U.P.B. Sci. Bull., Series A, Vol. 75, Iss. 4, 2013 ISSN 1223-7027

ON ENTANGLED PHOTON PAIR SOURCES

Octavian DĂNILĂ[1], Florian KAISER[2], Lutfi Arif BIN NGAH[3], Sebastien TANZILLI[4]

In this paper, we wish to present the most important experimental research behind the progresses in the realization of entangled photon pair sources with superior operational parameters. To this extent, both the physical phenomena and experimental solutions behind the different types of sources are analysed and operational parameters of the resulting sources are compared.

1. Introduction

Quantum key distribution [1] is the most important aspect of obtaining the unconditionally secure encryption keys used in quantum cryptography schemes. The quantum approach on information transmission proved itself by exhibiting two major advantages over the classical approach: First of all, the informational values extracted from manipulating quantum elements are purely random, as opposed to the quasi-random keys generated from classical algorithms [2], and secondly, the quantum exchange of information makes it possible for the participants to establish whether or not their transmission was listened on by an arbitrary eavesdropper. Two-particle entanglement [3] has been employed in cryptographic protocols as an improvement to costly single photon transmission experimental set-ups, that require each of the two participants to posess a single photon source for secure communications. This new approach is known to reduce the cost for hardware and it does not require source authentication. The source thus built can be used to transmit pairs of entangled photons, which the two participants use as information-bearing quantum elements, in order to exchange keys. The key transmission is not done directly, but rather by deduction, following the known entanglement type of the source. This means that recording and reading of the incoming photons need not be done at the same time, as in the case of single photon transmission, but rather at different times, lightening the work of the detection hardware. The most commonly used encryption observable of the photons is polarization, due to its manipulation convenience throughout the

[1]Assist., Physics Department, University POLITEHNICA of Bucharest, Romania,corresponding authors: octaviandanila2013@yahoo.com
[2] Researcher, Laboratoire Physique de Matière Condensée, Université de Nice Sophia-Antipolis, 06108, Nice Cedex 2, France
[3] Researcher, Laboratoire Physique de Matière Condensée, Université de Nice Sophia-Antipolis, 06108, Nice Cedex 2, France
[4] Researcher, Laboratoire Physique de Matière Condensée, Université de Nice Sophia-Antipolis, 06108, Nice Cedex 2, France

communications channel, but other observables can be used, such as time-of-arrival of the photons with same polarizations [4].

In this paper we review the main realizations of entangled photon pair sources that is based on either bulk crystals [5] or an integrated optical solution, namely a periodically poled lithium niobate waveguide [4],[17]. Different studies also used a potassium titanyl phosphate waveguide [6]. Theoretical [7] and experimental studies on the geometry and layout of the guiding device are currently researched, in order to couple as much pump light as possible. The paper also reveiws solutions for manipulation of photons for optimal net photon pairs and entanglement visibility at the two detection stages. Furthermore, the qualities of the sources are outlined, keeping in mind the chronological context and the development stage of the serving industry. The paper is organised as follows: section II will give a brief outline of entanglement based cryptography, section III will present the most important entangled photon pair sources that were developed and section IV will draw the conclusions of our review.

I. Entanglement based quantum cryptography

The field of quantum cryptography focuses on providing any participant to a conversation with an unconditionally secure encryption key for the desired message. Up until now, there is only one value-based protocol that successfully offers secure keys. This is called the Vernam protocol [8], and it employs a key string K associated to the desired transmission message string M. Literature denotes the two participants to the conversation Alice and Bob. If Alice wishes to securely transmit her message string to Bob, she encrypts the message with the key by a simple modulo 2 addition, and then sends the result on the channel. At detection, Bob applies the inverse of the key with the same operation and thus recovers the key. The whole process can be written as:

$$M \xrightarrow{encryption} T = M \oplus K \xrightarrow{communication} T \xrightarrow{decryption} M = T \oplus K^{-1} \qquad (1)$$

For the Vernam protocol to work, some conditions must apply. First of all, the key and message strings must have the same sizes. The protocol uses the key string only once per transmission, and thus requires purely random keys to be generated. The latter condition proved to be a significant impediment to classical cryptography, as no purely random key strings can be obtained using classical methods. The closest to this desired result has been obtained by factorization of very large integers, which offers a quasi-random key string, but such a key can be decoded with a finite computing power. This further opens the way for quantum treatment of the encrypting key, which offers both purely random key strings and, as a bonus, permits the detection of a potential eavesdropper, called Eve in literature. Quantum cryptography uses qubits instead of bits as units of information. Just as the classical bit takes the logical values 0 and 1, the qubit is a quantum state that can reside in the orthogonal states $|0\rangle$ and $|1\rangle$, but also in any superposition of the two $\alpha|0\rangle + \beta|1\rangle$, with α and β being the probability amplitudes of the orthogonal states [3]. Depending on the protocol, the quantum state carriers are chosen to be photons, and the measured observable is the polarization. Polarizations are assigned the values 0 and 1 according to the conventional analyzer angles determined by the construction of the protocol. The most important quantum key distribution protocol is based on the transmission of single photons. Alice sends photons in both horizontal-vertical and diagonal-antidiagonal bases and keeps a copy of the states for herself. Bob sets his analyzers at the same angles as Alice and, after recording the incoming photons, he announces the values he obtained. Alice eliminates the entries in which the bases do not coincide, and then compares the values with Bob's. Ideally, the two obtained keys must coincide at this point. If any eavesdropper is on the line though, any foreign measurement of the transmitted states will change the polarization angle according to its chosen bases (Eve does not know what polarisation angles Alice and Bob use as bases) and thus introduce errors in the two final keys. This yields the qubit error rate parameter, responsible for eavesdropper detection. If the qubit error rate is greater than a fixed value, convened by Alice and Bob before the conversation starts, the conversation is dropped. Otherwise, Alice will proceed to send her message by creating a new secure key. This protocol is generically called BB84, and it was invented by Charles Bennett and Gilles Brassard [1].

The use of entanglement has proven to be a very beneficial alternative to single photon quantum cryptography. Entangled states have been theoretically characterised as multi-dimensional states that exhibit an irreversible link between the states of the composing systems. The simplest example that is used to illustrate such states is the maximally entangled Bell states, which can be written as:

$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle \pm |10\rangle\right) \tag{2}$$

$$|\phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle \pm |11\rangle\right) \tag{3}$$

The most basic method of discerning between separable and entangled states is called Bell's inequality [9], later expanded into the CHSH inequality [10]. For an entangled state in which any expectation value of a measurement done on a subsystem with two observables *a* and *b* may yield a ± 1 result, the CHSH inequality is written as:

$$S = \left|E(a_1,b_1) + E(a_1,b_2) + E(a_2,b_1) - E(a_2,b_2)\right| \leq 2 \tag{4}$$

where *S* represents the Bell parameter and $E(a_i, b_j)$ is the correlation experiment between the *a* observable of subsystem *i* and the *b* observable of subsystem *j*. It has been proven that for the case of entangled states, this inequality is no longer respected, up to the maximum value of $S = 2\sqrt{2}$. This is the case of the Bell states shown in (2) and (3).

The use of such states as a resource for quantum key distribution has been done extensively, beginning with an idea developed by Artur Ekert [11]. He proposed that rather than Alice have to send the single photons for recording and comparison, and thus having to detain complex single photon generation apparatus, both Alice and Bob act as detectors and share two keys that come from an independent photon pair source. The source can act as a server and does not need to be trustworthy *i.e.* Bob does not need to know that the message comes from Alice up until he can verify his key with that of Alice. This is a major implementation advantage. The protocol works as follows: A polarization entangled photon pair source, emits either $\left|\phi^{\pm}\right\rangle$ (type 0 source) or $\left|\psi^{\pm}\right\rangle$ (type II) to both Alice and Bob. For simplicity, we shall consider a type II source. Both detectors will have three polarization analysis angles, each set exclusively at 0^o, 22.5^o, 45^o, 67.5^o and 90^o, such as one polarization angle is common and the other two are different. The most common set-up is having Alice's analyzers set at 0^o, 22.5^o, 45^o and Bob's analyzers at 45^o, 67.5^o and 90^o. They both shift randomly between the chosen states, and obtain the desired key for cases when both have the same analyzer angle. The keys obtained in different analyzer bases are used for entanglement quality measurements, such as Bell measurements. After publication of results, ideally Alice and Bob's are exactly opposite qubit for qubit. Any deviation to this ideal case represent the presence of an eavesdropper on the communication channel.

II. Source Development

The central device of an entanglement based quantum key distribution communication scheme is the entangled photon pair source, consisting of three stages: entangled photon generation, photon manipulation and detection. While generation and detection have a straightforward meaning, manipulation usually consists of subsidiary control stages. These ensure identical photons are sent to the detection stage, and use a post-selection scheme in order to project the generated entangled state to the detectors. Ideally, the source must be able to send as many entangled photon pairs as possible, while maintaining a good entanglement visibility for the transmitted pairs. This is easier said than done, as in real experiments, the two photons must be kept identical for any other type of measurement except that which defines the entangled state. Usually, even small perturbations induced by the environment can very easily destroy the entangled state, which translates directly into a decrease in entanglement visibility. Furthermore, the efficiency of the entangled state generation device must be as high as possible, in order to provide a longer encryption qubit string. The entangled photon pair is created by employing a non-linear optical effect – spontaneous parametric down conversion into bulk crystals and non-linear waveguide structures. The sources presented in the paper rely exclusively on this process, but use somewhat different photon manipulation set-ups in order to provide the best quality. The layout of any polarization-based (type I and II) entangled photon pair source is presented in Figure 1, with the addendum that extraction of a type 0 entangled state cannot be done directly, and thus requires some different manipulation schemes

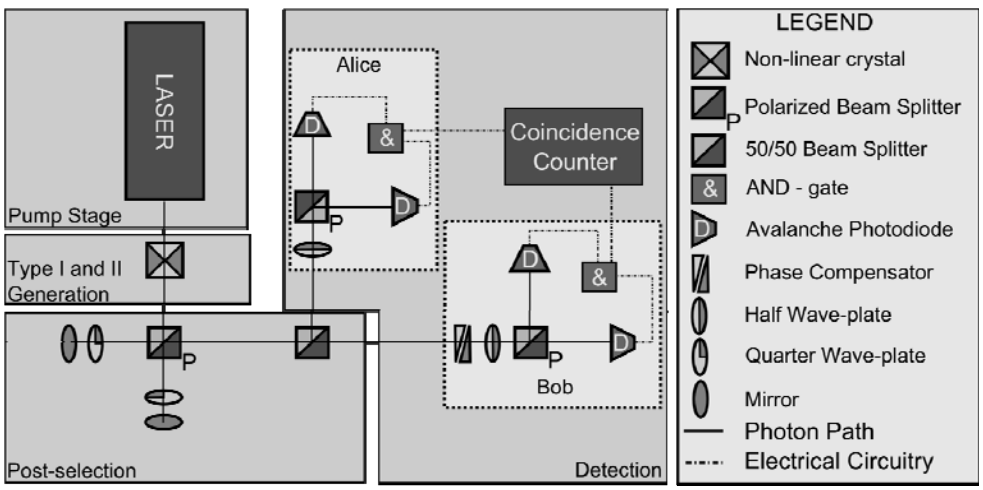

Fig. 1: Detailed layout of a type I and II entangled photon pair source

One of the first endeavors in creating a successful source model was devised by a team led by Paul Kwiat [12]. The source is responsible for producing maximally entangled Bell states, of the user's choosing. The central device was a bulk non-linear BBO (beta-barium borate) crystal, that produced entangled photons at the degenerate wavelengths of 702 nm, with a bulk birefringent walk-off compensation. The reported Bell parameter ranged from -2.6489 ± 0.0064 to 2.557 ± 0.014, while raw coincidence rates added to 45 coincidences/s. Entanglement visibility was established at 95%, strongly violating Bell's inequality. Other similar sources [13], [36] reported slight improvements to this set-up.

The experimental setup was respected by many other sources that followed, technological progress in manufacturing the component devices of the sources contributing in an essential manner to the improvement of operational parameters. The first direction the new set-ups undertook was the shifting of the degenerate wavelength to the infrared spectrum, making the sources more compatible with the optical fibre devices that enable long-distance communication.

The most widely-approached entangled photon pair sources make use of creating polarization entanglement. The polarization entangled photon pair sources reported in [14] and [5] have employed a combination of bulk and fibred solutions at 1560 and 1310 nm respectively, with superior coincidence rates and high entanglement visibility (> 98%). Both set-ups used a periodically poled lithium niobate waveguide as an entangled photon pair generator. An alternative to this waveguide was reported by E. Pomarico et al. [15] in the form of a Ti:PPLN waveguide. A fully fibered solution, together with a birefringent walk-off compensation and deterministic post-selection stage is reported in [16], with an entanglement visibility of 99.5% and 1100 coincidences/s. This represents a very performant system, capable of attaining superior key exchange rates in terms of quantum key distribution.

The source reported in [16] makes use of a very powerful Ti:Sa laser device, capable of providing high-power continuous wave output of 2.5W, and emitting at a wavelength of 769.883 nm. Such power was necessary for obtaining a large number of generated photon pairs, being reminded that the average generation efficiency of the non-linear waveguide that was used in the experiment was measured at 10^{-7}, while the pump wavelength was chosen that which yielded the maximum second harmonic generated photons. The generating device was chosen a periodically poled lithium niobate waveguide [16], that was stabilized in terms of temperature and corrected in terms of non-linear emissions up to the appropriate 1539.766 nm wavelength.

As every non-linear optical device is concerned, the material's most important property, anisotropy, may prove to be a very destructive factor in terms of entanglement preservation. The delay introduced by the waveguide will only apply to one polarization of the generated two, establishing different a time-of-arrival at the detectors. This renders polarization measurement useless, as it can be easily inferred from a temporal measurement. To counter for this obstacle, a length-specific anisotropic optical fiber was coupled to the output of the waveguide in order to slow down the faster propagating photon. The length was calculated in such a manner that the fast and slow components of the entangled pair exit the fiber simultaneously. Furthermore, instead of just using a typical beam-splitter to achieve post-selection, a deterministic approach was reported, namely by splitting the spectrum of the overlapping photons into two adjacent transmission windows, and knowing that, according to the phase matching rule [18], [37] that makes entangled photon pair generation possible

$$\omega_p = \omega_s + \omega_i \quad (5)$$

if one photon of the pair is detected in one window, the other one is bound to be detected in the complementary window. In equation 5, subscripts *p,s* and *i* stand for *pump*, *signal* and *idler* photons.

Detection was achieved with the help of state-of-the art avalanche photodiodes [19] running in synchronized gated mode, the master photodiode commanding the slave photodiode to open at a certain time after detecting its photon. A complete graphical description of the source can be found in Fig. 2.

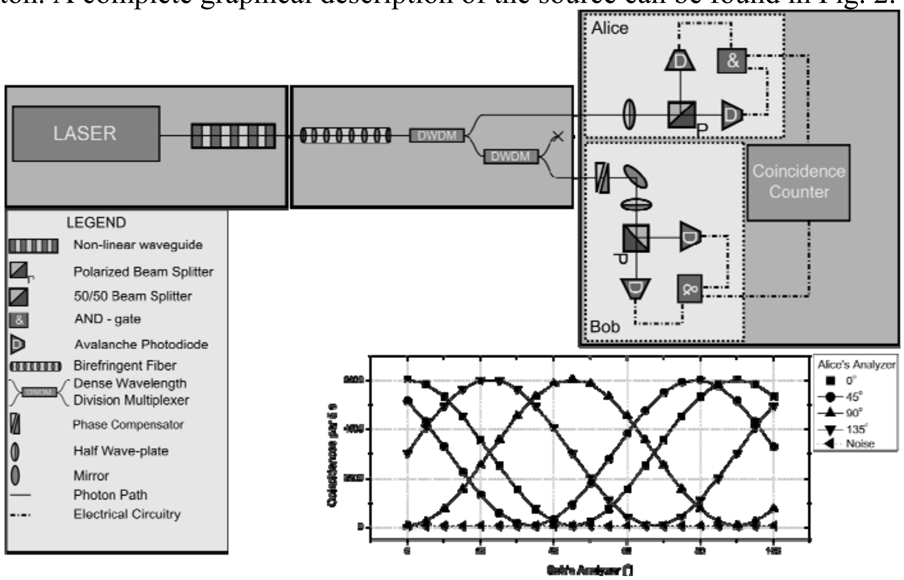

Fig. 2: Layout and results of an ultra-performant type II source. Adapted from [16].

Conversely the type 0 Bell state described in Equation (3) cannot be post-selected by means of polarization control. This implies that a different observable must be measured. A simple solution was proposed in [4] by post selecting in such a way that one polarization is delayed from the other one, ensuring that whenever a type 0 Bell state is generated, is indistinguishable at detection. On the other hand, any other types of entangled states are easily detected because of the different time-of-arrival. The set-up closely resembles the type I and II source arrangement. To illustrate this principle-of-operation, let us consider that at the post-selecting 50/50 beam-splitter arrives an identically polarized photon pair. Due to the construction of the source, this pair will either be transmitted or reflected at the output ports, and the pair components will follow the same path, thus arriving at the same time at the detectors. If, however, at the beam-splitter, an orthogonally polarized photon pair arrives, only one photon of the pair is reflected to the delay line, inducing a controllable (thus detectable) delay at detection. These states will be discarded in order to ensure the creation of pure type 0 entangled states. The detailed source setup is presented in Figure 2. Photon manipulation is easier in terms of wavelegth-temperature drift, but much more difficult in terms of pump wavelength stabilization, where special methods have to be used. The reported raw entanglement visibility for the respective source is $99 \pm 3\%$, with a Bell parameter of 2.82 ± 0.02. This is a great improvement from other implementations [20], which reports a raw entanglement visibility of 85%. The main difference between the two sources is the use of a pulsed pump in [20] as opposed to its continuous-wave counterpart in [4]. Apart from this, the improvement relies mainly on the technological progress of the constituting devices.

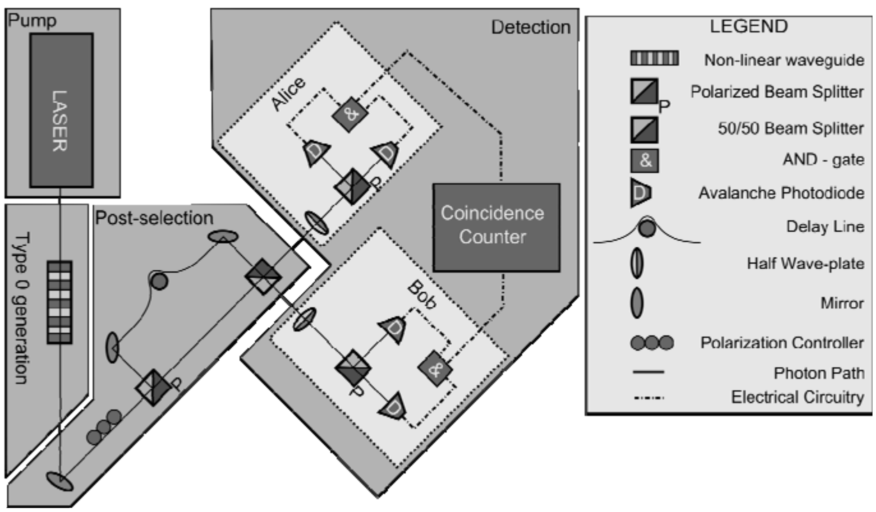

Fig. 3: Layout for a type 0 entangled photon pair source. Adapted from [4]

Another method of of obtaining the desired type 0 Bell states at detection is based on Sagnac interferometry [21] and the use of a periodically poled KTP crystal, yielding a reported fidelity of 98.2%. The Sagnac interferometer is a device that allows passage in either clockwise or counterclockwise direction, depending on the pump photon polarization. In the respective set-up, the Sagnac interferometer consisted of a polarization separator and combiner, a polarization flipping stage and the SPDC stage. If at the input a horizontally polarized photon is provided, it passes to the generation stage, yielding a horizontally polarized entangled pair. The polarization flipping provides a vertically polarized pair at the output of the interferometer. Conversely, if a vertically polarized photon arrives at the input, it passes through the flipping stage first, changing its polarization to a vertical one, and then undergoes the SPDC stage, yielding a vertically polarized entangled pair at the output. This method ensures a reliable post-selection for the type 0 entangled state, together with a phase compensation of the two state contributions.

To overcome the temporal randomness of the entangled photon pair generation process, there have been devised solutions that rely on higher order photon pair emissions. The first approach [22] reported the control of the entangled state production via a synchronous three-pair generation, in which two pairs that are detected announce the presence of the third pair. This type of source was coined as a *heralded source*, with reported applications in routing or entanglement swapping [3].

The operating principle of the heralded source according to [22] is the following: As a consequence of previous research [23], it has been demonstrated that production of deterministically manageable or heralded photon pairs with conventional down-conversion sources and linear optical devices must be provided with at least three entangled pairs. The source successfully creates six photons simultaneously and passed through a narrow-band filter before being coupled into optical fibers. They are analyzed in the $|H/V\rangle$ and $|\pm 45°\rangle$ basis sets. By analysis of the four-fold coincidences in the reflected ports of the two polarized beam-splitters placed at the output of the source, the complementary state corresponding to the transmission ports of the beam-splitters can be deduced without direct measurement. As is intuitively expected, the resulting probability of obtaining a heralded photon pair is roughly exponentially dependent on the transmission ratios of the two beam-splitters, with a Poissonian error.

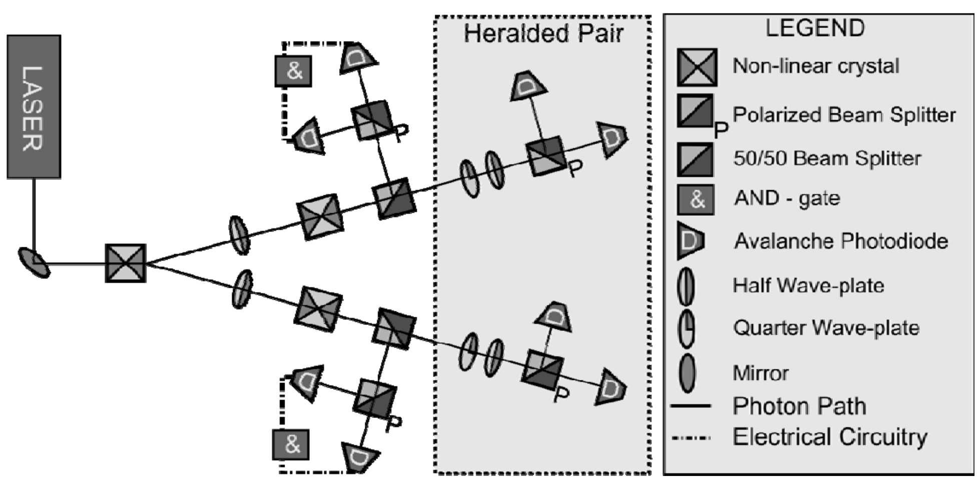

Fig. 4: Layout of the heralded photon source. Adapted from [22].

Other experimental approaches were not limited to the creation of Bell states (although these states offer the desired amount of security). In this sense, the source developed in [24] exploits the generation of GHZ (Greenberger Horne Zeilinger) states

$$|GHZ\rangle = \frac{1}{\sqrt{2}}\left(|000\rangle + |111\rangle\right) \quad (5)$$

The source uses cascade SPDC generation of the photons, yielding a triplet count of 5.6 ± 1.1per hour. The phenomenon of three-dimensional cascaded SPDC generation consists of using either the signal or idler photon resulting from a typical SPDC process as a pump for another generation stage. As it may be deduced, this second SPDC process has its own efficiency, which by cummulation leads to a very low generation efficiency, typically in the 10^{-15} region. The low count rates make it impossible to establish a measurement of entanglement visibility, but higher power lasers may be able to resolve this impediment.

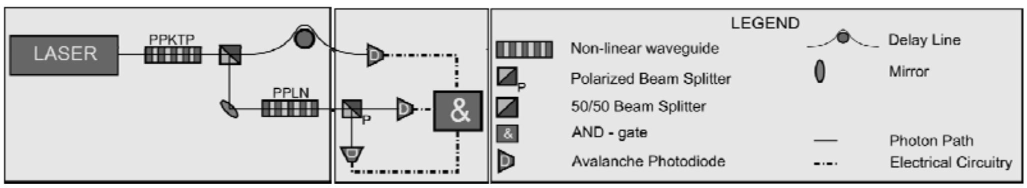

Fig. 5: Layout of a tri-dimensional entangled (GHZ) photon pair. Adapted from [24].

The observation and generation of high-quality entangled photon states allowed the perspective of harnessing entanglement from other types of quantum particles. Thus, extensive research has been carried out for demonstrating an making use of atom-photon entanglement, atom-atom entanglement, quantum dots, and, most recently nuclear particles such as entangled neutrino pairs as a result of tau-lepton decay [25].

Atom-photon and atom-atom entanglement are responsible for the development of static entanglement swapping and teleportation of the state transported by the input photon to the output of the atomic swapping device. Atomic ensembles that can fulfill this operation are generically called quantum memories. The operation of such a device is divided into two main stages: entrapment of the photon for a sufficiently long period of time and the actual extraction its state. Photon traps are built as an electromagnetical resonator, that develops an energy sufficiently large as to compensate for the inertial momentum of the atoms. By bombarding the suspended atoms with the carrier photons, the state is translated by absorbtion to the atoms, and can be translated to the output by stimulated photon emissions.

Entangled nuclear pairs exhibit the same properties as their photonic counterpart, but at higher energies. This equivalence opens new perspectives on transmitting information between systems that are opaque to photons but transparent to nuclear particles. The most proeminent entanglement-generating process is the tau-lepton decay into an entangled neutrino pair, although muon decay can also generate the same entangled neutrino pairs. Neutrinos from muon decays are emitted at lower energies, and thus are influenced by the various magnetic fields in space. The advantage of neutrinos against the photons is that neutrinos can penetrate almost any environment, due to their high energy. If for photons and atoms the main observable is polarization, for neutrinos, the measured observable is the flavour of the particle.

Although the main application of entangled photon pair sources is quantum key distribution, which was extensively researched in literature [3], another field that makes use of such states is quantum computing. Creating an entangled state from two independent states is achieved by employing quantum gates. A quantum gate is the equivalent of the classical gate, in the sense that any quantum realizes the same logical operation as its classical counterpart, but it takes qubits rather than bits as inputs. However, there are quantum gates that have no classical equivalents. As a uni-dimensional example, the most important is the Hadamard gate, which transforms a basis state into a superposition of basis states:

$$H\left|0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle + \left|1\right\rangle\right) \tag{6}$$

$$H\left|1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|1\right\rangle - \left|0\right\rangle\right) \tag{7}$$

For the bi-dimensional case, the controlled NOT (or CNOT) quantum gate has no classical equivalent. The gate has two inputs (control and data inputs) and two outputs (control and data output). The operation of a CNOT gate is as detailed as follows: If at the control input a $\left|0\right\rangle$ state is received, the data input is transmitted unmodified to the output. If, however, a $\left|1\right\rangle$ state is received at the control input, the data input state is inversed to its orthogonal counterpart and transmitted to the output. In both cases, the control input is transmitted unmodified at the control output. The gate operation can be summarized with the following expressions:

$$CNOT\left|00\right\rangle = \left|00\right\rangle \tag{8}$$

$$CNOT\left|01\right\rangle = \left|01\right\rangle \tag{9}$$

$$CNOT\left|10\right\rangle = \left|11\right\rangle \tag{10}$$

$$CNOT\left|11\right\rangle = \left|10\right\rangle \tag{11}$$

By combining the two quantum gates in a convenient way, Bell states can be obtained from two independent uni-dimensional states. Explicilty, the antisymmetric Bell state can be obtained from:

$$\left|\psi^{+}\right\rangle = CNOT\left(H\left|0\right\rangle\right) \tag{12}$$

$$\left|\psi^{-}\right\rangle = CNOT\left(H\left|1\right\rangle\right) \tag{13}$$

From an experimental point of view, while the Hadamard gate is implemented by a device as simple as a polarized beam-splitter, the CNOT gate has proven to be a very difficult device to manufacture. However, literature reports realizations of such gates ([26], [34] and references thereon) as a combination of heralded states, SPDC processes similar to those exhibited in the dedicated sources and linear optical components (beam-splitters with different transmission/reflection ratios). The effectiveness of any CNOT gate can be quantified by measuring its ability of producing an entangled state. The entanglement visibility of this state is then compared to visibilities achieved by dedicated sources. Other realizations [27] report the realization of a Knill-Laflamme-Millburn (KLM) CNOT gate with various other linear optical solutions. Other quantum computation experiments are detailed in [28] and [29].

A very new direction of study, in which entanglement and thus entangled photon pair sources are required, is the quantum controlled delay choice experiment. By purely random switching of the type of measurement executed on a quantum element, experiments show that a morphing behaviour between the particle and wave nature of quanta can be obtained. Consequently, this behaviour will erase the information of the measured element. Recent studies [30], [31] have shown that by employing an entangled pair and measuring just one half of the pair according to the delay choice scheme, the morphing behaviour can be avoided, by direct communication and deduction of the measured state. This new findings open the way to a new series of experiments which delve even stronger into the unknown which consitutes the quantum world.

III. Conclusions

The aim of this paper was to investigate the most important solutions devised in order to enhance the reader's grasp on a rapidly growing field of expertise, where every photon, or rather every photon pair counts. With entangled photon pair production and manipulation becoming an ever more demanding operation in terms of operational parameters, all the continued improvements in the design and construction of entangled photon pair sources make quantum communication and quantum computing projects such as those described essential. By providing the participants with high-fidelity entangled photon pairs over increasingly longer distances between them, quantum key distribution can be integrated into conventional encryption-decryption applications. In addition to this, special new methods of treating information can be devised, by manipulating the morphing behaviour of quantum elements with surprising results.

Acknowledgements

The authors wish to thank Marc de Micheli for fruitful discussions on non-linear optical devices and their underlying physical phenomena. Also, Paul Sterian and Andreea Rodica Sterian have given a great deal of insight in this field, and are acknowledged as a consequence of this.

This research was sponsored by the POSDRU 60203 European Union Human Resource Grant, the CNRS, the ERA-SPOT program and the ICT-2009.8.0 FET project, the e-QUANET project and the Regional Council PACA.

REFERENCES

[1] *C. Bennett, G. Brassard,* Conference on Computers, Systems and Signal Processing, Bangalore, India, 175, 1984

[2] *R. L. Rivest, A. Shamir, L. Adleman*, A method for obtaining digital signatures and public key cryptosystems, Communications of the ACM, vol. 21, iss. 2, pp. 120-126, 1978.

[3]. *R. Horodecki, P. Horodecki, M. Horodecki, K. Horodecki*, "Quantum Entanglement", Rev. Mod. Phys. 81, pp. 865-942 , 2009

[4] *F. Kaiser, A. Issautier, L. A. Ngah, O. Alibart, A. Martin, S. Tanzilli*, "A versatile source of polarisation entangled photons for quantum network applications", e-print arXiv:1111.5683v3 [quant-ph], 2012

[5] *A. Martin, V. Cristofori, P. Aboussouan, H. Herrmann, W. Sohler, D. B. Ostrowsky, O. Alibart, S. Tanzilli,* "Integrated optical source of polarization entangled photons at 1310 nm", Optics Express **17**, 2, 2009.

[6] *H. Hübel, D. R. Hamel, A. Fedrizzi, S. Ramelow, K. J. Resch, T. Jennewein*, "Direct generation of photon triplets using cascaded photon-pair sources", Nature **466**, pp. 601-603.

[7] O. *Danila, M. Demicheli, P. Aschieri, et al.,* "Theoretical studies and simulation of graded index segmented LiNbO3 waveguides for quantum communications", Optoelectronics and Advanced Materials – Rapid Communications **6**, 1-2, pp. 40 - 43, 2012.

[8] *G. S. Vernam*, J. American Inst. Elec. Eng. **55**, 109-115, 1926

[9] *J. S. Bell*, Physics **1**, 195, 1964

[10] *J. F. Clauser, M. A. Horne, A. Shimony, R. A. Holt,* Phys. Rev. Lett. 23, 880, 1969

[11] *A. Ekert*, Phys. Rev. Lett. 67, 661, 1991

[12] *P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, Y. Shih*, "New High-Intensity Source of Polarization-Entangled Photon Pairs", Phys. Rev. Lett. **75**, 1995

[13] *C. E. Kuklewicz, M. Fiorentino, G. Messin, F. N. C. Wong, J. H. Shapiro*, "A high-flux source of polarization-entangled photons from a periodically poled KTP parametric downconverter", e-print arXiv:quant-ph/0305092v1, 2003

[14] *A. Martin, A. Issautier, H. Herrmann, W. Sohler, D. B. Ostrowsky, O. Alibart, S. Tanzilli*, "Polarization entangled photon-pair source based on a type-II PPLN waveguide emitting at a telecom wavelength", New J. Phys. **12**, 103005, 2010.

[15] *E. Pomarico, B. Sanguinetti, N. Gisin, R. Thew, H. Zbinden, G. Schreiber, A. Thomas, W. Sohler*: "Waveguide-based OPO source of entangled photon pairs", New J. Phys **11**, 113042, 2009

[16] F. *Kaiser, A. Issautier, L. A. Ngah, O. Danila, H. Herrmann, W. Sohler, A. Martin, S. Tanzilli*, "High-quality polarization entanglement state preparation and manipulation in standard telecommunication channels", New J. Phys. **14**, 085015, 2012

[17] *S. Tanzilli, H. de Riedmatten, W. Tittel, H. Zbinden, P. Baldi, M. de Micheli, D. B. Ostrowsky, N. Gisin,* e-print arXiv:0107125v1

[18] *P. Sterian*, “Fotonica”, Printech Press, Bucharest, ISBN 973-652-161-3, 2000.
[19] ID Quantique Corporation, www.idquantique.com
[20] *J. Brendel, N. Gisin, W. Tittel, H. Zbinden*, “Pulsed energy-time entangled twin-photon source for quantum communication”, Phys. Rev. Lett. **82**, 12, 1999.
[21] *M. Hentschel, H. Hübel, A. Poppe, A. Zeilinger*, “Three-color Sagnac source of polarization-entangled photon pairs”, Optics Express **17**, 25, 2009.
[22] *S. Barz, G. Cronenberg, A. Zeilinger, P. Walther*, “Heralded generation of entangled photon pairs, Nature Photonics **4**, pp. 553 – 556, 2010.
[23] *J. L. O’Brien, G. J. Pryde, A. G. White, T. C. Ralph, D. Branning*, “Demonstration of an all-optical quantum controlled-NOT gate”, Nature **426**, pp. 264-267, 2003.
[24] *H. Hübel, D. R. Hamel, A. Fedrizzi, S. Ramelow, K. J. Resch, T. Jennewein*, “Direct generation of photon triplets using cascaded photon-pair sources”, Nature **466**, pp. 601-603.
[25] *O. Danila, P. Sterian, A. R. Sterian*, “Perspectives on entangled nuclear particle pairs generation and manipulation in quantum communication and cryptography systems”, Advances in High Energy Physics, 801982 2012.
[26] *J. L. O’Brien, G. J. Pryde, A. G. White, T. C. Ralph, D. Branning*, “Demonstration of an all-optical quantum controlled-NOT gate”, Nature **426**, pp. 264-267, 2003.
[27] *R. Okamoto, J. L. O’Brien et al.* “Realization of a Knill-Laflamme-Milburn controlled-NOT photonic quantum circuit combining effective optical nonlinearities” Proceedings of the National Academy of Sciences USA, **5**, 7, 2011.
[28] *M. Dima, M. Dulea, M. Pauna, et al*., “The Quantgrid Project - Quantum Security In Grid Computing Applications”, Romanian Journal of Physics **54** (5-6) pp. 441-448 2009.
[29] *M. Dima, M. Dulea, D. Aranghel, et al*., “Classical and quantum communications in grid computing” Optoelectronics and Advanced Materials-Rapid Communications, **4**, 11, pp.1840-1843, 2010.
[30] *F. Kaiser, T. Coudreau, P. Milman, D. B. Ostrowsky, S. Tanzilli*, “Entanglement-enabled delayed choice experiment”, e-print arXiv:1206.4348v1 [quant-ph], 2012
[31] *R. Ionicioiu, D. R. Terno*, “Proposal for a quantum delayed-choice experiment”, Physical Review Letters **23**, 107, 230406, 2011.
[32] *P. E. Sterian*, “Analytical Model of Dissipative Coupling Coefficients in Laser Structures”, Proceedings of the Romanian Academy, Series A, **3**, 3, pp. 123-126, 2002
[33] *P. E. Sterian*, “Communications Based on Chaotic Signals”, Proceedings of the Romanian Academy, Series A, **3**, 1-2, pp. 45-48, 2002
[34] *P. Kok, S. Braunstein*, “Limitations on the creation of maximal entanglement”, Physical Review A **62**, 064301, 2000.
[35] *B. A. Stefanescu et al.*, “Applications of quantum cryptology for data transmissions implemented in a student laboratory”, Annals of the Academy of Romanian Scientists Series on Science and Technology of Information ISSN 2066-8562, **5**, 1, 2012.
[36] *P. Trojek, H. Weinfurter*, “Collinear source of polarization-entangled photon pairs at non-degenerate wavelengths” Appl. Phys. Lett. **92**, 21, 2008
[37] *O. Danila, M. Demicheli, P. Aschieri, et al.*, “Theoretical studies and simulation of graded index segmented LiNbO3 waveguides for quantum communications”, Optoelectronics and Advanced Materials – Rapid Communications **6**, 1-2, pp. 40 - 43, 2012.
[38] *C. E. Kuklewicz, M. Fiorentino, G. Messin, F. N. C. Wong, J. H. Shapiro,* “A high-flux source of polarization-entangled photons from a periodically poled KTP parametric downconverter”, e-print arXiv:quant-ph/0305092v1, 2003