Hawking radiation: Evidence meets speculation

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Abstract

Scientist predicted the existence of quantum Hawking radiation and now he measures the entanglement of the Hawking pairs in an analogue black hole --- A theory which was almost impossible to verify in actual black hole has recently got its experimental confirmation in analog system.

Human assumption, calculation, logical deduction and experimental observation complete the new challenges in science. The begining of the modern classical era starts in seventeenth century with the works of Sir Issac Newton[1] . In spite of the glamorous success of the classical physics in resolving various questions of nature, it completely failed in explaining the physics in subatomic domain. Around the begining of the twentieth century, the ultimate excellence and enthusiasm of a group of scientiests gave birth to a new theory of physics-- Quantum physics, which revolutionised the past concepts and built the foundation of today's modern physics[2,3]. In the year 1905, Albert Einstein[4], a famous German physicist published four ground breaking papers on the photoelectric effect, Brownian motion, special relativity, and the equivalence of mass and energy preceding his 1915 proposal of the general theory of relativity[5]. Thereafter, science has travelled a long way being based on the twin pillars of physics applicable in two different realms of physics --- physics on large scale: the general theory of relativity and the physics on a small scale: the weird and enigmatic world of quantum, though the clash between these two incompatible fundamental theories has been persisting for more than a century. In course of time numerous conceptual and theoretical developments have established the intriguing field of quantum gravity with the aim in describing gravity successfully with the theory of quantum mechanics.

In the year 1973, J. D. Bekenstein, a Mexican-American theoretical physicist, realized that the black hole has entropy as well as effective temperature and introduced the field of black hole thermodynamics[6]. Next year, combining quantum field theory with curved space time near a black hole, S. W. Hawking, an English theoretical physicist came with a bunch of brilliant theories[7] where he showed that the black hole should emit the radiation with the temperature as suggested by Bekenstein. This is accompanied by the emission of thermal distribution of particles from the black hole event horizon and each Hawking particle is entangled with a patner particle falling into the black hole. This surprising new discovery presented a new puzzle of information loss and unitarity of quantum physics[8] encouraging the verification of the existence of finite entanglement between the infalling and outgoing particles of Hawking pairs. But, the extremely weak Hawking radiation from a black hole prevented any experimental confirmation and the observation of both sides of a real black hole event horizon was practically impossible .

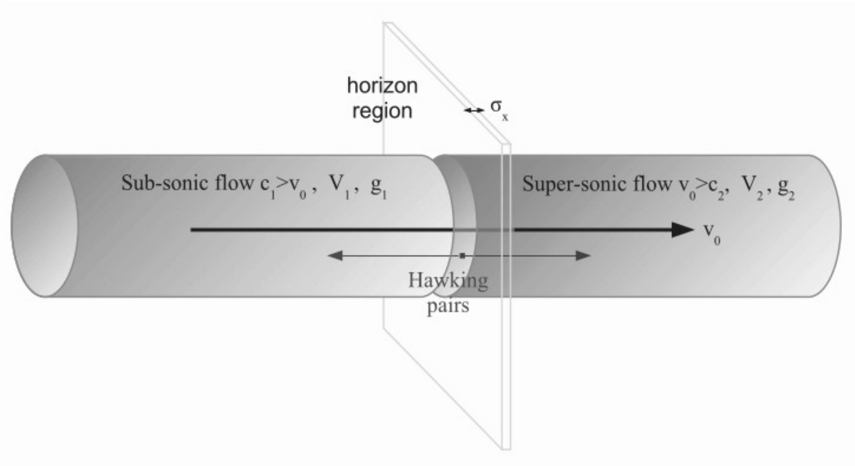

Figure 1 | Schematic diagram of physical system (One dimensional moving atomic Bose-Einstein condensed system) acting as acoustic black hole taken from Carusotto L. et al[9]. 'c_1' and 'c_2' indicate the speed of phonons outside and inside the horizon. The external potential and the atom atom interactions are denoted by 'V' and 'g' respectively. A step like spatial modulation of thickness 'σ_x' is applied for creating the horizon in this analog system. Outside the black hole the fluid flow 'v_0' is subsonic and inside it is supersonic. The horizon emits Hawking particles (i.e., phonons in case of acoustic black holes) which are entangled with its negative energy partner particles going inside the black hole.

In 1981, W. G. Unruh[10], a Canadian physicist, came up with the notion of analog black hole where, on the basis of analogy between propagation of waves in moving inhomogeneous media and porpagation of waves on a curved space time background, he proposed that any system which develops a horizon for some wavy perturbation can be considered as an analog system for a real black hole. In particular, this analog black-hole configuration contains a sonic horizon seperating a region of subsonic flow (velocity of the flow is smaller than the speed of sound) outside the black hole and a supersonic flow (fluid flows at a higher speed than that of sound) inside a black hole (Fig. 1) such that the phonons (quanta of sound waves) at the outside of black hole can travel against the fluid flow and eventually can escape the sonic black hole and the phonons that are inside are trapped and can't reach the horizon. Since, it is sound waves rather than light waves in real black hole that can't escape the horizon, this analog system is often termed as sonic black holes. These revolutionary findings made the idea of experimental confirmation of Hawking radiation plausible and over past several years many systems e.g. superfluid liquid helium, Bose-Einstein condensates, degenerate Fermi gases, surface waves in water tank, an electromagnetic waveguide etc. have been proposed as candidates for actual experimental detection of Hawking radiation though the studies remained limited to only the theoretical observation[9,11] of Hawking radiation. Theoretical studies of density-density correlation[12] function between the distant points in space on the opposite sides of the horizon not only confirmed the entanglement of Hawking pairs in high energy tail of Hawking distribution but it also brought a new opportunity towards the experimental detection of Hawking radiation in near future..

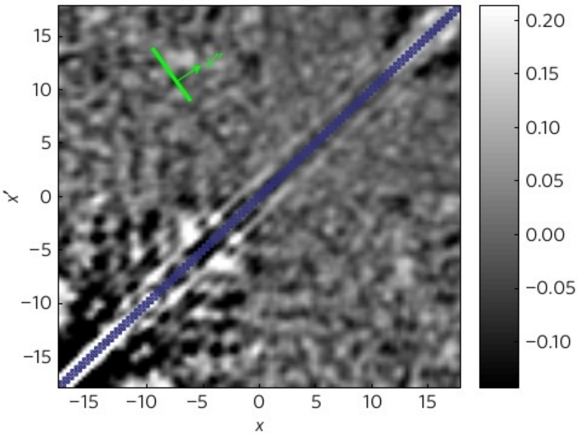

Figure 2 | Observation of Hawking/Partner pairs. J. Steinhauer[15] reports the measurement of two body correlation function between pairs of points (x,x') along the analog black hole. The diagonal region shaded in blue encounters smoothing effect due to filtretion to remove the unwanted noises during experiment. Upper left and lower right quadrants show the correlations between points of opposite sides of the horizon, horizon being at the origin. The dark band of these points is visible emenating from the horizon.

In 2010, Lahav et al.[13] first successfully created an analog black hole in a BEC of ^{87}Rb atoms which acted as sonic black hole. Following this, in 2015 Jeff Steinhauer, a scientist from Technion- Israel Institute of Technology observed self amplifying Hawking radiation[14] in the analogue system of a charged black hole where black hole event horizon is followed by an inner horizon. In this work, the interference between negative energy Hawking partner particle and the negative energy particles reflected from the inner horizon was reported. But the surprise undoubtedly had to come! The observation of density density correlation function which was still limited upto the theory, has recently acheived its experimental justification through August-2016 observation[15] by the Steinhauer. He observes the spontaneous Hawking radiation stimulated by quantum vacuum fluctuations emanating from a sonic black hole of BEC ^{87}Rb atoms and measures the density density correlation function which confirms the entanglement of high energy Hawking pairs. This correlation function is computed from an ensemble of 4600 repetations of the experiment. The upper left and lower right quadrants of Fig. 2 show this correlation. Since such correlation exists in a real black hole within Hawking's approximation, this measurement provides an interesting verification of Hawking's calculation and has a profound consequence in the field of quantum gravity.

In his experiment, Steinhauer makes the horizon to oscillate at a definite frequency generating correlated waves travelling inwards and outwards from the horizon. This oscillating horizon is equivalent to incoming particles and is governed by the Hawking temperature. He observes that the long-wavelength Hawking pairs are less correlated than expected and a broad energy spectrum of entangled Hawking pairs is observed with decreasing entanglement for decreasing energy. Moreover, the measured population of real and virtual phonons emanating from analog black hole agrees reasonably well with the theoretical distribution of Hawking radiation at $k_B T_H = 0.36mc^2_{out}$. This measurement also determines the Hawking temperature of 1.2 nK which is well within the upper limit of 2.7 nK for quantum entanglement verifying the quantum nature of the experiment.

Although there is a long way to go before resolving all the puzzles of information loss in a real black hole, Steinhauer's 2016 experimental observation is a remarkable achievement through which the confluence between theoretical insight and experimental realisation once again has become possible.

References

1. Newton, I. *Philosophiae naturalis principia mathematica*, Imprimatur S. Pepys, Reg. Soc. Praeses, juHi 5, 1686, Londini anno MDCLXXXVll (1687).
2. Planck, M. *The theory of heat radiation*, second edition, translated by M. Masius, Blakiston's Son & Co, Philadelphia, pages 22, 26, 42, 43 (1914).
3. *Schrödinger, E. An Undulatory Theory of the Mechanics of Atoms and Molecules*, Phys. Rev., ***28** (6), 1049-1070 (1926).*
4. Einstein, A. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt. Annalen der Physik (1905).*
5. Einstein, A. *Die Feldgleichungen der Gravitation*. Königlich Preussische Akademie der Wissenschaften, 844-847 (1915).
6. Bekenstein, J. D. *Blackholes and entropy*, Phys. Rev. D **7**, 2333-2346 (1973).
7. Hawking, S. W. *Black hole explosions?* Nature **248**, 30–31(1974). Hawking, S. W. *Particle creation by black holes*. Commun. Math. Phys. **43**, 199–220 (1975). Hawking, S. W. *Breakdown of predictability in gravitational collapse*. Phys. Rev. D **14**, 2460–2473 (1976).
8. Susskind, L. *The paradox of quantum black holes*. Nature Phys. **2**, 665–677 (2006).
9. Carusotto, L., Fagnocchi, S., Recati, A., Balbinot, R. And Fabbri, A. *Numerical observation of Hawking radiation from acoustic black holes in atomic Bose-Einstein condensates*. New J. Phys. **10**, 103001 (2008).
10. Unruh, W. G. *Experimental black hole evaporation?* Phys. Rev. Lett. **46** 1351 (1981).
11. Giovanazzi, S. *Hawking radiation in sonic black holes.* Phys. Rev. Lett. **94**, 061302 (2005). Recati, A. , Pavloff, N. & Carusotto, I. *Bogoliubov theory of acoustic Hawking,radiation in Bose–Einstein condensates*. Phys. Rev. A **80**, 043603 (2009). Zapata, I., Albert, M., Parentani, R. & Sols, F. *Resonant Hawking radiation in Bose–Einstein condensates*. New J. Phys. **13**, 063048 (2011).
12. Steinhauer, J. *Measuring the entanglement of analog Hawking radiation by the density-density correlation function.* Phys. Rev. D **92**, 024043 (2015).
13. Lahav, O. Et al. *Realization of a sonic black hole analog in a Bose-Einstein condensate.* Phys. Rev. Lett. **105**, 240401 (2010).
14. Steinhauer, J. *Observation of self-amplifying Hawking radiation in an analogue black hole laser.* Nature Phys. ***10,*** 864-869 (2014).
15. Steinhauer, J. *Observation of quantum Hawking radiation and its entanglement in an analogue black hole. Nature Phys. (2016).*