# Lab 1b Spontaneous parametric Down Conversion - Week 2

**Phys434L Quantum Mechanics Lab**
**2018**

**March 19, 2018**

## 1 Spontaneous Parametric Down-conversion

The first step in this experiment is to set up the apparatus to produce spontaneous parametric down conversion. It is a weak process; about a fraction of $10^{-10}$ photons get converted.

### 1.1 Theory

In this process, a pump photon of energy $E_0$ is converted into two photons of energy $E_1$ and $E_2$ such that

$$E_0 = E_1 + E_2, \tag{1}$$

or expressed in terms of the wavelength in vacuum via $E = hc/\lambda$,

$$\frac{1}{\lambda_0} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}, \tag{2}$$

In a birefringent medium, spontaneous parametric down-conversion occurs due to the interaction of the light and the medium. For down-conversion to occur, momentum must be conserved:

$$\vec{p}_0 = \vec{p}_1 + \vec{p}_2. \tag{3}$$

The propagation of the light in a medium is accounted for by the index of refraction $n$, so $p = 2\pi n\hbar/\lambda$. If the two photons are not degenerate, then by conservation of momentum in the transverse direction, and because the input momentum in the y direction is zero, then

$$p_{0y} = p_{1y} + p_{2y} = 0, \tag{4}$$

or

$$\frac{n_1}{\lambda_1}\sin\theta_1 - \frac{n_2}{\lambda_2}\sin\theta_2 = 0. \tag{5}$$

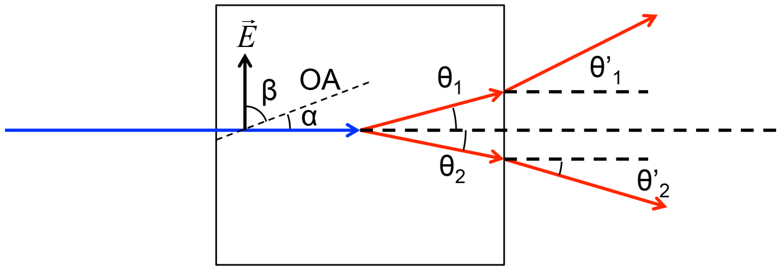


Figure 1: Geometry of the down-conversion process. OA is the optic axis, which forms an angle $\beta$ with the electric field of the pump beam, and an angle $\alpha$ with the propagation direction. The angles formed by the down-converted photons with the incident direction inside the crystal are $\theta_1$ and $\theta_2$, and the angles that they form outside the crystal are $\theta_1'$ and $\theta_2'$.

If the down-converted photons have different energy, then they come at different angles, as shown in Fig. 1. In any medium the index or refraction depends on the wavelength. Conservation of momentum in along the direction of the input beam is

$$p_{0x} = p_{1x} + p_{2x} = p \tag{6}$$

or

$$\frac{n_0}{\lambda_p} = \frac{n_1}{\lambda_1}\cos\theta_1 + \frac{n_2}{\lambda_2}\cos\theta_2. \tag{7}$$

If we consider the case when $\lambda_1 = \lambda_2$, then from Eq. 5, $\theta_1 = \theta_2$ and so Eq. 7 together with $\lambda_1 = \lambda_2 = 2\lambda_0$ reduces to

$$n_0 = n_1 \cos\theta_1. \tag{8}$$

If we consider the case of collinear emission ($\theta_1 = \theta_2 = 0$), then it occurs only if

$$n_0 = n_1. \tag{9}$$

In these experiments we use beta barium borate (BBO) crystals, which are birefringent. In birefringent crystals the index of refraction depends on whether the light is orthogonal to the optic axis or not. If the electric field is orthogonal, then the index of refraction is known as "ordinary." When the electric field is parallel to the optic axis, the index is known as "extraordinary." For BBO the two indices are given by

$$n_e = \left(2.3753 + \frac{0.01224}{(\lambda/1\mu m)^2 - 0.01667} - 0.01516(\lambda/1\mu m)^2\right)^{1/2} \tag{10}$$

and

$$n_o = \left(2.7359 + \frac{0.01878}{(\lambda/1\mu m)^2 - 0.01822} - 0.01354(\lambda/1\mu m)^2\right)^{1/2}. \tag{11}$$

A graph of the indices is shown in Fig. 2.

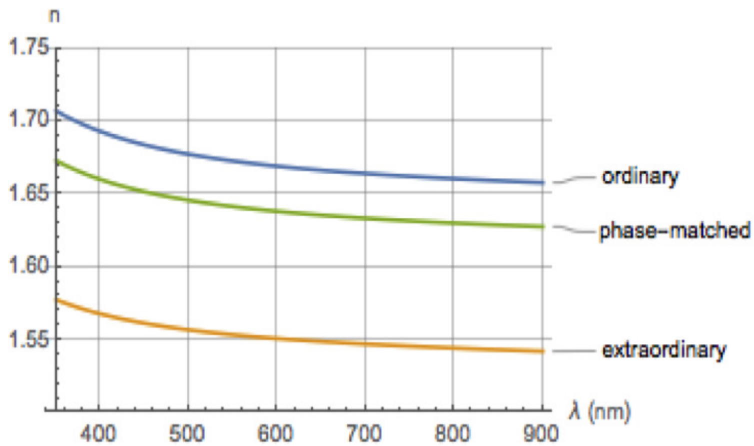

Figure 2: Indices of refraction for BBO.

Note that the indices depend on the wavelength of the light. The indices of refraction for pump-beam light of wavelength 405 nm are $n_{e0} = 1.5671$ and $n_{o0} = 1.6919$. Similarly, the indices for the down-converted photons at 810 nm are $n_{e1} = 1.5442$ and $n_{o1} = 1.6603$. Note that for the index of a given kind ($e$ or $o$), $n_0 > n_1$, which implies that Eqs. 8 or 9 can never be satisfied if the polarizations of the pump and down-converted photons are the same.

The extraordinary index can be tuned by having the polarization of the light form an angle $\beta$ with the crystal axis. It is usual to express the new index of refraction in terms of the complement of this angle: $\alpha = \pi/2 - \beta$, which is also the angle that the direction of propagation forms with the crystal axis. In that case the index of refraction is given by

$$n_{e,\alpha} = \left( \frac{\cos^2 \alpha}{n_o^2} + \frac{\sin^2 \alpha}{n_e^2} \right)^{-1/2}. \tag{12}$$

It is possible for the crystal to help with the emission of photons with a polarization such that Eq. 8 is satisfied. In type-I parametric down conversion, the down-converted photons have a polarization that is *perpendicular* to that of the pump photons, a situation known as *phase matching*. When this occurs the indices of refraction may satisfy Eq. 8 at a specific angle $\alpha$. This is shown in Fig. 2. For example, if the angle between the axis and the propagation direction is 29.25°, we have that $n_{e0,\alpha} = 1.6594$. Down-converted photons at 810 nm will be generated at an angle

$$\theta_1 = \cos^{-1} \left( \frac{n_{ep,\alpha}}{n_{o1}} \right), \tag{13}$$

which for our case is $\theta_1 = 1.8°$. Outside the crystal the down-converted photons get refracted, so applying Snell's law, they come out at an angle

$$\theta_1' = \sin^{-1}(n_{o1} \sin \theta_1), \tag{14}$$

or $\theta_1' = 3.05°$ for the conditions mentioned. For other wavelengths, down-conversion occurs at different angles. Figure 3(a) shows the emission angles, outside the crystal, of down-converted photons as a function of wavelength when $\alpha = 29.1°$. From the graph one can

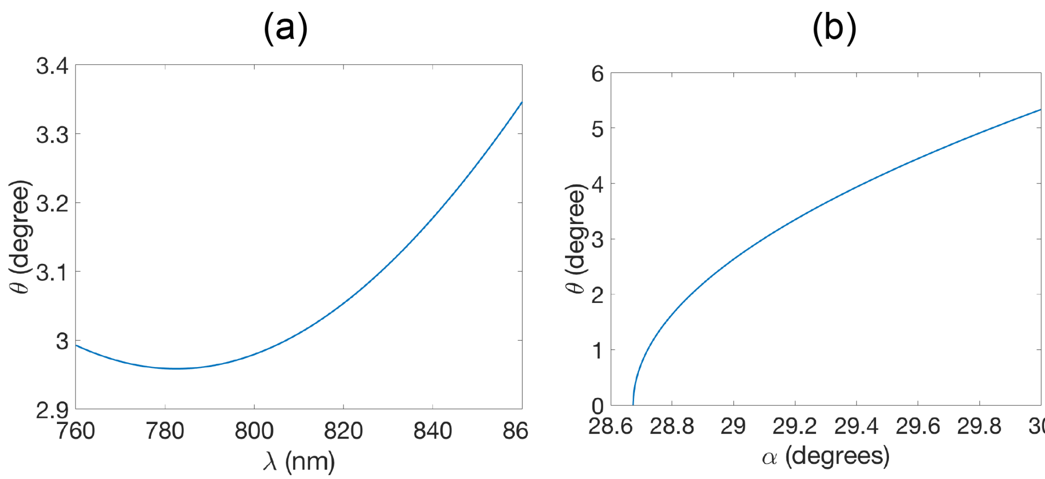


Figure 3: Graphs showing the angles at which down-converted photons are emitted: (a) as a function of wavelength for fixed $\alpha = 29.1°$, and (b) as a function of $\alpha$ for fixed $\lambda = 810$ nm.

obtain that if $\lambda_1 = 840$ nm, the emission angle outside the crystal is $\theta_1' = 3.17°$, whereas its partner photon at $\lambda_2 = 782$ nm appears at $\theta_2' = 2.96°$

The graph in Fig. 3(b) shows the dependence of the angle of the down-converted photons as a function of the angle $\alpha$ inside the crystal. As can be seen, changes by only a fraction of a degree have a corresponding effect on the angle of the down-converted photons. In actuality, there is also a slight difference between the directions of the pump photon outside and inside the crystal due to refraction. In practice, also the input crystal face may not be perpendicular to the input beam. However, those modifications do not alter significantly the results shown in Fig. 3, relating the down-converted angles to the wavelength and phase-matching angle $\alpha$.

## 1.2 Procedure

The parts that are needed are listed in the table below. The parts refer to Fig. 4.

| Qty | Part | Description/Comments |
|---|---|---|
| 1 | Flip-mirror | (F) So it flips in and out of HeNe beam path. It is on a translation mount. |
| 1 | Plumb bob | For aligning the beams with marks on the table. |
| 1 | Curved plate with 1-m radius of curvature | For help with the adjustment in the placement of collimators to detect partner photons. |
| 1 | GaN diode laser | 405 nm, $>$ 20 mW, polarized. |
| 1 | BBO crystal | Type-I, mounted, 29° phase matching, with optical axis on horizontal plane. |
| 1 | Mirror + translation stage | (D) For easy aligning of the pump beam. |
| 2 | Fiber collection assembly | (DA and DB) Multimode fiber with mounted collimator, plus iris mounted on the collimator mount. |
| 2 | Band-pass filters | 800-810 nm center wavelength, 40-nm bandwidth. |
| 2 | Detectors | Avalanche photodiodes, fiber-coupled. |
| 1 | Beam dump | For safety, to stop the pump beam. |
| 1 | Laser goggles | For safety, to block 405 nm during alignment. |
| 1 | Electronics | To record singles counts and coincidences. |
| 1 | Computer | Interfaced to the apparatus. |

To set up the experiments we first need to carefully position each component in a deliberate order, described below.

1. After exercising how to align optical beams with the rows of holes on the optical breadboard, we need to set up the path of the beams relevant for down-conversion: those of the pump beam and the down-converted photons, with the former forming angles of 3° with the latter. These paths are shown in Fig. 4(a). Use the path of the HeNe laser from the alignment exercise, which uses mirrors A and B, as shown in the figures in Lab ,1 to mimic the path of one of the down-converted photons. Place a mark ("×") at the approximate location shown in Fig. 4(a) exactly under the HeNe beam. A small plumb-bob can help with this: casting a shadow when it is in the path of the beam. The down-conversion crystal will be placed at this location. Make three "+" marks at 1-m down-stream from the location of the crystal, as shown in the figure. One mark is just 1-m downstream from the "×" mark. An easy angle for down-conversion experiments is $\theta'_1 = \theta'_2 = 3°$, so make marks 1-m from the "×" mark in directions forming 3° and 6° from the direction of the HeNe beam. It is useful to know that $\sin 3° = 0.052$. If available, place a plate with 1-m radius of curvature with the curved surface along the "+" marks.

2. Place the fiber collimator so that the light from HeNe beam reflected by mirror (B) enters the fiber. The base of the collimator must rest on the curved plate, if available. There are techniques to do this alignment. The best one involves attaching an iris to the collimator mount and adjust the unit so that the beam is aligned with the iris. The collimator has to look into the beam. To accomplish this we place a mirror up against the collimator/iris, and the tilt the mount until the HeNe beam is reflected

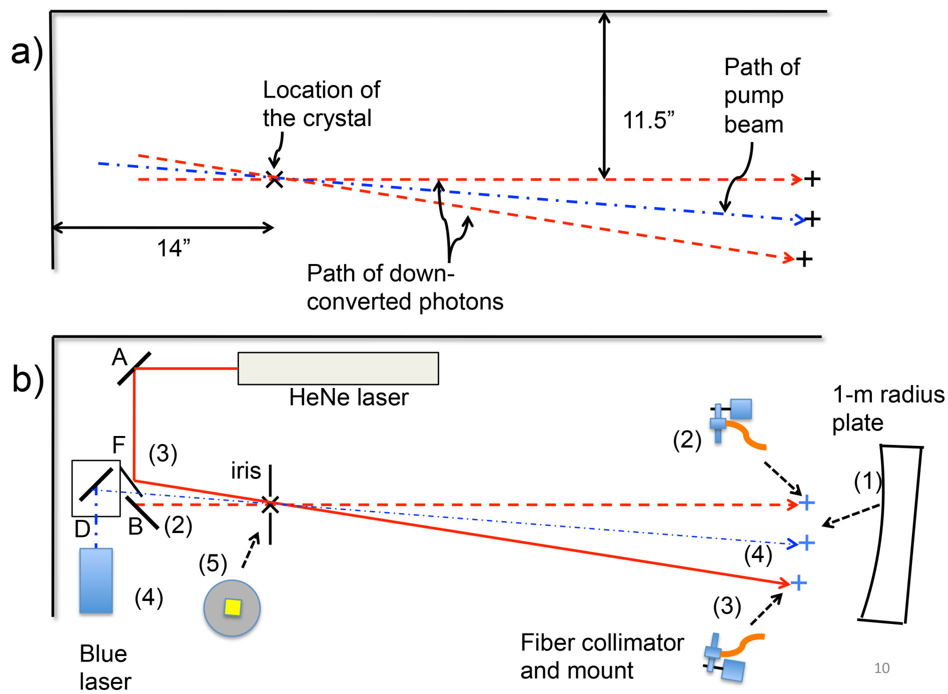


Figure 4: (a) Schematic of the paths of the pump photons (blue, dash-dot line) and down-converted photons (red, dashed line). (b) Schematic of the set up and alignment of the parts of the optical setup, which includes mirrors A, B, F (which flips), and D (on a translation stage). The numbers refer to steps in the procedure.

straight back. This is an iterative process because tilting the collimator may change its position relative to the beam.

3. Mirror (F) is mounted on a “flipper mount,” and placed on top of a translation stage. It can flip in and out of the path of the HeNe beam. Place mirror (F) (Fig. 4(b)) such that it steers the light along the path of the second down-converted beam. Use the adjustment of the translation stage in combination with the steering knobs of the mount. The beam path off the flipper mirror must go over the location of the crystal and go above the corresponding “+” mark downstream. The use of irises placed at the two locations helps significantly. Once the beam follows the right path we need to place a second collimator and adjust it so that the light enters the fiber, similarly to what was done with the first collimator. The collimator base must rest against the plate, if available.

4. Now the pump laser is added to the table. The height of its output beam must match that of the HeNe beam. Steer the light from the pump laser with mirror (D) so that it follows the path shown in the figures: half-way in between the paths of the down-converted photons. It helps to place mirror (D) on a translation stage and the use of irises at the crystal and “+” mark locations.

5. Finally, place the crystal in the "×" location. The HeNe and pump beams should cross at the crystal location.

6. Place band-pass filters in front of the collimators. The other end of the optical fibers attached to the collimators must be connected to the detectors. Turn off the HeNe laser. Turn off the lights in the room (green LED lights can be on because that light is blocked by the filters). Turn-on the detectors and the electronics that records coincidences.

7. Maximize the raw counts from each detector, the "singles," by tilting the crystal. If the input polarization is horizontal, and the crystal is oriented properly, the tilt axis is vertical. The singles signals should be very sensitive to the tilt of the crystal: they should peak at a certain tilt of the crystal and sharply go down for other tilts. If the singles from the two detectors do not peak at the same tilt angle, then the collimators are not at the right angles. At that point you adjust the tilt to peak one detector, and displace the other collimator along the curved plate until the singles for the corresponding detector go through a peak. At this point you have to check that you have real down-conversions. The coincidence counts of the two detectors must be larger than the accidental coincidences, given by

$$N_{\text{acc}} = N_1 N_2 \Delta T, \tag{15}$$

where $N_1$ and $N_2$ are the singles counts per second and $\Delta T$ is the maximum time delay between pulses that is considered a coincidence. For example, a typical coincidence circuit has $\Delta T = 50$ ns. If the singles are 20,000 $\text{s}^{-1}$ for each detector, then we should expect an average of 20 accidental coincidences per second. Optimal alignment should produce coincidences that are 10% of the singles counts.

## 1.3 Questions: Due 2/12/18

1. If a 50 mW pump beam with a wavelength of 405 nm is used to produced down-converted photons, a fraction of $\times 10^{-10}$ photons get converted. How much power is in the down-converted light at 810 nm?

2. Down-converted photons are produced at random times, but suppose that in the average they are evenly separated in time, if the photons were to travel past the confines of the optical table, how far apart would consecutive photons be?

3. If the angle $\alpha = 29.5°$,

   (a) What is the new index of refraction of the pump beam inside the crystal?

   (b) What is the new angle $\theta$ formed by downconverted photons inside the crystal?

   (c) What is the new angle $\theta'$ formed by downconverted photons outside the crystal?

4. With the setup of Fig. 4(b) record singles and coincidences from detectors A and B. Calculate the accidental coincidences and compare them with the measured one. Propagate errors: you can consider the statistics to be Poissonian, and so the error in the number of recorded counts $N$, is $\sqrt{N}$.