Lab1: Entanglement and Bell's Inequalities

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ABSTRACT

We show an experimental approach to study the entanglement, one of the most striking phenomena in quantum mechanics. Our mathematical tool to distinguish such quantum effect from classical behaviors regards in Clauser, Home, Shimony and Hall version of Bell's inequalities. After this calculation was done, we obtained the value 2.32 for the parameter $|S|$, which indicates a violation of Bell's inequalities. The heart of our experiment consists in generating two cross-polarized entangled photons, this by taking advantage of the Spontaneous Parametric Down-Conversion (SPDC) produced by two Beta Barium Borate crystals. The quantum correlation was done measuring the number of coincidences in two avalanche photodiodes (APDs).

Keywords: Entanglement, Bell's inequalities, spontaneous parametric down conversion, polarized states, entangled photons.

1.- INTRODUCTION

1.1.- Ideas of entanglement

Entanglement is one of the most amazing phenomena in quantum mechanics. It is a condition that allows us to have non-local properties of physical quantities between two particles. This is a consequence of the restriction in describing certain quantum state with the individual properties of the particle under study. Instead, two quantum systems are described with a single state vector, and such state vector cannot be factorized into single particle states. This can be observed in the following expression:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|V\rangle_{q1}|V\rangle_{q2} + |H\rangle_{q1}|H\rangle_{q2}\right) \tag{1}$$

Where $|V\rangle_{q_i}$ and $|H\rangle_{q_i}$ are polarized states. In fact, the behavior described by Eq. (1) is independent of the distance between the two systems. In other words, the perturbation of one of the states will modify the state of the other, quoting J. Kimble "*tickle one of the two systems, causes the second laugh*". This idea can also be illustrated with Schrödinger cat paradox [1].

It is completely unusual to figure out the non-local properties described above. In 1935, A. Einstein, B Podolsky and N. Rosen [2] wrote a paper where they attributed such non-locality to the incompleteness of quantum theory, therein the proposal of hidden variables.

In 1964 John Bell [3] proposed a set of mathematical inequalities that allowed him to conclude the conflict between the hidden variables theory with quantum mechanics, as well as the non-locality that quantum mechanics introduced and that resulted in the violation of the Bell's inequalities.

Following the ideas of A. Aspect et al [4], we generated correlated entangled photons and measured correlations using a pair of single-photon counting avalanche photodiodes module, by detecting the number of coincidences in the polarization states of the down-converted cross-polarized photons. Finally in order to conclude when Bell's inequalities were violated the parameter $|S|$ was calculated using the number of coincidences obtained experimentally.

1.2 Generation of entanglement.

As we have already mentioned, in our experiment we use polarization states of photons, such polarization states play the role of quantum states, and the idea is to have the control of such states in order to perform well-defined operations. In fact most of the experiments in quantum information and quantum cryptography make use of a source of correlated photon pairs [5].

Fortunately the development of nonlinear optics techniques in 1980s and 1990s [6], allowed us to use down conversion processes instead of atomic cascades in calcium, like those used in early experiments. In our experiment the creation of cross-polarized entangled photons is a fundamental part, therein the reason to clarify up how the Beta Barium Borate (BBO) crystals were used to produce the polarized entangled photons.

The function of the BBO crystals is based on a second order nonlinear optical effect called Spontaneous Parametric Down-Conversion (SPDC) [7]. The SPDC process splits one incident polarized photon into two new photons called idler and signal (see Fig 1-a), with a down-converted efficiency of the order of 10^{-10}.

It is important to point out that BBO crystal is a uniaxial crystal, and as most of the nonlinear crystals is a birefringent crystal, therefore they produce two types of phase matching, or regimes where we have constructive interference, such phase matching condition obeyed the conservation of energy and momentum; this is illustrated in the following figure.

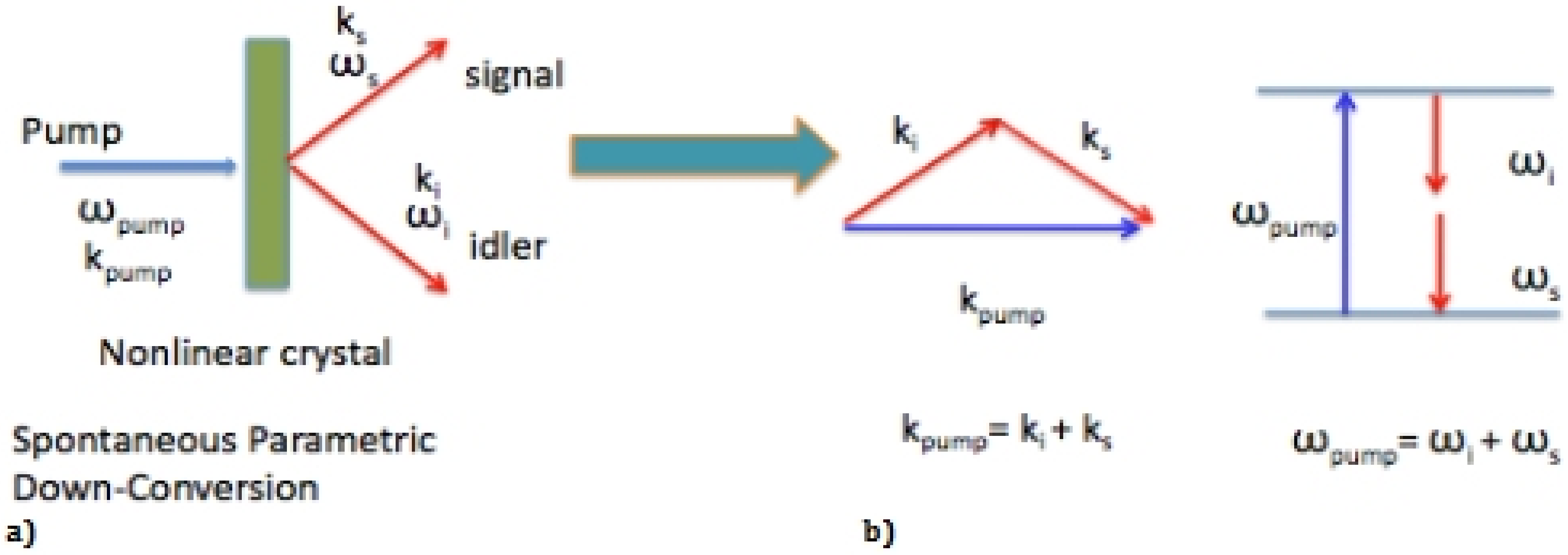

Figure 1.- This figure illustrates the spontaneous down conversion process, and two important point that are the conservation of momentum and energy.

There are different situations to satisfy the phase-matching conditions, if the generated frequencies are equal, this process is called degenerated, and non-degenerated otherwise.

As a consequence of the birefringence, which allows compensating the dispersion of the crystal, we have two types of phase matching. In type I the down-converted photons are parallel to each other and perpendicular to pump photon, while type II the down-converted photons have orthogonal polarizations. In our case, we used the type I degenerated phase matching.

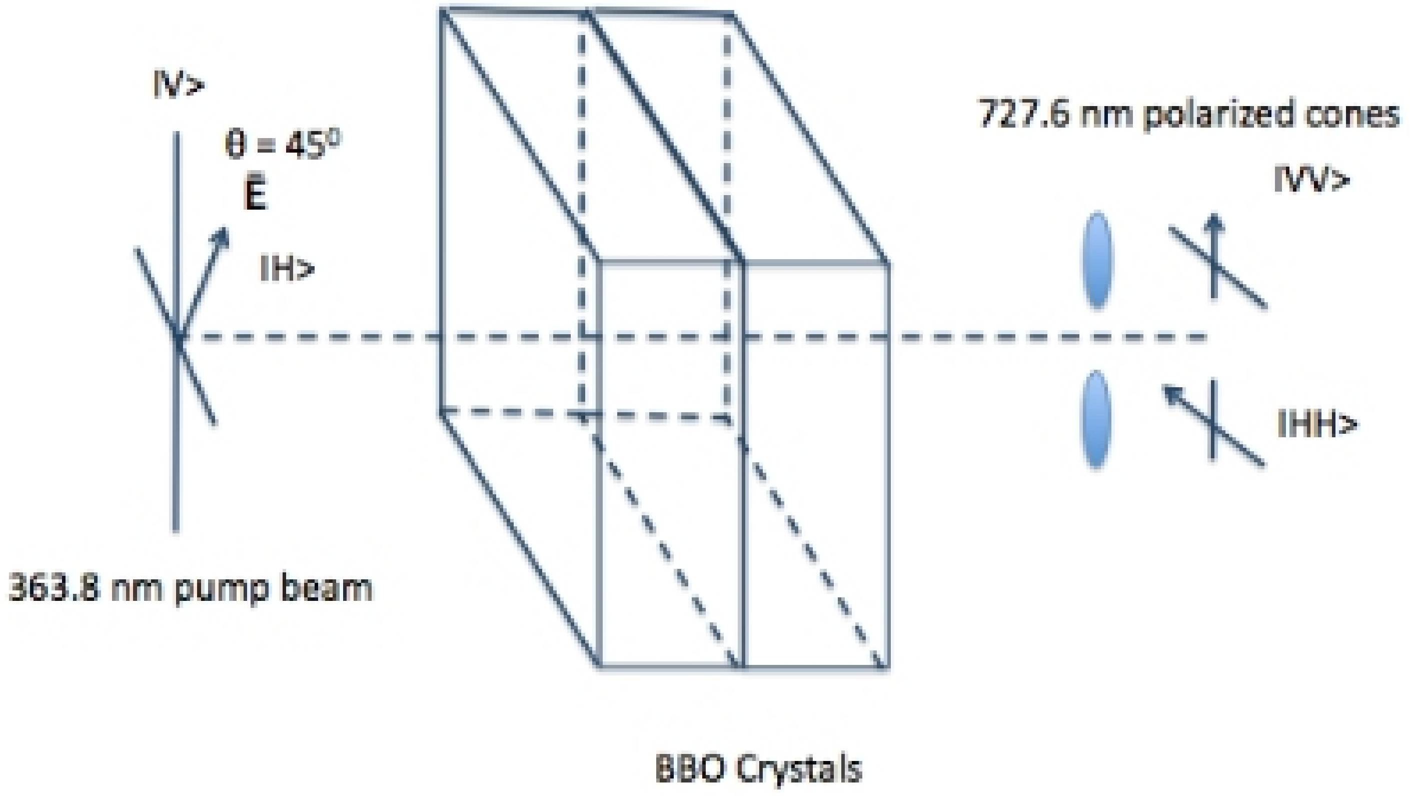

Figure 2.- 45^0 linearly polarized light goes perpendicularly trough BBO crystals, then entangled photons are generated with perpendicular polarization states relative to the initial photons polarization.