國立交通大學
National Chiao Tung University

Taiwan-France joint school on Quantum Information Science & Workshop on Quantum Measurement
台法雙邊量子資訊學校暨量子量測國際研討會
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Sun Moon Lake Teachers' Hostel, Nantou

Schemes to generate entangled photon pairs via spontaneous parametric down conversion

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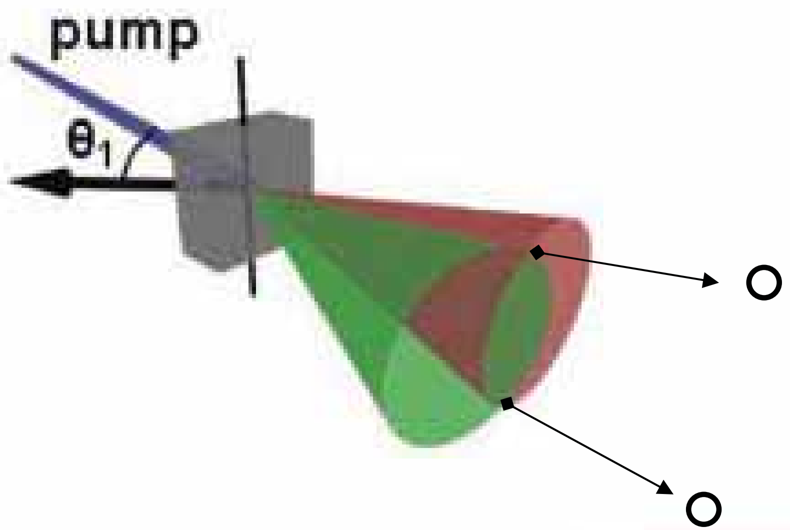

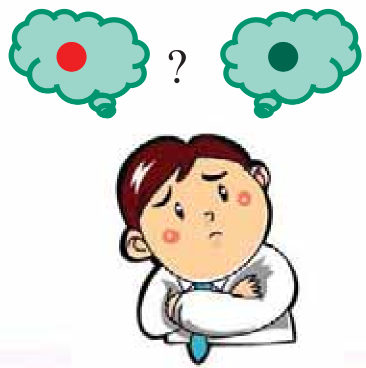

Outline

- Introduction
  - Optical parametric processes
    - Opt. param. amplifier (OPA)
    - Spontaneous param. down conv. (SPDC)
- Application | classical
  - **Broadband generation | for short pulse**
- Application | quantum
  - Entangled photon pairs
  - Ghost imaging | wave vector
  - **Ghost spectroscopy | frequency**
  - Quantum key distribution (QKD) | polarization
  - **Multiplex QKD | polarization and frequency**
  - **Entangled photon beam**
- Conclusion

Our work

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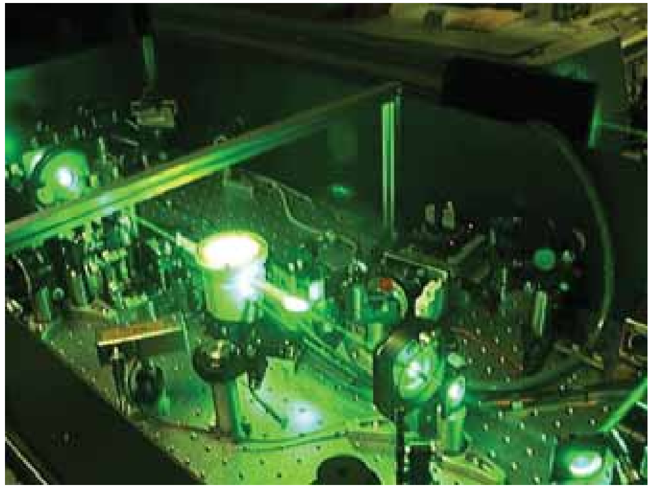
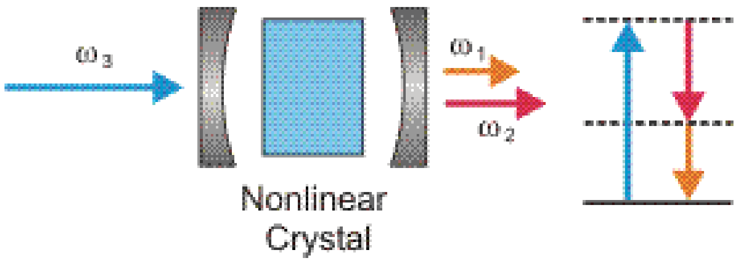
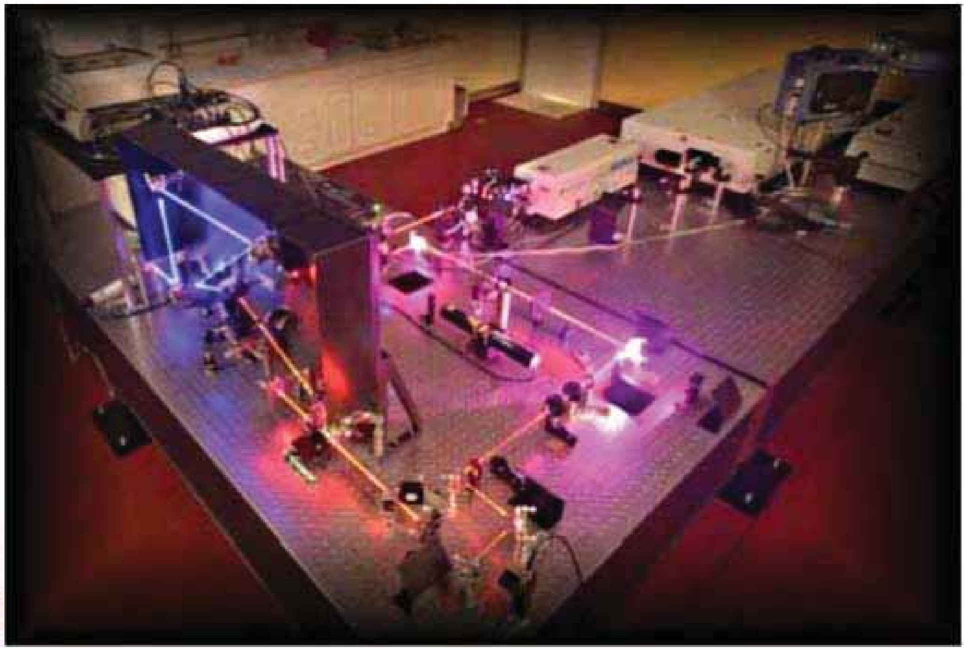
Our work

Outline

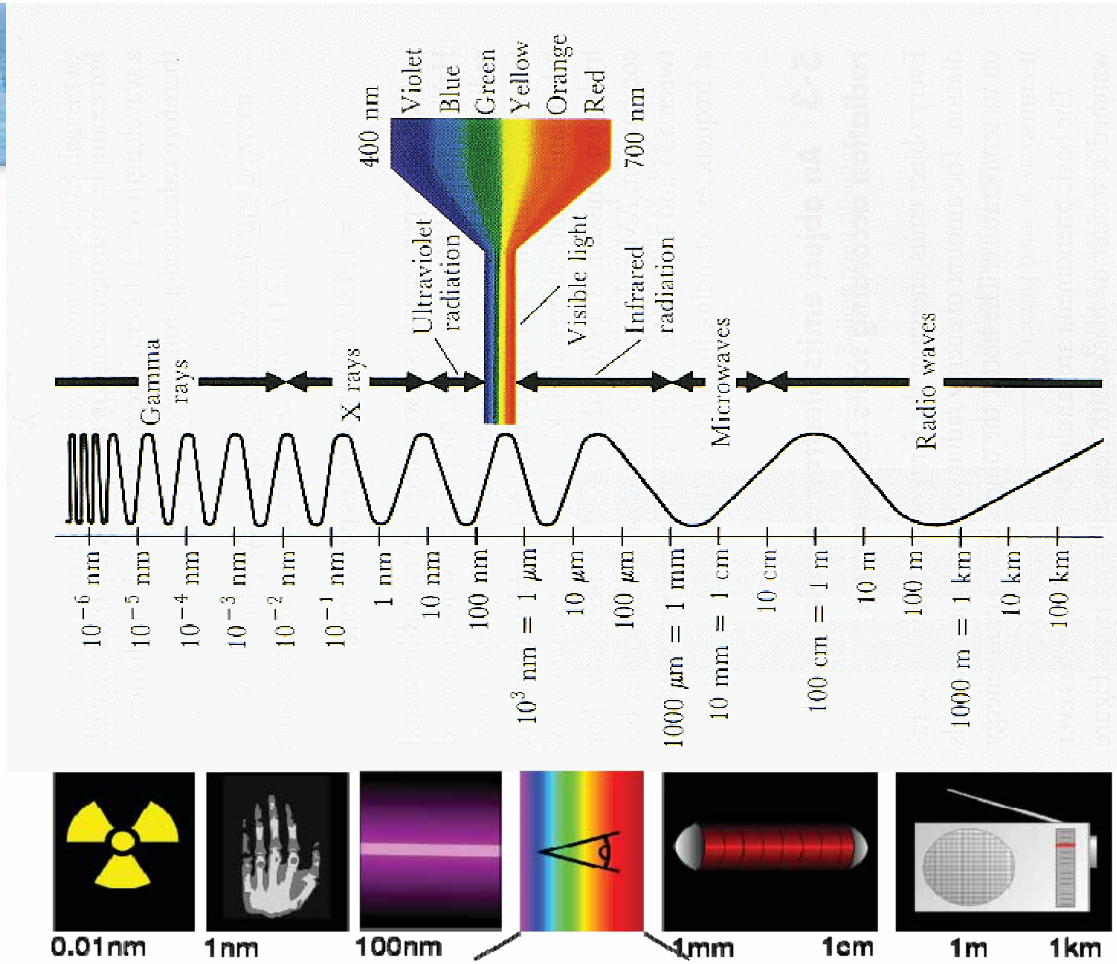
- ➢Introduction | OPA and SPDC
  - ●Light is …
  - ●Light-matter interaction
  - ●Frequency conversion
    - •SHG and SPDC
    - •SPDC⇔OPA
    - •OPA is …?
  - ●Why OPA?
  - ●Why SPDC?







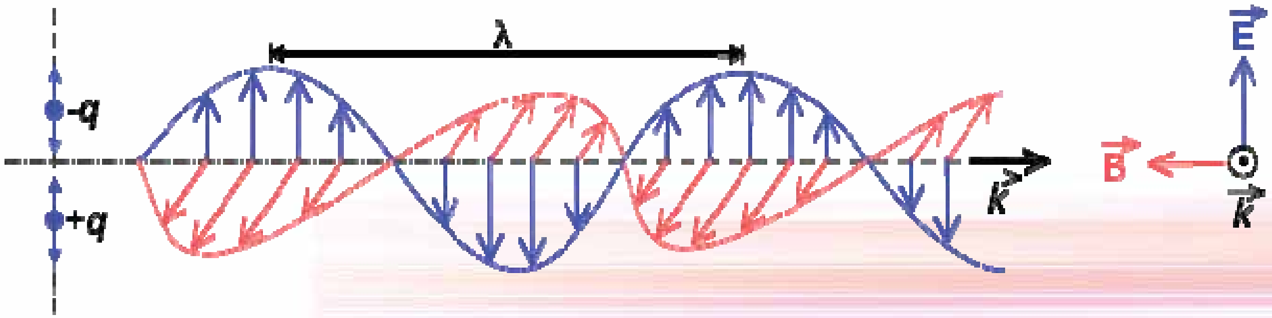
Introduction



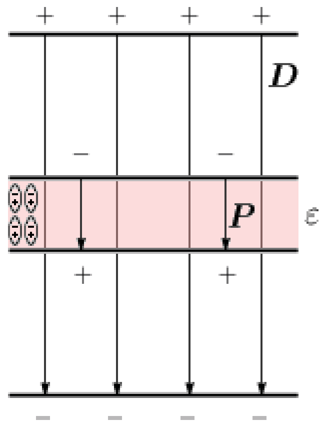
Light

- gamma-ray
- X-ray
- Ultraviolet
- visible
- infrared
- radio wave

=> Electro-magnetic wave



Introduction



Light-matter interaction

Electric field make dielectric polarization

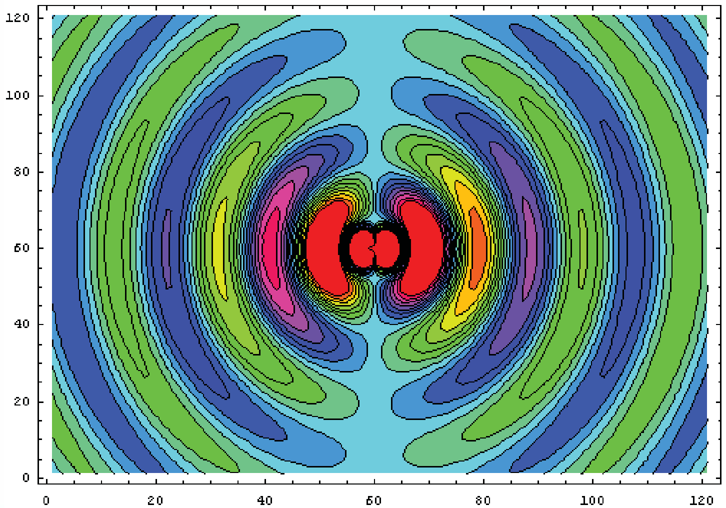
$$P = \varepsilon_0(\chi^{(1)}E + \chi^{(2)}EE + \chi^{(3)}EEE\cdots)$$

Emission from dipole

oscillating in vertical direction

E : exp(-iωt)

E*E : exp(-i2ωt)



Second harmonic generation (SHG)

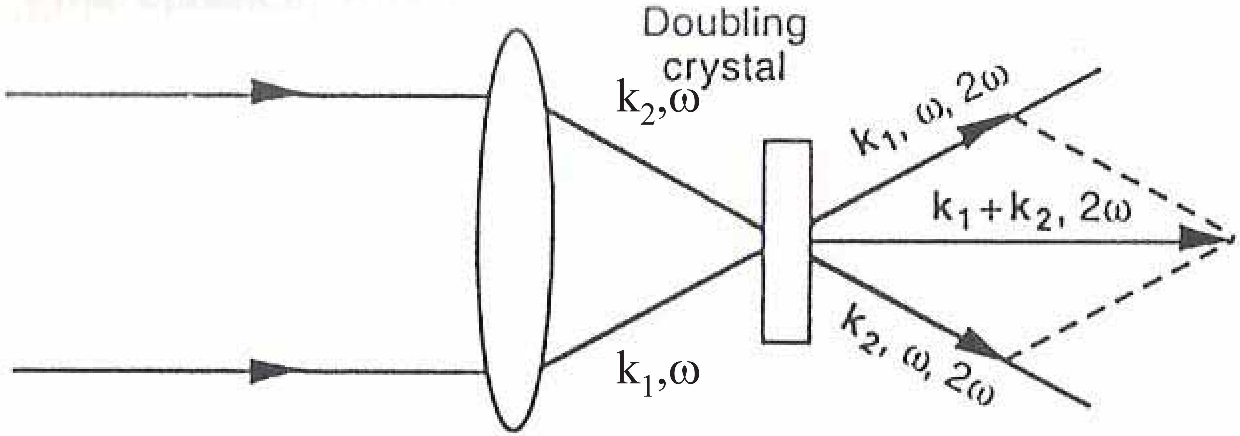
using **a *non-linear* crystal**

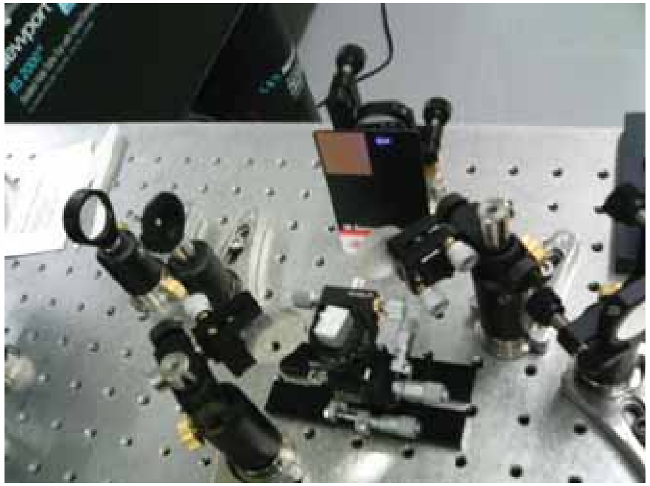
within some limitation from physical law…

BBO crystal
β-BaB_2O_4

Introduction

energy / momentum conservation in frequency mixing





$$\hbar\omega_{SHG1} = \hbar\omega_1 + \hbar\omega_1 \qquad \mathbf{k}_{\mathbf{SHG1}} = \mathbf{k}_1 + \mathbf{k}_1$$

$$\hbar\omega_{SHG2} = \hbar\omega_2 + \hbar\omega_2 \qquad \mathbf{k}_{\mathbf{SHG2}} = \mathbf{k}_2 + \mathbf{k}_2$$

$$\hbar\omega_{SFG} = \hbar\omega_1 + \hbar\omega_2 \qquad \mathbf{k}_{\mathbf{SFG}} = \mathbf{k}_1 + \mathbf{k}_2$$

Introduction

SHG (second harmonic generation)

ω ➔ 2ω

Reversible? YES!

Reverse process

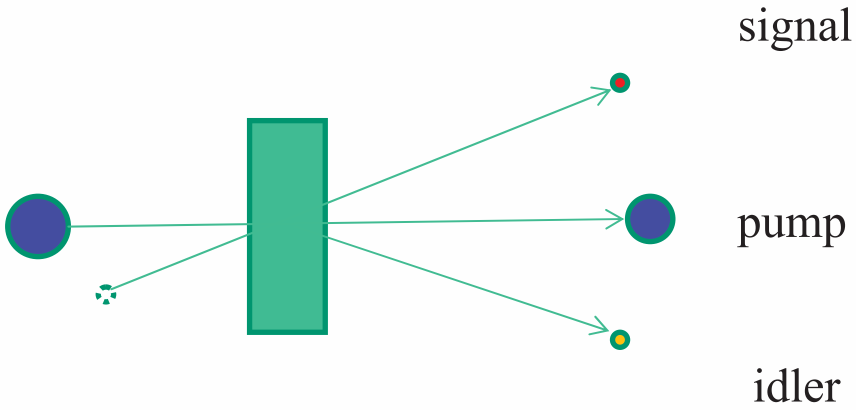
spontaneous parametric down conversion (SPDC)

- spontaneous → occur by itself
- parametric → 2ω=>ω+ω, 2ω=>0.8ω+1.2ω
- down conversion → 2ω=>ω+ω

Introduction

How does **SPDC** occur?

similar as **OPA** (optical parametric amplification)



process | difference frequency generation

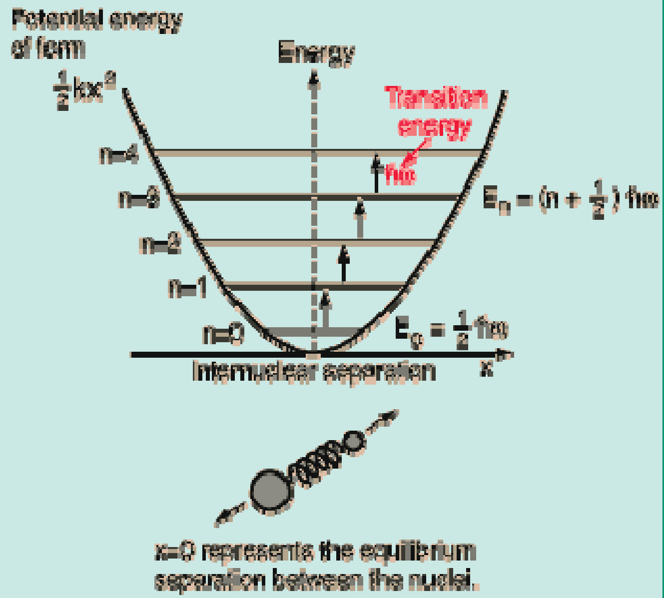
$$h\nu_{pump} - h\nu_{signal} = h\nu_{idler}$$

Energy conservation

$$h\nu_{pump} = h\nu_{signal} + h\nu_{idler}$$

#signal=#idler

SPDC starts with vacuum noise (no seed for signal)



quite low efficiency ~10^{-10}

Introduction

Why **SPDC**? low conversion efficiency

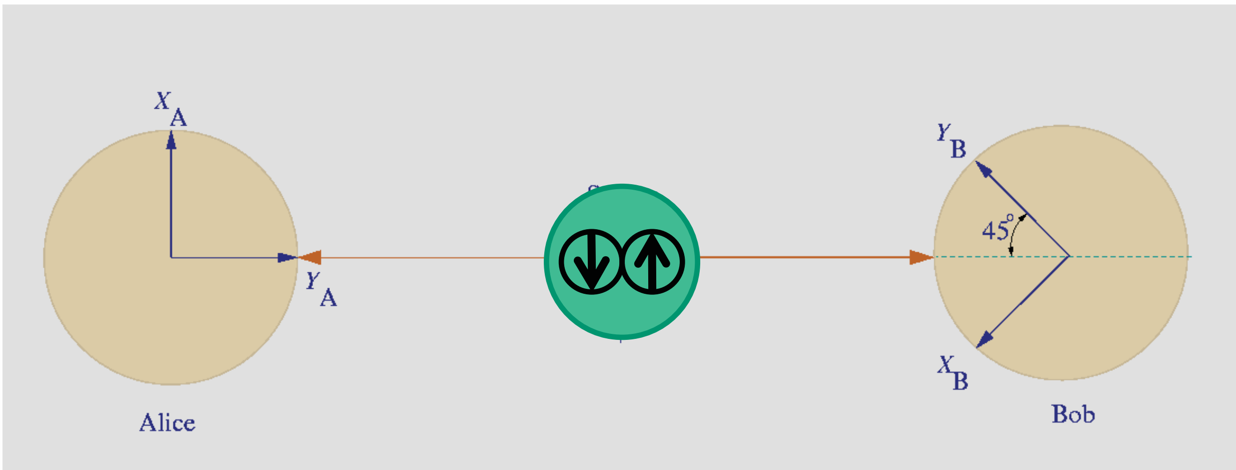
interesting character of **entanglement**

never broken security | quantum communication

easy to transfer | *via* optical fiber

Other method?

singlet (a pair of spin ½ particle)



Introduction

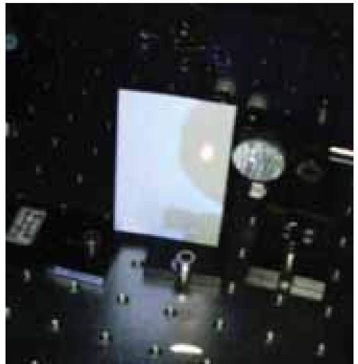
seed | w/o amp

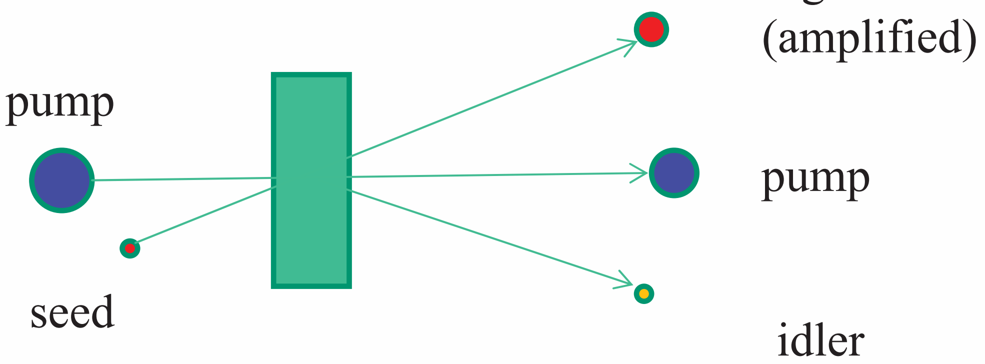
OPA (optical parametric amplification)

…what is **OPA**?

similar as SPDC, much higher efficiency

signal | amplified





process | difference frequency generation

$$h\nu_{pump} - h\nu_{signal} = h\nu_{idler}$$

Energy conservation

$$h\nu_{pump} = h\nu_{signal} + h\nu_{idler}$$

Introduction

Why **OPA**? complicated setup

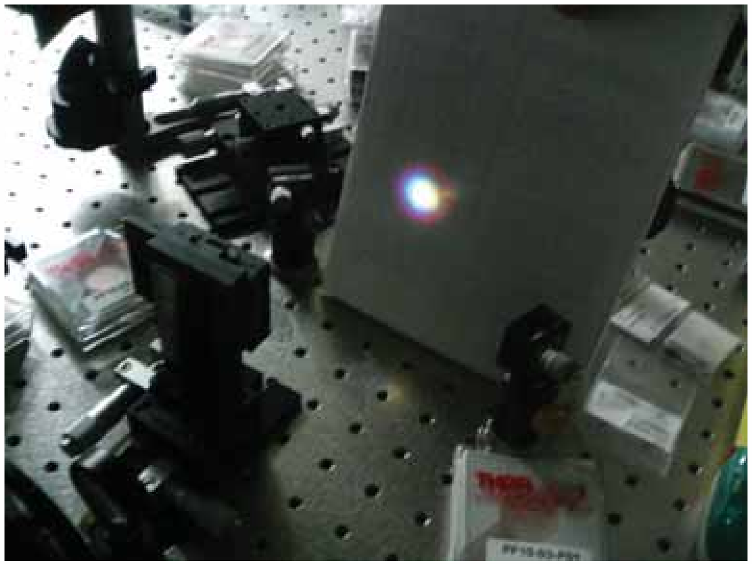
intense laser at ***different*** wavelength

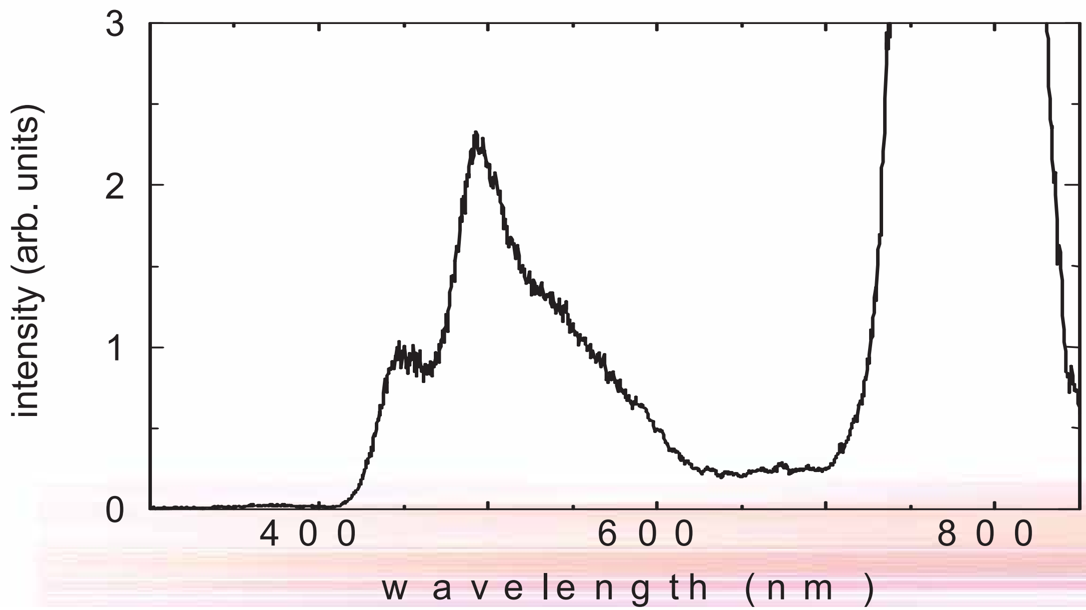
non-linear spectroscopy in UV/visible/IR…

(ultrafast spectroscopy, Raman for vibration study, …)

Other method?

self phase modulation (SPM) | low efficiency





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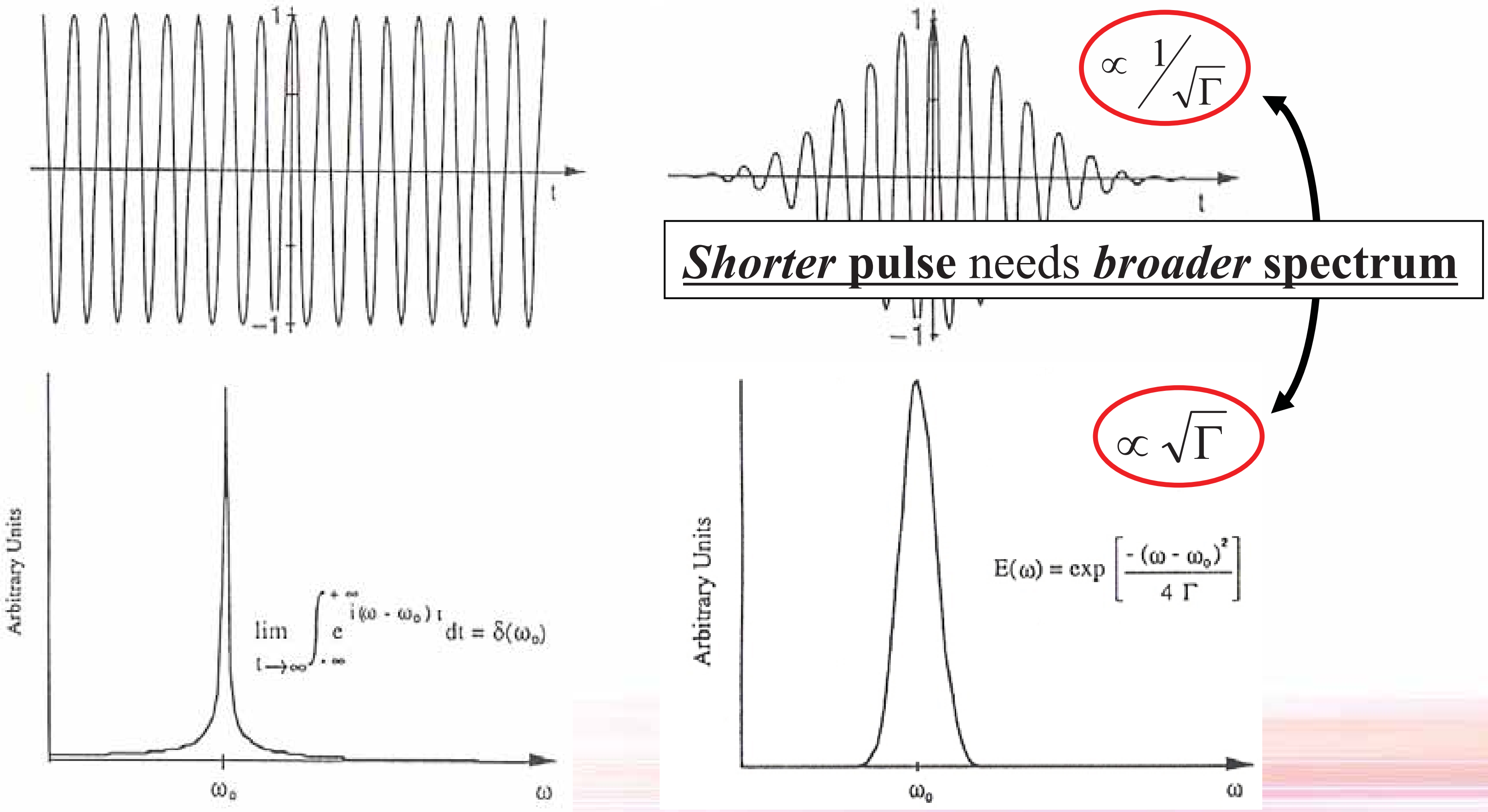
Application | *classical*

Broadband generation | for short pulse

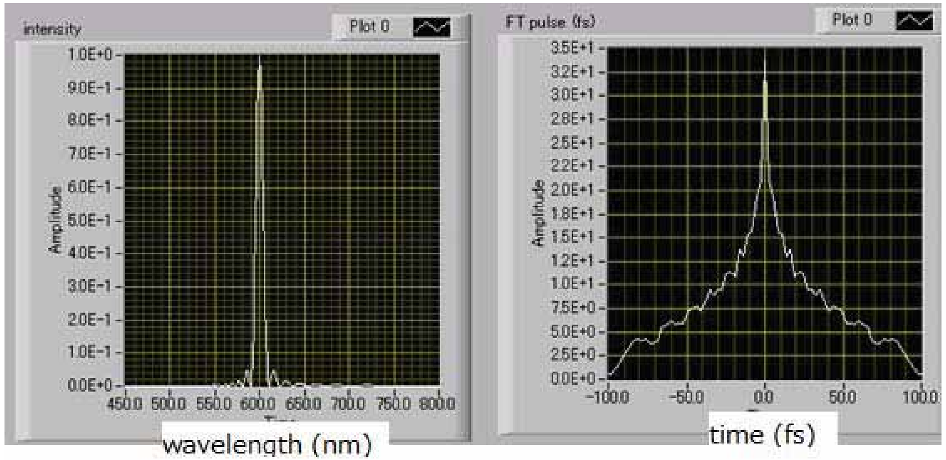
$$E_y = \mathrm{Re}\left(E_0\, e^{i\omega_0 t}\right) \qquad E_y = \mathrm{Re}\left(E_0\, e^{(-\Gamma t^2 + i\omega_0 t)}\right)$$

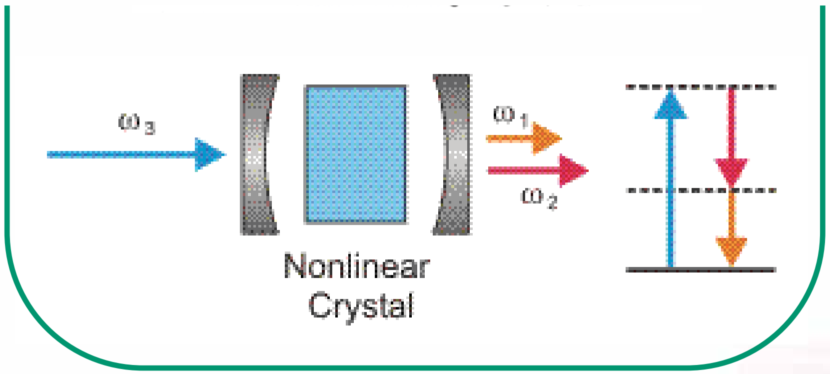


Application | classical

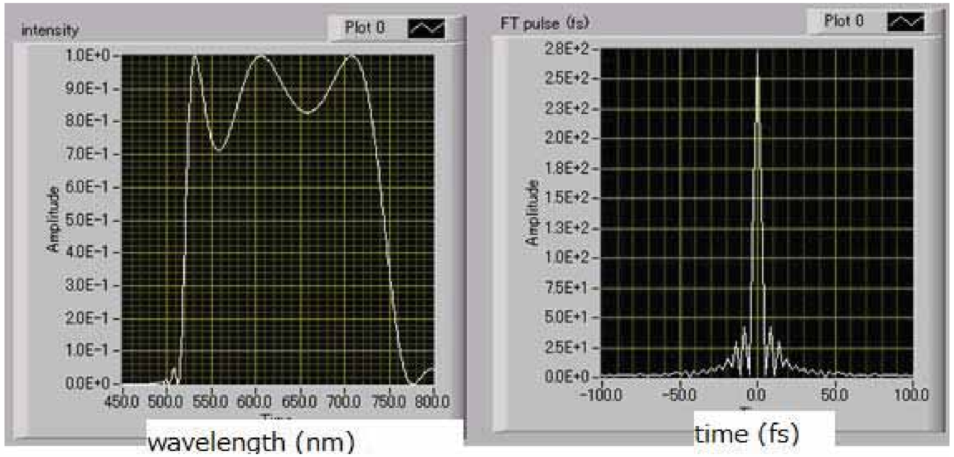
Broadband generation | for short pulse

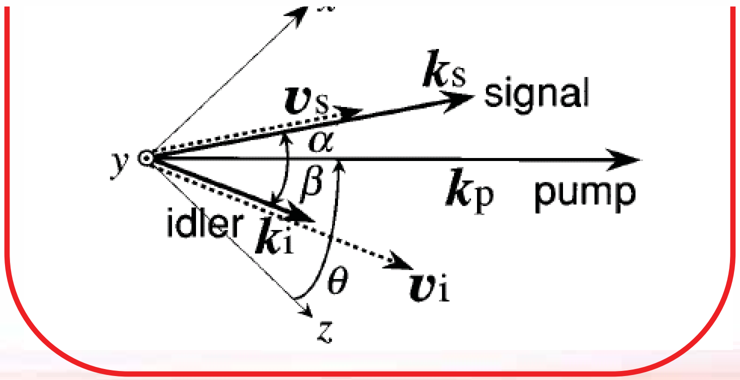
Optical parametric amplifier (OPA)





Non-collinear OPA (NOPA)

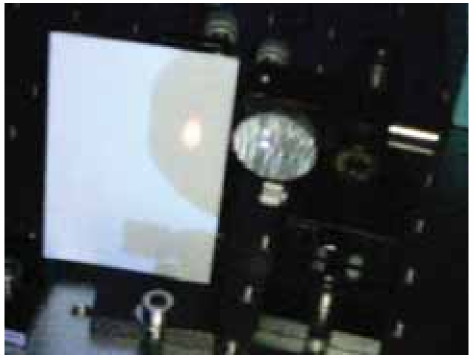


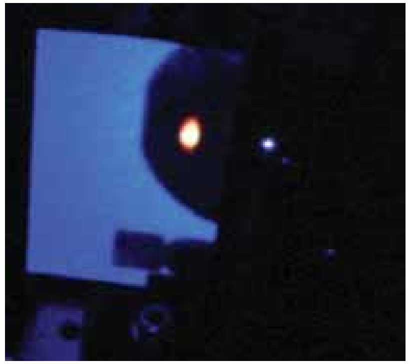


Application | classical

Broadband generation | for short pulse

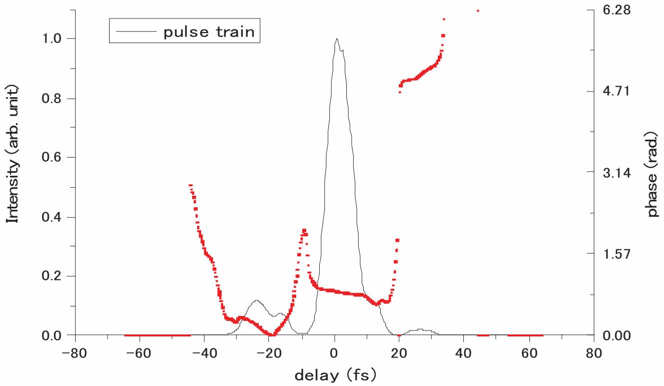
WLC

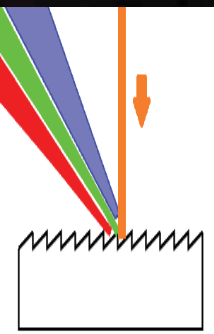




OPA (OPG with WLC)

pulse width=~9fs





Spectrum diffracted by grating

Visible broadband

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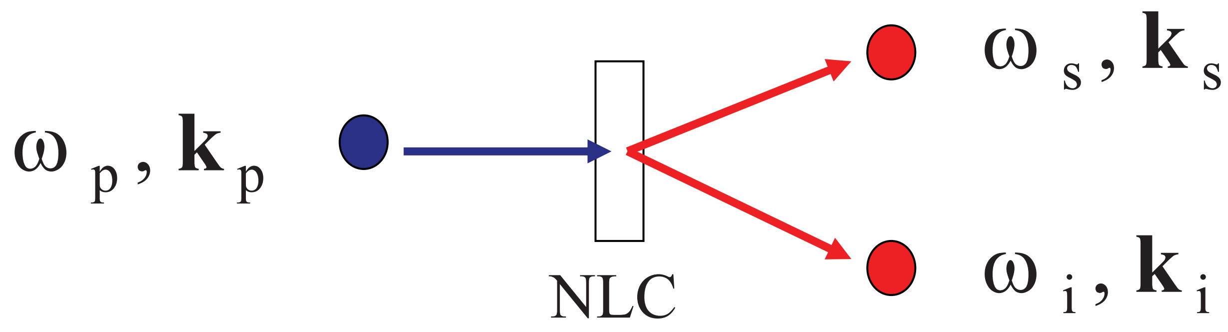
Application | quantum

SPDC generates photon pairs (low efficiency)



correlated parameters

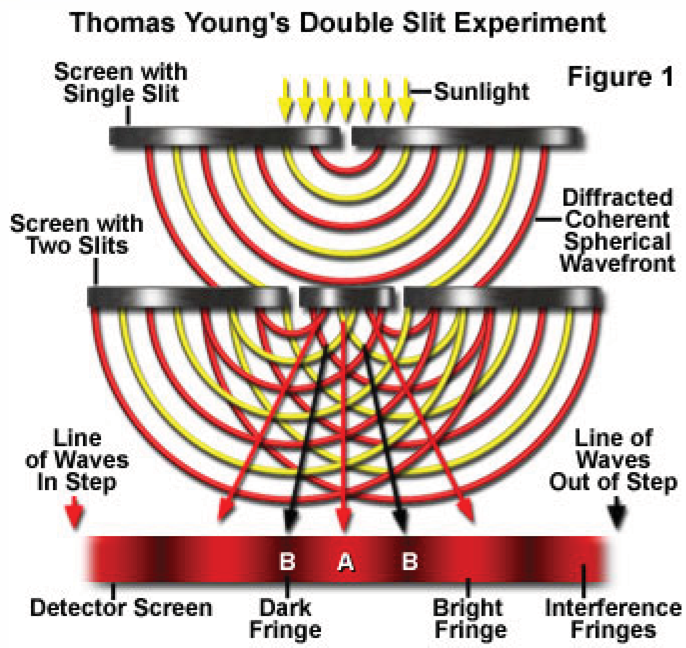
(1) wave vector : $\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$

(2) frequency : $\omega_p = \omega_s + \omega_i$

(3) polarization: $\frac{1}{\sqrt{2}}\left[|H\rangle_s\,|V\rangle_i + |V\rangle_s\,|H\rangle_i\right]$

(in case of Type-II crystal)

Application | quantum



So, what is ***entanglement***?

Let's remind "Young's double slit"

photon comes one by one

if you block one of the slits…

Interference only in unknown case **path entanglement**

Interference of "probability", "wavefunction"

different from statistics of classical phenomena=**quantum**

Are there any other entanglements?

Yes, we will see them in the following pages!

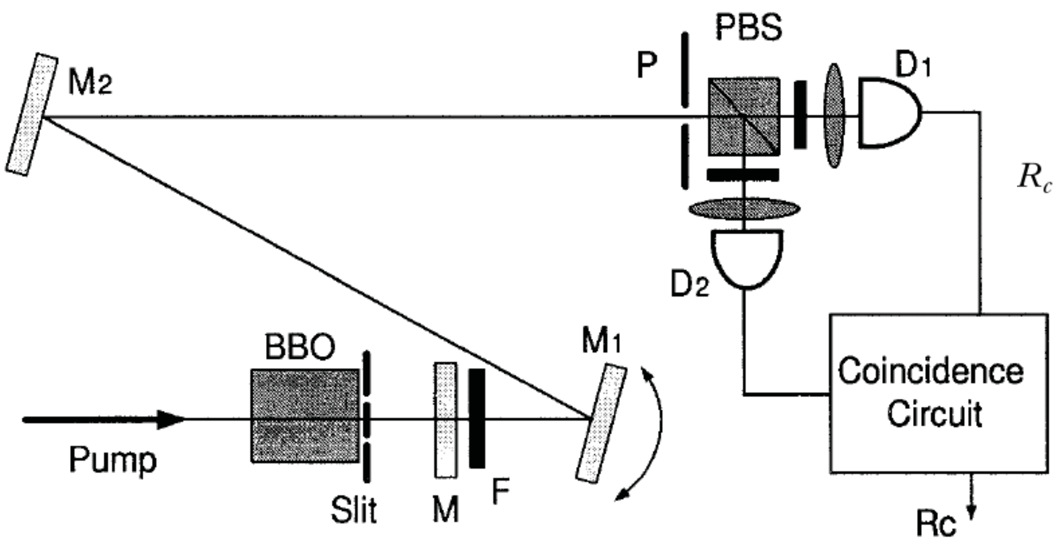
Application | quantum

Y. Shih, J. Mod. Opt. 49, 2275 (2002)

quantum lithography | wave vector

better resolution (than classical limit) ~ $\lambda_p = \lambda/2$

Schematic set-up



$$E_1^{(+)} = a_s \exp(ik\, r_{A1}) + b_s \exp(ik\, r_{B1})$$
$$E_2^{(+)} = a_i \exp(ik\, r_{A2}) + b_i \exp(ik\, r_{B2})$$

$$R_c \propto P_{12} = \epsilon^2 |\exp(ik\, r_A + i\varphi_A) + \exp(ik\, r_B + i\varphi_B)|^2$$
$$\propto 1 + \cos[k\,(r_A - r_B)]$$

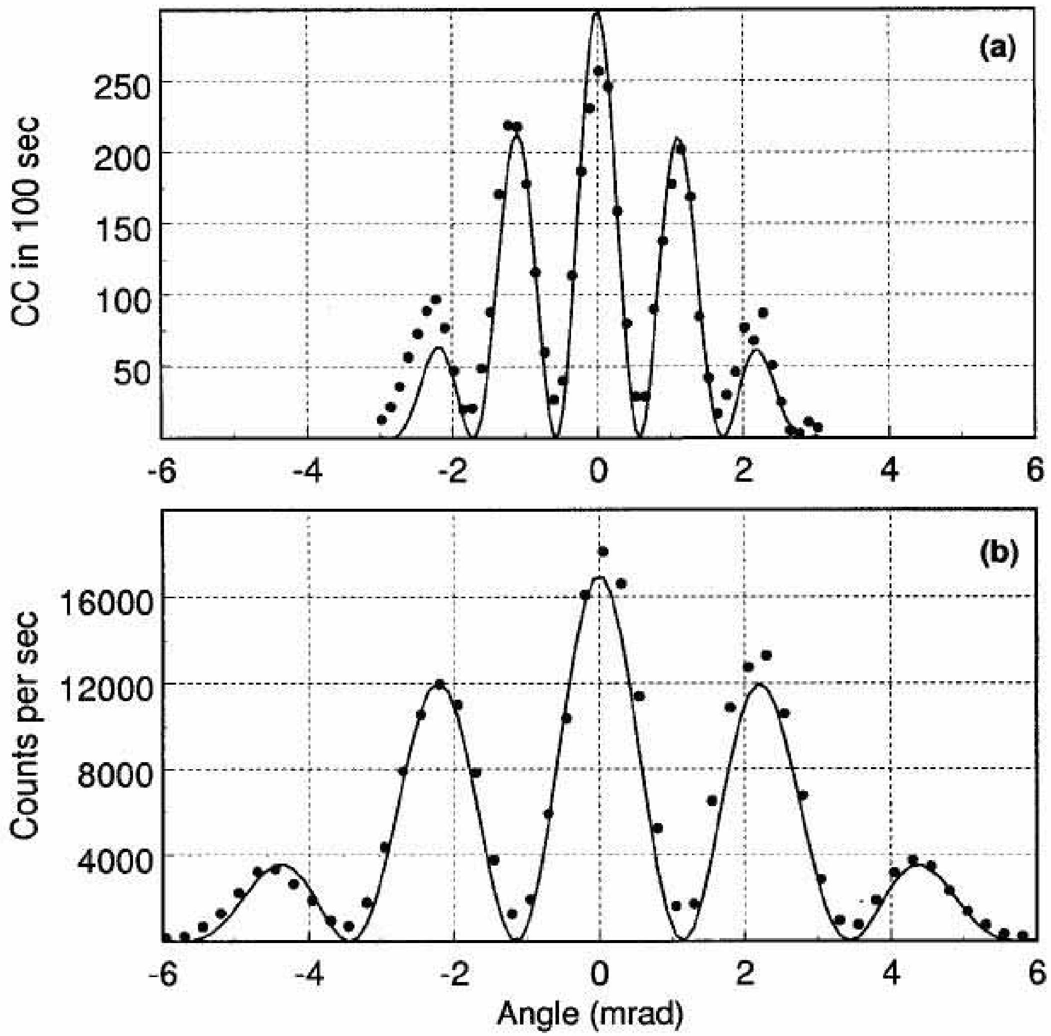
$$R_c(x) \propto \text{sinc}^2[(2\pi a/\lambda)\theta)\, \cos^2[(2\pi b/\lambda)\theta]$$

half!

(Young's : $\cos^2[(2\pi b/2\lambda)\theta]$)

"SPDC photon pairs" v.s. "classical light"

Experimental result (quantum lithograph)



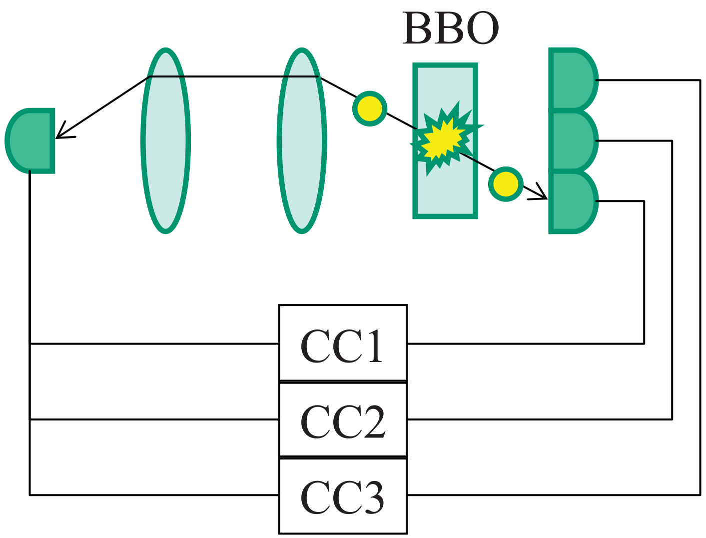
quantum

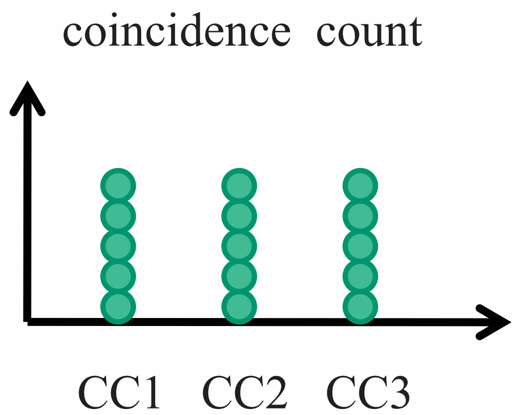
classical

Figure 8. (*a*) Experimental measurement of the coincidences for the two-photon double-slit interference-diffraction pattern. (*b*) Measurement of the interference-diffraction pattern for classical light in the same experimental setup. With respect to the classical case, the two-photon pattern has a faster spatial interference modulation and a narrower diffraction pattern width, by a factor of 2.

Application | quantum

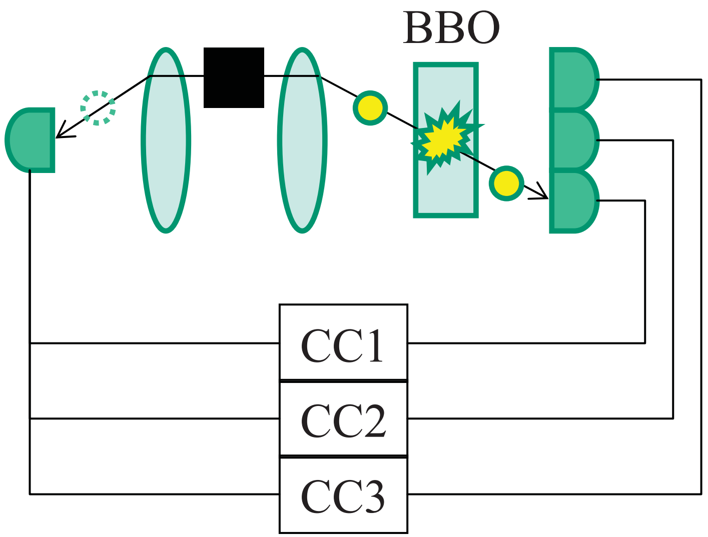
ghost imaging | wave vector

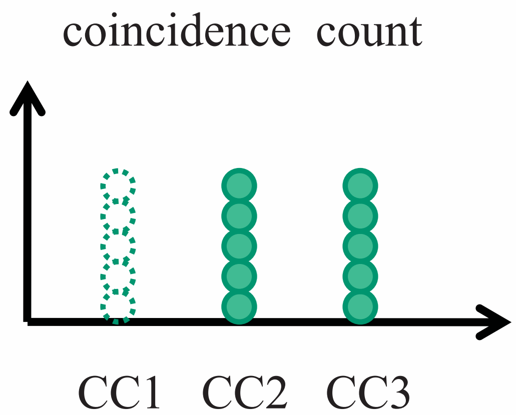


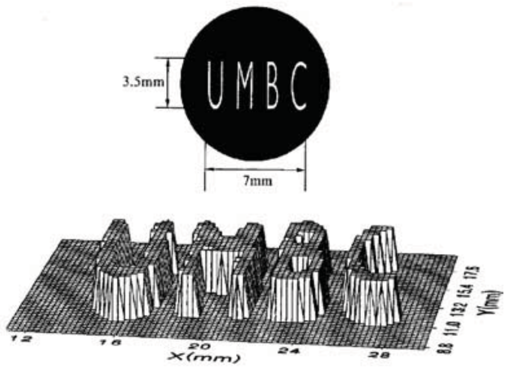


Application | quantum

ghost imaging | wave vector





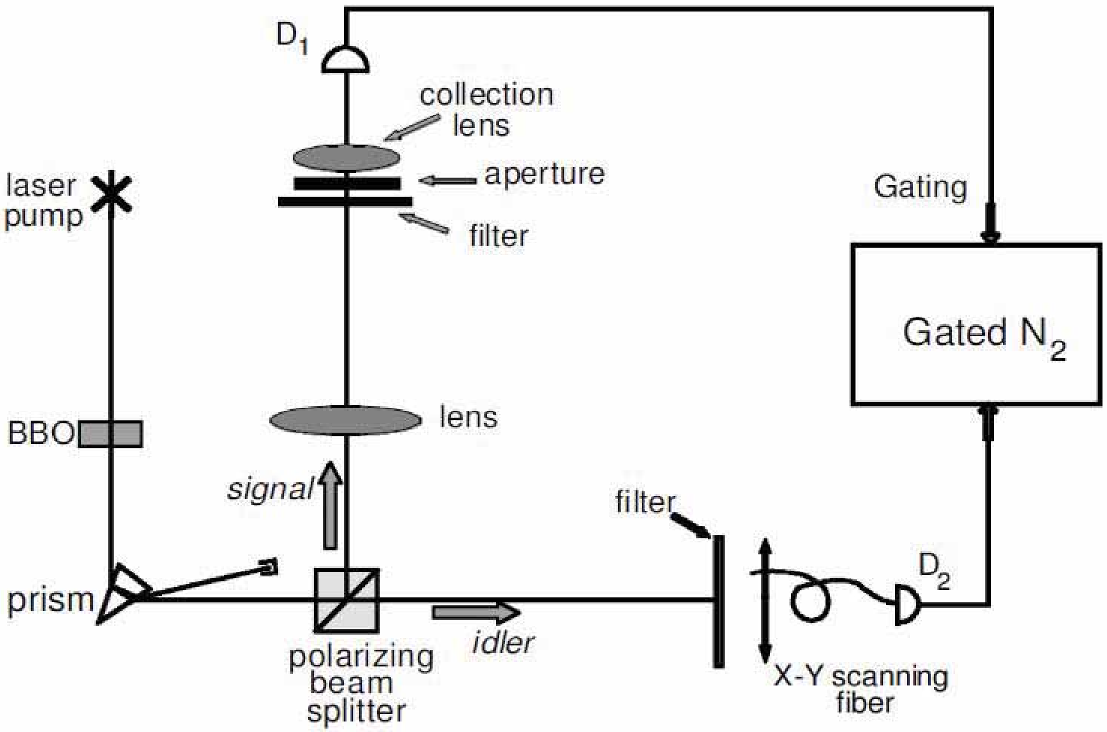


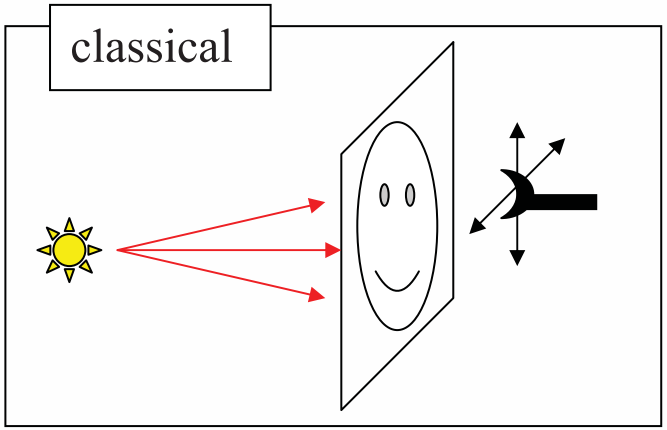
Application | quantum

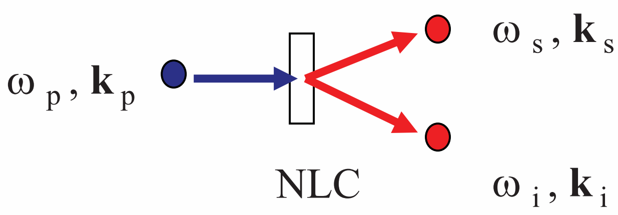
ghost imaging

measure the shape of an object

Detector does NOT scan after object



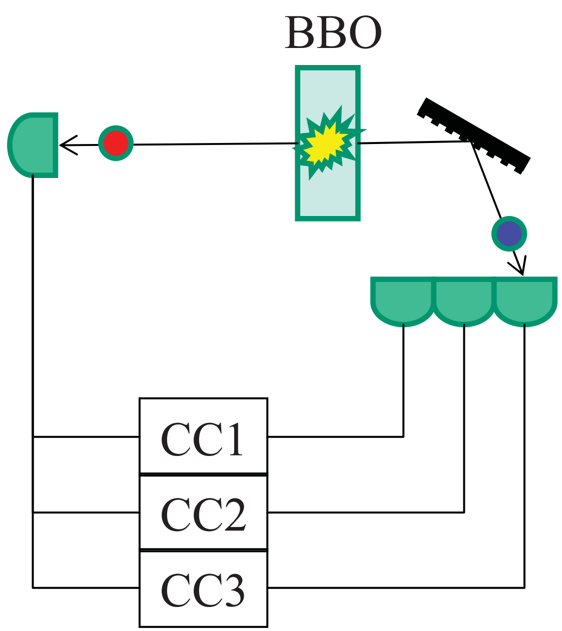


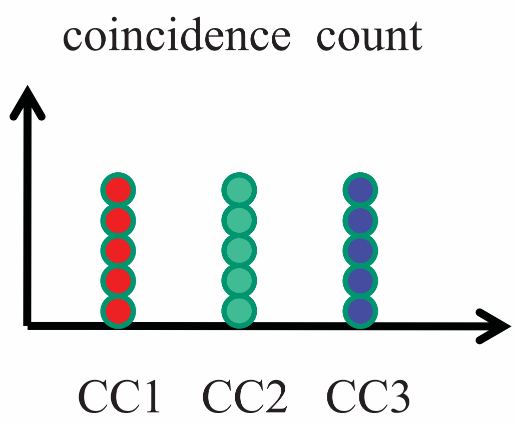


Y. Shih, J. Mod. Opt. 49, 2275 (2002)

Application | quantum

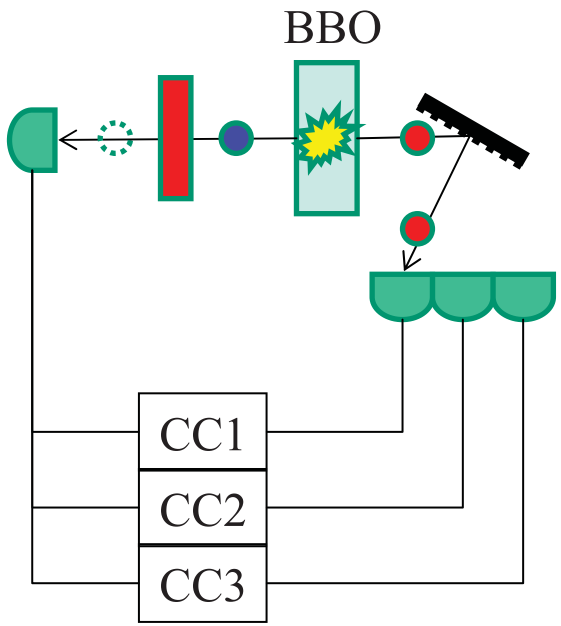
ghost spectroscopy | frequency

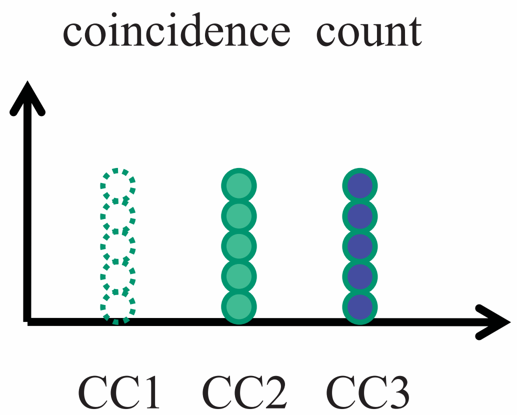




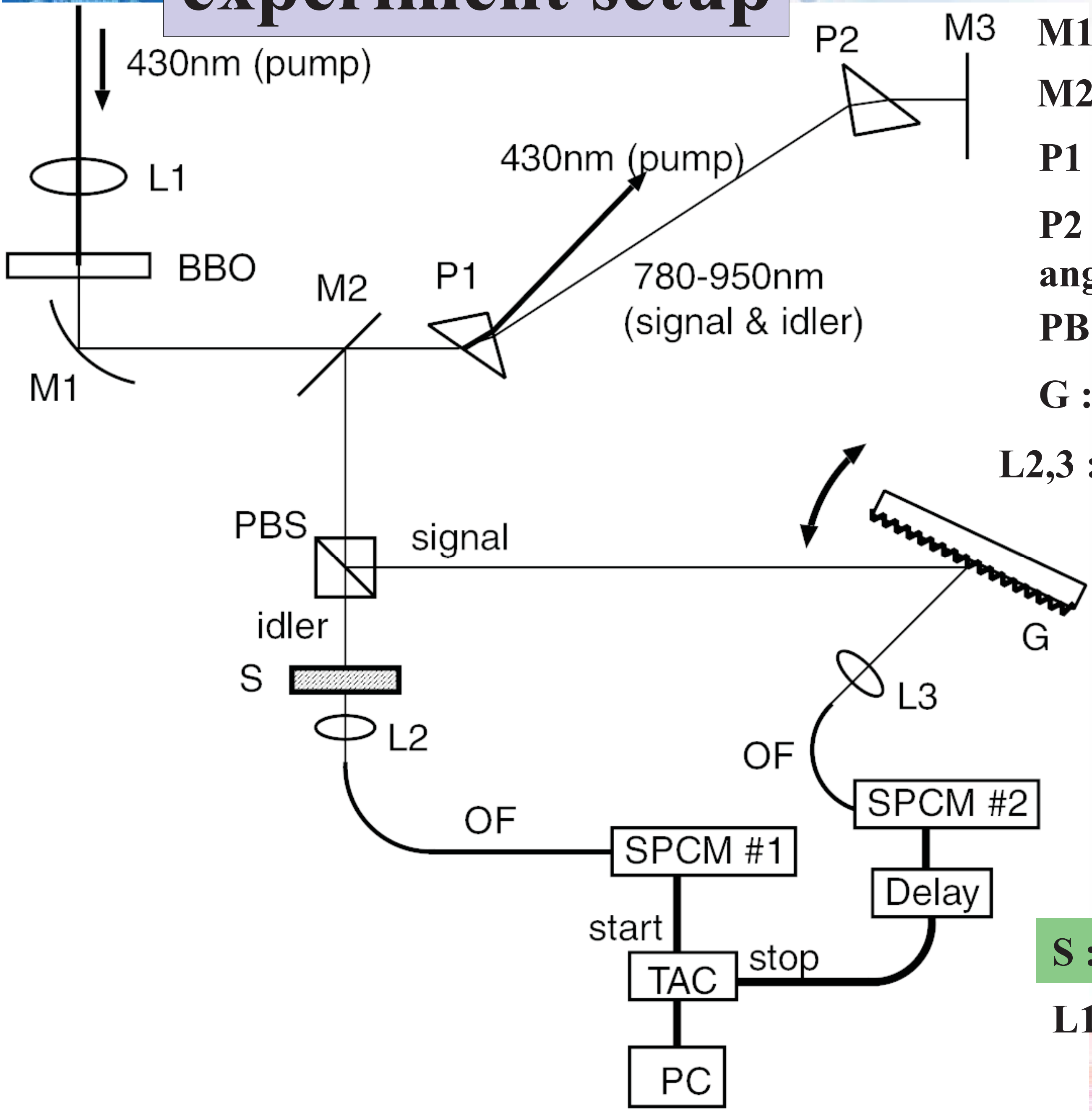
Application | quantum

ghost spectroscopy | frequency





experiment setup



BBO : non-linear crystal

M1 : parabolic mirror

M2,3 : plane mirror

P1 : prism (remove pump)

P2 : prism (compensate angular dispersion)

PBS : polarizing beam splitter

G : diffraction grating

L2,3 : fiber coupling lens

OF : optical fiber

SPCM : single photon counting module

TAC : time-to-amplitude converter

Delay : delay module

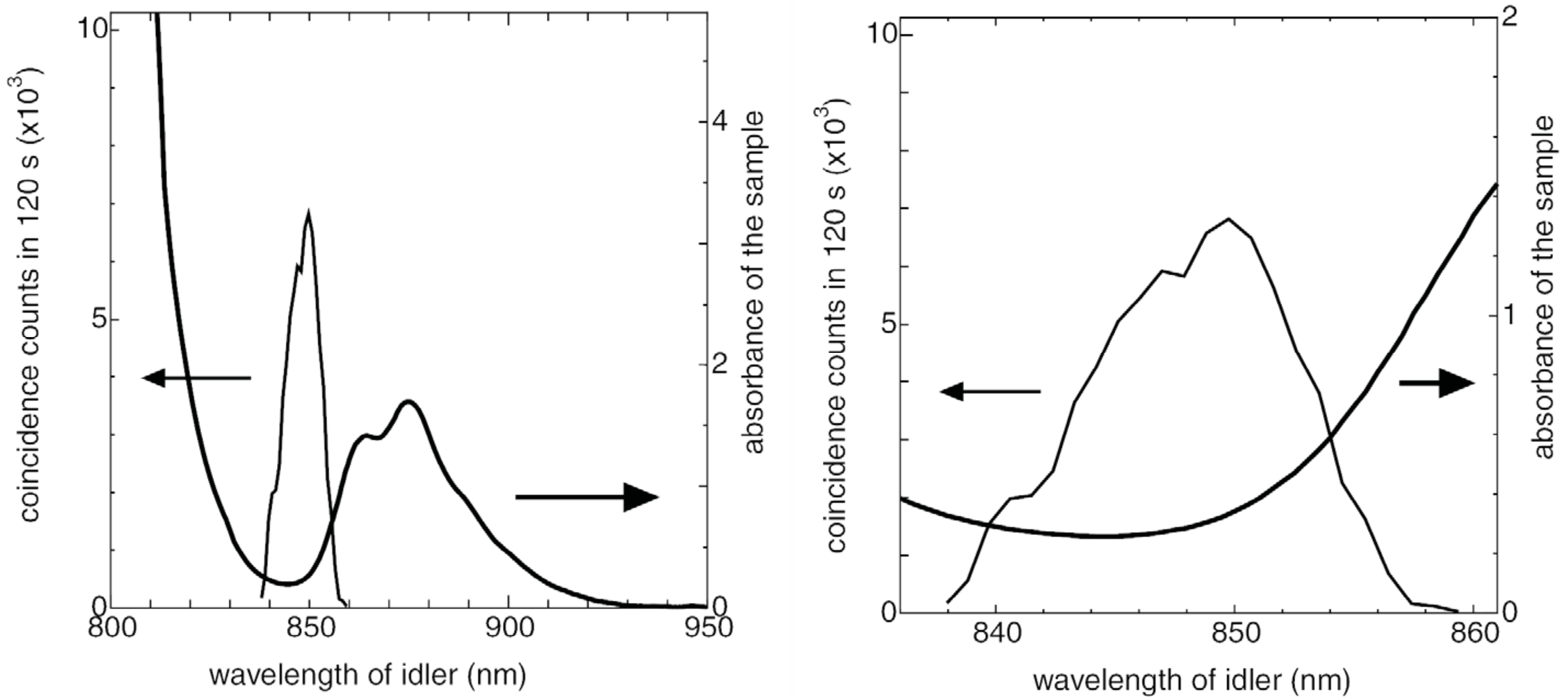
PC : computer

S : sample (Nd^{+3}–doped glass)

L1 : focusing lens (f=100mm, 8mm)

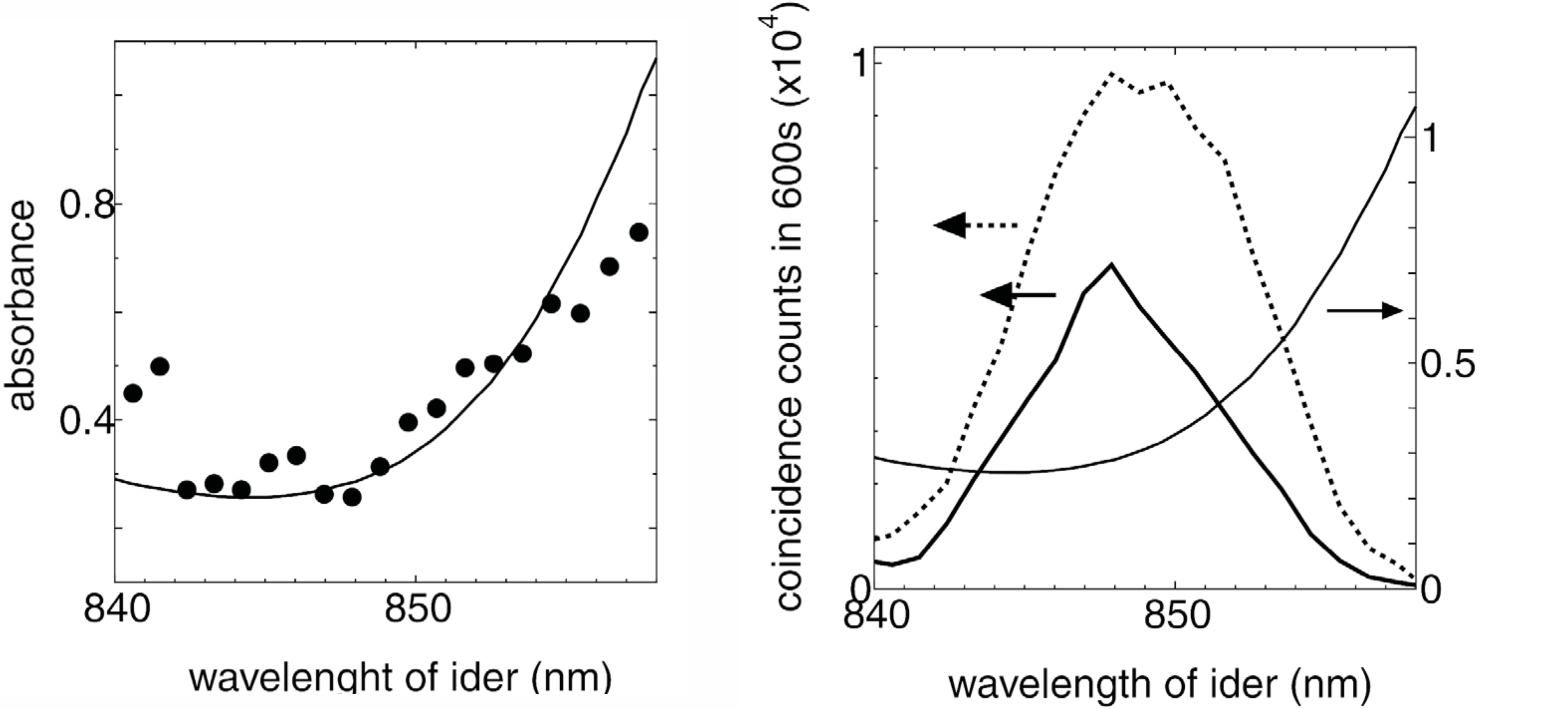
Spectrum of photon pairs and absorption spectrum of the sample

pump focusing lens (f=100mm)



more absorption in longer wavelength

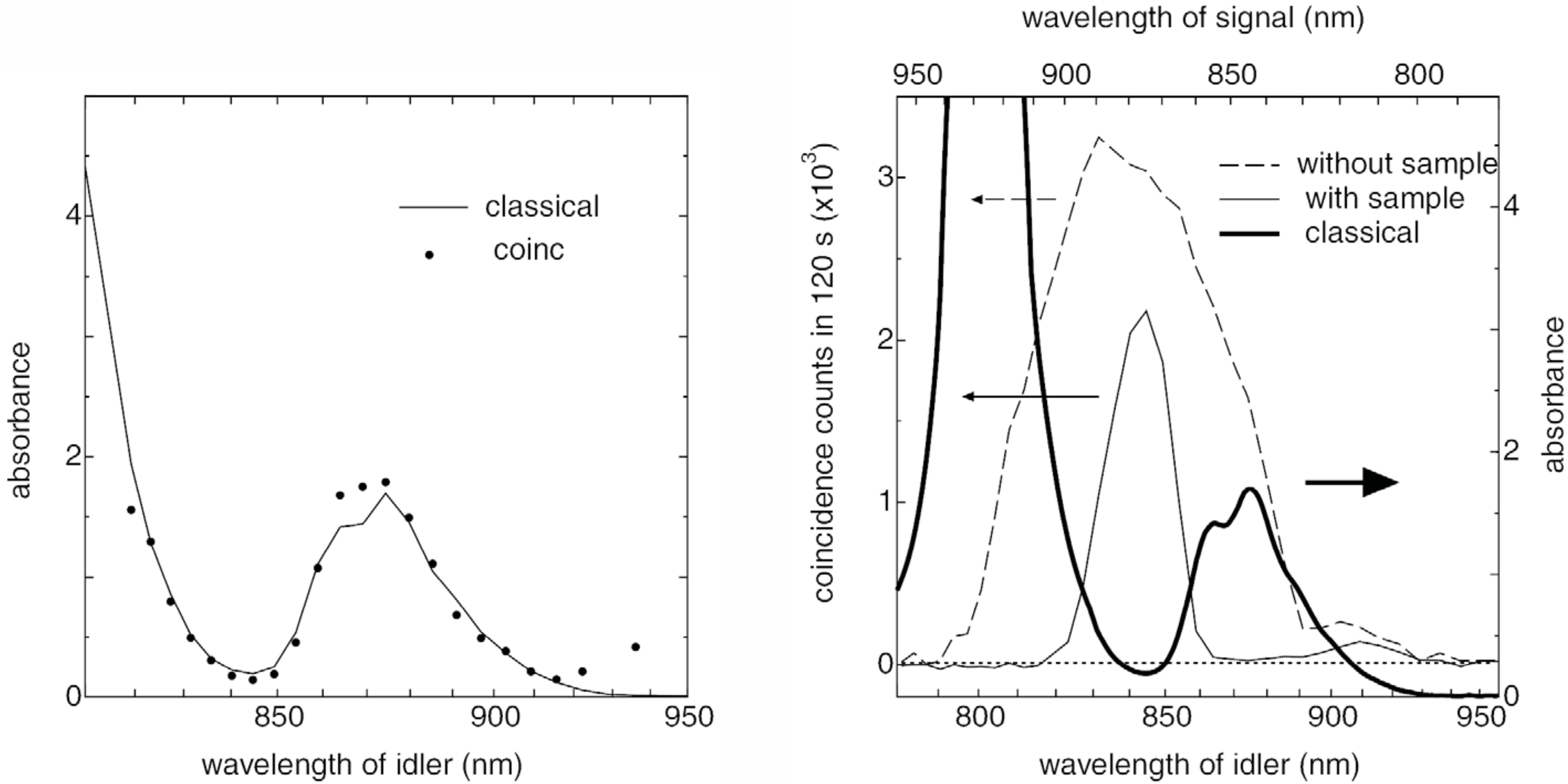
result : absorption spectrum



calculate absorption spectrum from the ratio

→ agree with the result by a spectrometer

result : absorption spectrum



agree with the result by a spectrometer

summary of this section

- **spectrum of SPDC photon pairs**

  spherical lens → objective lens

  (f=100 → 8mm)

  spectrum was broadened (11,11→63,69nm)

- Nd^{3+} -doped glass (in the **idler** light path)

  coincidence resolving **signal** light's frequency

  → absorption spectrum was measured

- **fit well with the result measured by a spectrometer**
- **without resolving the frequency of photon transmitted through the sample**

A. Yabushita et. al., Phys. Rev. A 69, 013806 (2004)

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Our work

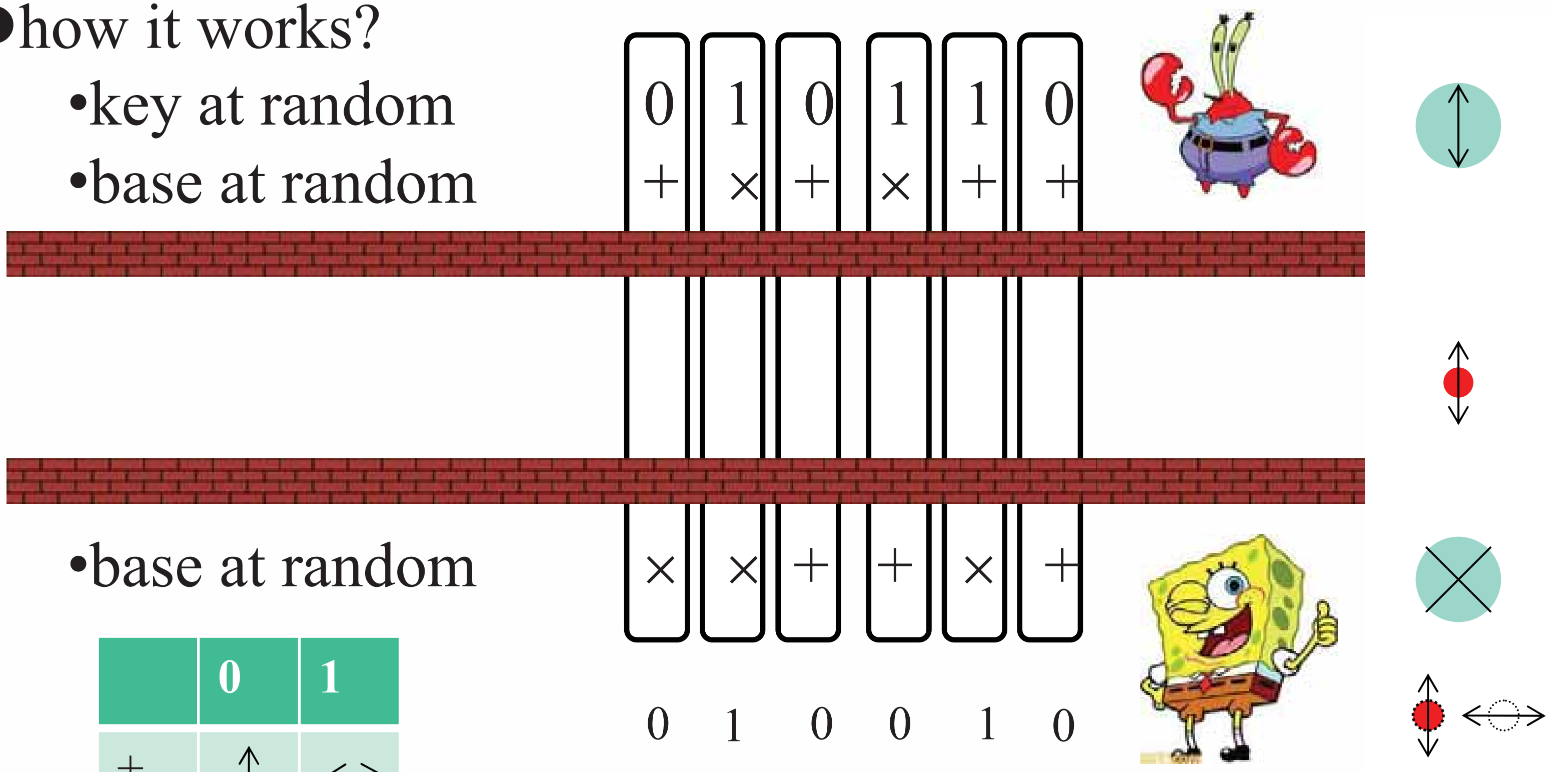
Application | quantum

Outline for "Quantum Key Distribution (QKD)"

- BB84 protocol | single photon
  - how it works
  - can it be safe?
- E91 protocol | polarization entangled photon pair
  - polarization entanglement?
  - how it works
  - can it be safe?

Application | quantum

- BB84 protocol | single photon
  - Purpose : to share a secret key
  - how it works?
    - key at random
    - base at random
    - base at random



	0	1
+	↕	↔
×	⤢	⤡

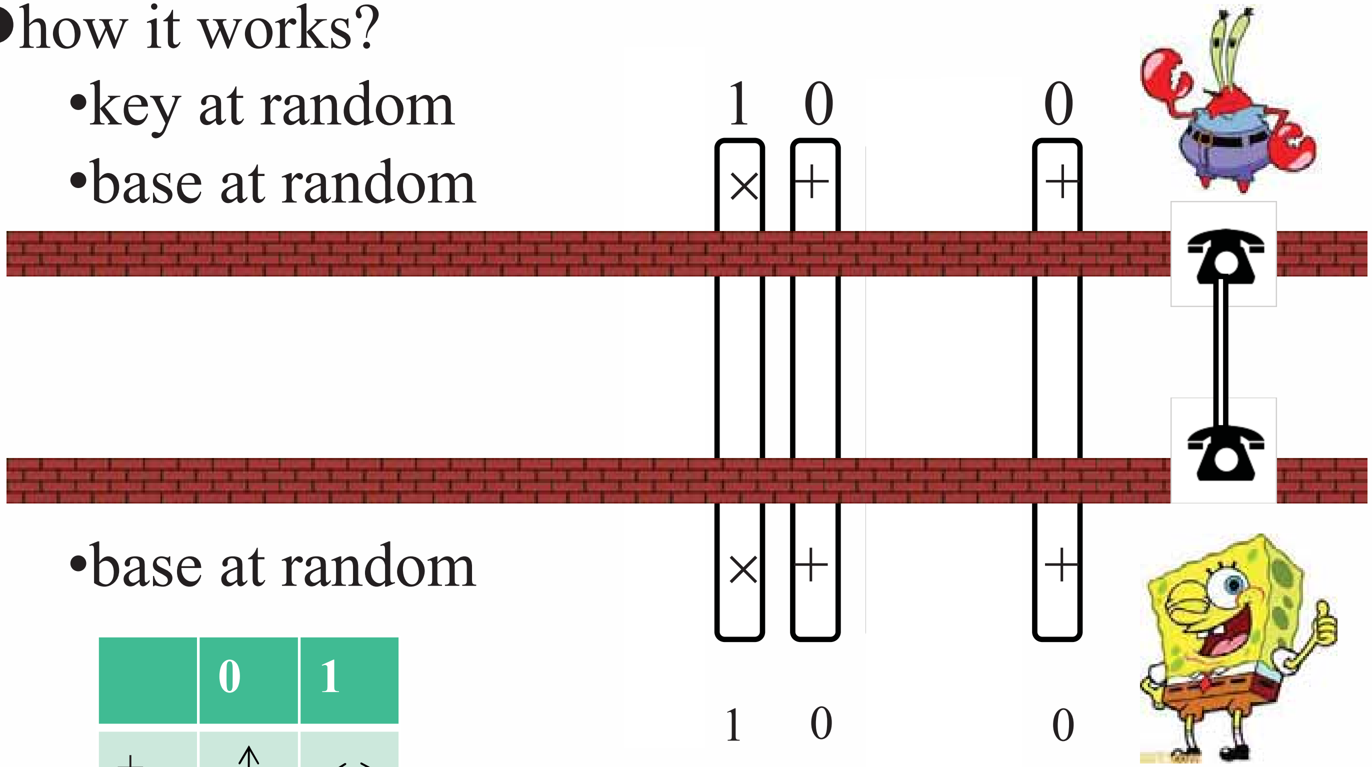
Application | quantum

50% of keys can be shared (shared keys are same)

complicated…**But secure!**

How can it be secure??

- BB84 protocol | single photon
  - Purpose : to share a secret key
  - how it works?
    - key at random
    - base at random



- base at random

	0	1
+	↕	↔
×	⤢	⤡

Application | quantum

0 1 1 1 1 0

- BB84 protocol | single photon
  - Can it be secure?
    - key at random 0 1 0 1 1 0
    - base at random + × + × + +

↕ ⤡ ↕ ⤡ ↔ ↕

base? (random try) + × × × + ×

result ↕ ⤡ ⤡ ⤡ ↔ ⤢

(bit) 0 1 1 1 1 0

copy ↕ ⤡ ⤡ ⤡ ↔ ⤢

- base at random × × + + × +

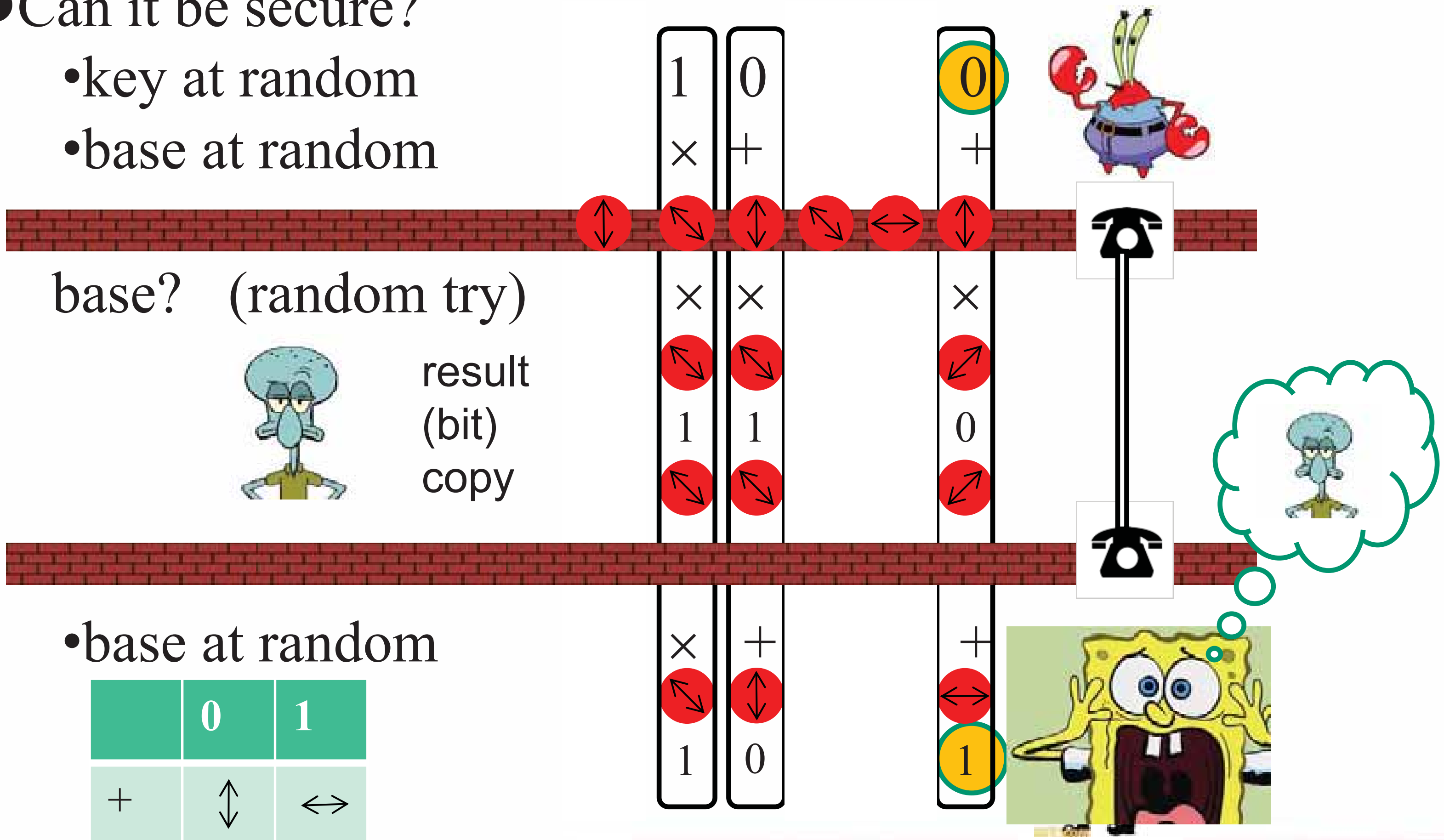
↕ ⤡ ↔ ↕ ⤡ ↔ → ⤢ ⤡ ↔ ↕ ⤡ ↔

0 1 1 0 1 1

	0	1
+	↕	↔
×	⤢	⤡

Application | quantum

- BB84 protocol | single photon
  - Can it be secure?
    - key at random
    - base at random

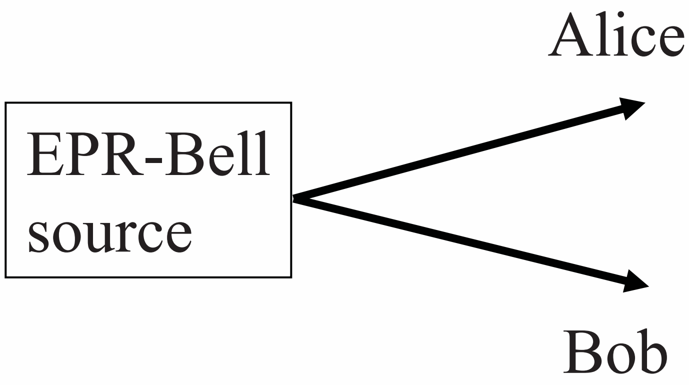


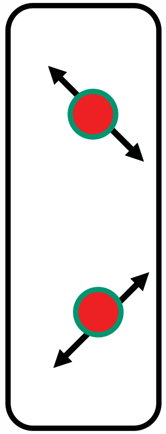
- base at random

	0	1
+	↕	↔
×	⤢	⤡

Error!

polarization-entangled photon pairs



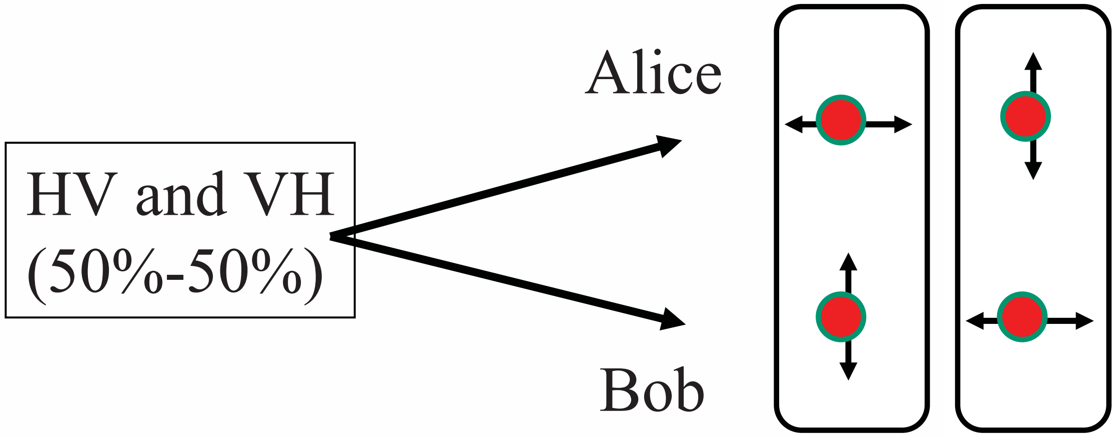


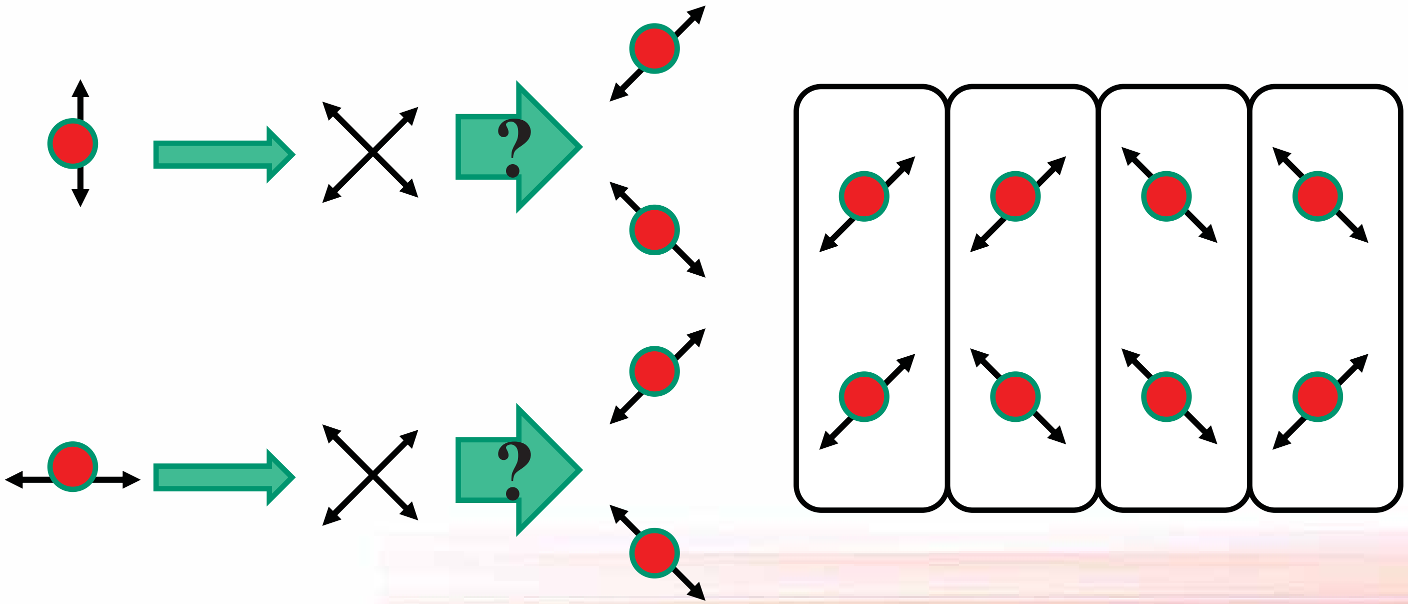
$$\left|\Psi_{12}\right\rangle = \frac{1}{\sqrt{2}}\left[\left|\updownarrow\right\rangle_1\left|\leftrightarrow\right\rangle_2 - \left|\leftrightarrow\right\rangle_1\left|\updownarrow\right\rangle_2\right]$$

$$= \frac{1}{\sqrt{2}}\left[\left|\nearrow\right\rangle_1\left|\searrow\right\rangle_2 - \left|\searrow\right\rangle_1\left|\nearrow\right\rangle_2\right]$$

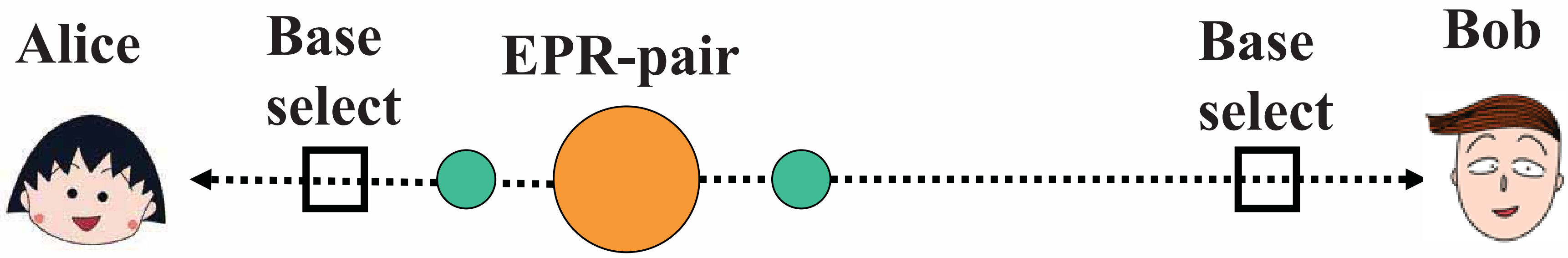
$$\left|\updownarrow\right\rangle \frac{1}{\sqrt{2}}\left(\left|\nearrow\right\rangle + \left|\searrow\right\rangle\right) \qquad \left|\leftrightarrow\right\rangle \frac{1}{\sqrt{2}}\left(\left|\nearrow\right\rangle - \left|\searrow\right\rangle\right)$$

Mixed state (statistical mixture)





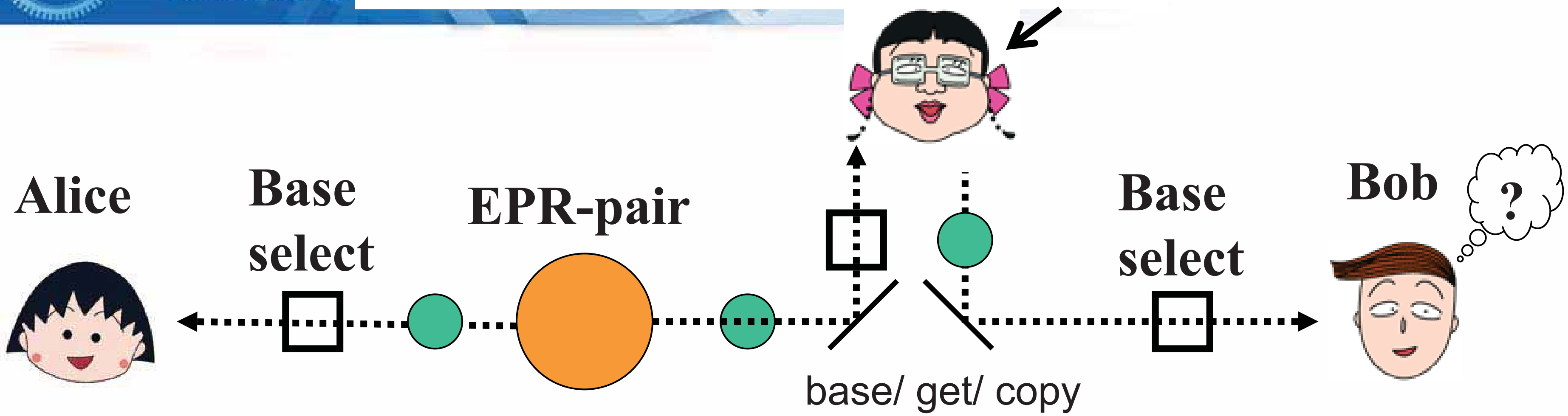
QKD example (without Eve)



Alice bit	Alice state	Alice base	Bob base	Bob state	Bob bit
0	H	+	+	V	0
1	V			H	1
1	V			H	1
0	H			V	0
	⋮			⋮	
0	R	○	○	L	0
1	L			R	1

If they use the same base,
“100%” correlation
(quantum key distributed!)

QKD example (with Eve)

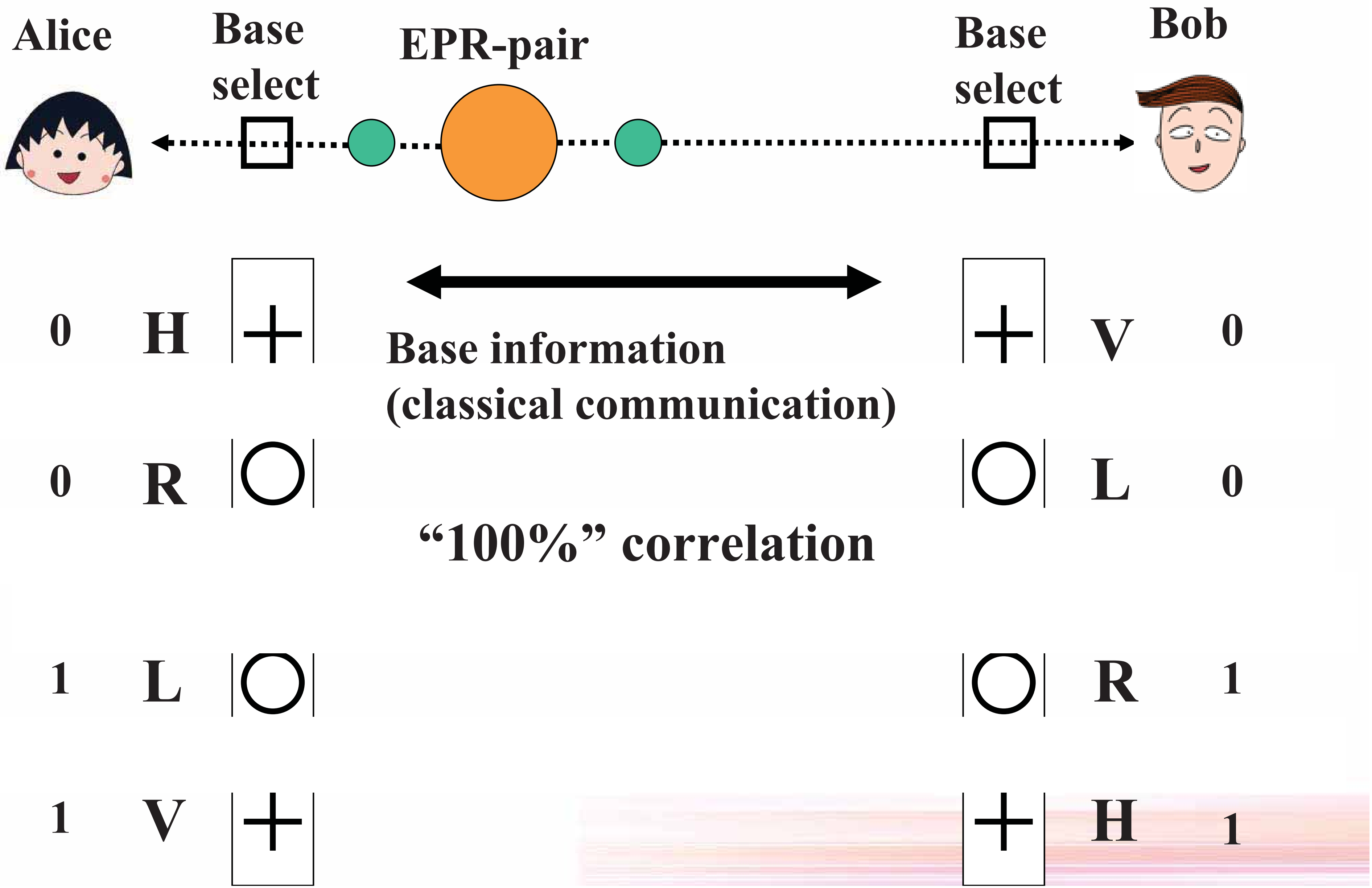


0	H	+	+	V	V	+	V	0
1	V			H	H		H	1
1	V			H	H		H	1
0	H			V	V		V	0
	⋮			⋮	⋮		⋮	

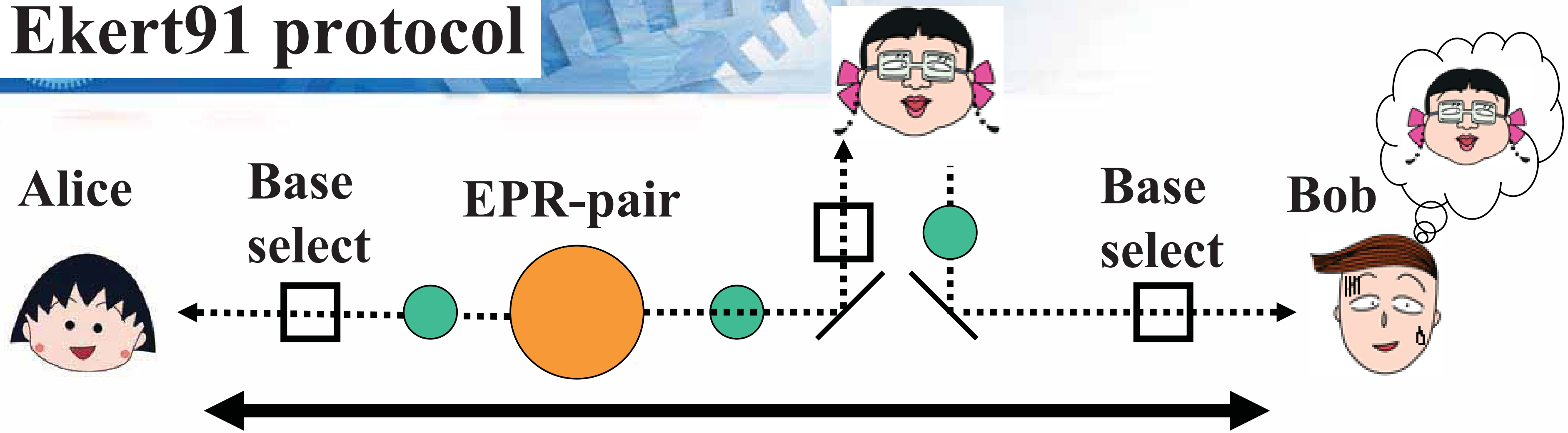
Eve also share the key (NOT secure QKD…)

How can it be improved?

Ekert91 protocol



Ekert91 protocol



Base information

			base/ get/ copy						
0	H	+	○	R	R	+	*V*	0	OK
0	R	○	○	L	L	○	L	0	OK
1	L	○	+	H	H	○	*L*	0	NG!
1	V	+	+	H	H	+	H	1	OK

Bob can detect Eve (secure!)

Experimental example of QKD

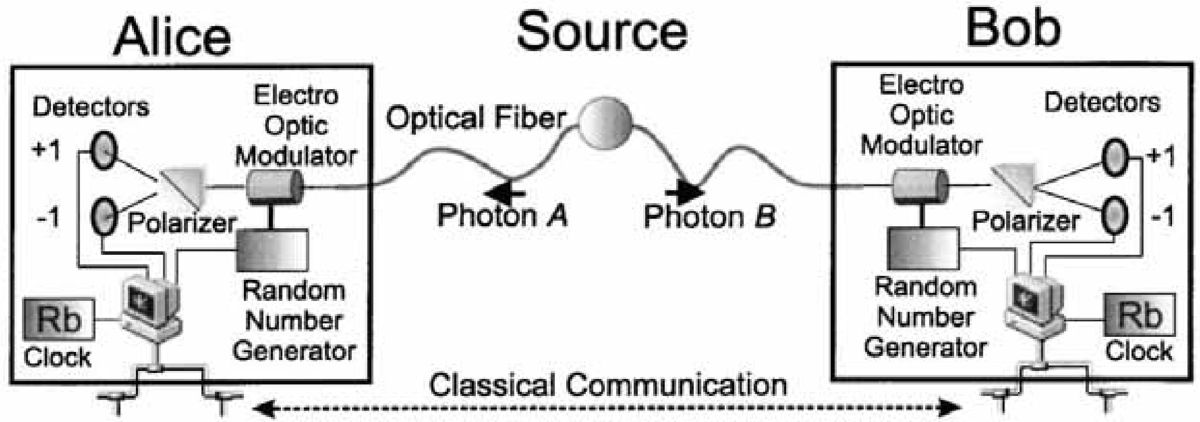


FIG. 2. The polarization entangled photons are transmitted via optical fibers to Alice and Bob, who are separated by 360 m, and both photons are analyzed, detected, and registered independently. After a measurement run the keys are established by Alice and Bob through classical communication over a standard computer network.

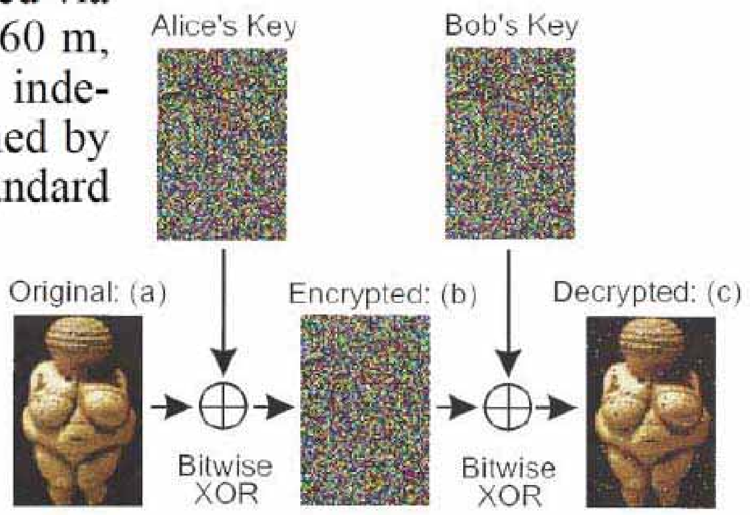


FIG. 3 (color). The 49984 bit large keys generated by the BB84 scheme are used to securely transmit an image [23] (a) of the "Venus von Willendorf" [24] effigy. Alice encrypts the image via bitwise XOR operation with her key and transmits the encrypted image (b) to Bob via the computer network. Bob decrypts the image with his key, resulting in (c) which shows only a few errors due to the remaining bit errors in the keys.

T. Jennewein et. al., PRL 84, 4729 (2000)

Outline

Our work

- Introduction
  - Optical parametric processes
    - Opt. param. amplifier (OPA)
    - Spontaneous param. down conv. (SPDC)
- Application | classical
  - **Broadband generation | for short pulse**
- Application | quantum
  - Entangled photon pairs
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  - **Ghost spectroscopy | frequency**
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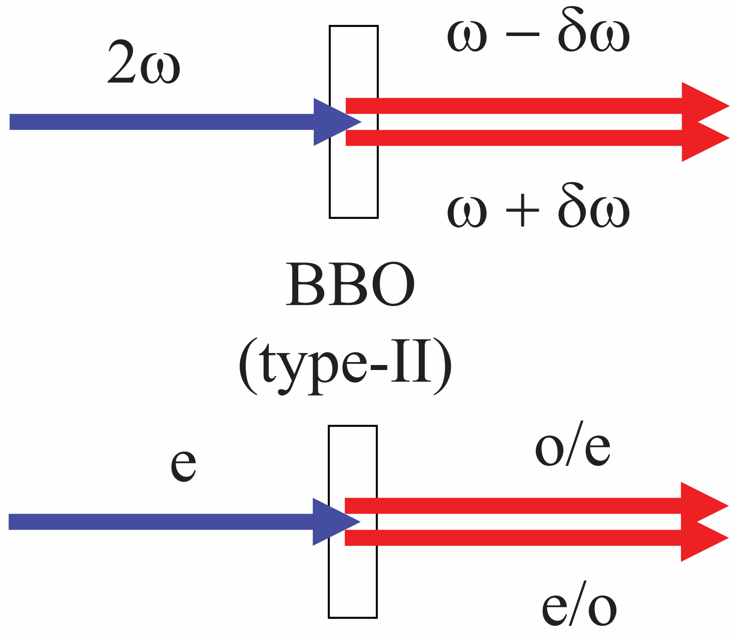
  - **Multiplex QKD | polarization and frequency**
  - **Entangled photon beam**
- Conclusion

Generation of photon pairs entangled in their frequencies and polarizations (for WDM-QKD)



frequency-entangled

+

polarization-entangled

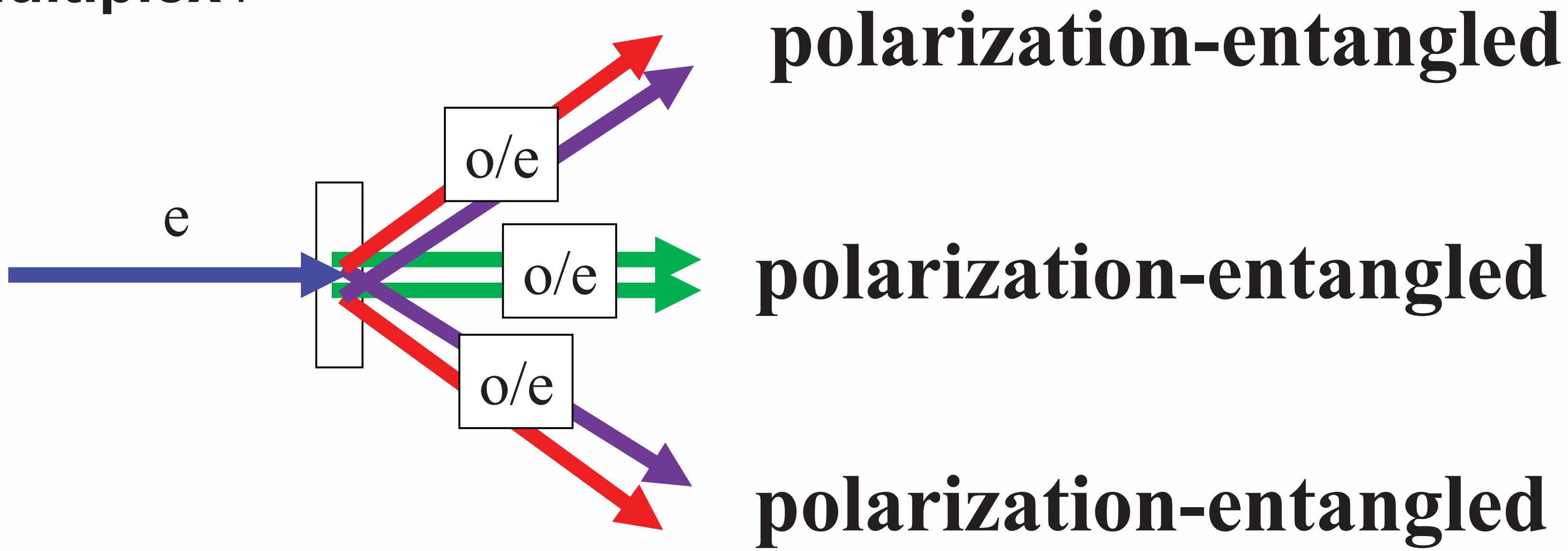
polarization-entangled pair

at many wavelength combinations

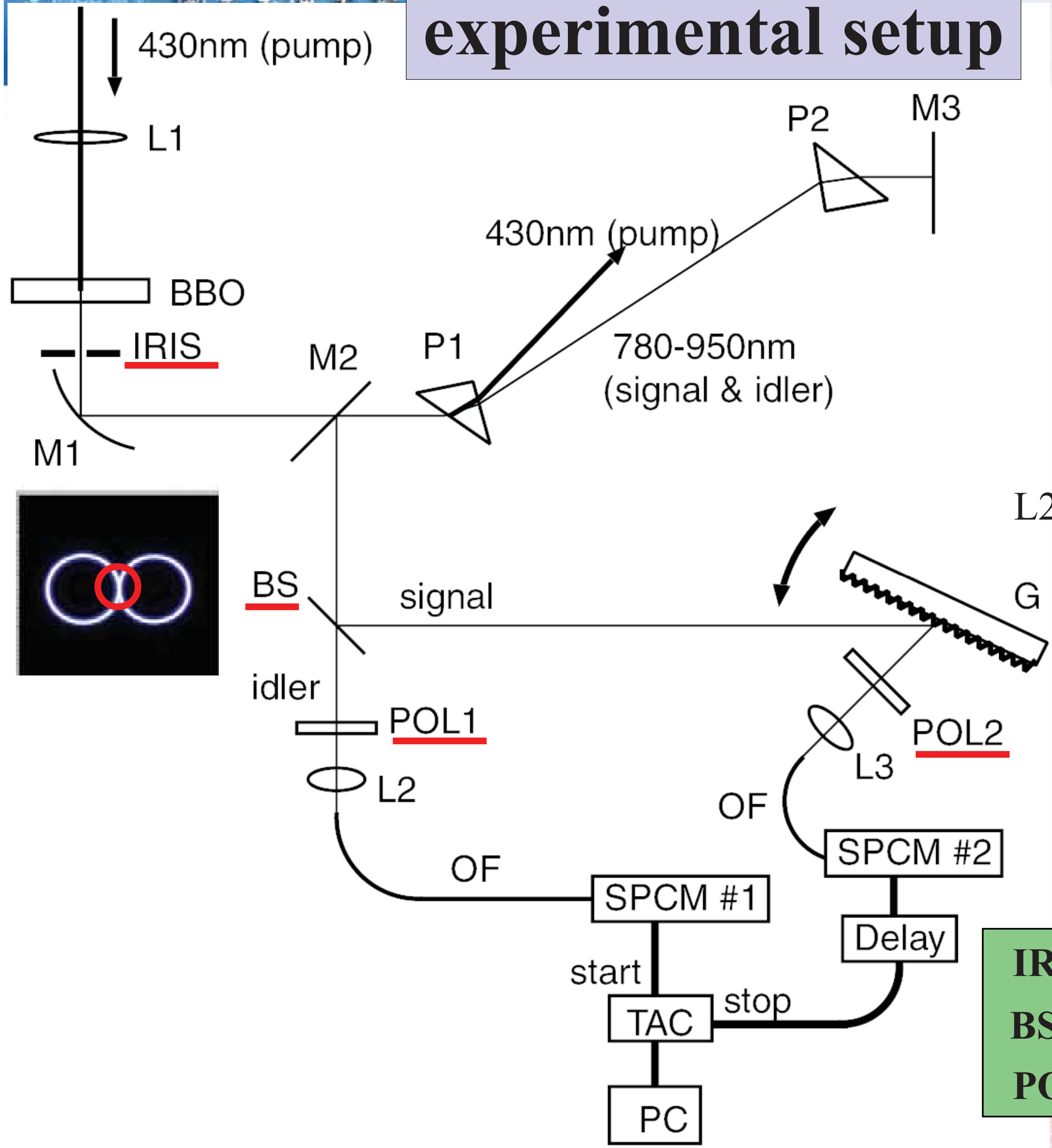
light source for WDM-QKD

Standard :

Multiplex :



experimental setup



L1 : focusing lens

BBO : non-linear crystal

M1 : parabolic mirror

M2,3 : plane mirror

P1 : prism (remove pump)

P2 : prism (compensate angular dispersion)

G : diffraction grating

L2,3 : fiber coupling lens

OF : optical fiber

SPCM : single photon counting module

TAC : time-to-amplitude converter

Delay : delay module

PC : computer

IRIS : iris diaphragms

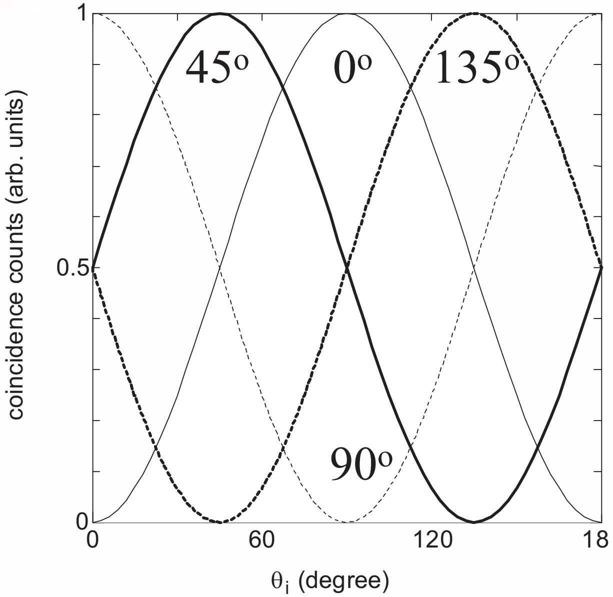
BS : non-polarizing beam splitter

POL1,2 : linear polarizer

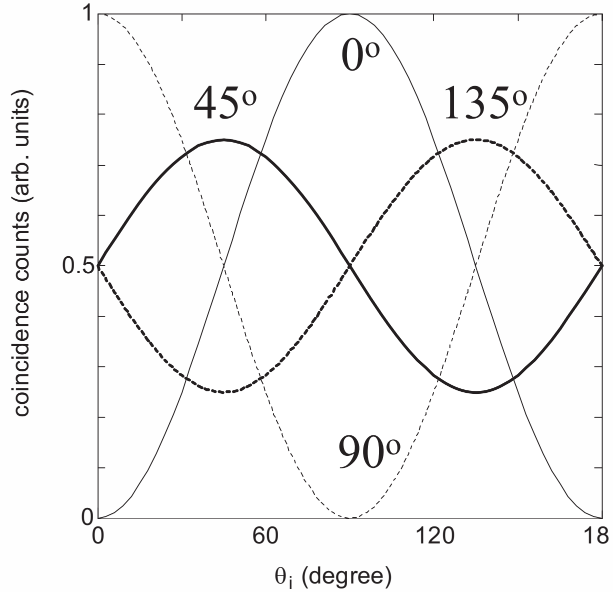
simulation

$$|\psi\rangle = |H\rangle_s |V\rangle_i + f \cdot e^{i\alpha} |V\rangle_s |H\rangle_i$$

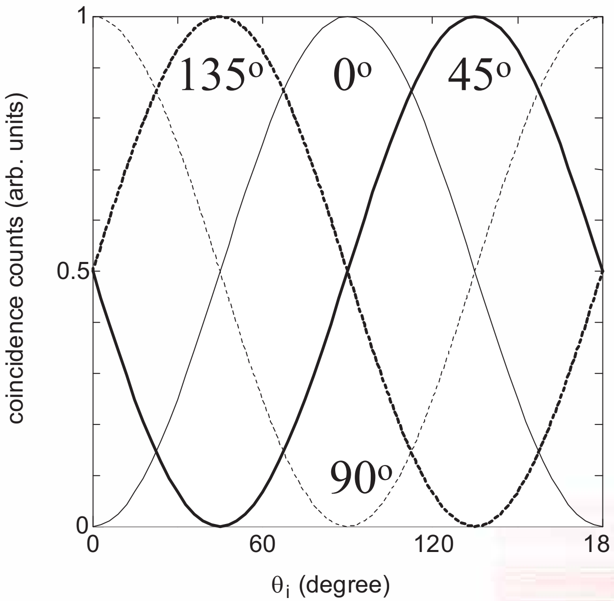
f=1
α=0°



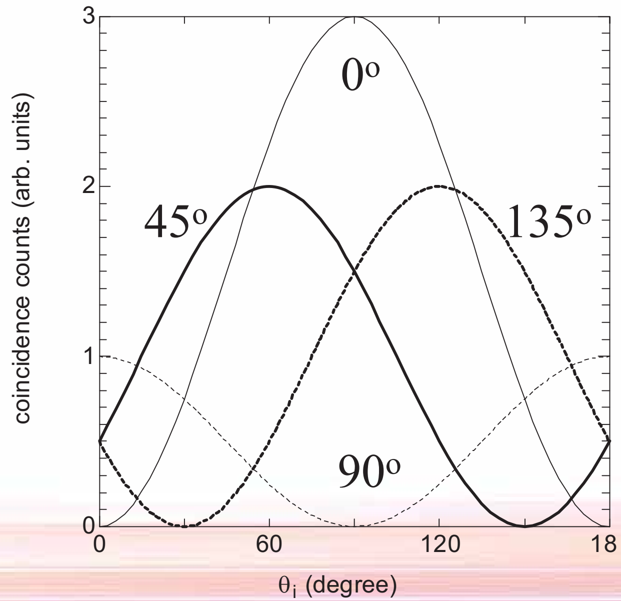
f=1
α=60°



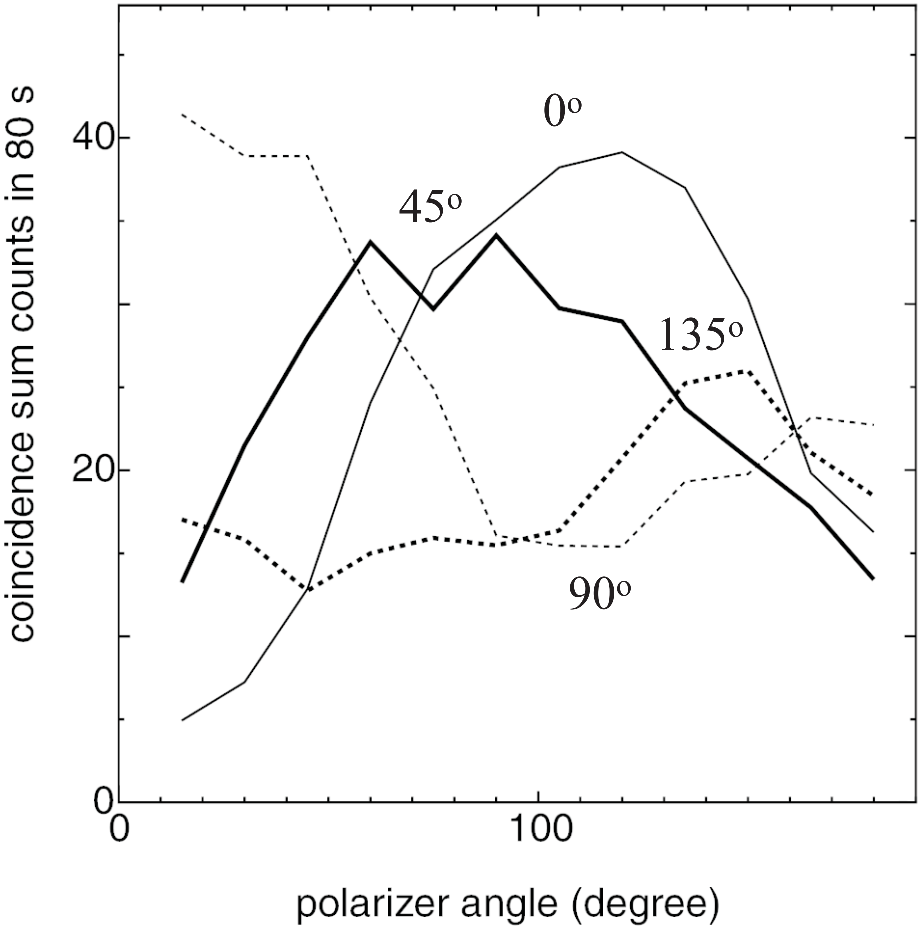
f=1
α=180°



f=1.732
α=0°



polarization correlation (1st diffraction@870nm)



$$|\psi\rangle = |H\rangle_s |V\rangle_i + f \cdot e^{i\alpha} |V\rangle_s |H\rangle_i$$

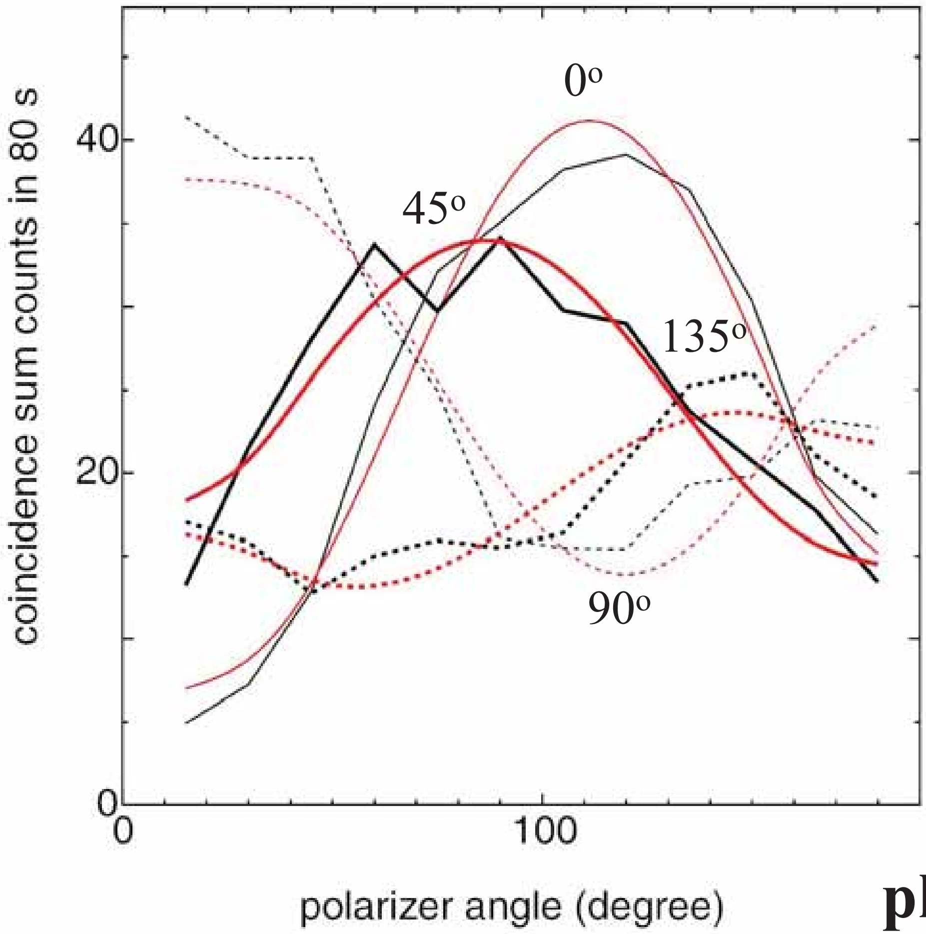
phase shift (866nm)
< phase shift (870nm)

$$f = 1.7 \rightarrow 1$$

visibility < 100%

$$\alpha \neq 0, 180^o$$

polarization correlation (1st diffraction@870nm)



$$\left|\psi\right\rangle = \left|H\right\rangle_s \left|V\right\rangle_i + f \cdot e^{i\alpha} \left|V\right\rangle_s \left|H\right\rangle_i$$

	visibility	relative phase
0°	0.75	
45°	**0.43**	**-25°**
135°	**0.31**	**35°**
90°	0.50	-81°

phase shift (866nm)
< phase shift (870nm)

$f = 1.7 \rightarrow 1$

visibility<100% $\alpha \neq 0, 180^o$

- $\begin{cases} \text{no entanglement (iris open)} \\ \text{entangled (iris 1mm)} \end{cases}$
- **phase shift (866nm) < phase shift (870nm)** $\because f = 1.7 \rightarrow 1$

  but phase shift<45^o **to improve : walk-off compensation**
- **visibility<100% (866nm, 870nm)** $\because \alpha \neq 0, 180^o$

  to improve : group velocity compensation

frequency resolved photon pairs are entangled in polarization

(light source for WDM-QKD)

future : compensations of walk-off and group velocity (improve pol-entanglement)

A. Yabushita et. al, J. Appl. Phys., 99, 063101 (2006)

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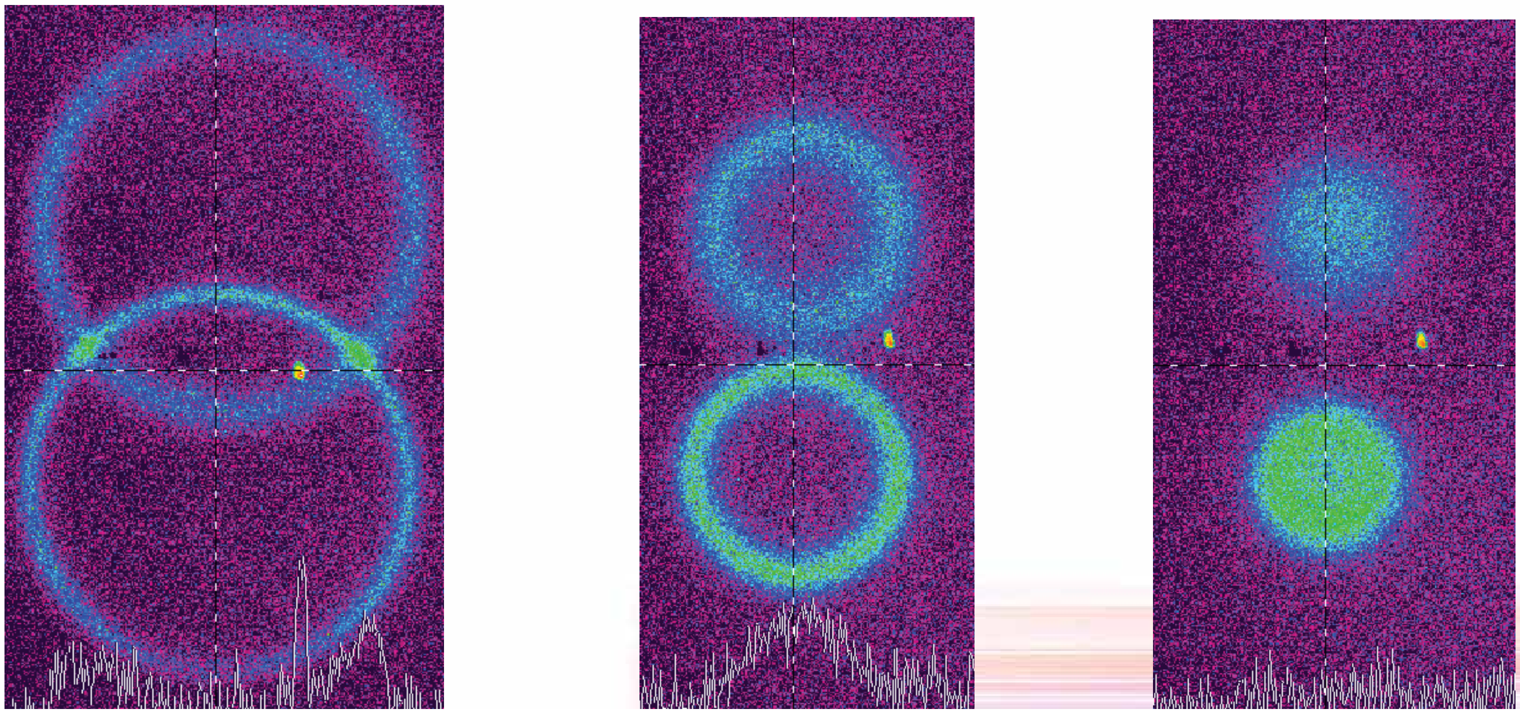
Our work

Beam-like photon pair generation for 2photon interference & polarization entanglement



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Ultrafast Dynamics Lab
超 快 動 力 學 研 究 室

ALRC
Advanced Laser Research Center
先 進 超 快 雷 射 研 究 中 心

國立清華大學
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National Chiao Tung University

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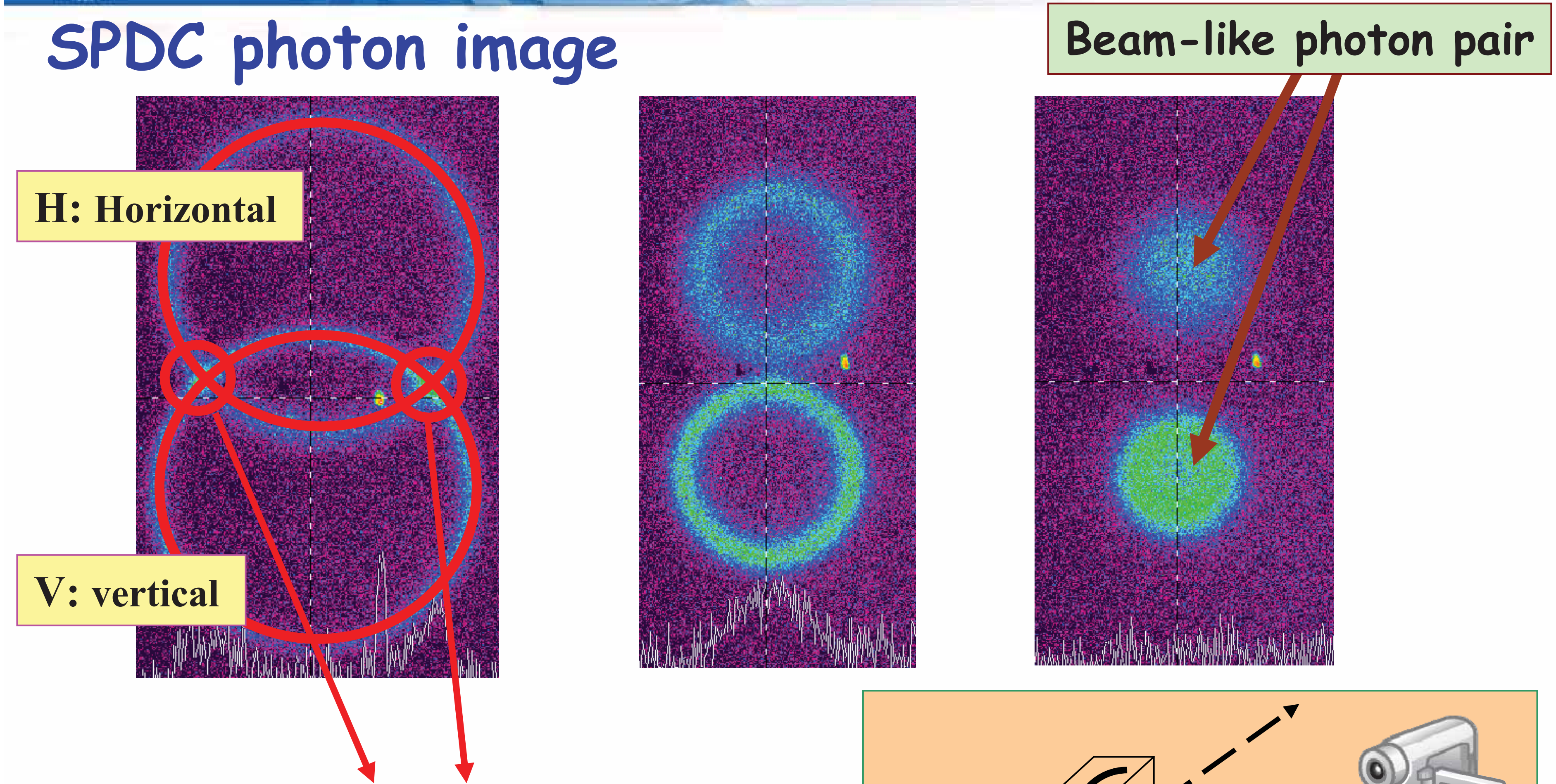
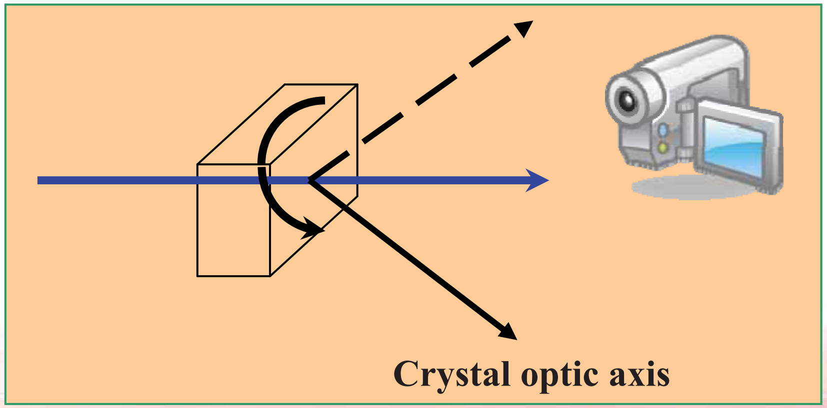
NSC 98-2112-M-009-001-MY3, NSC 99-2923-M-009-004-MY3

SPDC photon image

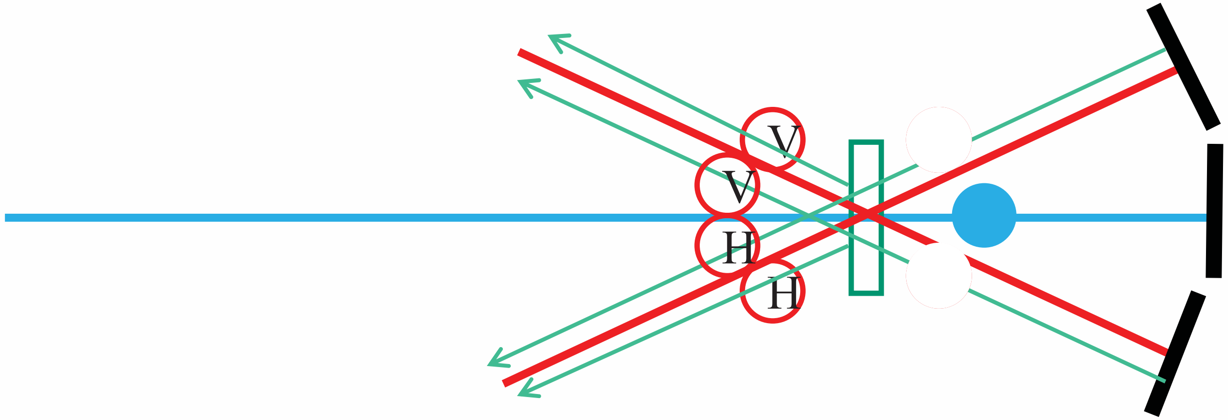


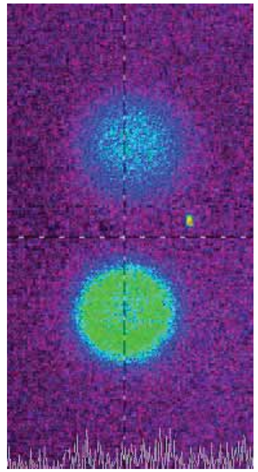
$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|H_1\rangle|V_2\rangle + |V_1\rangle|H_2\rangle]$$

Polarization Entangled photon pair

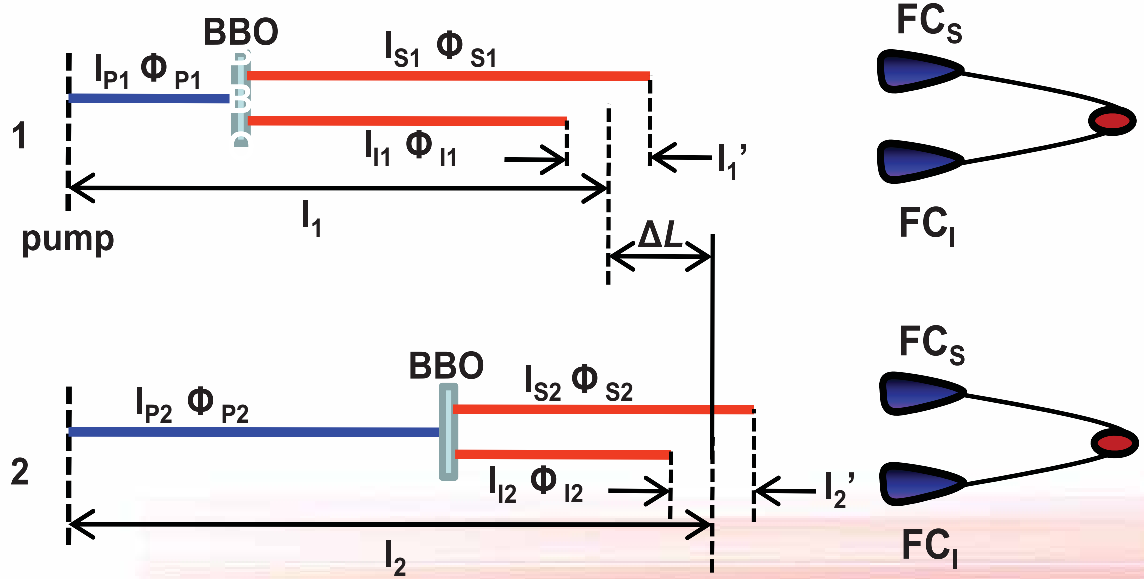


Main idea (2photon interference)

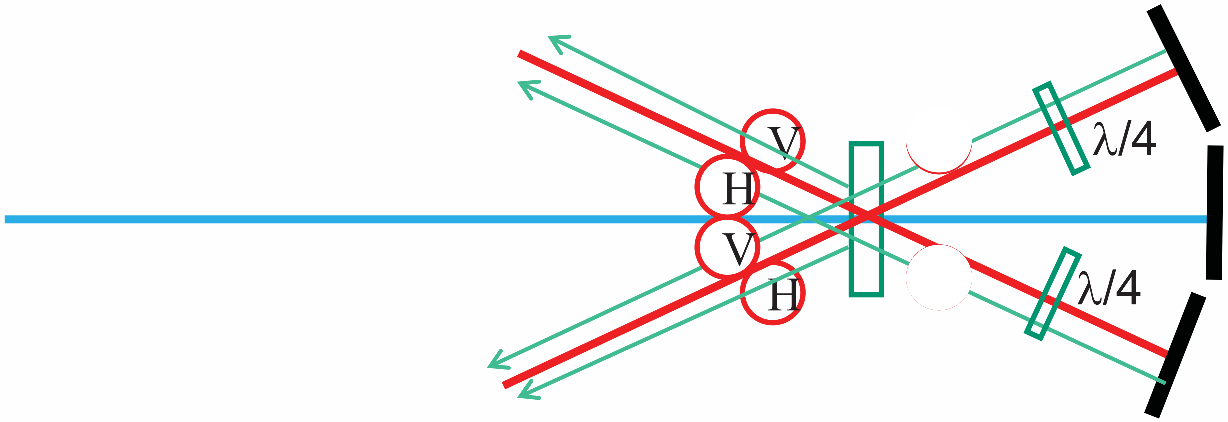


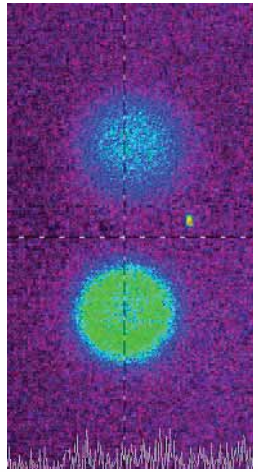


$$R_c \propto 1 + \gamma(\Delta L)\gamma'(\Delta L')\cos\left[k_{P0}\Delta L + \left(\frac{k_{S0} - k_{I0}}{2}\right)\Delta L' + \Delta\varphi\right]$$



Main idea (polarization entanglement)



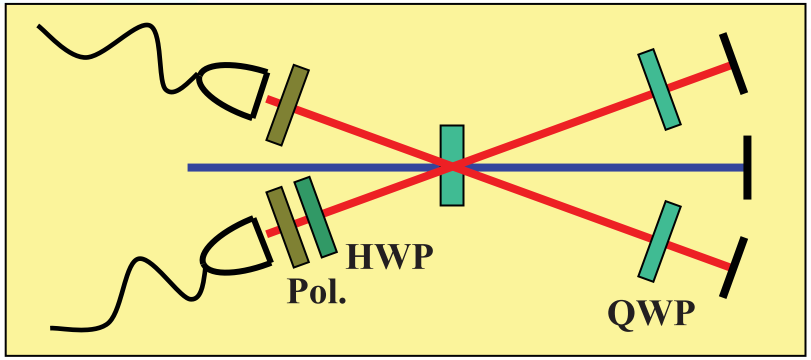


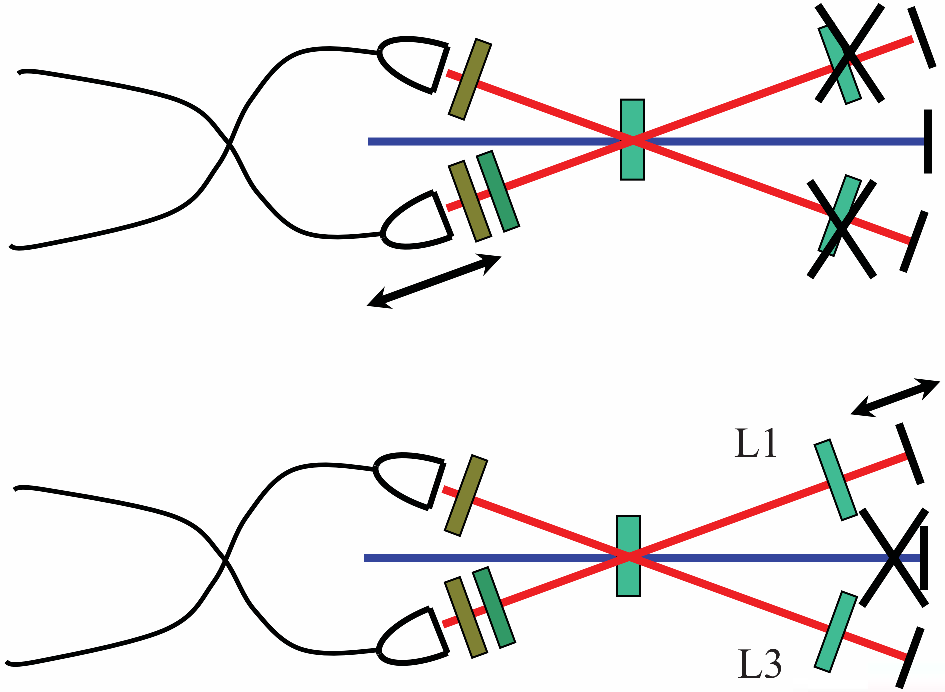
$$|\Psi\rangle = \frac{1}{\sqrt{2}} e^{i\phi} [|H_1\rangle|V_2\rangle + (e^{i\varphi}|V_1\rangle)|H_2\rangle]$$

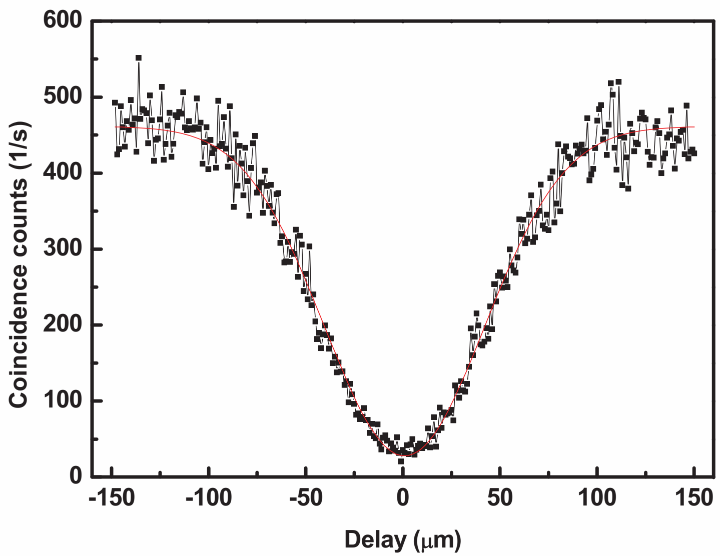
adjust phase

$$|\Psi\rangle = \frac{1}{\sqrt{2}} [|H_1\rangle|V_2\rangle + |V_1\rangle|H_2\rangle]$$

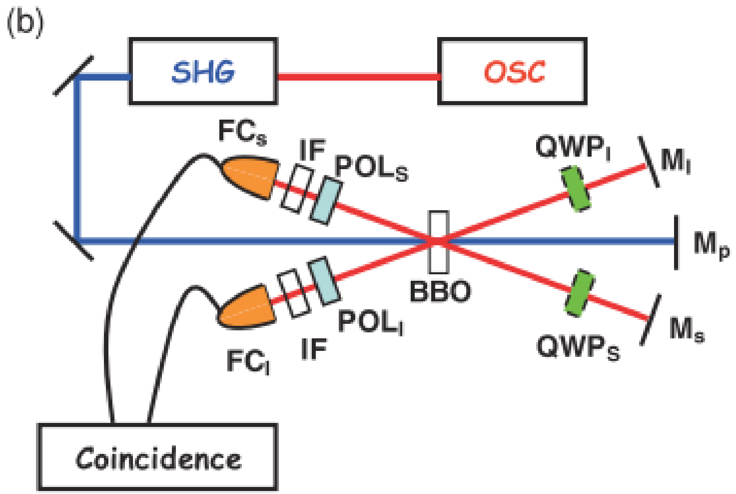
HOM interference measurement (adjust path length)

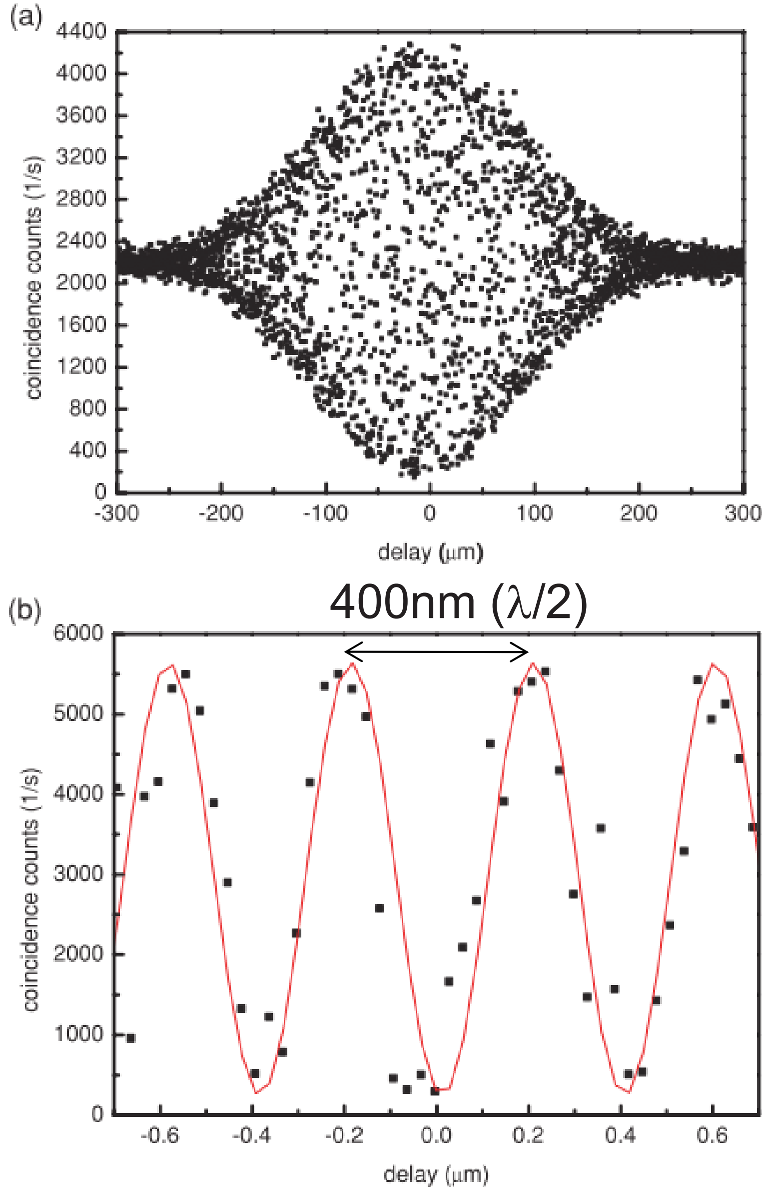






2photon interference
by photon pair beams

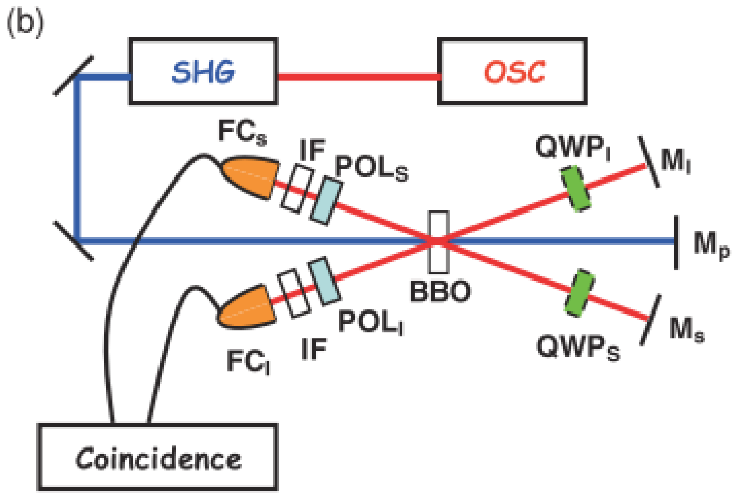


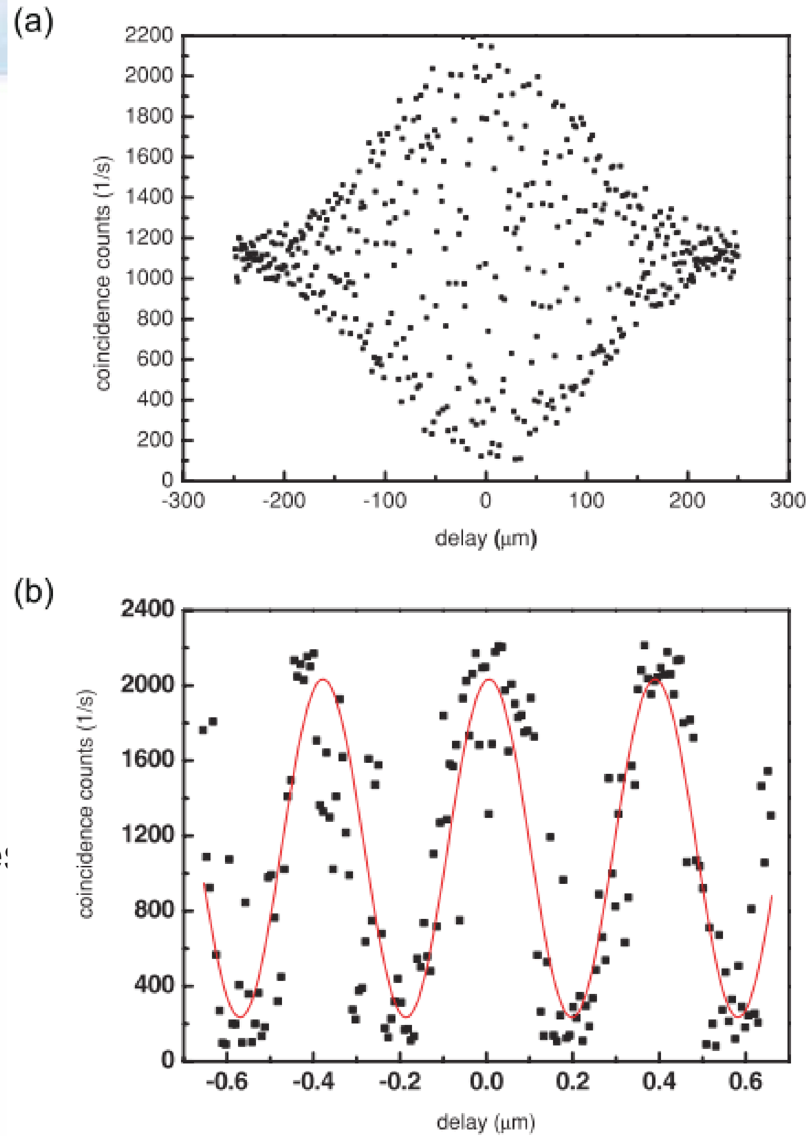


classical lithography
resolution~ λ

2-photon interference (quantum lithography)
2 times higher resolution

polarization entanglement
by photon pair beams





rotate polarization 90 degrees by QWP plates

$$|H_1\rangle|V_1\rangle + e^{i\phi}|H_2\rangle|V_2\rangle$$

⇩

$$|V_1\rangle|H_1\rangle + e^{i\phi}|H_2\rangle|V_2\rangle$$

(max entangle at $\phi = n\pi$ n:integer)

measure coincidence scanning ϕ

visibility = 0.90±0.05

(highly entangled)

Our new scheme to generate photon pair beams

for two purposes

- two-photon interference
- polarization entanglement

Our new scheme

resolution of 2-photon interference ($\lambda/2$)

2 times higher than classical limit (λ)

all photon pairs can be polarization entangled

efficient generation of polarization entangled pairs

cf.) traditional method : only crossing points of light cones

Hsin-Pin Lo et al., Beamlike photon-pair generation for two-photon interference and polarization entanglement, Phys. Rev. A 83, 022313 (2011)

PHYSICAL REVIEW A 83, 022313 (2011)

Beamlike photon-pair generation for two-photon interference and polarization entanglement

Hsin-Pin Lo,[1,2] Atsushi Yabushita,[2] Chih-Wei Luo,[2] Pochung Chen,[1] and Takayoshi Kobayashi[2,3,4,5]
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(Received 25 October 2010; published 14 February 2011)

Beamlike photon pairs were generated by spontaneous parametric down-conversion using a type-II β-BaB_2O_4 crystal. A pump laser generated photon pairs when it transmitted through the crystal and was reflected back into the crystal by a mirror to generate more photon pairs. The photon pairs generated when the pump laser first transmitted through the crystal (first photon pairs) were also reflected back into the crystal to overlap with the light path of the photon pairs generated in the second transmission of the pump laser through the crystal (second photon pairs). We observed interference between the first and second photon pairs modulated with a half period of the wavelength of the photon pairs, which demonstrates two-photon interference using the beamlike photon pairs. The fringe period confirms that the observed interference is not classical interference but quantum two-photon interference. Through rotating the angles of quarter-wave plates in the light paths of the photon pairs, we generated beamlike photon pairs with entangled polarization. The phase between the first and second photon pairs could be tuned by changing the position of mirrors reflecting the pump pulses and photon pairs. The fringes of coincidence counts showed that the beamlike photon pairs have polarization entanglement.

DOI: 10.1103/PhysRevA.83.022313 PACS number(s): 03.67.Bg, 03.65.Ud

You can find more detail information in this paper.

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  - **Ghost spectroscopy | frequency**
  - Quantum key distribution (QKD) | polarization
  - **Multiplex QKD | polarization and frequency**
  - **Entangled photon beam**

Our work

on-going in National Chiao-Tung University

Thank you for your attention!