Quantum Cryptography and Quantum Entanglement for Engineering Applications

Quantum Robotics and Autonomy

ETM 4990 Mechatronics

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Quantum Engineering

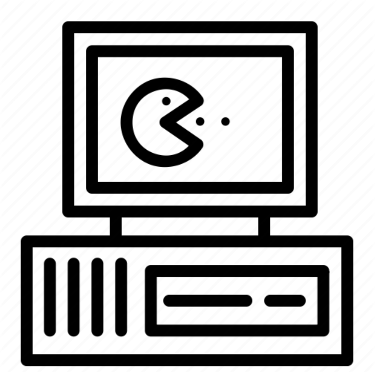
- Experimental Quantum Entanglement
- Experimental Quantum Cryptography
- Quantum technologies for robotics and autonomy applications

Mechanical Systems + Classical Computers

Mechanical Systems

+

Classical Computers/Technologies



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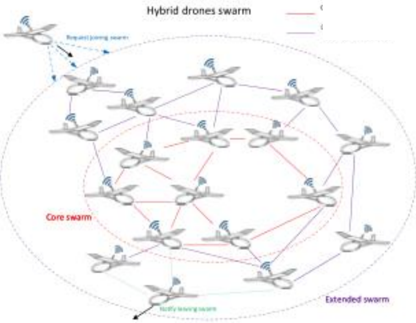
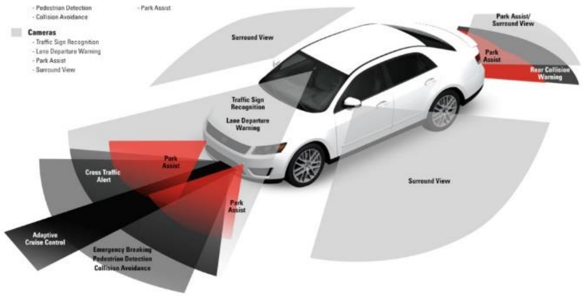
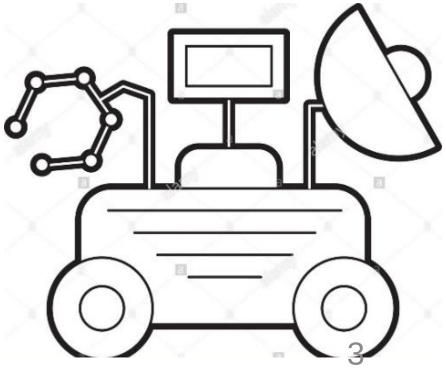
The State of the art



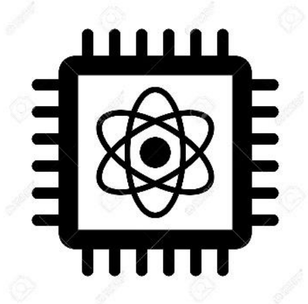




Mechanical Systems + Quantum Technologies

Mechanical Systems

\+



Quantum
Computers/Technologies

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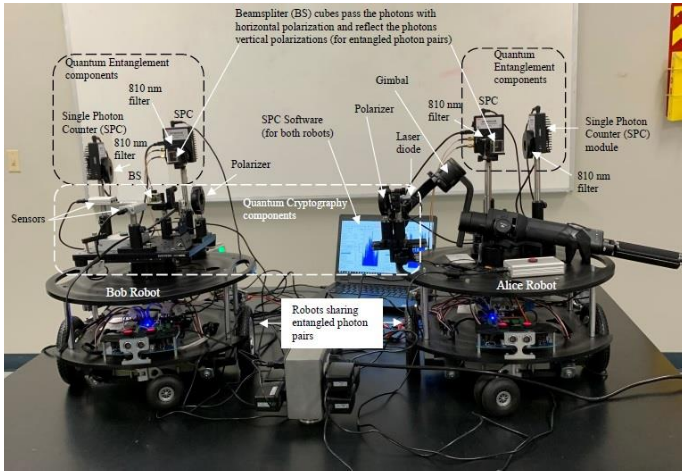
Quantum Robotics
and Autonomy
(e.g., The Alice and
Bob Robots)



Literature review (Mechanical Systems and/or Education + Quantum Technologies)

- Drone-to-Drone Quantum Key distribution (Kwiat, P., et al., 2017). The aim is to enhance quantum capability (not mechanical systems).

- Space and underwater Quantum Communications (various references). The aim is enhancing communication not mechanical systems.

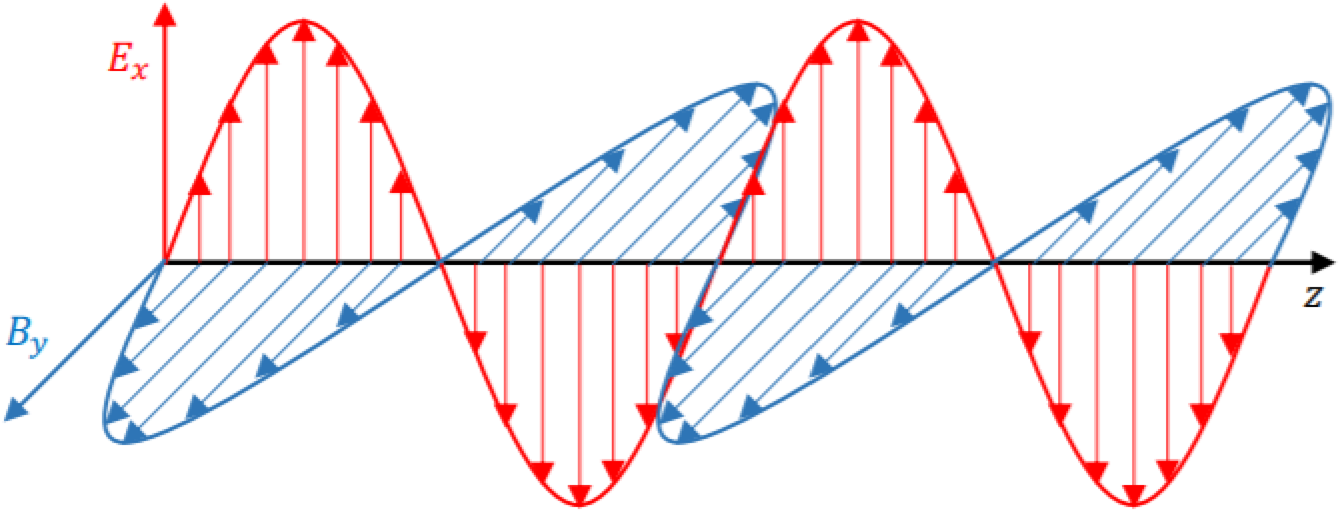
- Preparing for the quantum revolution -- what is the role of higher education? (https://arxiv.org/abs/2006.16444)

- Achieving a quantum smart workforce (https://arxiv.org/abs/2010.13778).

Introduction

- When quantum technologies/computers become available in a multi-agent robotic system: How the quantum computer is integrated to mechanical systems (e.g., robots, autonomous systems)
- Hybrid quantum-classical technologies for autonomous systems – quantum is good for solving some problems and classical for others

Photon Quantum Mechanics



Electromagnetic wave

↕ V: Vertical Polarization

↔ H: Horizontal Polarization

Polarization of light:

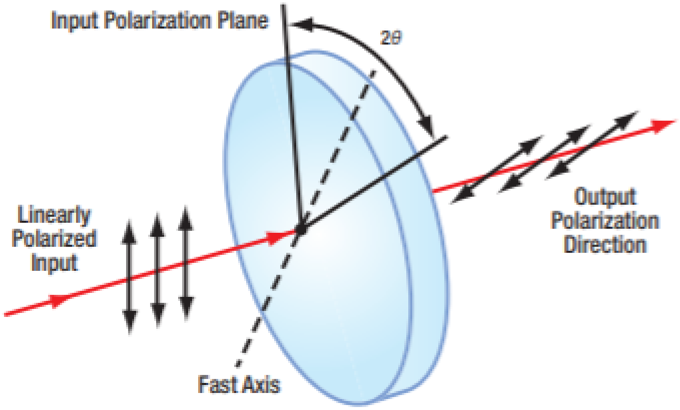
https://www.youtube.com/watch?v=6_C8KyU67RU

Quantum Entanglement Lab - by Scientific American:

https://www.youtube.com/watch?v=Z34ugMy1QaA&t=

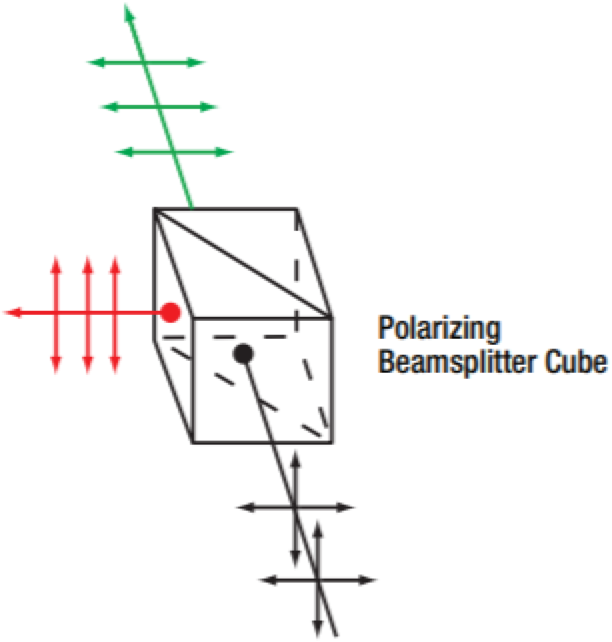
When we talk about the “0°” and “90°” settings from now on (later “-45°” and “45°”), this angle always refers to the *rotation angle of the polarization* and never the rotation angle of the $\lambda/2$ plate.

A sketch describing how the $\lambda/2$ plate operates is shown in the diagram to the right. Light incident on the wave plate is altered such that polarization components not aligned with the fast axis of the birefringent crystal are retarded. For linearly polarized light, the result is that the polarization is rotated by a value twice as large as the rotation of the $\lambda/2$ plate.



The receiving unit “Bob” consists of a polarizing beamsplitter cube and two detectors. The polarizing beamsplitter cube reflects the vertically-polarized (90°) component of the incident light, while passing the horizontally-polarized (0°) component, as seen in the diagram to the right.

If the polarization state of the light sent by Alice is set to 0°, the photon will pass through the beamsplitter (designated as event “0”). If the wave plate is set to rotate the polarization by 90°, the photon will be reflected by the beamsplitter (designated as event “1”).



Ref: Thorlabs: https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf

Parametric Down Conversion Process
Barium borate (BBO) Crystal

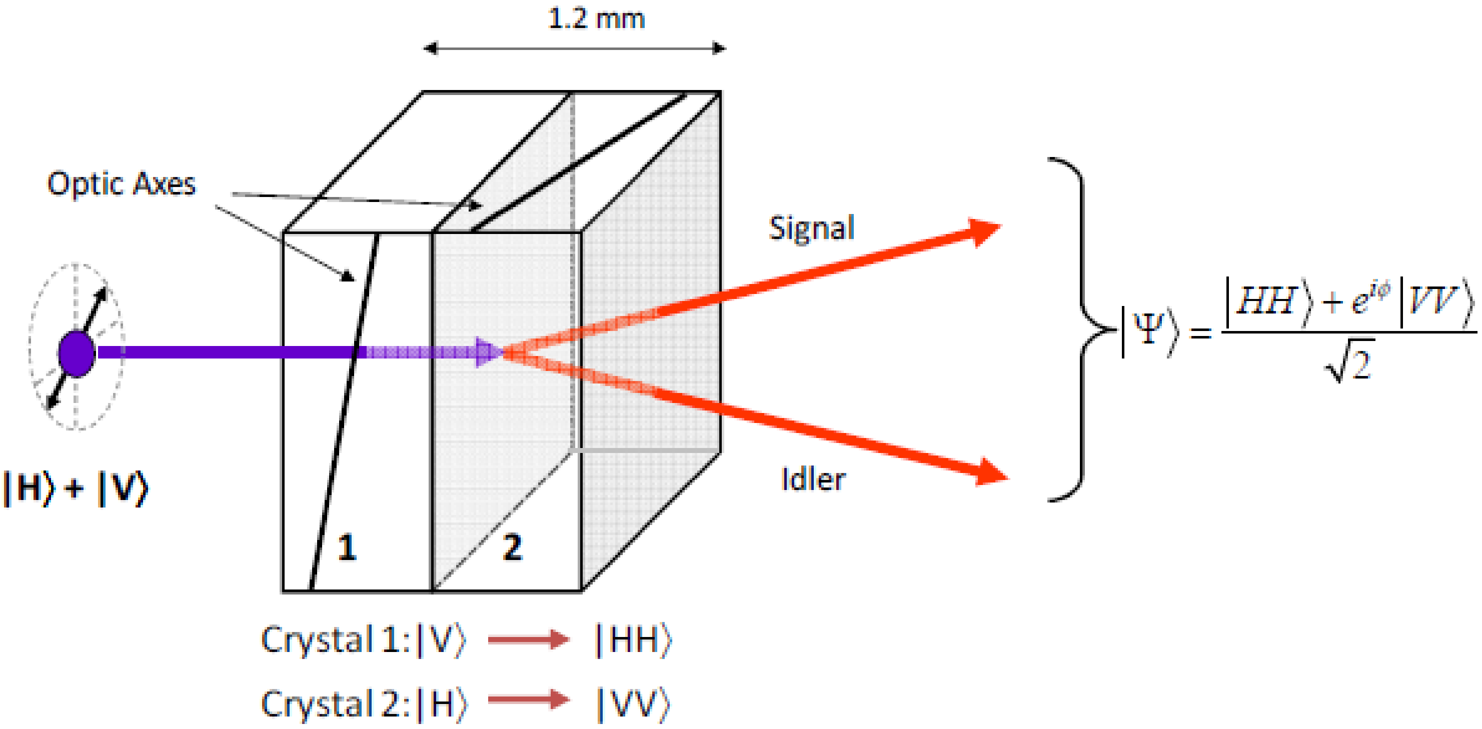
- Parametric Down Conversion Visualization

https://www.youtube.com/watch?v=5Iv6dJD4q4A

- One Photon In, TWO Photons Out

https://www.youtube.com/watch?v=1MaOqvnkBxk

BBO Crystal



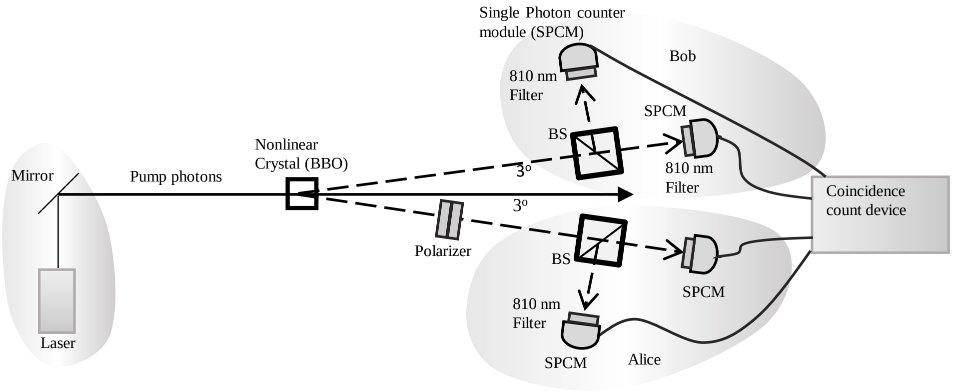
$$|\Psi\rangle = \frac{|HH\rangle + e^{i\phi}|VV\rangle}{\sqrt{2}}$$

↕ V: Vertical Polarization

↔ H: Horizontal Polarization

R. Rangarajan, M. Goggin, and P. Kwiat, "Optimizing type-I polarization-entangled photons," Opt. Express 17, 18920-18933 (2009).

Schematic of the Quantum Entanglement Experimental Setup

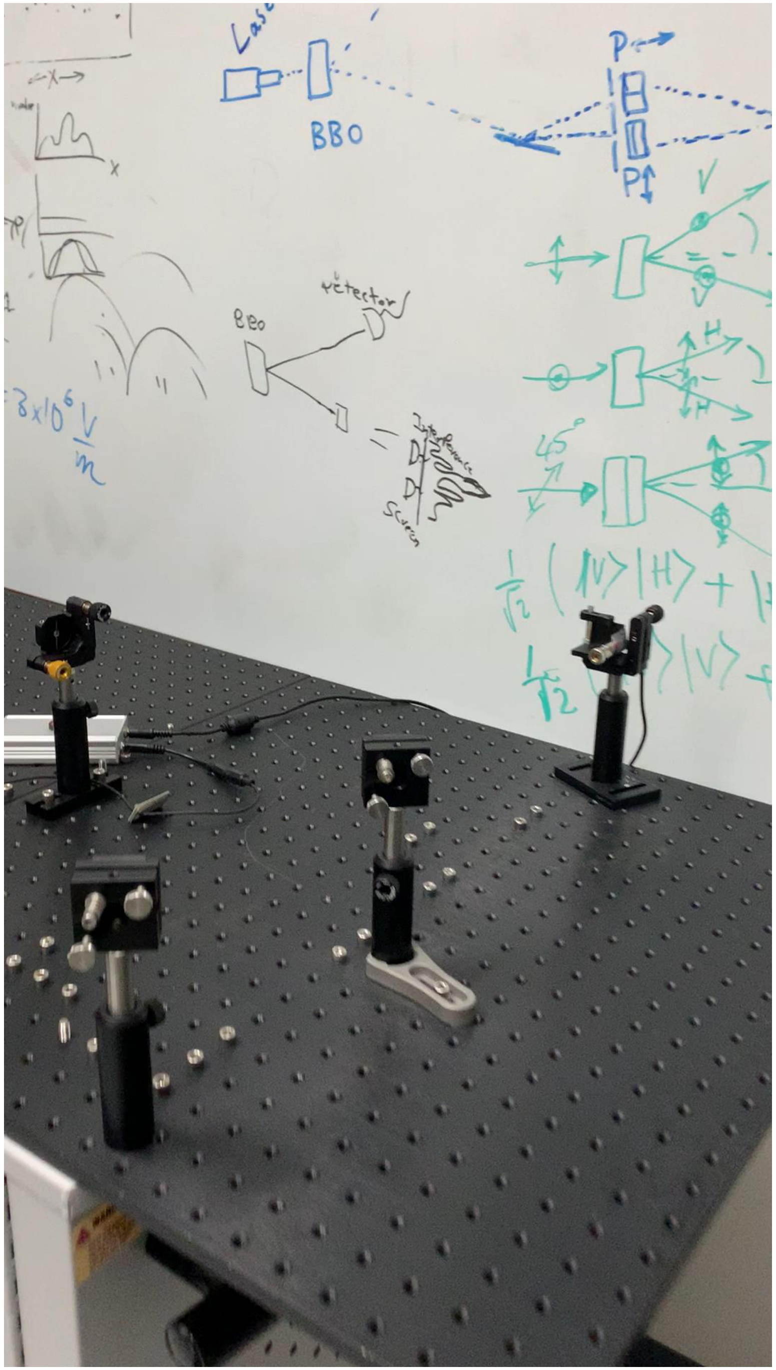


Information about the set up is available in Section 2.1 in "Quantum Teleportation for Control of Dynamic Systems and Autonomy": https://arxiv.org/ftp/arxiv/papers/2007/2007.15249.pdf

References on "Quantum Robotics and Autonomy": https://arxiv.org/search/?query=khoshnoud&searchtype=all&source=header

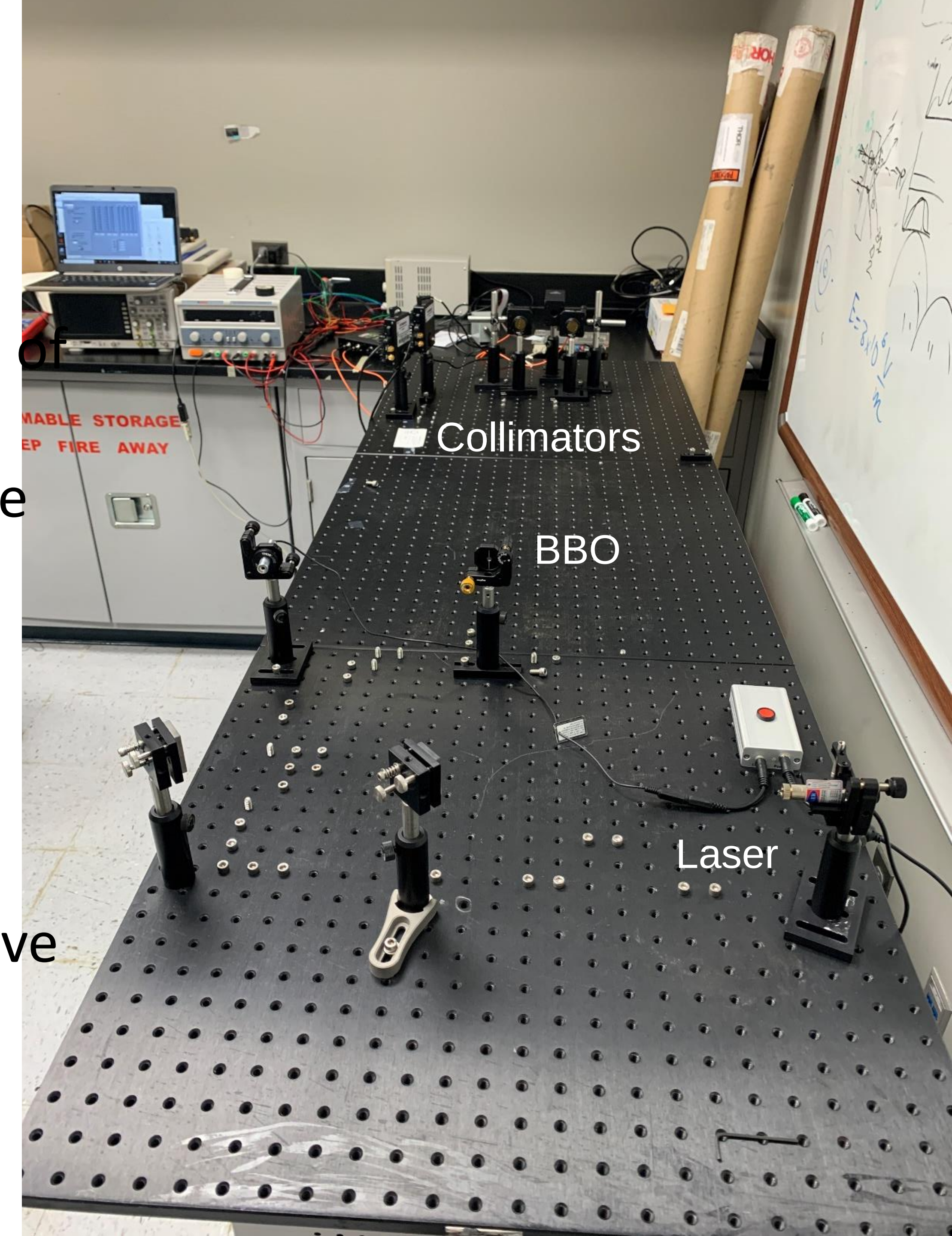
Note: Only two detectors (two channels of the SPCM) are used in the experiment shows in the next slides, and the polarizer is not used in this initial test.

An overview of the Quantum Entanglement Experimental Setup

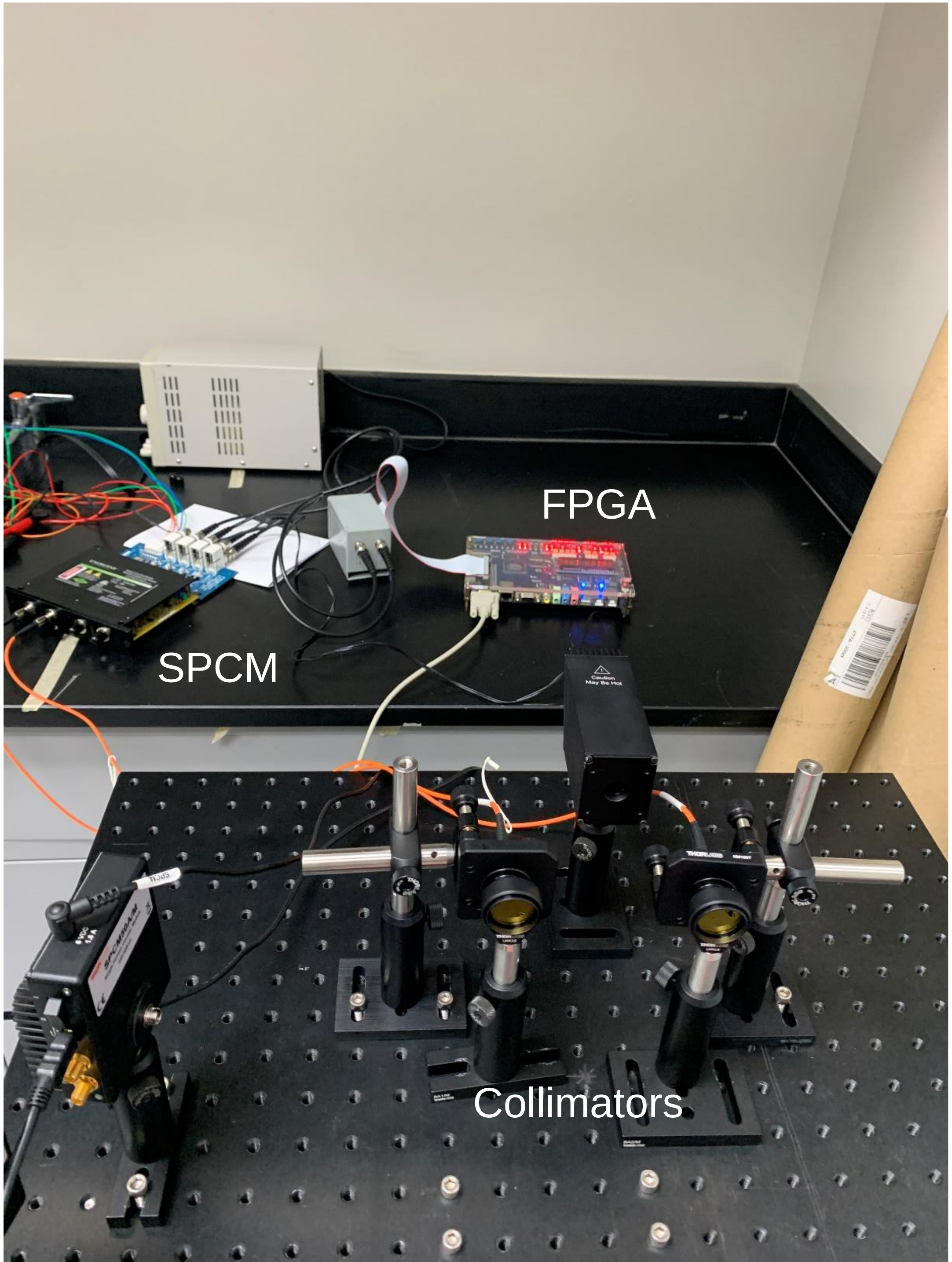


The setup:

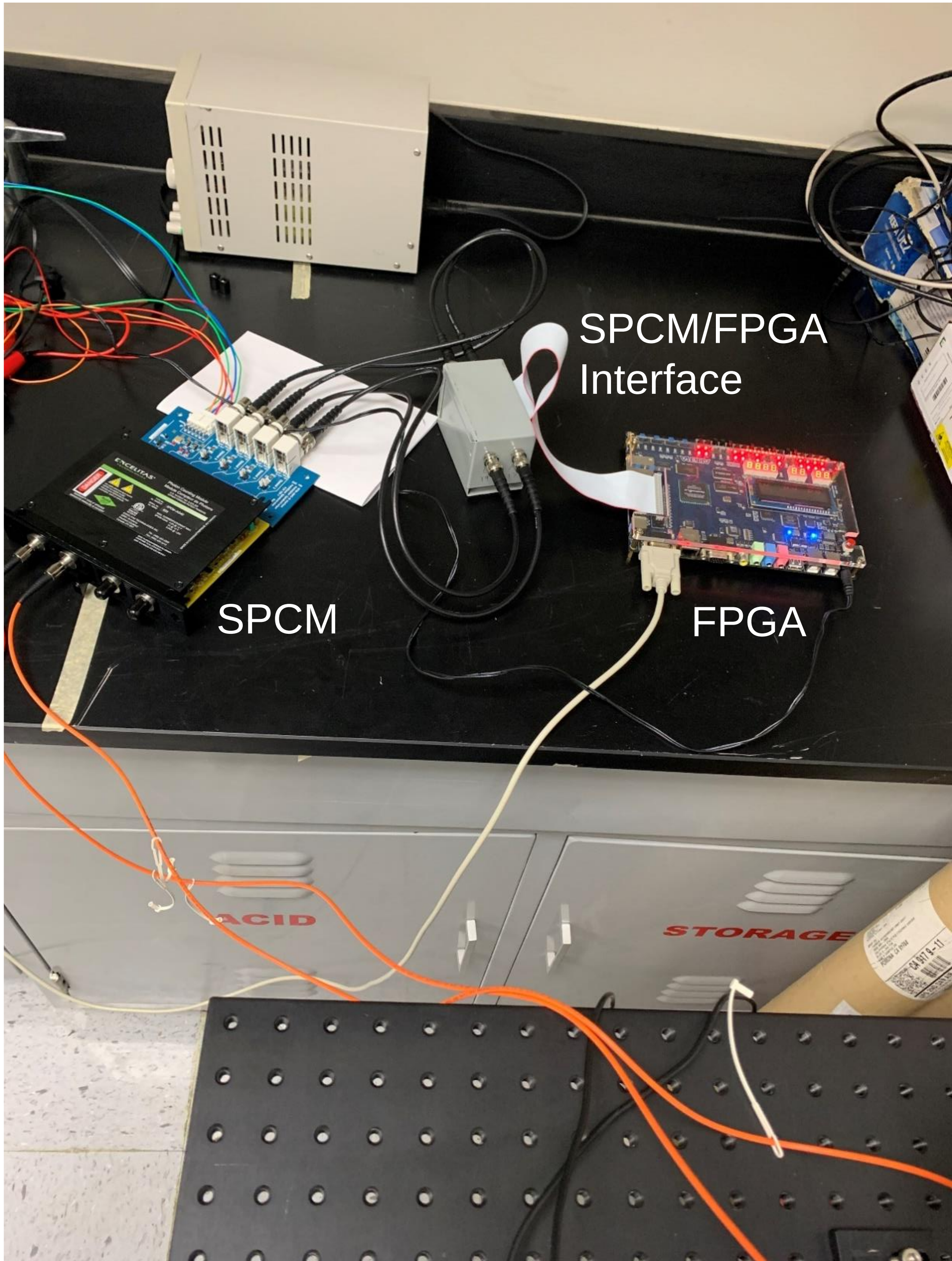
- 405 nm 100 mW Laser
- A BBO crystal
- Two 810 nm filters in front of two Collimators
- Fiber optic cables (from the collimators to the SPCM)
- A Single Photon Counter Module (SPCM-AQ4C)
- FPGA (used as a photon coincidence counter)
- LabView program (to receive and show the data)

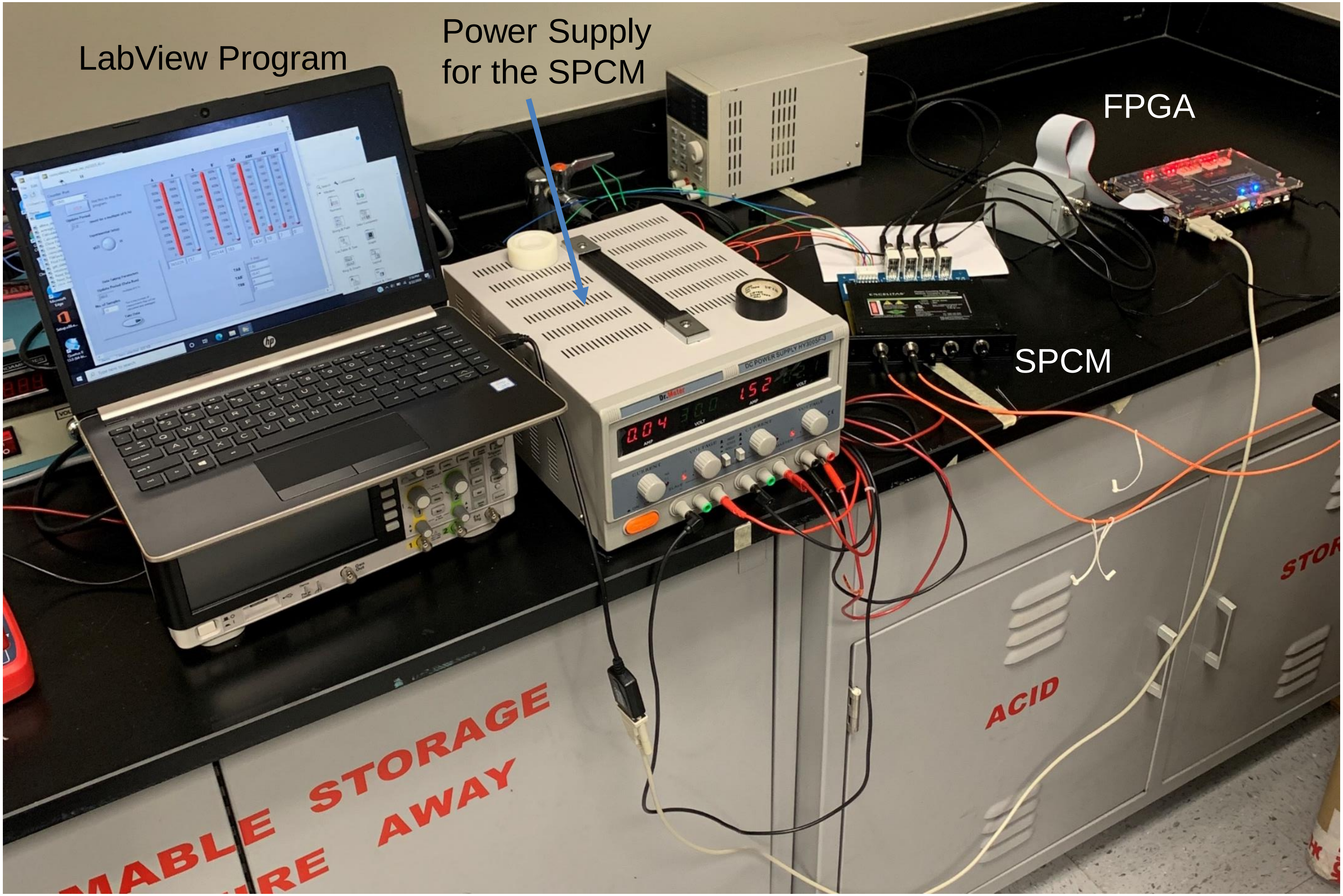


The setup:
Two 810 nm filters in front of two Collimators , Fiber optic cables (from the collimators to the SPCM), a Single Photon Counter Module (SPCM-AQ4C), FPGA (used as a photon coincidence counter), LabView program (to receive and show the data)



The setup:
A Single Photon Counter Module (SPCM-AQ4C), FPGA (used as a photon coincidence counter)



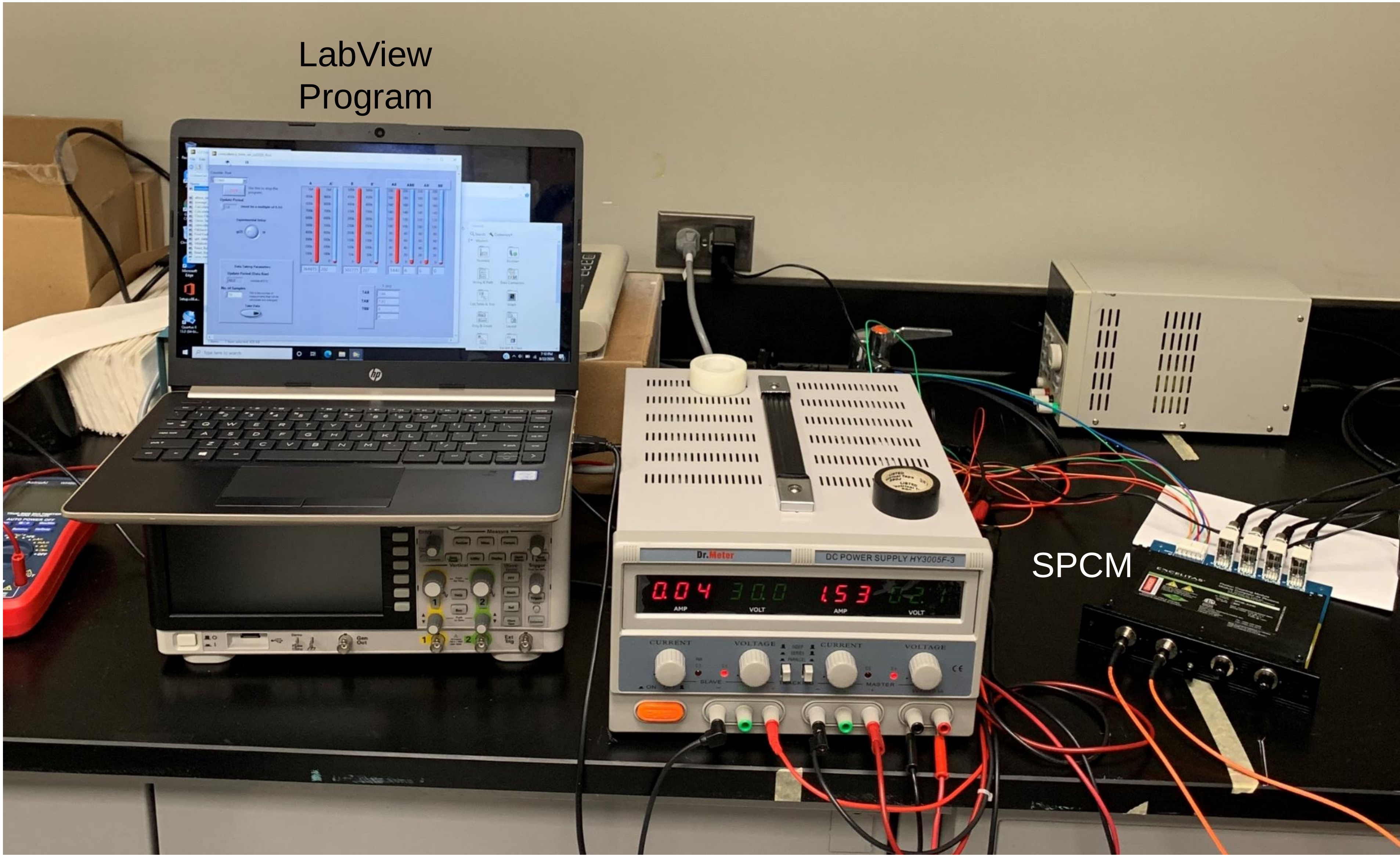


LabView Program

Power Supply for the SPCM

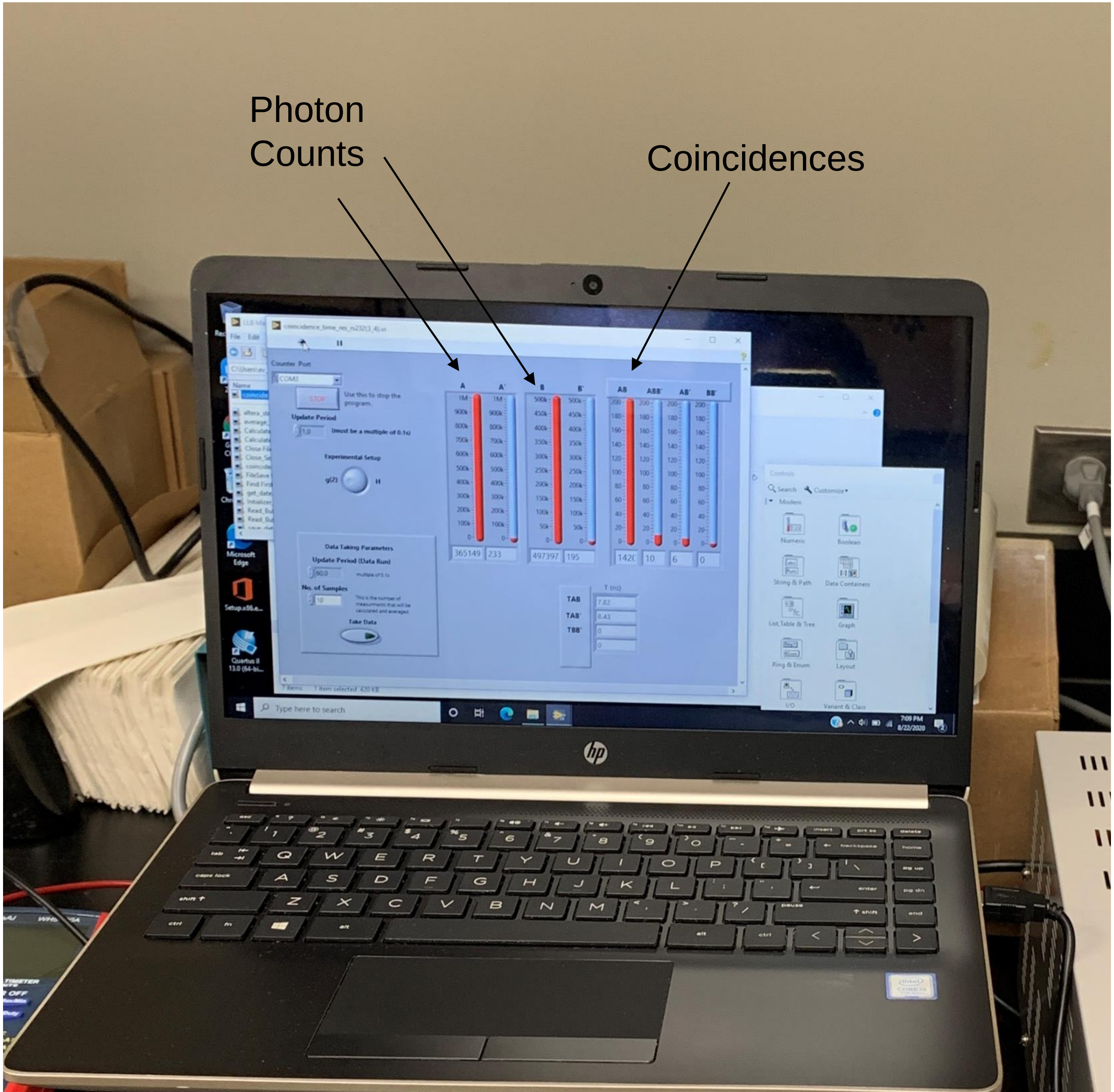
FPGA

SPCM



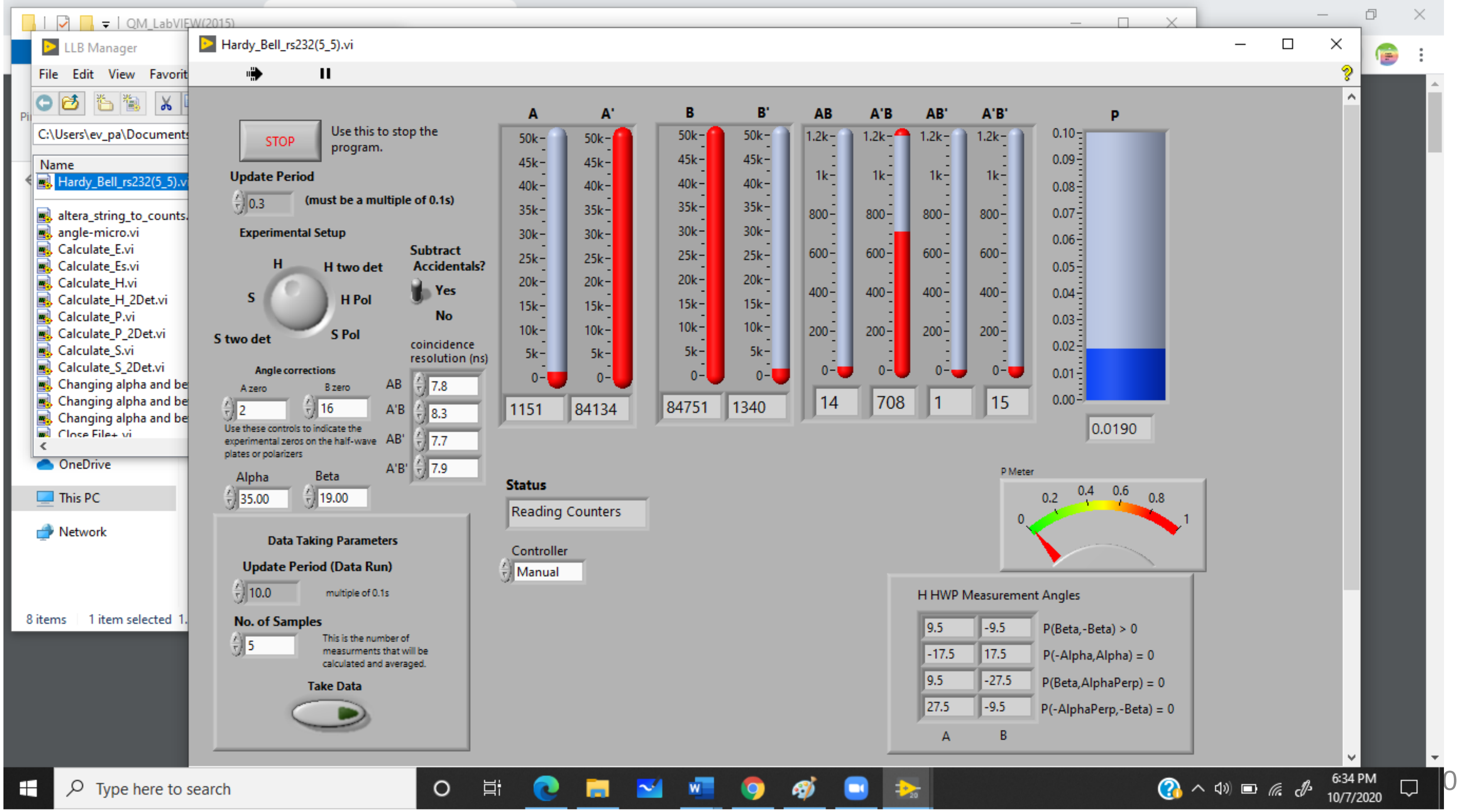
LabView Program

SPCM


Photon Counts
Coincidences

Experimental results

The single counts for two (SPCM) detectors (A’ and B) show 84751 (for A’), and 84751 (for B) and coincidence counts of 708 for A’B coincidences (in Figure below):



Use this to stop the program.

Update Period: 0.3 (must be a multiple of 0.1s)

Experimental Setup: H, H two det, H Pol, S Pol, S two det, S

Subtract Accidentals? Yes / No

coincidence resolution (ns)

AB 7.8
A'B 8.3
AB' 7.7
A'B' 7.9

Angle corrections

A zero 2
B zero 16

Use these controls to indicate the experimental zeros on the half-wave plates or polarizers

Alpha 35.00
Beta 19.00

Data Taking Parameters

Update Period (Data Run) 10.0 multiple of 0.1s

No. of Samples 5

This is the number of measurments that will be calculated and averaged.

A	A'	B	B'	AB	A'B	AB'	A'B'	P
1151	84134	84751	1340	14	708	1	15	0.0190

Status: Reading Counters

Controller: Manual

H HWP Measurement Angles

A	B	
9.5	-9.5	P(Beta,-Beta) > 0
-17.5	17.5	P(-Alpha,Alpha) = 0
9.5	-27.5	P(Beta,AlphaPerp) = 0
27.5	-9.5	P(-AlphaPerp,-Beta) = 0

Quantum Cryptography (demonstration kit)

Ref: Thorlabs:

https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf

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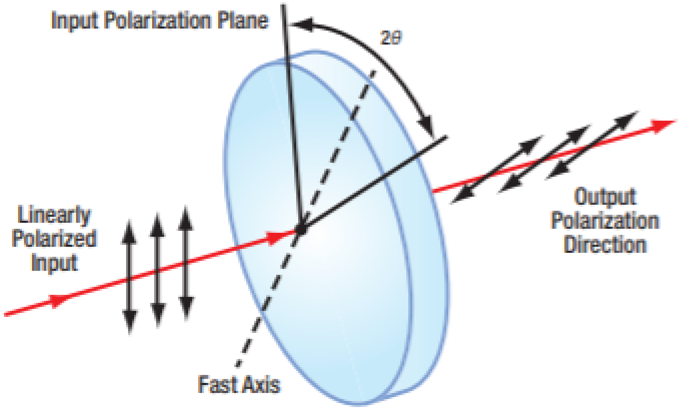

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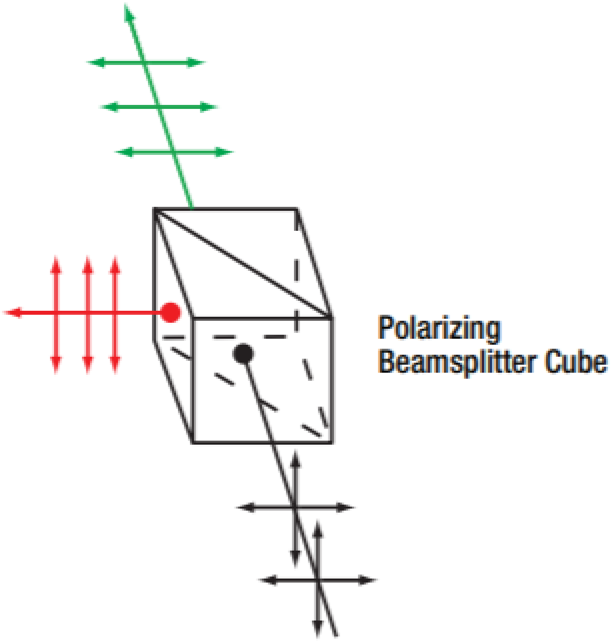

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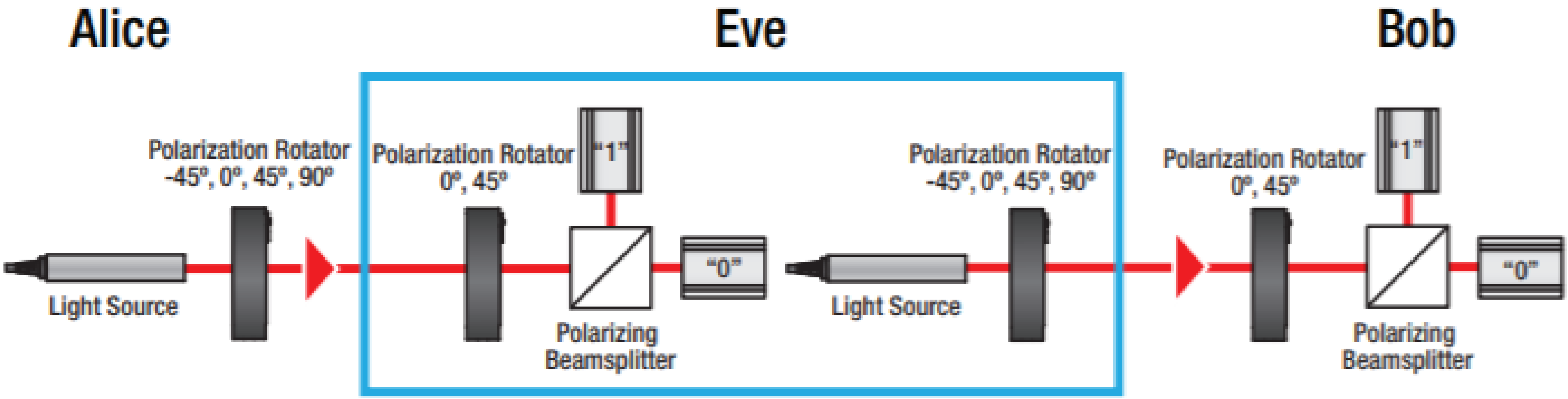
Quantum Cryptography



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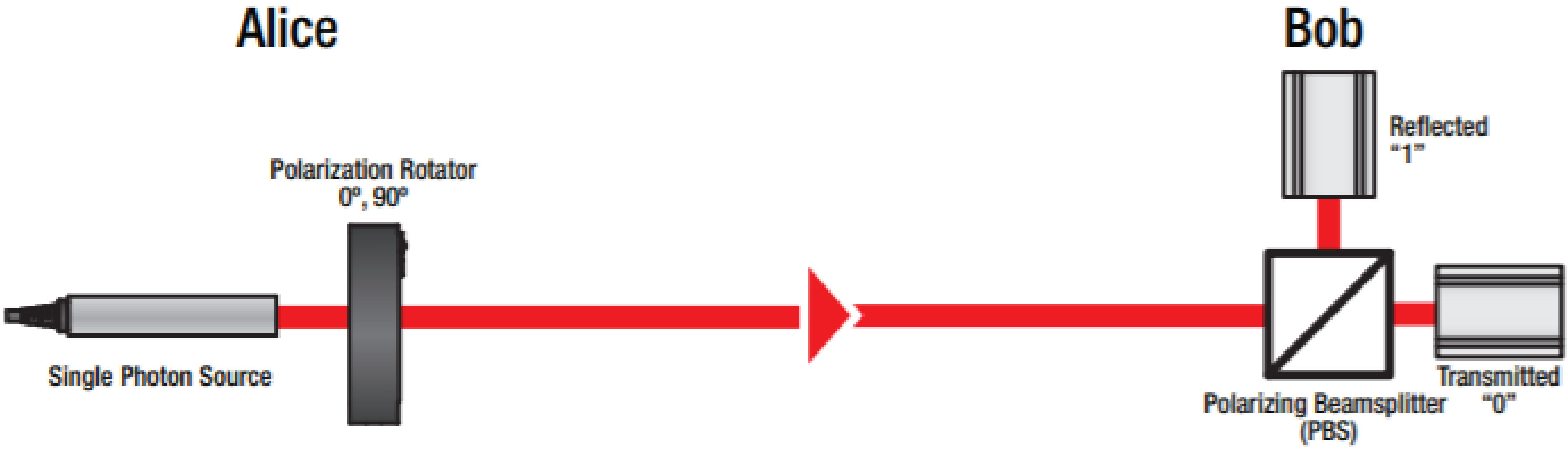

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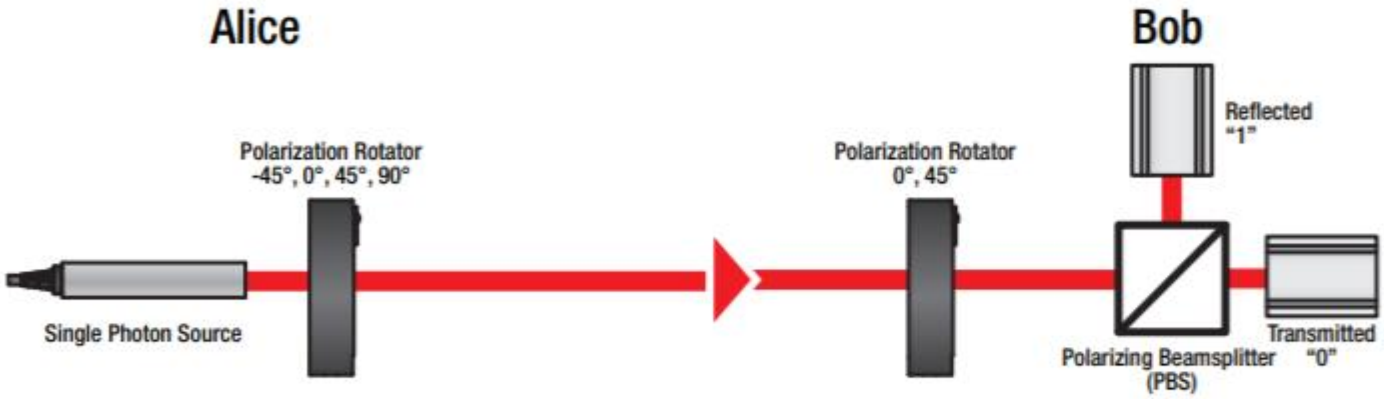


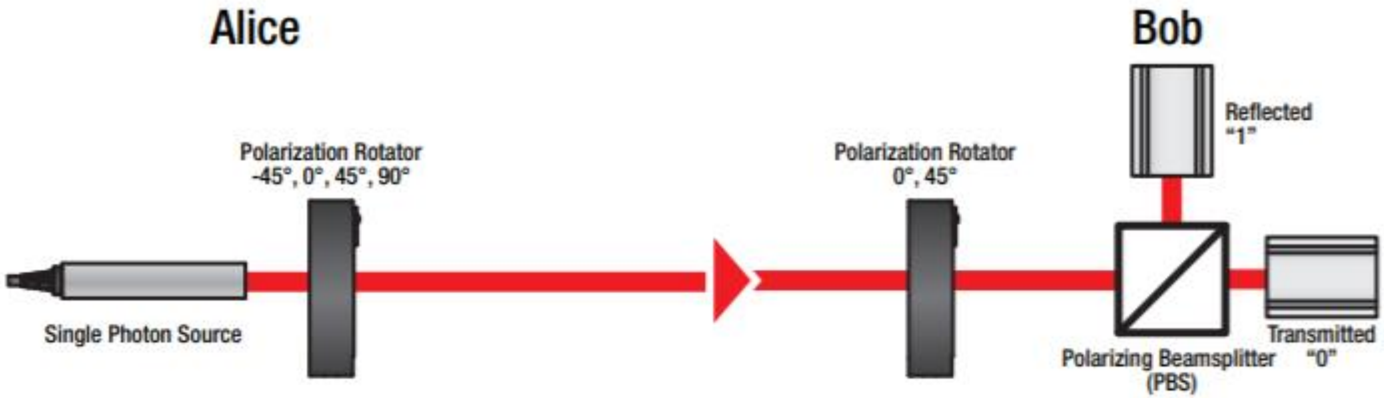
Figure 3 Quantum Cryptography Setup with the Bases + (0° and 90°) and x (-45° and 45°)

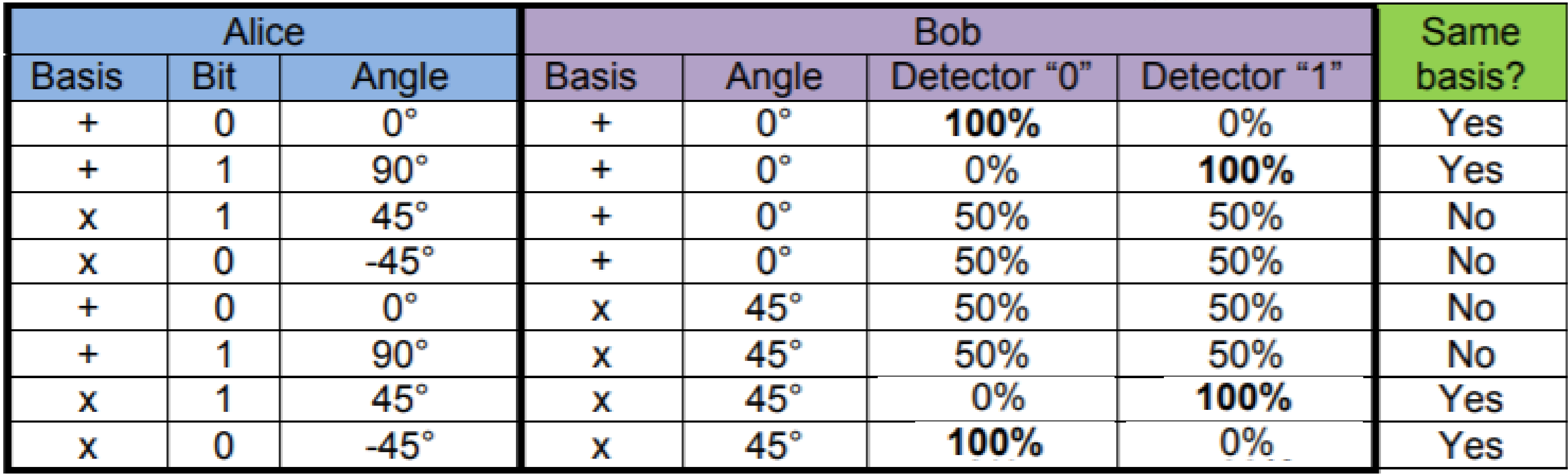
Now Alice has to make two *random* decisions for key generation:

- Alice has to select her basis at random, + or x
- Alice has to select a random bit, 0 or 1
  - Selecting 0 with the + basis means the setting 0°
  - Selecting 1 with the + basis means the setting 90°
  - Selecting 0 with the x basis means the setting -45°
  - Selecting 1 with the x basis means the setting 45°

Ref: Thorlabs: https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf

Quantum Cryptography

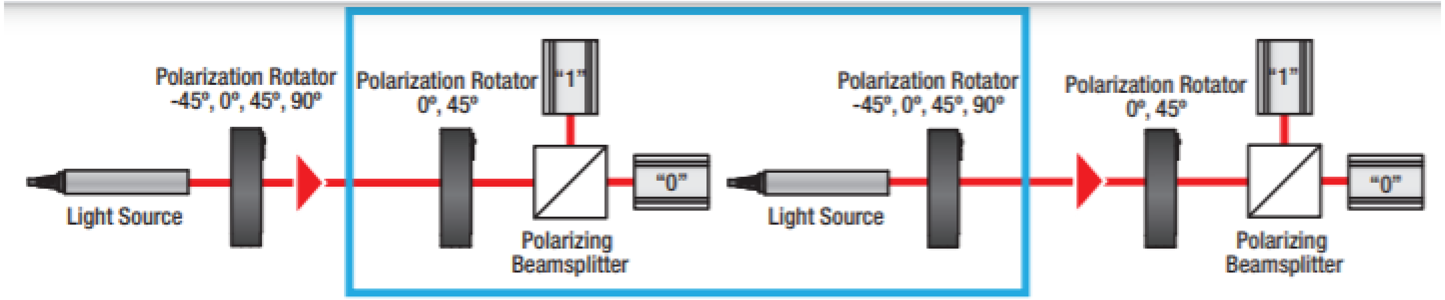


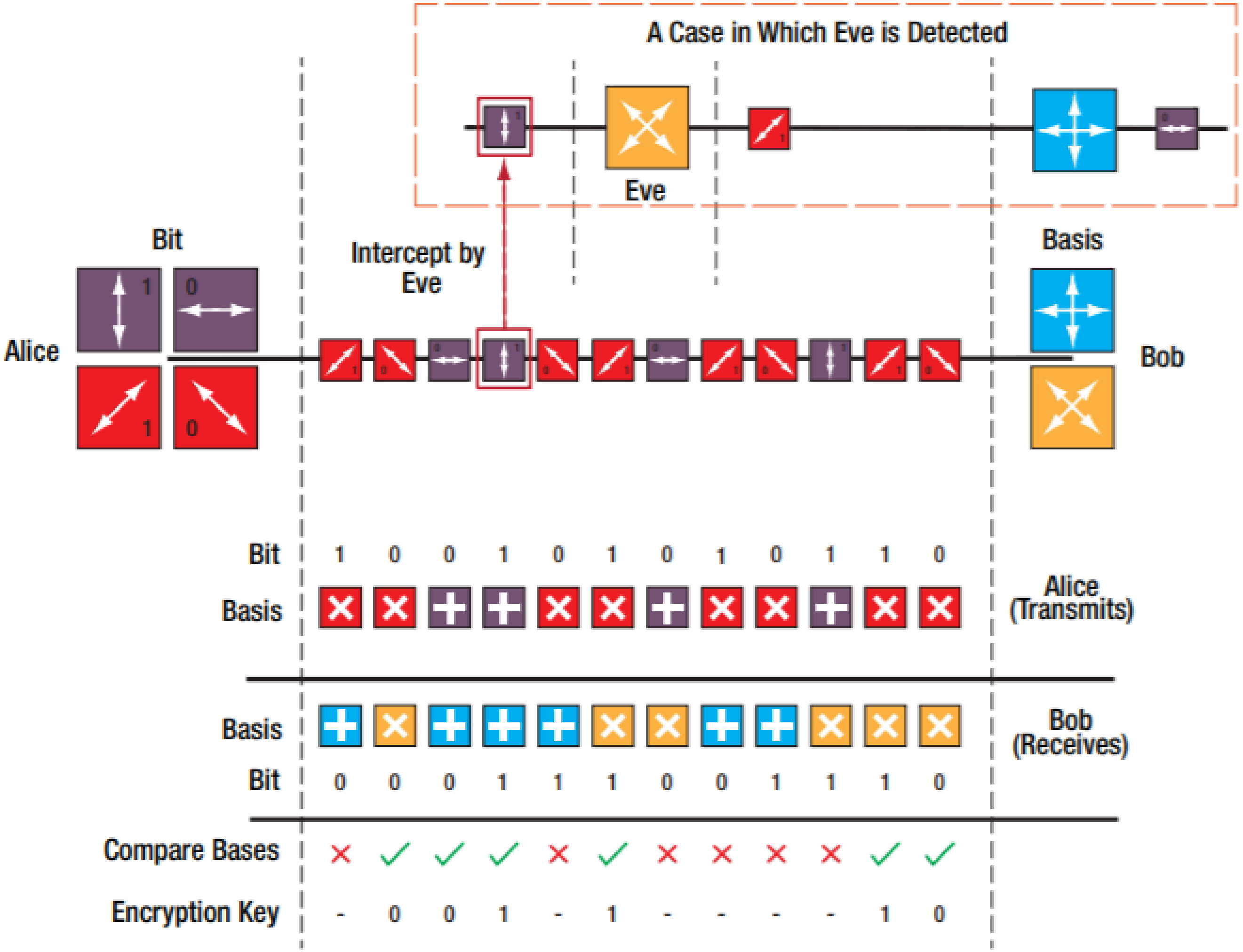


Alice			Bob				Same basis?
Basis	Bit	Angle	Basis	Angle	Detector "0"	Detector "1"	
+	0	0°	+	0°	**100%**	0%	Yes
+	1	90°	+	0°	0%	**100%**	Yes
x	1	45°	+	0°	50%	50%	No
x	0	-45°	+	0°	50%	50%	No
+	0	0°	x	45°	50%	50%	No
+	1	90°	x	45°	50%	50%	No
x	1	45°	x	45°	0%	**100%**	Yes
x	0	-45°	x	45°	**100%**	0%	Yes

Quantum cryptography, animated: https://www.youtube.com/watch?v=LaLzshIosDk

Ref: Thorlabs:
https://www.thorlabs.com/drawings/7dc1a0a51f66aa9b-610D055E-0A11-1562-E8F38E3EDDF533AA/EDU-QCRY1_M-EnglishManual.pdf





Bit	1	0	0	1	0	1	0	1	0	1	1	0	Alice (Transmits)
Basis	×	×	+	+	×	×	+	×	×	+	×	×	
Basis	+	×	+	+	+	×	×	+	+	×	×	×	Bob (Receives)
Bit	0	0	0	1	1	1	0	0	1	1	1	0	
Compare Bases	✗	✓	✓	✓	✗	✓	✗	✗	✗	✗	✓	✓	
Encryption Key	-	0	0	1	-	1	-	-	-	-	1	0	

Ref: Thorlabs:
[https://www.thorlabs.c EnglishManual.pdf](https://www.thorlabs.c)

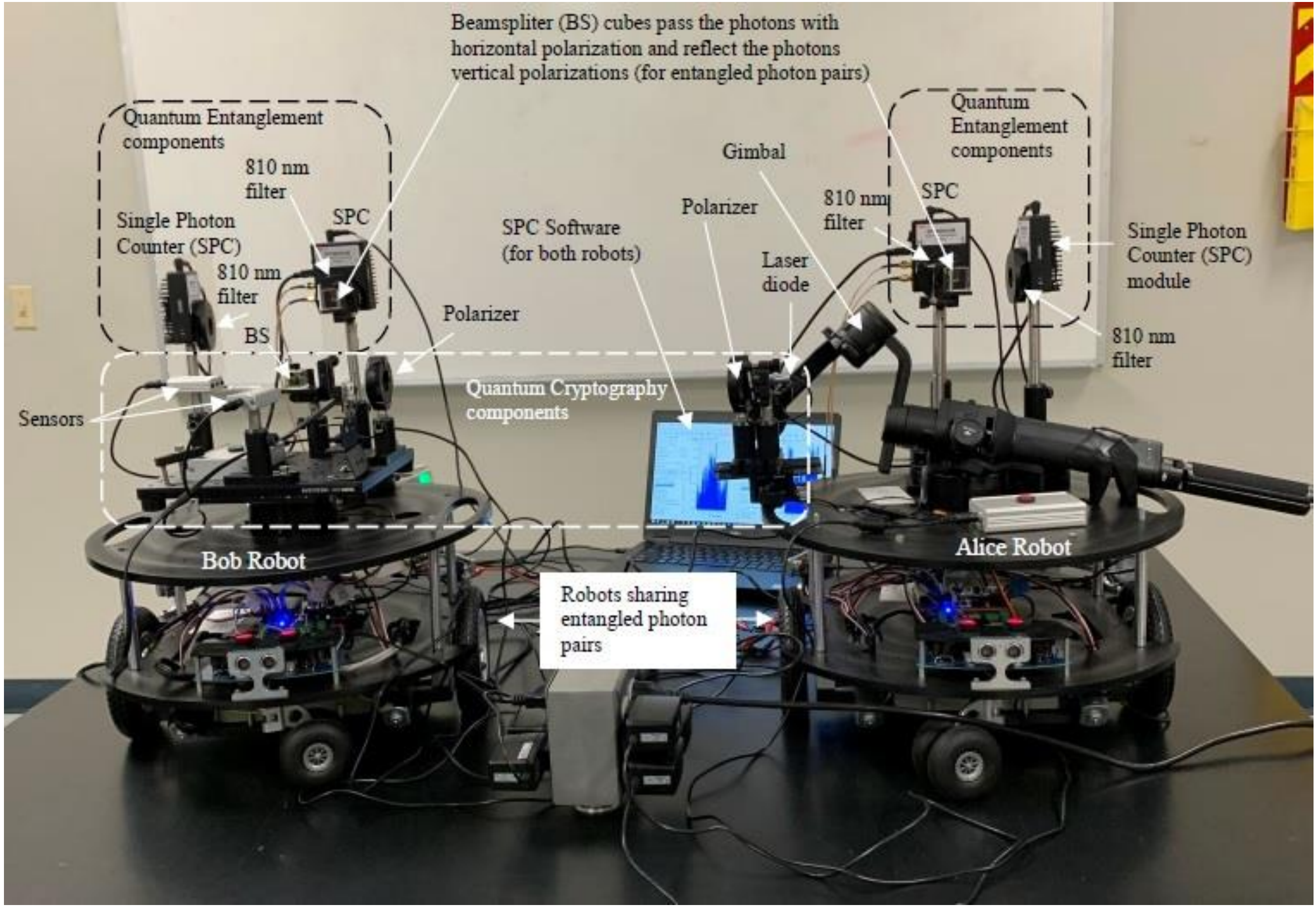
Quantum Robotics and Autonomy

Integrating Quantum Technologies with physical Engineering Systems (at macroscale)

Pushing the engineering boundaries beyond classical techniques

Quantum Multibody Dynamics Initiative: Pushing the engineering boundaries beyond existing techniques
https://www.youtube.com/watch?v=ForcnzWzG1M&t=

- Implementing Experimental **Quantum Entanglement** for Robots (robots to share entangled photons) to utilize and enable quantum entanglement, “**spooky action at a distance**”, for cooperative autonomy.
- Accessing guaranteed security for cooperative autonomy by **Quantum Cryptography**.
- **Quantum Teleportation** for communications in between multi-agent autonomous systems by teleporting quantum states.



Beamspliter (BS) cubes pass the photons with horizontal polarization and reflect the photons vertical polarizations (for entangled photon pairs)

Robots sharing entangled photon pairs

Ref.: Farbod Khoshnoud, I.I. Esat, C.W. De Silva, Marco B. Quadrelli (JPL), **Quantum Network of Cooperative Unmanned Autonomous Systems**, *[Unmanned Systems journal, Vol. 07, No. 02, pp. 137-145, 2019]()*.

F. Khoshnoud, I.I. Esat, S. Javaherian, B. Bahr, **Quantum Entanglement and Cryptography for Automation and Control of Dynamical Systems**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 4, pp. 109-127, 2019. [Preprint PDF].

F. Khoshnoud, I.I. Esat (Brunel), Marco B. Quadrelli (JPL), Dario Robinson (UPD Police), **Quantum Cooperative Robotics and Autonomy**, *Special issue of the Instrumentation Journal*, *Edited by C.W. de Silva*, Vol. 6, No. 3, pp. 93-111, 2019. VIDEO. [Preprint PDF]

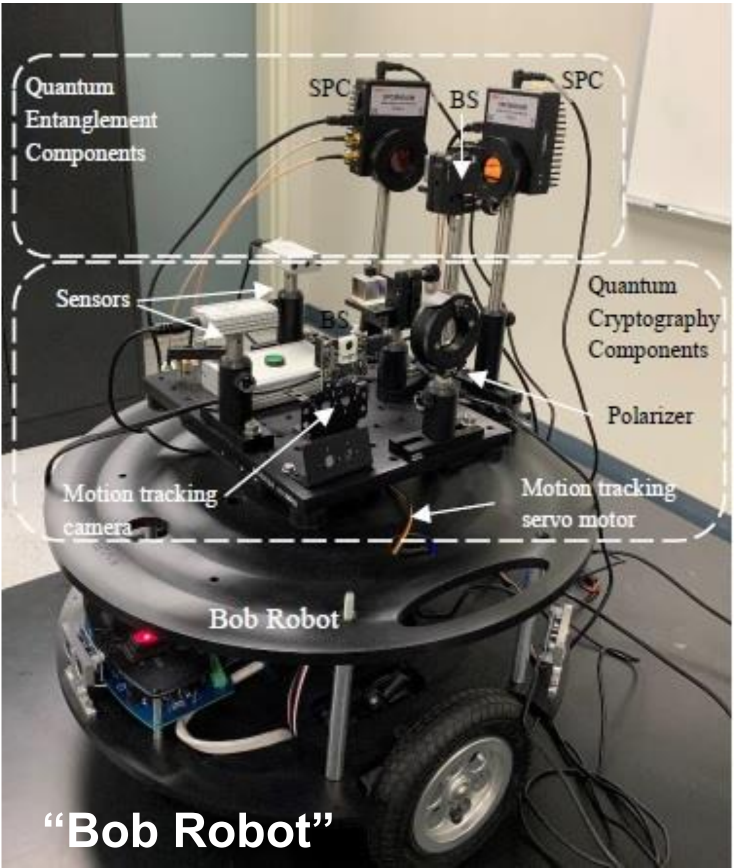
Integration of Quantum Technologies with Engineering Systems to Access Quantum Supremacy at Macroscale

Quantum Entanglement, Cryptography, and Teleportation For Control of Dynamical Systems and Autonomy

- Polarizations of the entangled photons will be converted to classical digital information for digital control and autonomy applications,
- or in case of accessing quantum computers in future, will be used directly by quantum computers* for autonomy

*in fact, using any classical transfer of information between robots equipped with quantum processors/computers (when quantum computers become available in future) can actually defeat the advantage of quantum computers.

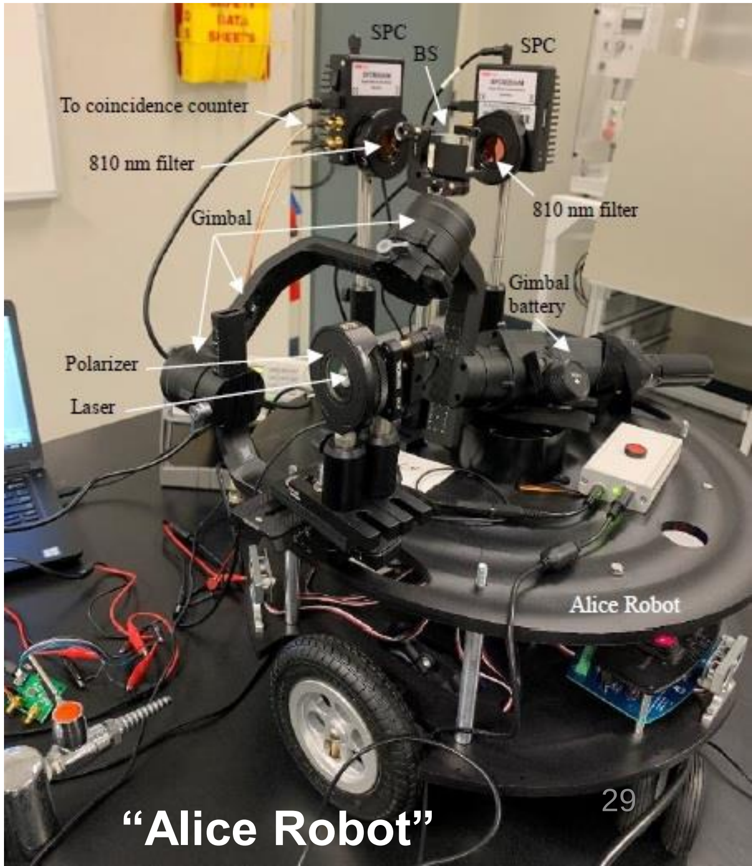
“Alice Drone”



“Bob Robot”

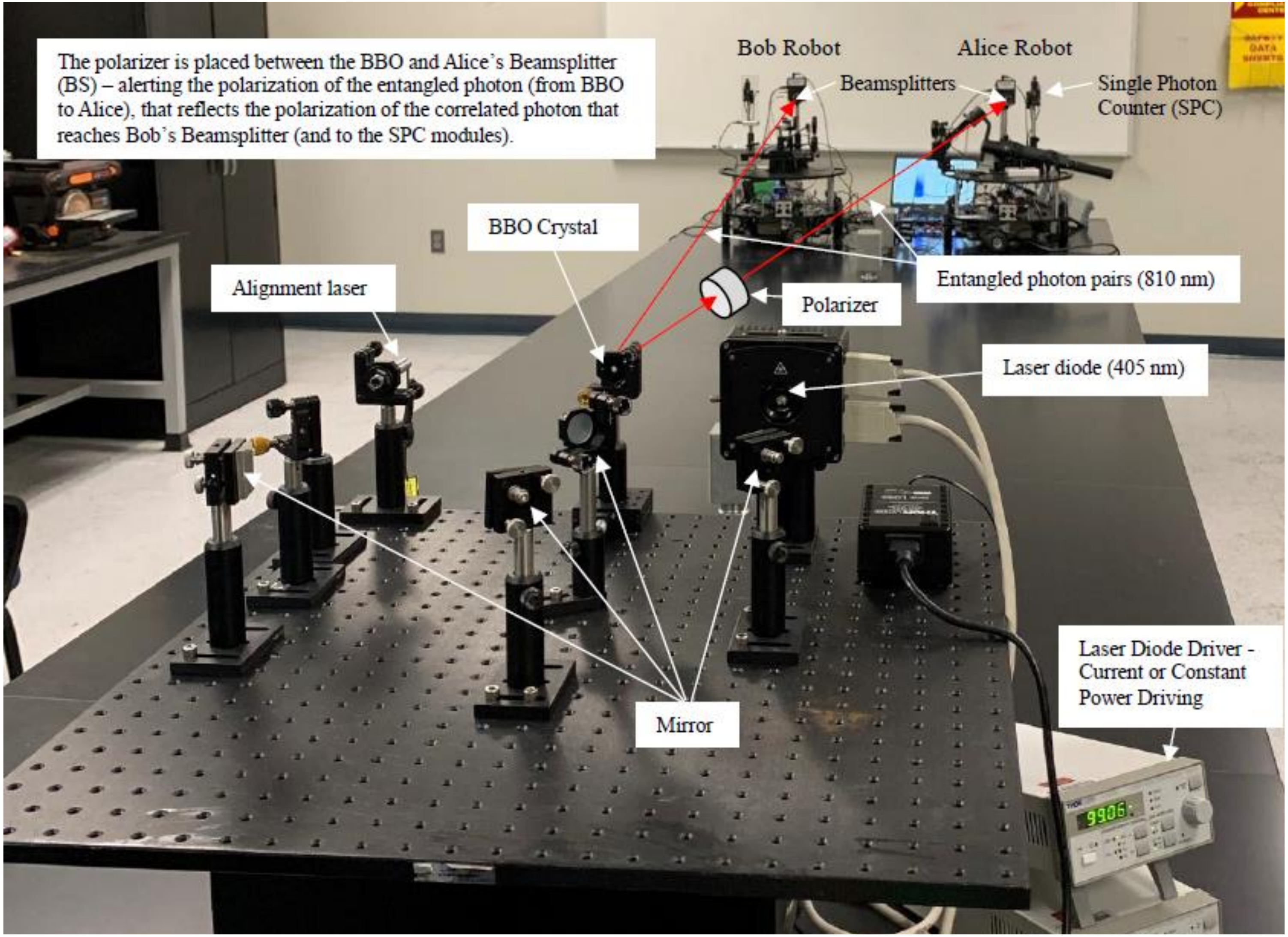
Entangled Photons are generated by ‘Spontaneous Parametric Down Conversion’, and sent to Alice and Bob Robots

Quantum Entangled Photons will be received by the Single Photon Counter (SPC) modules placed on the robots



“Alice Robot”

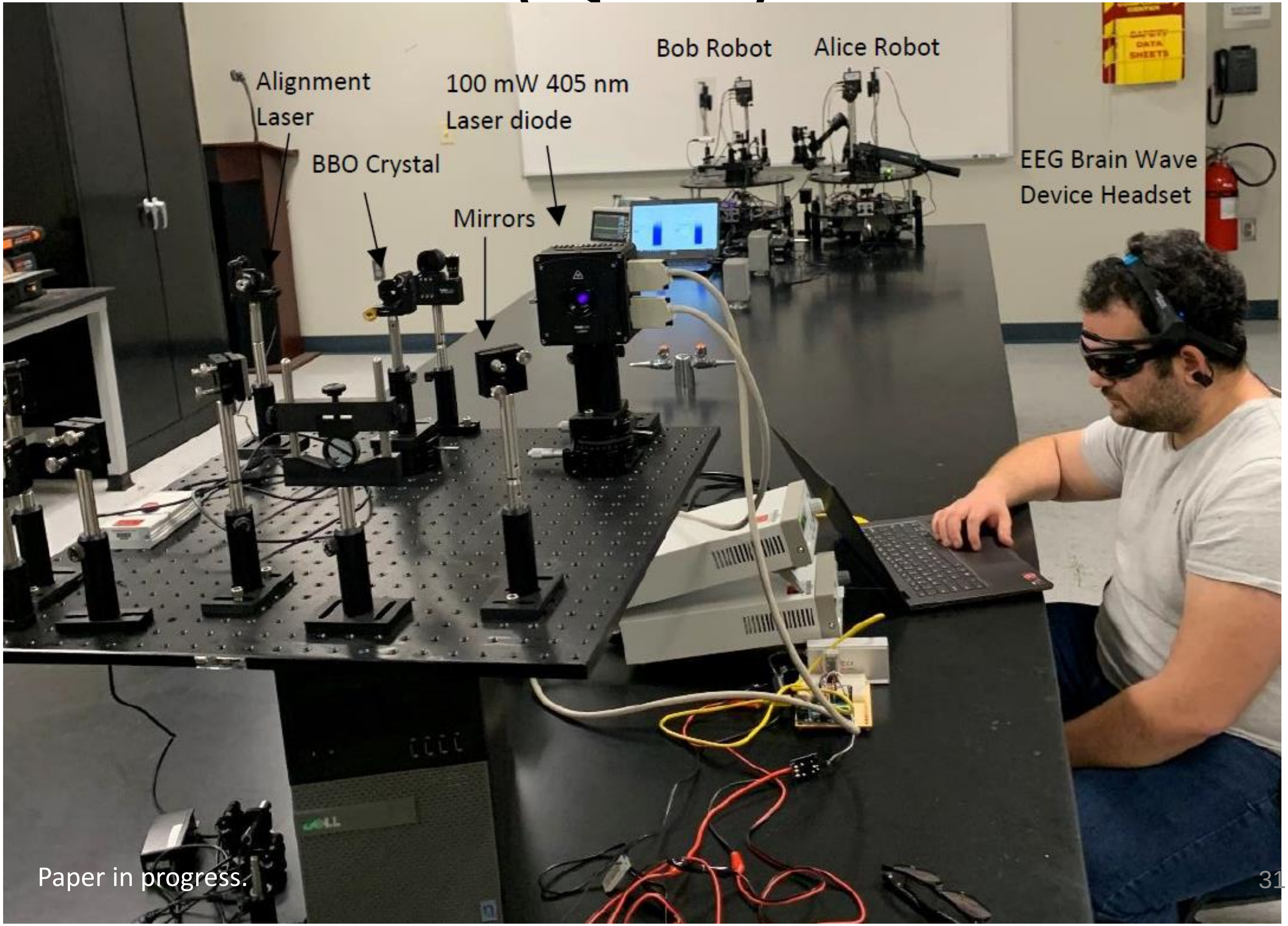
Quantum Teleportation
for Control of Dynamic Systems and Autonomy



The polarizer is placed between the BBO and Alice's Beamsplitter (BS) – alerting the polarization of the entangled photon (from BBO to Alice), that reflects the polarization of the correlated photon that reaches Bob's Beamsplitter (and to the SPC modules).

Farbod Khoshnoud, Lucas Lamata (Sevilla), Clarence W. De Silva (UBC), Marco B. Quadrelli (JPL), ***Quantum Teleportation for Control of Dynamic Systems and Autonomy***, *Mechatronic Systems and Control Journal*, 2020, [Preprint link].

Quantum Brain-Computer Interface (Q-BCI)



Paper in progress.

Quantum **Algorithms** for Multi-agent Autonomous Systems (An example)

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security

Singlet state

$$|\psi\rangle_s = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$$p_{\uparrow\uparrow}^{(s)} = p_{\downarrow\downarrow}^{(s)} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right)$$

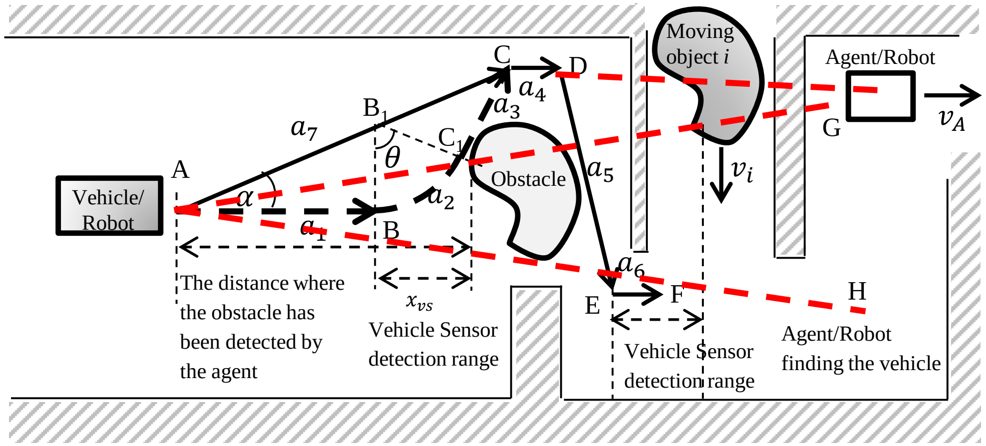
$$p_{\uparrow\downarrow}^{(s)} = p_{\downarrow\uparrow}^{(s)} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right)$$

Triplet state

$$p_{\uparrow\uparrow}^{(t)} = p_{\downarrow\downarrow}^{(t)} = \frac{1}{2}\cos^2\left(\frac{\alpha}{2}\right)$$

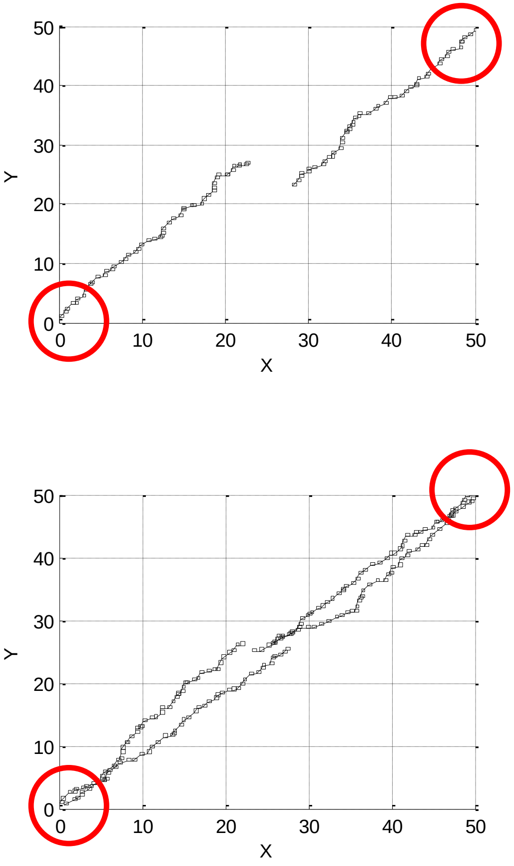
$$p_{\uparrow\downarrow}^{(t)} = p_{\downarrow\uparrow}^{(t)} = \frac{1}{2}\sin^2\left(\frac{\alpha}{2}\right)$$

- *Choose a random direction for a task (e.g., moving, applying force).*
- *The probability of random directions can be enhanced via probability weight factors for "suitable" directions.*
- *Decide to perform the task by the quantum measurement of the spin of the particle (for the vehicle/robot) reserved for this direction.*

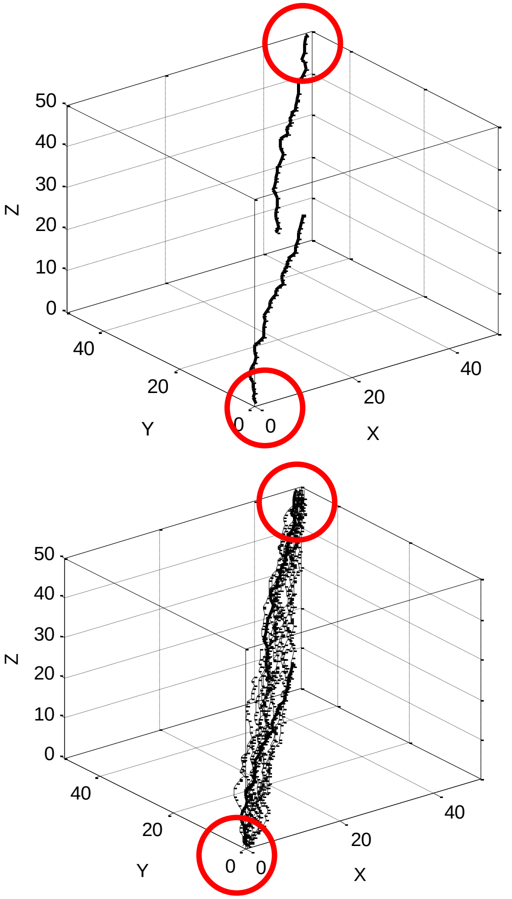


Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physical security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security



2D problems

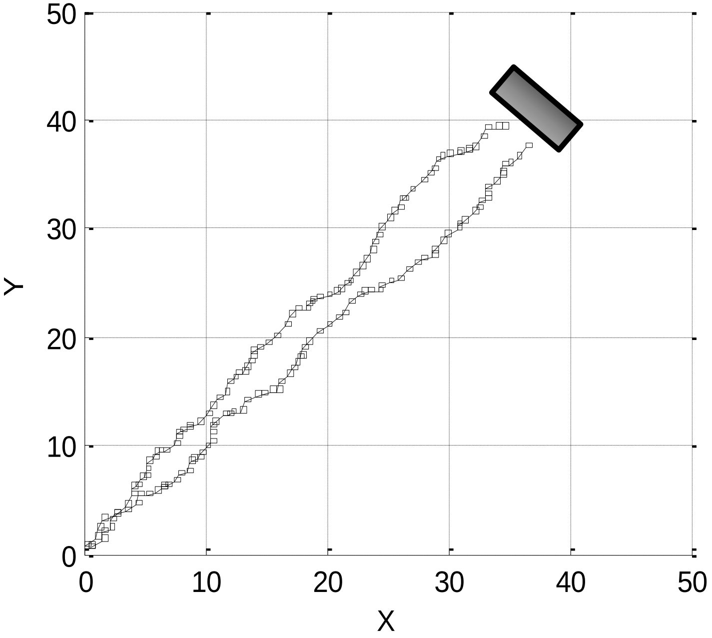


3D problems

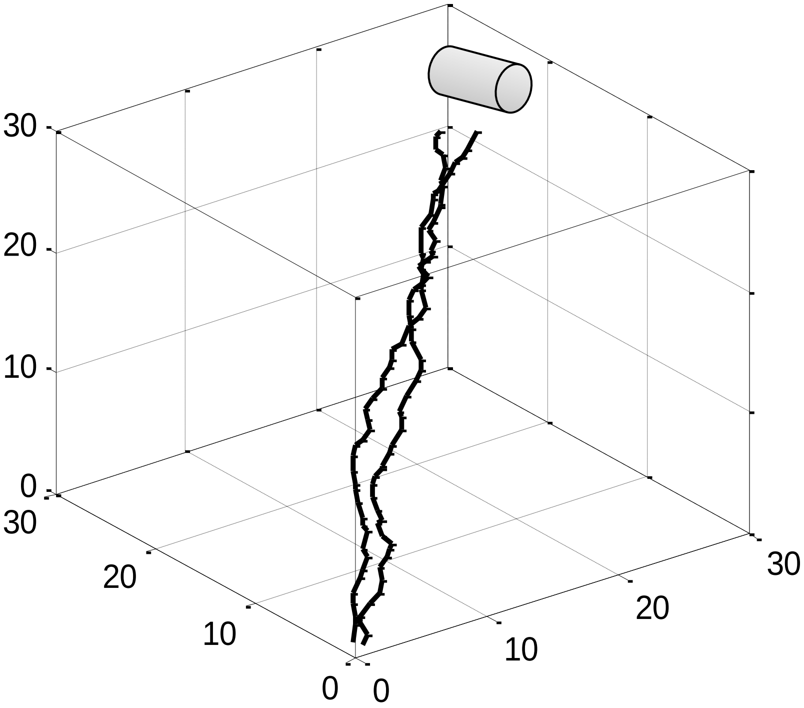
Autonomous Vehicles finding each other with no communication

Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physica security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

Quantum Entanglement of Autonomous Vehicles for Cyber-physical security



2D Simulation



3D Simulation

Autonomous Vehicles performing a task (pushing an object) with no communication.

Farbod Khoshnoud, C. W. de Silva, and I. I. Esat, Quantum Entanglement of Autonomous Vehicles for Cyber-physical security, IEEE International Conference on Systems, Man, and Cybernetics, Banff, Canada, October 5–8, 2017.

Quantum Computing

- Research
  - Quantum algorithms/computing

- **Quantum Games** (multi-agent robotic systems preforming tasks)
  - There is a higher chance of wining a quantum game compare with a corresponding classical game
  - When robot sensors fail or limited in performing a task, quantum game can enhance the probability of successfully complete the task
- **Quantum Annealing** for multi-agent robotic trajectory optimization
  - Quantum optimization can help in optimizing a trajectory of robots in a multi-agent robotic scenario
- Implementing the quantum algorithms
- Testing the algorithms
- Uploading the quantum algorithms on classical microcontrollers on the robots

Automated Alignment

- Research
  - Quantum algorithms/computing
  - Experimental photon quantum mechanics for entanglement, teleportation, and cryptography

- A current limitation of Experimental quantum techniques for robotic applications is alignment of the photon beams to the detectors when robots are moving:

A feedback control system for continuous alignment of beam sources to the detectors are implemented for robotic applications

Quantum Classical Integration

- Research
  - Quantum algorithms/computing
  - Experimental photon quantum mechanics for entanglement, teleportation, and cryptography
  - Integration

- The robots will operate for performing some autonomous tasks (for example moving to a target or pushing an object cooperatively).

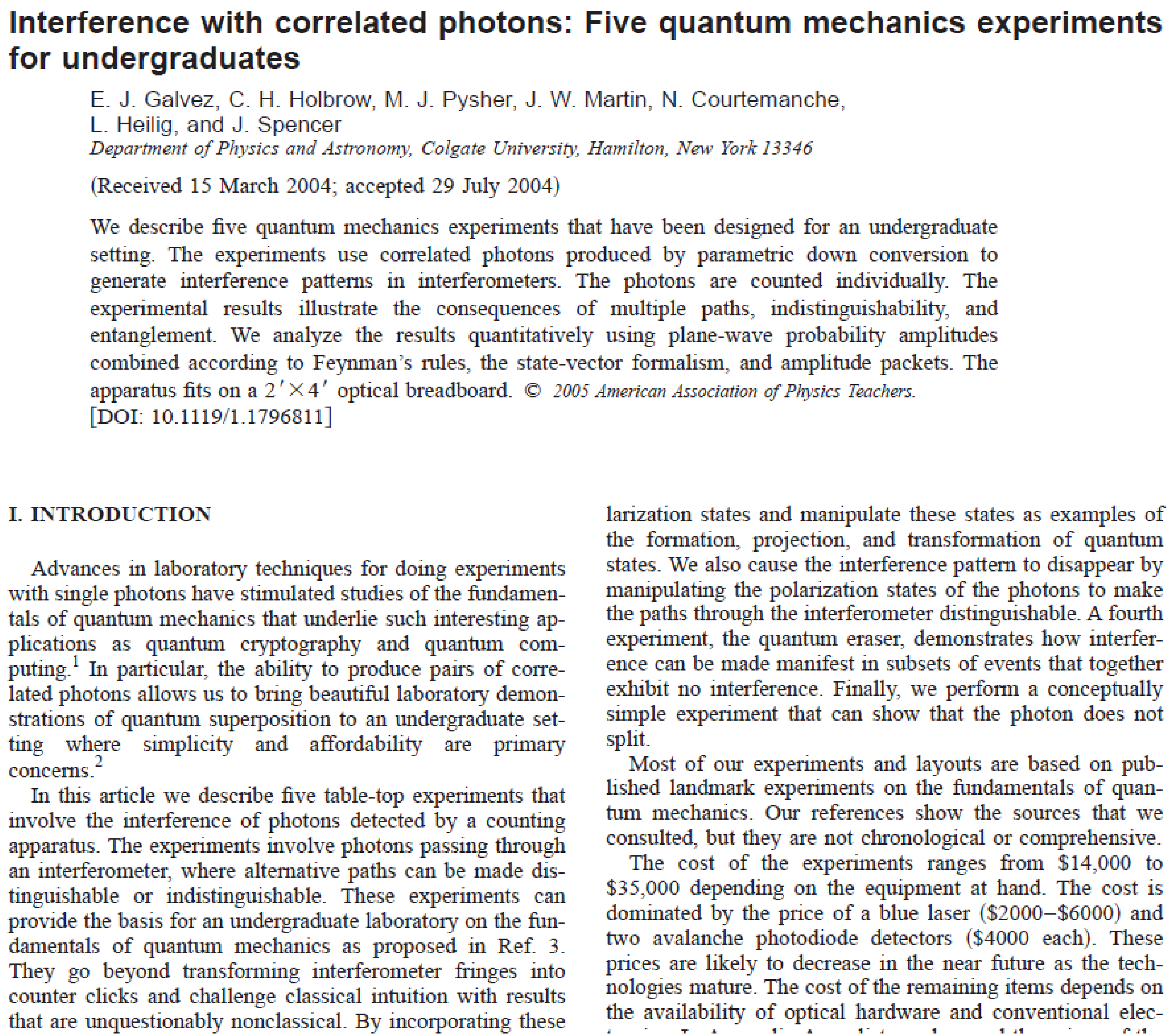
- Innovation: It has not been done before. The basic quantum robotic tasks in will pave the way to more advanced and novel techniques.

- Examples of the impacts: Demonstration of Emergency response and security applications when robotic sensors fail or limited in responding in Phase.

Quantum Robotics and Autonomy

- Research
  - Quantum algorithms/computing
  - Experimental photon quantum mechanics for entanglement, teleportation, and cryptography
  - Integration
- Education
  - Development of Integrated Quantum Engineering (Mechatronics) lab experiments for teaching

Quantum Mechanics experiments for education



Interference with correlated photons: Five quantum mechanics experiments for undergraduates

E. J. Galvez, C. H. Holbrow, M. J. Pysher, J. W. Martin, N. Courtemanche,
L. Heilig, and J. Spencer
Department of Physics and Astronomy, Colgate University, Hamilton, New York 13346

(Received 15 March 2004; accepted 29 July 2004)

We describe five quantum mechanics experiments that have been designed for an undergraduate setting. The experiments use correlated photons produced by parametric down conversion to generate interference patterns in interferometers. The photons are counted individually. The experimental results illustrate the consequences of multiple paths, indistinguishability, and entanglement. We analyze the results quantitatively using plane-wave probability amplitudes combined according to Feynman's rules, the state-vector formalism, and amplitude packets. The apparatus fits on a $2' \times 4'$ optical breadboard.
[DOI: 10.1119/1.1796811]

I. INTRODUCTION

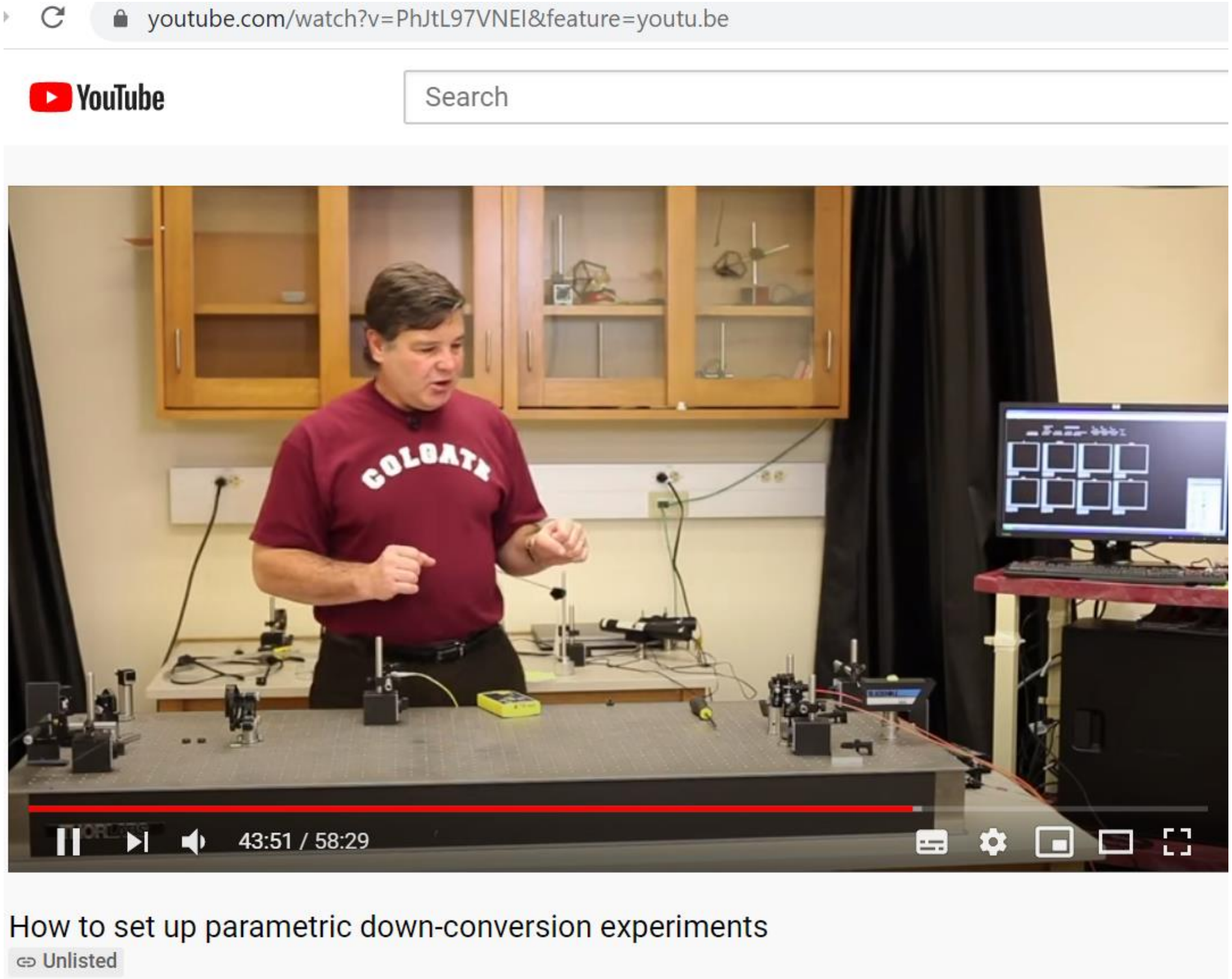
Advances in laboratory techniques for doing experiments with single photons have stimulated studies of the fundamentals of quantum mechanics that underlie such interesting applications as quantum cryptography and quantum computing.[1] In particular, the ability to produce pairs of correlated photons allows us to bring beautiful laboratory demonstrations of quantum superposition to an undergraduate setting where simplicity and affordability are primary concerns.[2]

In this article we describe five table-top experiments that involve the interference of photons detected by a counting apparatus. The experiments involve photons passing through an interferometer, where alternative paths can be made distinguishable or indistinguishable. These experiments can provide the basis for an undergraduate laboratory on the fundamentals of quantum mechanics as proposed in Ref. 3. They go beyond transforming interferometer fringes into counter clicks and challenge classical intuition with results that are unquestionably nonclassical. By incorporating these larization states and manipulate these states as examples of the formation, projection, and transformation of quantum states. We also cause the interference pattern to disappear by manipulating the polarization states of the photons to make the paths through the interferometer distinguishable. A fourth experiment, the quantum eraser, demonstrates how interference can be made manifest in subsets of events that together exhibit no interference. Finally, we perform a conceptually simple experiment that can show that the photon does not split.

Most of our experiments and layouts are based on published landmark experiments on the fundamentals of quantum mechanics. Our references show the sources that we consulted, but they are not chronological or comprehensive.

The cost of the experiments ranges from $14,000 to $35,000 depending on the equipment at hand. The cost is dominated by the price of a blue laser ($2000–$6000) and two avalanche photodiode detectors ($4000 each). These prices are likely to decrease in the near future as the technologies mature. The cost of the remaining items depends on the availability of optical hardware and conventional elec-

How to set up parametric down-conversion experiments



How to set up parametric down-conversion experiments

https://www.youtube.com/watch?v=PhJtL97VNEI&feature=youtu.be

Remote laboratory

Online remote teaching (Online Quantum Robotics and Autonomy). Example:

https://medialibrary.colgate.edu/Watch/Hw6b2A5R

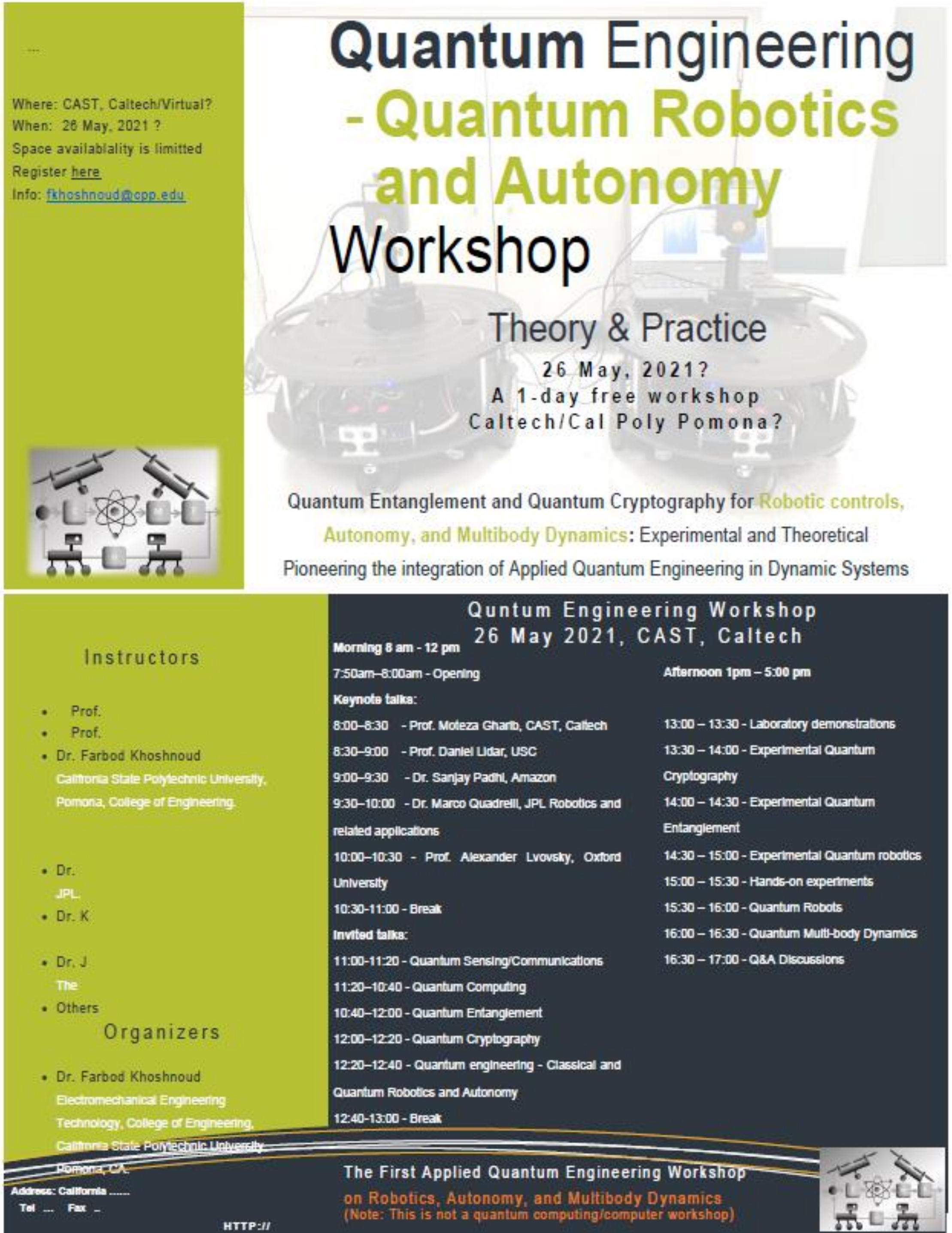
Modernizing Mechatronics Education

Five quantum engineering experiments for undergraduates for Mechatronics Courses:

- **Experimental Photon Quantum Entanglement**
- **Quantum Cryptography**
- **Quantum algorithms using Amazon Braket.**
- **Quantum Communication for multi-agent robotics**
- **Quantum Classical Integration.**

Quantum Engineering Workshop (**NOT Finalized yet**)

Workshops at CAST, Caltech/Cal Poly - Quantum Robotics and Autonomy Workshops for Students and Instructors



Where: CAST, Caltech/Virtual?
When: 26 May, 2021 ?
Space availablality is limitted
Register here
Info: fkhoshnoud@cpp.edu

Quantum Engineering
- Quantum Robotics and Autonomy
Workshop

Theory & Practice

26 May, 2021?
A 1-day free workshop
Caltech/Cal Poly Pomona?

Quantum Entanglement and Quantum Cryptography for Robotic controls, Autonomy, and Multibody Dynamics: Experimental and Theoretical

Pioneering the integration of Applied Quantum Engineering in Dynamic Systems

Instructors

- Prof.
- Prof.
- Dr. Farbod Khoshnoud
  Califronia State Polytechnic University, Pomona, College of Engineering.
- Dr.
  JPL.
- Dr. K
- Dr. J
  The
- Others

Organizers

- Dr. Farbod Khoshnoud
  Electromechanical Engineering Technology, College of Engineering, California State Polytechnic University Pomona, CA.

Address: California ......
Tel ... Fax _
HTTP://

Quntum Engineering Workshop
26 May 2021, CAST, Caltech

Morning 8 am - 12 pm

7:50am–8:00am - Opening

Keynote talks:

8:00–8:30 - Prof. Moteza Gharib, CAST, Caltech
8:30–9:00 - Prof. Daniel Lidar, USC
9:00–9:30 - Dr. Sanjay Padhi, Amazon
9:30–10:00 - Dr. Marco Quadrelli, JPL Robotics and related applications
10:00–10:30 - Prof. Alexander Lvovsky, Oxford University
10:30-11:00 - Break

Invited talks:

11:00-11:20 - Quantum Sensing/Communications
11:20–10:40 - Quantum Computing
10:40–12:00 - Quantum Entanglement
12:00–12:20 - Quantum Cryptography
12:20–12:40 - Quantum engineering - Classical and Quantum Robotics and Autonomy
12:40-13:00 - Break

Afternoon 1pm – 5:00 pm

13:00 – 13:30 - Laboratory demonstrations
13:30 – 14:00 - Experimental Quantum Cryptography
14:00 – 14:30 - Experimental Quantum Entanglement
14:30 – 15:00 - Experimental Quantum robotics
15:00 – 15:30 - Hands-on experiments
15:30 – 16:00 - Quantum Robots
16:00 – 16:30 - Quantum Multi-body Dynamics
16:30 – 17:00 - Q&A Discussions

The First Applied Quantum Engineering Workshop
on Robotics, Autonomy, and Multibody Dynamics
(Note: This is not a quantum computing/computer workshop)

Future work

- Fault-tolerant quantum computation.
- Error-correcting codes.
- Implementation of Quantum Capabilities for Small Satellites in the lab.
- Applications of Quantum Robotics and Autonomy for Emergency Response, and Situation Awareness.