Thermal conduction force under zero average temperature gradient

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I . Introduction

For the thermal conduction mechanism, the radiation pressure between liquid-liquid phases or liquid-solid phases under the constant temperature gradient has been studied to explain the thermal diffusion based on the phenomenological assumption of thermal conduction' s wave-like feature [1, 2]. However, under the circumstance of solid-solid phases, since the heat can indeed propagate as a wave (the second sound mode) [3, 4], it is a big question whether a similar force effect (also called second sound radiation force) exists due to the zero average temperature gradient. Besides the experimental difficulties, the nonlinearity of second sound and nonequilibrium features of the phonon systems further complicates this research [5, 6]. Here, we investigate the thermal conduction process with wave-like behaviors in dielectric crystals (corresponding to the zero average temperature gradient).

Ⅱ. Theory

As shown in Fig. 1(a-c), to investigate the thermal conduction force between solid-solid phase, our theory is based on the following assumptions. Firstly, the temperature we consider is about 10 K, a typical value that satisfies the condition that the phonon transport process is at the hydrodynamic regime for some natural crystals. Meanwhile, we assume the collisions between phonons are sufficiently frequent that local equilibrium can be established for the phonon system. Next, we further assume there is a fixed spherical impurity particle with a radius of a along the direction of wave propagation in the crystal, and the boundary of the particle is adiabatic. Combining the Debye model and considering the wave propagation along z axis, the second sound radiation force can be obtained,

$$F = -\iint \sum_{q} \hbar q_z v_z (f - f_0) dS, \qquad (1)$$

where $\hbar$, q, v, f, f_0 here represent the Planck constant, wave vector, and group velocity of phonon, the local equilibrium distribution function, and the equilibrium distribution function, respectively.

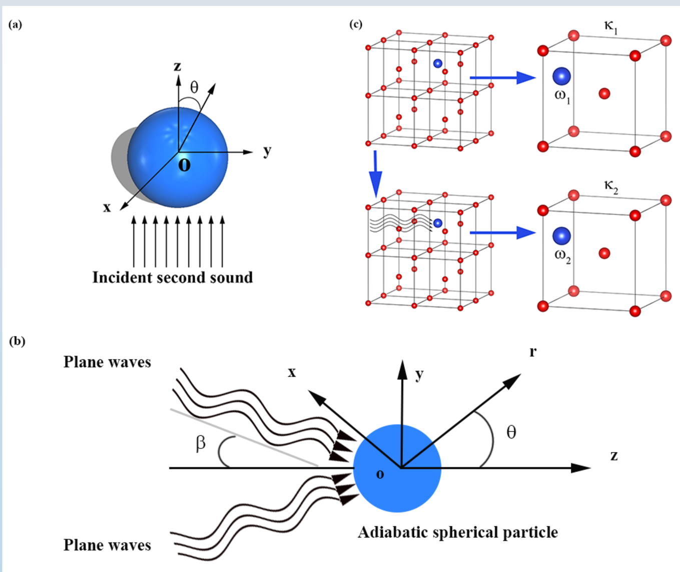

Fig. 1 Scheme diagram of: (a) coordinate axes; (b) Bessel second sound; (c) local thermal conductivity tuner..

II. Applications

As applications of the theory, we research the second sound radiation force (represented by the radiation force per unit cross section and unit energy Y) of three different wave profiles, as shown in Fig. 2(a-c). Amazingly, we find the radiation force can be opposite to the wave propagation direction.

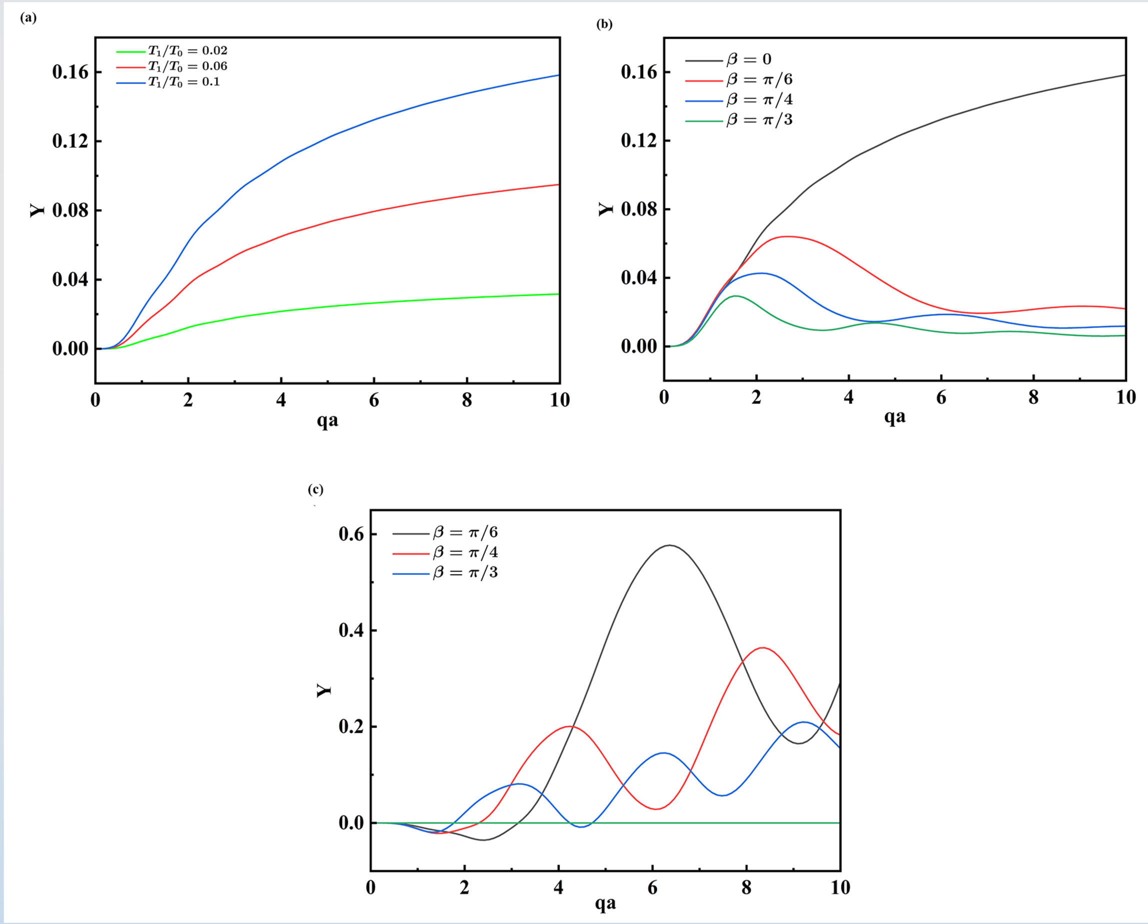

Fig. 2 Numerical Simulation results for three different wave profile: (a) plane second sound; (b) zero-order Bessel second sound; (c) one-order Bessel second sound

III. Higher-order results

Moreover, based on the theory established above, we research the second sound radiation force for higher-order Bessel second sound. The numerical simulation results is shown in Fig. 3(a-c). Likewise, we find the radiation force can also be opposite to the wave propagation direction as before.

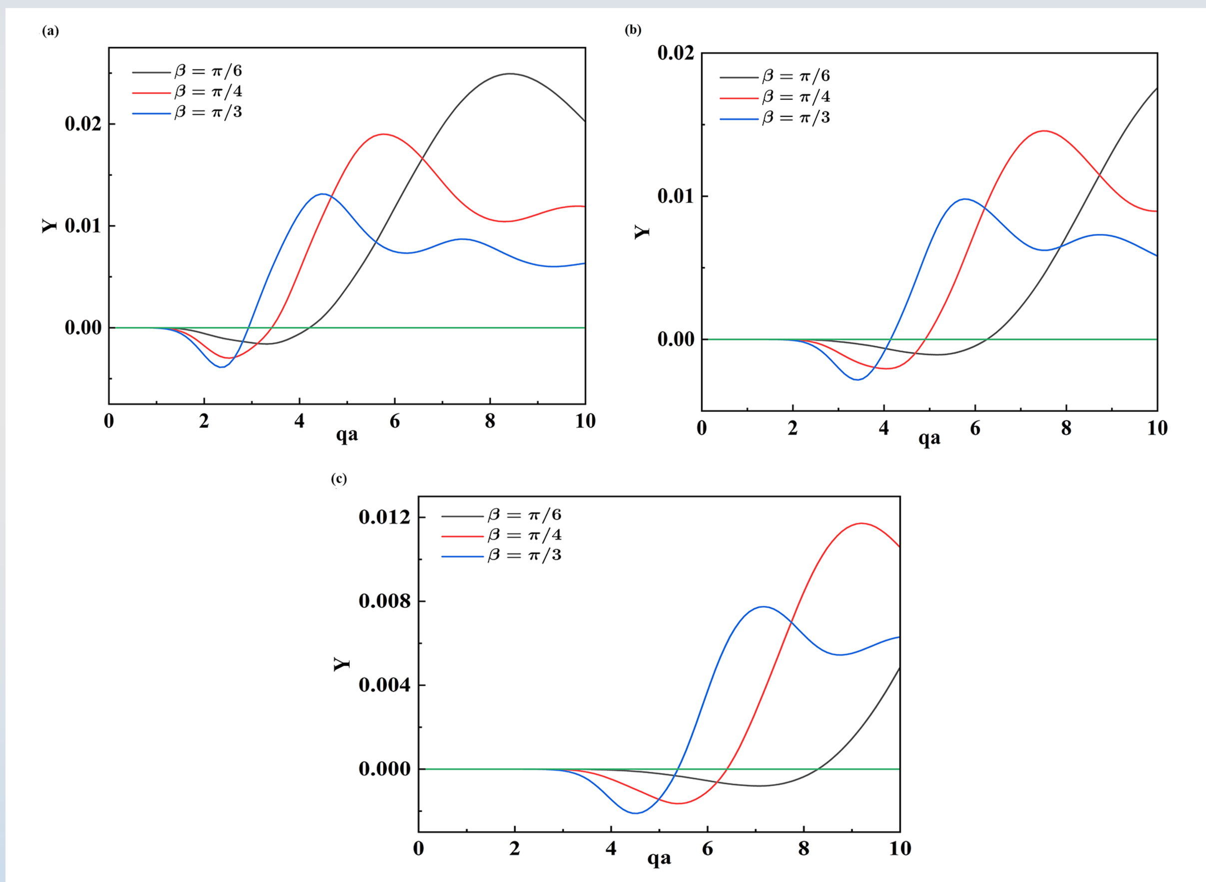

Fig. 3 Numerical simulations of higher-order Bessel second sound radiation force:
(a) two-order second sound; (b) three-order Bessel second sound; (c) four-order Bessel second sound

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