Spectrally Ultrabright Heralded Single Photons Generated from a Hot Atomic Vapor

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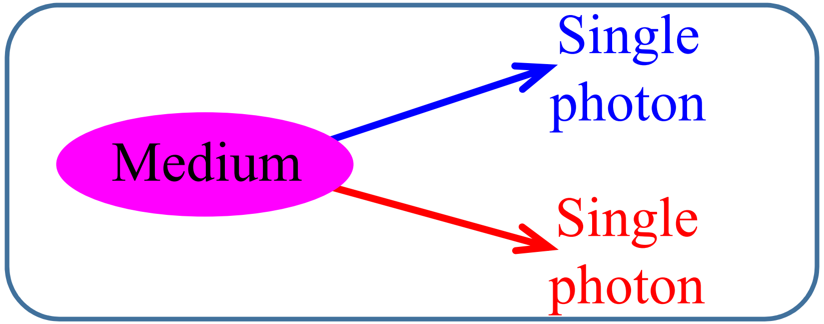
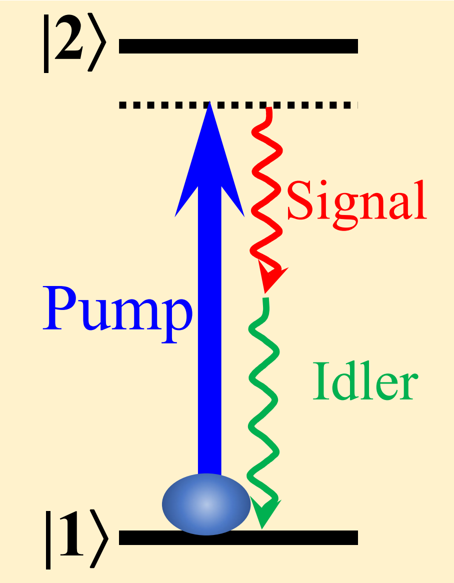
Introduction

What are biphotons or heralded single photons?
Why are they useful in quantum information processing?



- The **biphoton** is a pair of time-correlated single photons.
- Single photons appear randomly in time. It is difficult to use them in the random timing.
- Biphotons also appear randomly in time. Nevertheless, we can use the first photon of the biphoton to trigger a quantum operation, and employ the second one in the quantum operation. So, the second one is called the heralded single photons.

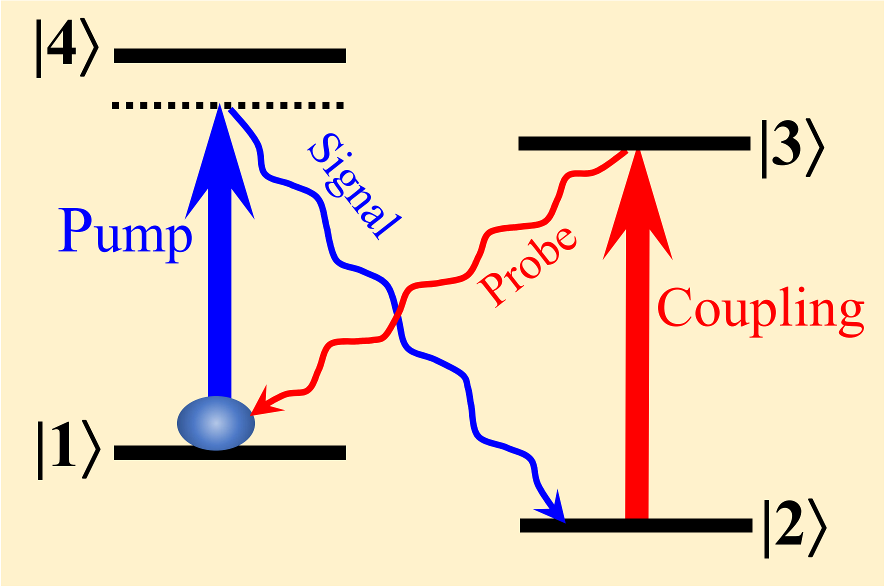
Mechanisms for Generation of Biphotons — SPDC



Spontaneous Parametric Down Conversion

- SPDC: A pump photon is converted to a signal and an idler photons induced by the vacuum fluctuation.
- Typical media are nonlinear crystals.
- Since 1970.

Mechanisms for Generation of Biphotons — SFWM

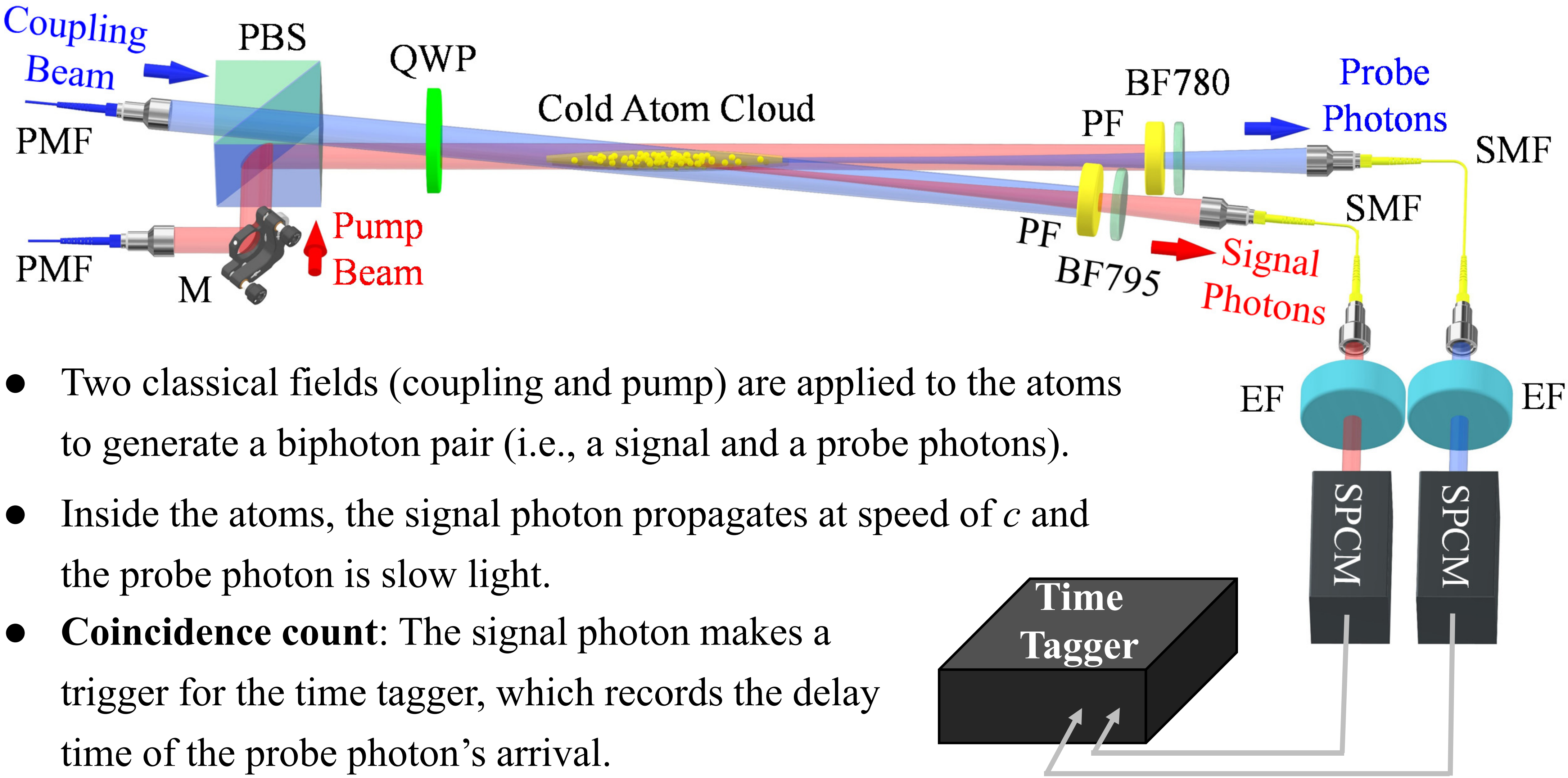


Spontaneous Four-Wave Mixing

- SFWM: The vacuum fluctuation induces a Raman transition to generate the signal photon and also the coherence between states 1 and 2. The coupling field utilizes the coherence to generate the probe photon similar to the electromagnetically induced transparency (EIT) effect.
- The EIT effect makes the probe photon become slow light.
- Typical media: cold atoms since 2005 and room-temperature or hot atomic vapors since 2016.

Illustration of Biphoton Generation and Wave Packet

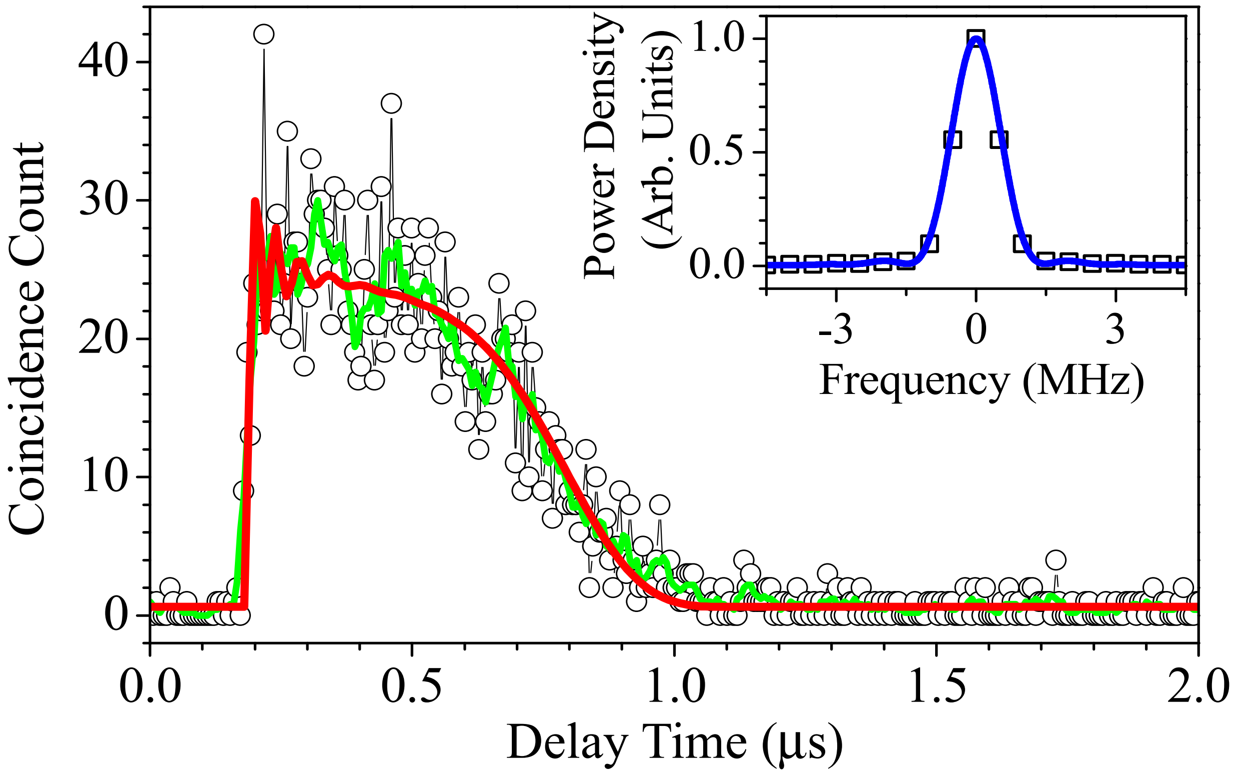
Biphoton Generation from Cold Atoms



- Two classical fields (coupling and pump) are applied to the atoms to generate a biphoton pair (i.e., a signal and a probe photons).
- Inside the atoms, the signal photon propagates at speed of *c* and the probe photon is slow light.
- **Coincidence count**: The signal photon makes a trigger for the time tagger, which records the delay time of the probe photon's arrival.

Temporal Profile of the Biphoton Wave Packet in Cold Atoms

Data represent biphoton wave packet $|\psi|^2$, where ψ is the wave function of two-photon correlation.



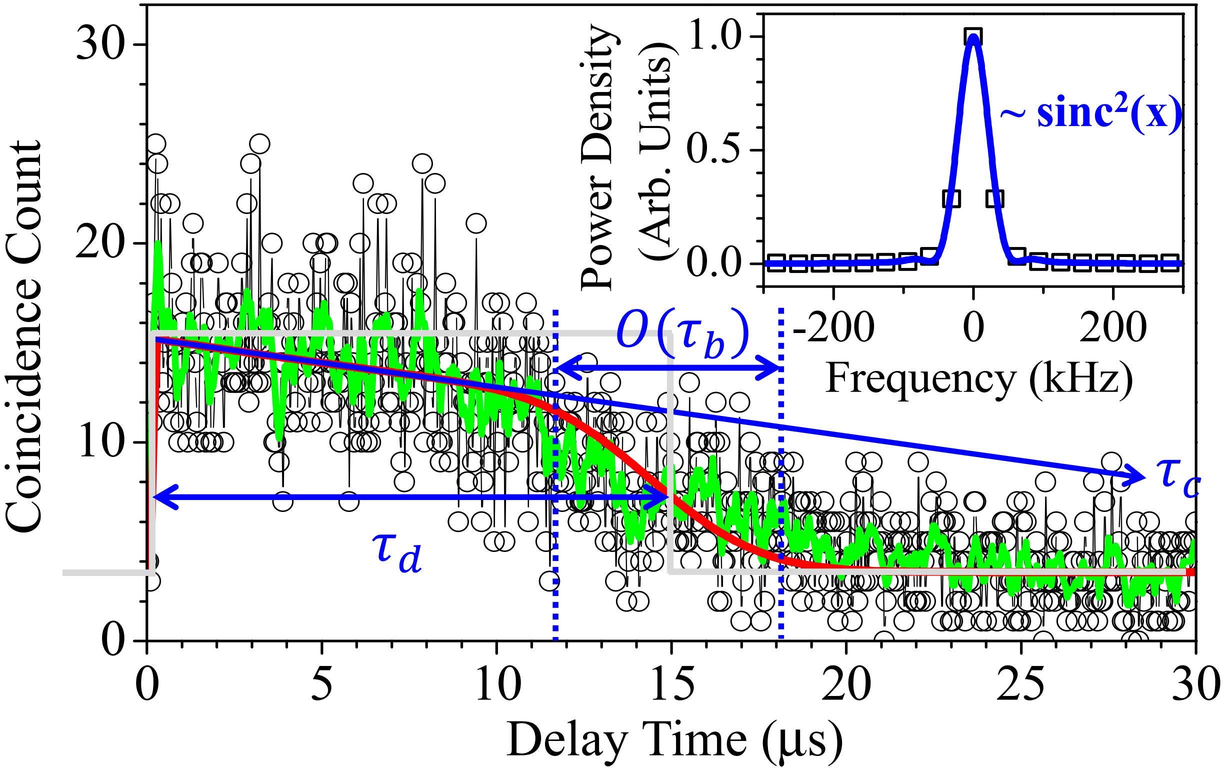
Temporal FWHM 0.57 μs

Spectral FWHM 1.2 MHz

- Circles are the two-photon coincidence counts, green line is the result of 4-point moving average of the circles, and red line is the theoretical prediction.
- In the inset, squares and blue line are the Fourier transforms of the data and the prediction.

The Longest Biphoton with the Narrowest Linewidth in the World

Y.-S. Wang, K.-B. Li,
C.-F. Chang, T.-W. Lin,
J.-Q. Li, S.-S. Hsiao,
J.-M. Chen, Y.-H. Lai,
Y.-C. Chen, Y.-F. Chen,
C.-S. Chuu, and I. A. Yu,
arXiv:2205.13778.

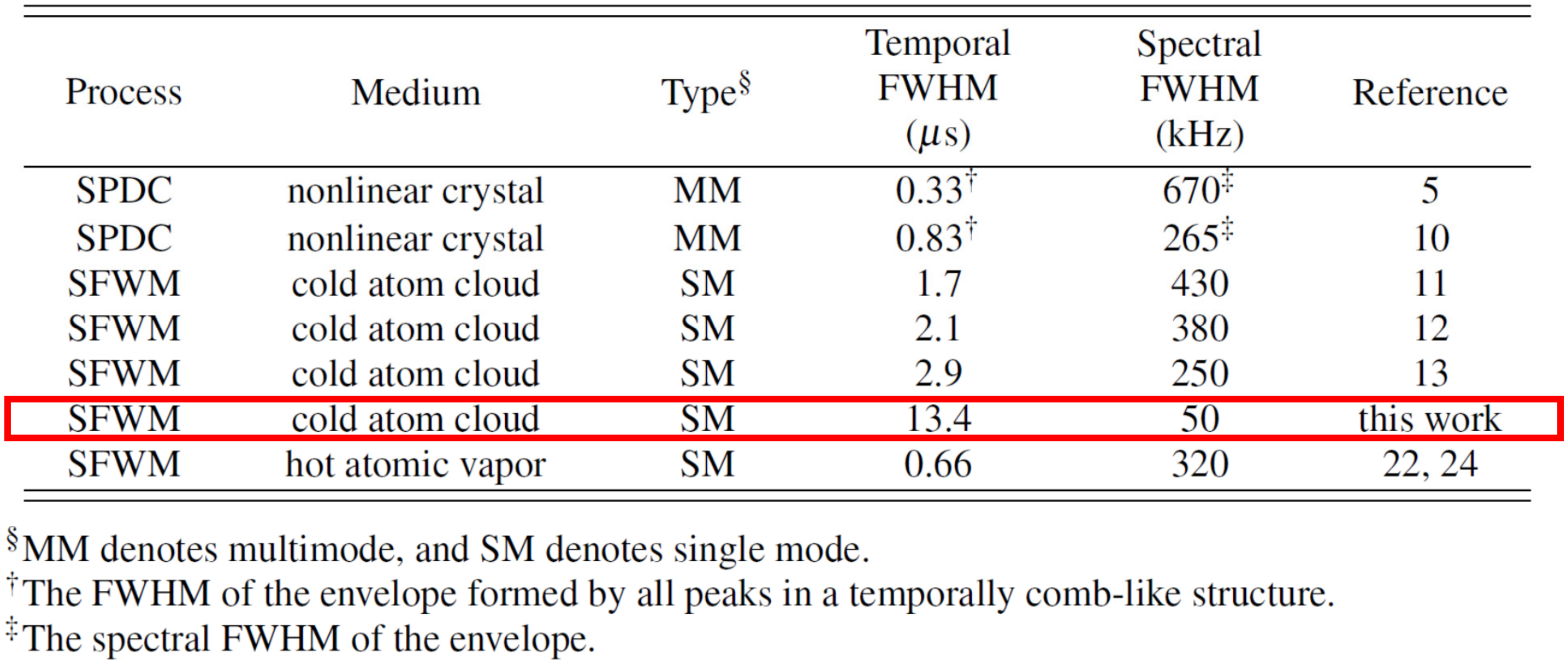


Temporal FWHM 13.4 μs

Spectral FWHM 50 kHz

- A system with a low decoherence rate of 2π×1.8 kHz and a high optical depth of 110 makes an ultralong biphoton wave packet.
- Coherence time τ_c: 43 μs; propagation delay time τ_d: 16 μs; (EIT bandwidth)$^{-1}$ τ_b: 2 μs.

Biphoton Sources with Spectral Profiles of FWHM below 1 MHz



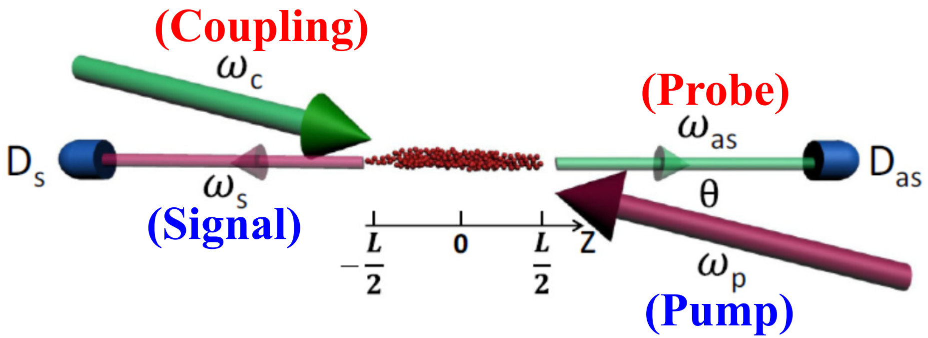
Process	Medium	Type[§]	Temporal FWHM (μs)	Spectral FWHM (kHz)	Reference
SPDC	nonlinear crystal	MM	0.33[†]	670[‡]	5
SPDC	nonlinear crystal	MM	0.83[†]	265[‡]	10
SFWM	cold atom cloud	SM	1.7	430	11
SFWM	cold atom cloud	SM	2.1	380	12
SFWM	cold atom cloud	SM	2.9	250	13
SFWM	cold atom cloud	SM	13.4	50	this work
SFWM	hot atomic vapor	SM	0.66	320	22, 24

[§] MM denotes multimode, and SM denotes single mode.
[†] The FWHM of the envelope formed by all peaks in a temporally comb-like structure.
[‡] The spectral FWHM of the envelope.

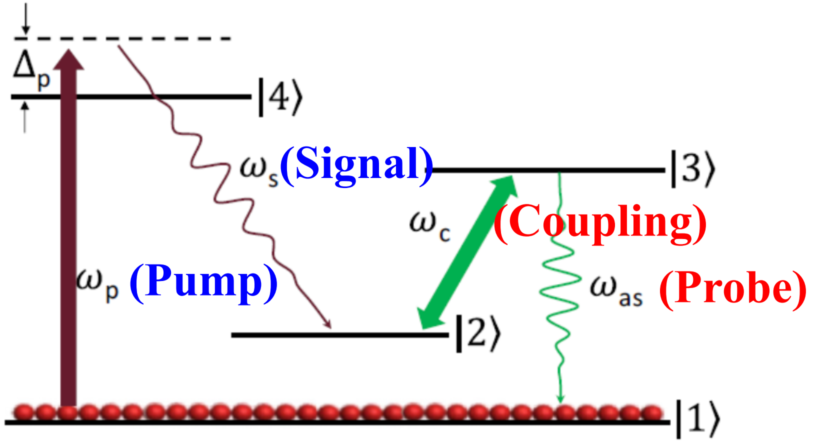
- However, the duty cycle of the biphoton generation with cold atoms is low, e.g., 0.8% in our case and the average generation rate is merely about 30 pairs/s.
- The data in each figure were accumulated by about one hour.

Features of Our Hot-Atom Biphoton Source

Phase Mismatch in Others' Biphoton Experiments



Counter-Propagation



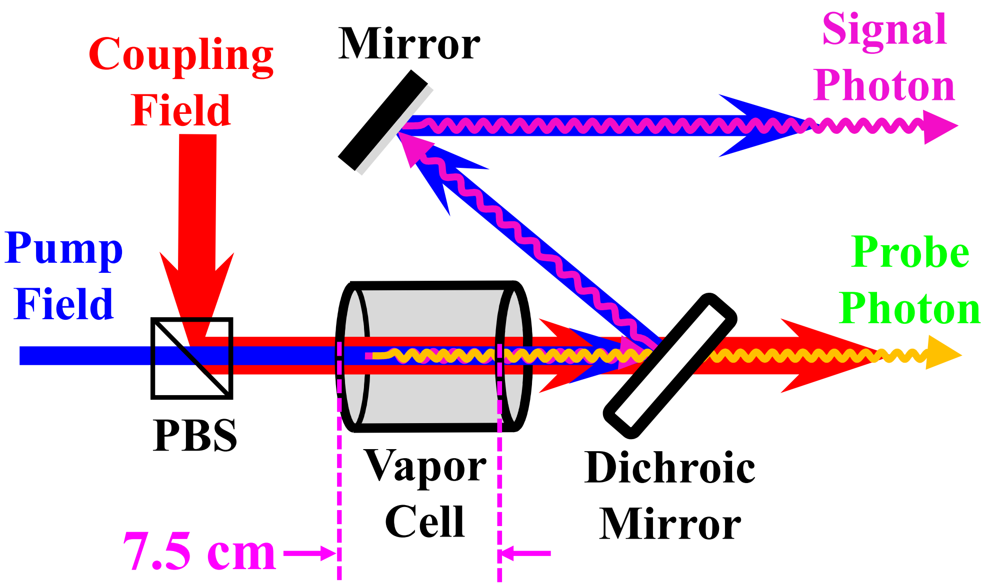
Two absorption-emission processes

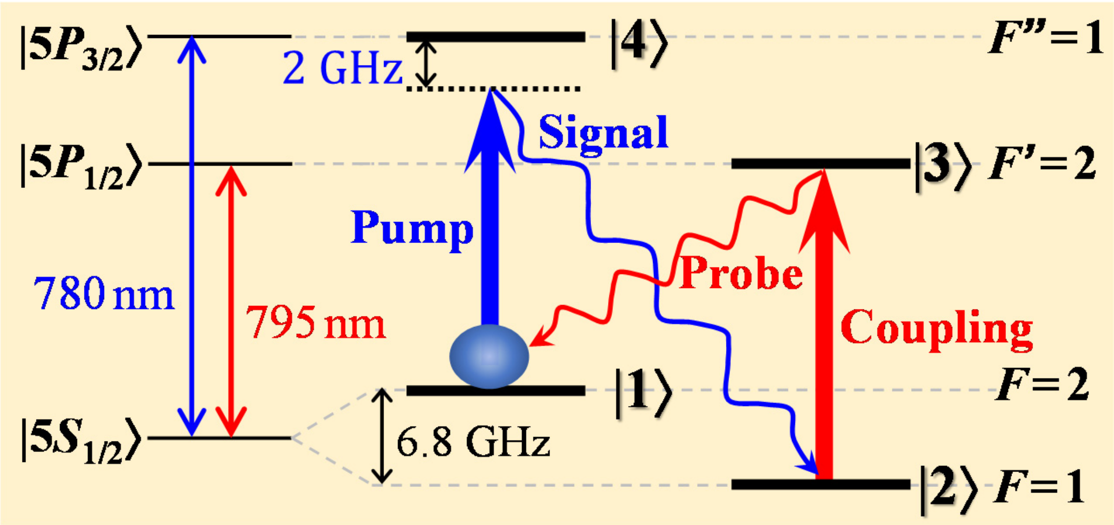
$$\Delta\vec{k} = \left(\vec{k}_{\text{pump}} - \vec{k}_{\text{signal}}\right) + \left(\vec{k}_{\text{coupling}} - \vec{k}_{\text{probe}}\right) = \left(\frac{\omega_{21}}{c}\right)(-\hat{z}) + \left(-\frac{\omega_{21}}{c}\right)\hat{z} = -\frac{2\omega_{21}}{c}\hat{z}$$

Typically, $\omega_{21} = 2\pi \times 6.8$ GHz. $\left|\Delta\vec{k}\right| = \frac{2\pi}{8.8\ cm}$

- Previously, SFWM biphoton sources utilized the counter-propagation scheme.
- The degree of phase mismatch is given by $L\left|\Delta\vec{k}\right|$ (*L*: the medium length). At *L* = 7.5 cm, the phase mismatch reduces the generation rate by 1000 folds!

Phase-Mismatch-Free in Our Biphoton Experiment

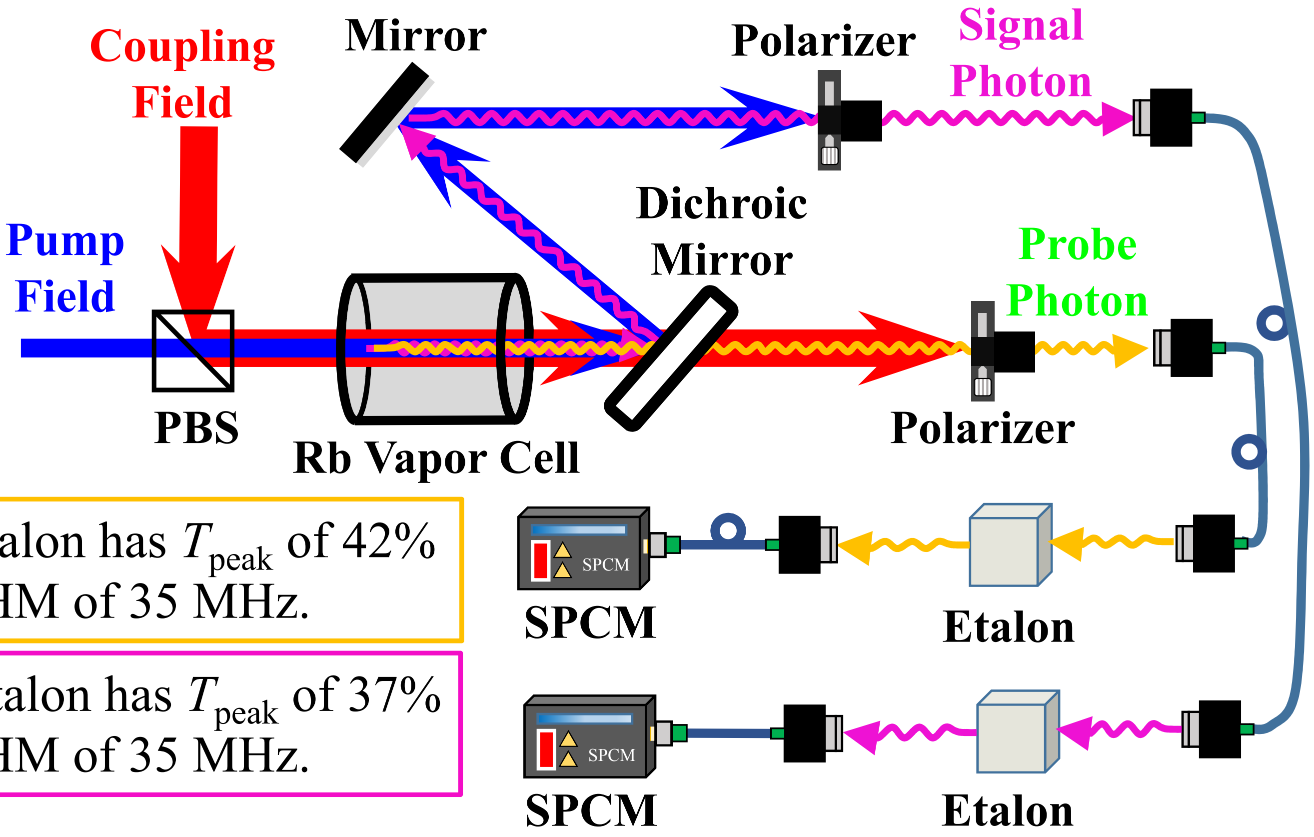




$$\Delta\vec{k} = \left(\vec{k}_{\text{pump}} - \vec{k}_{\text{signal}}\right) + \left(\vec{k}_{\text{coupling}} - \vec{k}_{\text{probe}}\right) = \left(-\frac{\omega_{12}}{c}\right)\hat{z} + \left(\frac{\omega_{12}}{c}\right)\hat{z} = \mathbf{0!}$$

- Our biphoton source utilized the all-copropagation scheme.
- The all-copropagation scheme ensures the phase match, and also maintains a low decoherence rate, which enables a narrow linewidth.

High Extinction for Laser Light



The polarization filter provides an extinction ratio (ER) of 60 (48) dB to block the pump (coupling) field.

The probe etalon blocks the coupling field with an ER of 88 dB.

The signal etalon blocks the pump field with an ER of 74 dB.

The probe etalon has T_{peak} of 42% and the FWHM of 35 MHz.

The signal etalon has T_{peak} of 37% and the FWHM of 35 MHz.

- Laser light of a power up to 40 mW, and the single-photon pulse of a power as low as 0.4 pW.
- Fortunately, an overall ER of ~135 dB to block the pump and coupling fields.

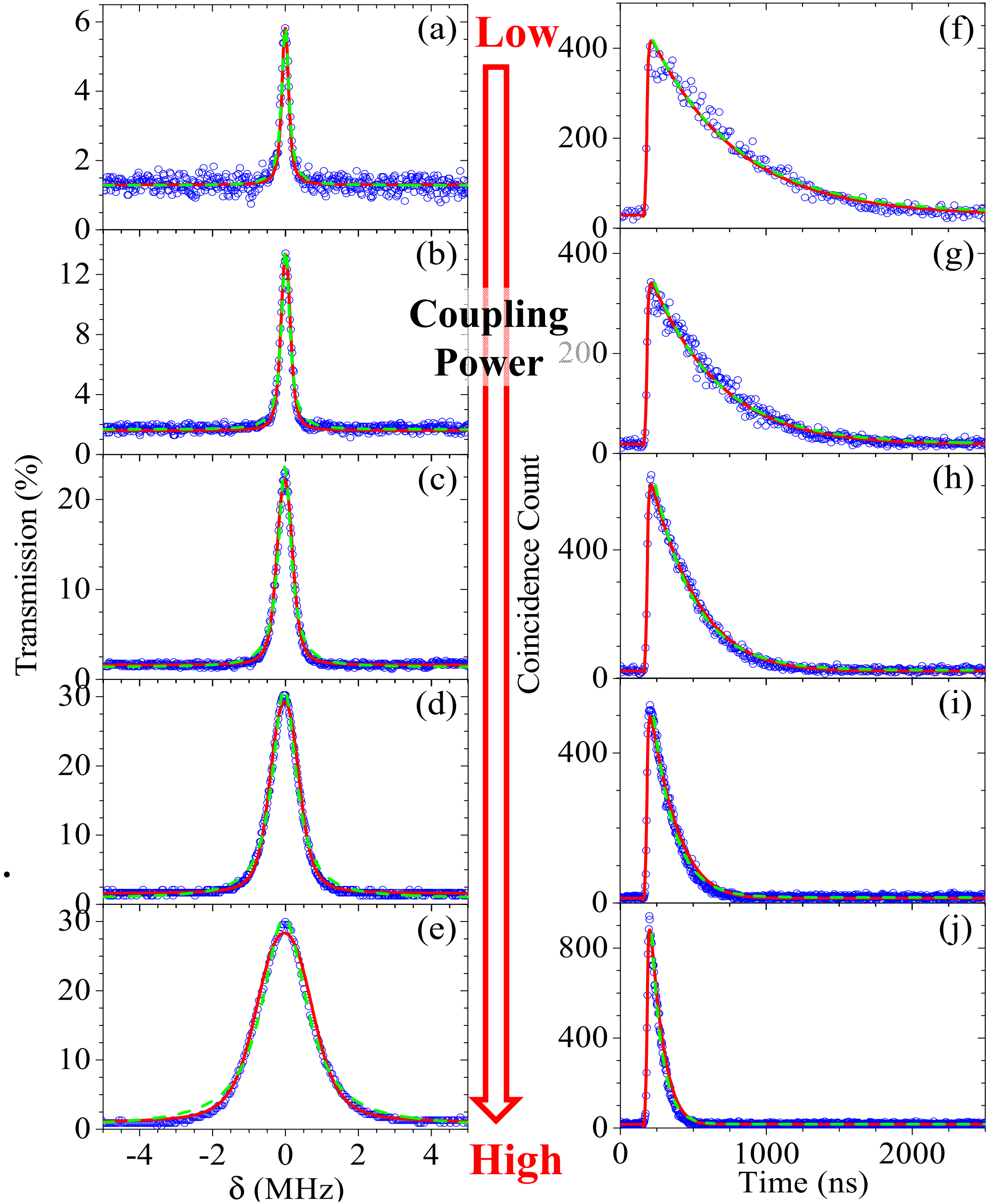
A Narrow-Linewidth, High-Generation Rate, High-Spectral Brightness Biphoton Source

Biphoton Wave Packet and EIT Spectrum of Hot Atoms

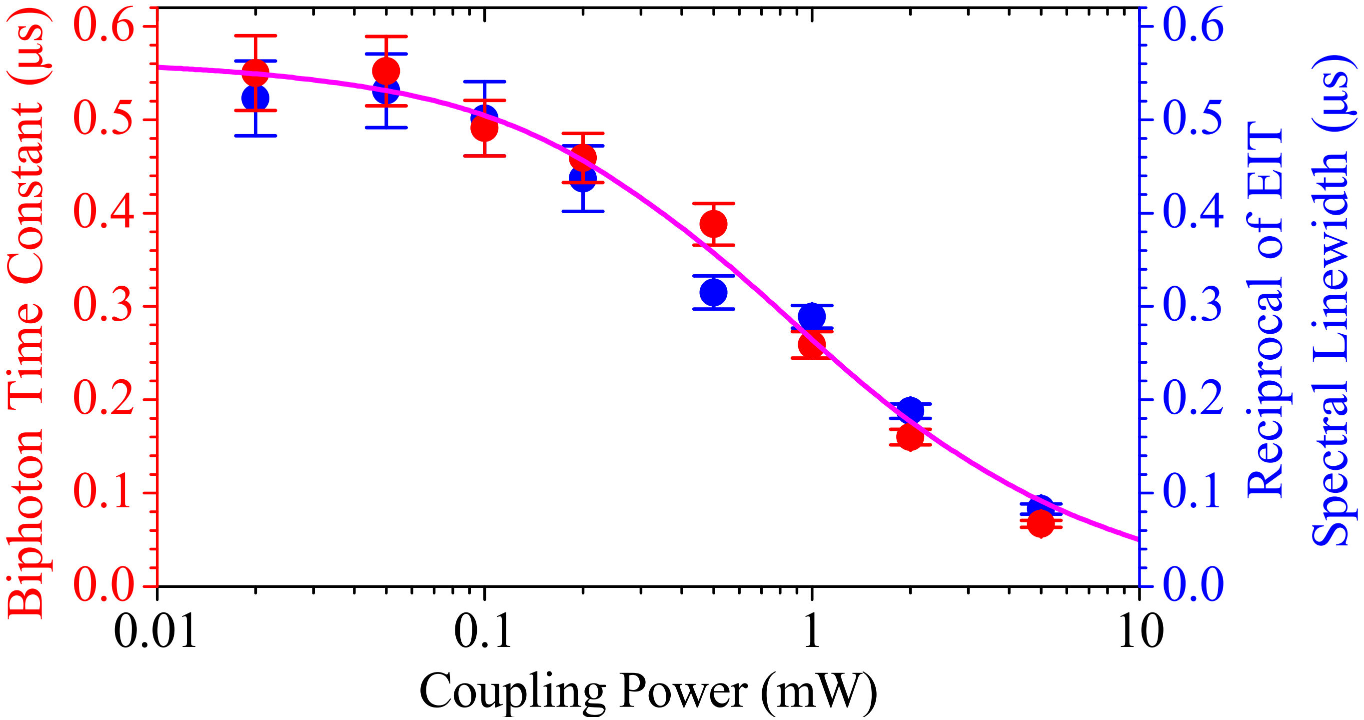
S.-S. Hsiao, W.-K. Huang, Y.-M. Lin, J.-M. Chen, C.-Y. Hsu, and I. A. Yu, Phys. Rev. A 106, 023709 (2022).

In hot atoms, the biphoton wave packet is mainly determined by the EIT spectrum; in cold atoms, it is strongly influenced by the propagation delay time as shown by the earlier slide.

- A higher coupling power makes a broader EIT linewidth & a narrower biphoton temporal width.
- The EIT spectral profile is a Lorentz function.
- The biphoton temporal profile is an exponential-decay function.



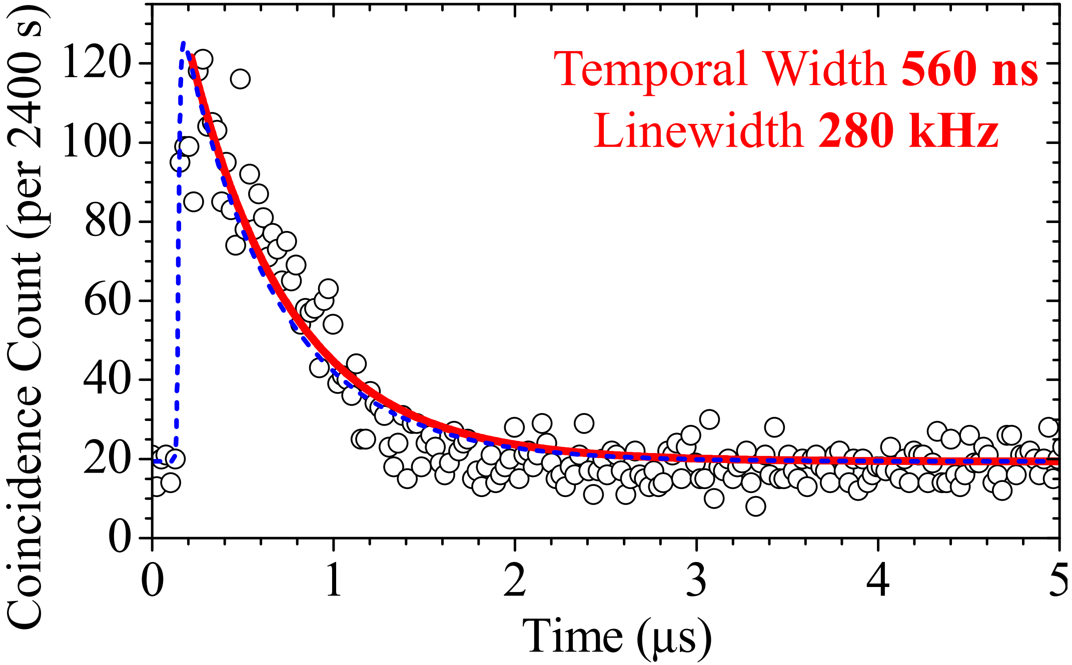
A Biphoton Source with a Highly Tunable Temporal Width

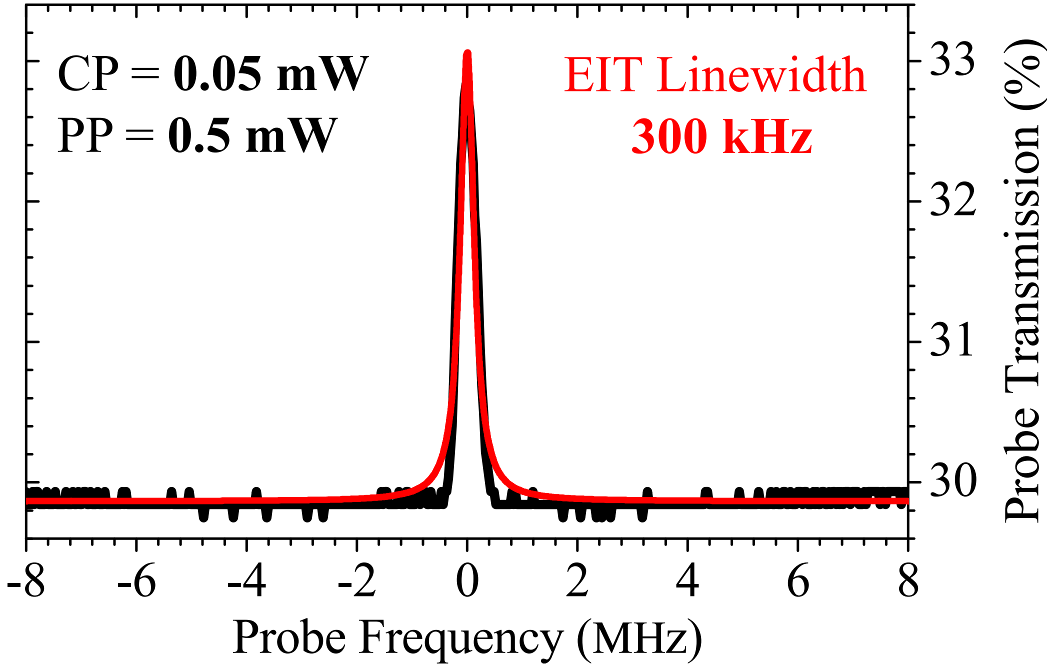


- Data of biphoton temporal widths (red) are consistent with results calculated from those of EIT linewidths (blue), and also in agreement with the theoretical predictions (line).
- The temporal width or spectral linewidth of biphotons can be tuned by about one order of magnitude (from 60 to 560 ns). A higher laser power can make the tuning range larger.

The Narrowest-Linewidth Biphotons Generated from Hot Atoms in the World

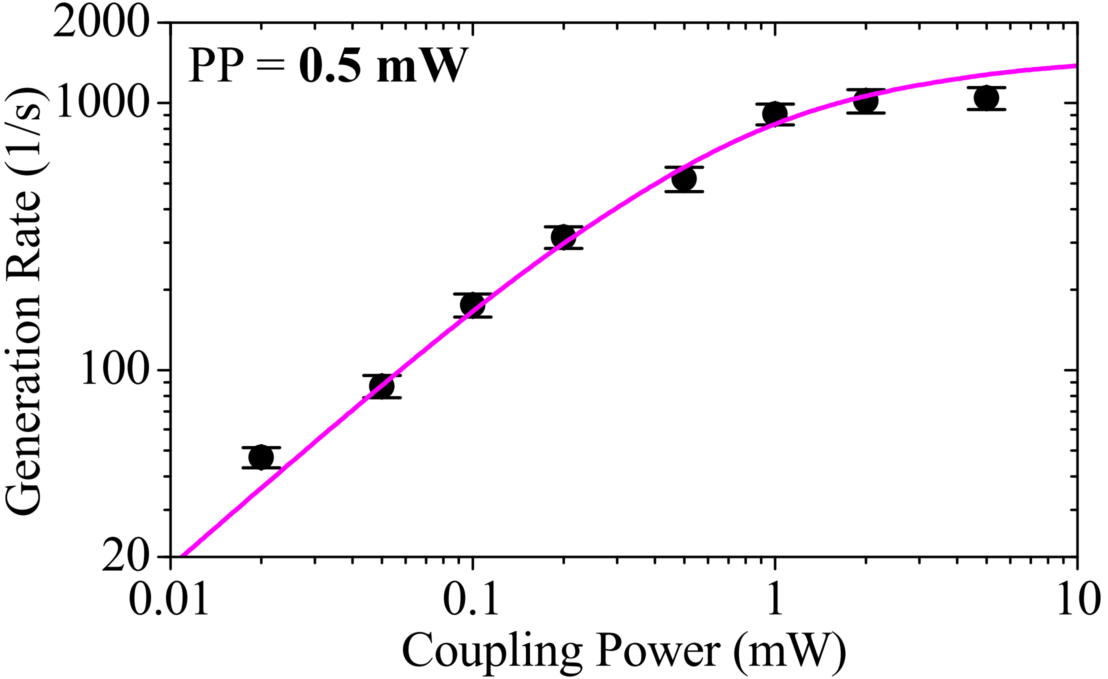
C.-Y. Hsu, Y.-S. Wang, J.-M. Chen, F.-C. Huang, Y.-T. Ke, E. K. Huang, W. Hung, K.-L. Chao, S.-S. Hsiao, Y.-H. Chen,
C.-S. Chuu, Y.-C. Chen, Y.-F. Chen, I. A. Yu, Opt. Express 29, 4632 (2021). **Editors' Pick.**

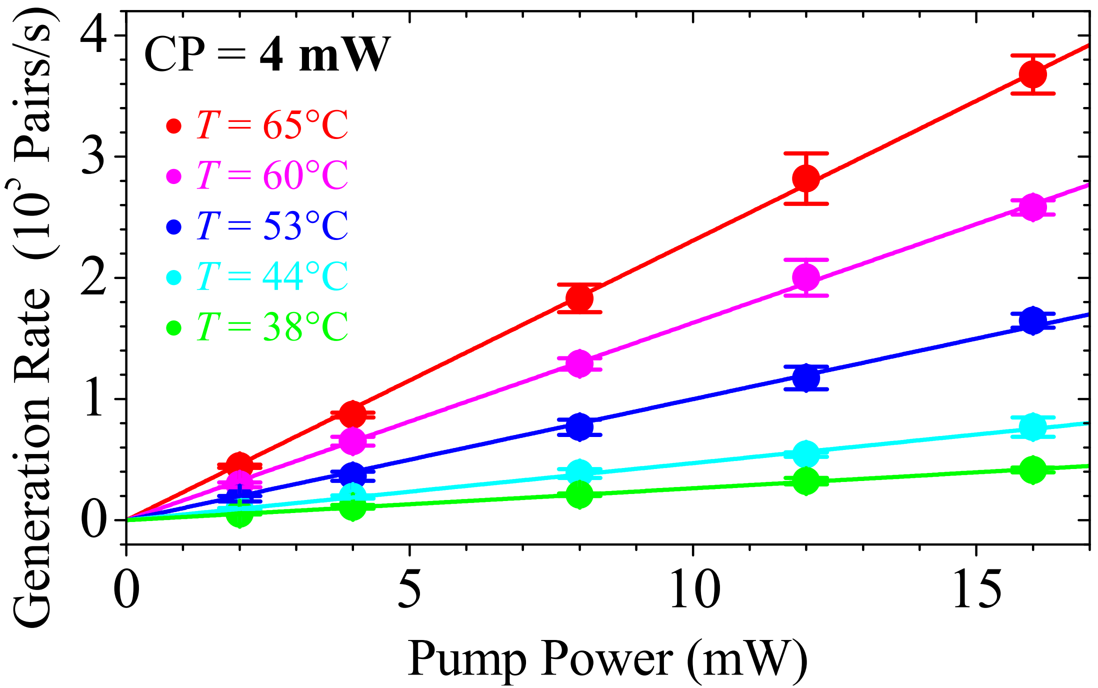




- Biphoton wave packet (left) and EIT spectrum (right) were measured at the same condition.
- The decoherence rate in the experimental system limits the narrowest linewidth.

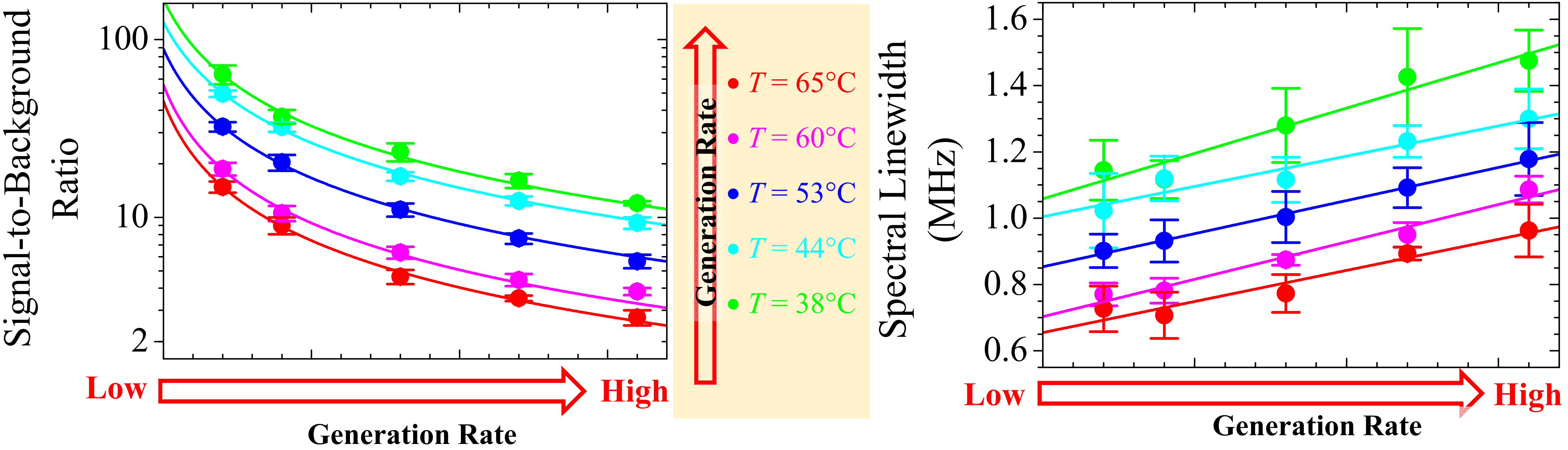
Generation Rate of the Biphoton Source (1/2)





- At large coupling powers, the generation rate saturates.
- The generate rate is linearly proportional to the pump power, and increases with the atom temperature, i.e., the optical depth.
- Experimental data are consistent with theoretical predictions.

Generation Rate of the Biphoton Source (2/2)



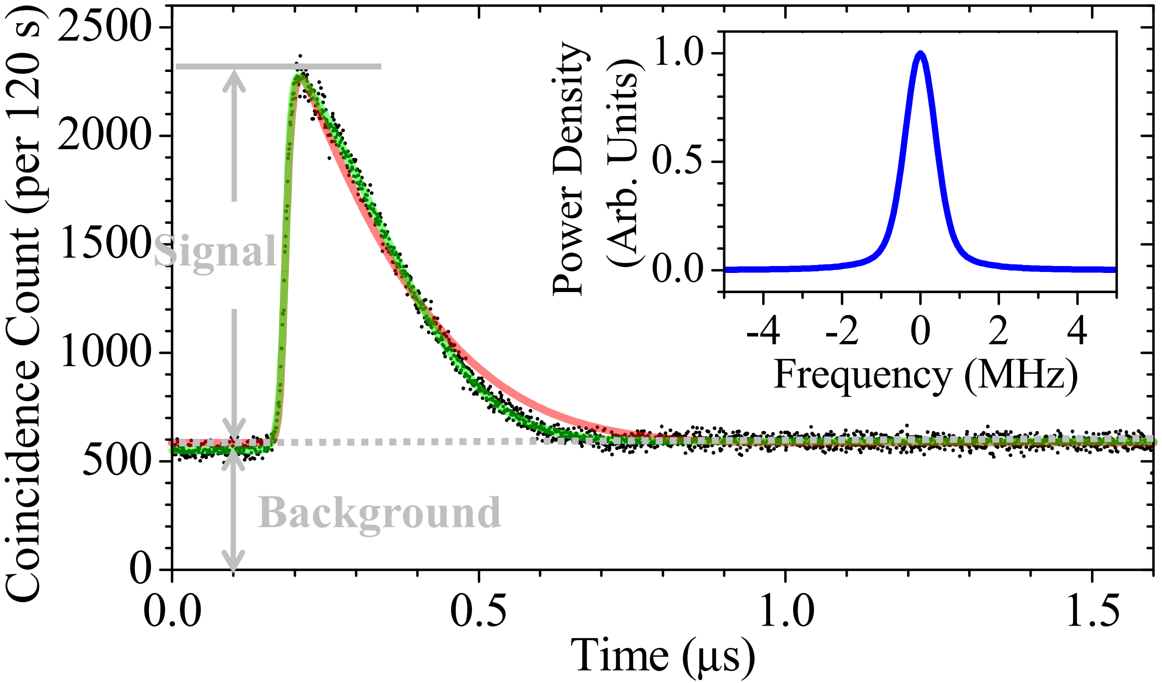
- A larger the signal-to-background ratio (SBR) makes a higher purity of the single photon. However, as the generate increases, the SBR decreases.
- A narrower biphoton's linewidth makes a higher success probability of a quantum process, e.g. quantum memory. However, as the generate increases, the linewidth becomes broadened.

The Highest Spectral Brightness in the World

J.-M. Chen, C.-Y. Hsu, W.-K. Huang, S.-S. Hsiao, F.-C. Huang, Y.-H. Chen, C.-S. Chuu, Y.-C. Chen, Y.-F. Chen, and I. A. Yu, Phys. Rev. Res. 4, 023132 (2022).

Generation Rate
3.7 × 10^5 pairs/s

Linewidth
960 kHz



SBR
3.1

Violate Cauchy-Schwartz inequality for classical light by **4.2 folds**

- The spectral brightness, i.e., generation rate per linewidth, is the measure of success rate of a quantum information process.
- The high generation rate, together with the narrow linewidth, results in a spectral brightness of 3.8 × 10^5 pairs/s/MHz, better than all known results with all kinds of media.

Comparison between Different Kinds of Biphoton Sources

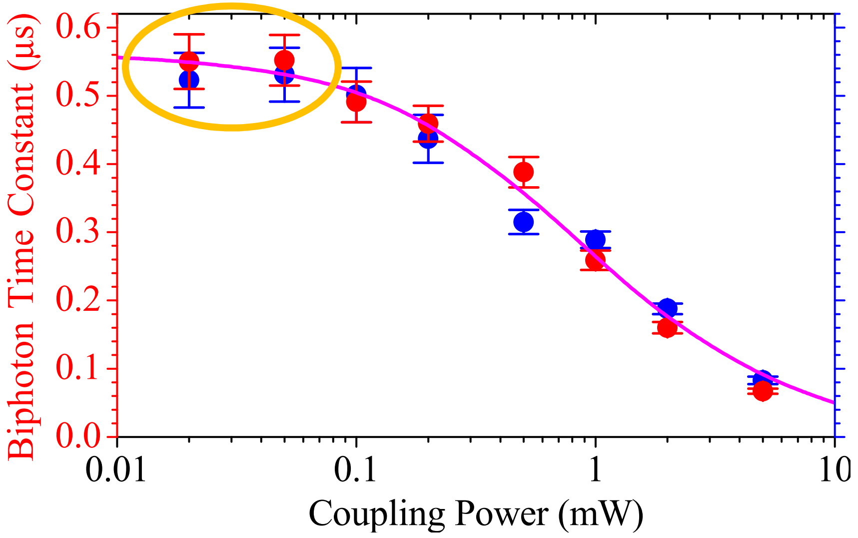
		Best Linewidth	Best Spectral Brightness	Linewidth Tunability	Frequency Tunability	Notes
Single-Mode SPDC		3 MHz[1]	3.5×10^5 pairs/s/MHz[5]	N.A.	a few GHz	
Multi-Mode SPDC		265 kHz[2]	4,300 pairs/s/MHz[6]	N.A.	a few GHz	The values refer to one of the frequency modes.
Cold-Atom SFWM		**50 kHz**[11]	4,700(×10%) pairs/s/MHz[7]	one order of magnitude	N.A.	Duty cycle ≤ 10%.
Integrated Photonics Devices		92 MHz[3]	1.4×10^5 pairs/s/MHz[3]	N.A.	160 MHz[3]	Micro-ring resonator[3] with Q of $\sim10^6$.
Hot-Atom SFWM	Earlier Works	2 MHz[4]	1.4×10^4 pairs/s/MHz[8]	one order of magnitude	600 MHz (Rb atoms)	The frequency tunability is determined by width of the Doppler broadening.
	These Works	**290 kHz**[9]	**3.8×10^5 pairs/s/MHz**[10]			

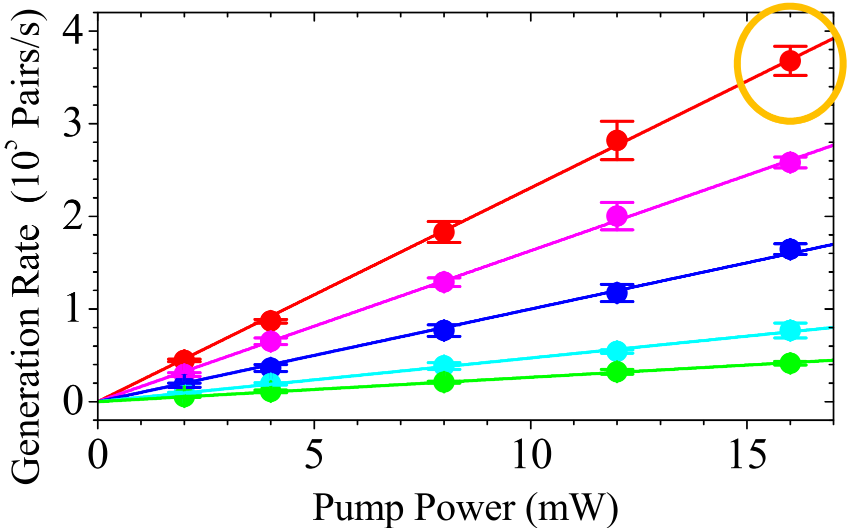
[1] New J. Phys. 18, 123013 (2018).
[2] APL Photon. 5, 066105 (2020).
[3] PRX Quantum 2, 010337 (2021).
[4] Nat. Commun. 7, 12783 (2016).
[5] Phys. Rev. A 92, 063827 (2015).
[6] APL Photon. 4, 090804 (2019).
[7] Optica 1, 84 (2014).
[8] Appl. Phys. Lett. 110, 161101 (2017).
[9] Opt. Express 29, 4632 (2021).
[10] Phys. Rev. Res. 4, 023132 (2022).
[11] arXiv:2205.13778.

Conclusion

Conclusion

- The linewidth of our hot-atom biphotons can be as narrow as 290 kHz, which is the narrowest among all kinds of single-mode biphotons generated from room-temperature or hot media.
- The spectral brightness of our hot-atom biphoton source can be as high as 3.7×10^5 pairs/s/MHz, which the highest spectral brightness of all biphoton sources.
- Our biphoton source not only surpasses the sources produced with the hot atoms in the previous works, but also competes with the sources produced with the nonlinear crystals and integrated photonic devices.





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2014/9/10 桃山

http://atomcool.phys.nthu.edu.tw/

Thank you for your attention