FREQUENCY UP-CONVERSION IN INTERACTING PHONON BEAMS IN LIQUID 4He

Y. Korczynskyj, A. Wyatt

FREQUENCY UP-CONVERSION IN INTERACTING PHONON BEAMS IN LIQUID ^{4}He

Y. Korczynskyj[o] and A.F.G. Wyatt[+]

[o] Department of Physics, University of Nottingham, University Park, Nottingham NG7 2RD, England
[±] Department of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, Devon, England

Résumé.- Nous avons étudié l'interaction due à l'intersection de faisceaux de phonons en fonction de la pression en utilisant comme détecteurs des jonctions tunnel supraconductrices Al. Des phonons de haute fréquence créés par l'annihilation de deux phonons de plus basse fréquence sont détectés à des pressions < 13 bars. La fréquence critique pour cette conversion vers le haut est bien définie et est en bon accord avec la valeur trouvée à partir de la désintégration de phonon via le processus à 3 phonons.

Abstract.- The interaction between intersecting phonon beams in liquid ^{4}He has been studied as a function of pressure using superconducting Al tunnel junction detectors. For pressures < 13 bar we detect high frequency phonons which are created by the annihilation of two lower frequency phonons. The critical frequency for this upconversion is well defined and is in good agreement with the value found from phonon decay via the 3 phonon process.

1.INTRODUCTION.- It is now well established that the dispersion curve $\varepsilon(q)$ for liquid ^{4}He shows initial upward curvature from linearity at low hydrostatic pressures. The various aspects of this anomalous dispersion and the general subject of phonon-phonon interactions in liquid ^{4}He have recently been reviewed by Maris /1/. Briefly, the slight upward curvature allows energy and momentum to be conserved in the three phonon processess (3pp), for small angle collision, up to a critical phonon energy ε_c with $\varepsilon_c \sim 9$ K at SVP. As the pressure is increased this "anomalous" behaviour decreases, disappearing at $\sim$ 19 bar when $\varepsilon_c = 0$ /2,3/.

The 3pp has had its most dramatic demonstration in attenuation measurements /4/ utilizing heat pulse techniques and superconducting tunnel junction detectors which only respond to phonon of energy $\varepsilon > 2\Delta$ where Δ is the superconductor energy gap. The effect of the 3pp decay is to drastically reduce the mean free paths of all phonons with $\varepsilon<\varepsilon_c$, particularly those with $\varepsilon \lesssim \varepsilon_c$, while leaving the long mean free paths for those with $\varepsilon > \varepsilon_c$ unaltered. In the insert of figure 2 we show schematically the situation arising (at SVP and $2\Delta = 4.33$ K) when a continuous number spectrum of phonons is injected into the helium (a), and (b) after propagating a typical experimental distance to a detector, $\sim$ 10mm.

The time reversal of the 3pp decay is the interaction between two phonons to produce a single one of higher frequency and in this paper we report how we have detecte this up-conversion. The study of this process not only has intrinsic interest but provides detailed information concerning the thermalization of phonon pulses and the concomitant establishment of anisotropic temperature distributions. The latter become possible through the small angle nature of the 3pp /1,5/.

2.EXPERIMENTAL PRINCIPLES AND TECHNIQUES.- In essence the experiment consists of having two phonon "beams" intersecting and then searching for an increase in the number of phonons at higher frequency. This is a non-linear interaction and so we would expect that it would depend on the phonon density in the beam and of course care must be taken to ensure that other non-linear processes in the detecting system do not contribute. A consequence of the small angle nature of the 3pp is that in order to maximise its effect the angles subtended by the heaters at the detector should be small.

A schematic diagram of the experimental arrangements we have used is shown in figure 1. Four narrow thin films heaters were fabricated close together on a substrate of sapphir and opposite them on another substrate were deposited two narrow tunnel junctions of superconducting Al /6/. Each heater could be pulsed separately for $\sim$ 1μs to inject a phonon pulse into the He. Further, they could also be pulsed coincidently so that 2, 3 or 4 phonon pulses were generated and occupied the same volume of ^{4}He. The sequence of the measurement was that the first heater (H_1) was pulsed and the signal (S_1), detected by the tunnel junction, was digitised and stored /6/. Then H_2 was pulsed and

S_2 added to S_2 to give $(S_1 + S_2)$.

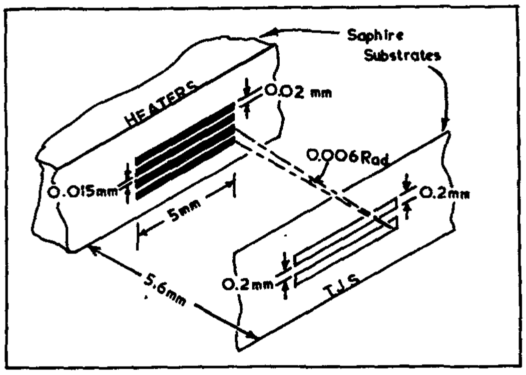

Fig. 1 : Schematic diagram of the experimental arrangement.

The two heaters H_1 and H_2 were then pulsed simultaneously with pulses identical to those which gave S_1 and S_2. The tunnel junction response for the simultaneous pulses $(\overline{S_1 + S_2})$ was then compared with the sum of the sequential pulse responses $(S_1 + S_2)$. This procedure was extended to simultaneous pulses on 3 and 4 heaters.

3.RESULTS.- The results are shown in figure 2.

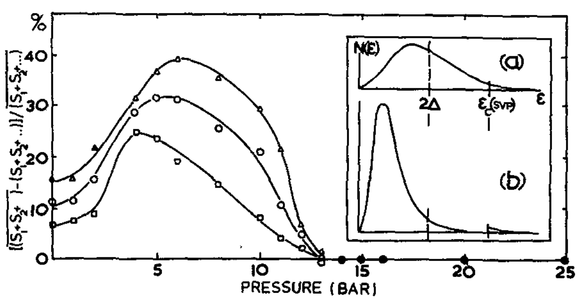

Fig. 2 : The interaction signal due to intersecting phonon beams as a function of pressure. The lines through the data points are merely guides for the eye. (See text for an explanation of the ordinate). □heaters 1 and 2 ; O heaters 1, 2 and 3 ; Δ heaters 1, 2, 3 and 4. The power dissipated in each heater was 2.5 mW. The insert shows a schematic representation of the phonon number distributions at various stages in the helium (see text).

Where we plot the percentage difference between the signal due to the simultaneous pulses and the sum of the individual signals i.e. the percentage of the total simultaneous signal that is due to interactions. It is evident that the interactions produce a large change in the $\varepsilon > 2\Delta$ signal for pressures < 13 bar, and further that no interaction signal is present for pressures > 19 bar, which verifies the linearity of the detecting system ; indeed the interaction signal becomes zero for all pressures > 13 bar.

4.DISCUSSION AND CONCLUSION.- These features of the data may be interpreted within the framework of model which assumes that ε_c (13 bar) = 2Δ. Then for pressures < 13 bar the phonons injected into the ^{4}He with $\varepsilon > \varepsilon_c$ are stable with respect to the 3pp whilst those with $\varepsilon < \varepsilon_c$ rapidly decay to form a 'quasi equilibrium' distribution /5/ and then, when the two pulses overlap, the number density of the phonon cloud increases and a new quasi equilibrium is established via the 3pp, with a higher number of phonons in the high frequency tail. This tail increases the number of phonons with $\varepsilon > 2\Delta$ and so increases the detected signal.

If the cut-off in the interaction signal corresponded to $\varepsilon_{c,n} = 2\Delta$ where $\varepsilon_{c,n}$ is a higher energy threshold for decay into n phonons /7,1/, then we should certainly expect to see discontinuous changes in the interaction signal for pressures < 13 bar. Within the experimental accuracy of 1 - 2 % for the data shown in figure 2 we conclude there is no sign of multiphonon decay. Further, if the upper energy limit to the 3pp ε_c, were such as to allow a significant decay probability for phonons with $\varepsilon > \varepsilon_c$ /8,1/, then we should see evidence for this at pressures > 13 bar. Since the interaction signal is zero for these pressures we conclude that the cut-off for the 3pp is indeed sharp. The above considerations give ε_c = 4.33 K at 13 bar which is in good agreement with other measured values of ε_c at this pressure /3,4/.

ACKNOWLEDGEMENTS.- One of us (Y.K.) would like to acknowledge many fruitful conversations with R.M. Bowley and help received from G.N. Crisp, S. Balibar, and J. Middleton during the running of the experiments and the latter also for his skilled fabrication of various pieces of the experimental apparatus. The authors are grateful to the Science Research Council for their support under grant B/RG/4231.

References

/1/ Maris, J.M., Rev. Mod. Phys. 49 (1977) 341

/2/ Mills, N.G., Sherlock, R.A. and Wyatt, A.F.G., Phys. Rev. Lett. 32 (1974) 978

/3/ Dynes, R.C. and Narayanamurti,V., Phys. Rev. B. 12 (1975) 1720 and Proc. European Phys. Soc. Topical Conf. 1974, Ed. Kuper,C.G., Lipson,S.G. and Revzen,M.

/4/ Wyatt, A.F.G., Lockerbie,N.A. and Sherlock,R.A., Phys. Rev. Lett. 33 (1974) 1425

/5/ Gurevich,V.L. and Laikhtman,B.D., Zh. Eksp. Teor. Fiz. 69 (1975) 1230 (Eng. trans. Sov. Phys. J.E.T.P. 42 (1976) 628

/6/ A similar experimental and signal retrieval system has been described in some detail by : Wyatt, A.F.G., Lockerbie, N.A. and Sherlock,R.A., J. Phys.C : Solid State Phys. 9 (1976) 959 and Sherlock,R.A., Wyatt, A.F.G., and Lockerbie,N.A., J.Phys.C : Solid State Phys. 10 (1977) 2567

/7/ Pitayevski, L.P. and Levinson, Y.B., Phys. Rev. B. 14 (1976) 263

/8/ Sluckin, T.J. and Bowley, R.M., J. Phys. C, 7 (1974) 1779