December 15, 2008

Submitted for the partial fulfilment of the course PHY 434

Lab. 1: Entanglement and Bell's Inequalities

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Abstract

The aim of this experiment is to test violation of Bell's inequalities by using polarization-entangled photons produced by spontaneous parametric-down conversion in a pair of Type-I BBO crystals.

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1. Introduction

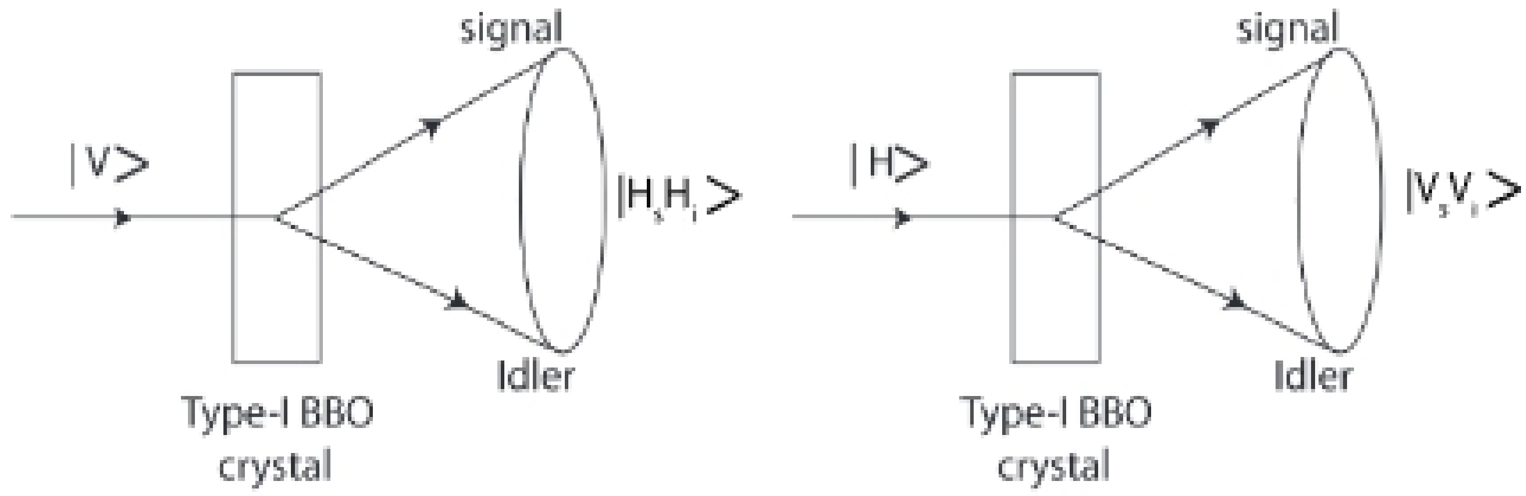
In 1935, Einstein, Podolsky and Rosen published a classic paper entitled "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"[1]. In that paper they illustrated by an example, a contradiction among the principle of locality and the principles of the quantum mechanics. This example is now often referred as EPR paradox. However their analysis was in a qualitative level. In 1965, Bell came out with a mathematical representation of EPR paradox (see, for example, [2]). He proposed a class of inequalities which are satisfied if the behavior of a system is governed by the principles of locality and are violated if it is governed by the principles of quantum mechanics. In this experiment we test violation of Bell's inequalities by using polarization-entangled photons. We follow more or less the technique shown by Kwiat *et. al.* [3] (see also, [4, 5]).

2. Theory and Experimental set-up

According to the usual interpretation of the quantum mechanics, there exists certain two particle states with the property that measurement of a chosen variable of one particle completely determines the outcome of the measurement of the corresponding variable of the second particle. Such a situation may arise when both particles are emitted from a common source in some entangled (non-factorized) quantum state, for example,

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\phi_1\rangle\,|\chi_2\rangle - |\chi_1\rangle\,|\phi_2\rangle). \tag{1}$$

As Einstein, Podolsky and Rosen (EPR) pointed out that, at the time of measurement, the particles may be so far apart that no influence resulting from one measurement can possibly propagate to the other particle in available time [1]. Since the measurement of a variable of one particle has already determined the outcome of measurement of the corresponding variable of the second without any uncertainty, it contradicts the idea of quantum mechanics. At the end of Ref. [1], Einstein, Podolsky and Rosen concluded that the quantum theory is incomplete. Their conclusion was based on their firm belief on the principle of locality. This paradox posed by Einstein, Podolsky and Rosen can be seen as conflict among the principle of locality and the principles of quantum mechanics. To make exclusive conclusion one requires to perform an experiment to verify which of the principle is valid. Bell's inequalities play a



(a)Production of two horizontally polarized photons from one vertically polarized photon by parametric down-conversion.

(b)Production of two vertically polarized photons from one horizontally polarized photon by parametric down-conversion.

FIG. 1: Production of down-converted photon pairs by a type-I BBO crystal. Here the suffices s and i stand for signal and idler respectively.

key role in verifying experimentally whether a system is governed by the principle of locality or by the laws of quantum mechanics.

In this experiment we show violation of Bell's inequalities by using polarization-entangled photons which are produced in two type-I Beta Barium Borate (BBO) crystals through the process of spontaneous parametric down conversion (see, for example, Ref. [6]).

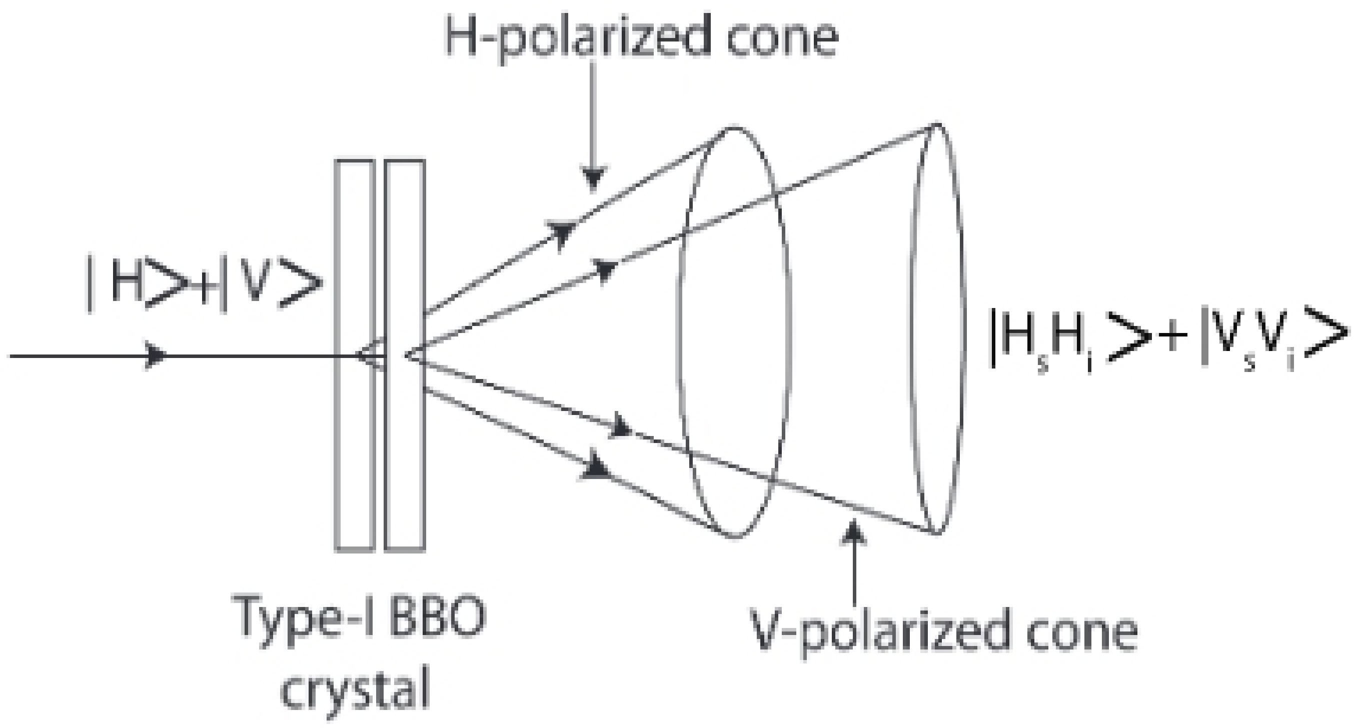


FIG. 2: Production of polarization-entangled photons by two type-I BBO crystals.

If a horizontally (vertically) polarized photon of wavelength λ is incident on a type-I cut BBO crystal, then two photons of vertical (horizontal) polarization of wavelength 2λ emerges from the crystal in a cone as shown in Figs. 1. Now if two type-I BBO crystals are are placed back to back and an incident beam, polarized at an angle 45° is used, then