Contract No:

This document was prepared in conjunction with work accomplished under Contract No. 89303321CEM000080 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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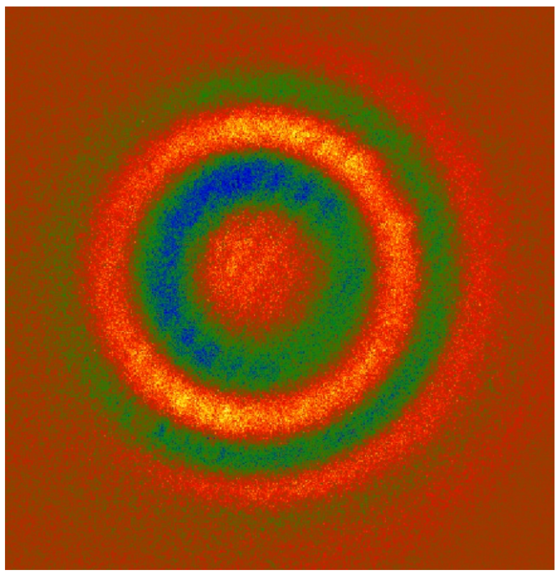
Photon Entanglement Spectroscopy and Imaging in Actinide Research

Project Start and End Dates
Project Start Date: November1, 2019
Project End Date: September 30, 2021

This project aims to develop advanced imaging techniques by leveraging quantum entangled photons to provide a mechanism to provide imaging capabilities for applications in which other techniques are not applicable. A breadboard system to generate quantum entangled photons was constructed and used to demonstrate unique imaging capabilities.



Project Team
Principal Investigator: Eliel Villa-Aleman
Team Members: Patrick Ward, Don DeWayne Dick
External Collaborators: None
Project Type: Seedling

Abstract
Quantumly entangled particles are capable of affecting the quantum state of their entangled counterpart instantaneously once one particle has changed. Herein, quantumly entangled photons are generated by spontaneous parametric down conversion through a temperature controlled non-linear crystals. This process generates two pairs of photons of lower energy of which the sum of energy equals the energy of the pump photons. These entangled photons can be separated and provide imaging capabilities by using one set of photons for imaging and the other set of photons for detection.

FY 2021 Objectives

- Improve system stability (allows interference to be better observed)
- Optimize system alignment
- View quantum entanglement image of various slits (ultimately, this still needs further refinement)

REVIEWS AND APPROVALS

1. Authors:

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Name and Signature Date

2. Technical Review:

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Name and Signature Date

3. PI's Manager Signature:

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Name and Signature Date

4. Intellectual Property Review:

This report has been reviewed by SRNL Legal Counsel for intellectual property considerations and is approved to be publicly published in its current form.

SRNL Legal Signature

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Name and Signature

Introduction

Second order non-classical interference has been demonstrated previously with indistinguishable photon pairs. [1,2] The generation of photon pairs from a non-linear optic (signal and idler) by spontaneous parametric down conversion provides photons which can be separated based on their wavelength by dichroic mirrors. When idler photons are perfectly aligned with another set of idler photons generated in a second non-linear optic, the photons are now indistinguishable and therefore satisfy the indistinguishability requirement necessary for quantum interference. This allows for interference to be observed in the signal photons generated from the first non-linear optic and therefore imaging of an object from photons which have never actually physically interacted with that object. This methodology opens a multitude of possibilities for imaging solutions since the photons interacting with the object of interest do not need to be detected directly. Instead, their entangled photons can be observed to provide the image of the interest.

Inspired by recent illustrations of this ability to image using undetected photons [3,4], we have set out to develop our own breadboard quantum imaging system and advance the technique to provide application in practice.

Approach

A 532nm signal longitudinal mode (SLM) laser is used to generate quantum entangled photon pairs by spontaneous parametric down conversion in a pair of periodically poled potassium titanyl phosphate (ppKTP) crystals. A SLM laser and bandpass filters for the signal photons are used to significantly reduce the bandwidth of the beams and therefore increase the coherence length. A breadboard system was constructed to focus idler photons from the first non-linear optic onto the beam profile of idler photons generated from a second non-linear optic. The wavelengths generated from each non-linear optic were measured in a spectrometer and the temperature of the ppKTP (non-linear optic) adjusted to provide identical wavelengths for photon pairs generated from each non-linear optic. The idler photons from non-linear optic 1 were aligned to pass through an object of interest and the signal photons aligned with the signal photons from the second non-linear optic. The signal photons were then split in a 50:50 beamsplitter and half of the beam sent to a CCD detector for imaging and the other half dumped.

Fiscal Year 2021 Accomplishments

- Breadboard quantum imaging system was modified to dampen vibrations that were preventing entangled image via interference pattern from being seen (see Figure 1).
- Verified the generation of entangled photons by observing a change of interference fringes while slightly varying the 1550nm light path.
- SRNL's first quantum image detected (see title image on page 1).
- Taken the quantum image of slits with various sized openings (see Figure 2).
- Demonstrated a dynamic shift in interference patterns for gases with different indices of refraction.
- Setup an advanced quantum imaging system based on the literature that is simpler in design, requiring only one crystal, and allows for a larger sample/fiber optic cavity. In principle, this would allow for remote sensing much more readily than the first design.

Future Directions

- Improve quantum image resolution.
- Generate samples for imaging using constructed breadboard system.

- Demonstrate use of fiber optics to transport light over greater distances and therefore provide higher application fidelity for advanced imaging techniques.

FY 2021 Peer-reviewed/Non-peer reviewed Publications
None

Intellectual Property
None

Total Number of Post-Doctoral Researchers
1 Post-Doctoral researcher, Don DeWayne Dick (SRNL, until mid-January, post-doc converted to Senior Scientist thereafter)

Total Number of Student Researchers
None

References

1. Zou, X.Y.; Wang, L. J.; Mandel, L. Induced Coherence and Indistinguishability in Optical Interference. *Phys. Rev. Lett.*, **1991**, *67*, (*3*), 318-321.
2. Wang, L. J.; Zou, X. Y.; Mandel, L. Induced Coherence without Induced Emission. Phys. Rev. A 1991, 44, (7), 4614-4622.
3. Lahiri, M.; Lapkiewicz, R.; Lemos, G. B.; Zeilinger, A. Theory of Quantum Imaging with Undetected Photons. *Phys. Rev. A* **2015**, *92*, 013832-1 - 1013832-8.
4. Lemos, G. B.; Borish, V.; Cole, G. D.; Ramelow, S.; Lapkiewicz, R.; Zeilinger, A. Quantum Imaging with Undetected Photons. *Nature* **2014**, *512*, 409-412.

Acronyms

CCD – Charge coupled device
ppKTP – periodically poled potassium titanyl phosphate
SLM – Single longitudinal mode

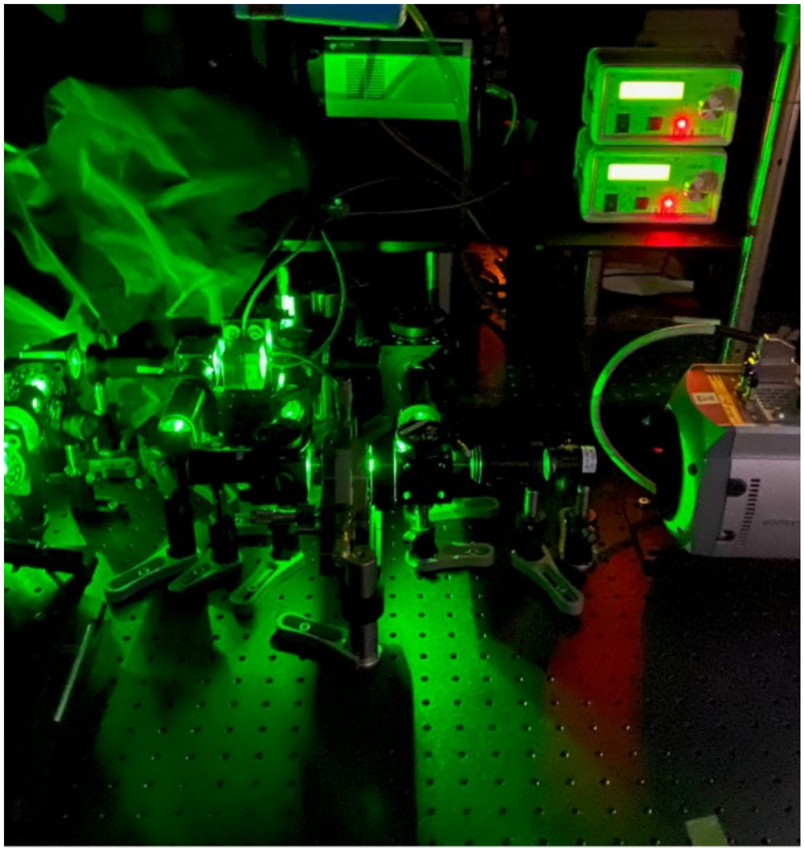

Figure 1: Image of breadboard system during operation.

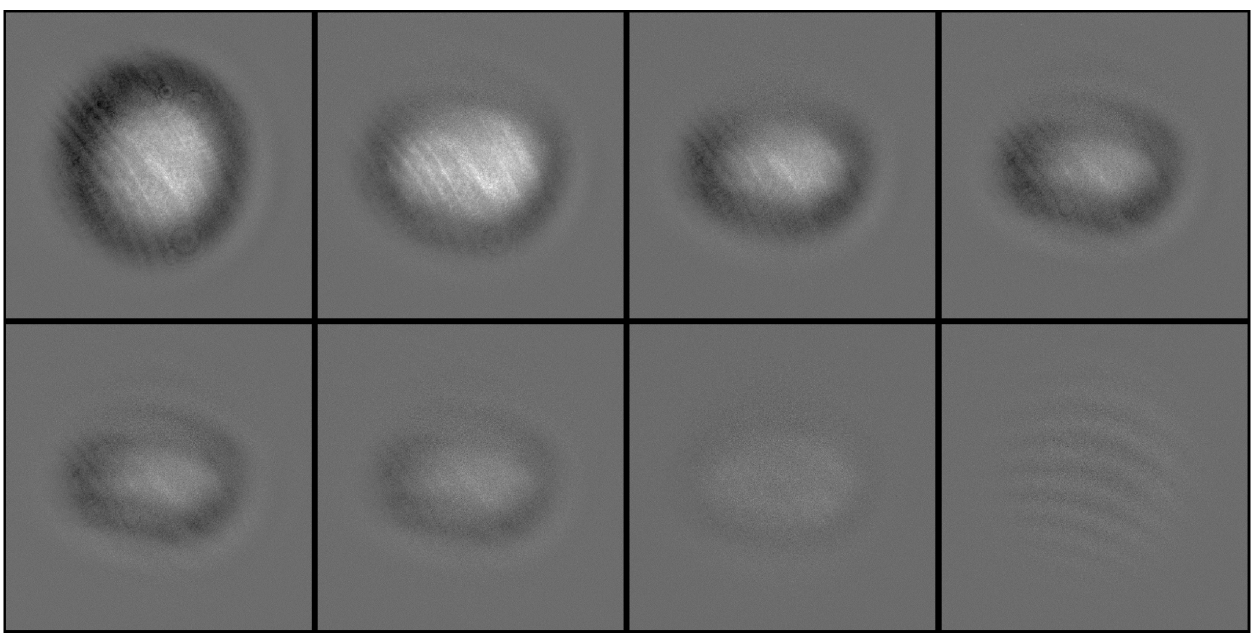

Figure 2: Quantum entangled image of 1550 nm passing through 8 different slits opening. As the narrowest slit opening visible is ~1 mm, this shows that the image resolution needs to be improved.