Ballistic Phonon Trajectories in Heat Distribution

Diego A. Juarez[1], Jorge A. Muñoz[1], Daniel R. Ladiges[2]

[1]Department of Physics, The University of Texas at El Paso, El Paso, TX, 79968

[2]Center for Computational Sciences and Engineering, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720

Abstract

This work presents results from simulations using AMReX-enabled code libraries for stochastic hybrid models and algorithms for fluids (FHDeX)- *Phonon Detector* . The simulations are based on an experiment of heat guiding and focusing via ballistic phonon transport in phononic nanostructures [1]. The phonon source was varied within the plane to detect different frequencies and lifetimes, and wall parameters like surface roughness and temperature were adjusted, aiming at future dark matter detection.

AMReX

AMReX is a framework for writing massively parallel, block-structured adaptive mesh refinement (AMR) applications.

Phonon Detector Experiment

From Figure 1, three lasers are identified: two green metallic ones and one yellow. The yellow laser emits light onto the pink pad, generating phonons that travel ballistically through the green plane. These phonons interact with the walls, either diffusively or specularly, before reaching one of the two red walls. The red walls, also targeted by the green lasers, detect the impact of these phonons.

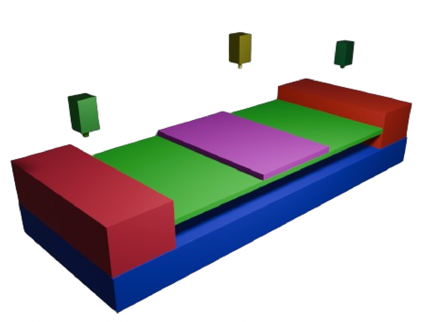

Figure 1: Illustration of Phonon Detector Experiment

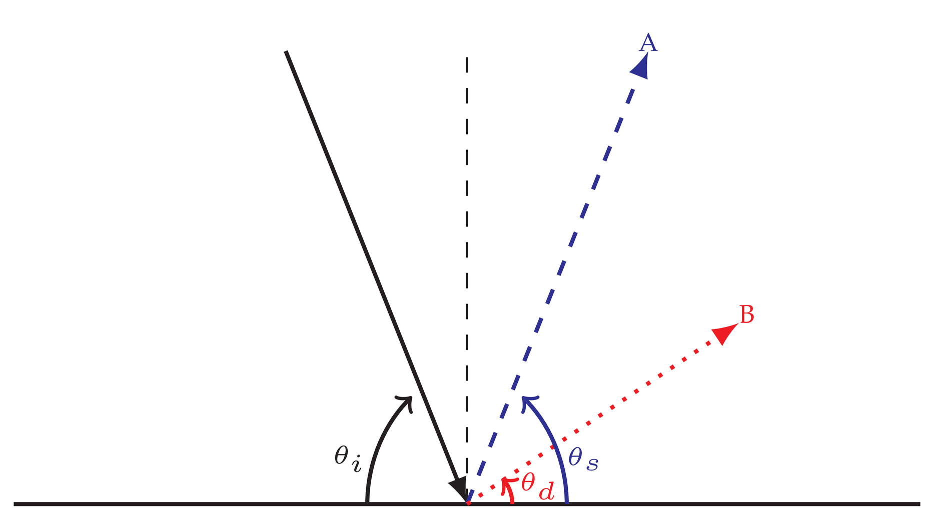

Figure 2: **A)** Specular interaction **B)** Diffusive interaction

Simulations Features

Adjusting the Parameters

Phonons are generated stochastically using Planck's distribution:

$$B(\omega, T) = \frac{3\hbar}{2\pi^2 \nu_D^3} \frac{\omega^3}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1} \tag{1}$$

To determine whether the phonon-wall interaction is either diffusive or specular, the code employs the following probabilistic equation:

$$p = \exp\left(-16\pi^2 \left(\frac{\eta}{\lambda}\right)^2 \cos^2 \alpha\right) \tag{2}$$

A series of simulations was performed employing the values detailed in Tables 1 and 2

Positioning the Phonon Source within the Plane

By adjusting the position of the phonon source within the plane, the trajectories of the phonons can be guided. This allows for the observation of changes in phonon detection, as well as variations in their frequencies and lifetimes.

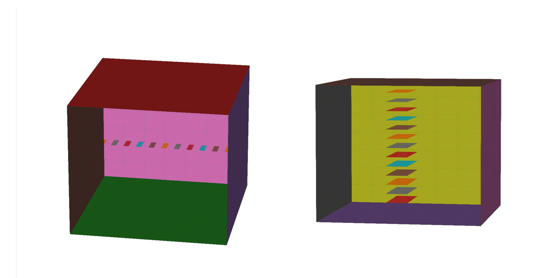

Figure 6: Variation in the position of the phonon source within the plane.

Different simulations were conducted with two different position of the source:

- In the first configuration, the phonon source was positioned directly in front of the detector wall (red square).
- In the second configuration, the phonon source was placed on the opposite side of the detector wall (blue square).

These setups are illustrated in Figure 4 and results in graph 5

Research Question

Can Phonon Detection Be Used to Detect Dark Matter?

Experimental schematics

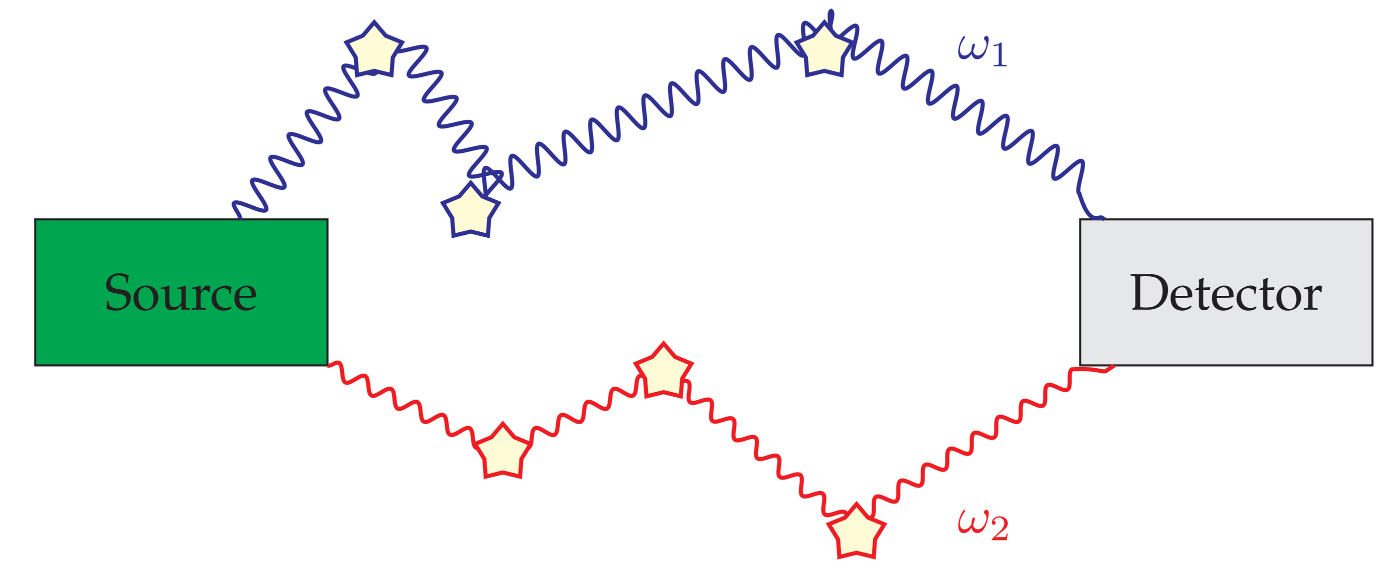

Figure 3: Illustration of two different frequency phonons. Stars represent phonon-wall collisions, while the blue and red serpentine paths trace the trajectories of the phonons. It highlights how differences in scattering probability affect the total distance traveled. High-frequency phonons scatter more, taking a longer path, while low-frequency phonons scatter less, traveling a shorter distance.

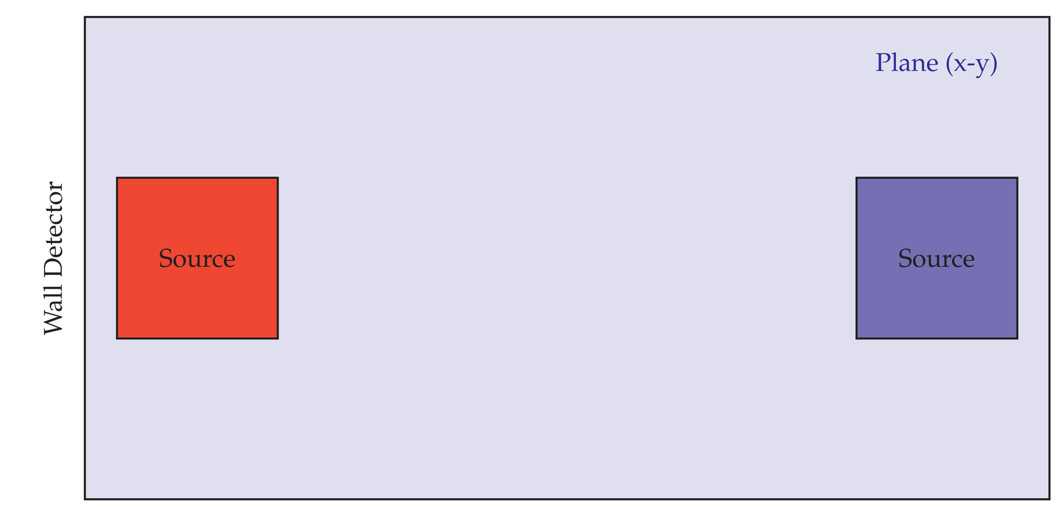

Figure 4: Diagram Illustrating Experiment Positioning the Phonon Source Within Plane.

Results

Temperature (K)	Specular Fraction Average
0.2	0.99725
0.4	0.99033
10	0.1828
20	0.05225
40	0.01343
100	0.00162

Table 1: Temperature at Roughness $2 \times 10^{-7} m$

Roughness (m)	Specular Fraction Average
2×10^{-05}	0.00000
2×10^{-06}	0.00016
2×10^{-07}	0.01344
2×10^{-08}	0.54879
2×10^{-09}	0.98913
2×10^{-10}	0.99989

Table 2: Roughness at temperature 40 K

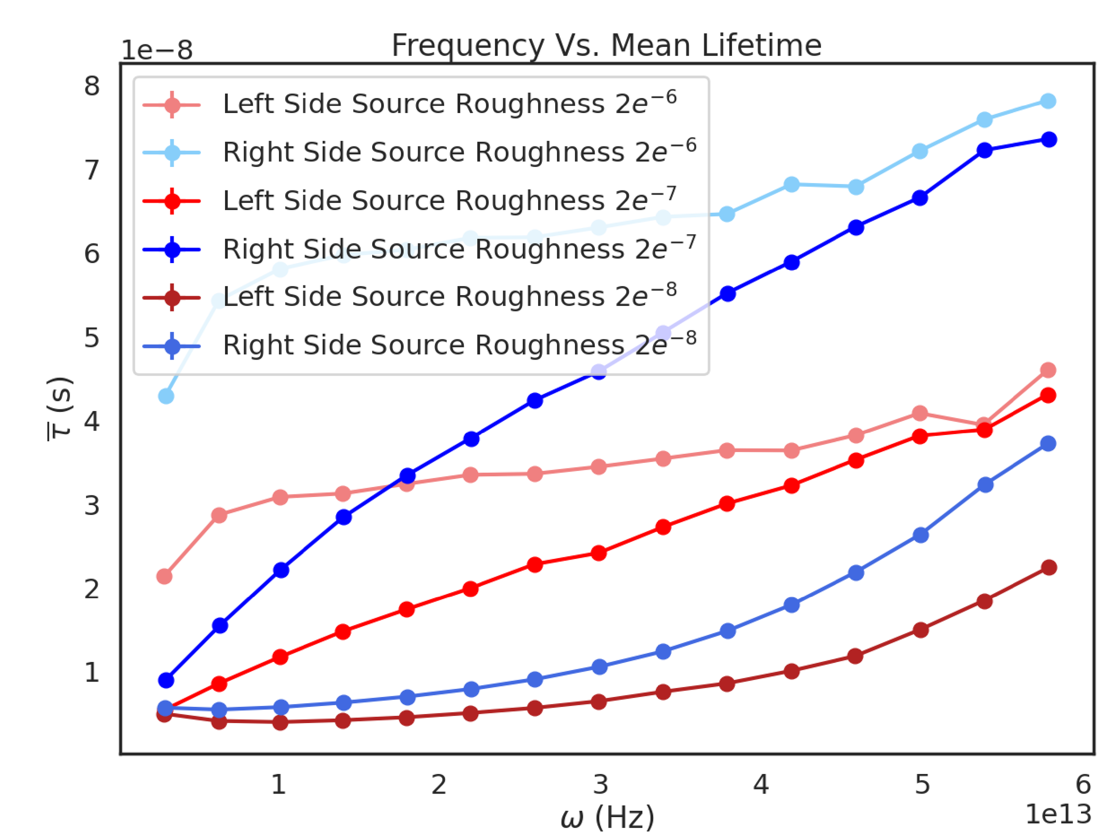

Figure 5: Frequency Vs. Mean Lifetime, Experiment Positioning the Phonon Source within plane, with different Roughness Surface at Temperature $40K$.

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References

[1] Jeremie Maire Roman Anufriev, Aymeric Ramiere and Masahiro Nomura. Heat guiding and focusing using ballistic phonon transport in phononic nanostructures. *Nat. Commun.*, 8:15505, May 2017.