Sonic Compton scattering in an analogue gravity model

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Analogue gravity models provide an indirect way to probe the physics of relativistic systems for which the actual (i.e., non-analogue) experiments are currently inaccessible, provided that the analogue model can be faithfully mapped to the actual physical system of interest. Here, we investigate a simple toy model of phonon scattering from a Newtonian particle as an analogue to Lorentz-violating Compton scattering. In particular, we wish to know what *in-universe observers* – observers who use sound in their analogue gravity medium to operationally measure distance and duration [1] – can determine from carrying out scattering experiments of this kind. Unsurprisingly, the Newtonian particle appears to be a Lorentz-violating particle to in-universe observers; scattering experiments from these particles can be used by in-universe observers to determine their absolute state of motion with respect to the medium.

Hawking's famous result that black holes should act as black-body emitters was built on assumptions whose validity is questionable. Unruh used a hydrodynamical model as a sonic (or acoustic) analogue to a black hole to study, by analogy, how a breakdown of these assumptions might manifest (provided, of course, that the analogy is appropriate) [2]. This started the modern day analogue gravity research effort, and follow-up work by Unruh and others suggests that Hawking's result should be robust to a breakdown of his original assumptions.

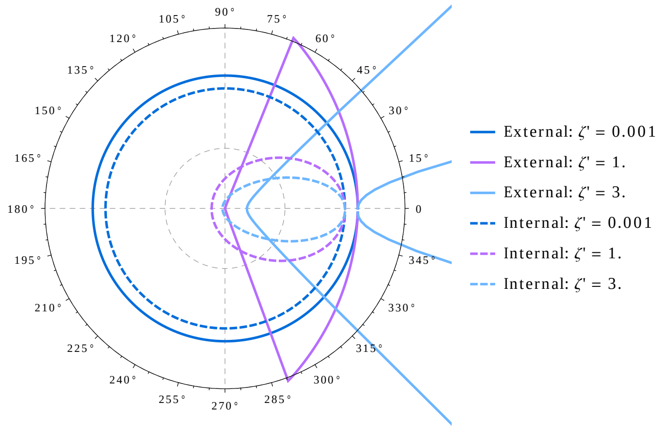
In an effort to understand how far analogue gravity models can be pushed, we investigate a toy model of Lorentz-violating Compton scattering and compare it with a toy model of Lorentz-obeying Compton scattering. We start with an analogue-gravity medium whose excitations are phonons that we treat as a scalar field; the phonon field obeys the Klein–Gordon equation and thus admits a (sonic-)Lorentz symmetry with characteristic speed c_s the speed of sound in the analogue gravity medium. The frame in which the analogue gravity medium is stationary defines the *laboratory frame*, and it is in this frame that we define all of our dynamical physical quantities and perform all calculations. In the laboratory frame, the phonon dispersion relationship is $E = pc_\mathrm{s}$ with $\mathbf{p} = \hbar\mathbf{k}$.

We then separately consider phonon scattering from two types of particles:

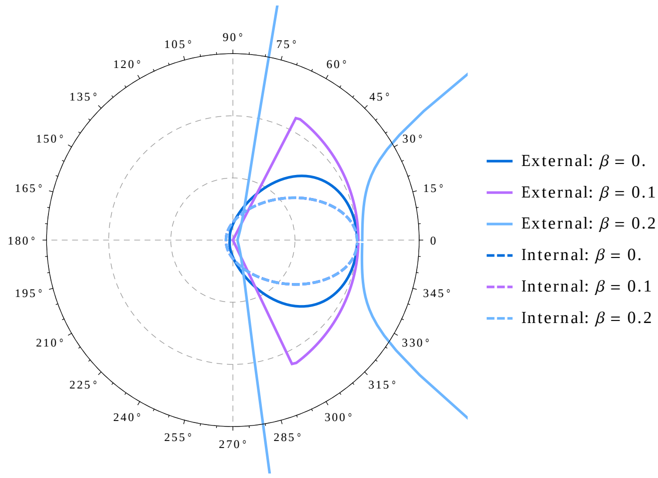
i. *Internal particles* possess a sonically-relativistic dispersion relationship $\gamma_\mathrm{s}^2 E^2 = \gamma_\mathrm{s}^2 p^2 c_\mathrm{s}^2 + m^2 c_\mathrm{s}^4$ (where here E and $\mathbf{p}$ have their usual Newtonian definition and are measured in the laboratory frame, and γ_s is the sonic Lorentz-factor which is defined as per the usual Lorentz factor but with characteristic speed c_s the speed of sound);

ii. *External particles* possess a Newtonian dispersion relationship $E = p^2/2m$ (where, again, E and $\mathbf{p}$ have their usual Newtonian definition).

By performing the sonic analogue to Compton scattering from external particles, in-universe observers can determine their state of motion with respect to their medium. By comparison, phonon scattering from internal particles is a process that is entirely Lorentz obeying, and reveals nothing to in-universe observers about their state of motion with respect to their medium.



(a) $\beta := v/c_\mathrm{s} \approx 0.3106$. For scattering from external particles, $\zeta' = 0.001$ results in scattering at all angles; $\zeta' = 1$ is a critical value for which scattering is restricted to a closed window of angles; $\zeta' = 3$ is past the critical value of ζ': here we see two disjoint curves, though only the "inner" (or rightmost) such curve is physical. Note that in this plot we have $\zeta' := \hbar\omega'/mc_\mathrm{s}^2$, where ζ and ω are primed, i.e. these are co-moving in-universe observer frame measured values.



(b) $\zeta := \hbar\omega/mc_\mathrm{s}^2 = 1.8$. For scattering from external particles, $\beta = 0$ results in scattering at all angles; $\beta = 0.1$ is a critical value for which scattering is restricted to a closed window of angles; $\beta = 0.2$ is past the critical value of β: here we see two disjoint curves, though only the "inner" (or rightmost) such curve is physical. Note that all of the dashed curves sit on-top of one another. Finally, note that ζ and ω are unprimed, i.e. these are laboratory frame measured values.

Figure 1: Differential scattering cross-sections of phonons scattering from external (solid) and internal (dashed) particles in the co-moving in-universe observer frame where **(1a)** phonons have different initial energies and particles have fixed initial velocity, and **(1b)** phonons have fixed initial energy and particles have different initial velocities.

References

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[2] Unruh, W. G., "Experimental Black-Hole Evaporation?," Physical Review Letters **46**, 1351–1353 (1981).