Single and Entangled Photons

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Quantum computing is a sought after technology that will greatly increase the speed and security of computations and communications. The understanding of quantum computing and information technology is dependent upon the understanding of quantum interactions. The difference between current computers and quantum computers lies in the fundamental units of information utilized. The qubit, which is a unit of quantum information in quantum computing, is analogous to the bit in classical information theory. A bit can be either of two states, often denoted as 1 and 0. However, a qubit can be either of the two states or a superposition of the two states. Unlike classical bits, qubits can also become entangled. Entanglement is a quantum phenomenon in which two particles interact in such a way that when they separate they can only be represented by the same description/wave function. Another important concept in quantum based technology is the single photon source.

Quantum entanglement applies to various particles such as electrons, photons, atoms, molecules, etc. One can never truly know simultaneously the location and momentum of any of these particles, because of Heisenberg's uncertainty principle.

$$\Delta x \Delta p \geq \frac{\hbar}{2} \qquad \text{eq(1)}$$

Where Δx is uncertainty of position, Δp is uncertainty of momentum, and $\hbar$ is Planck's constant, h, divided by 2π. In Heisenberg's original version it was $\Delta x \Delta p \approx h$ [1]. Therefore, to represent a quantum particle, one must represent the probability distribution of where it probably is using a wave function. One does not know what a particle is doing until it is measured; so many properties are indefinite. Because these values are indefinite, if one particle interacts with another in such a way that the other particle's future actions become dependent on an indefinite event in the past, they become entangled[2]. The concept of entanglement, introduced by Einstein, Podolsky, and Rozen [2], was developed by Schrödinger who coined this term [3]. In Schrödinger's 1935 paper, he wrote an example of entanglement involving a cat. The thought experiment is set up so that there is a cat in a box. In the box with the cat there is a radioactive material, and a device that releases poison if the material decays. When we close the box, we are uncertain if the atom has decayed or not, it is represented by a superposition of probabilities of the state of being decayed and not being decayed. The cat is entangled with this process and its state cannot be separated from the radioactive material it is entangled with. In this paradox, the cat is both dead and alive because of the superposition of states, it is entangled with (the radioactive material).

This phenomenon of entanglement has some very incredible features. Suppose that two photons whose polarizations are entangled were headed in opposite directions towards two detectors at any distance. If one photon is detected to have a certain polarization, the other polarization is known as well no matter the distance. It is incredible to think someone light years away could detect a photon whose polarization is determined by another's measurement. This information seemingly travels faster than the speed of light, instantaneously even. However, one must ask what is even being communicated? Upon further analysis it can be realized that the receiver has no idea of knowing what the sender is doing, or what the significance of a certain state is. The sender cannot force a signal with indeterminate photons. The measurements do collapse the wave functions of photons, but the sender cannot force photons to collapse to a certain polarization state, making communication via this phenomenon unachievable.

The limitations of entanglement are just as important to understand as its capabilities. Quantum entanglement is the basis of certain qubit information schemes, the quantum information analog to classical information theory. It has the 0, 1, and undetermined superposition of states. This extra degree of freedom can lead to faster processing than ever before. There is a catch though when it comes to the stability of qubits, sudden death. Ambient environment conditions cause decay among quantum entangled entities, which usually follows a half-life law, just like radioactive decay. As long as a computation or process can be done quickly enough, quantum computing can still be performed. However, it has been shown that such decay can be much faster. Entanglement sudden death, considered by Joseph Eberly, is a phenomenon in which entanglement can be destroyed almost instantly, defying the half-life behavior, by even weak environmental factors [4]. This effect is clearly a threat to quantum computing. It may be possible though to finish a computation before sudden death occurs.

Single photon sources also offer revolutionary possibilities. If one is communicating with single photons, an eavesdropper could not intercept the signal without alerting the communicators to the absence of signal. Even if the eavesdropper wanted to copy the signal he could not. According to No-Cloning Theorem [5], it would not be possible for an eavesdropper to entangle a photon with the signal photon allowing him to listen to the signal undetected. No-Cloning Theorem forbids the creation of identical copies of an arbitrary unknown quantum state. Such secure communication possibilities are highly desirable. The limiting factor of progress in this technology is a dearth of high quality single photon sources. Controlling single photons is clearly no small task!

A single photon source can produce single photons that do not come in groups, releasing only one photon at a time. Single photon sources are anti-bunching photon sources. A laser field that is attenuated to a single photon level does not qualify as anti-bunching. Attenuated laser fields will have random photons that are next to each other or very far apart. An example of anti-bunching is when a photon is emitted from an atom, and excited again. The atom cannot emit immediately, there is a delay (fluorescence time). This delay keeps the photons separated in time [6]. The reality of constructing such a mechanism is very difficult and is an active area of research today.

Besides the single atom scheme, quantum dots are another example of single photon sources. Quantum dots can intercept an incoming field and re-emit only one photon at a time due to the quantum effect of confinement, with a certain bandwidth [7]. The sizes of these tiny structures determine the wavelengths they operate at. To use a quantum dot as a single photon source still requires very specific conditions. There is still a need for more efficient single photon sources.

Quantum computing poses risks to security due to its vast computational capacity. Quantum cryptography is an equally promising field that can thwart these intimidating issues. In quantum cryptography, quantum phenomena are used to keep information secure. This idea will become ever more important as quantum computing progresses. One application of single photon sources is quantum cryptography (quantum key distribution). Quantum computing can compromise classical encryption more effectively than current computers and can be malignantly used if placed in the wrong hands, making security a very real concern. Quantum key distribution is extremely secure. A message can be encrypted in a way that is completely randomly generated by quantum probability. This quantum state can then be sent to the other party. This key is completely unknown to others and in the same manner described above cannot be intercepted without detection [8].

Quantum entanglement and single photon sources are vital to the success of quantum computing and quantum communication (quantum cryptography). These technologies will dramatically change the way information is manipulated. Any security problems that are procured by quantum computing can be mitigated by more application of quantum phenomenon. The vast increase of computational capacity will allow for the computation of problems that would have previously been impossible.

References

[1] Heisenberg, W (1927). "Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik", *Zeitschrift für Physik* **43** (3-4): 172–198.

[2] Einstein A, Podolsky B, Rosen N (1935). "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?". *Phys. Rev.* **47** (10): 777–780.

[3] Schrödinger E. (1935). "Die gegenwärtige Situation in der Quantenmechanik (The present situation in quantum mechanics)". *Die Naturwissenschaften* **23**(48): 807–812.

[4] Eberly J, Yu T (2009). "Sudden Death of Entanglement". *Science* **323:** 598 – 601.

[5] Wootters W, Zurek W (1982). "A Single Quantum Cannot be Cloned". *Nature* **299**: 802–803.

[6] Dagenais M, Kimble H, Mandel L (1977). *Phys. Rev. Lett.* **39**: 691.

[7] Ekimov A, Onushchenko A (1981). "Quantum size effect in three-dimensional microscopic semiconductor crystals". *JETP Lett.* **34**: 345–349.

[8] Bennett C, Bessette F, Brassard G, Salvail L, Smolin J (1992). "Experimental Quantum Cryptography". *Journal of Cryptology* **5**: 3–28.