Experiment: using down converted entangled photons in correlated events experiments

Quotes about nomenclature (reference 1) : " "Entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently—instead, a quantum state may be given for the system as a whole." "Measurements of physical properties such as position, momentum, spin, polarization, etc. performed on entangled particles are found to be appropriately correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise. Because of the nature of quantum measurement, however, this behavior gives rise to effects that can appear paradoxical: any measurement of a property of a particle can be seen as acting on that particle (e.g. by collapsing a number of superimposed states); and in the case of entangled particles, such action must be on the entangled system as a whole. It thus appears that one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances.

Quantum entanglement is an area of extremely active research by the physics community, and its effects have been demonstrated experimentally with photons, electrons, molecules the size of buckyballs, and even small diamonds Research is also focused on the utilization of entanglement effects in communication and computation.""

Technology: Beta Barium Borate (BBO) parametric down DC conversion crystal

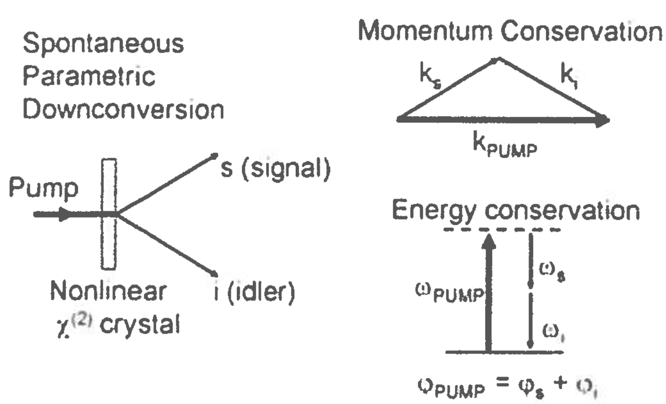


Fig 1. Nonlinear crystal is used to split photons. Special case is when energies are the same (reference 1)

The photon splitting , DC, takes place 1 in 10^{12} of events so lasers whit high number of photons are used in DC processes.

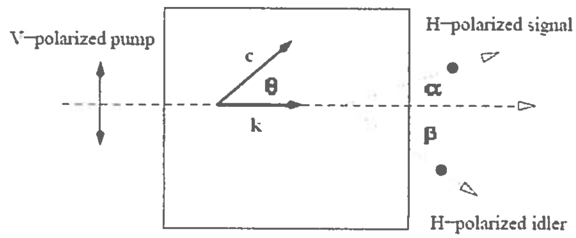


Figure 2.2: A pump photon splits into signal and idler photons in type-I phase matched SPDC.

Fig 2 (reference 2)

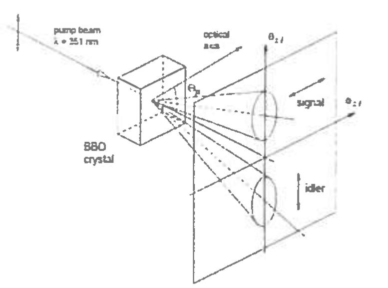


Figure 1. Geometrical arrangement for type-II parametric down conversion. A collimated UV pump beam is sent as -polarisation in a nonlinear optical crystal. Due to parametric conversion, pair photons are generated, which are emitted in a manyfold of two cones for a given wavelength, referred to as signal and idler, where one of the cones is polarised in direction, and the other one in -direction.

converted into pairs of photons, obeying energy and momentum conservation. For a fixed

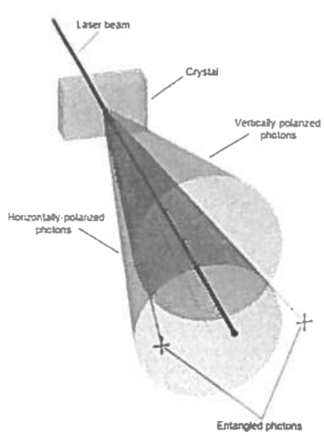


Fig 3 a and b (references 3, 4)

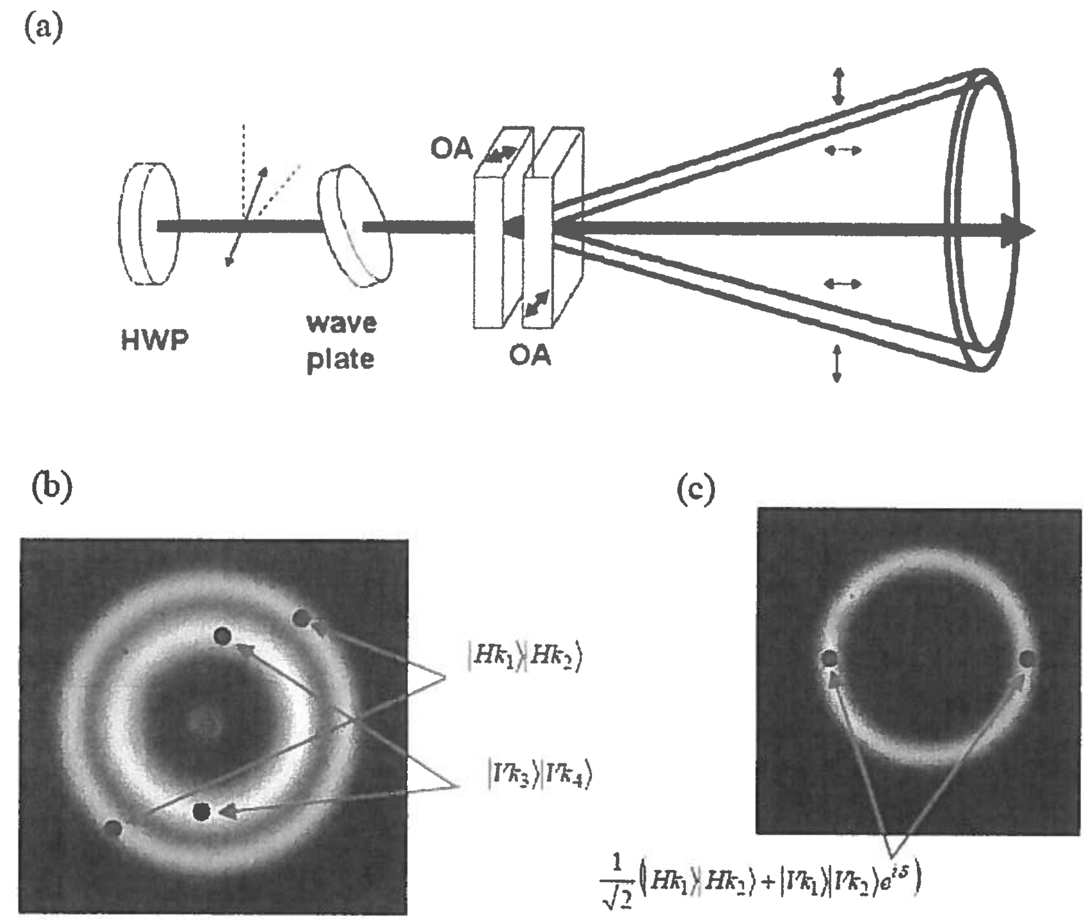
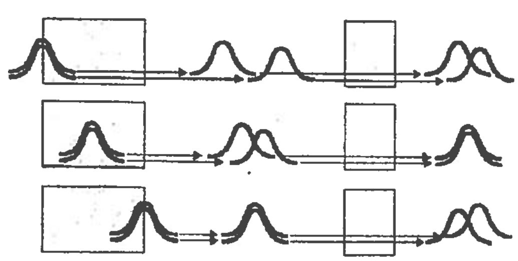


Fig. 19. Method of producing entangled states. (a) schematic; (b) two cones; (c) indistinguishable cones. Photo courtesy Air Force Research Lab.



$$|\psi\rangle = 2^{-1/2}\left(|H\rangle_1 |H\rangle_2 + |V\rangle_1 |V\rangle_2 \right).$$

$$|\psi\rangle = 2^{-1/2}\left(|D\rangle_1 |D\rangle_2 + |A\rangle_1 |A\rangle_2 \right).$$

Fig 4 (ref, se Analysis) Note that for d = 0 we can use Diagonal and Antidiagonal eigenvalues system

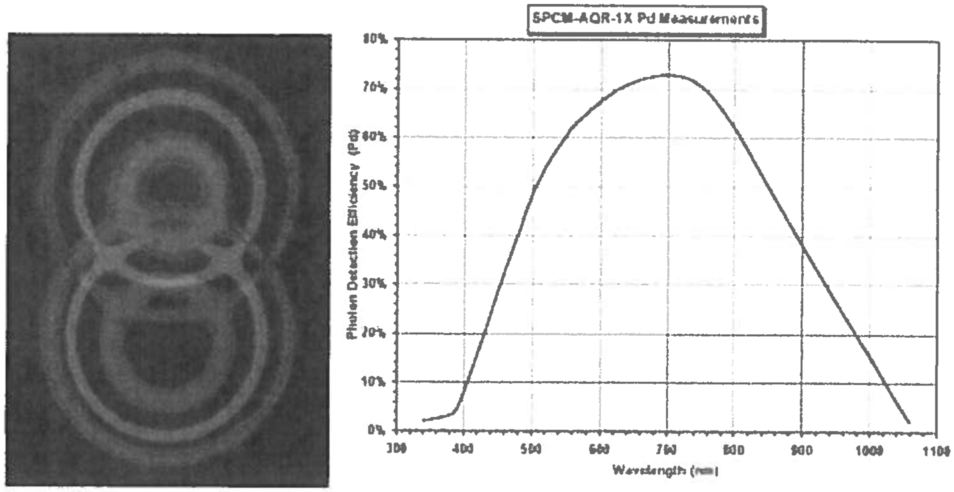
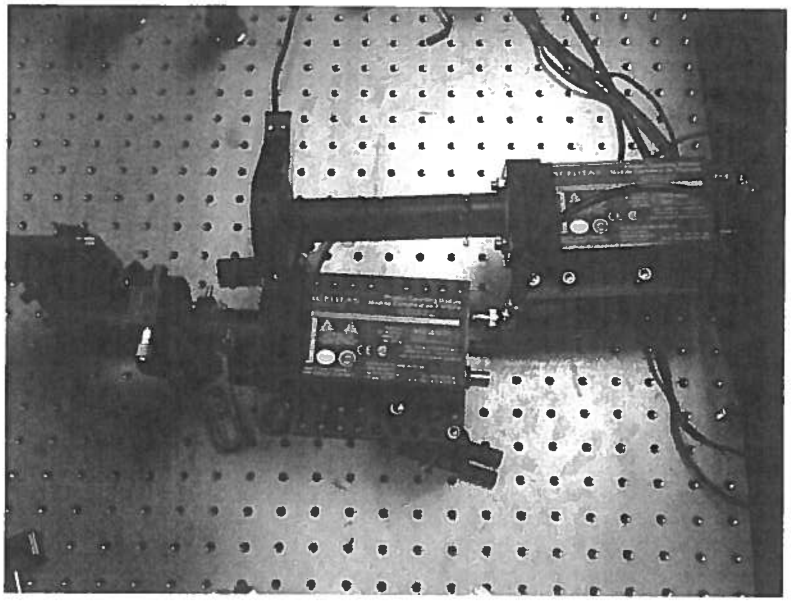
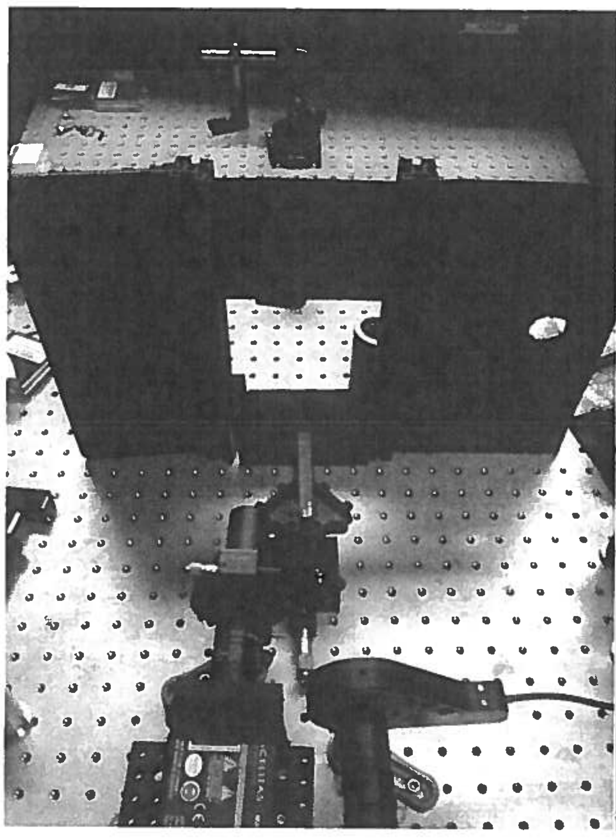


Fig 5 (reference 6,9) Detection SPD or sensitive CCD

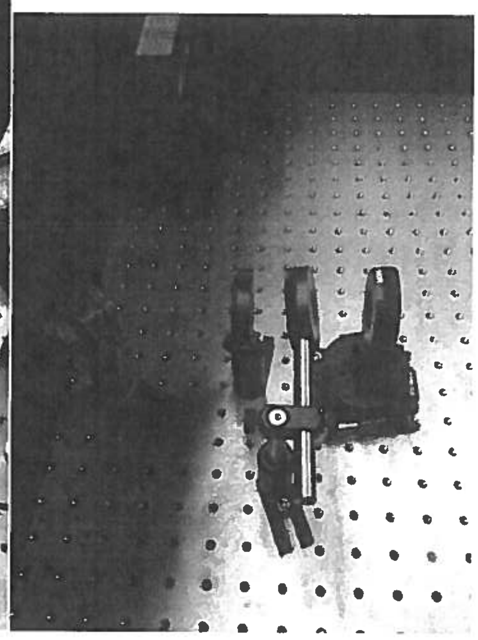
Fig 5 Experimental configuration – complete system covered



Single photon detectors with filters



Two detectors with precise polarizers



405 nm laser, L/2, Phase shifter and BBO

Fig 5 Experimental configuration

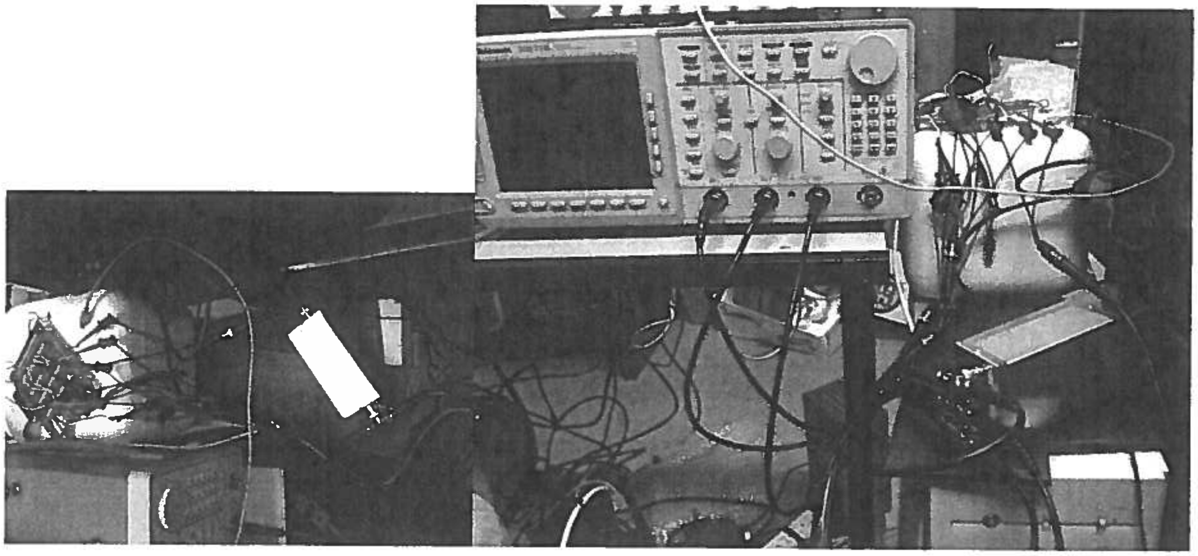


Fig 6 coincidence apparatus

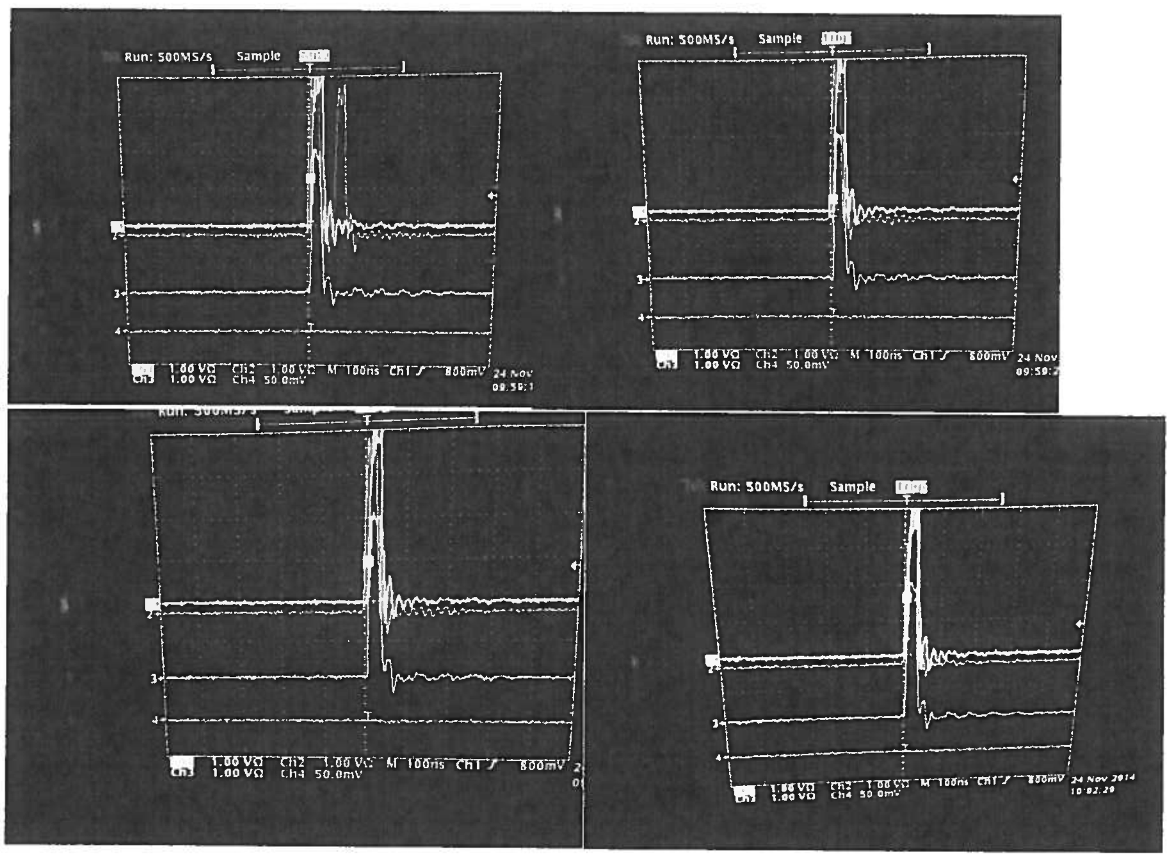


Fig 7 Coincidence- oscilloscope

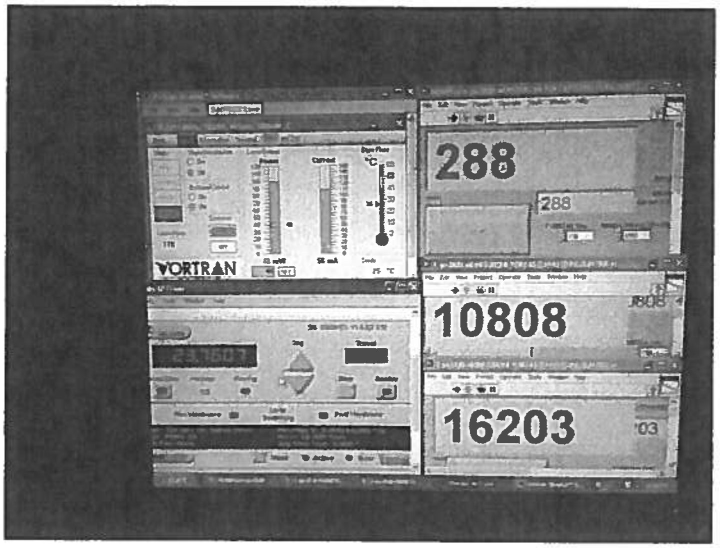


Fig 8 coincidence counts -LabView counter software, Laser control and polarization rotation control

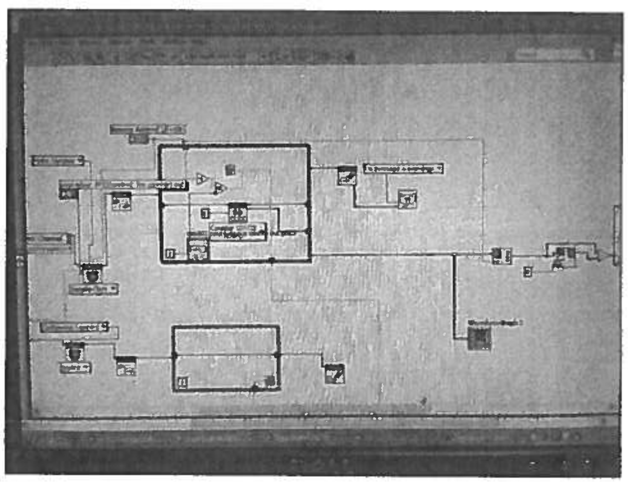


Fig 9   LabView software insight

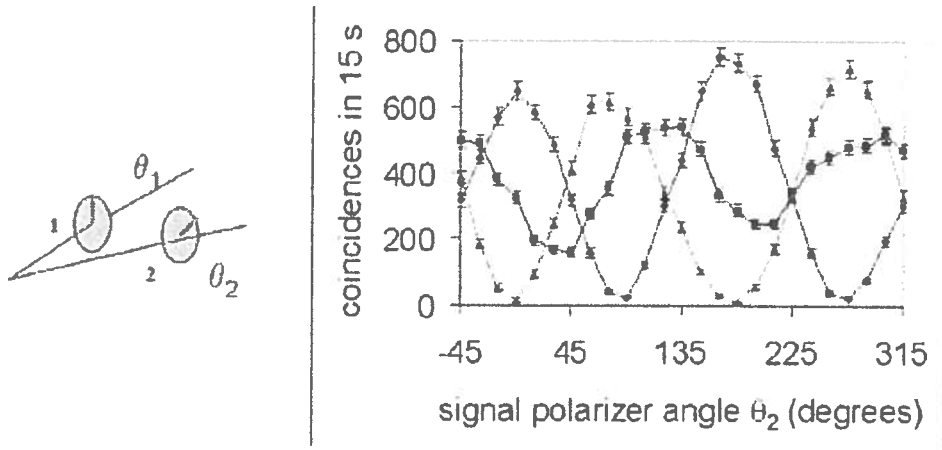


Fig 10 Results (reference0

Results and assignments

Coorrelated/entangled/COINCIDENT		HV superposition	DA basis	
position 1 Polarization	position 2 Polarization		entangled f=0 photons	
45	45	ALL	coincidence	
45	-45	NO	no coincidence	
non corelated H V	MIXED state			
45	45	50	50	25%
45	-45	50	50	25%

In this experiment you will produced superposition of states from correlated entangled photons and measure coincidences at different polarizations, using a rotating precise polarizer in front of each of the two detectors measuring polarizations of two split photons.

You will interpret results using the "analysis " material below. You can use Mathematica (or MatLab etc.) application for visualization and quantitative work.

After completing that part you will use an assigned molecular system and measure correlated electron-nuclear components.

Analysis

This state is called a "product state" because the wavefunction of the pair is the product of the wavefunctions of the two particles.

As we have seen before, a polarizer projects the state of the light into the direction of the transmision angle of the polarizer. If the polarizer is rotated an angle θ relative to the horizontal then the polarizer eigenstates of transmission and extinction are in the basis rotated by an angle θ. These are the states $|\mathrm{H}'\rangle$ and $|\mathrm{V}'\rangle$, related to $|\mathrm{H}\rangle$ and $|\mathrm{V}\rangle$ via the transformation of Fig. 2, represented by the relations

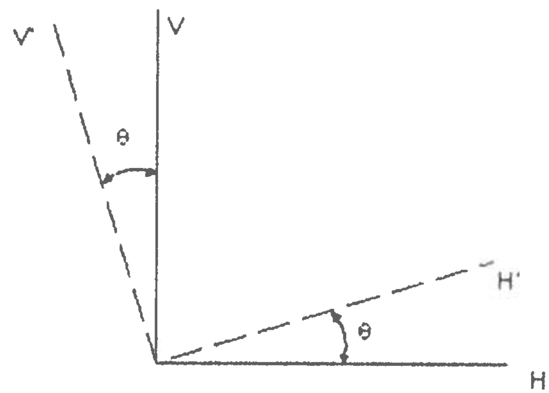


Figure 2: Two bases to represent states of polarization.

$$|\mathrm{H}\rangle = \cos\theta|\mathrm{H}'\rangle - \sin\theta|\mathrm{V}'\rangle \quad (2)$$

$$|\mathrm{V}\rangle = \sin\theta|\mathrm{H}'\rangle + \cos\theta|\mathrm{V}'\rangle. \quad (3)$$

Thus, if we decide to measure the two photons with polarizers set to angles θ_1 and θ_2 then we express the state of each photon in the rotated bases

$$|\psi_{\mathrm{P}}\rangle = (\sin\theta_1|\mathrm{H}'\rangle_1 + \cos\theta_1|\mathrm{V}'\rangle_1)(\sin\theta_2|\mathrm{H}'\rangle_2 + \cos\theta_2|\mathrm{V}'\rangle_2). \quad (4)$$

and as done in a previous lab, we treat the polarizers as devices that project the state of the light into one of the states $|\mathrm{H}'\rangle$. The probability of joint detection (i.e., of detecting both photons past the polarizers) is the square of the probability amplitude of being in state $|\mathrm{H}'\rangle_1|\mathrm{H}'\rangle_2$

$$P_P = |\langle\mathrm{H}'|_1\langle\mathrm{H}'|_2|\psi_{\mathrm{P}}\rangle|^2. \quad (5)$$

In the previous operation the two particles had separate subspaces, so the bra's of particle 1 only operate on the kets of particle 1, and similarly for particle 2.

Question 1 Show that Eq. 5 results in $P_P = \sin^2\theta_1 \sin^2\theta_2$

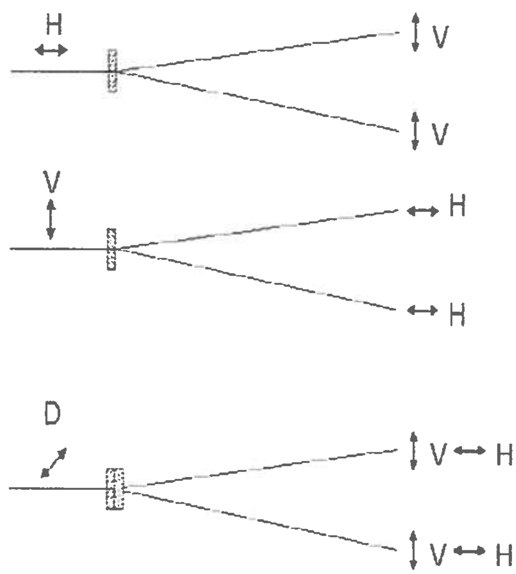


Figure 3: Method to produce polarization-entangled states: the bottom setup is a superposition of the two cases above.

The polarization state of the down-converted light that we created in previous labs was due to a pump beam that was horizontally polarized incident on an appropriately oriented crystal. In that case we used collinear down conversion. By adjusting the crystal we can have down-converted pairs at 804 nm come out forming an angle with the incident direction, as shown in Fig 1. If we change the polarization of the pump to vertical we would not get down-conversion. However, if we rotate the crystal by 90° we get horizontally polarized pairs.

Question 2 Find the joint detection probability P_P past the polarizers when the initial state is $|\psi_P\rangle = |H\rangle_1 |H\rangle_2$.

A few years ago Paul Kwiat (U. Illinois) came up with a clever trick: to put two thin down-conversion crystals back to back but rotated by 90° with respect to each other. He then sent a pump beam polarized at 45° to the pair of crystals, as shown in Fig. 3. This way the horizontal component of the pump polarization produces vertically polarized pairs with one crystal and the vertical component produces horizontally polarized pairs with the other crystal. If the crystal separation is thinner than the coherence length and if the crystal width is smaller than the beam width, then there is no way to tell in which crystal the photon pairs were created. Thus when the paths are indistinguishable the photon pairs get created into a state that is a superposition of the two possibilities:

$$|\Phi_{\rm ent}\rangle = \frac{1}{\sqrt{2}}\left(|{\rm H}\rangle_1|{\rm H}\rangle_2 + |{\rm V}\rangle_1|{\rm V}\rangle_2 e^{i\delta}\right). \tag{6}$$

where δ is a phase between the two possibilities. For simplicity, and without much loss of generality let us assume that $\delta = 0$. The state is then

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|{\rm H}\rangle_1|{\rm H}\rangle_2 + |{\rm V}\rangle_1|{\rm V}\rangle_2\right). \tag{7}$$

The skeptical physicist may say: "What about a mixed state?" A mixed state would be the situation where the light is not in a superposition of both horizontal and both vertical. Rather, half the time the pairs come horizontal and half the time they come vertical. How can we distinguish the two? The answer to this questions leads us straight to Bell.

Before we discuss Bell let us study in more detail the entangled state given by Eq. 6. What would the form of the state be in the diagonal-antidiagonal basis? If you recall, the diagonal basis states are related to the horizontal-vertical states by:

$$|{\rm D}\rangle = \frac{1}{\sqrt{2}}\left(|{\rm H}\rangle + |{\rm V}\rangle\right) \tag{8}$$

$$|{\rm A}\rangle = \frac{1}{\sqrt{2}}\left(-|{\rm H}\rangle + |{\rm V}\rangle\right). \tag{9}$$

Question 3 Put $|{\rm H}\rangle$ and $|{\rm V}\rangle$ in terms of $|{\rm D}\rangle$ and $|{\rm A}\rangle$ for each particle in Eq. 6, and show that

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|{\rm D}\rangle_1|{\rm D}\rangle_2 + |{\rm A}\rangle_1|{\rm A}\rangle_2\right). \tag{10}$$

In the H-V basis the photons are in a superposition of being parallel to each other in two different ways. In the rotated basis they are also in an entangled state that is a superposition of the two possibilities in which they can be parallel! This is an interesting but unique aspect of state $|\Phi^+\rangle$.

State $|\Phi^-\rangle$ corresponds to state $|\Phi_{\rm ent}\rangle$ of Eq. 6 with $\delta = \pi$. In the diagonal basis $|\Phi^-\rangle$ becomes

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}\left(|{\rm D}\rangle_1|{\rm A}\rangle_2 + |{\rm A}\rangle_1|{\rm D}\rangle_2\right). \tag{11}$$

That is, in state $|\Phi^-\rangle$ the light switches from being parallel in the H-V basis to being orthogonal in the D-A basis. Let us go back to $|\Phi^+\rangle$. Suppose that we now rotate the basis for each photon separately, at an angle θ_1 for photon 1 and θ_2 for photon 2. Then we replace the relations of Eq. 3 in Eq. 7. If we do some algebra and group the terms we get

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}[\cos(\theta_1-\theta_2)|{\rm H}'\rangle_1|{\rm H}'\rangle_2 + \cos(\theta_1-\theta_2)|{\rm V}'\rangle_1|{\rm V}'\rangle_2 \tag{12}$$

$$+ \sin(\theta_1-\theta_2)|{\rm H}'\rangle_1|{\rm V}'\rangle_2 + \sin(\theta_2-\theta_1)|{\rm V}'\rangle_1|{\rm H}'\rangle_2] \tag{13}$$

As done before, polarizers project the state of each photon. The probability of detecting a pair in the entangled state is

$$P_{\text{ent}} = |\langle H'|_1 \langle H'|_2 |\Phi^+\rangle|^2 = \frac{1}{2}\cos^2(\theta_1 - \theta_2) \tag{14}$$

The above probabilities are the ones predicted by entanglement. You can see that the detection of one "influences" the result of the detection of the other one. In inspecting Eq. 14 you can see that we get maximum probability when the two angles are the same. That is, the photon pairs in state $|\Phi^+\rangle$ are parallel in *any* basis. As soon as we measure one of the photons to be polarized along one direction (with probability 1/2) we get that the other one is polarized in the same direction with unity probability. Thus, one can think of the "1/2" in Eq. 14 as the probability of detecting the first photon, and the cosine term as the conditional probability of detecting the other given that the first one was detected at the angle θ. This correlation is the basis for *nonloacality*: that the detection of one photon immediately "collapses" the wavefunction of the two, instantaneously at faster than the speed of light. This is the view advocated by Bohr in the so called "Copenhagen interpretation" of quantum mechanics, which Einstein criticized and derided as "spooky action at a distance."

One last point. The "1/2" term stems from the randomness of quantum mechanics. When we detect the polarization of the first photon anything can happen. It may be transmitted or not. It is the detection of the second one that is conditional to the *result* of the first detection. Thus, this is not faster-than-light communication of *information*, because we do not control the outcome of the first measurement.

Yet, pagans abound. How do we know that we are in a mixed state? This is the "realistic view." In this view the photons had their state of polarization defined before the measurement was done. What is the probability of detection predicted for the mixed state? It is given by

$$P_{\text{mix}} = \frac{1}{2}|\langle H'|_1 \langle H'|_2 |H\rangle_1 |H\rangle_2|^2 + \frac{1}{2}|\langle H'|_1 \langle H'|_2 |V\rangle_1 |V\rangle_2|^2 \tag{15}$$

$$P_{\text{mix}} = \frac{1}{2}\cos^2\theta_1 \cos^2\theta_2 + \frac{1}{2}\sin^2\theta_1 \sin^2\theta_2. \tag{16}$$

The one half represents the situation that the light is in either state, $|H\rangle_1|H\rangle_2$ or $|V\rangle_1|V\rangle_2$ half the time. Notice that Eqs. 14 and 16 have a different functional form. Thus, we have a chance to find out which one is correct. When $\theta_2 = 0$ both give the same answer:

$$P_{\text{ent}} = P_{\text{mix}} = (1/2)\cos^2\theta_1.$$

However, if $\theta_2 = \pi/4$ they give a different answer:

$$P_{\text{ent}} = (1/2)\cos^2(\theta_1 - \pi/4).$$

where $|\psi_{DC}\rangle$ is given by Eq. 2.19. We can substitute Eq. 2.21 into the expression for $P_{VV}(\alpha,\beta)$ and simplify with $\langle V||V\rangle = 1$, $\langle V||H\rangle = 0$, and $|\psi|^2 = \psi^*\psi$ as follows:

$$\begin{aligned} P_{VV}(\alpha,\beta) &= \left|\langle V_\alpha|_s(\cos\beta\langle V|_i - \sin\beta\langle H|_i)(\cos\theta|H\rangle_s|H\rangle_i + e^{i\phi}\sin\theta|V\rangle_s|V\rangle_i)\right|^2 \\ &= \left|(\cos\alpha\langle V|_s - \sin\alpha\langle H|_s)(\cos\beta\sin\theta|V\rangle_s e^{i\phi} - \sin\beta\cos\theta|H\rangle_s)\right|^2 \end{aligned}$$

$$= \left|\cos\alpha\cos\beta\sin\theta e^{i\phi} + \sin\alpha\sin\beta\cos\theta\right|^2 \qquad (2.23)$$

$$\begin{aligned} &= (\cos\alpha\cos\beta\sin\theta e^{-i\phi} + \sin\alpha\sin\beta\cos\theta)(\cos\alpha\cos\beta\sin\theta e^{i\phi} + \sin\alpha\sin\beta\cos\theta) \\ &= \cos^2\alpha\cos^2\beta\sin^2\theta + \sin^2\alpha\sin^2\beta\cos^2\theta \\ &\qquad + \sin\alpha\cos\alpha\sin\beta\cos\beta\sin\theta\cos\theta(e^{i\phi} + e^{-i\phi}) \end{aligned}$$

$$= \cos^2\alpha\cos^2\beta\sin^2\theta + \sin^2\alpha\sin^2\beta\cos^2\theta + \frac{1}{4}\sin 2\alpha\sin 2\beta\sin 2\theta\cos\phi \qquad (2.24)$$

Photon pairs collected over a finite solid angle and wavelength range will have a spread in the phase lag ϕ. The actual state collected is better represented by substituting $\langle\cos\phi\rangle = \cos\phi_m$ for $\cos\phi$.

Special cases occur when $\theta = \pi/4$ and $\phi = 0, \pi$. Then

$$|\psi_{DC}^{\pm}\rangle = (|H\rangle_s|H\rangle_i \pm |V\rangle_s|V\rangle_i)/\sqrt{2}, \qquad (2.25)$$

and $P_{VV}(\alpha,\beta)$ simplifies from Eq. 2.23 to

$$P_{VV}(\alpha,\beta) = \frac{1}{2}\cos^2(\alpha \mp \beta), \qquad (2.26)$$

which depends only on the relative angle $\alpha \mp \beta$. For a better understanding of how S varies with for different sets of four angles, the reader may wish to use these mathematically simple cases and plugin angles to find some values of S. For example, quantum mechanics predicts S has a maximum of $2\sqrt{2} > 2$ for the set of angles $(a, a', b, b') = (-\frac{\pi}{4}, 0, -\frac{\pi}{8}, \frac{\pi}{8})$, which violates the Bell inequality derived earlier.

Applications

Quantum information – correlated projections on two positions. Polarization is a message. Message in one detector is correlated to the message in the other. If a third party interferes there will be new correlate state /superposition state and initial massage will be changed. That means the intrusion will be recognized and results destroyed in the sense that the information is changed.

Also there is not only 0 and 1 option it is an infinite number of states.

"SPDC allows for the creation of optical fields containing (to a good approximation) a single photon. As of 2005, this is the predominant mechanism for experimentalists to create single photons.Recently, an alternative electrically driven semiconductor source was proposed based on the newly observed effect of two-photon emission from semiconductors. The single photons as well as the photon pairs are often used in quantum information experiments and applications like quantum cryptography and Bell test experiments".

Related media interest etc. : "Teleportation", "Faster than light speed"

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

"Such phenomena were the subject of a 1935 paper by Albert Einstein, Boris Podolsky and Nathan Rosen,and several papers by Erwin Schrödinger shortly thereafter,describing what came to be known as the EPR paradox. Einstein and others considered such behavior to be impossible, as it violated the local realist view of causality (Einstein referred to it as "spooky action at a distance"), and argued that the accepted formulation of quantum mechanics must therefore be incomplete. Later, however, the counterintuitive predictions of quantum mechanics were verified experimentally.[5] Experiments have been performed involving measuring the polarization or spin of entangled particles in different directions, which—by producing violations of Bell's inequality—demonstrate statistically that the local realist view cannot be correct. This has been shown to occur even when the measurements are performed more quickly than light could travel between the sites of measurement: there is no lightspeed or slower influence that can pass between the entangled particles.Recent experiments have measured entangled particles within less than one part in 10,000 of the light travel time between them.According to the formalism of quantum theory, the effect of measurement happens instantly,It is not possible, however, to use this effect to transmit classical information at faster-than-light speeds (see Faster-than-light → Quantum mechanics)."

Quantum teleportation allows to transfer an unknown quantum state from a sender to a receiver. This was proposed by Bennet et al. [3]. Already in 1997 experimental results were published in [12].

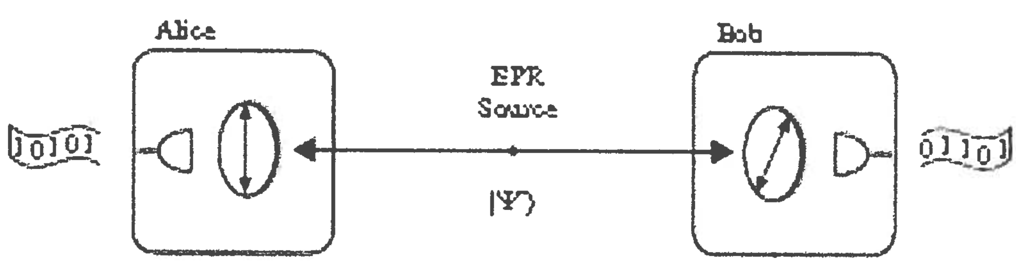


Figure 2.4: *Ekert Protocol: Two entangled photons are distributed to Alice and Bob; they can make polarization measurements in randomly chosen basis and can generate a key for secure communication*