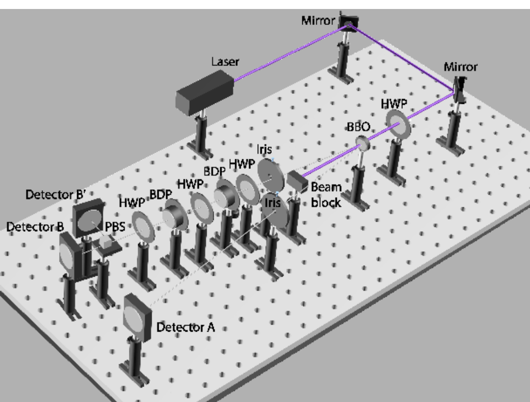
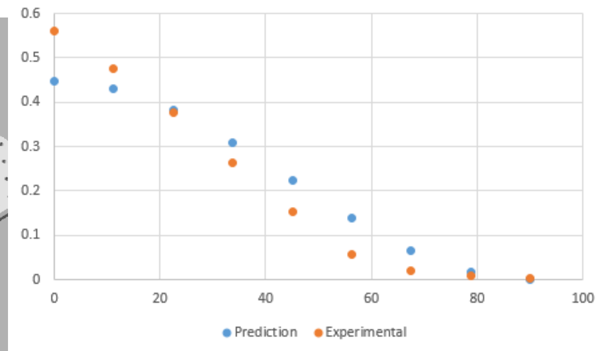
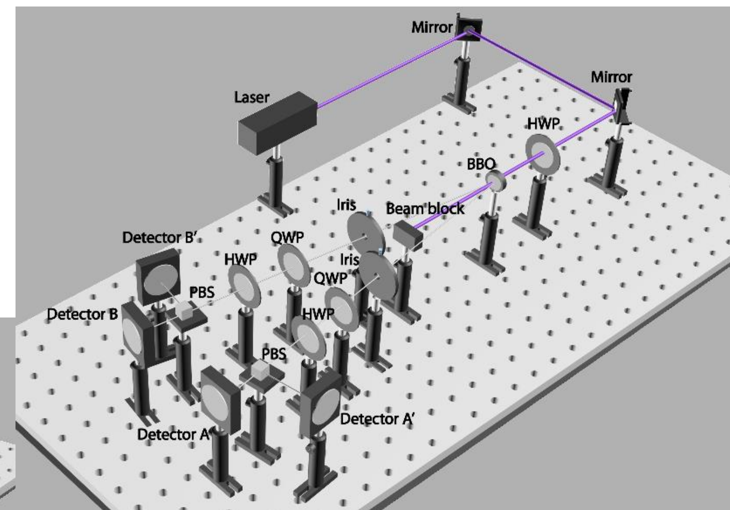
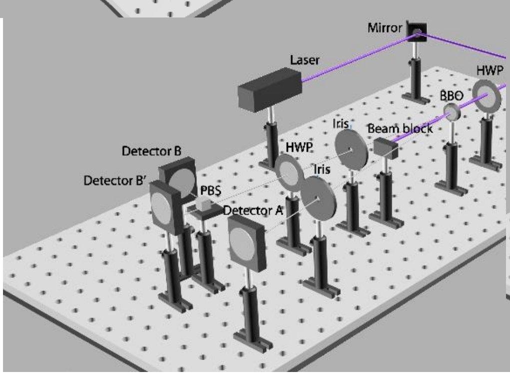
Single Photon Quantum Information Experiments Any Physics Department Can Build!

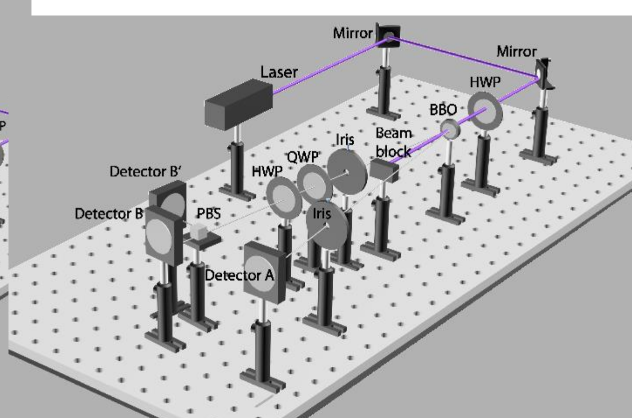
Muhammad Sabieh Anwar

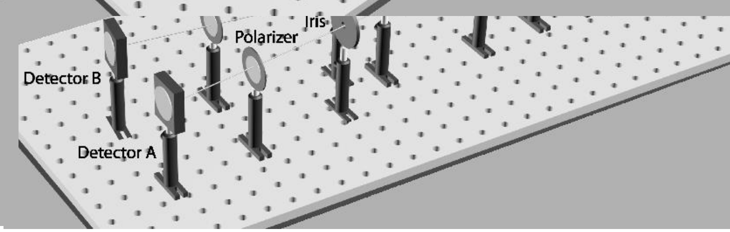


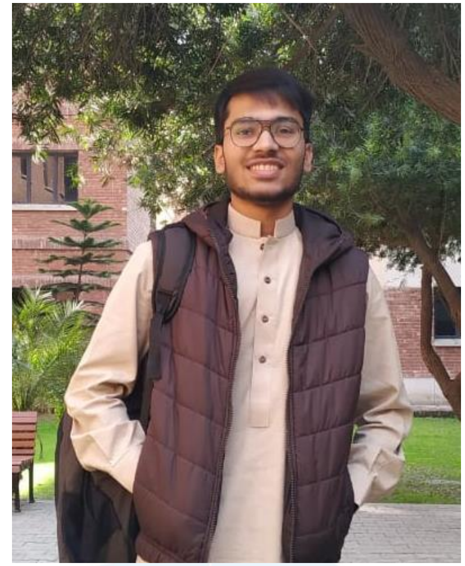












Ibn Sahl Corner for Optics

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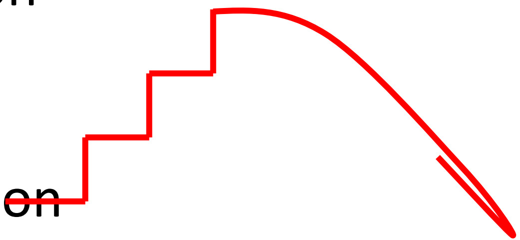
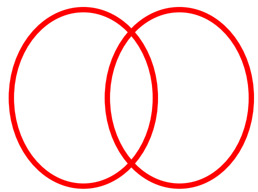
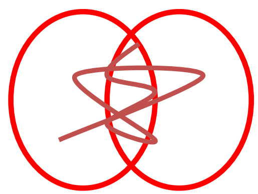
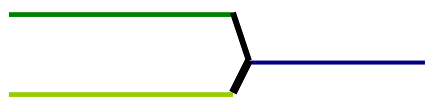
Salient Features of a Quantum Understanding of the World

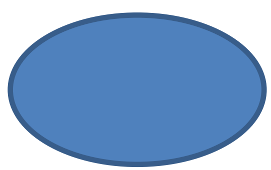
- Quantization
- Superposition
- Entanglement
- Interference
- Uncertainty
- Measurement

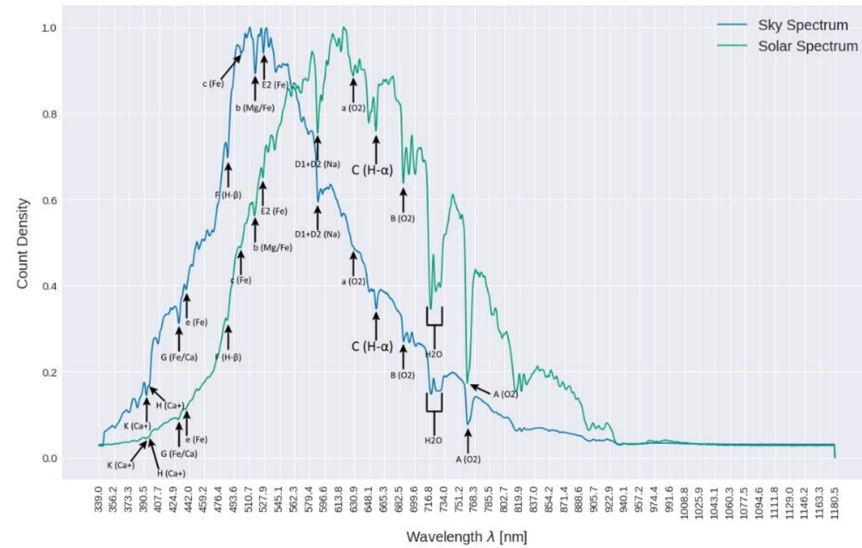


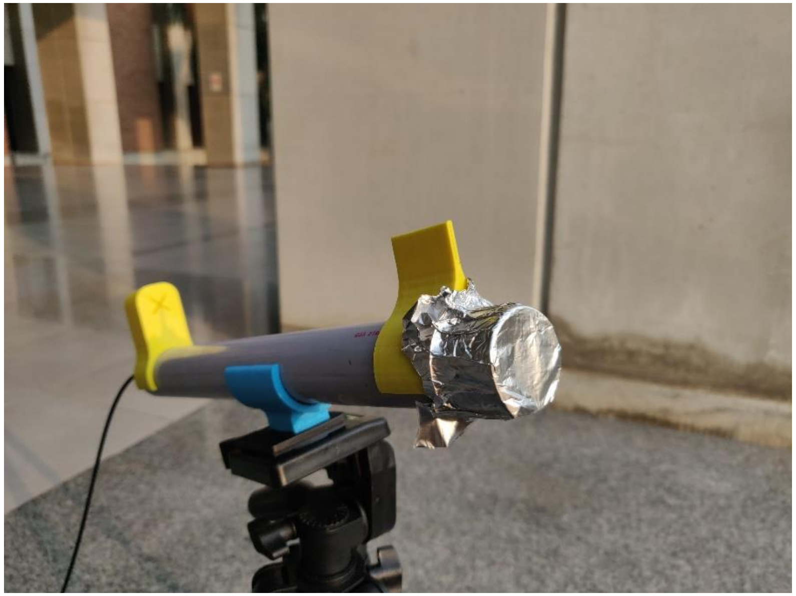






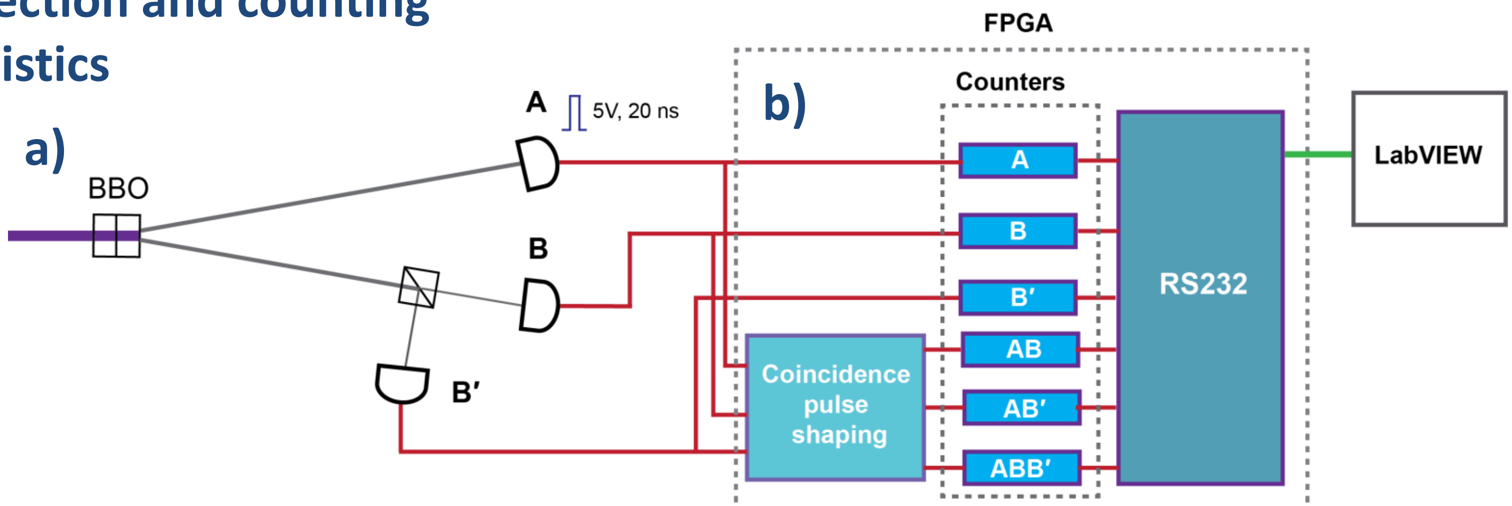


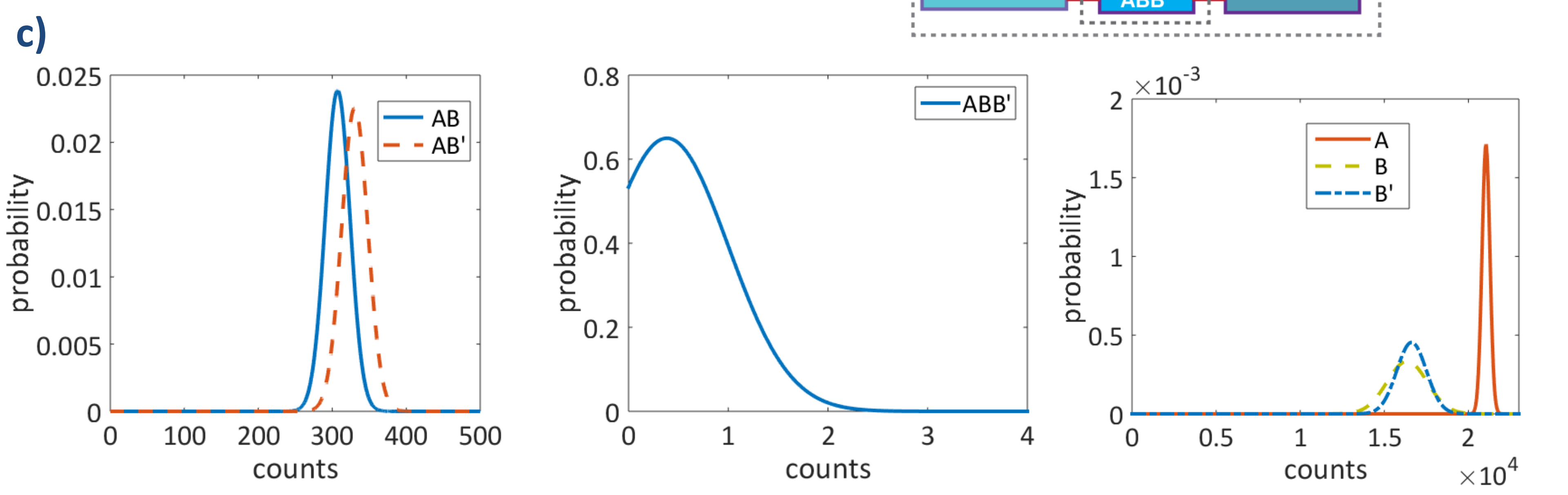


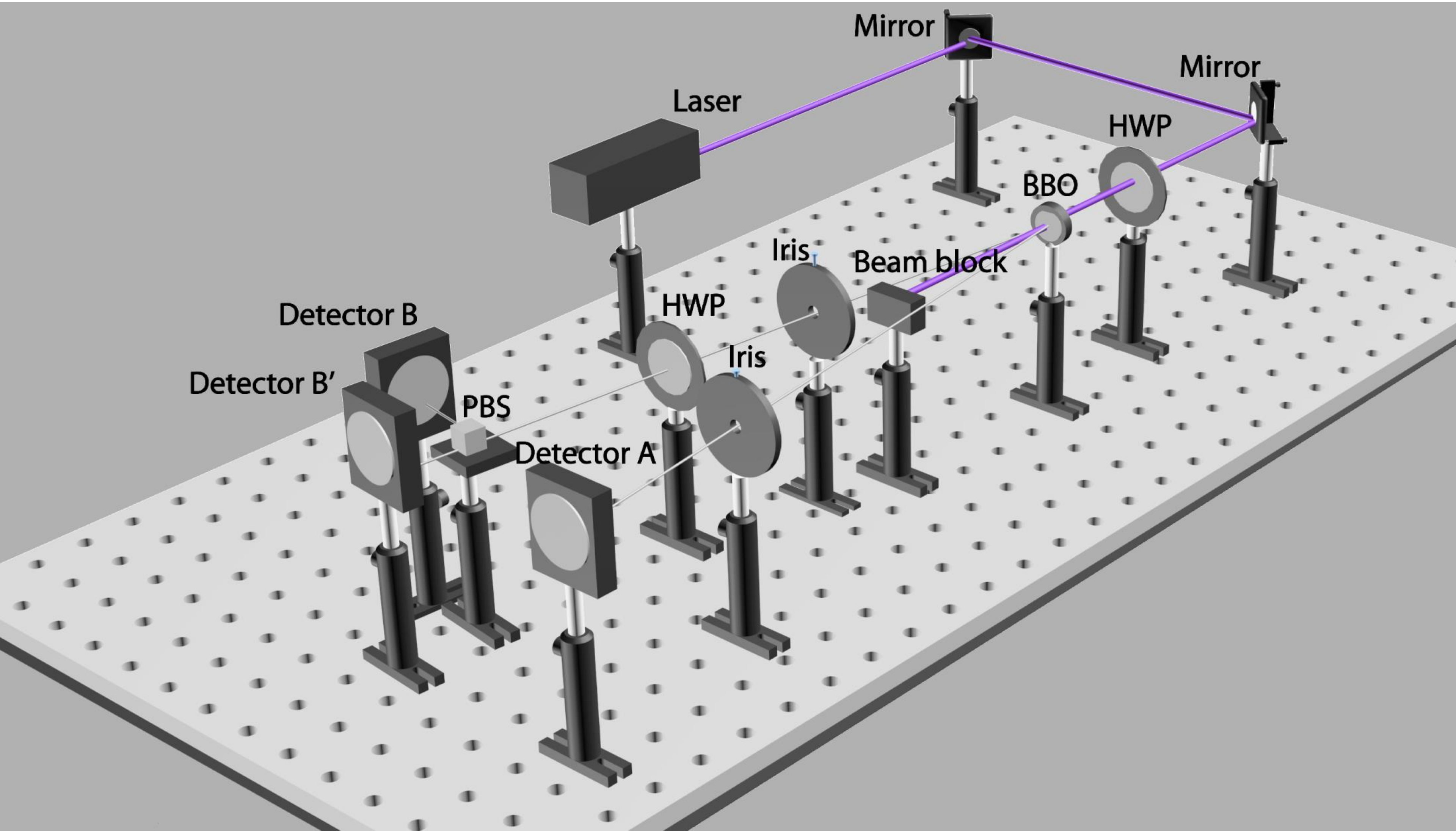


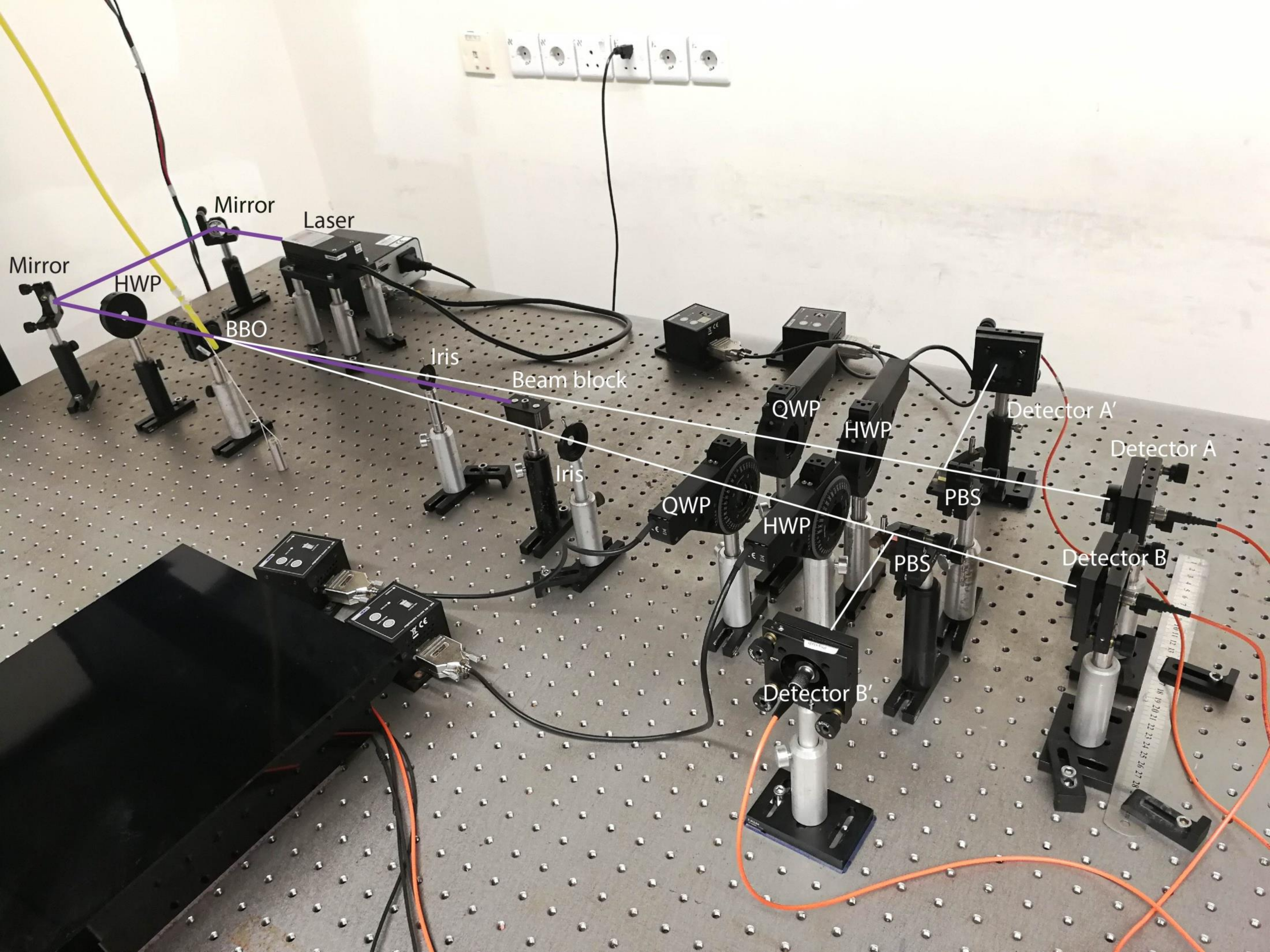
Overview of the single photon lab

a) **Optical setup**
b) **Photon detection and counting**
c) **Photon statistics**






Mirror
Mirror
Laser
HWP
BBO
Iris
Beam block
HWP
Detector B
Iris
Detector B′
PBS
Detector A



Mirror
Laser
Mirror
HWP
BBO
Iris
Beam block
QWP
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Detector A′
Detector A
Iris
QWP
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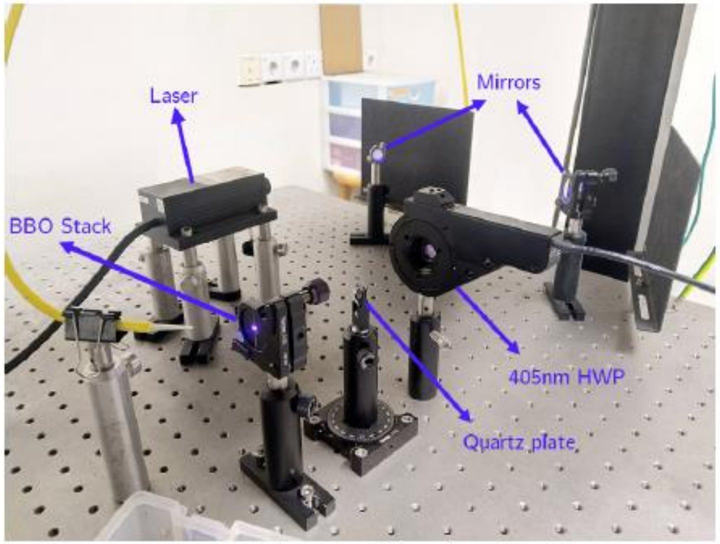
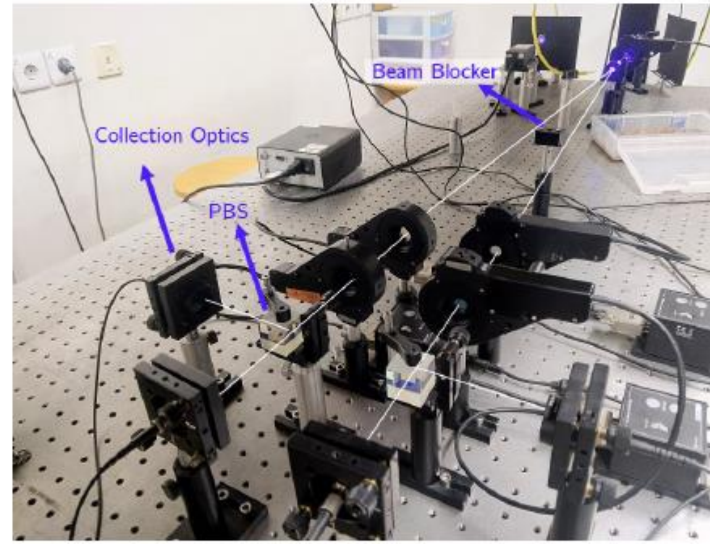
PBS
PBS
Detector B
Detector B′



(a) *Photon generation.*



(b) *Photon collection.*

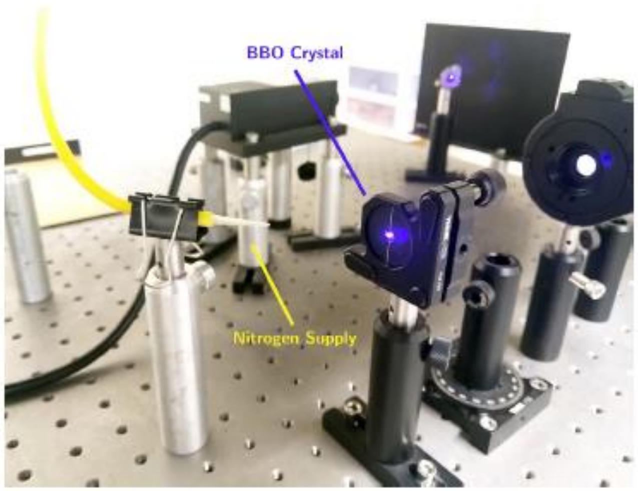


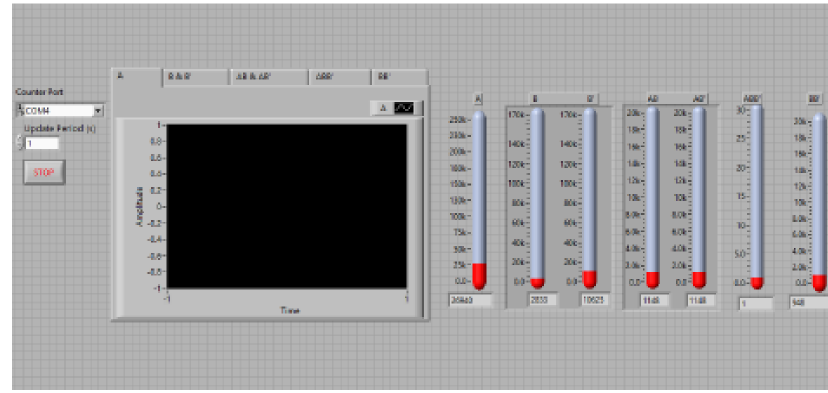
Figure 1.4: *405 nm pump beam hitting the BBO crystal stack. BBO crystals down-convert 405nm photons into two 810nm photons.*

Figure 1.6: *An SPCM on the left and its power supply on the right.*

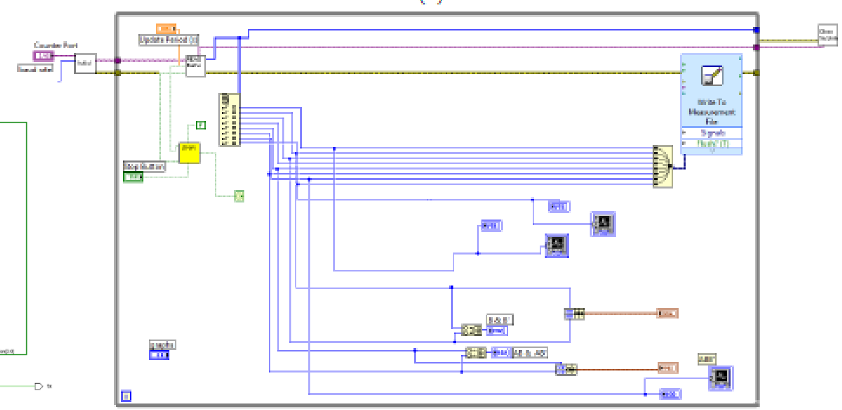
(a) *Pmod connector on a Nexys A7.*

(b) *UART serial communication devic*

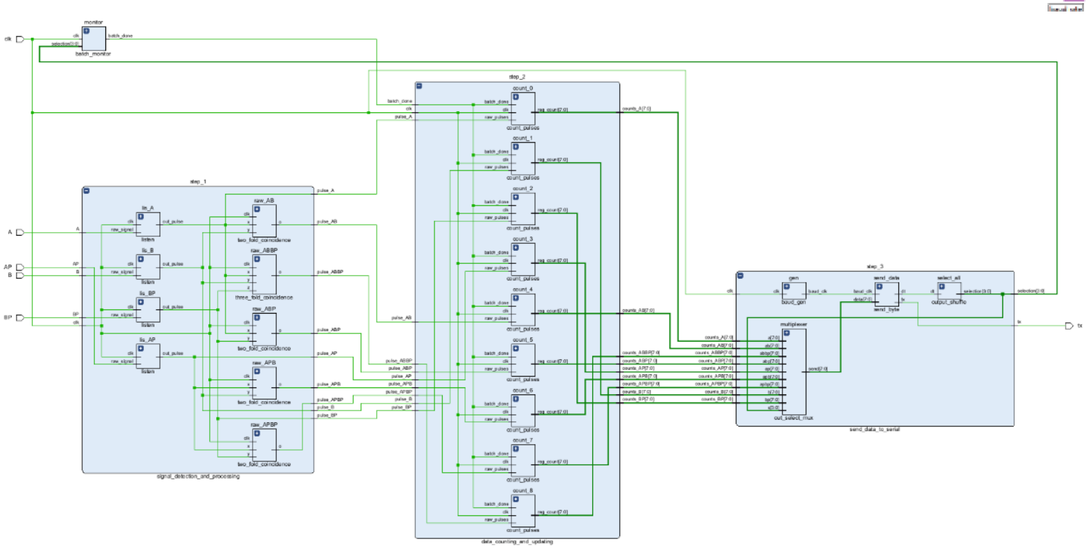
(c) *Nexys A7 FPGA.*



(a)

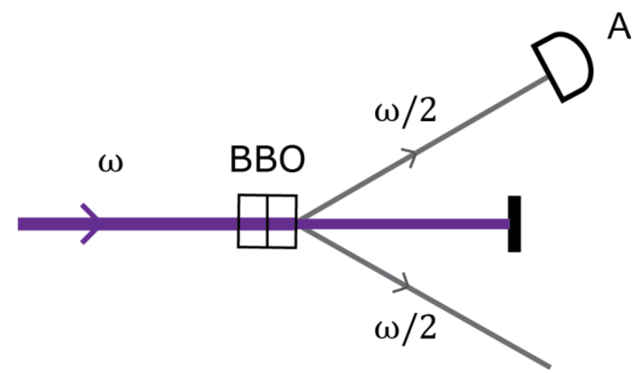


(b)

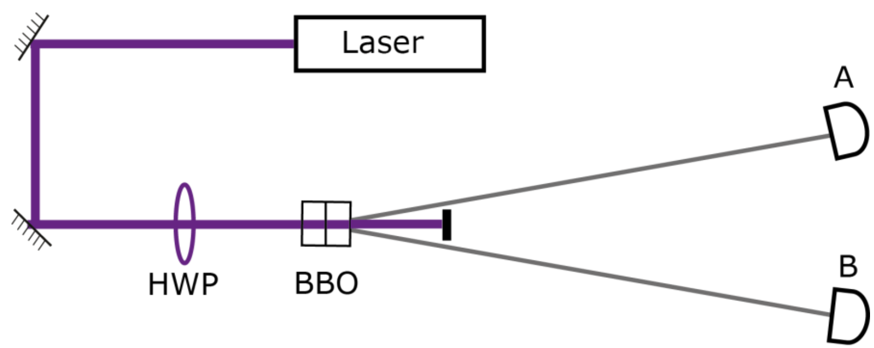


Producing single photons

- Type I spontaneous parametric downconversion with β-barium borate (BBO)[1]
- Pump beam 405 nm, 50 mW

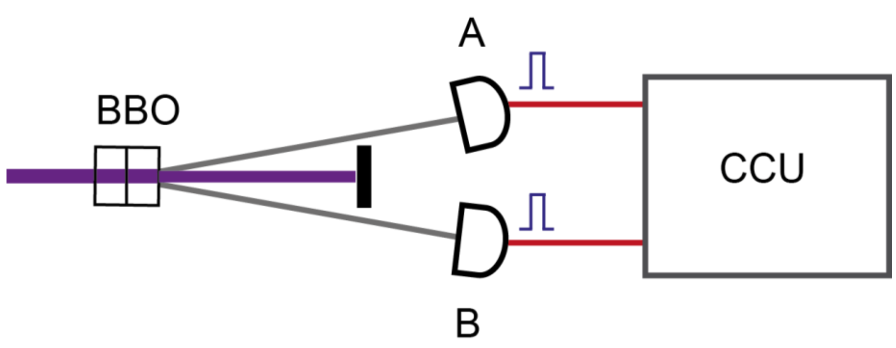


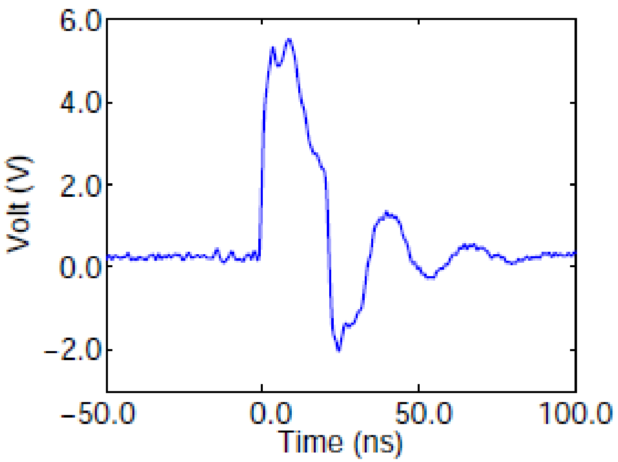
- Generation of of polarization-entangled photon beams
- Gating of one beam at detector A projects the other beam into single photon state.



Detecting single photons

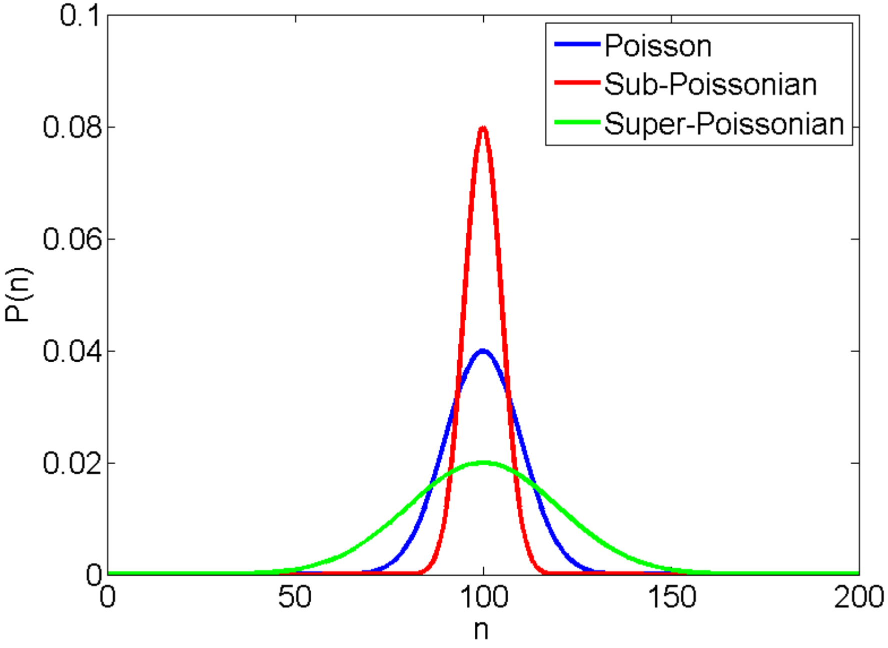
- Each detector comprises an avalanche photodiode that outputs a 20 ns 5V pulse on each detection of a photon.
- Pulses coincident at two or more detectors are counted by a coincidence counting unit (CCU).
- Pulses from individual detectors are also counted by the CCU.
- The counts are transmitted to a computer for visualization and analysis of results.





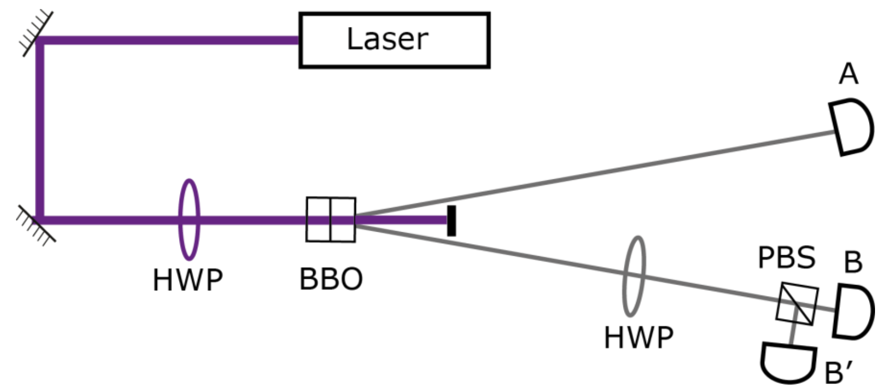
What do photon statistics tell us?

- Classically, sub-Poissonian ($\Delta n < \sqrt{\bar{n}}$) light is impossible.
- A coherent source shows Poissonian ($\Delta n = \sqrt{\bar{n}}$) whereas a fluctuating source shows super-Poissonian ($\Delta n > \sqrt{\bar{n}}$) statistics.
- Our single-detector counts show super-Poissonian while the gated (coincidence) counts show sub-Poissonian statistics.



Particle nature of light

- Hypothesis: a single particle can only be detected at one place[4].



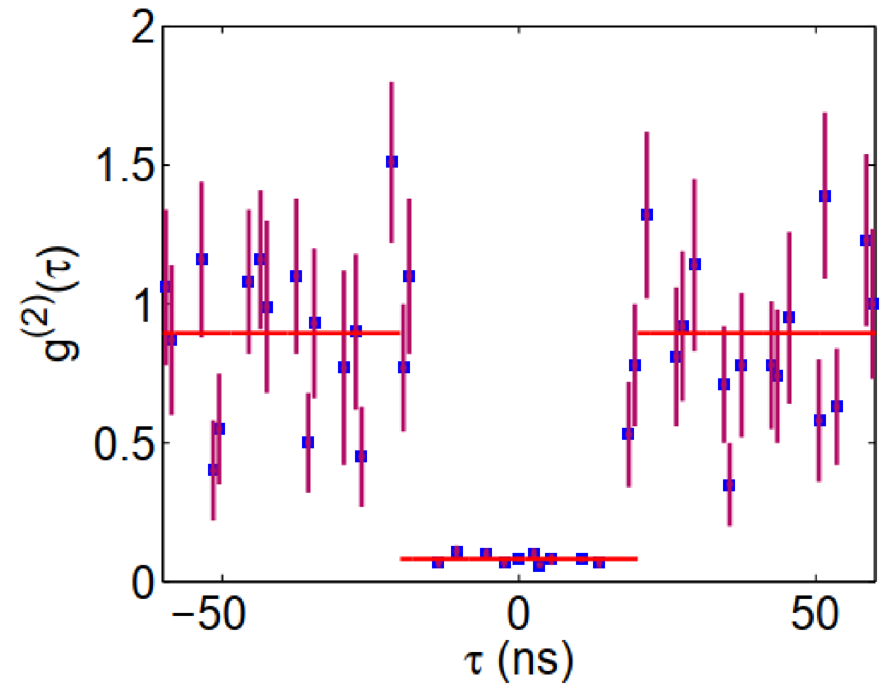
- 2nd order correlation function

$$g^{(2)}(0) = \frac{P_{ABB'}}{P_{AB}P_{AB'}}$$

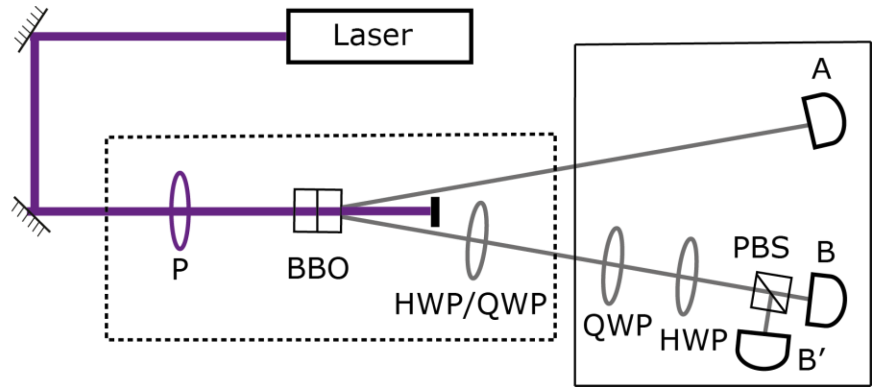
- In an experimental run of 10 minutes, we obtained

$$g^{(2)}(0) = 0.080 \pm 0.005$$

- Hanbury Brown-Twiss experiment



Measuring the quantum state - I

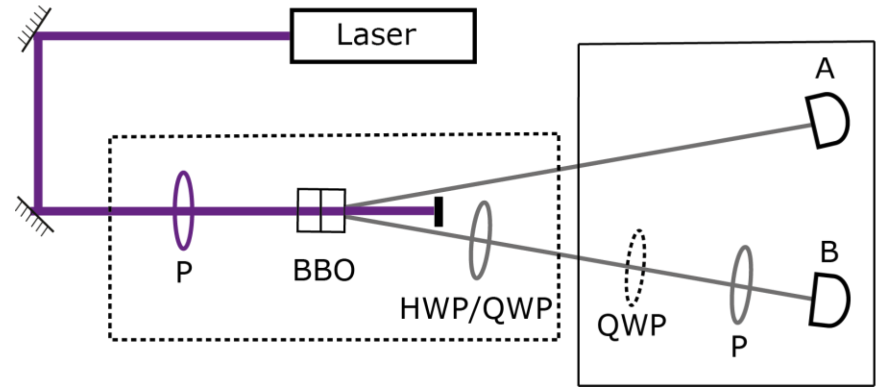


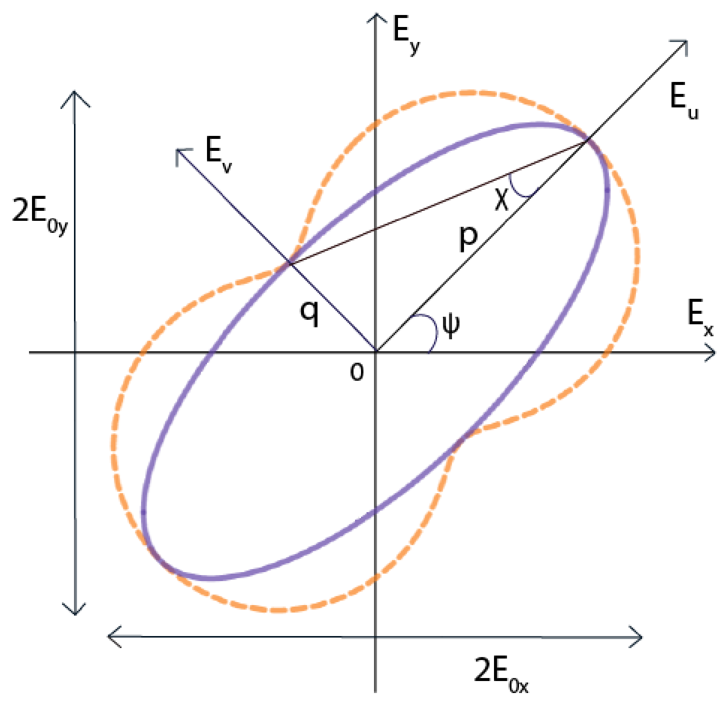
- A general pure state can be expressed as $|\Psi\rangle = a\,|H\rangle + be^{i\phi}\,|V\rangle$
- Measurement destroys the single photon. So we perform measurements on identically prepared photons.
- Three parameters require us to make measurements in three different bases.

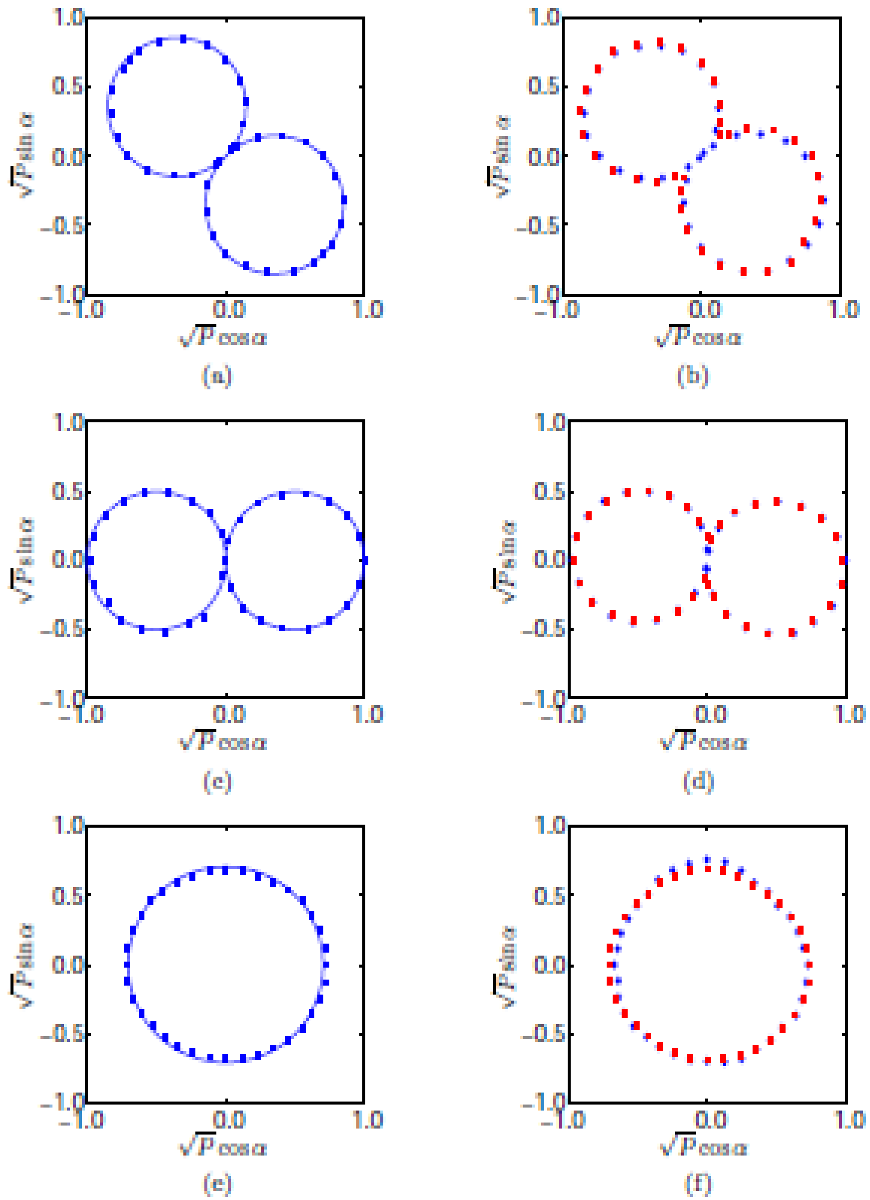
Input	Prediction	Measurement
$\|H\rangle$	$a = 1.000,\ b = 0.000$	$a = 0.986(2),\ b = 0.165(2),$ $\theta = -1.450(5)$
$\|45°\rangle$	$a = 0.707,\ b = 0.707,$ $\theta = 0.000$	$a = 0.743(2),\ b = 0.669(2),$ $\theta = 0.184(2)$
$\|L\rangle$	$a = 0.707,\ b = 0.707,$ $\theta = -1.571$	$a = 0.663(2),\ b = 0.749(2),$ $\theta = -1.539(5)$

Measuring the quantum state - II

- The peanut method
- Used in antenna polarimetry, optical polarimetry, quantum state measurement
- Applies both to classical and quantum light (single qubit)
- Can be used to determine the Stokes parameters or the ellipse parameters







Polarization state	One-shot measurement	Quantum hippopede	Classical hippopede
Horizontal	$S_0 = 1.00 \pm 0.00$ $S_1 = 0.94 \pm 0.00$ $S_2 = 0.04 \pm 0.00$	1.00 ± 0.04 0.95 ± 0.04 -0.16 ± 0.04	1.00 ± 0.04 0.92 ± 0.04 -0.15 ± 0.04
Vertical	$S_0 = 1.00 \pm 0.00$ $S_1 = -0.86 \pm 0.00$ $S_2 = 0.20 \pm 0.00$	1.00 ± 0.02 -0.98 ± 0.02 -0.08 ± 0.02	1.00 ± 0.02 -0.92 ± 0.02 -0.09 ± 0.02
Anti-diagonal	$S_0 = 1.00 \pm 0.02$ $S_1 = -0.03 \pm 0.00$ $S_2 = -1.00 \pm 0.00$	1.00 ± 0.00 0.11 ± 0.02 -0.97 ± 0.02	1.00 ± 0.03 0.13 ± 0.03 -0.93 ± 0.03
Diagonal	$S_0 = 1.00 \pm 0.00$ $S_1 = 0.10 \pm 0.00$ $S_2 = 0.98 \pm 0.00$	1.00 ± 0.00 0.04 ± 0.02 1.00 ± 0.00	1.00 ± 0.00 0.04 ± 0.02 1.00 ± 0.00
Left circular	$S_0 = 1.00 \pm 0.00$ $S_1 = -0.12 \pm 0.00$ $S_2 = 0.03 \pm 0.01$	1.00 ± 0.04 -0.04 ± 0.04 -0.02 ± 0.04	1.00 ± 0.02 0.06 ± 0.02 -0.03 ± 0.02
Right circular	$S_0 = 1.00 \pm 0.00$ $S_1 = 0.07 \pm 0.00$ $S_2 = 0.09 \pm 0.00$	1.00 ± 0.04 -0.07 ± 0.04 -0.04 ± 0.06	1.00 ± 0.02 0.06 ± 0.02 -0.04 ± 0.02

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applied optics

Hippopedal intensity plots: drawing comparisons between antenna and optical polarimetry

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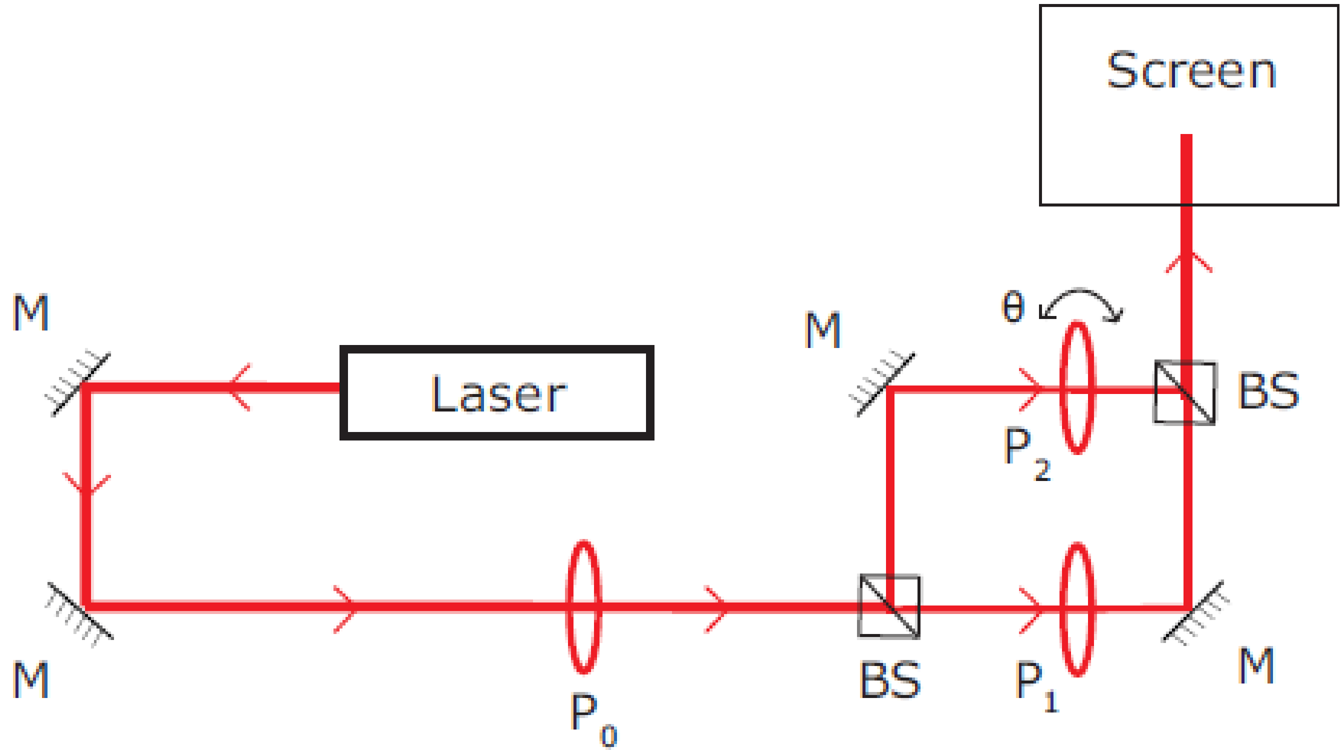
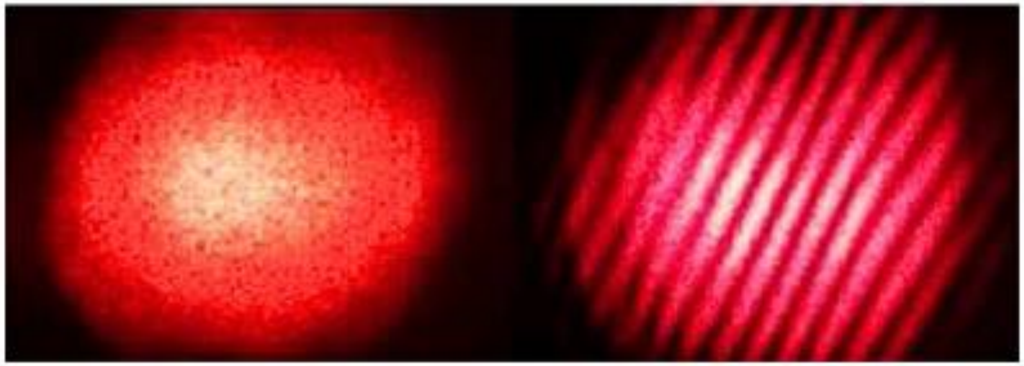
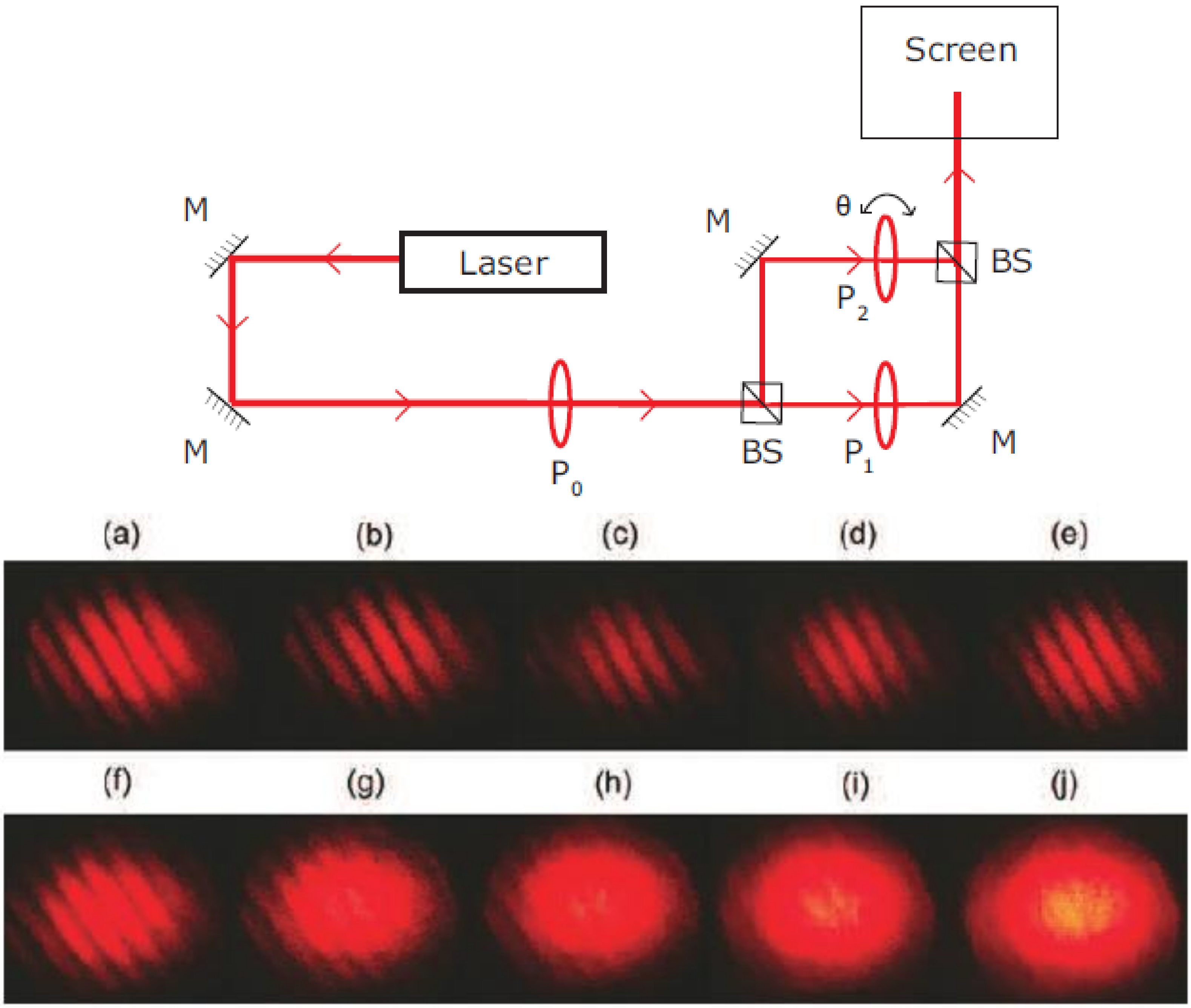
Classical Erasure Experiment



(a) (b)




Screen
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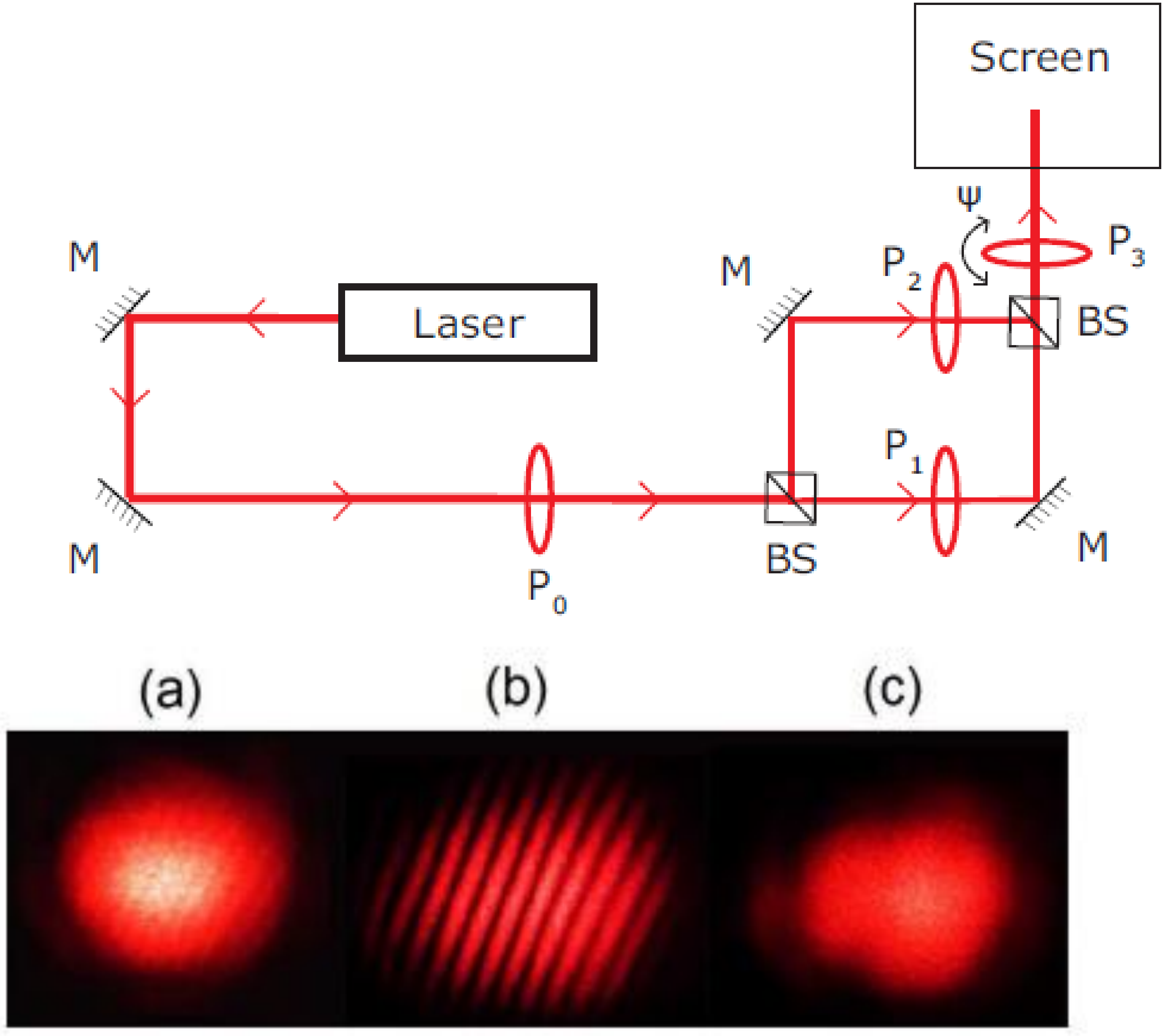
Screen
Ψ
P_3
P_2
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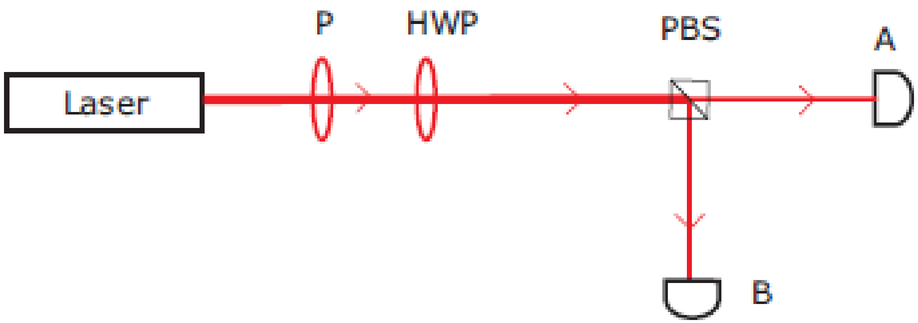
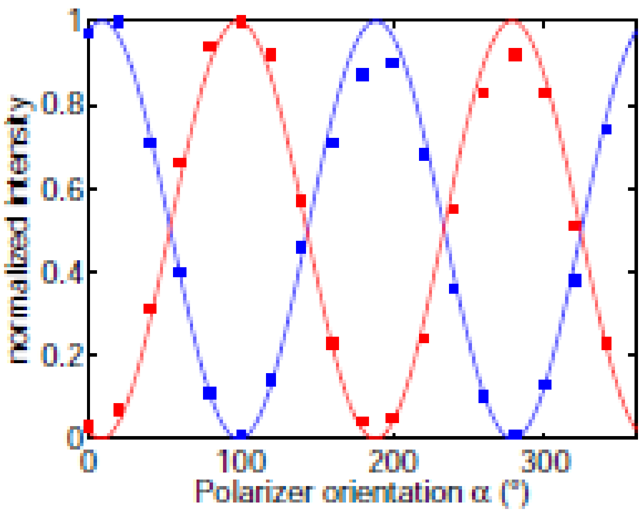
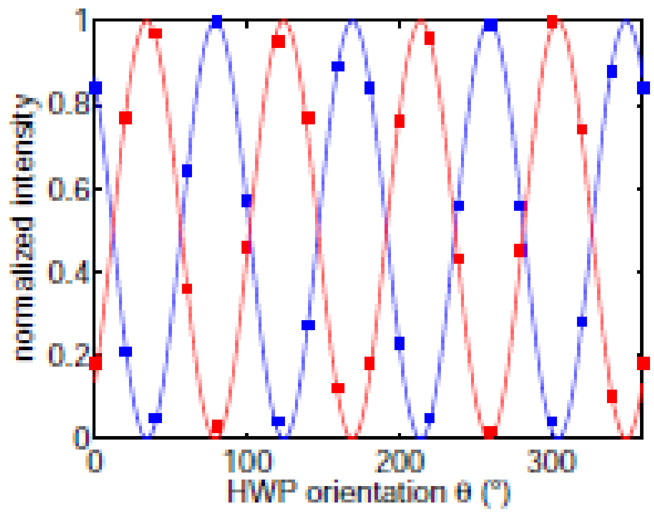
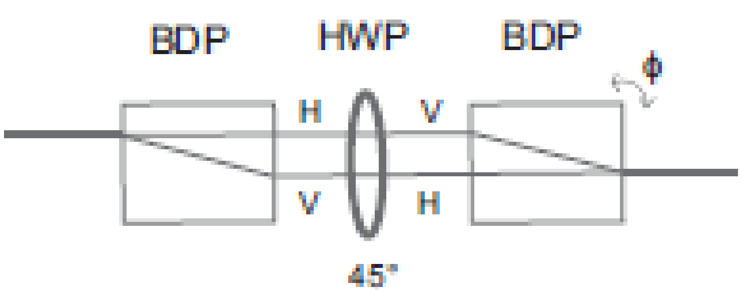
(a)
(b)
(c)

Interferometry and Quantum Erasure

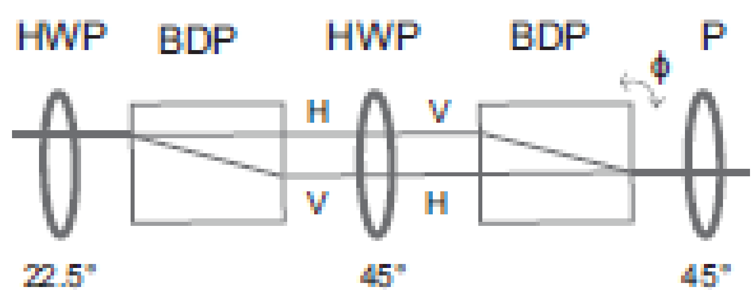




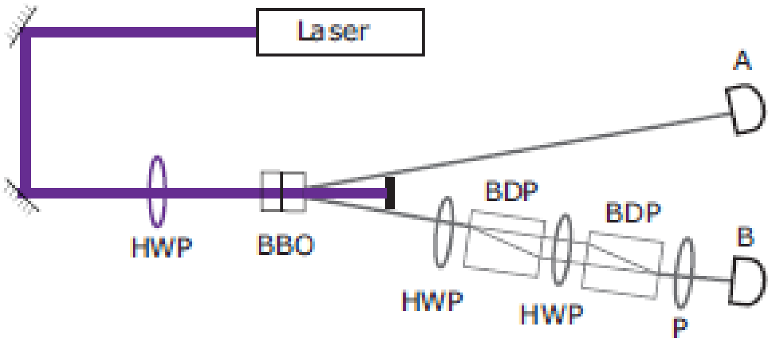




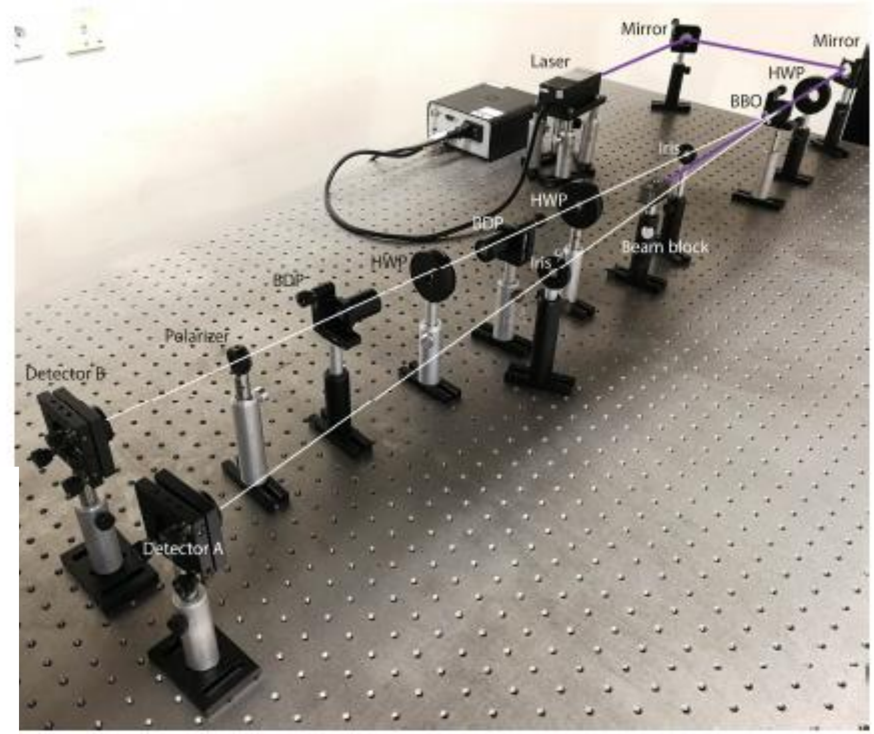
(a)

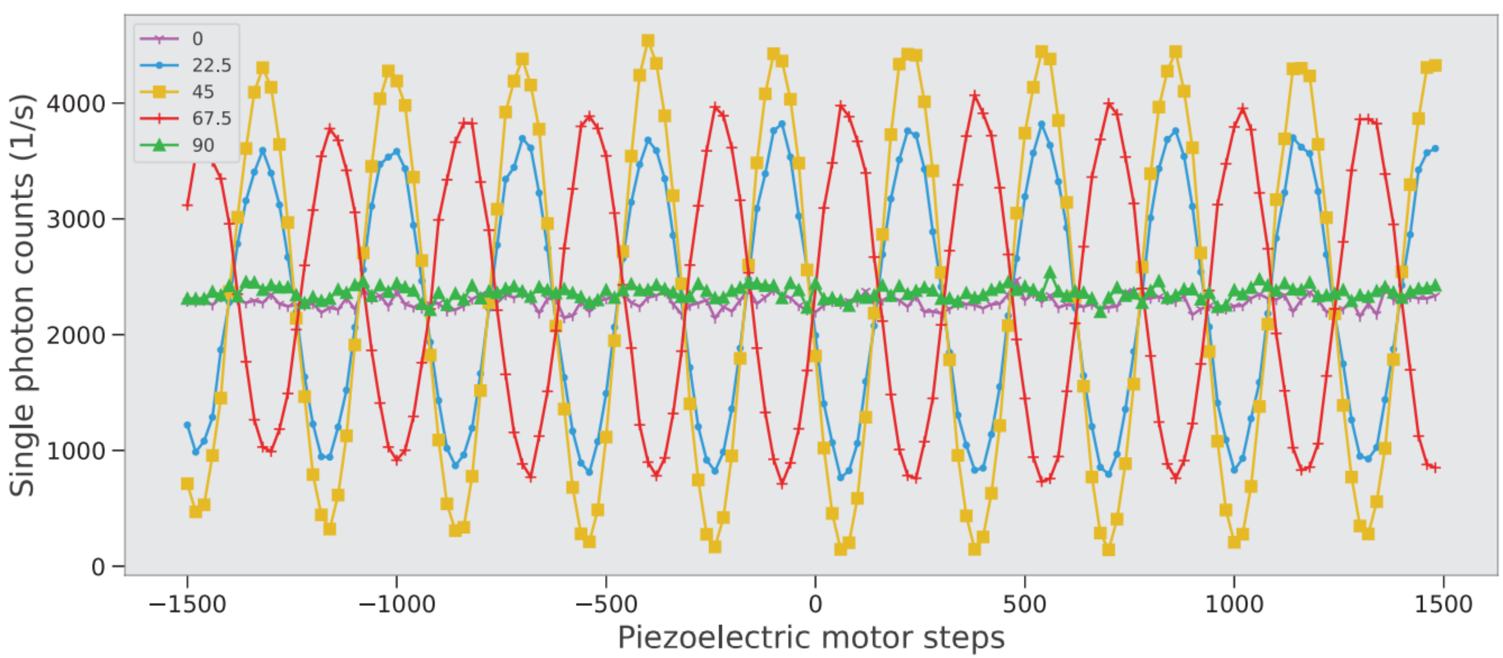


(b)



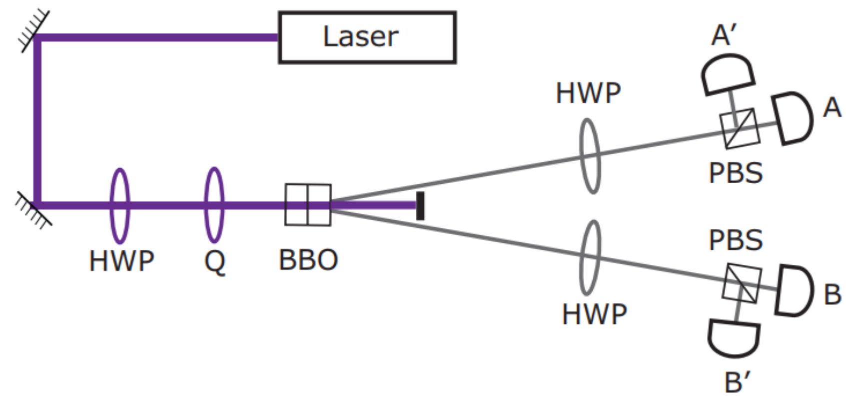
Polarizer orientation (°)	Measured Visibility	Predicted Visibility
0.0	0.08	0.00
22.5	0.56	0.71
45.0	0.84	1.00
67.5	0.58	0.71
90.0	0.11	0.00





Testing entanglement – Nonlocality I

- Entanglement gives rise to 'spooky action at a distance'. There could be a hidden variable involved.
- Bell inequalities – experimental tests for local realistic theories.



- We prepared the state

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B)$$

and for the angles

$$a = -45°,\ a' = 0°,$$
$$b = -22.5°,\ b' = 22.5°$$

we obtained

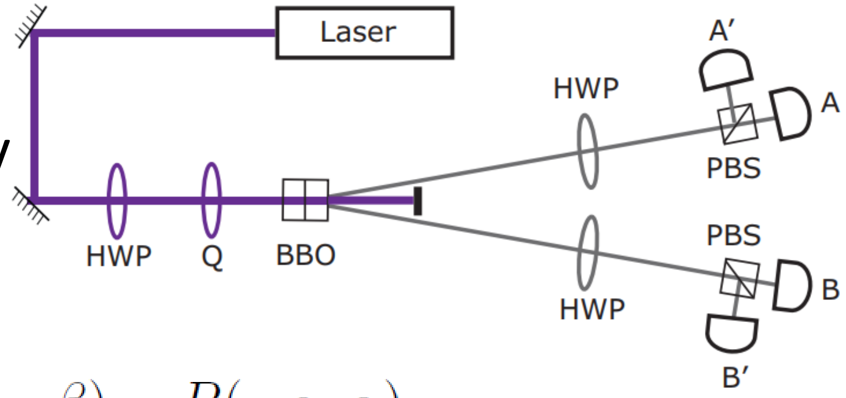
$$S = 2.331 \pm 0.004$$

- CHSH test of local realism[7]

$$|S| \leq 2$$
$$S = E(a,b) - E(a,b') + E(a',b) + E(a',b')$$
$$E(\alpha,\beta) = P_{HH} + P_{VV} - P_{HV} - P_{VH}$$

Testing entanglement – Nonlocality II

- Hardy's test of local realism
- Another test – another inequality



$$H \leq 0$$

$$H = P(\beta, -\beta) - P(\beta, \alpha^{\perp}) - P(-\alpha^{\perp}, -\beta) - P(-\alpha, \alpha)$$

- We created the state

$$|\psi\rangle = \sqrt{0.8}\,|H\rangle_A\,|H\rangle_B + \sqrt{0.2}\,|V\rangle_A\,|V\rangle_B$$

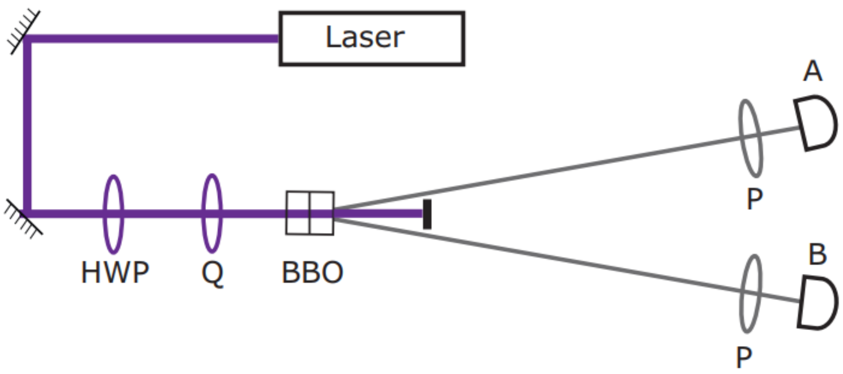
and obtained

$H = 0.107 \pm 0.002$ which violates local realism.

Testing entanglement – Nonlocality III

- Freedman's test of local realism
- Yet another inequality!

$$\delta = \left| \frac{N(22.5^\circ) - (67.5^\circ)}{N_0} \right| - \frac{1}{4} \leq 0$$



- We created the state

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B)$$

and obtained

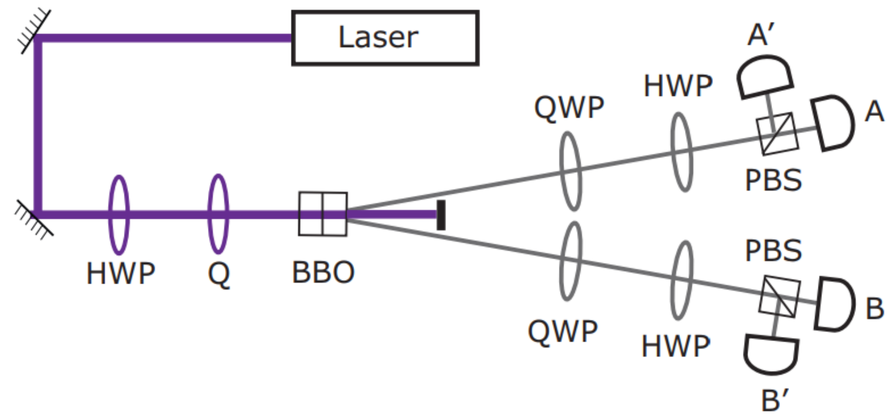
$\delta = 0.095 \pm 0.003$ which violates local realism.

How do we check if the state is perfectly entangled?

Gauging entanglement? Tomography!

- A set of measurements with different bases to determine the two-qubit density matrix[9]:

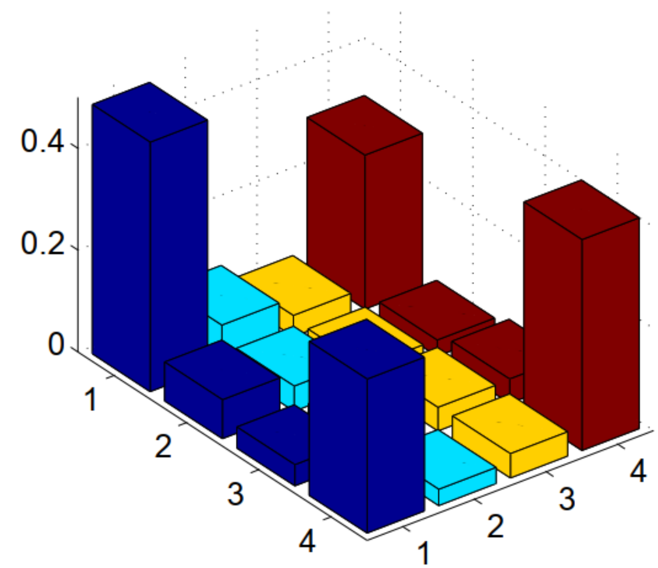
$$\hat{\rho} = \frac{1}{4} \sum_{i,j=0}^{3} S_{ij} \hat{\sigma}_i \otimes \hat{\sigma}_j$$



- For the Bell state

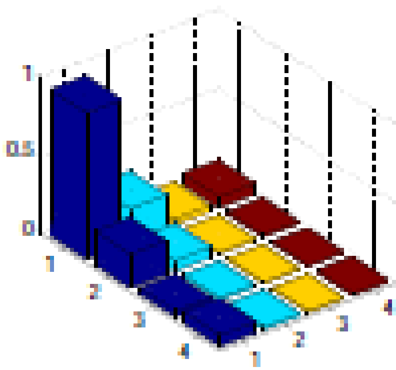
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B)$$

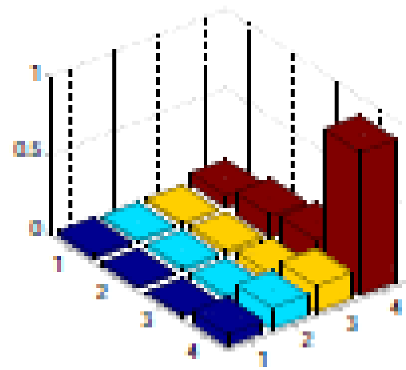
we obtained the density matrix with fidelity 0.75 using maximum likelihood estimation[9].

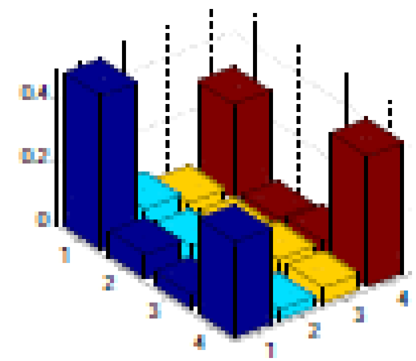


State	Predicted density matrix	Measured density matrix
$\|H\rangle$	$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0.97 & -0.04 - 0.31i \\ -0.04 + 0.31i & 0.03 \end{pmatrix}$
$\|V\rangle$	$\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0.07 & 0.10 + 0.22i \\ 0.10 - 0.22i & 0.93 \end{pmatrix}$
$\|D\rangle$	$\begin{pmatrix} 0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix}$	$\begin{pmatrix} 0.55 & 0.32 - 0.17i \\ 0.32 + 0.17i & 0.45 \end{pmatrix}$
$\|A\rangle$	$\begin{pmatrix} 0.5 & -0.5 \\ -0.5 & 0.5 \end{pmatrix}$	$\begin{pmatrix} 0.49 & -0.45 - 0.04i \\ -0.45 + 0.04i & 0.51 \end{pmatrix}$
$\|L\rangle$	$\begin{pmatrix} 0.5 & 0.5i \\ -0.5i & 0.5 \end{pmatrix}$	$\begin{pmatrix} 0.44 & 0.01 + 0.43i \\ 0.01 - 0.43i & 0.56 \end{pmatrix}$
$\|R\rangle$	$\begin{pmatrix} 0.5 & -0.5i \\ 0.5i & 0.5 \end{pmatrix}$	$\begin{pmatrix} 0.53 & 0.04 - 0.47i \\ 0.04 + 0.47i & 0.47 \end{pmatrix}$

Table 6.1: Results of single qubit tomography.







State	Predicted density matrix	Measured density matrix	Fidelity
$\|HH\rangle$	$\begin{pmatrix}1&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{pmatrix}$	$\begin{pmatrix}0.93&-0.11&0.03&-0.03\\-0.11&0.06&0.00&0.01\\0.03&0.00&0.00&0.00\\-0.03&0.01&0.00&0.01\end{pmatrix}$	0.93
$\|VV\rangle$	$\begin{pmatrix}0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&1\end{pmatrix}$	$\begin{pmatrix}0.02&-0.01&-0.01&0.07\\-0.01&0.02&0.01&-0.10\\-0.01&0.01&0.05&0.05\\0.07&-0.10&0.05&0.91\end{pmatrix}$	0.91
$\frac{\|HH\rangle+\|VV\rangle}{2}$	$\begin{pmatrix}0.5&0&0&0.5\\0&0&0&0\\0&0&0&0\\0.5&0&0&0.5\end{pmatrix}$	$\begin{pmatrix}0.49&0.05&0.01&0.30\\0.05&0.05&0.02&0.01\\0.01&0.02&0.05&-0.01\\0.30&0.01&-0.01&0.41\end{pmatrix}$	0.75

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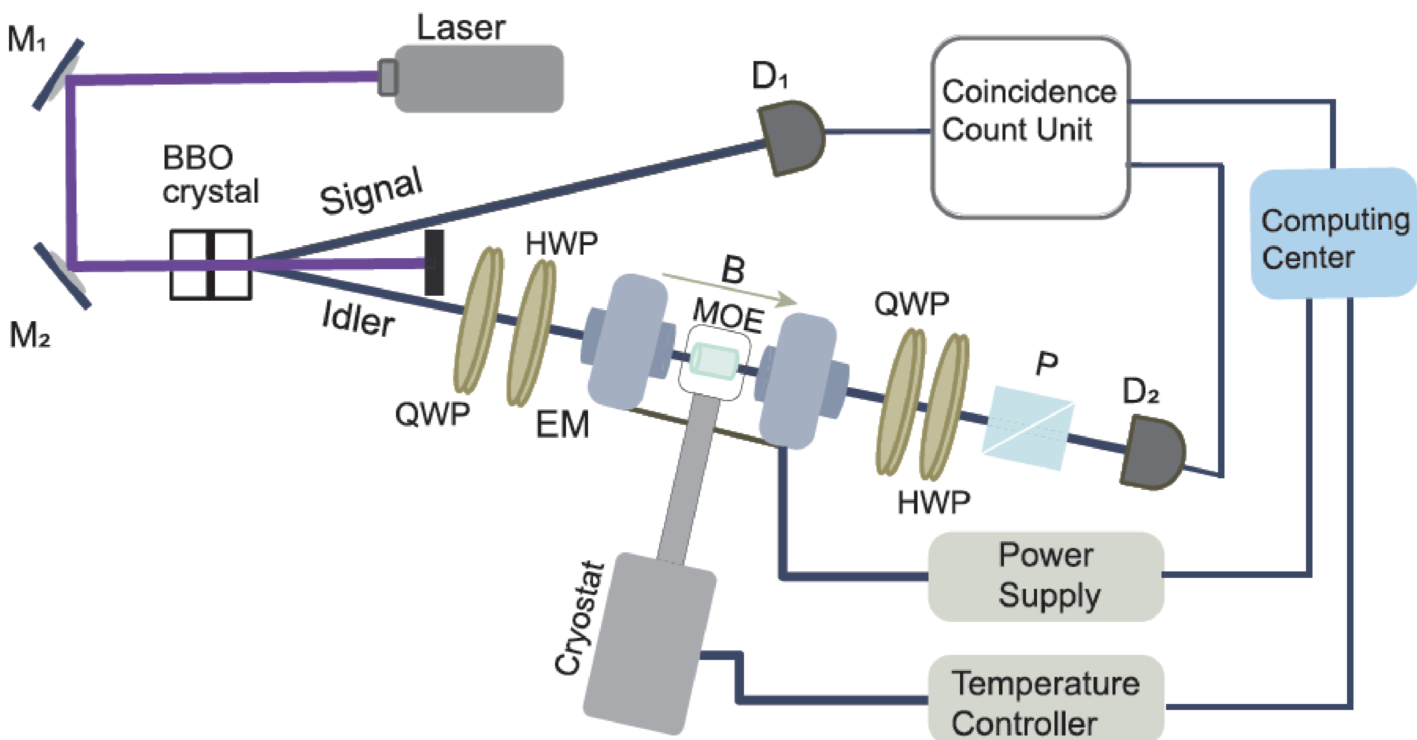
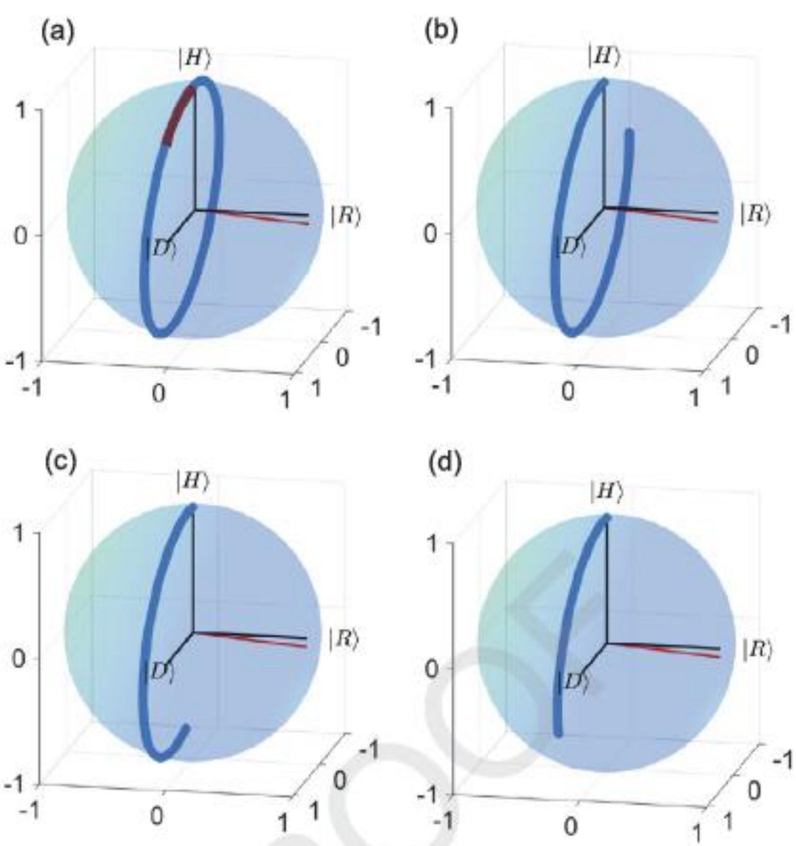
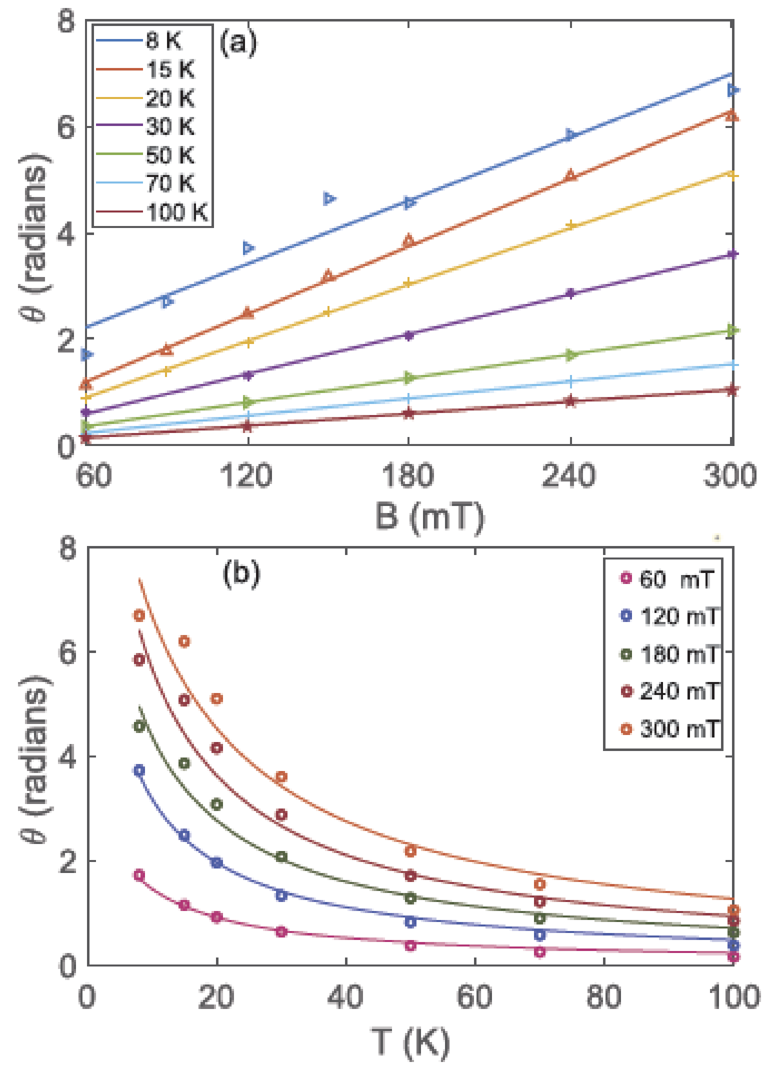
Quantum process tomography of a magneto-optic transformation

Ali Akbar, Faizan-e-Ilahi, Muhammad Sabieh Anwar *



$$
\chi^F = \begin{pmatrix} 0.71 & -0.024\,i & 0.45\,i & 0.051\,i \\ 0.024\,i & 0.00 & -0.015 & 0.00 \\ -0.45\,i & -0.015 & 0.29 & 0.032 \\ -0.051\,i & 0.00 & 0.032 & 0.00 \end{pmatrix}
$$





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