Bell Inequality Experiment for a High Brightness Time-Energy Entangled Source

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INTRODUCTION

With the advances in quantum computing - and the subsequently decreasing security of classical encryptions protocols - interest is being directed toward quantum communication systems. Unlike their classical counterparts, quantum systems are able to ensure privacy from eavesdroppers by utilizing Heisenberg's uncertainty principle and the "no-cloning" theorem. For these new systems to be viable, especially for future aero and space applications, it is necessary to employ single-photon sources that can maintain data rates comparable to today's technologies. One way achieve this is through the manufacture and characterization of high-brightness, time-energy entangled photon sources. Recently, NASA has been assessing one such source (Fig. 1), which is capable of producing entangled photons at a rate up to 250 MHz.*

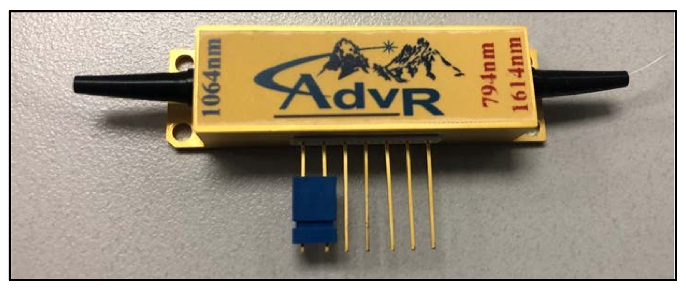

Fig. 1 Image of AdvR entangled photon source.

FRANSON INTERFEROMETER

To determine if the photon's produced by a source are entangled (a process that involves tying two photons together such that a measurement of one photon affects the outcome of the measurement of the other), it is necessary to show a violation of Bell's equality[1]. For time-energy entangled photons, the process requires the use of a Franson interferometer[2], a modified version (based on work by *Kwiat et al* [3]) is shown in Fig. 2.

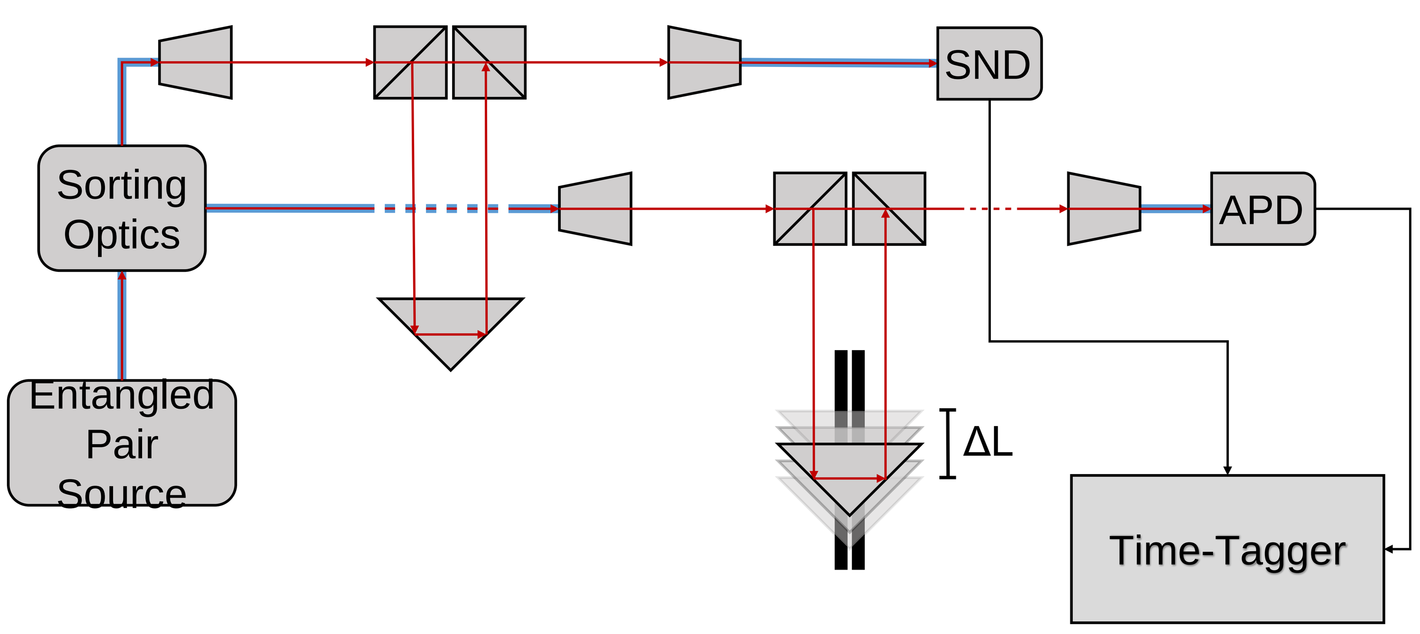

Fig. 2 Schematic diagram of the modified Franson interferometer.

A Franson Interferometer is an assembly of two identical (but imbalanced) Mach-Zehnder interferometers (MZs).

The long path of each MZ must be:

1) greater than the single photon coherence length
2) shorter than the coherence length of the pump laser
3) Equal to within the two-photon correlation length

By separating the entangled photons and sending them through different MZs, it is possible measure coincidences between entangled photons that take different paths: short/long, long/short, long/long, short/short. Varying the long path length of one MZ by small amounts, *ΔL*, allows observation of interference between the short/short and long/long coincidences, and produces "fringes". These fringes are indicative of entanglement.

SOURCE CHARACTERIZATION

Time-energy entangled photon pairs are created by means of spontaneous parametric down conversion, utilizing a pumped MgO:LN waveguide source provided by AdvR. (Fig. 1). The entangled 794 nm and 1614 nm photons are separated and directed by a series of sorting optics containing a dichroic beam splitter, optical filters, and aspheric lenses[4].

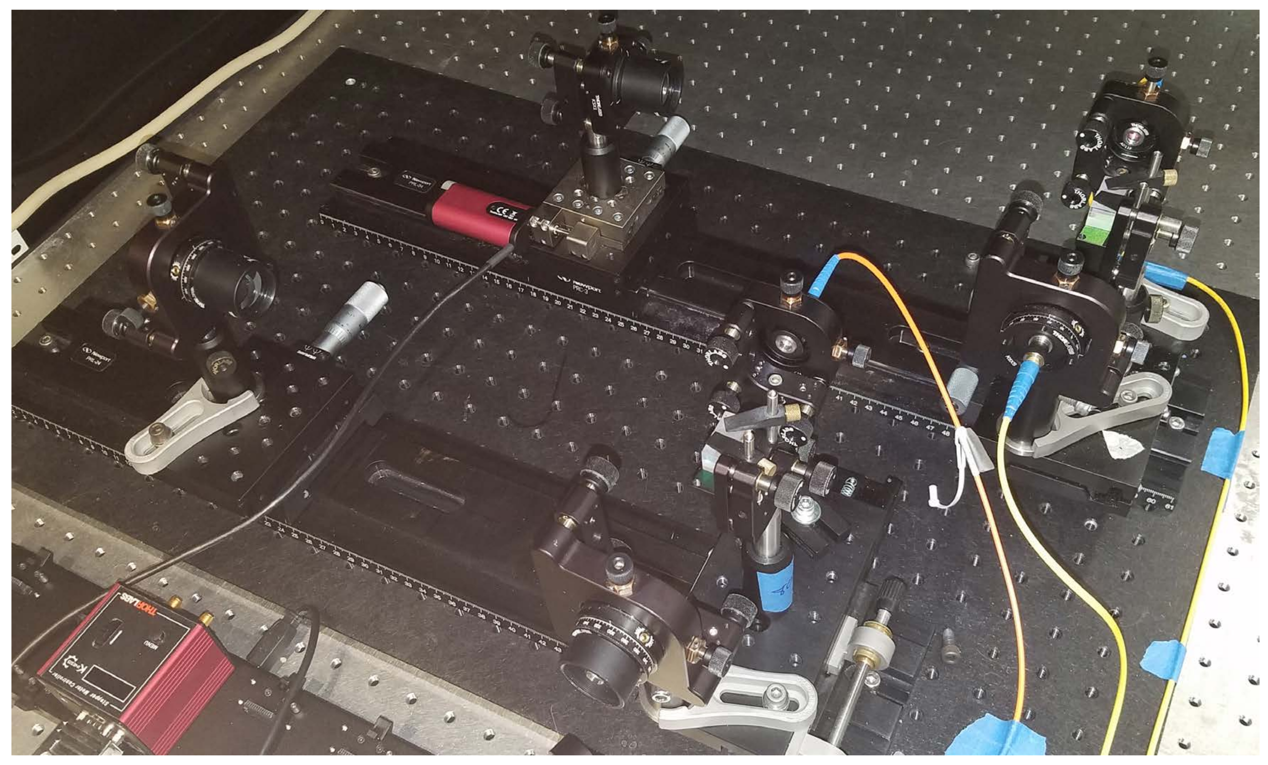

Fig. 3 Image of Franson interferometer setup.

The respective photons are directed to and from separate MZs via fiber optic cabling as can be in in Figs. 2 and 3. The 794 nm photons are detected with an avalanche photo diode (APD), and the 1614 nm photons are detected with a superconducting nanowire detector (SND). Detector output signals are sent to a time tagger with bin resolution as narrow as 100-ps for coincidence counting. The results are then recorded and plotted as a histogram (example shown in Fig. 3). The 1614 MZ interferometers' long path is incrementally increased by 10nm over ~1.5µm, with data taken at each position. The distinguishable short-long and long-short processes are removed by setting a measurement window to be appropriately small to reject these measurements. Fig. 4 shows an example of this.

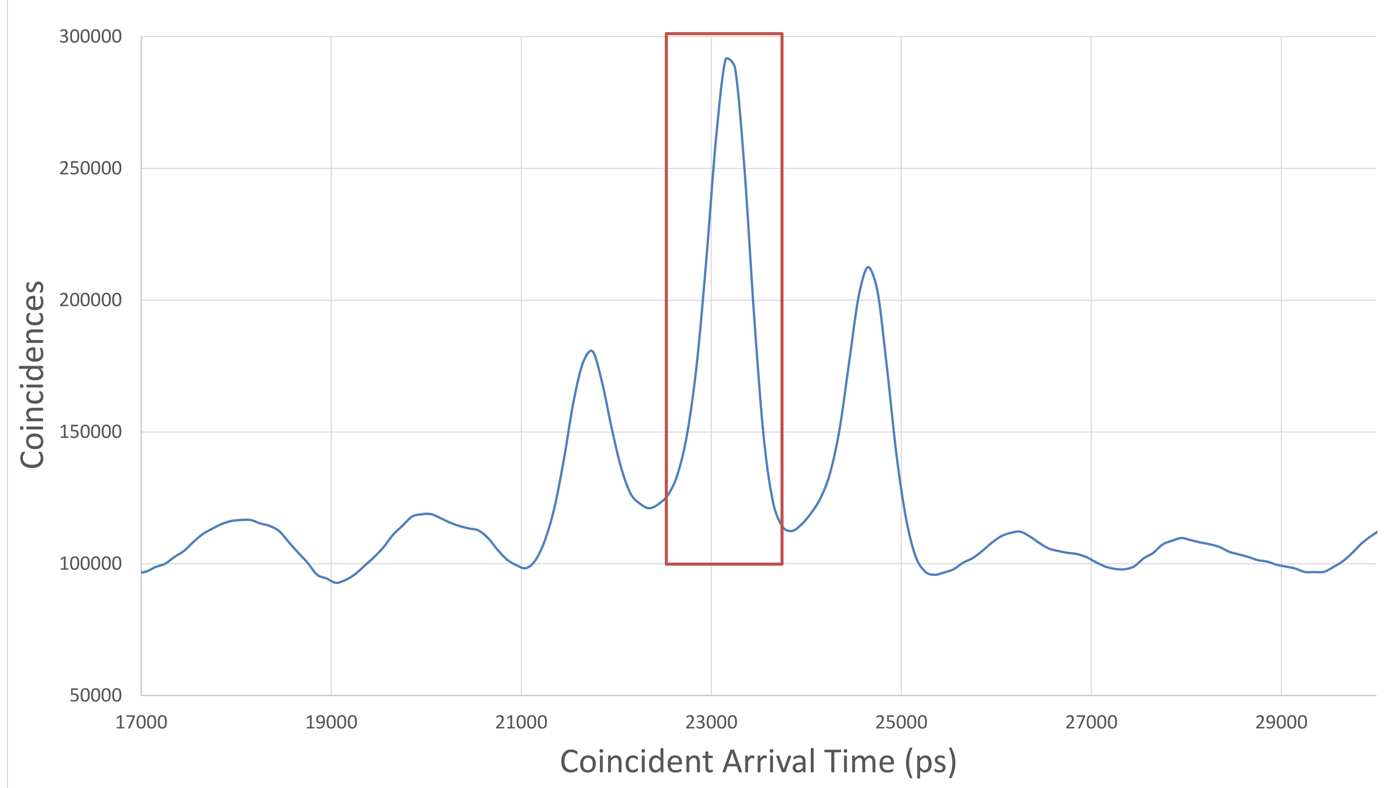

Fig. 4 Example coincidence histogram, the highlighted area indicates the desired coincidence data.

By integrating over the truncated measurement windows for each bin, adding them, and subtracting noise, the true coincidence counts are obtained. Observing how this value changes – due to Interference in the long/long and short path coincidences – through the incremental linear variation MZs long path length leads to the production of the desired fringes.

RESULTS

By post processing the data interference in coincidence measurements - that were not the result of single photon interference - were successfully found. The data were fit to a sinusoid in order to obtain an estimate of the fringe visibility. The observed visibility is larger than the 50% condition set to violate Bell's inequality[4], with observations of 58.3%, and a period of 794 nm (Fig. 5). However, this visibility is still relatively low, and the period does not exactly match what is expected from the pump source - which indicates a period of 532 nm. While this sort of discrepancy is not unexpected, and has been seen in other work.

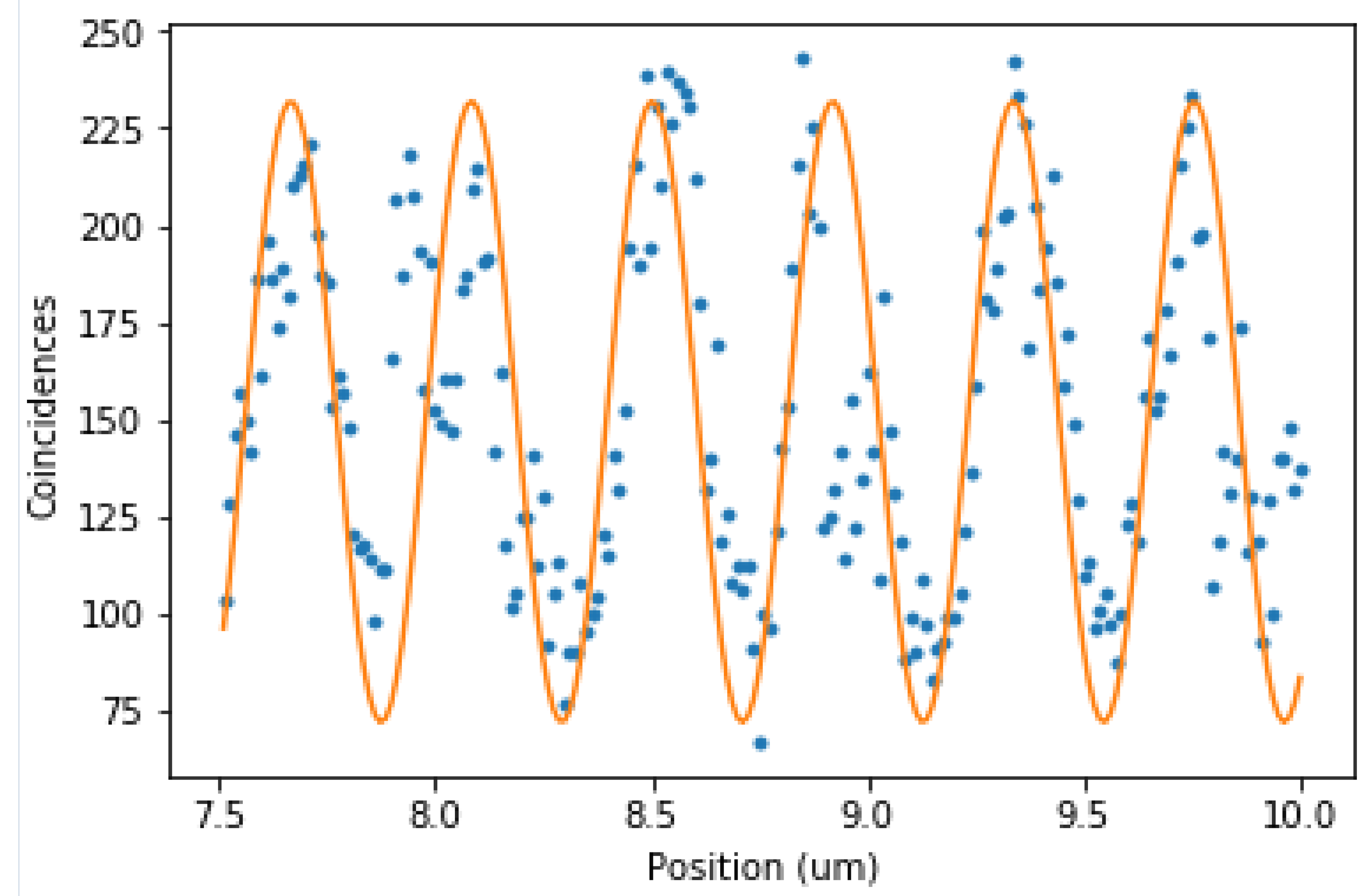

Fig.5 Observed interference fringes (dot) plotted with a sinusoidal fit (solid). Fringes show a 58.3% visibility.

CONCLUSIONS

Through use of a Franson interferometer it was possible to observe high visibility fringes, which indicate a satisfactory level of coincidence interference between entangled photons. This in turn indicates that the AdvR source indeed produces time-energy entangled photon pairs, and is a viable tool for the field of quantum communications.

For future work, it will be possible to increase fringe visibility by refining the alignment of the MZs, as well as by including apertures to clean up spatial resolution. Also, by reducing the core size of the fiber optics used, a significant amount of fringe visibility may be gained - though this would come with a decrease in total coincidences. Additionally, the fringe spacing may be improved upon by including a laser rangefinder to more accurately monitor the position of the variable MZ's long path.

REFERENCES

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* 250 GHz is an estimated maximum based on current studies at Glenn Research Center