Hydrodynamic heat transport regime in bismuth: a theoretical viewpoint

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Currently, a lot of attention is devoted to the study of phonon-based heat transport regimes in nanostructures. Of particular interest is the hydrodynamic regime, in which a number of fascinating phenomena such as Poiseuille's phonon flow and second sound occur, and where temperature fluctuations are predicted to propagate as a true temperature wave of the form $e^{i\,(\mathbf{k}\cdot\mathbf{r}-\omega t)}$. Together with solid helium and NaF, bismuth is one of the rare materials in which second sound has been experimentally observed, and regimes of heat transport vary with the increase of the (yet cryogenic) temperature: from heat transport via ballistic phonons, to the regime of Poiseuille's flow with second sound, to the diffusive (Fourier) propagation [1].

In this work [2,3], a major advance consists of accounting for the phonon repopulation by the normal phonon-phonon processes in the framework of the exact variational solution of the Boltzmann transport equation, coupled to the ab initio description of anharmonicity: three-phonon collisions turn out to be particularly strong at low temperatures and lead to the creation of new phonons in the direction of the heat flow (normal processes), which enhance the heat transport. This induces time and length scales over which heat carriers behave collectively and form a hydrodynamic flow that cannot be described by independent phonons with their own energy and lifetime.

Our exact calculations predict the occurrence of this Poiseuille phonon flow between ≈1.5 and ≈3.5 K, in a sample size of 3.86 and 9.06 mm, consistent with the experimental observations. Hydrodynamic heat flow characteristics are given for any temperature: heat wave propagation length, drift velocity, and Knudsen number. We finally discuss a Gedanken experiment allowing us to assess the presence of a hydrodynamic regime in any isotopically pure bulk material.

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