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Physica B 284–288 (2000) 133–134

PHYSICA B

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Resonator design for stimulated third sound amplification in ^{4}He films

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Abstract

We propose a new resonator to detect the amplification of third sound waves due to stimulated condensation of normal vapor atoms into the superfluid film. We describe the phenomenon and present the conditions required for its achievement. Third sound amplification by stimulated condensation (TASC) is thus an extension of film growth at a fixed DC velocity to a situation involving a continuous AC energy transfer. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: ^{4}He film; ^{4}He superfluid; Stimulated condensation; Third sound

1. Introduction

In the process of quantum condensation [1] helium atoms from the vapor become affiliated with the velocity field of a persistent current circulation state [2]. As a result, the superfluid component absorbs the mass, and the excitations of the normal component account for the energy and momentum of the condensing atom. Condensing atoms will be assimilated into the macroscopic flow velocity state of third sound since the flow field of the wave, on the time and size scale of the condensing event, is indistinguishable from that of a persistent current. Superfluid mass can be removed from a resonance of a non-zero angular momentum state by DC film flow, preserving the AC energy in the third sound mode. This results in a gain that should be observed as an increase in the quality factor Q of the third sound resonance as a non-equilibrium flux of vapor particles is condensed into the film.

Since each condensing particle picks up the local kinetic energy of the third sound mode, the power input to the resonance is just this local kinetic energy weighted by the local net vapor flux, $\Phi(\boldsymbol{r})$, entering the film:

$$W_{\text{in}} = \int \tfrac{1}{2} m_4 v(\boldsymbol{r})^2 \Phi(\boldsymbol{r})\,\mathrm{d}A. \tag{1}$$

The input power, W_{in}, depends on the particular resonance mode under consideration, and the magnitude and spatial distribution of the vapor flux. In effect, the gain comes from the coherent conversion of normal particles into the macroscopic superfluid state. It is also accompanied by a heating of the film due to the latent heat of the condensing atoms and a DC film flow out of the resonator.

2. Design consideration

To detect third sound amplification by stimulated condensation (TASC), the input power must be noticeable relative to the other dissipative mechanisms associated with the third sound. We have designed a new resonator configuration that satisfies all of the following requirements: the resonator must be open such that the flow antinodes can be exposed to a vapor source; it must be mechanically supported, and coupled to transducers in a way that minimizes third sound radiation; it must be able to dissipate both the latent heat and the mass of the condensing atoms; and finally the third sound must have an inherently high Q.

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PII: S0921-4526(99)02144-4

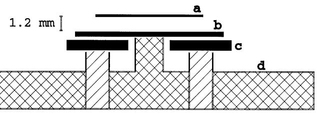

Fig. 1. Schematic of the third sound resonator: a – heater, b – sapphire disk, c – capacitor plates, d – base with a post.

The resonator cross section is shown in Fig. 1. It consists of a loop-shaped vapor source (a) independently supported above a flat sapphire resonator disk (b). The disk is coated on all surfaces with evaporated silver and epoxied to a post in a copper base (d). Four other posts in the base support a concentric quartz plate (c), the upper surfaces of which are patterned into four evaporated silver capacitive transducers. The superfluid film coats upper and lower sides of the disk as well as all other surfaces in the experimental chamber enclosing the apparatus. The top surface of the disk is open to the flux of vapor atoms which can be varied by changing power of the heater loop. The film on the bottom surface of the disk is within the capacitor gaps for both driving and detecting.

In order to maximize the sensitivity to input power, we have based our design on a target Q of 10^5 associated with each dissipation mechanism. Previous experience with closed resonators [3], suggests moderately thick films of 8–12 layers. Thermo-mechanical dissipation through vapor coupling in the open geometry requires temperatures below 0.26 K, where the equilibrium vapor pressure rapidly diminishes. Consideration of the radiation down the post from a 13 mm diameter disk imposes constraints on both the length and diameter of the post. The mechanical stability of the resonator excluded working with the lowest $m = 1$ mode (m is the angular Bessel function index) but a 3 mm long by 2.4 mm diameter post proved sufficient for the lowest $m = 2$ mode. The transducers are optimized for coupling to this mode with the added advantage of insensitivity to any lateral vibrational swaying of the disk.

Finally, consideration of the vapor flux distribution requires care in the design of the source ring. We wish to deposit the maximum amount of vapor over the flow antinodes of the $m = 2$ mode with constraints on the maximum flux impinging the film (causing local heating of the film), the total latent heat that must be dissipated by the resonator into the base, and the overall total heater power required by the ring. A ring diameter of 11 mm placed 2 mm above the resonator disk was a reasonable compromise.

We expect that a deposited power of 1 μW will challenge the conductance of the whole system, causing the maximum temperature in the film to rise above our working limit of 0.26 K. At powers well below this, we anticipate that the input power, W_{in} of Eq. (1) will be easily distinguished by a change in $1/Q$ proportional to the applied vapor source heater power.

We have currently assembled a prototype of the described resonator, and see no obvious obstacle for the successful observation of the TASC effect.

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