

UNIVERSITY OF ROCHESTER  
THE INSTITUTE OF OPTICS

OPT 453, OPT 253, PHY 434

# Lab. 1. Entanglement and Bell's Inequalities

**Instructor: Dr. Svetlana G. Lukishova**  
sluk@lle.rochester.edu

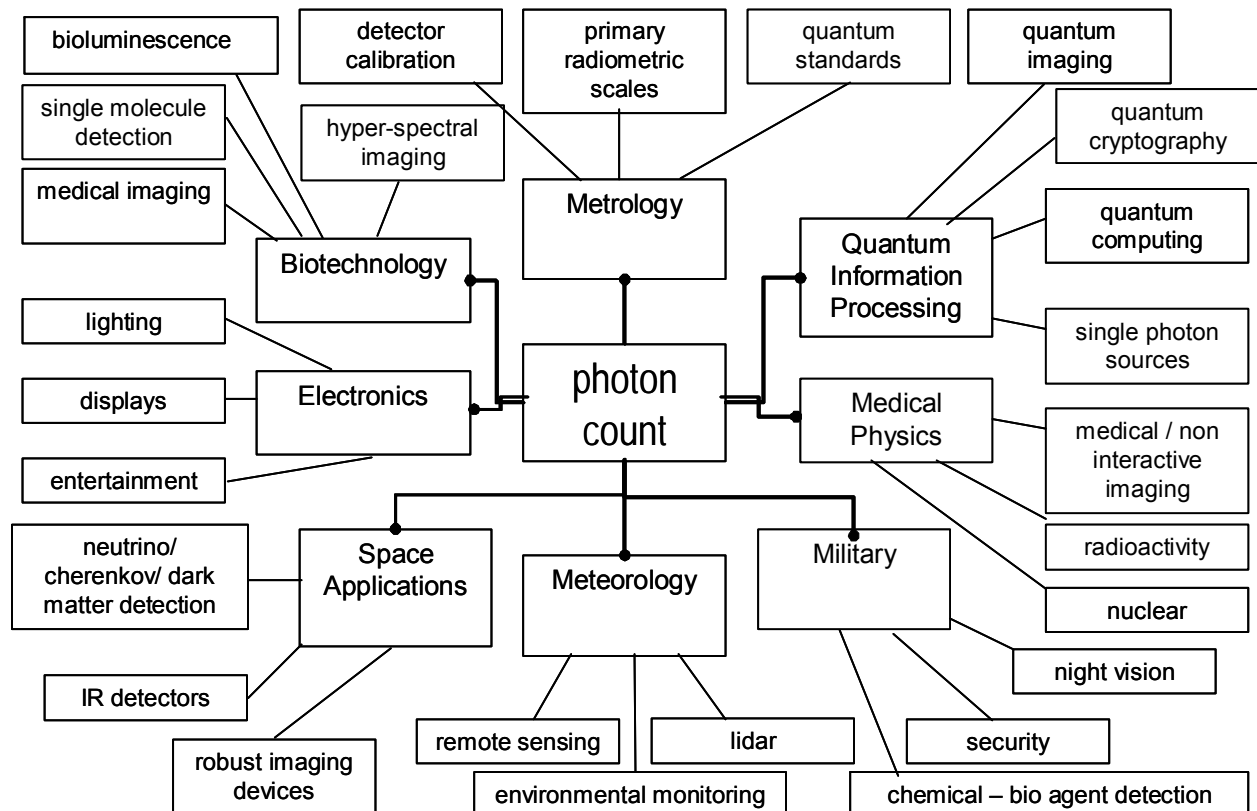
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*"I cannot seriously believe in quantum theory because it cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at a distance." - Albert Einstein*

## Summary of this Lab

- Entanglement is the most exciting and mysterious property of some quantum mechanical systems when property of one particle depends on the property of the other. It does not matter how far apart such entangled particles are located. Among the best known applications of entanglement are quantum communication and quantum state teleportation.
- Bell's inequality is a classical relation. For entangled particles it is violated.
- In this lab you will obtain an entangled state of two photons and will calculate Bell's inequality using measurements of the coincidence counts between two single-photon detectors. You will work on modern, cutting edge photon counting instrumentation widely used in quantum information science and engineering. The table below shows its other applications.

## Photon counting applications



Areas of applications of photon counting instrumentation (prepared by organizers of second international workshop "Single Photon: Sources, Detectors, Applications and Measurements Methods" (Teddington, UK, 24-26 October 2005))

# IMPORTANT SAFETY TIPS

## A. LASER SAFETY

The argon ion laser BeamLok 2060 emits laser radiation that can permanently damage eyes and skin. **To minimize the risk of injury or expensive repairs, carefully follow these instructions.**

### PRECAUTIONS FOR THE SAFE OPERATION OF CLASS IV-HIGH POWER LASERS

- Wear protective eyewear at all times; selection depends on the wavelength and intensity of the radiation, the conditions of use, and the visual function required. During the alignment of your setup you can reduce the power of the laser.
- Avoid looking at the output beam; even diffuse reflections are hazardous.
- Avoid blocking the output beam or its reflection with any part of your body.
- Try to maintain a high ambient light level in the laser operation area. This keeps the eye's pupil constricted, thus reducing the possibility of eye damage.
- Laser safety issue arises also from the **high voltage applied to the tube with the argon.**

## B. EQUIPMENT SAFETY

For the safety of the equipment,

- **NEVER TURN ON THE ROOM LIGHTS WHILE THE APDs AND EM-CDD-CAMERA ARE ON.**
- (1) After turning off the power switch always unplug the APD's before turning on the lights for the long period of time. (2) Also, make sure your Lab View program is turned off before turning on the lights.
- **If APD count rate will exceed 200,000 counts/sec, reduce laser power or put the screen in front of APD.**  
**DON'T SWITCH OFF APD UNDER A HIGH COUNT RATE!!!!**
- Don't turn on the BeamLok 2060 argon ion laser without water cooling (see instructions in Appendix I of this Manual).
- Keep water running during ~15 min after the laser turning off.

# PREPARATORY QUESTIONS

You should answer two sets of questions:

- (1) before your first laboratory session and
- (2) after each section of this Manual. All questions have a blue-color font.

## **Answer these questions before your first laboratory session**

1. What is entanglement? How will you create polarization entangled photons in this experiment?
2. How will you prove in your experiment that you have entangled photons?
3. What is spontaneous parametric down conversion?
4. Make a sketch of your experimental setup and describe its main components.
5. For what purpose do you need a quartz plate?
6. What are single photon counting avalanche photodiode modules? How to work with them without damaging these detectors?
7. What are Bell's inequalities? Can you calculate them for some classical objects?

## References and recommended literature:

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4. P.G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, "New high-intensity source of polarization-entangled photon pairs", *Phys. Rev. Lett.*, **75**, 4337 (1995).
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6. P.G. Kwiat, E. Waks, A.G. White, I. Appelbaum, P.H. Eberhard, "Ultrabright source of polarization-entangled photons", *Phys. Rev. A*, **60**, R773 (1999).
7. D. Dehlinger and M.W. Mitchell, "Entangled photons, nonlocality, and Bell inequalities in the undergraduate laboratory", *Am. J. Phys.*, **70**, 903 (2002).
8. D. Dehlinger and M.W. Mitchell, "Entangled photon apparatus for the undergraduate laboratory," *Am. J. Phys.*, **70**, 898 (2002).
9. J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, 2004.
10. J. Eberly, "Bell inequalities and quantum mechanics", *Amer. J. Phys.*, **70** (3), 286, March (2002).
11. M.A. Nielsen, I.L. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, 2000, pp. 111-117.
12. N. Boeuf, D. Branning, I. Chaperot, E. Dauler, S. Guérin, G. Jaeger, A. Muller, A. Migdall, "Calculating characteristics of noncollinear phase matching in uniaxial and biaxial crystals", *Opt. Eng.* **39**(4), 1016-1024 (April 2000).  
<http://physics.nist.gov/Divisions/Div844/facilities/cprad/index.html#contents>
13. BeamLok 2060 and 2080 Ion Lasers, *User's Manual*, Spectra-Physics.
14. Model 587 Z-Lok Etalon and Model 5870 Controller, *User's Manual*, Spectra-Physics.

# 1. INTRODUCTION

The purpose of this laboratory work is to introduce students to entanglement, one of the key concepts of quantum mechanics. While the concept of entanglement defies the classical intuition, in this lab you will gain a better understanding of entangled particles and experimentally verify the predictions of quantum theory.

If two particles (A and B) are entangled, their wave functions cannot be separated. The particles cannot be represented or talked about individually. Any measurement performed on A would change the state of B (and vice-versa), no matter how far apart A and B may be. The idea is illustrated in the cartoon below. There is no classical explanation for this phenomenon.

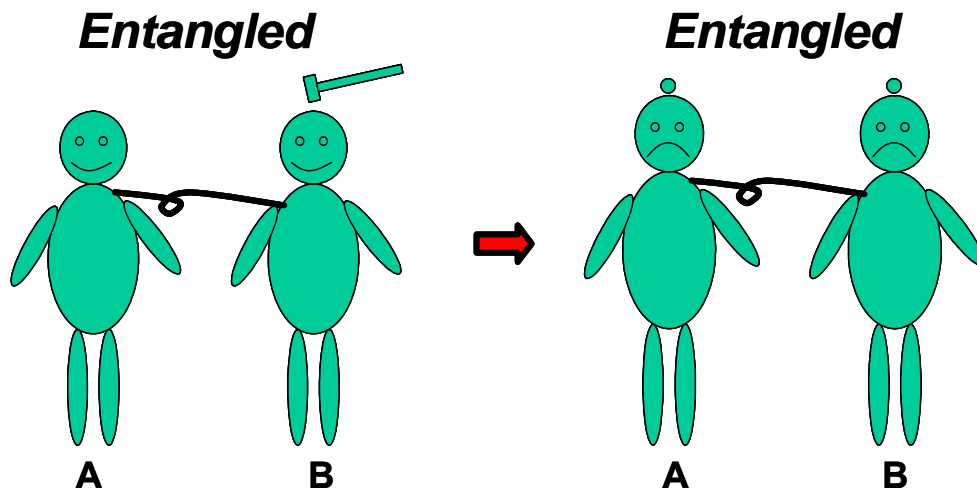


Figure 1. Cartoon of A.K. Jha and L. Elgin illustrating entanglement.

Entanglement between particles is always through some physical property. For example, the quantum mechanical state describing particles' momentum, spin or polarization may be entangled. You can read about entanglement in the books [1-3] for advanced undergraduate and graduate students.

In this laboratory two different photons whose polarization states are entangled will be investigated. These entangled photons are produced in a BBO crystal [4] through a process called Spontaneous

Parametric Down-Conversion [5]. This lab experiment was reported in 1999 as a research paper in Ref. 6 and developed for the students' lab by the authors of Refs. 7 and 8. Ref. 7 contains also some useful historical background.

Bell's Inequality [9-11] is a mathematical equation. "Inequalities of the Bell type by themselves have nothing to do with quantum theory. Contexts as different as downhill skiers and laundered socks have been used by Meystre and Bell to demonstrate this. Although Bell inequalities are almost tautological expressions, they have attracted much attention because they allow one to see the experimental consequences of alternative views of physical reality which are conveniently labeled classical and quantum mechanics" [10].

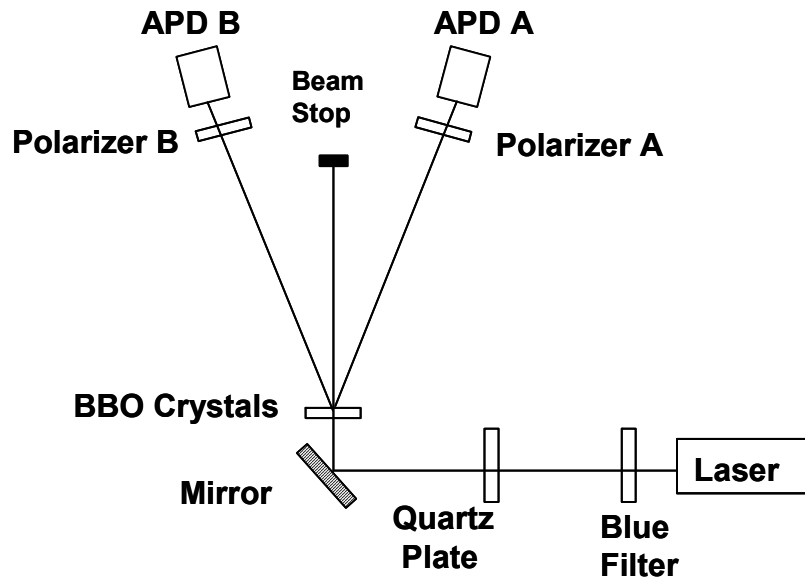
In this lab you will calculate Bell's Inequality predicting the maximum value of a sum of probabilities. The probabilities involved assume a classical correlation between two particles, whose polarization states are measured. Violating this inequality means that these particles do, in fact, have a quantum relationship that cannot be explained by classical mechanics.

## **2. EXPERIMENTAL SET UP**

As shown in the schematic diagram in Figure 2, light from a ~100 mW pump argon ion laser with a wavelength  $\lambda = 363.8$  nm and a vertical polarization passes through a blue filter and then a quartz plate. The blue filter removes parasite fluorescence from an argon plasma tube that may be present in the laser beam. Quartz is a birefringent material. When light passes through the quartz plate, a phase difference is introduced between two polarization components. This phase difference can be adjusted by rotating the quartz plate.

A mirror re-directs the beam through a pair of BBO crystals that are mounted back-to-back, at  $90^\circ$  with respect to each other. The majority of the laser light passes through the BBO crystals and is collected at the beam stop or rejected by the interference filters. The down-converted photons from the BBO crystals are emitted in cones [a horizontal and a vertical polarization cone for a beam with  $45^\circ$  incident polarization (relative to the BBO optical axis)]. Down-

converted photons from the BBO crystals with wavelength  $2\lambda = 727.6$  nm are detected by a pair of single-photon counting avalanche photodiodes (APDs) modules. The x-y position of the APDs can be adjusted using the x-y translator. APDs are single photon detectors that give rise to an electronic signal TTL pulse when a photon is incident on them.



**Figure 2. Schematics of experimental setup.**

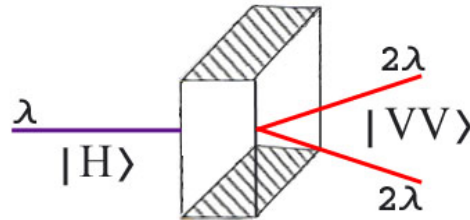
The APDs are kept at the same height as that of the BBO crystals. The APDs' positions are equidistant from the center of the crystal. This enables these two APDs to be on two diametrically opposite points of the downconverted cone. Data from the APDs are collected using a Lab View interface on a computer with a counter-timer board inside.

The interference filters with 10 nm bandwidth should be placed in front of each APD, so that only light near 730 nm (i.e. the down-converted photons) will reach the detectors. Additionally, polarizers are located in front of each APD, so that the polarization state of photons reaching the detectors can be selected.

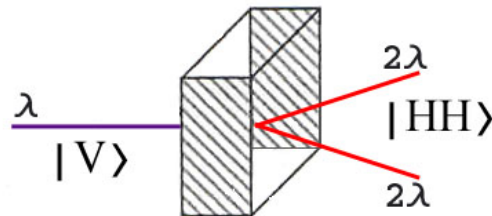


### 3. BBO CRYSTALS AND PARAMETRIC DOWN-CONVERSION

Beta Barium Borate (BBO) is a negative uniaxial nonlinear crystal with some very interesting and useful properties [12]. Crystals can be cut for the different types of nonlinear interactions. For a type I crystal cut, when a horizontally (vertically) polarized photon of wavelength  $\lambda$  is incident on the crystal, two photons of wavelength  $2\lambda$  emerge from the crystal with vertical (horizontal) polarization (Figure 3). This process is called spontaneous parametric down-conversion and is a standard method used to produce polarization-entangled photons [4, 6]. The down-converted photons are emitted in a cone from the crystal. The efficiency of this down-conversion process is only  $10^{-10}$  (out of  $10^{10}$  incident photons only one photon would get down-converted). For details in noncolinear phase matching conditions in parametric down conversion (Figs. 3, 4) see paper 12.



**Figure 3.** Down-conversion of photon with a horizontal polarization. (For this orientation of the crystal, photons with a vertical polarization pass straight through).

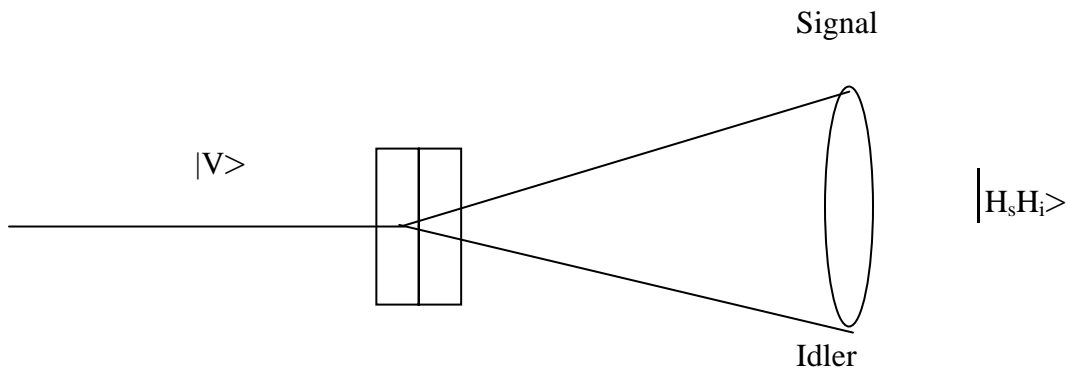


**Figure 4.** Down-conversion of photon with a vertical polarization. (For this orientation of the crystal, photons with a horizontal polarization pass straight through).

Since the majority of the laser light simply passes straight through the BBO crystals, the intensity of the down-converted photons is very low (you will not be able to see a down-converted light with naked eye). We will use single-photon counting avalanche photodiodes (APDs) sensitive to observe the down-converted photons

#### 4. PRODUCTION OF POLARIZATION ENTANGLED PHOTONS: THEORY

The production of a polarization-entangled quantum state using type I BBO crystals with a 45° incident polarization is explained below. The first crystal's optic axis and the pump beam define the vertical plane. Due to Type-I phase matching, a vertically polarized photon going through these crystals would get down-converted in first crystal producing two horizontally polarized photons (Figure 5).



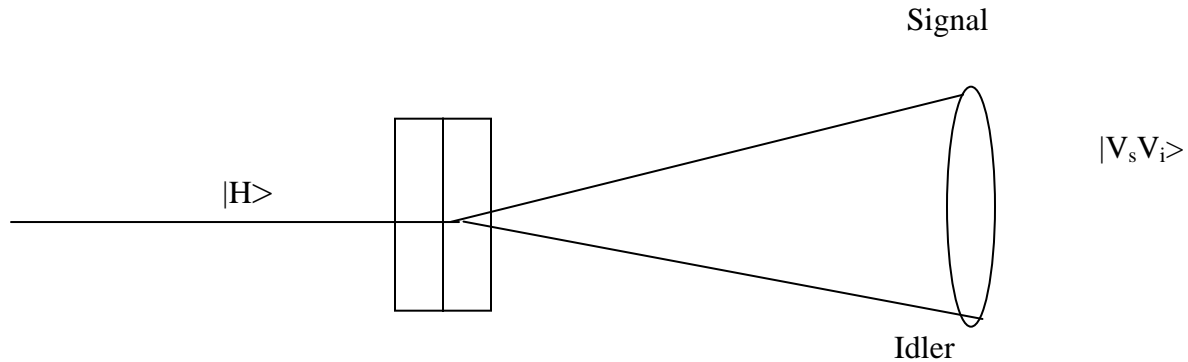
**Figure 5: Production of two horizontally polarized photons from one vertically polarized photon.**

Mathematically it can be represented as:

$$|V\rangle \rightarrow |H_s H_i\rangle$$

Here  $V$  and  $H$  represent a horizontally- or a vertically-polarized photon. For historic reasons, photons of a down-converted pair are called “signal” and “idler” photons, denoted by subscripts “s” and “i,” respectively.

On the other hand, a horizontally-polarized photon going through these crystals would get down-converted in the second crystal producing two vertical photons (Figure 6).

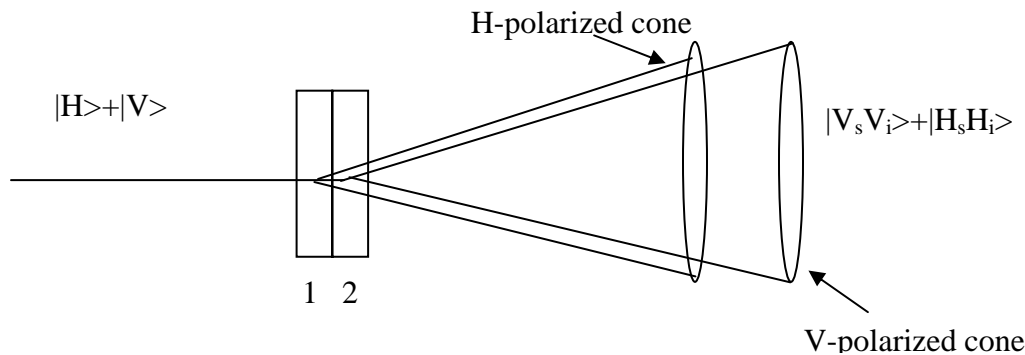


**Figure 6. Production of two vertically polarized photons from one horizontally polarized photon.**

Mathematically it can be represented as:

$$|H\rangle \rightarrow |V_s V_i\rangle$$

Now what happens if photons with  $45^\circ$  polarization are incident on a pair of BBO crystals, as shown in Figure 7 below?



**Figure 7. Production of polarization entangled photon pairs.**

A stream of  $45^\circ$ -polarized photons can be considered as a beam with half vertically and half horizontally polarized photons. So half of the time these photons would get down-converted in the first crystal, producing pairs of photons with horizontal polarization, and half of the

time they would pass through the first crystal and would get down-converted in the second crystal, producing pairs of photons with vertical polarization. Hence, for an incident beam of 45°-polarized photons, the same number of photon pairs having vertical and horizontal polarizations will be emitted from the two BBO crystals.

Mathematically this can be represented as:

$$\frac{|H\rangle + |V\rangle}{2} \rightarrow \frac{|V_s V_i\rangle + |H_s H_i\rangle}{\sqrt{2}} \equiv \Psi_{ent} \quad (1)$$

Here,  $\frac{|H\rangle + |V\rangle}{2}$  represents a 45° polarized photon.

Notice that the state  $\Psi$  cannot be factored into states purely dependent on the signal and idler photons, i.e.:  $\Psi \neq |1\rangle_s |2\rangle_i$ , for any choice of  $|1\rangle_s$  and  $|2\rangle_i$ . This means that the state of one particle cannot be specified without making reference to the other particle. **Particles related thusly are called entangled, and  $\Psi_{ent}$  is called an entangled quantum state.**

If we measure the polarizations of signal and idler photons in the  $H$ ,  $V$  basis, there are two possible outcomes: both vertical and both horizontal. Each occurs half of the time. We could instead measure the polarizations with polarizers rotated by an angle  $\alpha$ . We use the rotated polarization basis

$$\begin{aligned} |V_\alpha\rangle &= \cos \alpha |V\rangle - \sin \alpha |H\rangle, \\ |H_\alpha\rangle &= \sin \alpha |V\rangle + \cos \alpha |H\rangle \end{aligned} \quad (2)$$

Here  $|V_\alpha\rangle$  describes a state with polarization rotated by  $\alpha$  from the vertical, while  $|H_\alpha\rangle$  describes a state with polarization rotated by  $\alpha$  from the horizontal. In this basis the entangled state is

$$\Psi_{ent} = \frac{1}{\sqrt{2}} (|V_\alpha\rangle_s |V_\alpha\rangle_i + |H_\alpha\rangle_s |H_\alpha\rangle_i) \quad (3)$$

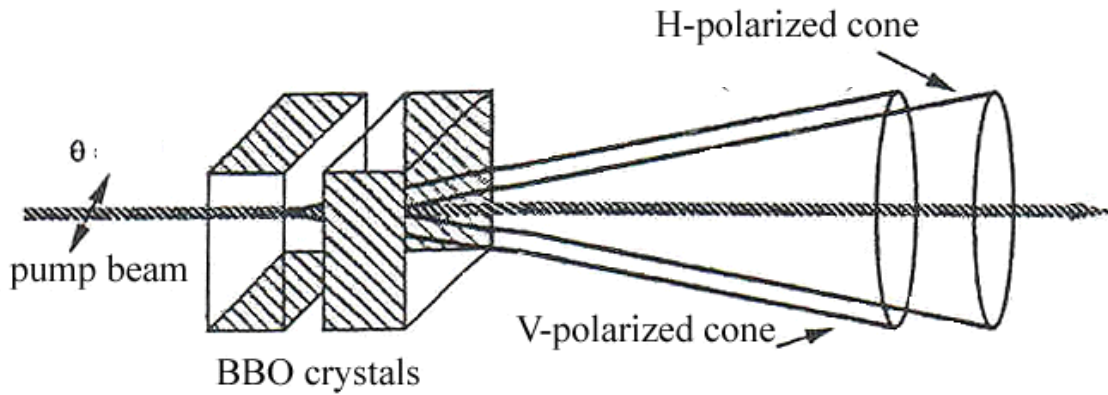
Clearly, if we measure in this rotated basis, we obtain the same results: half of the time both are  $|V_\alpha\rangle$  and half of the time both are  $|H_\alpha\rangle$ . Knowing this, we can measure the signal polarization and infer with certainty the idler polarization.

From Figure 7 you can see that a horizontal photon travels a larger distance inside the BBO crystals than a vertical photon before getting down-converted. This difference in distances traveled introduces a phase difference,  $\phi$ , between the two polarization states, resulting in a quantum state:

$$\Psi = |V_s V_i\rangle + e^{i\phi} |H_s H_i\rangle \quad (4)$$

If the incident (pump) laser beam has a polarization angle  $\theta$  from the vertical (see Figure 8 in which the crystal optical axis is parallel to the vertical direction), in general case the downconverted photons emerge in the state

$$|\psi_{DC}\rangle = \cos\theta |H\rangle_s |H\rangle_i + \exp[i\phi] \sin\theta |V\rangle_s |V\rangle_i \quad (5)$$



**Figure 8. Geometry of a downconversion process.**

By placing polarizers rotated to angles  $\alpha$  and  $\beta$  in the signal and idler paths, respectively, we measure the polarization of the downconverted photons.

For a pair produced in the downconverted state  $|\psi_{DC}\rangle$ , the probability of coincidence detection is

$$P_{VV}(\alpha, \beta) = |\langle V_\alpha |_s \langle V_\beta |_i | \psi_{DC} \rangle|^2, \quad (6)$$

The  $VV$  subscripts on  $P$  indicate the measurements outcome  $V_\alpha V_\beta$ , both photons vertical in the bases of their respective polarizers. More

generally, for any pair of polarizer angles  $\alpha$  and  $\beta$  there are four possible outcomes,  $V_\alpha V_\beta$ ,  $H_\alpha H_\beta$ ,  $H_\alpha V_\beta$ , and  $H_\alpha H_\beta$ .

Using the basis of Eq (2), we find after some trivial calculations

$$P_{VV}(\alpha, \beta) = (\sin^2 \alpha \sin^2 \beta \cos^2 \theta + \cos^2 \alpha \cos^2 \beta \sin^2 \theta + \frac{1}{4} \sin 2\alpha \sin 2\beta \sin 2\theta \cos \phi) \quad (7)$$

A special case occurs when  $|\psi_{DC}\rangle = |\psi_{ent}\rangle$ , that is, when  $\theta = \pi/4$  and  $\phi = 0$ . In this case

$$P_{VV}(\alpha, \beta) = \frac{1}{2} \cos^2(\beta - \alpha). \quad (8)$$

In this lab, you will obtain a relation (8) in your experiment selecting: (1) an optimal angle  $\theta$  of crystal rotation relative to the incident laser polarization (which is fixed) and (2) an optimal angle of rotation of a quartz plate to compensate phase  $\phi$ .

In the experiment you will measure a coincidence count rate  $N(\alpha, \beta)$  choosing a fixed interval of data acquisition (0.5-20 s). Assuming a constant flux of photon pairs, the number of  $N(\alpha, \beta)$  will be

$$N(\alpha, \beta) = A(\sin^2 \alpha \sin^2 \beta \cos^2 \theta + \cos^2 \alpha \cos^2 \beta \sin^2 \theta + \frac{1}{4} \sin 2\alpha \sin 2\beta \sin 2\theta \cos \phi) + C \quad (9)$$

where A is the total number of entangled pairs produced, and C is an offset to account for imperfections in the polarizers and alignment of the crystals. This offset is necessary to account for the fact that some coincidences are observed even when the polarizers are set to  $\alpha = 0$ ,  $\beta = 90^\circ$ .

In an ideal case ( $C = 0$ ), if  $\theta$  is fixed as  $45^\circ$  and  $\phi$  is determined to be minimized by rotating the quartz plate:

$$\begin{aligned}
N(\alpha, \beta) &= \frac{A}{2} (\sin^2 \alpha \sin^2 \beta + \cos^2 \alpha \cos^2 \beta + 2 \sin \alpha \cos \alpha \sin \beta \cos \beta) \\
&= \frac{A}{2} (\cos \alpha \cos \beta + \sin \alpha \sin \beta)^2 \\
&= \frac{A}{2} \cos^2(\alpha - \beta)
\end{aligned} \tag{10}$$

**QUESTION 4.1.** How will a count rate of APD detector A (singles' count rate) depend on the angle  $\alpha$  of a polarizer A and on the angle  $\beta$  of a polarizer B?

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**QUESTION 4.2.** What are the conditions for maximum and minimum coincidence count rates for setup with two polarizers in front of each APD?

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## 5. EXPERIMENT 1: ALIGNMENT PROCEDURE FOR PREPARING AN ENTANGLED STATE

**(Caution: never switch the APD or EM-CCD-camera on in room light !) ALL YOUR EXPERIMENTS SHOULD BE CARRIED OUT IN ABSOLUTE DARKNESS!!!**

As it was described in Section 4, in this lab you will produce the quantum entangled state  $\Psi = |H_s H_i\rangle + |V_s V_i\rangle$  by adjusting both the quartz plate and the BBO crystal set. Your first actions will be as follows:

- Because the laser has a vertical polarization, you need to rotate the optical axes of a BBO crystal set which direction for one of the crystal is marked on the crystal mount. Rotation angle around a horizontal axis perpendicular to the mount surface

- should be near  $45^\circ$  from the vertical (incident laser polarization direction).
- By rotating the BBO crystals around two other axes and using an EM-CCD camera you should maximize the brightness of the image of the cone of the downconverted photons.
  - You need to maximize singles' counts of APD detectors A and B as well as the coincidence count. APD detectors in the two arms are kept at an angle of several degrees where maximum counts are observed (see photo of the old setup shown in Figure 9).



**Figure 9. Photograph of the old setup of entanglement lab.**

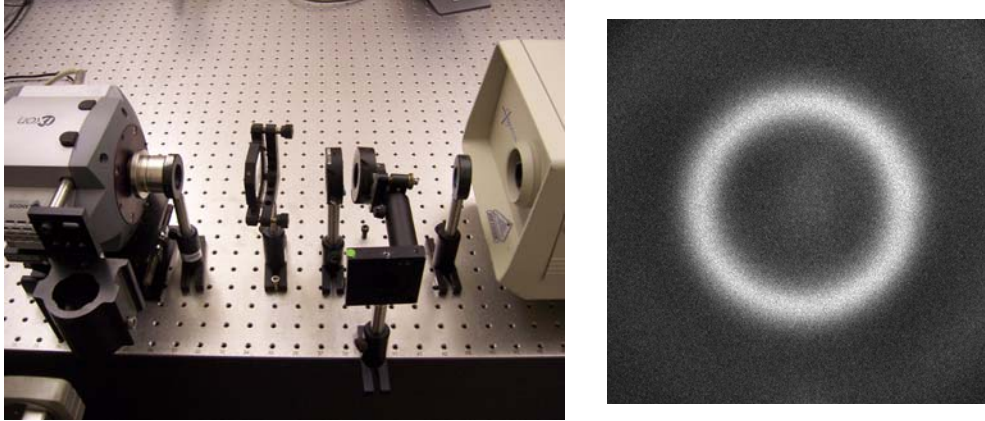
### **5.1. Observing the down-converted light cone by an EM-CCD camera**

Using the imaging lens and two or three interference filters with 10 nm transmission bandwidth at 730 nm in front of the EM-CCD camera, obtain the images of the cones of downconverted photons.

Select an optimum cone angle for your setup by rotating a BBO crystal. One of the interference filters should be placed at the camera



entrance (see Figure 10). You will observe a light cone similar to the image in Figure 10, right, but with more smeared edges because of much smaller thickness of the crystals in a current lab experiment ( $\sim 100 \mu\text{m}$ ).



**Figure 10. Left: setup for the observation of a cone of downconverted light. Right: image of a downconverted light cone for a 2mm thick type I single BBO crystal.**

## 5.2. Adjusting APDs for maximum counts:

If APD count rate will exceed 200,000 counts/sec, reduce the laser power or put the screen in front of the APDs.

**DON'T SWITCH OFF APD UNDER A HIGH COUNT RATE!!!!**

Recall that Count A and Count B in the Labview program refer to the counts in APD-A and APD-B, respectively. Coincidence Count measures the number of photon pairs simultaneously reaching the two detectors. The term “singles count” refers to either Count A or Count B.


1. Make the time window in a LabView program to be 0.5 seconds (or 500 ms). Hit the run  $\Rightarrow$  button and then “START”. Check that you have “0” counts when APDs are off. If the program is running continuously leave it like that. Otherwise, stop the LabView program by hitting  $\odot$ . Right click on “START”. Go to ‘mechanical action’. Select ‘switch when pressed’. Hit the run

(  $\Rightarrow$  ) button and then "START". Make sure that it is running continuously.

2. Switch the lights off. Make sure that the door is locked. Make sure that the laser is off.
3. Switch on the APDs in a presence of TA.
4. Record the counts when the laser is off and APDs are covered by the dark tissue. These are dark counts. Record the counts when the laser is on but the output from the BBO crystals is blocked by the screen. These are background counts.

**Background Count A: \_\_\_\_\_, Background Count B: \_\_\_\_\_,  
Background Coincidence Count: \_\_\_\_\_**

(Background counts should not be more than 500).

5. Switch the laser off
6. Remove Polarizers A and B.
7. Switch the laser on. Work at the laser output power  $\sim$  10-30 mW.
8. The counts should now have increased. Maximize the counts by adjusting the 'X-Y' translator and after that the angle of the APD's direction to the BBO crystals. Once you have maximized the counts you should have at least a couple of hundred coincidences.
9. Switch the laser off.
10. Switch the APDs off.
11. Stop the Labview program by hitting  Right click on the "START" button. Go to 'mechanical action' and select 'latch when pressed'.
12. Put Polarizers A and B at  $0^\circ$ .

### **Next step:**

1. Set the time window to be 5 seconds (or 5000 ms). Hit the run  $\Rightarrow$  button and then "START"
2. Switch the lights off. Make sure that the door is locked. Make sure that the laser is off.
3. Switch the APDs on in the presence of TA.
4. Hit "START" in the labview program. That is the background count. Note background for singles in Table 1 and that for coincidence in Table 2.

5. Switch the laser on. While Polarizers A and B are at  $0^\circ$ , record the singles count by clicking “START” in the labview program and note it in Table 1(column II and III )..
6. Next put the polarizers at  $10^\circ, 20^\circ, \dots, 360^\circ$  and each time record Count A and Count B and note them in Table 1.
7. Remove the Polarizer A and put Polarizer B at  $0^\circ$  and hit the “START” button and note down the coincidence count in Table 2.
8. Next put the Polarizer B at  $10^\circ, 20^\circ, \dots, 360^\circ$  and each time record the coincidence count and note it down in Table 2.
9. Plot Count A, Count B and Coincidence count versus the polarization angle of Detector B.

**Table 1:** Time window = 5 seconds,  
 $\alpha$  = polarization angle of Polarizer A  
 $\beta$  = polarization angle of Polarizer B  
 Net count = Actual count – background count

$\alpha=\beta$ (deg)	Background Count A:		Background Count B:	
	Count A		Count B	
	Actual	Net	Actual	Net
0				
10				
20				
30				
40				
50				
60				
70				
80				
90				
100				
110				
120				
130				
140				
150				
160				
170				
180				
190				
200				
210				

220				
230				
240				
250				
260				
270				
280				
290				
300				
310				
320				
330				
340				
350				

**Table 2:** Time window = 5 seconds,  
 $\alpha$  = polarization angle of Polarizer A  
 $\beta$  = polarization angle of Polarizer B  
Net count = Actual count – background count

Background Coincidence Count:					
$\beta$ (deg) (Polarizer A removed)	Coincidence Count		$\beta$ (deg) (Polarizer A removed)	Coincidence Count	
	Actual	Net		Actual	Net
0			170		
10			180		
20			190		
30			200		
40			210		
50			220		
60			230		
70			240		
80			250		
90			260		
100			270		
110			280		
120			290		
130			300		
140			310		
150			320		
160			330		
170			340		
180			350		

The plots for the singles counts are not exactly flat, as you should have predicted. The plots seem to have some sinusoidal characteristic. We define a quantity called **Visibility (V)** to check the flatness of a curve.

$$V = \frac{Max - Min}{Max + Min} \times 100\%$$

Here '*Max*' and '*Min*' are the maximum and minimum counts. Find the '*Max*' and '*Min*' of your data and calculate the visibility.

**Max:** \_\_\_\_\_, **Min:** \_\_\_\_\_, **Visibility:** \_\_\_\_\_

**QUESTION 5.1:**

You know that you have the quantum state  $\Psi = |H_s H_i\rangle + |V_s V_i\rangle$ . How do you expect Count B to change as you rotate Polarizer B from 0° to 360°, but Polarizer A is set for a fixed angle  $\alpha$ ?

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**QUESTION 5.2:**

If Polarizer A was removed how would you expect the coincidence count to change as you rotate Polarizer B from 0° to 360° ?

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**QUESTION 5.3:**

What would you expect the visibility to be for a perfectly flat curve?

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**QUESTION 5.4:**

What does it mean to have a 100% visibility?

## 6. EXPERIMENT 2: LOOKING AT THE ENTANGLEMENT

In this activity we will see how photons in two arms are entangled and how this entanglement affects the properties of one photon when a measurement is performed on the other photon.

### QUESTION BEFORE STARTING:

What would you expect for the Coincidence Count if you put Polarizer A at  $\alpha = 0^\circ, 45^\circ, 90^\circ, 135^\circ$  and in each case rotate Polarizer B from  $\beta=0^\circ$  to  $360^\circ$ ? Show the mathematical basis for your prediction. (Hint: fixing  $\alpha$  at some angle is like making a measurement in that basis).

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### Next steps to check your suggestions:

1. Set the Labview program for a measurement time of 5 seconds (or 5000 ms)
2. Fix  $\alpha = 0$  and put  $\beta = 0$ . Switch the lights off. Make sure that the door is locked. Make sure that the laser is off.
3. Ask the TA to switch on the APD.
4. Record the coincidence count by clicking "START" in the Labview program. Note the results in Table 3 (Column II).
5. Next put the Polarizer B at  $\beta = 10^\circ, 20^\circ, \dots, 360^\circ$ . Record the coincidence count and note the results in Table 3 (Column II).
6. Repeat steps 5 and 6 for  $\alpha = 45^\circ, 90^\circ, 135^\circ$  and note down the counts in Table 3 (Column III, Column IV and Column V, respectively).
7. Plot Coincidence Counts for the different  $\alpha$  values versus the angle of polarization  $\beta$ . (There should be four plots, one for each value of  $\alpha$ ).

**Table 3:** Time window = 5 seconds,

$\alpha$  = polarization angle of Polarizer A

$\beta$  = polarization angle of Polarizer B

Net count = Actual count – background count

Background Coincidence Count:								
$\beta$ (deg)	Coincidence Count ( $\alpha=0$ )		Coincidence Count ( $\alpha=90$ )		Coincidence Count ( $\alpha=45$ )		Coincidence Count ( $\alpha=135$ )	
0								
10								
20								
30								
40								
50								
60								
70								
80								
90								
100								
110								
120								
130								
140								
150								
160								
170								
180								
190								
200								
210								
220								
230								
240								
250								
260								
270								
280								
290								
300								
310								
320								
330								
340								
350								

This dependence you observed is actually the evidence of quantum entanglement. You should have seen that the maximum coincidence count occur at the angle where  $\alpha$  has been fixed. (For  $\alpha=0$ , you get the maximum of coincidence at  $\beta=0$ . For  $\alpha=90$ , you get the maximum of coincidence at  $\beta=90$ .)

**Question 6.1:**

What equation of the section 4 matches the experimental results proving the entanglement?

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**Question 6.2:**

Compare the coincidence plot with Polarizer A removed to the plots at different values of  $\alpha$ . What is the difference between coincidence plot with no polarizer and coincidence plot with the polarizer at  $\alpha=0$ ?

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**Question 6.3:**

How does choosing different values of  $\alpha$  change the coincidence plots than  $\beta$  is fixed?

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**7. EXPERIMENT 3: TESTING QUANTUM THEORY BY BELL'S INEQUALITY VIOLATION**

In this activity, we will mathematically check if quantum theory is correct by calculating Bell's Inequality in a form of Clauser, Horne, Shimony, and Holt [4, 7]. In the previous activity, we saw evidence of entanglement. In this activity we will try to perform a mathematical check by violating Bell's Inequality. (Look at the Refs 7, 9-11 for an explanation of Bell's inequality.) The maximum possible value of S in Bell's Inequality is always less than  $|2|$ , for any classical correlation. Getting a value greater than  $|2|$  for S would



confirm the violation of this inequality. S is defined as follows [4, 7]:

$$S = E(a, b) - E(a, b') + E(a', b) + E(a', b') \quad (7)$$

We will calculate the value of S for

$$E(\alpha, \beta) = \frac{N(\alpha, \beta) + N(\alpha_{\perp}, \beta_{\perp}) - N(\alpha, \beta_{\perp}) - N(\alpha_{\perp}, \beta)}{N(\alpha, \beta) + N(\alpha_{\perp}, \beta_{\perp}) + N(\alpha, \beta_{\perp}) + N(\alpha_{\perp}, \beta)} \quad (8)$$

$N(\alpha, \beta)$  is the coincidence count when Polarizer A is at  $\alpha$  and Polarizer B is at  $\beta$ .

1. Set the Labview program for a measurement time of 20 seconds (or 20000 ms).
2. Switch the lights off. Make sure that the door is locked. Make sure that the laser is off.
3. Ask the TA to switch on the APDs.
4. Put Polarizer A at  $\alpha = -45^{\circ}$  and Polarizer B at  $\beta = -22.5^{\circ}$ .
5. Record the coincidence count by hitting "START" in the Labview program and note it down in Table 4.
6. Repeat this until you have collected data for all of the Table 4.
7. Finally Put  $\alpha = 0^{\circ}$ ,  $\beta = 90^{\circ}$  and note down the coincidence count. Subtract this count from each coincidence reading of Table 4. Ideally, you should get '0' counts for this setting of polarizers, but due to the poor quality of the polarizers used, this is not the case. By subtracting this count from your readings you are correcting for the poor quality of polarizers [ $N(\alpha, \beta)$  is the count after subtracting  $N(0,90)$ ].
8. For  $a = -45^{\circ}$ ,  $a' = 0^{\circ}$ ,  $a_{\perp} = 45^{\circ}$ ,  $a'_{\perp} = 90^{\circ}$ ,  $b = -22.5^{\circ}$ ,  $b' = 22.5^{\circ}$ ,  $b_{\perp} = 67.5^{\circ}$ ,  $b'_{\perp} = 112.5^{\circ}$ , calculate S in Equation (8) and note it down.

**Table 4:** Time window = 20 seconds

$\alpha$  = polarization angle of Polarizer A

$\beta$  = polarization angle of Polarizer B

Net count = Actual count –  $N(0,90)$

$N(0,90) =$			
$\alpha$ (deg)	$\beta$ (deg)	Coincidence Count	
		Actual	Net
-45	-22.5		
-45	22.5		
-45	67.5		
-45	112.5		
0	-22.5		
0	22.5		
0	67.5		
0	112.5		
45	-22.5		
45	22.5		
45	67.5		
45	112.5		
90	-22.5		
90	22.5		
90	67.5		
90	112.5		

**S** = \_\_\_\_\_

Violation of Bell's Inequality can be seen at any angle. The maximum is observed at the angles chosen above. You should observe that there are accidental coincidences (or random coincidences) in the system. These random coincidences result from the probability that the two uncorrelated photons from two different down-conversion events will arrive within the coincidence interval. This background is small and acts to decrease  $|S|$ . A finding  $|S| > 2$  thus cannot be a result of the (random) accidental coincidences.

**Question 7.1:**

What is the value of experimental error in your measurements of  $S$ ?

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**Question 7.2:**

The predicted value of  $|S|$  from quantum theory at the angles you used in this activity is 2.82. Discuss why you did not get this value of  $|S|$  (i.e., what are the sources of experimental errors).

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## APPENDIX 1



### Beam-Lok Laser Operation

#### a) Startup Procedure [13,14]

The output beam of this laser is a safety and fire hazard. Avoid directly viewing the beam and its reflection or blocking it with clothing or parts of the body.

1. Place a beam block or power meter in the beam path, clear the beam path of reflective objects, and open the shutter.
2. Turn on the cooling water supply. The FLOW indicator should turn off within a few seconds. Water flow rate should be 3.0 gal/min (11.3 l/min), water pressure should be 25 psig (172 kPa), water temperature should be 10 – 35°C (50 – 95°F).
3. Turn on the main power. The P.S. STATUS indicator on the power supply should turn on. Input power should be 3-phase with ground; input voltage should be 208 V<sub>ac</sub> + 10%, - 5%; maximum current is 60 A per phase at 208 V; power consumption is 21 kW.
4. Turn on the key switch and wait for 5-10 min. Using the left knob on a power supply control box, increase the current, but don't exceed 50 A. To control the power, press the right black button into the power mode (depending on a switching order, the value of current, power or voltage will appear on a display).
5. The emission indicator turns on, and after a 15 second delay, the plasma discharge starts and the laser beam emerges if current will exceed ~ 40A.

During routine start-up, **start the system with BeamLok enabled** with the laser output aperture in open position. This keeps the output beam aligned while the laser is warming up.

## **b) BeamLok system [13,14]**

**The BeamLok system provides an automatic means of holding the output beam on a fixed reference point. The system consists of an actuator, beam position detector, and a remote control module.**

When BeamLok is on, the beam position detector senses any change in beam position and adjusts the output coupler to compensate. When the laser is in *power* mode, BeamLok actively controls both output power and beam position.

**BeamLok will disengage when there is insufficient laser output power to drive it. Simply increase output power to relock it onto the beam.**

Beam Lok is controlled through the Model 2474 remote control module. The remote control module has a push-button and an indicator, a low signal indicator and a x-y display. *The push-button in the lower left corner of the remote module has been included for future system enhancements. It is not functional at this time.*

## **c) Shutdown procedure [13,14]**

1. Turn off the key switch.
2. Remove the key.

Do not leave the laser accessible to people who are untrained in laser safety or operation.

**If you leave the main power on, the laser will return to the operating condition it was in before shutdown.**

3. **After allowing the unit to cool down for 15 minutes**, turn off the water.
4. If the unit is not to be used for some time, turn off the main power at the circuit breaker.