Third Sound Amplification and Detailed Balance

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Abstract. Condensation of atoms from the vapor into a third sound resonance is expected to be capable of acoustic amplification. This results from normal to superfluid conversion that coherently accommodates atoms into the third sound velocity field. Consideration of third sound in light of the equilibrium detailed balance between vapor particles and the superfluid film provides further evidence that acoustic amplification is attainable.

Keywords: superfluidity, quantum condensation, third sound.
PACS: 67.40 Db, 67.40 Hf

INTRODUCTION

Condensation of vapor atoms into the superfluid He II is a phase transition that involves a change in order. The gas to liquid transition involves an increase in order, but the quantum degeneracy condition characterizing the superfluid requires that condensing atoms also take on the momentum order associated with the condensed state. This conversion of disordered vapor into ordered kinetic energy has been previously observed for the case of a film in a persistent current state. Henkel et al[1], referred to it as a "crystal-like growth" of the superfluid state. This direct conversion of disordered atoms into ordered kinetic energy is an interesting example of a heat engine illustrated schematically in Fig 1(A). The flow of heat through the system (driving the condensation process) results in mechanical energy (an increase in macroscopic kinetic energy). Alternatively, the process can also be interpreted as an example of a "matter laser" — particles coherently join the macroscopic deBroglie wave structure upon condensing.

In a more recent work, a similar coherent condensation process has been proposed.[2] Schematically shown in Fig. 1(B), the ordered kinetic energy state consists of the macroscopic film flow of a third sound oscillation. The mechanical "output" in this case is the acoustic energy of the third sound oscillations. Here, the analogy of coherent condensation to a matter laser is more obvious. Condensing atoms take up the role of transitions within an inverted population pumped by a temperature difference. The transitions involve adding particles into a macroscopically occupied cavity mode, in this case a third sound wave mode instead of a photon mode. The presence of multiple acoustic modes separates the acoustic energy gain process from the recycling of mass out of the film. This separation allows for a continuous gain similar to CW laser operation.

In this paper we discuss the consequences of the equilibrium film-vapor particle exchange to the coherent condensation process.

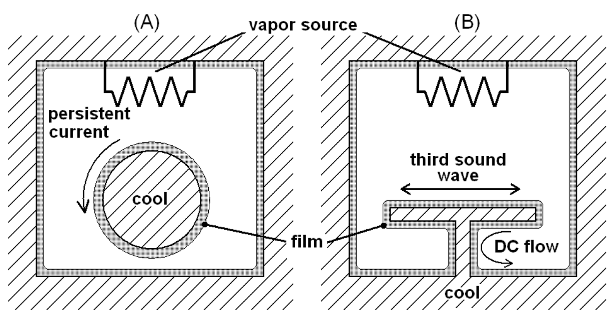

FIGURE 1. Kinetic energy of a persistent current (A) or a third sound mode (B) is generated by the condensation of atoms into the macroscopic quantum state of the film. In principle, moving slabs of film could be extracted from (A) and acoustic energy from (B).

DISCUSSION

With the assumption that condensing atoms coherently join the instantaneous macroscopic kinetic energy configuration of the third sound wave, an intuitive explanation of the self-oscillation condition is

CP850, *Low Temperature Physics: 24th International Conference on Low Temperature Physics;*
edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirschfeld, and A. M. Goldman

obtained. The particles need to condense and be recycled through the cavity at a rate that exchanges all of the particles in the resonance region of the film during a time on the order of the third sound decay. The rate of energy input is determined by the average kinetic energy of the mode, and the rate of energy loss is the natural damping of the third sound.

$$\frac{dN}{dt} = \frac{N}{\tau} \frac{\langle E \rangle_{resonator}}{\langle KE \rangle_{exposed}}. \qquad (1)$$

This expression is exact with the kinetic energy average appropriately weighted by the spatial distribution of condensing atoms. The assumption that condensing atoms coherently join the local kinetic energy state of the film is crucial. Henkel's experiment demonstrated this for a persistent current state, but the validity of the assumption for a non-persistent macroscopic third sound flow is not entirely clear. Although the time and size scales of atomic condensing events are far removed from the corresponding time and size scale of the third sound, one would like a rigorous demonstration that the condensing atoms interact with the moving third sound film in the same way as with a persistent current. Here we make the case using the concept of detailed balance applied to the experimental fact that third sound takes a relatively long time to decay.

Consider the rate at which gas particles are accommodated into the film at equilibrium. At low temperatures (0<T<1 K), the vapor pressure (P_{film}) becomes quite small, particularly above a thin film. The degeneracy of the gas is totally negligible so classical kinetic theory can be applied. The approximate time for exchanging all atoms composing the film is given by

$$\tau = \frac{\rho h}{\alpha m} \frac{\sqrt{2\pi mkT}}{P_{film}} \qquad (2)$$

where α is the absorption probability for particles impinging on the film, ρ is the liquid density, and h is the film thickness. Theoretical[3] and experimental[4] evidence shows that α is close to unity until the perpendicular wavenumber of the impacting atom approaches zero. With wavenumbers characteristic of 0.2 K, α has dropped to 90%. In spite of the low vapor pressure, the film exchange time including the accomadation factor is quite short, as shown in Fig. 2.

What is remarkable about this result is that, in equilibrium at most temperatures, all of the atoms in the film are replaced on a time scale much shorter than the typical decay time of a third sound wave, shown as the dashed line in the Fig. 2. The exchange at elevated temperatures is even more impressive: at 0.6 K, refreshing the film's particles on the order of one cycle of the third sound wave oscillation. We take this as a demonstration that condensing atoms are accommodated into the kinetic motion of the third sound resonance. Any other fate of the atoms would contribute to an anomalously large sound attenuation.

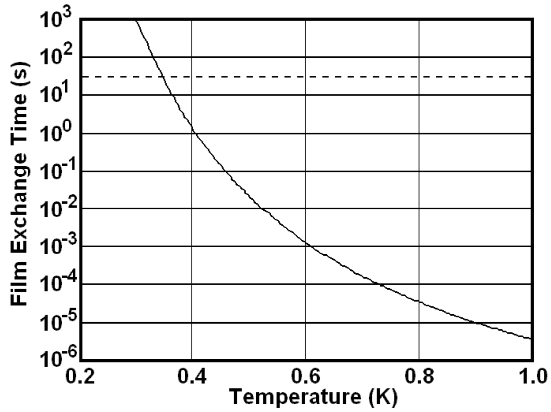

FIGURE 2. Characteristic time for the exchange of all atoms in an equilibrium film. The time scale for the decay of a high Q third sound resonance is shown as the dashed line.

The amplification by stimulated condensation is the product of a small imbalance of the equilibrium exchange, with the imbalance creating the gain as additional particles join the macroscopic quantum flow state. It is effectively a normal to superfluid conversion process that also increases the number of particles in the system. The liquid-vapor interface is, in some sense, acting as a semi-permeable membrane allowing the normal fluid excitations (as actual particles in the vapor) through while confining the superfluid state.

We are engaged in an experimental effort to achieve third sound amplification through the condensation of a vapor flux onto a resonating film. Our efforts are currently focused on mechanical issues.

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