Generating Correlated Photon-Pairs for Quantum Technologies

Imperial College London

Benyam Dejen & Dimitrie Cielecki

Supervisor: Dr Alex S Clark, The Centre for Cold Matter, Imperial College London

Summary & Motivation

Quantum technologies play a crucial role in the enhancement of current sensing, computation and communication capabilities [1].

Correlated photon-pairs are essential components of future quantum systems. Rubidium atoms have demonstrated suitability as quantum memories [2] and dibenzoterrylene (DBT) molecules as single-photon emitters[3], both with transitions around 780 nm. We investigate and assess the suitability of two non-linear processes to generate correlated photons in this wavelength regime: spontaneous four-wave mixing (sFWM) in a commercially available fibre and spontaneous parametric down-conversion (sPDC) in a non-linear biaxial crystal (bismuth triborate, BiBO) [1,4].

We examine the performance of commercially-available birefringent optical fibres to produce technologically-beneficial photons via spontaneous four-wave mixing. We demonstrate the use of sPDC to generate narrowband photons compatible with optical transitions at 780 nm, efficiently heralded by photons compatible with existing detection and transmission technologies.

We propose and aim to use the optimised source and heralded spectroscopy to take low-noise measurements of Rb or DBT absorption spectra as a quantum application.

Methods

Experiment design:

- Assessing simulated performances of sPDC and sFWM, we opt to design and build sPDC photon-pair source with a BiBO crystal:
  - The birefringence of available fibres is not suitable for the desired source and Raman scattering may be an issue in the case of sFWM in this regime (increased noise levels);
  - The BiBO non-linear biaxial crystal possesses all requirements for efficient generation of photons.
- The geometry of optics was informed by simulations (beam waist and opening angle of generated beams). We use the birefringence of the crystal and conservation of momentum to find the optimum angles (see diagram below).

Characterisation

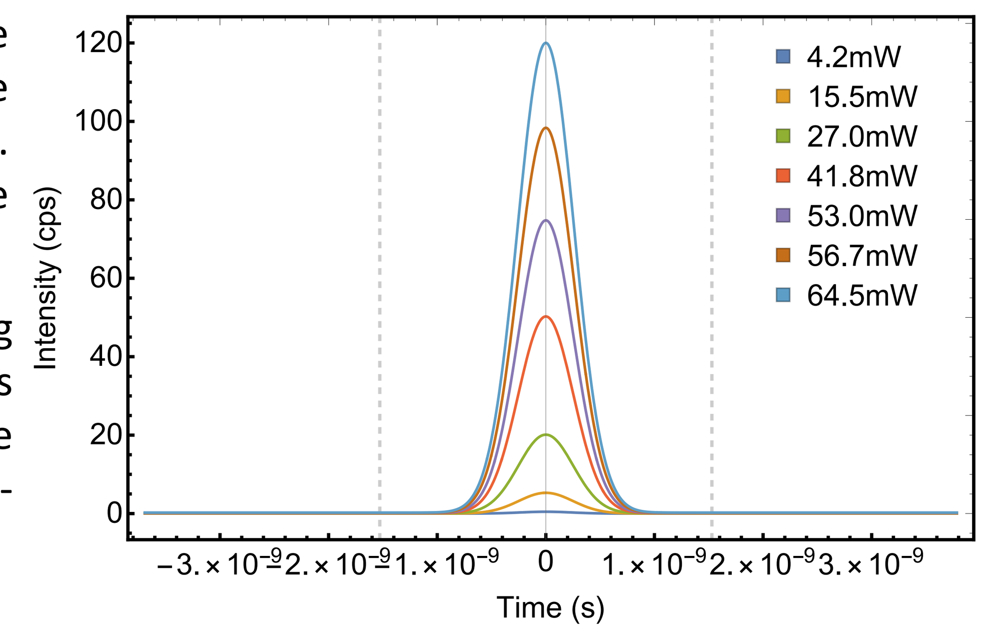
Coincidence-to-accidental ratio (CAR) quantifies the level of noise in the output and is calculated using the following equation in which b is the total background counts in the interval and G is the fitted Gaussian.

$$\text{CAR} = \frac{\text{coincidences}}{\text{accidentals}} = \frac{\int_{interval} \mathcal{G}(a,\mu,\sigma)\, d\tau - b}{b}$$

A coincidence is the event of both photons arriving simultaneously at the detectors, within a defined time window (vertical lines in figure below). Accidentals are defined as the background noise in this window.

Klyshko efficiency is the heralding efficiency of the source. It quantifies the likelihood of heralding the corresponding photon in the photon-pair [1].

$$\eta = \frac{\int_{interval} \mathcal{G}(a,\mu,\sigma)\, d\tau - b}{\text{heralding photon counts}}$$

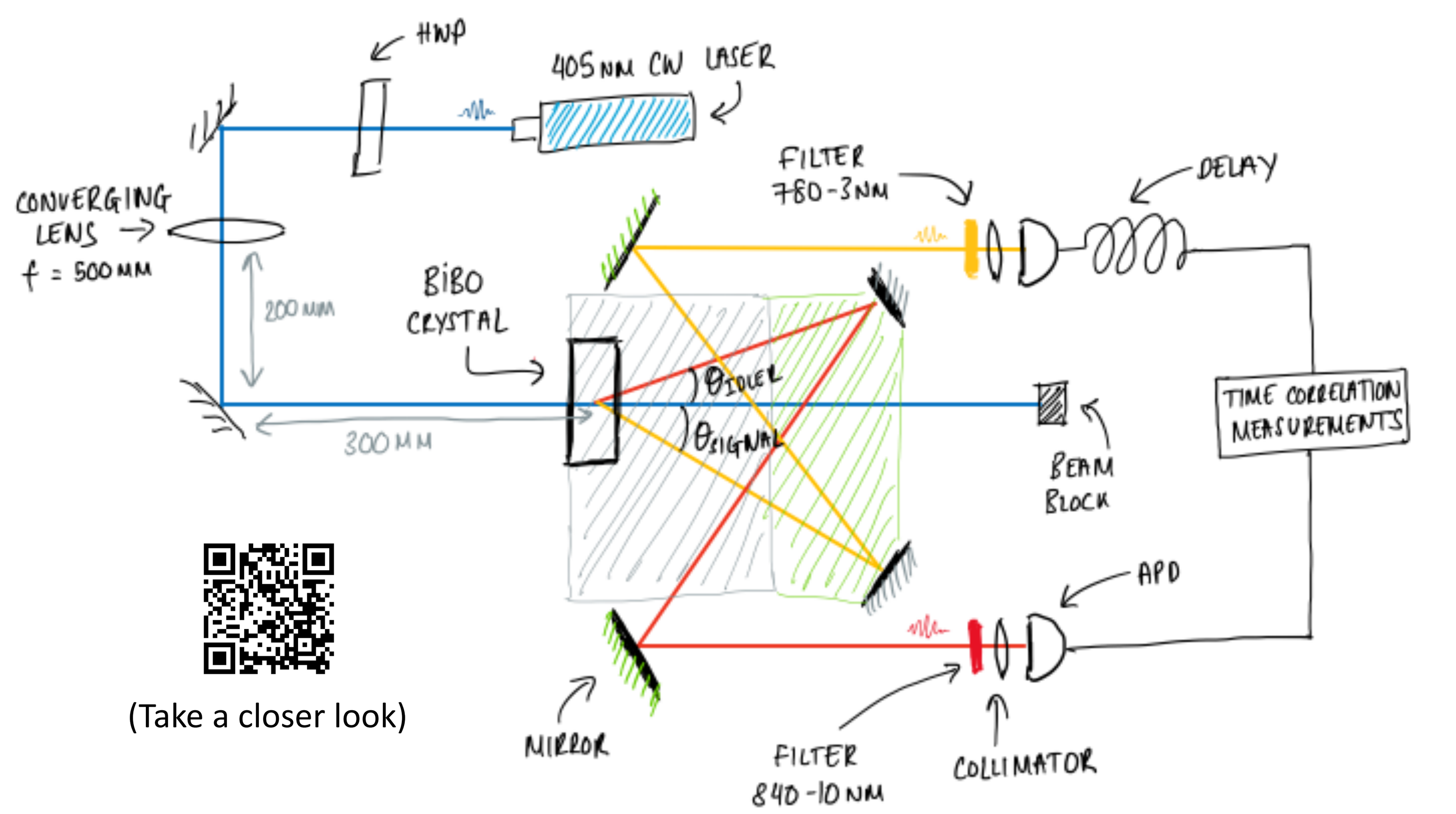


Optimization

- Maximise brightness and minimize noise: *build an efficient set-up, with appropriate components, ensuring a precise alignment.*
- Maximise heralding efficiency: *use appropriate narrowband filters with high transmissivity.*
- Maximise generation rate: *achieve optimal focus using a converging lens, whilst considering the generation of multi-photon states.*
- Ensure photons are emitted in collimated beams by keeping the pump diameter constant inside the crystal over the Rayleigh length.

Main Objectives

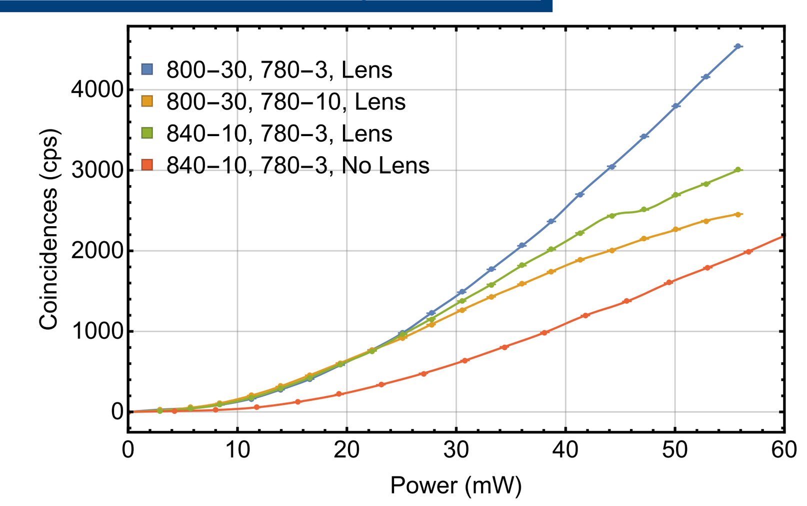
- Build a source of heralded narrowband photons that are compatible with transitions at a wavelength of 780 nm;
  - 780 nm corresponds to D_2 transition line in rubidium (Rb) and dibenzoterrylene (DBT). The transitions impose restrictions on the required source emission linewidths: sub-MHz required for Rb;
- Produce desirable heralding photons compatible with existing detection and transmission technologies;
- Build an energy-efficient source in a cost-effective and resourceful manner;
- Characterise the performance of the photon-pair source: brightness, heralding efficiency, noise levels, input power dependence;
- Demonstrate applicability, such as heralded spectroscopy;
- Provide foundations for future quantum applications and further research e.g. Rb quantum memories.



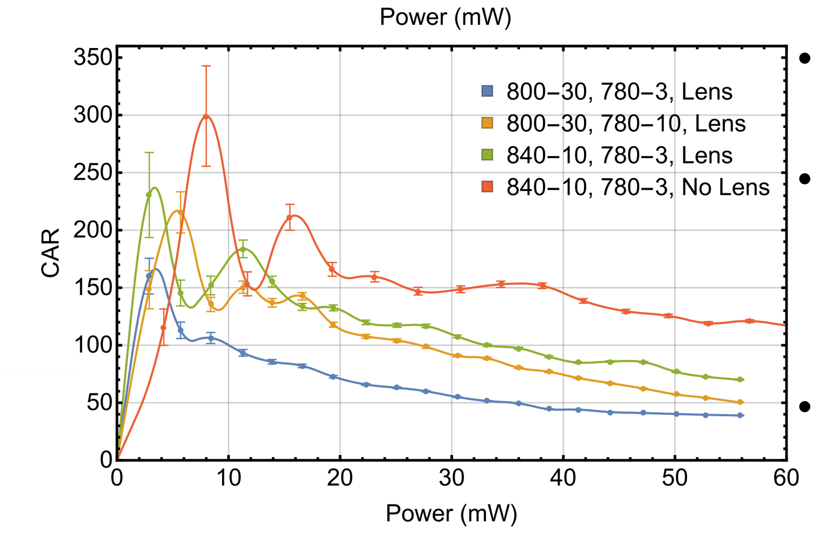
(Take a closer look)

Conclusions & Next Steps

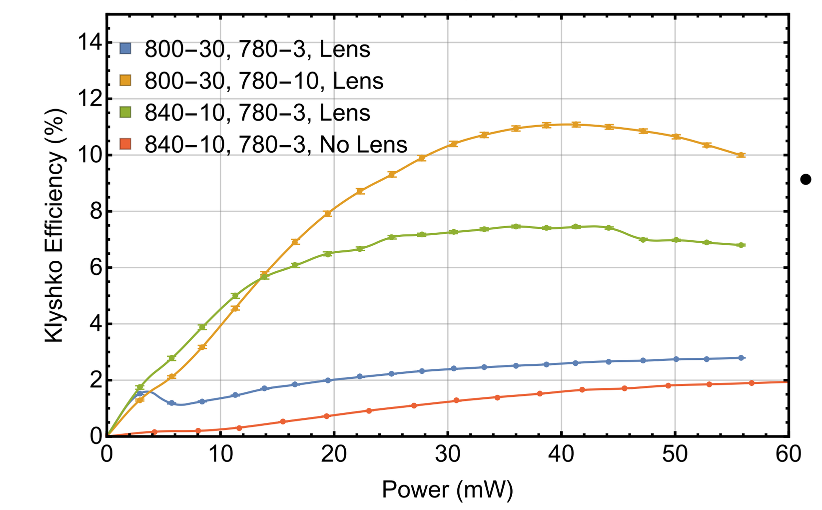
- Demonstration of a bright source of photon-pairs at the desired wavelength.
- Best performance: narrowest filters & a lens.
- Worst performance: wide filters with low transmission & no lens.
- Our source allows interfacing photons with DBT molecules.
- Further optimization may enable the probation of Doppler-broadened hyperfine rubidium transition.



- Coincidences at high powers demonstrate expected linear power dependence.
- Implementation of lens improves brightness by increasing photon-pair generation rate.



- CAR follows expected trend with power.
- Use of narrower filtering improves values of CAR due to efficient photon selection.
- No lens provides higher CAR since there is lower multi-photon state.



- Combination of narrower filtering and use of lens improves the Klyshko efficiency.

Heralded Spectroscopy:

We aim to demonstrate a version of ghost imaging, which utilises coincidence counts to measure an optical absorption spectrum [1]. The video shows a demonstration of the setup and the expected results for Rb.

Background

The generated state of the photon-pair is described quantum mechanically by the equation below.

$$|\Psi\rangle = \iint f(\omega_s,\omega_i)\, \hat{a}_s^\dagger(\omega_s)\, \hat{a}_i^\dagger(\omega_i)\, |0,0\rangle\, d\omega_s\, d\omega_i,$$

The state takes into account the phase-matching conditions: conservation of energy and momentum.

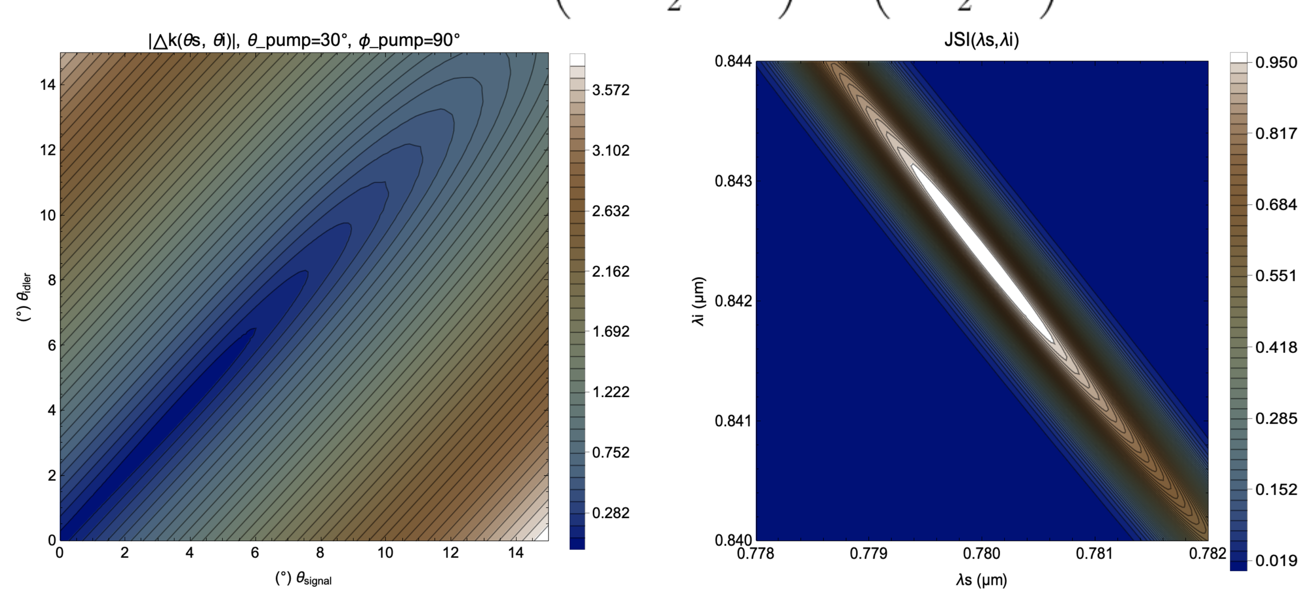
$$f(\omega_s,\omega_i) = \alpha(\omega_s+\omega_i)\, \Phi(\omega_s,\omega_i),$$

Joint spectral amplitude | Pump envelope (energy conservation) | Phasematching function (momentum conservation)

Spontaneous Parametric Down-Conversion: Pump → Signal + Idler

We find the emission angle where the intensity of generation is greatest. The joint spectral intensity (JSI) illustrates the generation probabilities of photon-pairs at different angles by a particular BiBO crystal orientation.

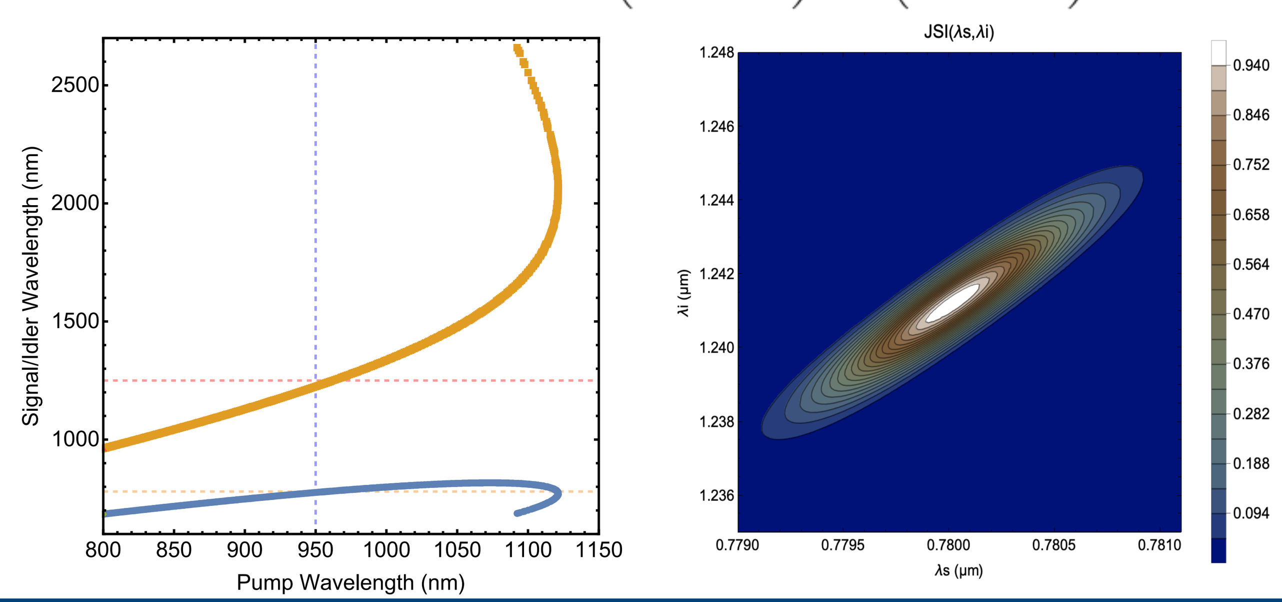
$$\Phi(\omega_s,\omega_i) = \exp\left(\frac{-w^2 k_\perp(\omega_s,\omega_i)}{2}\right) \operatorname{sinc}\left(\frac{l k_\parallel(\omega_s,\omega_i)}{2}\right)$$



Spontaneous Four-Wave Mixing: 2 x Pump → Signal + Idler

We calculate the phase-matching curves using the birefringence of multiple fibres to determine possible wavelengths of the photon-pairs. The JSI plot illustrates the generation probabilities for a specific fibre and pump wavelength.

$$\Phi(\omega_s,\omega_i) = \operatorname{sinc}\left(\frac{k(\omega_s,\omega_i)l}{2}\right) \cos\left(\frac{k(\omega_s,\omega_i)l}{2}\right)$$



References:

[1] E. Pearce, C. C. Phillips, R. F. Oulton, and A. S. Clark, "Heralded spectroscopy with a fiber photon-pair source," *Appl. Phys. Lett.*, vol. 117, no. 5, 2020.

[2] P. Burdekin, S. Grandi, R. Newbold, R. A. Hoggarth, K. D. Major, and A. S. Clark, "Single-photon-level sub-Doppler pump-probe spectroscopy of rubidium," pp. 1–9, 2020.

[3] S. Grandi, K. D. Major, C. Polisseni, S. Boissier, A. S. Clark, and E. A. Hinds, "Quantum dynamics of a driven two-level molecule with variable dephasing," *Phys. Rev. A*, vol. 94, no. 6, 2016.

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