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Optical Analogs of Hawking Radiation in the Quantum Regime

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14. ABSTRACT
In the context of this grant, we were able to obtain some interesting results. We demonstrated the first photon pair source based on the spontaneous four wave mixing (SFWM) process in fused silica micro spheres, yielding the shortest SFWM photon-pair bandwidths reported to date (Ortiz Ricardo 2021). We obtained results in terms of engineering entanglement in polarization and frequency based on SFWM in a photonic crystal fiber (de la Torre 2021). We have worked on artificial intelligence, on the one hand having developed a neural network algorithm to identify serious cases of COVID-19 (Quiroz-Juárez 2021), and a separate system to identify particle mixture though machine learning-assisted diffraction (Villegas 2022). We have demonstrated an experimental realization of an optical analogue of Hawking radiation, with an interferometric arrangement which can boost our signal by a factor of 4 (Elizarraras 2022). We have demonstrated an experiment, along with a novel analysis methodology, designed to probe organic compounds through entangled two photon absorption (Corona-Aquino 2022). We have demonstrated a quantum optical coherence microscopy device which embodies a number of key aspects drastically increasing the available signal (Yépiz-Graciano 2022). We have proposed a strategy based on NOON-state interferometry for the certification of entangled two-photon absorption (Martínez-Tapia 2023). We have presented a tutorial paper covering various aspects of fiber-based photon pairs sources, ranging from phasematching properties to photonpair characterization (Garay-Palmett 2023). Finally, we have developed a technique based on genetic algorithms for the retrieval of the internal morphology of samples, e.g. biological in nature (Li-Gomez 2023).

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Abstract: In the context of this grant, we were able to obtain some interesting results. We demonstrated the first photon pair source based on the spontaneous four wave mixing (SFWM) process in fused silica micro spheres, yielding the shortest SFWM photon-pair bandwidths reported to date (Ortiz Ricardo 2021). We obtained results in terms of engineering entanglement in polarization and frequency based on SFWM in a photonic crystal fiber (de la Torre 2021). We have worked on artificial intelligence, on the one hand having developed a neural network algorithm to identify serious cases of COVID-19 (Quiroz-Juárez 2021), and a separate system to identify particle mixture though machine learning-assisted diffraction (Villegas 2022). We have demonstrated an experimental realization of an optical analogue of Hawking radiation, with an interferometric arrangement which can boost our signal by a factor of 4 (Elizarraras 2022). We have demonstrated an experiment, along with a novel analysis methodology, designed to probe organic compounds through entangled two photon absorption (Corona-Aquino 2022). We have demonstrated a quantum optical coherence microscopy device which embodies a number of key aspects drastically increasing the available signal (Yépiz-Graciano 2022). We have proposed a strategy based on NOON-state interferometry for the certification of entangled two-photon absorption (Martínez-Tapia 2023). We have presented a tutorial paper covering various aspects of fiber-based photon pairs sources, ranging from phasematching properties to photon-pair characterization (Garay-Palmett 2023).

have developed a technique based on genetic algorithms for the retrieval of the internal morphology of samples, e.g. biological in nature (Li-Gomez 2023).

Experiment and theoretical results

The main subject matter of this grant is the further study of fiber-optical analogs of Hawking radiation. We have published a paper (see item 5, below) in which we demonstrate the analog Hawking radiation effect seeded by attenuated laser light, in a particular dual-pulse arrangement so that constructive interference between two separate Hawking radiation sources leads to a four-fold signal enhancement. Our main aim in this work is the observation of weakly-seeded Hawking radiation, by which we mean seeded by a single photon obtained through heralding from a spontaneous four-wave mixing photon-pair source. It is my pleasure to report that we have some highly-promising preliminary results in this direction, which will form the basis for a forthcoming paper from our group.

In what follows we present a summary for each of the published contributions from our group, in the context of the two years covered by this AFOSR grant.

1) Mayte Y. Li-Gomez, Pablo Yepiz-Graciano, Taras Hrushevskyi, Omar Calderón-Losada, Erhan Saglamyurek, Dorilian Lopez-Mago, Vahid Salari, Trong Ngo, Alfred B. U'Ren, and Shabir Barzanjeh "Quantum enhanced probing of multilayered-samples" Phys. Rev. Research 5, 023170 (2023)

Quantum optical coherence tomography (QOCT) is a technique, based on quantum interference, for the retrieval of the internal morphology of samples, e.g. biological in nature. QOCT is based on the appearance of a separate Hong-Ou-Mandel interference dip for each interface in the sample. However, the QOCT interferogram can exhibit other features, including a cross-interference artifact for each pair of interfaces, echoes resulting from multiple reflections between interfaces, artifacts resulting from cross-interference between interfaces and echoes, as well as artifacts resulting from cross-interference between pairs of echoes. As the number of interfaces grows, the interferogram rapidly increases in complexity, making it increasingly challenging to identify individual features, and making accurate inferences about the source morphology extremely challenging. In this work, we have developed: i) a model for the QOCT interferogram fully taking into account multiple reflections, and ii) a genetic algorithm which searches in the parameter space of possible morphologies for the specific morphology for which the modelled interferogram best fits the experimentally-obtained one. It is hoped that this approach can prove useful for the development of practical QOCT implementations for clinical settings.

2) K. Garay-Palmett, D.-B. Kim, Y. Zhang, F.A. Dominguez-Serna, V.O. Lorenz, A.B. U'Ren "Fiber-based photon pair generation: a tutorial" Journal of the Optical Society of America B 40(3) 469-490 (2023)

This is an invited paper, in which we present a tutorial of fiber-based photon-pair sources utilizing the spontaneous four-wave mixing (SFWM) process. This paper is the result of the combined expertise of three research groups, those headed by Dr. Virginia Lorenz (UI Urbana Champaign) and Dr. Karina Garay (CICESE), as well as my own. We present a general overview of the SFWM spectrally-dependent phasematching characteristics for different transverse mode combinations among the

four participating fields. We present known strategies for ultrabroadband and ultranarrowband photon-pair generation, as well as for the generation of pairs in factorable states. We present the use of non-degenerate pumps in the SFWM process, covering both spectral non-degeneracy as well as counter-propagating pumps. We discuss the preparation of two-photon states exhibiting entanglement in various degrees of freedom, and/or combinations of dregrees of freedom such as: polarization, frequency-transverse mode, frequency-polarization, as well as discrete frequency. We discuss various methods for photon-pair characterization.

3) A. Martínez-Tapia, S. Corona-Aquino, F. Triana-Arango, C. You, R.-B. Jin, O.S. Magaña-Loaiza, S.-H. Dong, A.B. U'Ren, R. de J. León-Montiel, "Witnessing Entangled Two-Photon Absorption via Quantum Interferometry" APL Photonics 8 036104 (2023)

There is a recent debate on the feasibility of observing entangled two photon absorption (ETPA) in organic compounds, while relying on the photon-pair flux reduction that would result from the ETPA process. An important aspect in this debate is the role which linear losses may play in yielding experimental behaviors which may mimic the expected ETPA effects. Particularly, a concentration-dependent transmission reduction may result from ETPA, but may also be attributable to linear losses. In this paper, we investigate a promising strategy, based on a NOON-state interferometer, to certify ETPA (i.e. unambiguously determine the ETPA despite the presence of linear losses). In our theoretical study, we find that such a NOON-state interferometer is highly sensitive to ETPA-like two-photon losses but is entirely insensitive to linear losses.

4) P. Yepiz-Graciano, Z. Ibarra-Borja, R. Ramírez-Alarcón, G. Gutiérrez-Torres, H. Cruz-Ramírez, D. Lopez-Mago, A. B. U'Ren, "Quantum-Optical Coherence Microscopy for Bio-imaging Applications" Accepted Physical Review Applied (2022)

Quantum-optical coherence tomography (QOCT) is an optical sectioning modality based on the quantum interference of photon pairs, obtained from a spontaneous parametric downconversion (SPDC) source. The promise of QOCT derives from two quantum-conferred advantages when compared to equivalent classical optical coherence tomography (OCT) systems: a factor of 2 axial resolution enhancement, as well as dispersion cancellation. However, the technique is far from being competitive with current OCT devices due to the long required acquisition times. Here, we on the one hand demonstrate a quantum optical coherence microscopy (QOCM) technique that is designed to overcome some of the limitations of previous QOCT implementations, and on the other hand test it on representative samples, including glass layers with manufactured transverse patterns and metal-coated biological specimens. We use a collinear SPDC source, so that the entire emitted photon pair flux may contribute to the measurements, together with a multi-mode detection design. We employ a Michelson interferometer with the sample placed as end-mirror in one of the interferometer arms, instead of the more typical Hong-Ou-Mandel used in QOCT implementations. In order to probe biological samples we transition from a Michelson to a Linnik interferometer by placing a microscope objective in the sample arm. In our setup, while the idler photon is collected with a multi-mode fiber, the signal photon is

detected by an ICCD camera, leading to full-field transverse reconstruction through a single axial acquisition sequence. Interestingly, our setup permits concurrent OCT and QOCT trace acquisition, the former with greater counts and the latter with the benefit of quantum-conferred advantages. We hope that our current results will represent a significant step forward towards the actual applicability of QOCT, e.g. in clinical settings.

5) R. Felipe-Elizarraras, H. Cruz-Ramirez, K. Garay-Palmett, A.B. U'Ren, and D. Bermudez, "Effective Michelson interference observed in fiber-optical analogue of Hawking radiation," Opt. Express 30, 8063-8074 (2022)

We experimentally observe the stimulated analogue of Hawking radiation produced in a photonic-crystal fiber, with a pulsed pump and a continuous-wave probe. In particular, we propose and demonstrate an innovative method to boost the efficiency and probe the coherence characteristics of the analogue Hawking effect relying on a double pump pulse with a controlled temporal delay. We show that the emitted analogue Hawking radiation corresponds to the coherently-added, interfering Hawking signals resulting from the probe interacting with each pump pulse. We introduce a simple effective Michelson interference model, and demonstrate excellent agreement between our experimental data and the predictions derived from this model. Importantly, while naively increasing the pump power in an attempt to boost the Hawking-radiation generation efficiency results in the distortion of the output signal, we show that at the maxima of the observed Hawking-signal interference pattern, the signal can be increased by a factor of >3 (up to 4 under ideal experimental conditions). This approach could be extended to the use of sequences of m pulses, resulting in a Hawking-signal enhancement of m^2.

6) S. Corona-Aquino, O. Calderón-Losada, M. Li-Gomez, H. Cruz-Ramirez, V. Álvarez-Venicio, M.P. Carreón-Castro, R. de J. Leon-Montiel, A.B. U'Ren "Experimental study of the validity of entangled two-photon absorption measurements in organic compounds" J. Phys. Chem. A 126 2185 (2022)

Entangled two-photon absorption (ETPA) has recently become a topic of lively debate, mainly due to the apparent inconsistencies in the experimentally reported ETPA cross sections of organic molecules obtained by a number of groups. In this work, we provide a thorough experimental study of ETPA in the organic molecules Rhodamine B (RhB) and zinc tetraphenyl-porphirin (ZnTPP). Our contribution is 3-fold: first, we reproduce previous results from other groups; second, we on the one hand determine the effects of different temporal correlations introduced as a controllable temporal delay between the signal and idler photons to be absorbed on the strength of the ETPA signal, and on the other hand, we introduce two concurrent and equivalent detection systems with and without the sample in place as a useful experimental check; third, we introduce, and apply to our data, a novel method to quantify the ETPA rate based on taking into account the full photon-pair behavior rather than focusing on singles or coincidence counts independently. Through this experimental setup we find that, surprisingly, the

purported ETPA signal is not suppressed for a temporal delay much greater than the characteristic photon-pair temporal correlation time. While our results reproduce the previous findings from other authors, our full analysis indicates that the signal observed is not actually due to ETPA but simply to linear losses. Interestingly, for higher RhB concentrations, we find a two-photon signal that, contrary to expectations, likewise does not correspond to ETPA.

7) A. Villegas, M.A. Quiroz-Juarez, A.B. U'Ren, J.P. Torres, R.J. Leon-Montiel "Identification of Model Particle Mixtures Using Machine-Learning-Assisted Laser Diffraction" Photonics 9 74 (2022)

We put forward and demonstrate with model particles a smart laser-diffraction analysis technique aimed at particle mixture identification. We retrieve information about the size, shape, and ratio concentration of two-component heterogeneous model particle mixtures with an accuracy above 92%. We verify the method by detecting arrays of randomly located model particles with different shapes generated with a Digital Micromirror Device (DMD). In contrast to commonly-used laser diffraction schemes—in which a large number of detectors are needed—our machine-learning protocol makes use of a single far-field diffraction pattern contained within a small angle ($\sim 0.26^{\circ}$) around the light propagation axis. Therefore, it does not need to analyze particles of the array individually to obtain relevant information about the ensemble, it retrieves all information from the diffraction pattern generated by the whole array of particles, which simplifies considerably its implementation in comparison with alternative schemes. The method does not make use of any physical model of scattering to help in the particle characterization, which usually adds computational complexity to the identification process. Because of its reliability and ease of implementation, this work paves the way towards the development of novel smart identification technologies for sample classification and particle contamination monitoring in industrial manufacturing processes.

8) E. Ortiz Ricardo, C. Bertoni Ocampo, M. Maldonado-Terrón, A. García Zurita, R. Ramirez-Alarcon, H. Cruz Ramirez, R. Castro-Beltran, A.B. U'Ren, "Submegahertz spectral width photon pair source based on fused silica microspheres", Photonics Research 9 2237 (2021)

High-efficiency submegahertz bandwidth photon pair generators will enable the field of quantum technology to transition from laboratory demonstrations to transformational applications involving information transfer from photons to atoms. While spontaneous parametric processes are able to achieve high efficiency photon pair generation, the spectral bandwidth tends to be relatively large, as defined by phase-matching constraints. To solve this fundamental limitation, we use an ultrahigh quality factor (Q) fused silica microsphere resonant cavity to form a photon pair generator. We present the full theory for the spontaneous four-wave mixing (SFWM) process in these devices, fully taking into account all relevant source characteristics in our experiments. The exceptionally narrow (down to

kilohertz-scale) linewidths of these devices result in a reduction in the bandwidth of the photon pair generation, allowing submegahertz spectral bandwidth to be achieved. Specifically, using a pump source centered around 1550 nm, photon pairs with the signal and idler modes at wavelengths close to 1540 and 1560 nm, respectively, are demonstrated. We herald a single idler-mode photon by detecting the corresponding signal photon, filtered via transmission through a wavelength division multiplexing channel of choice. We demonstrate the extraction of the spectral profile of a single peak in the single-photon frequency comb from a measurement of the signal–idler time of emission distribution. These improvements in device design and experimental methods enabled the narrowest spectral width (366 kHz) to date in a heralded single-photon source based on SFWM.

9) D. de la Torre-Robles, F. Dominguez-Serna, G. Lorena Osorio, A.B. U'Ren, D. Bermudez, K. Garay-Palmett "Frequency and polarization emission properties of a photon-pair source based on a photonic crystal fiber" Scientific Reports 11 18092 (2021)

In this work, we experimentally demonstrate a photon-pair source with correlations in the frequency and polarization degrees of freedom. We base our source on the spontaneous four-wave mixing (SFWM) process in a photonic crystal fiber. We show theoretically that the two-photon state is the coherent superposition of up to six distinct SFWM processes, each corresponding to a distinct combination of polarizations for the four waves involved and giving rise to an energy-conserving pair of peaks. Our experimental measurements, both in terms of single and coincidence counts, confirm the presence of these pairs of peaks, while we also present related numerical simulations with excellent experiment-theory agreement. We explicitly show how the pump frequency and polarization may be used to effectively control the signal-idler photon-pair properties, defining which of the six processes can participate in the overall two-photon state and at which optical frequencies. We analyze the signal-idler correlations in frequency and polarization, and in terms of fiber characterization, we input the SFWM-peak experimental data into a genetic algorithm which successfully predicts the values of the parameters that characterize the fiber cross section, as well as predict the particular SFWM process associated with a given pair of peaks. We believe our work will help advance the exploitation of photon-pair correlations in the frequency and polarization degrees of freedom.

10) M.A. Quiroz-Juárez, A. Torres-Gómez, I. Hoyo-Ulloa, R. León-Montiel, A.B. U'Ren AB "Identification of high-risk COVID-19 patients using machine learning" PLoS ONE 16(9): e0257234 (2021)

The current COVID-19 public health crisis, caused by SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2), has produced a devastating toll both in terms of human life loss and economic disruption. In this paper we present a machine-learning algorithm capable of identifying whether a given patient (actually infected

or suspected to be infected) is more likely to survive than to die, or vice-versa. We train this algorithm with historical data, including medical history, demographic data, as well as COVID-19-related information. This is extracted from a database of confirmed and suspected COVID-19 infections in Mexico, constituting the official COVID-19 data compiled and made publicly available by the Mexican Federal Government. We demonstrate that the proposed method can detect high-risk patients with high accuracy, in each of four identified clinical stages, thus improving hospital capacity planning and timely treatment. Furthermore, we show that our method can be extended to provide optimal estimators for hypothesis-testing techniques commonly-used in biological and medical statistics. We believe that our work could be of use in the context of the current pandemic in assisting medical professionals with real-time assessments so as to determine health care priorities.

Papers published during the grant's two-year duration

|1) Mayte Y. Li-Gomez, Pablo Yepiz-Graciano, Taras Hrushevskyi, Omar Calderón-Losada, Erhan Saglamyurek, Dorilian Lopez-Mago, Vahid Salari, Trong Ngo, Alfred B. U'Ren, and Shabir Barzanjeh "Quantum enhanced probing of multilayered-samples" Phys. Rev. Research 5, 023170 (2023)

2) K. Garay-Palmett, D.-B. Kim, Y. Zhang, F.A. Dominguez-Serna, V.O. Lorenz, A.B. U'Ren "Fiber-based photon pair generation: a tutorial" Journal of the Optical Society of America B 40(3) 469-490 (2023)

3) A. Martínez-Tapia, S. Corona-Aquino, F. Triana-Arango, C. You, R.-B. Jin, O.S. Magaña-Loaiza, S.-H. Dong, A.B. U'Ren, R. de J. León-Montiel, "Witnessing Entangled Two-Photon Absorption via Quantum Interferometry" APL Photonics 8 036104 (2023)

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6) S. Corona-Aquino, O. Calderón-Losada, M. Li-Gomez, H. Cruz-Ramirez, V. Álvarez-Venicio, M.P. Carreón-Castro, R. de J. Leon-Montiel, A.B. U'Ren "Experimental study of the validity of entangled two-photon absorption measurements in organic compounds" J. Phys. Chem. A 126 2185 (2022)

7) A. Villegas, M.A. Quiroz-Juarez, A.B. U'Ren, J.P. Torres, R.J. Leon-Montiel "Identification of Model Particle Mixtures Using Machine-Learning-Assisted Laser Diffraction" Photonics 9 74 (2022)

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