Progress towards an ultrabright narrowband source of polarization-entangled photon pairs

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Previous Downconversion Source

- Type-II downconversion from a PPKTP crystal
- Simple single pass, collinear source of degenerate pairs
- Produces polarization-entangled triplet states
- Verified by CHSH Bell violation of $2.711 \pm 0.017$ (classical limit of 2)
- Submitted to PRA (quant-ph/0305092)
- Simplified layout sketched below:
Features of Single Pass Downconversion

• Disadvantages of Single Pass
  – Entanglement is only present at the degenerate wavelength for on-axis photon pairs only
  – Must use interference filter (IF) to limit the wavelength of collected pairs
  – Must use iris to limit collected pairs to those on axis
  – Half of the pairs do not separate at the 50/50 beamsplitter and are lost
  – Collected pairs are broadband
  – All the filtering results in a low flux of polarization entangled pairs

• Improvements to Single Pass
  – Bi-directional pumping removes the need for filtering and produces a much higher flux of polarization-entangled photon pairs
  – A cavity can be used to narrow the bandwidth of the emitted pairs
Background and Motivations

Traditional BBO source
• Type-II noncollinear downconversion
• Only one wavelength and one direction of emission are entangled
• Filtering is required

Is it possible to create a source of polarization entanglement that does not require filtering?
• Features
  – Extremely high photon-pair flux
  – Broadband
  – Spatially extended
  – Tunable
• Benefits
  – Increased qubit rates in existing communication protocols
  – Demonstrations of new quantum computing and communication protocols
PPKTP Bidirectional Pump Source

An old idea…
- Combine two sources of orthogonally polarized photon pairs

…with a new twist
- PPKTP source
- Type-II collinear downconversion
- One crystal and a split cw pump produce two indistinguishable sources
- Entanglement is independent of direction of emission and wavelength
Experimental Setup

\[ |\Psi\rangle = \frac{|HV\rangle + e^{i\phi} |VH\rangle}{\sqrt{2}} \]

- **Pump**
  - Frequency doubled cw Ti:sapphire laser
  - 5 mW
  - 397.5 nm

- **PPKTP crystal**
  - 10x4x1 mm³
  - 9.01 µm poling period

- **Si single photon detectors**

- We control the phase \( \phi \) of the state \( \Psi \) by locking the pump interferometer
Bell’s Inequality Violation

Singlet state
No filter
4 mm iris

\[
\theta_1 = H \quad \theta_1 = 45^\circ \\
V = 100 \pm 1\% \quad V = 85 \pm 3\% \\
S = 2.599 \pm 0.006 \\
\text{measured in 160 s}
\]
• 12000 pairs s\(^{-1}\) mW\(^{-1}\), visibility 90%, conditional probability 15-20%
• Limiting factors: crystal poling irregularities, wavefront distortion, and asymmetric clipping
Tunability

- Tunable for 5 nm around degeneracy without loss of visibility
Modified Experimental Setup

- Short path to limit the asymmetric clipping
- Fewer optical elements to limit wavefront distortions

- Preliminary results show a 3-4% increase in the visibility

This work has been submitted to PRL and appeared in quant-ph/0309071
Doubly Resonant Oscillator (DRO) Downconversion

- A DRO is a cavity for both output polarizations
- Cavity mirrors transmit the pump, so the pump is single pass
- A DRO must be tuned so that both degenerate output polarizations are resonant at the same time
- This simultaneous resonance can be achieved in a few ways:
  - Use a PBS inside the cavity and separate cavity mirrors for H and V
  - Use rotated KTP compensating crystals to cancel birefringence
  - Use a quarter-wave plate (QWP) inside the cavity to swap H and V
- The degenerate narrowband output modes should be in the resonant gaussian spatial mode
- A DRO has a resonant enhancement in the total rate of pair generation, making it brighter than single pass downconversion or a singly resonant cavity
• Test of coincidence detection and timing resolution
• No birefringence compensation
• Histogram of delay between H and V photon detection
• Central peak corresponds to H and V photons leaving the cavity at the same time
• FWHM of the double exponential is 4.88 ns, yields finesse of 52.7
• This “photon pair finesse” agrees with finesse measurements made with transmitted probe light
• 100 seconds of data, taken while the cavity length was being swept
**Preliminary Interference Measurements**

- Upper curve: HWP set at 0°
- Lower curve: HWP set at 22.5°
- Beamsplitter effect => lower counts = half of upper counts (red curve)
- At 22.5°, interference is similar to the minimum of a HOM dip experiment
- At degeneracy, some entangled pairs interfere at PBS, so lower curve is below the red line
- Thus we have observed some polarization entanglement
- 1000s of data per curve, taken while sweeping the cavity
Cavity Measurement with Quarter-Wave Plate (QWP)

- The QWP was set so that H ↔ V for each round trip.
- After two round trips, signal and idler photons of a pair see the same total cavity length.
- Signal photon exits the output coupler after $N_s$ round trips and idler photon after $N_i$ round trips.
- If $(N_s - N_i)$ is odd then they do not separate at the PBS and so every other peak in the histogram is missing, making the remaining peaks easily distinguishable.
- 1000s of data, taken while sweeping the cavity.
Linear Doubly Resonant Oscillator

- This is currently being constructed
- Two compensating KTP crystals are used, each is half the length of the PPKTP crystal
- This compensation scheme allows both polarizations to have the same cavity lengths and therefore they are resonant at the same time
- FWHM of narrowband peaks: ~30 MHz
- Free Spectral Range: ~1.24 GHz (spacing of the narrowband peaks)
- Filter cavity transmits only the degenerate narrowband peak
**Theory of Linear DRO**

Spectrum of signal photons from linear DRO at double resonance

\[ l = \text{PPKTP length (1 cm)}, \quad L_{\text{eff}} = \text{optical path length between mirrors}, \]

\[ \omega_0 = \text{degenerate frequency}, \quad A_P = \text{pump amplitude}, \quad R = \text{output mirror reflectivity} \]

\[
\text{Power}_s[\omega] = \frac{(\kappa |A_P| l)^2(1 - R)^2 \text{Sinc} \left[ \frac{l(n_l - n_s)\omega}{2c} \right]}{(1 + R - 2\sqrt{R} \cos[2L_{\text{eff}}(\omega_0 - \omega)/c])(1 + R - 2\sqrt{R} \cos[2L_{\text{eff}}(\omega_0 + \omega)/c])}
\]

![Peaks near degeneracy](peaks.png)

![Envelope of peaks](envelope.png)
Summary

• **Bi-directional source of polarization-entangled photons**
  – 12000 pairs s⁻¹ mW⁻¹ detected
  – 10 times more flux than other cw sources
  – All generated pairs are polarization-entangled, no filtering required
  – Tunable around degeneracy (5 nm)
  – Spatially extended source

• **Cavity source of narrowband photons**
  – Data shows quantum interference
  – Linear DRO under construction

• **Future: Combine bi-directional pumping and a ring cavity geometry**
  – Ultrabright source of polarization-entangled pairs
  – Narrowband spectrum