Sources of Single and Entangled Photons

Scott Barker

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The ability to produce single photons and entangled photon pairs in desired quantum states is essential in any system intended to handle quantum information. Single photons serve as qubits in quantum computers, and the most powerful operations in those computers are performed by entangling them. Further, entangled pairs of photons are the carriers for signals in quantum-encrypted communications.

Traditionally, single photons could only be produced by the aggressive attenuation of stronger signals. Entangled photons were traditionally produced by spontaneous parametric down conversion. In the latter process, a nonlinear optical crystal annihilates a high-frequency photon and creates two lower-frequency photons. This is a random process with a very low probability of happening, so it requires a very high-intensity source at the input, but this is relatively easy to supply, so SPDC remains a proven method of generating entangled photons.

As random processes, these two methods share a pair of distinct but related disadvantages: First, it seriously limits the system's ability to produce a photon at a specific time, which is an impediment to creating any kind of clock-based quantum system. Second, it means that there may be multiple photons created at a given time, which destroys the absolute security of quantum cryptography.

The condition that photons should be separated in time may be called antibunching or sub-Poisson behavior. Important early work in this area was done by Kimble, Dagenais and Mandel [1]. These are the photon producers that may properly be called sources of single and entangled photons, and the desire to create effective implementations of them has driven much of the recent research in quantum optics. In the last decade in particular, many novel sources have been developed to address this need.

A common feature of single- and entangled- photon sources is that they rely on the excitation and relaxation of a single emitter of some kind. Use of a single emitter promotes antibunching due to its characteristic fluorescence lifetime, during which it stays in the excited state and cannot be triggered further. The emitter can take any of several forms: atoms, molecules, cavities, and quantum dots have all been used. The excitation can come from either optical or electrical sources.

One important class of sources in consideration have used quantum dots embedded in semiconductor devices [2][3][4]. This technology takes advantage of the Purcell effect, an increase in the rate of spontaneous emission by resonant cavities. It has the advantage of being electrically, rather than optically, driven, which makes for easier integration with and control by existing technology. Further, they can be used to create either single photons or entangled pairs. The latter is accomplished by setting up a biexciton, a state with two excited electron-hole pairs. [5]

An similar method[6] uses nanoscale imputities in specially-fabricated diamonds as the resonant source. A key advantage of this method is that it functions at higher temperatures than quantum dots. Recent refinements[7] have improved the power output this type of source can produce, making it a more viable candidate.

In addition to nanotech solutions, individual atoms have been made into single-photon sources [8][9]. These methods, which are generally optically driven, make use of the energy levels inherent to the atom's structure.

Although the technology for producing entangled photons is still in its infancy, there have already been dramatic successes in its application. Notable among these is an experiment undertaken in 2007, in which a quantum key was distributed to two receivers in the Canary Islands separated by 144 km [10].

In a sense, quantum information technology is in a state now comparable to the state of conventional computing in the middle of the twentieth century: there is already an extensive theory that describes the potential of this technology in detail, and there are sophisticated quantum algorithms that are just waiting for a platform with the power to execute them. Future developments of quantum optical devices such as those described above offer a way to construct that platform.

References

[1] H. J. Kimble, M. Dagenais, and L. Mandel. Photon antibunching in resonance fluorescence. *Phys. Rev. Lett.*, 39:691–695, Sep 1977.

[2] Zhiliang Yuan, Beata E. Kardynal, R. Mark Stevenson, Andrew J. Shields, Charlene J. Lobo, Ken Cooper, Neil S. Beattie, David A. Ritchie, and Michael Pepper. Electrically driven single-photon source. *Science*, 295(5552):102–105, 2002.

[3] Adrien Dousse, Jan Suffczyski, Alexios Beveratos, Olivier Krebs, Aristide Lemaitre, Isabelle Sagnes, Jacqueline Bloch, Paul Voisin, and Pascale Senellart. Ultrabright source of entangled photon pairs. *Nature*, 466(7303):217–20, 2010.

[4] C. L. Salter, R. M. Stevenson, I. Farrer, C. A. Nicoll, D. A. Ritchie, and A. J. Shields. An entangled-light-emitting diode. *Nature*, 465(7298):594–597, June 2010.

[5] R. M. Stevenson, R. J. Young, P. Atkinson, K. Cooper, D. A. Ritchie, and A. J. Shields. A semiconductor source of triggered entangled photon pairs. *Nature*, 439(7073):179–182, January 2006.

[6] Christian Kurtsiefer, Sonja Mayer, Patrick Zarda, and Harald Weinfurter. Stable solid-state source of single photons. *Phys. Rev. Lett.*, 85:290–293, Jul 2000.

[7] J. P. Hadden, J. P. Harrison, A. C. Stanley-Clarke, L. Marseglia, Y.-L. D. Ho, B. R. Patton, J. L. O'Brien, and J. G. Rarity. Strongly enhanced photon collection from diamond defect centers under microfabricated integrated solid immersion lenses. 97(24):241901, 2010.

[8] B. Darquie, M. P. A. Jones, J. Dingjan, J. Beugnon, S. Bergamini, Y. Sortais, G. Messin, A. Browaeys, and P. Grangier. Controlled single-photon emission from a single trapped two-level atom. *Science*, 309(5733):454–456, 2005.

[9] Shuai Chen, Yu-Ao Chen, Thorsten Strassel, Zhen-Sheng Yuan, Bo Zhao, Jörg Schmiedmayer, and Jian-Wei Pan. Deterministic and storable single-photon source based on a quantum memory. *Phys. Rev. Lett.*, 97:173004, Oct 2006.

[10] Tobias Schmitt-Manderbach, Henning Weier, Martin Fürst, Rupert Ursin, Felix Tiefenbacher, Thomas Scheidl, Josep Perdigues, Zoran Sodnik, Christian Kurtsiefer, John G. Rarity, Anton Zeilinger, and Harald Weinfurter. Experimental demonstration of free-space decoy-state quantum key distribution over 144 km. *Phys. Rev. Lett.*, 98:010504, Jan 2007.