Narrow-Angle Beams of Strongly Interacting Phonons

C.D.H. Williams, A.A. Zakharenko, and A.F.G. Wyatt

School of Physics, University of Exeter, Exeter EX4 4QL, UK

We demonstrate that narrow-angle phonon pulses of low energy phonons in liquid \(^4\)He are strongly interacting and rapidly come into equilibrium within a narrow cone in momentum space. The effect of collimation on such a system is to strongly reduce the axial phonon flux. This gives a method of separating high and low energy phonons.

PACS numbers: 67.40.-W 67.90.+Z 63.20

1. INTRODUCTION

Phonons in anisotropic beams can exhibit behaviours quite unlike those of isotropic distributions. In its simplest form, an anisotropic distribution of phonons occupies a cone in momentum space so it necessarily has a non-zero average momentum along the cone axis. In real space, this could be a beam, or a propagating pulse, of phonons with an angular width the same as that of the cone in momentum space (fig. 1). An example of the effect of anisotropy is the behaviour of a short phonon pulse injected into liquid \(^4\)He at temperatures low enough for ambient thermal phonons to be negligible. Such a pulse is found to break up into two spatially separated groups of phonons\(^1,2\) (fig. 2). The faster group contains low-energy (l) phonons and the slower one contains high-energy (h) phonons\(^3,4\). The h-phonons are created from the l-phonons by four phonon scattering (4pp)\(^5\) and are lost from the l-phonon group by dispersion. A model\(^6\) for this creation process is based on the theoretical prediction that the l-phonons are in thermodynamic equilibrium. In this paper we present experimental evidence that this is correct.

Isotropic systems of particles, such as atoms or phonons, in thermodynamic equilibrium due to interactions are quite familiar. So also is the behaviour of weakly-interacting particles, such as photons, which can be collimated into narrow-angle beams. In this paper we discuss the less famil-
iar behaviour of a narrow-angle beam of particles, namely phonons, which interact strongly and attain equilibrium within the beam.

If a beam of interacting particles is collimated then, after the formation stage, it diverges as it propagates because the particles scatter into unoccupied, but energetically accessible, momentum states. If the particles undergo large-angle scattering then an isotropic distribution is formed on a time-scale of several interaction times. However, the outcome is entirely different if only small-angle scattering processes are allowed. Then, if the cone-angle of the beam is the same or larger than the scattering angles, the cone-angle only slowly increases and the phonons will attain thermodynamic equilibrium with a Bose-Einstein distribution. This notion, that pulses of l-phonons in a cone interacting by three-phonon processes (3pp)\(^7,\,8\) are in equilibrium,\(^9\) is the basis of the theoretical model which describes the creation of high energy phonons from low energy ones for both short and long pulses, and predicts suprathermal densities of h-phonons.\(^11,\,12\) This paper reports an experiment that confirms this central idea. It also shows that the h-phonons interact weakly and so can be collimated into a much smaller cone-angle than the l-phonons. This experiment has some important implications, such as the possibility of creating an h-phonon pulse devoid of l-phonons.

2. EXPERIMENTAL METHOD

We investigate the interactions in a phonon pulse by seeing how it develops once it has passed through a collimator. Immediately after passing through the collimator, the pulse has a very narrow angular-width determined by the geometry. As the phonons are interacting, the angular width increases as the pulse propagates away from the collimator. The energy flux