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QIE, PHY424

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9:22 AM

Friday, Jan 13th

~~9:22AM~~: • The purpose of this experiment is to show the violation of Bell's inequalities by measuring the polarization of entangled photon pairs, prepared in the Bell state

• This will be done by passing laser photon's through a crystal which induces spontaneous down conversion, which splits a photon into an entangled pair with the same polarization

• Background reading: "Entangled Photon's Non-Locality, and Bell's Inequalities in the undergraduate laboratory" by Dehlinger & Mitchell

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• 2 photons: signal and idler
$|V\rangle$ = vertically polarized, $|H\rangle$ = horizontally polarized

• Rotate by angle α

$$\begin{cases} |V_\alpha\rangle = \cos\alpha\,|V\rangle - \sin\alpha\,|H\rangle \\ |H_\alpha\rangle = \sin\alpha\,|V\rangle + \cos\alpha\,|H\rangle \end{cases}$$

• In the $\{|V_\alpha\rangle, |H_\alpha\rangle\}$ basis, we want to prepare the two photons in the maximally entangled Bell State

$$|\psi_{EPR}\rangle = \frac{1}{\sqrt{2}}\left(|V_\alpha\rangle_s |V_\alpha\rangle_i + |H_\alpha\rangle_s |H_\alpha\rangle_i\right)$$

~~This state cannot be factorized~~

<u>Setup:</u>

• 5mW diode laser produces a beam of light, passed into a pair of BBO crystals

• The crystal induces the photon to decay spontaneously into a pair w/ the same polarization

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- The rest of the setup consists of two single photon detector modules preceeded by linear polarizers and red filters
- Red filters block scattered laser light

- The laser produces pump photons in states

$$\left\{ \begin{array}{l} |V\rangle_p \rightarrow |H\rangle_s |H\rangle_i \\ |H\rangle_p \rightarrow e^{i\Delta} |V\rangle_s |V\rangle_i \end{array} \right.$$

crystal

- We prepare the state

$$|\psi\rangle_{pump} = \cos\theta_I |V_p\rangle + e^{i\varphi_I} \sin\theta_I |H_p\rangle$$

- θ_I is set using a linear polarizer θ_I from the vertical
- φ_I is set using a birefringence quartz plate
- After the crystal, the state is

$$|\psi_{DC}\rangle = \cos\theta_I |H\rangle_s |H\rangle_i + e^{i\varphi} \sin\theta_I |V\rangle_s |V\rangle_i$$

where $\varphi = \varphi_I + \Delta$

- Measure the polarization of down converted photons w/ polarizers at angles α, β from vertical in signal and idler path's
- If the number of photon pairs collected by the detectors in some time interval T is $N(\alpha, \beta)$,

$$\left.\begin{array}{l} \tan^2\theta_I = \dfrac{N(90°, 90°) - C}{N(0°, 0°) - C} \\ \cos\varphi_{m} = \dfrac{1}{\sin(2\theta_I)}\left(4\,\dfrac{N(45°, 45°) - C}{A} - 1\right) \end{array}\right\} *$$

$\varphi_M = ?$

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where

$$\begin{cases} C = N(0^\circ, 90^\circ) \\ A = N(0^\circ, 0^\circ) + N(90^\circ, 90^\circ) - 2C \end{cases}$$

- Bell state has $\theta_I = 45^\circ$, $\varphi_m = 0^\circ$

* - Note $\cos \varphi_m = \langle \cos \varphi \rangle$. φ has a complicated dependence on many parameters and will vary, so we replace it w/ the average

- Our goal is to show $|S| > 2$. Ideally $S = 2\sqrt{2}$ for

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

where

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

w/ $\alpha_\perp = \alpha + 90^\circ$

- More Reading: UofT APL QIE Lab book

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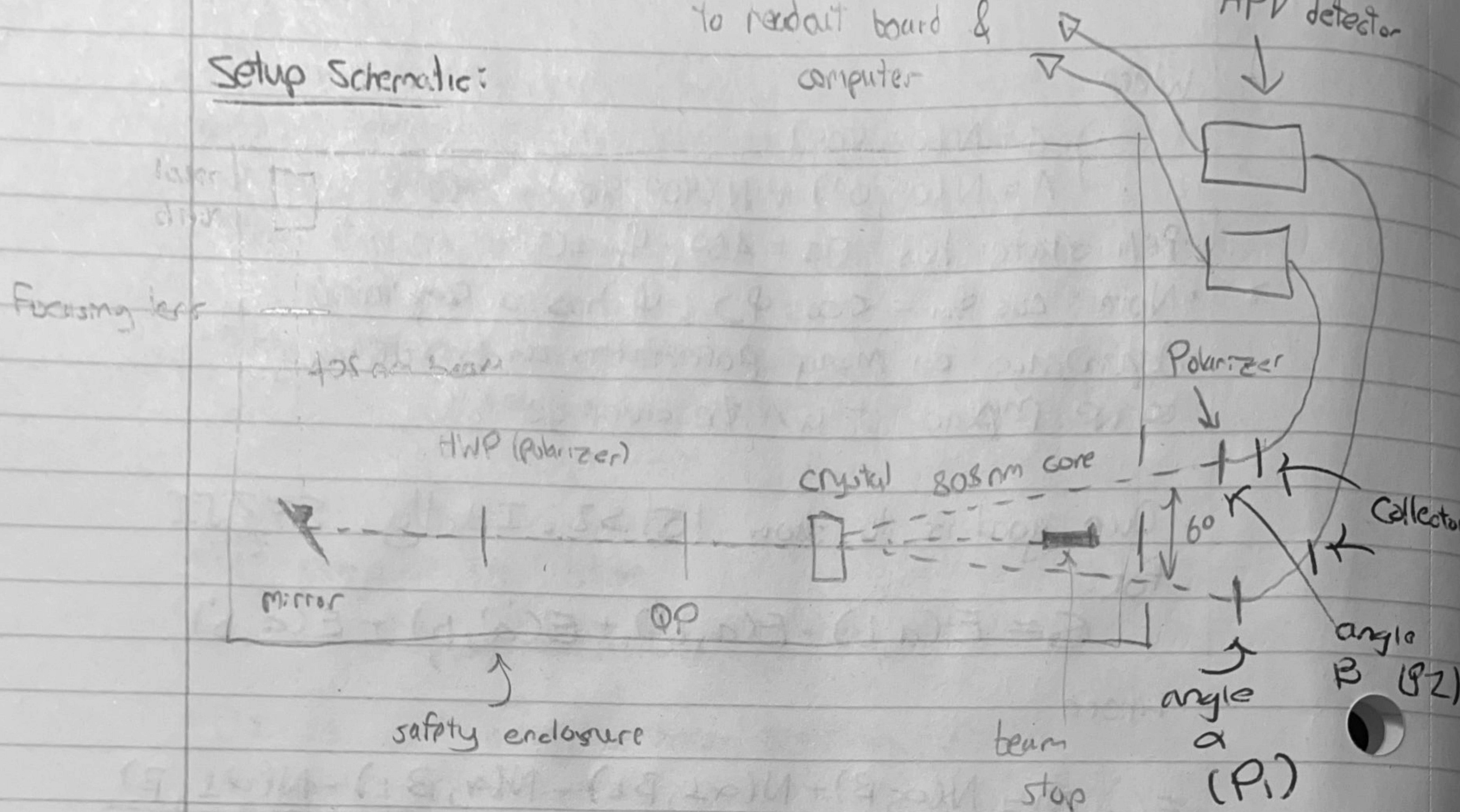
Setup Schematic:



Components:
- Pump laser produces 405nm light
- Laser threshold: 33mA. Laser max power ~100mW
- For safety, ~50mW will do
- Light is reflected off a mirror and passed into a Half-Way Plate (HWP) and Quartz plate (QP)
- HWP controls plane of incident beam polarization, θ_I
- The resulting polarization is twice the angle of the incident polarization and the HWP fast axis
- Rotating QP <u>about vertical</u> controls ϕ_I to account for Δ, the relative phase introduced by the crystal
- These processes are slightly coupled so ~~they~~ both ~~should~~ quantities should be measured for each change

Friday Jan 13th

- After exiting the QP, the beam passes through a BBO crystal
- Entangled ~810nm photon pairs exit the safety enclosure
- The main beam is stopped by beam stop
- Polarizers are oriented so ~0° setting passes vertically polarized light
- Photons follow fibre optic cables to detectors

Questions:
- Tuning the bell state requires ~~computing~~ measuring $N(\alpha,\beta)$ for four sets of angles
- The manual suggests fitting $N(\alpha,\beta)$ data to get these angles. Do we have to fit these for each ~~set of θ_I, ϕ_I~~ set up of the HWP and QP until we find one were $\theta_I \sim 45°$ and $\phi_m \approx 0°$?

Tues, Jan 17th

Measuring Coincidence window:

- Opened LabVIEW detection.vi
- Set update window to 5s
- Turned on lamp and disabled room lights (closed door)
- Turned on Altera board
- VISA Error
- LabVIEW was set wrong comport. We want Comport 6

Lab Tech helped w/ this

- Turned on APD power
- Photon counts began under detectors A and C :)
- Spent time attempting to export data from LabVIEW
- Turned on APD power
- Collected read outs for single photon detections and raw coincidences for 5 different flashlight positions
- Values for detector A seem to me much smaller than C.
- Array multiplication in python caused error in data. We did not realize this, and took a second data set.
- In the end, we had a coincidence window of 33 ± 2ns assuming perfect data
- To measure this I used scipy curvefit

$$N_{coin} = \frac{N_1 N_2}{T} \tau$$

where $T = 5s$. τ is the parameter we want to find

- To elaborate, I pointed the flashlight near the detectors, and turned away by a few (~5°?) degrees in between each measurement to decrease

Tues Jan 17^{th}

the photon counts. The measurements were

Fitted Data Set

Port ~~Detector~~ A	Port ~~Detector~~ C	AC
116383	784119	576
46840	308520	196
17659	100994	12
11997	54452	6
11520	52334	6
93598	515164	352
80491	468042	236
47379	292661	113
27038	159799	26
23815	135722	27

- The curve fit x data was $N_1 N_2 / T$ where N_1 and N_2 are the detector A and B data respectively
- AC is the y data, the raw coincidence count

Friday, Jan 20th

- To double check coincidence measurement, shined light near detectors w/ update period set to 5s and coincidence window set to 33ns to see if corrected counts averaged to 0
- Coincidence counts seem too large. ~50 for ~500 raw coincidences?

- Detector A reporting too much light even when no light in room except computer screen?
- TA suggested replacing faulty detector
- I replaced the detector labelled A
- LabVIEW behaviour did not change
- I then replaced the detector labelled 'C'
- Nothing changed
- I replaced the power cable 'A' w/ power cable 'D'
- ~~No~~ Issue fixed: Power cable A was faulty
- Covered fibre optic cables w/ paper to avoid excess light detection
- Still getting A and B readings??

- Retook coincidence window data
- This time I changed the sample window to 2s and held flashlight in place for several intervals before moving it to a new position, to collect several similar data points and account for fluctuation
- Using the uncertainty on measurement N as $\sqrt{N}$, I got a coincidence count 27 ± 3 ns
- Raw coincidences around 2-3, coincidence count seems to average around 0

Friday, Jan 20th

- I will write values here

Note: The other student was not present for this section. I had to read off these values from my phone screen which was recording the monitor. This may have impacted my ability to properly make out the digits

Single Photons (C)	Single Photons (D)	Raw Coincidences
19553	102167	114
146961	291071	521
213710	81106	294
107925	71895	113
49942	63354	84
29835	48076	30
~~34174~~ 39147	91327	48
53680	221865	171
45013	43020	35
43671	9911	7
48519	10447	12
50684	10909	9
81763	78012	174
30454	73067	28
35898	92743	56
49119	151412	9
44504	119926	92
184064	267373	939
401154	414330	2659
193207	298296	1214
11793	224098	441
18039	20207	12

I accidentally used uncertainty in x values here

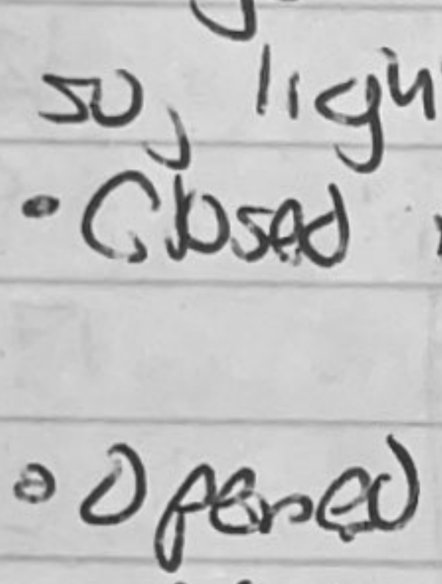
- My least squares fit for this data resulted in a linear fit w/ RCS of 84.4
- It's possible I have not correctly characterized the uncertainty
- Changing the sampling window to T = 5-10s should help eliminate statistical variation

Fri, Jan 20th

Laser Alignment

- Minimized light in room (single photon counts ~ 900)
- Put on safety goggles
- Turned on laser and detectors. Tuned amperage to ~ 60mA
- Read C = 5000 photons, D = 30000 photons
- Turned off everything
- Turned on room lights
- Removed fibre optics from APDs and capped the inputs
- Inserted fibre optic into fault detectors and turned them on. nothing
- Forgot to remove long pass filter. After doing so, light visible
- Closed irises for collectors and crystals

- Opened iris for one collector. Tuned knobs until ~~[illegible]~~ red dot was on center of crystal iris
- Opened crystal iris. Tuned knob until red dot was on the center of the other filter's iris. Repeated for ~~[illegible]~~ other collector
- Place alignment block. See red dots at
  $(4.7 - 2.1) \pm 0.1$ cm $= 2.6 \pm 0.1$ cm
- Block about 24.0 cm from crystal



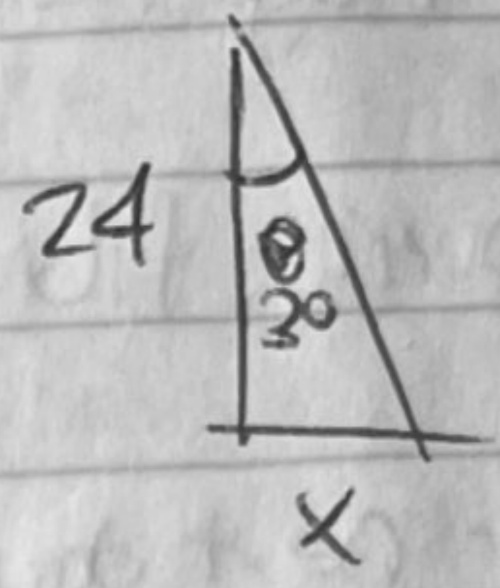
$\cancel{\tan\theta = \frac{24 \pm 0.1\,cm}{1.3 \pm 0.1\,cm}}$

- Alignment block not flush w/ wall

Fri, Jan 20th

- Left dot: 1.8 ± ~~0.1cm~~ 0.05cm
- Right dot: 4.3 ± ~~0.1cm~~ 0.05 cm
- Center: 3 ± ~~0.1cm~~ 0.05 cm

$\left\{\begin{array}{l} 1.2 \pm 0.1\text{ cm} \\ 1.3 \pm 0.1\text{ cm} \end{array}\right.$



$$x = (\tan(3^\circ)) \cdot (24 \pm 0.1\text{cm})$$
$$= 1.257 \pm 0.005\text{ cm}$$

- This is within uncertainty of the two measurements. Laser is aligned!

- Turned off fault detectors
- Removed fibre optics and reattatched to APD
- Ensured all irises are open and closed safety enclosure
  - Reattatched long pass filters
  - Covered fibre optics
  - In between each of the following attempts, laser and APD were switched off
- Turning on laser seems to not do anything! At 41.4 mA.
  - We forgot to remove the alignment block :(
  - D receiving ~15465 but C only 15192?.
- D detects many more photons than C for ambient light as well
- Tried swapping cable ~~B~~ C w/ cable B. No change
- Swapped detectors
- Swapped detector C w/ detector B (connected to cable C)

Fri, Jan 20th

- But now ~~detector~~ port C reads much more light than ~~det.~~ port D ← This was due to exposed fibre optic
- Now photon counts from 2 detectors are on the same order of magnitude (laser at 50mW)

after covering fibre optics, same level

- Goals for next day: discuss coincidence window w/ TA
- Not averaging near 0
- Remeasure window after swapping detectors?
- Allignment seems good.

Tuesday, Jan 24th

Remeasuring coincidence window

- Retrying with $T = 10s$
- Standard procedure: Turn off room lights, turn on altera board and detection software. Turn on APD power
- Varied flashlight position while lab partner read numbers off screen
- Turned off APD detectors and altera board

Single Photons (C)	Single Photons (D)	Raw Coincidences
220 044	457 080	357
223 322	984 283	797
109 982	260 738	166
89 342	105 084	29
131 964	93 249	39
70 465	114 322	34 ~~58~~
293019	65 528	58 ~~37~~
107 710	36 453	32
39961	28 850	7
42109	32 668	8

- This fit resulted in $\tau = 37 \pm 2ns$
- RCS was 4.6. The linear fit still characterizes the relationship as there is a large statistical uncertainty in the input data which is not accounted for
- For raw coincidences ~100 from flashlight, corrected ~30
- For raw ~30, corrected ~ -10

Tues. Jan 24th

- Next, we will vary coincidence window from 35 - 39ns and see how this affects corrected coincidences
~~3 corrected~~
- This didn't seem to have much effect. Stick to $\boxed{\tau = 37ns}$

Setting up quantum state

- Put polarizers in front of collectors
- smallest subdivision: ~~0.1°~~ 2°
- Polarizer angle uncertainty: ~~0.05°~~ 1°

- First we will measure $N(0°, 90°)$, $N(90°, 90°)$ and $N(0°, 0°)$ adjust the HWP until we get a decent measurement for θ
- Once this is done, we will measure all of these values again and $N(45°, 45°)$ to get φ, while monitoring θ. We will adjust ~~θ and φ~~ the QP until θ and φ are close to 45° and 0° respectively
- Once this is done, we will do several measurements and fit

$$N(\alpha, \beta) = A(\sin^2\alpha \sin^2\beta \cos^2\theta + \cos^2\alpha \cos^2\beta \sin^2\theta + 1/4 \sin(2\alpha) \sin(2\beta) \cancel{\cos}\,\sin(2\theta)\cos\varphi) + C$$

to get our θ on φ estimates more precisely

- ~~Both~~ HWP ~~and QP have~~ has smallest subdivision of ~~0.1°~~ 2°. Uncertainty is 1°
- QP has smallest subdivision 1° so uncertainty 0.5°
- Default setting: 204° ± 1° for HWP

Tues. Jan 24th

Thor labs
Vernier
s p polarization

Adjusting HWP

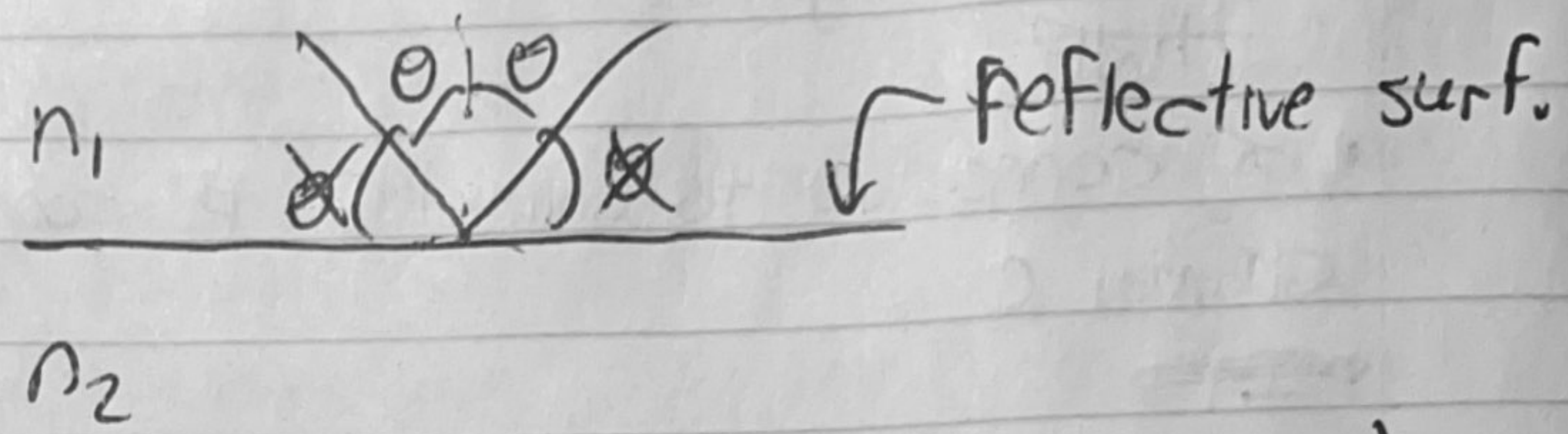
- Again, starting w/ 204° ± 1°
- Polarizers set to (0°, 0°)
- Closer polarizer is angle ~~α~~, farther is β
- ~~Turn off lights~~. T.
  ~~HWP~~
- α corrected to channel D. β connected to channel C
~~...~~
- In between each measurement, turn off laser and APD power, open safety enclosure. ~~set HWP~~ turn on light
- Turn HWP to desired angle. Close safety enclosure (and/or polarizers)
- Turn off lights, turn on ~~lase~~ APD power and laser power
- Read ~~sett~~ output on software
- Use sample window T=10s and coincidence window $\tau = 37ns$
- We will set laser amperage ~50mA (50.1 mA)
- Safety goggles worn whenever laser is turned on

HWP	N(0°,0°)	N(0°,90°)	N(90°,90°)	θ
204° ± ~~1°~~ 2°	11.6865	110.413	48.4547	38° ± 2°
210° ± ~~1°~~ 2°	6.20415	116.753	63.7865	35° ± 2°
200° ± ~~1°~~ 2°	16.1631	69.7895	33.4496	39° ± 3°
190° ± ~~1°~~ 2°				

- Prof Majoribanks came in and pointed out that polarizer angles <u>were not</u> correct. Data is not good

Thurs. Jan 26th

- Last Time, we learned that the 0° markers on the polarizers do not actually indicate ~~to~~ that vertically polarized light will pass
- To fix today, use Brewster's law



- Light reflecting at angle $\theta_p = \arctan\left(\frac{n_2}{n_1}\right)$

will be polarized ~~normal~~ parallel to reflective surface, normal to plane of incidence
- This will serve ~~of~~ as our horizontally polarized light source
- For the lab table, we will assume $n_2/n_1 \sim 1$ so we will hold the polarizers at ~45° to the table and turn the lenses until no light passes through at the 0° setting on the polarizers
- We will then return to the procedure ~~of~~ described in pages 14–15
- This should be enough to get $\theta \sim 45°$ and $\varphi \sim 0°$
- Afterwards, we will fit our measurements w/

I didn't end up using α_0 and β_0 in fit

$$
\begin{aligned}
N(\alpha,\beta) = A\big(&\sin^2(\alpha-\alpha_0)\sin^2(\beta-\beta_0)\cos^2\theta \\
&+ \cos^2(\alpha-\alpha_0)\cos^2(\beta-\beta_0)\sin^2\theta \\
&+ 1/4\,\sin(2(\alpha-\alpha_0))\sin(2(\beta-\beta_0))\sin(2\theta)\cos\varphi \\
&+ C
\end{aligned}
$$

Thurs. Jan 26th

where $A, C, \theta, \varphi, \alpha_0, \beta_0$ are parameters ~~TB~~ to be found
- Note that α_0 and β_0 will give the offset of the two polarizers from vertical (normal to the table) at the $0°$ setting.

* Thor Labs website details the axis of polarization

axis of polarization

- Got notches indicating axis within ~~2°~~ 4° of horizontal by ~~tag~~ setting the polarizer to 0°, placing a ruler across the 270° and 90° markers, and turning the polarizer lens until the notches were colinear with the ruler
- 4° uncertainty because the ruler alignment carries 2° and the ~~atg~~ polarizer being set to 0° carries an uncertainty of 2° and these are correlated
- Placed polarizers back in front of collectors

- Angle α is ~~to~~ angle of polarizer P1, which is connected to detector D, which is connected to port D
- Angle β is angle of P2, which is connected to detector B, connected to port C
- The port names are what we see in LabView

Thurs, Jan 26th

Adjusting HWP

- Do as on page 15

HWP	N(0°,0°)	N(0°,90°)	N(90°,90°)	θ
~~190°±1°~~ 190° ± 2°	94.9517	7.42105	48.8071	34° ± 3°
200° ± ~~1°~~ 2°	61.3416	28.6372	90.8224	54° ± 4°
194° ± 2°	97.8396	16.1393	67.5744	38° ± 3°
196° ± 2°	88.1173	18.662	82.4125	44° ± 3°

- Note that for each measurement, we waited a few sample windows after APD and laser power were on for coincidence counts to stabalize

Calibrating QP

- Same procedure as ~~method~~ calibrating HWP, but now measure N(45°,45°) as well
- Turn dial for QP, initially at 220° (aligned w/ 0 tick). Leave HWP at 196° for now

~~of the same values~~

QP	N(0°,0°)	N(0°,90°)	N(90°,90°)	N(45°,45°)	θ	φ
220°	84.9809	14.4704	70.2904	25.6	41° ± 3°	130° ± 2°
200°	90.516	19.0852	71.5641	36.3353	41° ± 3°	~~[illegible]~~

Thurs, Jan 26^{th}

We ran into issues calculating φ and its uncertainty because arccos is not a well behaved function. The combination of HWP at 196° and QP ~~HWP~~ at 200 resulted in

$$\left\{ \begin{array}{l} \theta = 41^\circ \pm 3^\circ \\ \cos\varphi \sim 0.97 \end{array} \right.$$

- With this in mind, we move on to fitting $N(\alpha, \beta)$
- I will start w/ $\alpha = 0°$ fixed. $T = 10s$ and $\tau = 37ns$
- Note N is the corrected coincidences

β	N	β	N
0°	94.4399	100°	11.7021
10°	87.8154	110°	25.1435
20°	81.41	120°	28.0823
30°	69.2916	130°	34.0586
40°	72.7868	140°	41.4093
50°	62.1861	150°	58.7906
60°	44.0527	160°	80.5508
70°	22.0501	170°	91.4897
80°	25.506	180°	78.6774
90°	22.2792		

- This data alone can't be used to fit $N(\alpha, \beta)$ for θ and φ since

$$N(0, \beta) = \cancel{A \cos}$$
$$= A\cos^2(\beta)\sin^2\theta + C$$

- Do $\alpha = 45°$

Fri, Jan 27th

- Today, repeat process on page 19, but for $\alpha = 45°$

β	N
0°	60.4976
10°	79.9712
20°	60.7304
30°	66.8787
40°	
50°	
60°	
70°	
80°	
90°	

- At this point, stopped to double check laser alignment
~~Comp~~ very misaligned,
- Aligned laser as on pg 10
- Put everything back

~~Cable D~~

- Start again $\alpha = 45°$

B	N
0°	
10°	
20°	
30°	
40°	
50°	
60°	
70°	
80°	
90°	

- At this point, no light from detector D
- So we replaced cable D ~~B~~ w/ ~~detector~~ cable ~~D~~ B
- Detector ~~D~~B still connected to cable C

Fri, Jan 27th

- Trust but verify: double check coincidence window and θ, φ

Coincidence window: set $T = 5s$. Repeat process in page

Single Photons (B)	Single Photons (C)	Raw Coincidences (BC)
172760	221961	222
258279	334811	554
169757	438789	436
39913	712365	191
27787	403575	91
24742	154629	27
25651 ~~25665~~	196064	28
~~24711~~	134846	25
17565	72385	11
5821	34848	2

- Fit result: $\tau = \cancel{32 \pm 1ns}$ $= \boxed{32.0 \pm 0.9ns}$
- RCS of 1.37

- Next, double check rough θ, φ values w/ $T = 10s$, $t = 32ns$

~~HWP~~	~~QP~~	~~N(0°,0°)~~	~~N(0°,90°)~~	~~N(90°,90°)~~	~~N(45°,45°)~~

- Crossed out value anomolously high replace w/ 31.3418 upon remeasurement

Fri, Jan 27th

HWP	QP	N(0°,0°)	N(0°,90°)	N(90°,90°)	N(45°,45°)	φ	cos φ
196°	200°	32.0846	11.4346	22.4962	18.6261	36° ± 7°	0
200°	200°	~~40.9592~~	10.1344	23.1706	18.5751	38° ± 6°	
204°	200°	11.005	13.7863				stopped
192°	200°	35.715	5.83631	22.6229	17.5671	36° ± 6.5°	
170°	200°	45.9347	5.75742	0.64535	23.0684	nan?	nan?
180°	200°			3.50644	~~3.50644~~		
220°	200°	0.840388	16.481	26.9377			
210°	200°	10.3276	12.3581				
~~200°~~	~~190°~~	12.4684					
~~200°~~	~~196°~~						
200°	190°	16.0121	~~12.46~~ 12.4689	27.4454	12.1369	63° ± 14°	3?
200°	210°	23.5966	10.48	33.0152	15.758	52° ± 6°	~0.84
200°	220°				4.0		
200°	212°	22.0029	8.3543	35.7704	26.6823	54° ± 5°	
200°	214°			30.6106	14...		

- Uncertainty in cos φ still massive, ~~~1000~~ ~64.
- Instead, we will try to maximize N(45°, 45°)
- * by guess & check
- HWP at 200° and QP at 212° is the best we're gonna get

- Note that the corrected coincidences were 20-30 which could be effecting accuracy of results
- Why did corrected coincidences go DOWN after realigning laser? >:(

Fri, Jan 27th

- Now, curve Fit, $a \approx 45°$

B	N	B	N
0°	11.3782	100°	
10°	21.3363	110°	
20°	17.6649	120°	
30°	14.5515	130°	
40°	25.7098	140°	
50°	22.9712	150°	
60°	17.1489	160°	
70°	16.1451	170°	
80°	9.53556	180°	
90°	7.64444		

- Fit uncertainties still way too big. What is happening?

several orders of magnitude

	B	C	Raw	Corrected
- Cleared polarizer lenses lenses ~~current 60mA~~	10^5	$1.3 \cdot 10^5$	66	20
current 50mA -> 60mA	$1.5 \cdot 10^5$	$1.9 \cdot 10^5$	128	36

- Why is the correction so large?

Fri, Jun 27th

- Removing polarizers, C displayed 50% more detections than B consistently. Could this be skewing results?

- ~~Increased pow~~ amperage to 65 mA

- Increased detection window to a full 30s, still very small values for corrected BC (~4)

- Statistical correction ~21
- Removing polarizer, still 43 corrected?

- ~~I believe the software is overestimating the statistical correction by a lot~~
- ~~when shin~~
- Typically, most of the raw coincidences (at least half) are not included in the corrected coincidences
- However, when shining flashlight near the detectors these corrections seem right. The program ~~se~~ rounds to ~0 corrected coincidences as expected
- Could there be something wrong w/ the crystal? How could I even check that?

~~Ore~~ or even something wrong with the laser itself.

This is probably the case

Tues, Jan 31

- Check that polarization angles are correct ✓
- Double check laser alignment
- It seems the lens on the nearest collector (connected to detector D and cable) G is a bit loose.
- I replaced the long pass filter afte realignment very carefully.

- Detectors seem to not be reporting much light from laser OR Flashlight. >10000 each

- Made sure everything was plugged in

- Detector B (cable C) is responsive.
- Detector D (cable B) is NOT
- Shining light at it results in minimal counts.
- Replaced with detector C

- Replaced cable A w/ a new cable and plugged it into detector G. This fixed the "too much light issue ~~fro~~ from page 8, but did not fix the counts reported by detector C.

- Could the fibre optics be at fault? To do this, swap detectors C and B set ups entirely
- Actually first, swap APD power cables
- That changed nothing. Swap back, and then swap fibre optics

Tues Jun 31st

- Swapping fibre optics changed everything!
- Now, detector C is responsive while B is not!

- Now both even despite no changes?

- Realigned laser
- 1.8 cm for left, 4.4 cm for right ✓

- Current set up
  - P1 → Detector B → Cable C
  - P2 → Detector C → Cable A
- The cable corresponds to the channel in detection.v1
- Channel A not getting as many as C
- Still getting ~30 raw counts
- Removed polarizers
- w/o polarizers, Channel A has 1/4 of channel ~~B's~~ C's light
- for T = 5s, A ~ ~~20k~~ 5k w/ C ~ ~~100k~~ 20K
- Swap fibre optics and turn laser back on
  A ~ 150K and ~~C ~ 65K~~ C ~ 6.5K
- Definitely the fibre optics
- TA came in, fibre optics were bent :(
- He suggested fine tuning alignment until both channels were getting similar amounts of light
- This seemed to only decrease the amount of light to channel C

Tues, Jan 31st

- It seems the only course of action is to align laser, lower channel A counts until they agree w/ channel C counts, check θ and φ, and attempt to measure S

- When removing fibre optics from ~~de~~ fault detector, the fault detector tip came off :(
- Stuck on fibre optic
- Larry fixed it
- Replaced faulty fibre optic w/ new one
- Channel A still getting nothing (detector C)
- The new fibre also not working ≤2000 at T=6s
~~Counts from laser while channel~~
- Replaced spare fibre w/ old one
- Replaced w/ brand new fibre, still nothing >4000 k
- Replaced w/ original fibre, still sub 4000 k
- Restarted software, no change

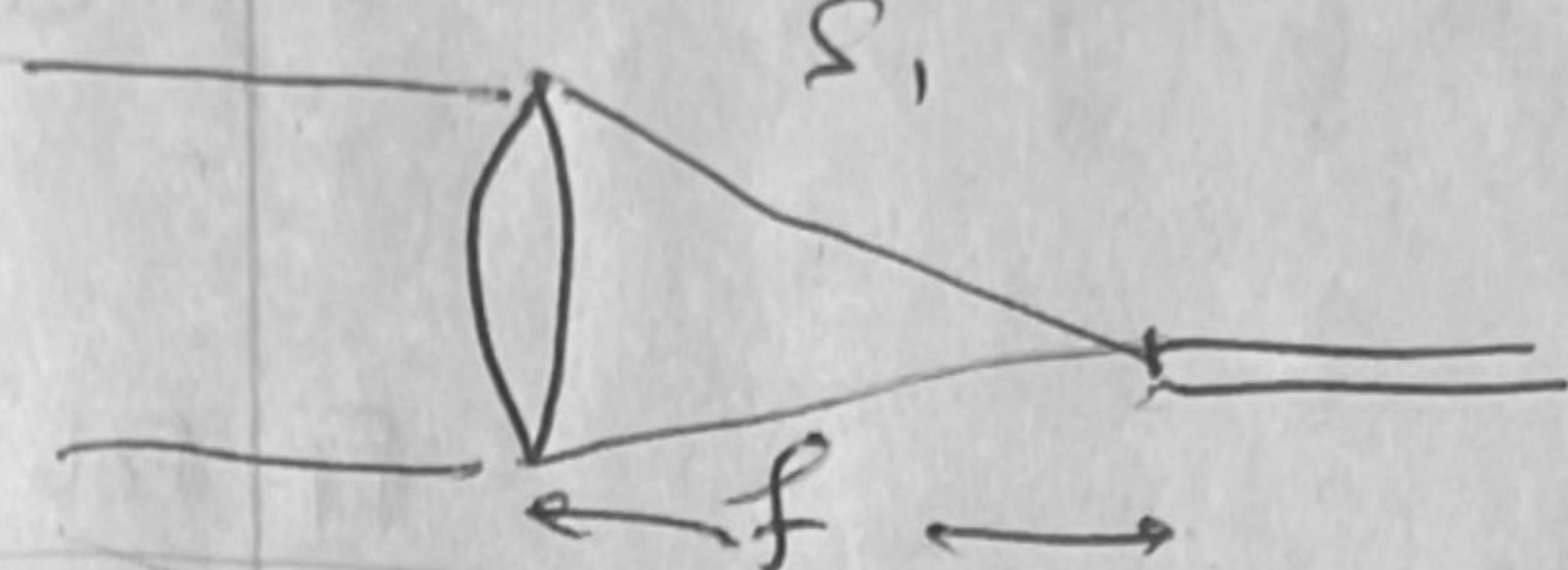
- When realigning laser, light emitted from collector A (was connected to C)
detector C

is unfocused. Instead of a ~~laser~~ point, we got a blur of unfocused light
- Swapping out fault detectors and fibre optics did not change this

Fri. Feb 3rd

- Fault detector tip got stuck again on fibre optic
- Lab tech got it off
- Turned on laser. single photon counts too low. ~5000 for each detector
- I believe the issue is w/ photon collector A (the nearest one)
- We will replace it w/ a spare
- Top of ~~detector~~ collector is at 12.1 ± 0.5 cm when base of ruler WESTCOTT ruler is on table
- There is no spare
- We ~~replaced~~ removed the collector. Removed its iris. Wiped lens w/ delicate tissue (task wipers) Kimtech and replaced at original height.
- Angle can be readjusted using knobs
- Marjorie banks entered and explained how fibre optics actually are supposed to connected
- Have to screw it in until the key latches
- This fixed the beam
- We made sure to replicate this for each fibre connection
- Turned on laser. ~20K for detector A ~30K for detector G after realigning collectors

Fri, Feb 3rd

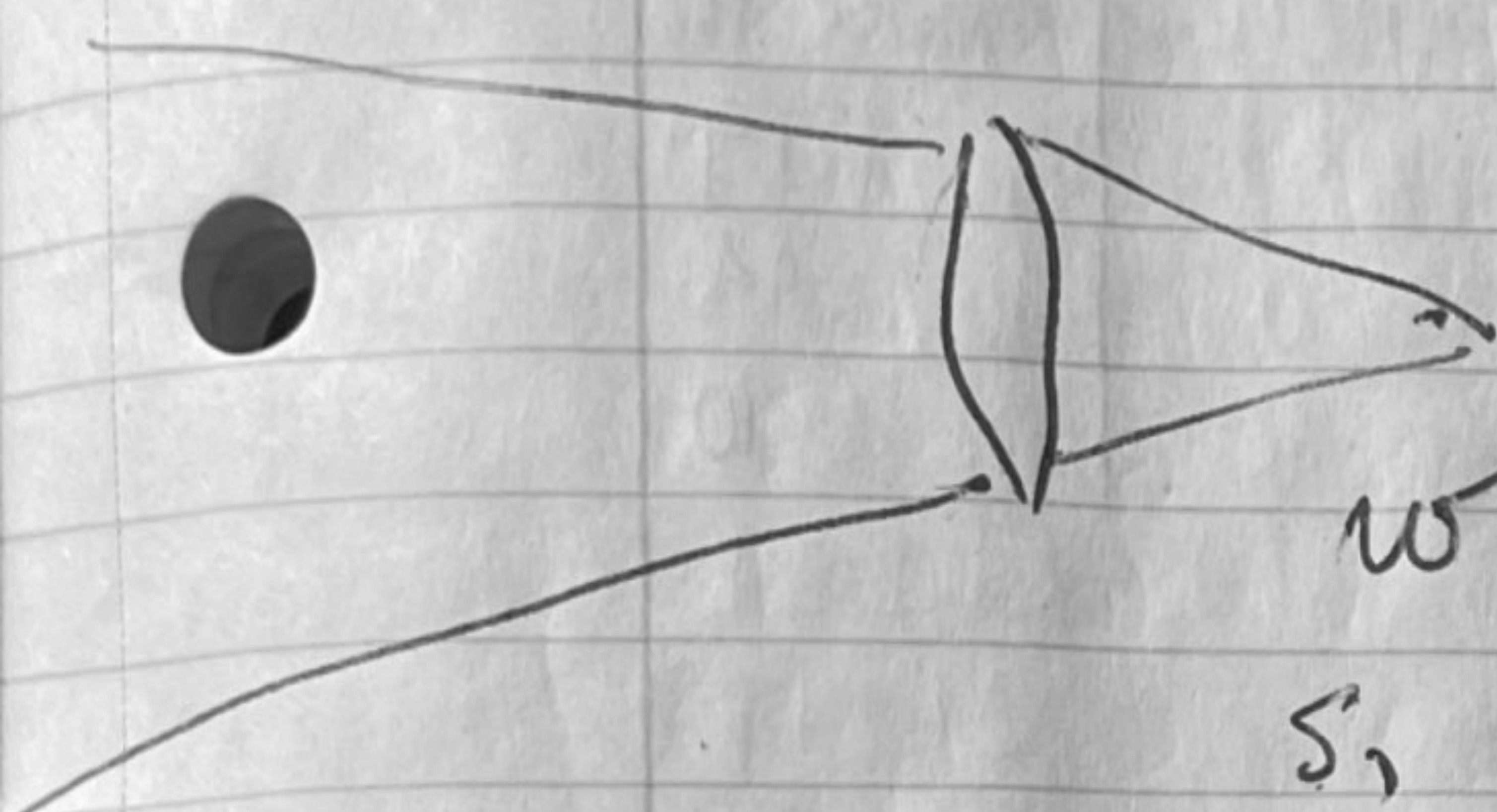


s_1 too big

$$\frac{1}{f} = \frac{1}{s_1} + \frac{1}{s_2}$$

correct: $s_1 = f$
$s_2 = \infty$
$\Rightarrow$ collimated

<u>you</u> see:



What does that mean?

s_1 too small, $s_1 < f$.

<u>Suggests</u> someone changed <u>lens</u> to compensate error in mounting fiber <u>too far</u> (<u>key</u> not mounted

Fri Feb 3rd

Measuring Coincident Window AGAIN

T=5s for this

Single Counts A	Single Counts C	Raw
55112	27384	11
59738	32670	14
60022	27422	12
67441	20584	5
~~53061~~ 53016	19784	10
41287	17742	9
57554	15768	9
88656	13142	9
78627	9929	4
103641	5638	10

- Fit has $\tau = 35 \pm 4$ ns
- 1.3 RCS
- We will use this value going forward
- Prof Marjoribanks suggested experimenting w/ alignment to check counts
- T=3s. I will adjust knobs on collectors to increase counts

A~50K C~80K

- Best we got: A~71K, C~83K

- Replaced polarizers in their locations
- Set T=10s again

Fri Feb 3rd

Now, HWP and QP again

~~HWP~~	QP	N(0°,0°)	N(~~90°~~ 0°, 90°)	N(90°,90°)	N(45°,45°)	θ

HWP	QP	N(0°,0°)	N(0°,90°)	N(90°,90°)	N(45°,45°)	θ	cos φ

HWP	QP	N(0°,0°)	N(0°,90°)	N(90°,90°)	N(45°,45°)	θ	cos φ
200°	212°	83.172	21.9218	74.5485	52.5863	43° ± 3°	-0.1 ± 0.[illegible]
200°	220°				9.53701		
	200°				50.3233		
	205°				49.08066		
	190°				14.3225		
	180°				30.7745		
	175°				9.3962		
	212°				63.8436		

- Calculation for cos φ is unreliable. We just tried to maximize N(45°, 45°) instead

Fri Feb 3rd

Measuring S

- We need 16 pairs of angles to do this
- set T = 15s for this.

α	β	A	B	Coincidences Corrected	Correction
-45°	-22.5°	145740	235588	59.8595	80.1415
-45°	22.5°	144740	231590	42.7859	42.7859
-45°	67.5°	142965	154932	122.317	51.683
-45°	112.5°	142618	163827	159.482	54.5176
0°	-22.5°	191456	233205	107.82	104.18
0°	22.5°	191368	229586	71.5198	102.48
0°	67.5°	191628	152546	20.7694	60.2306
0°	112.5°	191674	161647	91.7051	72.2944
45°	-22.5°	201270	245610	40.6542	115.346
45°	22.5°	197355	224470	82.3302	105.67
45°	67.5°	196155	153301	61.8344	70.1651
45°	112.5°	197181	160365	21.2178	73.7822
90°	-22.5°	146901	233202	36.12	79.88
90°	22.5°	146367	224811	58.2061	76.7934
90°	67.5°	145598	151375	120.574	51.4264
90°	112.5°	146598	161219	87.8531	55.1469

- For each, we took the SECOND set of measurements we saw to make sure the laser was on for the entire sampling interval
- If analysis is correct, $S = 1.1 \pm 0.4$
- Err $= \sqrt{N}$ where N = corrected coincidences
- Curve fitting resulted in: RCS = 16

  $\theta = 44.7° \pm 1°$, $\cos\phi = 0.2° \pm 1°$

  A = ~~147.6~~ ~~150±6~~ 147±62, C = 25±15

Fri Feb 3rd

- We need to fix $\cos\varphi$
- $T = 10s$

	HWP	QP	N(0°,0°)	N(0°,90°)	N(90°,90°)	N(45°,45°)	θ	cos φ
This is all right	200°	212°						
	200°	100°		~~I forgot to~~	~~write~~ something here	0		
	200°	150°				47.7715		
		140°				24.1095		
		145°				26.5785		
Wrong →		155°				72.0219		-2?
	~~200°~~	~~145°~~				~~72.0219~~		
	200°	156°	74.1152	24.0705	80.8817	72.0219	47.3°	-~~32~~?

- Still no luck
- A classical value of S, w/ ~~cor~~ corrections so large on page 32 might suggest that our photons are not actually down converted pairs
- When laser is off, no coincidences are detected in the room
- The laser must be producing this ~~an~~ 'ambient' light
- If I had more time, I would tweak the crystal orientation to try ~~produce more~~ and decrease the statistical correction value, so that my photons were actually down converted pairs
- The table on page 32 also supports this. The corrected coincidence count is often lower than the statistical correction value, suggesting that these photons

Fri Feb 3rd

are not entangled.

- The detectors are getting a large amount, and consistent number of photons
- ~~Perhaps the laser is not~~ ~~crystal~~
- The crystal may not be oriented properly to produce spontaneous down conversion
- More time is needed

Sun Feb 5th

- Note that S was calculated using

$$\cancel{E(\alpha,\beta) = N(\alpha,\beta) + N(\alpha+90°,\beta+90°)}$$

$$E(\alpha,\beta) = \frac{N(\alpha,\beta) + N(\alpha+90°,\beta+90°) - N(\alpha+90°,\beta) - N(\alpha,\beta+90°)}{N(\alpha,\beta) + N(\alpha+90°,\beta+90°) + N(\alpha+90°,\beta) + N(\alpha,\beta+90°)}$$

and

$$S = E(\alpha,\beta) - E(\alpha,\beta') + E(\alpha',\beta) + E(\alpha',\beta')$$

which choice of angles

$$\alpha = -45°, \quad \alpha' = 0°$$
$$\beta = -22.5°, \quad \beta' = 22.5°$$

- I forgot to mention these earlier but

θ and ϕ calculated in	get_theta_phi.py
$N(\alpha,\beta)$ was fit in	fit_N.py
coincidence window measured in	coincidence_window.py
S calculated in	calculate_S.py

- My biggest takeaway from this experiment is to not take ANYTHING for granted

Sun, Feb 5th

- I must do better to understand my equipment and the physics behind how it works
- If I had done more research towards understanding the BBO crystal, instead of sweeping it under the rug, this experiment may have seen more success!

- The abstract and summary are contained in the file ~~QIE_A~~ QIE_Summary_and_Abstract