the energy has decayed away and the system is equilibrated, the measured total change in temperature and the time function form of the temperature rise indicates the nature of the cascade.

## 2. Experimental Apparatus

The motor that was designed and built [3] can accelerate the mesh grid up to 50 $\frac{m}{s^2}$ and at speeds up to 1 $\frac{m}{s}$. The thermistors are sub-millimeter size and were built to have a small heat capacity to measure the possibly fast temperature change in the helium after the motion of the grid has stopped [2]. The experiment is mounted in a copper cell that is weakly thermally coupled to the mixing chamber of a dilution refrigerator. There is no sinter in the cell for heat exchange.

Our experimental procedure was to stabilize an isolated sample cell with a volume of liquid helium at a particular temperature. In the cell there is a grid (similar to Stalp et. al. [4]) suspended just above the two thermistors which are mounted on the bottom of, but isolated from, the cell wall. The grid is pulled upward away from our thermistors with a rapid acceleration, maintained at a constant speed, stopped and the held above the puddle or in the liquid helium for a short time until it is allowed to fall back. During this motion, the thermistor resistance was monitored with a bridge driven at 70 kHz and a time constant of 300 $\mu$s. The motion of the grid was monitored with a capacitive position sensor operated in a bridge driven at 90 kHz and a time constant of 300 $\mu$s. The motor, position sensor, thermistor, and cell body temperature were all controlled and/or monitored by a National Instruments Board and LabView program [5].

It is believed that the response time of our thermistors is restricted, not by our electronics, but by Kapitza bound resistances. Further investigation into this physical limit is underway. Calculations with reasonable estimates of the thermistor parameters have put the thermal relaxation time for a 10 mK change in temperature at T = 100 mK at $\sim$ 1 second. For this material we believe the calculated Kapitza estimate to be an overestimate, as inferred by the response we have observed. A simple resistive heater was energized in the cell and the heating we observed was faster than our calculation would have us believe, even though we have not considered the thermal response time of the heater. Characteristic responses for our system after application of a heat pulse are presented in Fig. 1. The figure shows two different time scales for the same data set, one short and one long. The short time scale picture shows the reaction speed of the heater to helium to thermistor sequence after a current pulse. The second plot shows the relaxation time for the $\mathrm{He}^4$ to cool down after being warmed. At T $\sim$ 500 mK our thermistors have a reaction time of less than a tenth of a second, shorter than predicted by calculation for the thermistor. When the experimental parameters are inserted into a Kapitza calculation ($T_{initial} = 500$ and$T_{final} = 620$) we predict a relaxation time of 0.2 s, but observe a relaxation of 0.15 s. It remains to be shown if this lag in response will extrapolate as $T^{-3}$ as is predicted.

The kapitza time constants were calculated from the definition. $R_k = A\Delta T/\dot{Q}$ where $R_k$ is the thermal Kapitza resistivity of the material, A is the exposed surface area, $\Delta T$ is the change in fluid temperature and $\dot{Q}$ is the heat flux. By assumption we write $\dot{Q}$ as $\frac{mc_fT_f - mc_iT_i}{\Delta t}$ when m is the sensor mass, $c_{i,f}$ are the heat capacities at the initial and final temperatures, $T_{i,f}$ are the initial and final temperatures and $\Delta t$ is the change in time. Solving for the time gives us an estimate for the time expected for the thermistor to equilibrate temperature:

$$\Delta t = (mc_fT_f - mc_iT_i) * R_k/A(T_f - T_i) \tag{1}$$

If we assume values for all of the parameters above, we can calculate Kapitza times for various temperatures and a temperature rise $\Delta T$ of 10 mK, as in Table 1.

Table 1: Relaxation times for heat transfer resulting in a 10 mK temperature rise in the thermistor. The values for the heat capacities in this calculation were experimentally determined [6].

| Temperature | Relaxation Time Ga doped | Relaxation Time As doped |
|---|---|---|
| 10 mK | 1849.24 s | 2339.5 s |
| 50 mK | 14.79 s | 18.71 s |
| 100 mK | 1.85 s | 2.34 s |
| 500 mK | 0.015 s | 0.019 s |

## 3. Data

In addition to the heater measurements, we also pulled our mesh grid through a bath of helium at low temperatures. Typical data from four separate grid pulls can be seen in Fig. 2. The plots are arranged such that the short time scales are on the top, while the longer timescales are on the bottom. The warmer runs are on the left and the cooler are on the right. After a grid pull there are many observed changes in the helium temperature. The pattern we see is as follows: immediately after the grid has stopped moving there is a rise in temperature of about 50 mK: after this heating there is a short period of cooling and following the brief cooling period is a second rise in temperature. The first rise in temperature produces a range of temperature changes, from less than 10 mK to above 50 mK. As of yet, we are not aware of the cause of this rise. The heating observed in this experiment is quite different from what we observed in our previous work [7]. We are currently investigating these discrepancies. They may be related to surface waves induced when the grid broke the helium surface in the previous measurements.

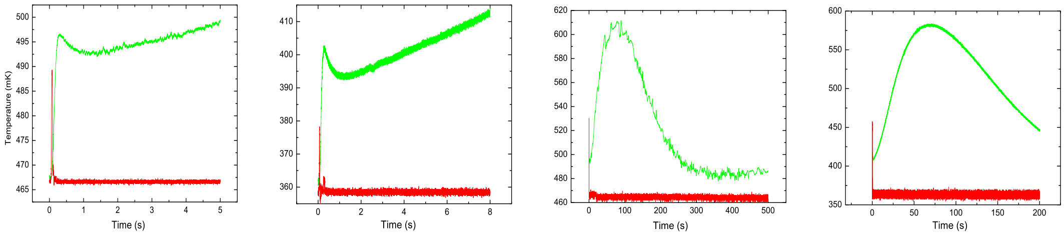

**Figure 2.** This figure shows heating patterns as measured by one of our thermistors after four separate grid pulls. The temperature change is shown as a function of time. The first two plots show short times. These plots show the "first" rise in temperature and the short cooling period that follows. The second two plots show the heating on a long time scale. In these plots the second and larger temperature rise can be seen.

The cooling seen to follow this is assumed to come from the helium interacting with the cold copper cell. Since we put heat into the helium and the heat capacity ratio of the copper in the cell to the helium is greater than one, there is a large cooling effect on the helium. After the cooling there is a large rise in temperature. The second rise is much larger than the first, and occurs over longer time.

One of the goals of our current work is to determine the cause of each change in temperature. We believe that once we fully understand the different processes involved during a grid pull, we can better design our system to observe the effects we are interested in rather than the possibly extraneous heating being produced. The heating observed in the larger temperature rise has a few possible sources. It could be due to heating from the superconducting solenoid, since current is in a transient state. We could also be observing the heating caused by eddy currents in our copper cell if the lead superconducting shield is failing, or it could be caused by friction in the mechanical bearings on the shaft. All three of these possible issues should be fixed with the cell we are currently constructing. Not only is heating a problem in our cell, but also the heat capacity of the copper cell produces a large cooling effect at low temperatures that needs to be rectified.

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