Overview of presently available sources of entangled photons

C1710833

December 2020

1 Introduction

The concept of entanglement refers to the dependence of a property of one quantum system on another system. The idea was given fame by Einstein, Podolsky and Rosen in 1935, referred to often as the 'EPR' paper. This acronym was promoted to a four-letter version when Bohm contributed his argument later in 1951, to EPRB.

Entanglement can involve different properties of the particles, for the case considered here it will be photons. The pairs can be polarisation entangled, time entangled or momentum entangled. Measured independently, the property of either photon is random. When two particles are correlated in one of these ways, making a measurement of one of the photons' property will instantaneously determine what the measurement is going to be of the other photon. Mathematically, an entangled state has a wave function which cannot be written as a product of the individual particles' wave functions. Entangled states for two particles are represented by Bell states, given by equation 1 for positive correlation, and 2 for negative correlation.

$$|\Phi\rangle = \frac{1}{\sqrt{2}}(|0_1, 0_2\rangle \pm |1_1, 1_2\rangle) \tag{1}$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0_1, 1_2\rangle \pm |1_1, 0_2\rangle) \tag{2}$$

The production of correlated photon pairs has proven to be very useful in applications in the field of quantum computing. This is still an active area of research and entanglement of three and more particles are possible.[1]

2 Entangled photon pair sources

2.1 Atomic Cascades in Calcium

This is a phenomenon used by a lot of the early experiments. In these experiments, the entangled photons are emitted in an atomic cascade in calcium from its $4p^2\ {}^1S_0$ excited state. The photons are then detected by a pair of photomultiplier tube (PMT) detectors. Both the initial and final states in the cascade have zero net angular momentum, $J = 0$. As a result, the emitted pairs of photons also have a zero angular momentum. In addition to the initial and final states being rotationally invariant, they have the same even parity. This means that the photon pairs have the polarisation correlation properties that are required for (EPRB) experiments which aim to test the entanglement of two photons. This can be tested

by checking for coincidences by using linear polarisers in front of both detectors. This was was done and demonstrated clearly that the coincidences only occurred when the axes of the polarisers were aligned parallel to each other, thereby indicating that only states of the form of (1) are produced.

The excited state is first de-excited to the intermediate 4p4s $^1P_1$ state, which is an allowed transition releasing a photon of a wavelength of 551.3nm. From there, a further de-excitation happens down to the $4s^2$ $^1S_0$ state, by the other allowed transition at 422.7nm. This isn't the only available decay route, and to select the desired photon wavelengths, narrow-band interference filters are placed in front of the PMT detectors.

This type of experiment was first performed by Kocher and Cummins in 1967. It used ultraviolet photons from a hydrogen arc lamp to excite the calcium atoms to the $4p^2$ $^1S_0$ level, which was done in two steps. First the atoms were excited from the ground state to the excited 4d4p $^1P_1$ state by 227.5nm photons. The atoms then are allowed to decay spontaneously to the $4p^2$ $^1S_0$, which is the desired state.

In later experiments done by Aspect *et al.* the atoms were directly excited to the $4p^2$ $^1S_0$ state using separate laser beams at 406nm and 581nm, allowing for two-photon absorption.[1]

2.2 Down-conversion in optical media

Correlated photons started to be created through down-conversion processes in the 1980s and 90s. This method was found to have higher flux rates than atomic cascades, and as a result has effectively replaced atomic cascade sources whenever polarisation entangled photons are needed.

In these processes, a single photon generated by a pump laser with angular frequency ω_0 is converted into a pair of photons at frequencies of ω_1 and ω_2 in a non-linear crystal. These are called signal and idler photons. Conservation of energy and momentum hold as in most closed physical systems, therefore requiring that

$$\omega_0 = \omega_1 + \omega_2 \tag{3}$$

and

$$\vec{k_0} = \vec{k_1} + \vec{k_2} \tag{4}$$

where $\vec{k_i}$ is the wave vector of photon i. Condition (4) is synonymous to the requirement that nonlinear waves and the fundamental beam stay in phase throughout the medium. When both of those conditions are satisfied, the conditions are called phase-matching. The down-conversion process is degenerate when $\omega_1 = \omega_2 = \omega_0/2$. Otherwise, it is non-degenerate.

The property of dispersion in optical materials produces a complication. Dispersion means that the refractive index of the material will be different for different frequencies meaning that, normally, the phase-matching condition would be impossible to achieve. Conveniently, nonlinear crystals are birefringent, so refractive indices also depend on the direction of the photons' polarisation. This allows for two different types of phase matching from balancing birefringence with dispersion. One in which the polarisations of the down-converted photons are parallel to eachother while being orthogonal to pump photons, and the second where all the photons have orthogonal polarisations to one another.

Degenerate down-conversion with type two phase matching can be done using a β-BaB_2O_4 (BBO) crystal with UV photons from a pump laser focused on it. The photons are down-converted to two photons at half the frequency, putting them in the red part of the EM spectrum. The photons emerge in two oppositely polarised cones, one vertically, one horizontally polarised, as determined by the phase-matching condition. This leads to the detected pattern of two intersecting rings. The conservation of momentum stated by equation (4) means that if

a horizontally polarised photon is detected at one of the intersections, then the photon at the other intersection is immediately known to be vertically polarised, or vice versa. Each of these photons could have come from either of the rings however, giving equal probability to it being in the horizontal state h or vertical v.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|h_1, v_2\rangle + e^{i\phi}\,|v_1, h_2\rangle) \tag{5}$$

The optical phase ϕ can be altered with the use of compensator plates. If the phase is set to 0 or $\pi/2$, the state becomes a Bell state, one of which is given by equation (1).[1]

Generating polarisation entangled pairs through in nonlinear media through down-conversion produces the photons at a very slow rate at > 0.1 photon pairs per pulse of excitation. This low rate is owing to the source obeying Poissonian statistics.[2]

2.3 Quantum dots

Quantum dots (QDs) are artificial nanostructures which behave like atoms, having discrete states for electrons to be bound in.

Semiconductor QDs can be used to generate pairs of entangled photons. The biexciton state is populated resonantly using a two-photon excitation (TPE) process. Then the biexciton decays in a cascade going from biexciton to exciton and then to ground state, emitting photon pairs, one from each of the decay steps. The most desired state of the entangled pair is the maximum entangled Bell state similar to (1) but with horizontal and vertical polarisations as basis states.

In GaAs QDs the emitted photons have a wavelength of about 780nm and are separated by about 2nm, which allows them to be split by colour. GaAs QDs are a viable source of entangled photons for applications such as QKD for which high brightness and strong entanglement is required for optimal functionality.[3]

Some of the best QD sources of entangled photons are based on micropillar 'molecules', photonic nanowires and optical antennae. These allow each photon of the pair to couple into a specific photonic channel which gives rise to bright entangled photon pairs.

One problem of using QDs as a source of entangled photons comes from the high refractive index of the semiconductor material surrounding the QD leads to low photon extraction efficiency. Some steps have been taken to improve photon pair brightness and indistinguishability, such as combining GaAs QDs with new broadband photonic nanostructures called circular Bragg resonators on highly efficient broadband reflectors (CBR-HBR). By a wide-field QD positioning technique, the QDs are precisely and optimally positioned at the centre of the cavity, improving the performance of entangled photon generation.[4]

Another, the electron-hole interaction in asymmetric QDs leads to reduced time-averaged entanglement fidelity[4], which is a measure of the preservation of entanglement through quantum channels[5]. This can be tackled by creating highly symmetric QDs. Arguments also exist for the short decay time of the second step of the biexciton decay being related to improvements in fidelity[4].

Using the decay of electron-hole pairs in QDs has a very high probability of emitting an entangled photon pair but it is very inefficient to extract them. It is possible to overcome this by coupling an optical cavity to the QD, in the form of an 'optical molecule'.[2]

2.4 Time-bin entanglement sources

Time-bin entanglement is also known as pulsed energy-time entanglement. This type of entanglement has an advantage over polarisation entanglement, that being that it is not effected

by changes in polarisation in optical media. The originally investigated source involves two pulses of a laser consecutively, which are generated using an unbalanced interferometer to pump nonlinear media. The photon pair is generated by parametric down-conversion.

Another method, which allows for high-repetition rates more suitable for quantum communication, is to use a laser pulse train for pumping the nonlinear media. The pump beam has a coherence time T_c and the pulses are separated in time by τ. One pulse lasts a time τ_p. For sequential time-bin entangled photons to be generated, the condition must be satisfied that $T_c \gg \tau \gg \tau_p$. In this case, an interferometer at the source side is not needed. This method has been successful at the 1550nm band using four-wave-mixing in dispersion shifted fibre, as well as spontaneous parametric down-conversion in periodically-poled $LiNbO_3$ or potassium titanyl phosphate (PPKTP) waveguides. The wave function of the resultant pair of signal and idler photons is

$$|\Psi\rangle = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} e^{n\phi_\tau} |n\tau\rangle_{signal} |n\tau\rangle_{idler} \tag{6}$$

provided that the number of pump pulses $N \gg 2$, the phase difference between consecutive pulses is ϕ_τ and that the $T_c \gg \tau \gg \tau_p$ condition is satisfied.

Using the PPKTP waveguide produces 895nm signal photons and 1310nm idler photons. The signal ones are useful for local optical networks and the longer idler radiation is suitable for long distance networks.[6]

3 Summary

The available sources of entangled photons include a variety of materials and methods, starting with atomic cascades, which are the longest known sources. These however proved inefficient and have become obsolete for a majority of applications today. Following this, the possibility of the use of down-conversion in optical crystals was discovered These however have very low extraction rates despite reliably producing entangled pairs of photons. These produce polarisation entangled photons. Biexciton decay in QDs also produced entangled photons, which are still being actively researched and improvements are widely suggested. The polarisation produced by this method is affected by the refractive index of the surrounding media. Time-bin entangled pairs are not affected by the changes in polarisation in optical materials, which is a convenient property of such sources.

The range applications appears endless, and the possibility of teleportation will excite any science fiction enthusiast.

References

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