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Maxime J. Jacquet

Negative Frequency at the Horizon

Theoretical Study and Experimental Realisation of Analogue Gravity Physics in Dispersive Optical Media

Doctoral Thesis accepted by
the University of St. Andrews, St. Andrews, UK

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Supervisor's Foreword

The two outstanding physical theories of the twentieth century are the theory of general relativity and the theory of quantum mechanics. Both of these have transformed our understanding of nature. General relativity is associated with large scales (the cosmos) and quantum mechanics is considered valid on small scales (the atom). They have led to remarkable success such as the understanding of binary pulsar dynamics or the detection of gravitational waves for relativity and the calculation of atomic orbits and the discovery of nonlocality for quantum mechanics. These theories are, however, more than merely approximations at different scales and as such do not offer an absolute length scale. In fact, they are notoriously difficult to combine without inevitable paradoxes. The question arises, whether quantum mechanics and general relativity could play a role on equal length scales simultaneously and which theory would describe this. Black holes are often portrayed as combining both sides, and thus as a benchmark for future theories of quantum gravity.

Black holes are a consequence of Einstein's theory of general relativity from 1915. Within months, Schwarzschild found that this theory would predict a gravitational field of a point mass, a black hole. The gravitational field in the vicinity of this point mass would be strong enough to capture all particles, even photons, i.e. light. The range over which the particles are captured is limited by the event horizon, which separates the—possibly—escaping fields from the fields falling into the black hole. Thus, the event horizon signifies the size of the black hole. Outside, the object would not emit light and be 'black'.

This was how black holes were viewed until 1974, when Stephen Hawking considered quantum fields around the event horizon. In a groundbreaking paper, Hawking showed that quantum effects would lead to the emission of particles from black holes, 'Hawking radiation'. This effect would be fuelled by the mass of the black hole and even intensify as the black hole mass reduces, leading to a final explosion of particles in the last phase of 'black hole evaporation'. At last, an object was found that leads to profound physical effects if the two theories are combined. Until now, Hawking's prediction has not been experimentally verified. The universe is a large laboratory, but we cannot isolate a black hole to perform measurements. In fact, it turns out that the cosmic microwave background is far stronger than Hawking radiation. Although the radiation exists and can be detected efficiently, the background radiation is too strong.

In physics, the observable effects are described by equations. Each equation, however, can describe different physical systems, and so it is possible to transfer the same physics from one system to another. In 1981, Bill Unruh discovered that fluid flow of water can simulate an event horizon and, in consequence, must emit 'analogue Hawking radiation' in the form of sound waves. Although this particular system is impractical too, it demonstrated in principle that Hawking radiation can be detected in a terrestrial laboratory without background noise. Since, various methods have been proposed for the production of analogue Hawking radiation in a variety of systems, such as Bose–Einstein condensates, polariton condensates or nonlinear optics. After all, the detection of the elusive Hawking radiation seems within reach.

A realisation in optics leads to the highest expected particle emission, the highest effective temperature and no thermal background. Maxime's thesis is devoted to this elegant variant of analogue Hawking radiation. The thesis is presented in a form accessible to interested undergraduate and postgraduate students. Maxime is a passionate science communicator and gives a full account of the topic in an introductory and clear way. Starting with the basis of special relativity, the thesis introduces the relevant concepts of general relativity, focusing on wave motion at the horizon. In particular, he introduces the thermodynamic physics of black holes and derives Hawking's seminal result. The thesis then systematically introduces a field-theoretical framework for optical analogues, including the kinematics governing the fields, for light–matter interaction in a dispersive medium. This model allows for an analytical calculation of the all-important conversion of vacuum fluctuations into Hawking radiation. For the first time, coupling to non-optical branches and all kinematic configurations are included in the description. Based on this, emission spectra and intensities are calculated which give unprecedented insight into the emission from a highly dispersive system, both from a theoretical as well as experimental point of view. Maxime also introduces the relevant concepts for fibre-optical analogues, such as soliton formation and propagation, as an experimental means to produce optical horizons.

In an experimental part, the thesis develops a clear and systematic way to experimentally approach the problem. Based on the formalism developed in the thesis, Maxime analyses the possibility to obtain an experimental signal of detectable strength, including aspects of spectral resolution and quantum efficiency. He then demonstrates the construction of an experimental setup and measurements of unprecedented sensitivity in the search for stimulation of the Hawking effect.

Major parts of the thesis were presented at key international conferences receiving great interest. The thesis itself was refereed by the 'founding father' of the field, Prof. William Unruh, Vancouver. Optical Hawking radiation has become more tangible due to Maxime's work and it is exciting times to possibly witness the first detection of optical Hawking radiation, unfortunately too late for Stephen Hawking. Yet, it is more than satisfying to see the enthusiasm of a new generation of future academics.

We gratefully acknowledge the support by the EPSRC for this research.

St. Andrews, UK
March 2018

Dr. Friedrich König

Abstract

Quantum vacuum fluctuations on time-dependant-curved spacetimes cause the emission of particles. This effect results from the mixing of positive and negative frequency waves, and its most famous instance is Hawking radiation from black holes. Unfortunately, the latter cannot be observed in astrophysics, because of its ultra-low temperature. This thesis considers the problem of recreating the physics of wave motion on curved spacetimes in the laboratory so as to enable the study the scattering of waves at the event horizon. Laboratory analogue gravity systems typically are inhomogeneous, dispersive media in which the velocity of waves may be controlled to mimic the effects of spacetime curvature. For example, this can be realised in optics. Here, I present an analytical description of spontaneous emission in optical analogues. I consider a moving refractive index perturbation in an optical medium, which exhibits optical event horizons. Based on the field theory in curved spacetime, I formulate an analytical method to calculate the scattering matrix that completely describes mode coupling leading to the emission of photon pairs in various kinematic configurations. I apply the method in a case study, in which I consider a moving refractive index step in bulk-fused silica. I calculate the emission spectrum, which is a key observable, in the moving frame as well as in the laboratory frame. I find that emission from horizons is characterized by an increased photon flux and a signature spectral shape. In particular, the spectra are dominated by a negative frequency mode, which is the partner in any Hawking-type emission. This is interesting as it has never been observed either theoretically or experimentally before. An experiment aimed at stimulating the emission into negative and positive frequency modes is assembled. The classical effect of mode conversion in this optical scheme is clearly shown to be a feature of horizon physics. These theoretical and experimental methods and findings pave the way to the observation of particles emitted from the event horizon by the Hawking effect in dispersive systems.

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As a young researcher, I was always welcomed by any member of the event horizon community I turned to. In particular, I am intellectually indebted to Stefano Finazzi, Ralph Schützhold, Bill Unruh, Silke Weinfurtner, Germain Rousseaux, Daniele Faccio and Iacopo Carusotto who were open to conversing with me. Many aspects of the thesis I wrote stem from those interactions. Special thanks go to Goëry Genty who took me aboard whilst in Varenna. In writing his lecture notes, I learnt a lot of nonlinear fibre optics.

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Cette thèse, l'écrit, le moment et l'aventure intellectuelle sont dédiés à Kahina.

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