Scattering of co-current surface waves on an analogue black hole

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Analogue gravity grew out of Unruh's insight [1] that, using the mathematical equivalence between wave propagation in curved spacetimes on the one hand and in condensed matter systems on the other, one can realize an analogue black hole in the laboratory and test Hawking's prediction that black holes emit radiation [2]. In this context, an analogue black hole is engendered by an accelerating flow which at some point becomes supersonic. The point where the flow crosses the speed of sound is the (acoustic) horizon for sound waves, in analogy with the (event) horizon for light at a gravitational black hole. Because wave propagation close to the horizon is equivalent in the two cases, the Hawking effect, which is derived from purely kinematical considerations, should be present also in the analogue system. This prediction has been the main driving force behind the analogue gravity program since its inception, with experimental studies in a wide range of physical systems [3,4].

One such example concerns surface waves on an effectively one-dimensional flow over an obstacle [5], and in recent years there have been several experiments probing various aspects of this analogue system [6-8]. However, none of these experiments worked in the transcritical regime where the mapping of the flow to a black-hole metric is valid. Short-wavelength dispersion therefore plays an important role in determining the scattering coefficients, breaking the analogue of Lorentz invariance and yielding a non-thermal Hawking spectrum [9]. Moreover, previous experiments have tended to focus on the blueshifting of waves associated with scattering at the "white hole" (i.e. decelerating) part of the flow. Although this is experimentally convenient as the relevant products of the scattering are short waves whose amplitudes are easier to extract, decelerating flows are associated with the production of a stationary undulation which resonates with the waves, thereby complicating the scattering [10].

We have realized – for the first time in an analogue gravity context – a transcritical flow in a flume, which maps to a $1+1$-dimensional spacetime metric with the analogue of a black-hole horizon and does not contain an undulation. The spacetime has been probed via the scattering of incident co-current waves sent by a wave maker in the upstream region, a process analogous to that by which a black hole absorbs infalling matter except that we here have access to the "interior" (i.e. supercritical) region. The incident wave partially scatters into counter-current waves on either side of the horizon, yielding a total of three outgoing waves (one of which has negative energy) and thereby corroborating the existence of the horizon. We have extracted the scattering coefficients describing the process, finding them to be in good agreement with the predictions of the hydrodynamical model in which the effective metric description is exact. Furthermore, the reflection coefficient is directly related to the "grey-body factor" which dresses the would-be Hawking spectrum, and we are thus able to comment on the corrections it would induce. Finally, by analogy with the density-density correlation function proposed as a means of detecting Hawking radiation in Bose-Einstein condensate analogues [11], we use the acquired data to artificially construct the two-point correlation function of free-surface deformations due to a thermal distribution of incident co-current waves. This construction shows the emergence of characteristic peaks in the correlation function which illustrate the emission of correlated quasiparticles on both sides of the horizon.

References

[1] W. G. Unruh, "Experimental black-hole evaporation?" Phys. Rev. Lett. **46**, 1351 (1981)
[2] S. W. Hawking, "Particle creation by black holes," Comm. Math. Phys. **43**, 199 (1975)
[3] C. Barcelò, S. Liberati, and M. Visser, "Analogue gravity," Living Rev. Relativ. **14**, 3 (2011)
[4] C. Barcelò, "Analogue black-hole horizons," Nat. Phys. **15**, 210 (2019)
[5] R. Schützhold and W. G. Unruh, "Gravity wave analogues of black holes," Phys. Rev. D **66**, 044019 (2002)
[6] G. Rousseaux, C. Mathis, P. Maïssa, T. G. Philbin, and U. Leonhardt, "Observation of negative-frequency waves in a water tank: a classical analogue to the Hawking effect?" New J. Phys. **10**, 053015 (2008)
[7] S. Weinfurtner, E. W. Tedford, M. C. J. Penrice, W. G. Unruh, and G. A. Lawrence, "Measurement of stimulated Hawking emission in an analogue system," Phys. Rev. Lett. **106**, 021302 (2011)
[8] L.-P. Euvé, F. Michel, R. Parentani, T. G. Philbin, and G. Rousseaux, "Observation of noise correlated by the Hawking effect in a water tank," Phys. Rev. Lett. **117**, 121301 (2016)
[9] S. Robertson, F. Michel, and R. Parentani, "Scattering of gravity waves in subcritical flows over an obstacle," Phys. Rev. D **93**, 124060 (2016)
[10] F. Michel, R. Parentani, and S. Robertson, "Gravity waves on modulated flows downstream from an obstacle: The transcritical case," Phys. Rev. D **97**, 065018 (2018)
[11] R. Balbinot, A. Fabbri, S. Fagnocchi, A. Recati, and I. Carusotto, "Nonlocal density correlations as a signature of Hawking radiation from acoustic black holes," Phys. Rev. A **78**, 021603 (2008)