Entangled Photon Source

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ABSTRACT

Entanglement is considered nowadays the heart of quantum theory and its origin goes to that of the theory itself. This unique behavior has brought a huge impact in many different fields, particularly in information technology, but its impact and development has depended in a good part on the availability of entangled photon sources, which are the scope of this essay.

Keywords: Quantum theory, Entanglement, Entangled Photon Sources, Quantum information.

1.- Why Entangled Photon Sources?

Entanglement 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:

$$\left| \psi \right\rangle = \frac{1}{\sqrt{2}} \left( \left| + \right\rangle_1 \left| - \right\rangle_2 - \left| - \right\rangle_1 \left| + \right\rangle_2 \right)$$

where $\left| + \right\rangle_n$ and $\left| - \right\rangle_n$ are the pair of states. In fact, the behavior described by Eq. (1) is independent on the distance between the two systems or non-local.

It is important to mention that $\left| + \right\rangle_n$ and $\left| - \right\rangle_n$ are the quantum equivalent version of classical bits used in classical information theory [1], called qubits, which obey the assumptions of the Schrödinger cat paradox, they can exist simultaneously in two states. In fact, it is easy to show that all the behaviors similar to Schrödinger cat can be written as (1) [2].

The similitude between classical bits and qubits allowed developing the Quantum Information theory and technology, including quantum communication, teleportation and quantum computation, where entanglement is the essential resource element. Examples of that are quantum key distribution and controlled quantum logic, therein the need of entangled photon sources. In 1967 and using a beam of Ca atoms, Kocher et al [3] carried out the first experiment related with entangled photons sources using atomic cascade transitions.

In these days the requirements are such that scientists have explored entangled sources based on semiconductor nanostructures, those based in nonlinear optics [4], where the goal is to engineer entangled source devices with different characteristics that goes from coherence to those where the interaction with the environment play an important role and lead to the entanglement sudden death [5].

2.- Entangled Photon Sources

In this section we will analyze the most important entangled photons sources. In fact, it is impressive how active is this topic. To date the most widely used technique to produce
entangled photons is spontaneous parametric down conversion (SPDC) [4], which takes the advantage of a second order optical nonlinear processes.

It is important to point out that exists a wide variety of nonlinear crystals that can be used for SPDC in a given range of frequencies [6]. That is the case of KTiPO₄, RbTiPO₄, LiNbPO₃, LiTaO₃ and BaB₂O₄. In fact, most of the nonlinear crystals are birefringent, 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. We have two types of phase matching [7], type I and type II. In type I the down-converted photons are parallel to each other and perpendicular to the pump photon, while type II the down-converted photons have orthogonal polarizations.

Other important sources are semiconductor nanostructures, particularly quantum dots, where electrons and holes can be trapped to form excitonic complexes [8] (states consisting of bound electron–hole pairs) that eventually will suffer radiative decay similarly to atomic cascades. In fact this technique is closely related to the generation of entangled photons in single atoms, therein the reason to call quantum dots as artificial atoms. In such radiative decay process photons emits entangled photons with certain polarization that can be controlled. It is important to mention that this technology has made real the possibility to have compact sources of entangled photons. Example of that can be devices like semiconductor light emitting diodes.

Now let us focus our attention in the biexciton. This means a quantum dot with two electron and two holes. In order to explain the ideas behind this source lets consider the following energy levels:

The state XX corresponds to the biexciton state and X to the exciton state. The pump light frequency used to excite the material is selected close to the maximum absorption of the quantum dot material (the most common materials are InAs and GaAs). Then the system, initially prepared in the biexciton state, falls down to exciton state. Here we can have different cases [9]. In the case of having asymmetries in the quantum dot we will have the case shown in figure 1a. There the degenerated exciton state is split and produces linearly polarized non correlated photons. Otherwise the conservation of momentum determinates the polarization of the emitted photons for the spin of the intermediate state X, figure 1b. Ideally in case to have degenerated X states, the polarization of the exciton photons is entangled with the biexciton photons polarization, forming the state described by equation 1, where \( |+\rangle_n \) and \( |−\rangle_n \) are polarized states. This is illustrated in figure 2.
3.- Applications

As we already mentioned, the applications are wide, but good part of them are within the quantum information field, which is quite surprising if we take into account that the first proves with quantum information theory was in 1991, by Artur K. Ekert [11].

From my point of view, one of the most interesting and surprising applications that critically rely in entanglement and its management are the photonic quantum memories [12]. They encapsulate the entangled photon sources, storage, and distribution among distant matter. In fact such memories promise a revolutionary advances in information theory. The other point that I believe that will bring a huge impact in quantum information is the quantum internet [13], as proposed by Jeff Kimble. Such technology implies the development of many quantum information technologies, where the entangled photon sources are the key element.

4.- References