Advance laboratory class 2

# FP2 - Entanglement and Bell's inequality

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**Abstract**

In this work we performed correlation measurements on entangled photons produced by spontaneous parametric down conversion (SPDC). The purpose of this experiment was to test Bell's inequality and thus check if quantum mechanics is complete or not. We found a Bell Parameter of $S = \pm$ which means that Bell's inequality doesn't hold.

# 1 Introduction

Historically quantum mechanics has been subjected of many critics due to its strange nature. Many attempts were made in order to explain this theory in a more intuitive way, one of these it the hidden variables interpretation of quantum mechanics. In order to test this interpretation Bell published an inequality [**?** ] that cannot be violated if the theory has hidden variable. The advantage of such inequality is that contains quantity that can be experimentally measured. This work it is a test of Bell's inequality, we used entangled photon in order to check this equality. Entangled photons are produced by SPDC inside a BBO ($\beta$ - $BaB_2O_4$) crystal. These photons are polarization entangled, this means that we can describe a state of two photons as, for example

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|HV\rangle + |VH\rangle\right),$$

where $H$ and $V$ refer to horizontal and vertical polarization respectively. It is also possible to write the same state as a function of the $D/A$ basis, which correspond to $\pm 45°$ polarization,

$$|D\rangle = \frac{1}{\sqrt{2}} \qquad |A\rangle = \frac{1}{\sqrt{2}}$$

(altra roba?).
There are different version of Bell's inequality, but for our experiment the most useful one was derived by Clauser, Horne, Shimony, and Holt [] and it is the following

$$S = |E(\alpha,\beta) - E(\alpha,\beta')| + |E(\alpha',\beta) + E(\alpha',\beta')| \leq 2,$$

where $S$ is called the Bell's parameter and $E(\alpha,\beta)$ is the expectation value of the polarization correlation measurements where the measure is made on a two photon system with the polarizers set at angle $\alpha$ and $\beta$. In our experiment, this expectation value can be calculated with the number of coincidences as

$$E(\alpha,\beta) = \frac{1}{N}(C(\alpha,\beta) + C(\alpha+90,\beta+90) - C(\alpha+90,\beta) - C(\alpha,\beta+90)),$$

where $C(\alpha,\beta)$ is the number of coincidences with polarizer $A$ set to $\alpha$ and polarizer $B$ set to $\beta$ and $N$ is

$$N = (\alpha,\beta) + C(\alpha+90,\beta+90) + C(\alpha+90,\beta) + C(\alpha,\beta+90).$$

## 2 Experiment setup

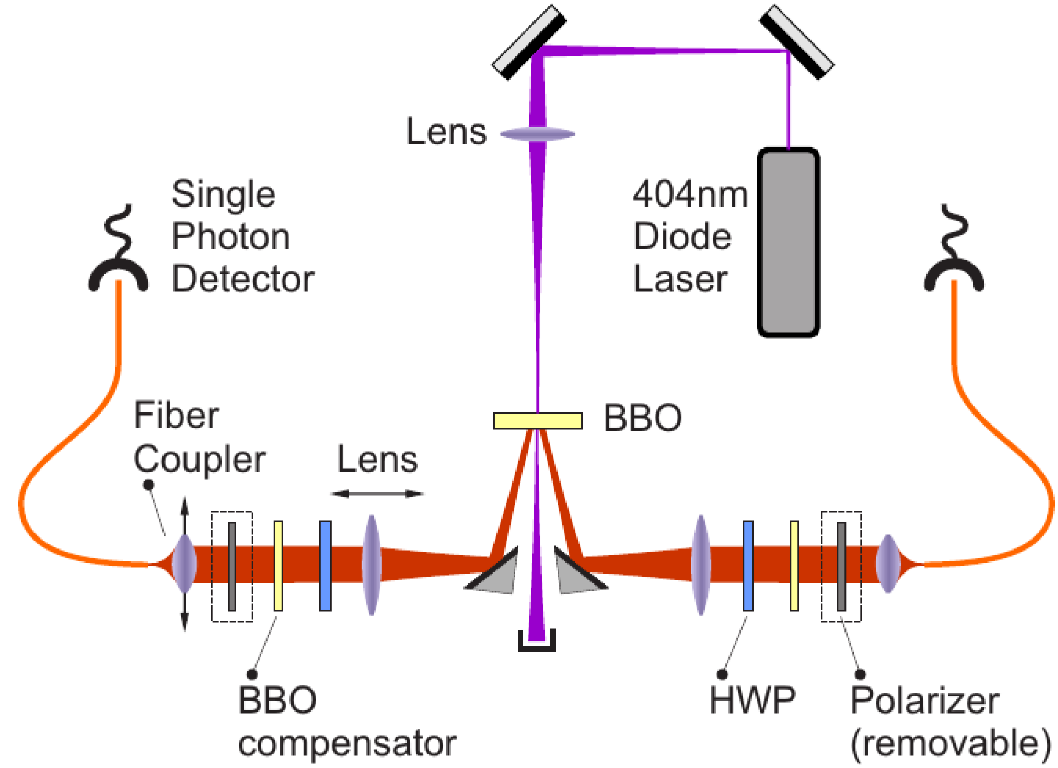


Abb. 1: Schematic of the experiment setup

In figure **??** the experiment setup is depicted. We used a blue laser source of 404 nm and 100 mW of power. With help of some mirrors this light is focused into a BBO crystal where SPDC happens and entangled photons are created. This process is purely quantum mechanically, one pump photon is converted into a photon pair, a signal photon with vertical polarization and a idler photon with horizontal polarization. Energy conservation in this process must hold and can be written as

$$\hbar\nu_{pump} = \hbar\nu_{signal} + \hbar\nu_{idler},$$

this means that the sum of signal and idler frequencies must be equal to the frequency of the pump photon. Moreover, the photons must also obey momentum conservation which can is

$$\hbar\mathbf{k}_{pump} = \hbar\mathbf{k}_{signal} + \hbar\mathbf{k}_{idler}.$$

This implies that signal and idler photons are emitted in opposite direction with respect to pump photon, since wavevector must be conserved.

# 3 Measurements and analysis

## References

[1] J. Bell, *On the Einstein Podolsky Rosen paradox*, Physics, 1 (1964), pp. 195–200.

[2] J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012)

[3] http://pdg.lbl.gov/2009/tables/rpp2009-sum-gauge-higgs-bosons.pdf

[4] The ATLAS Collaboration JHEP 1012(2010)060

[5] http://pdg.lbl.gov/2012/listings/rpp2012-list-z-boson.pdf

[6] http://pdg.lbl.gov/2012/listings/rpp2012-list-w-boson.pdf