Increasing Quantum Degeneracy by Heating a Superfluid

D.J. Papoular[1], G. Ferrari[1], L.P. Pitaevskii[1,2], S. Stringari[1]
[1] *INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, 38123 Povo, Italy and*
[2] *Kapitza Institute for Physical Problems, Kosygina 2, 119334 Moscow, Russia*

We consider a uniform superfluid confined in two compartments connected by a superleak and initially held at equal temperatures. If one of the two compartments is heated, a fraction of the superfluid will flow through the superleak. We show that, under certain thermodynamic conditions, the atoms flow from the hotter to the colder compartment, contrary to what happens in the fountain effect observed in superfluid Helium. This flow causes quantum degeneracy to increase in the colder compartment. In superfluid Helium, this novel thermomechanical effect takes place in the phonon regime of very low temperatures. In dilute quantum gases, it occurs at all temperatures below T_c. The increase in quantum degeneracy reachable through the adiabatic displacement of the wall separating the two compartments is also discussed.

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The thermomechanical effect is an important manifestation of superfluidity. It has historically been observed via the fountain effect, i.e. the increase in the pressure in a narrow tube, one of whose ends dips in a bath of superfluid Helium 4, when the tube is heated [1]. It has recently also attracted interest in the context of dilute ultracold atomic gases [2, 3] as a potential signature of superfluidity in these systems. These works have focused on the dynamical aspects of the phenomenon, using the hydrodynamic [2] or the classical field [3] approach.

The purpose of the present work is to investigate the thermomechanical effect by exploiting the conditions imposed by equilibrium thermodynamics, pointing out novel features exhibited by superfluids in properly chosen thermodynamic regimes. The experiment we propose is reminiscent of the original fountain effect [1], with one important difference. In the original experiment, the pressure at the surface of the liquid Helium bath is constantly equal to the saturated vapor pressure, and the height growth of the liquid in the narrow tube is determined by the equilibrium between gravity and the pressure increase $\delta p = s\delta T$ of the liquid near the superleak. Here δT is the temperature difference between the bath and the tube, and s is the entropy per unit volume in the liquid phase. In the situation considered in this paper, the quantum fluid instead occupies a fixed total volume, and the flow of particles through the superleak is caused by the density difference produced by the heating process. Consequently, it is determined by the compressibility of the fluid. In the case of liquid Helium, the compressibility is small; it is much larger in dilute quantum gases. We predict that, in the phonon regime of superfluid Helium, and for all temperatures below T_c in the case of dilute gases, atoms flow through the superleak from the hotter to the colder region, contrary to what happens in the fountain effect, and resulting in an increase of quantum degeneracy in the colder compartment. The cooling mechanism proposed in the present paper, based on a filtering process through the superleak,

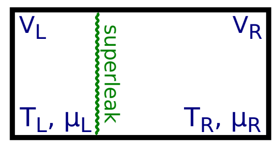

FIG. 1. Schematics of the proposed experiment. The left and right compartments, initially in equilibrium, have constant volumes and are filled with a homogeneous quantum fluid. Heating the right compartment, or displacing the superleak, causes the system to evolve towards a new thermodynamic state satisfying chemical, but not thermal, equilibrium.

differs from other adiabatic cooling mechanisms considered in ultracold atomic gases, like the adiabatic formation of Bose-Einstein condensation with non–harmonic traps [4] or the entropy exchange in mixtures of different atomic species [5].

We consider two compartments, hereafter called left (L) and right (R) compartments, filled with a homogeneous superfluid (liquid Helium 4 or a dilute atomic gas) and connected via a superleak, which only allows for the transmission of the superfluid component (see Fig. 1). Initially, the superfluids occupying the two compartments have the same temperature ($T_L^0 = T_R^0 = T^0$) and the same chemical potential ($\mu_L^0 = \mu_R^0$). If the right compartment is heated, the system will eventually reach a new equilibrium configuration characterized by equal chemical potentials, but different temperatures. The equilibrium between the final–state chemical potentials is ensured by the flux of the superfluid through the superleak. However, the condition of equal temperatures cannot be ensured because the superfluid component does not carry any entropy.

By calling $\delta T = T_R - T_L$, $\delta n = n_R - n_L$ and $\delta p = p_R - p_L$ the small differences between the final temperatures, densities and pressures of the two compartments, and imposing equal chemical potentials $\delta\mu = \mu(T_R, n_R) -$