# Chapter 18

# Entangled Delayed Quantum Erasure – The Weirdness Maxes Out

***What is quantum erasure? What is delayed erasure and does it challenge causality?***

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## 1. Measurement, Erasure, Causality

Quantum erasure is the phenomenon whereby a "measurement", which would destroy an interference pattern, can be erased and the interference regained. How can a measurement possibly be erased? Such erasures become even more intriguing when coupled with experiments on entangled pairs of particles because this provides the opportunity to carry out the erasure *after* the interference data has already been obtained. One particle, it is claimed in popular accounts, appears to "know" that a measurement will be carried out in the future on its entangled partner. Hence an interference pattern is re-established because of an erasure which will be carried out after the interference data has already been collected. This is often presented in popular accounts as posing a challenge to the correct temporal order of causality. It does not, of course, and this Chapter explains why.

Unfortunately, popular accounts of these issues are often desperately inaccurate. Indeed I am tempted to say that, "when I hear of delayed erasure I reach for my gun". The key to a sound understanding, as always with these matters, is the Hilbert state algebra. The algebra is virtually trivial and certainly far easier to follow than accounts of detailed experimental arrangements.

It will be seen that the key to understanding the possibility of erasure is the ambiguity of the word "measurement". Similarly the key to understanding why delayed erasure on entangled pairs does not conflict with proper causality is the distinction between local interference and correlated interference. Popular accounts are guilty of failing to distinguish clearly between the two.

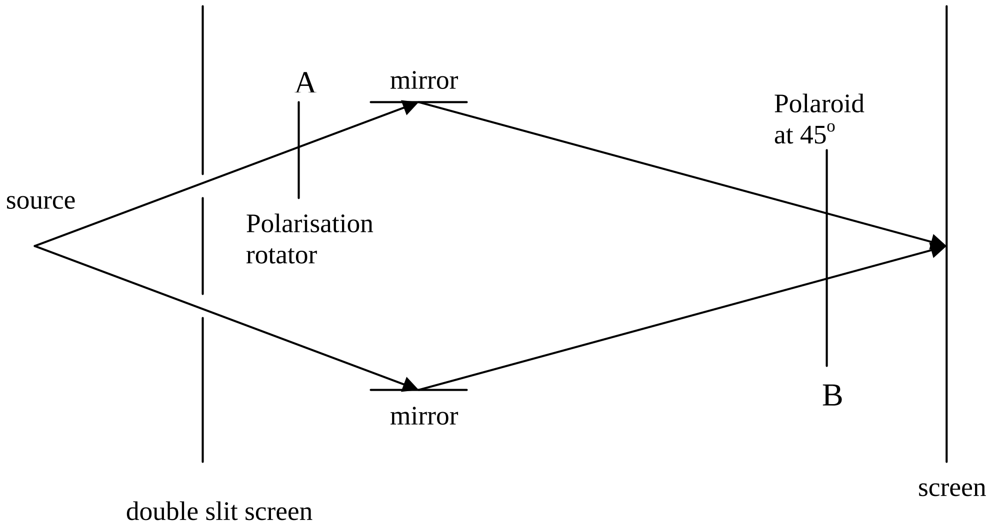
Experiments of the sort discussed in this Chapter are of considerable importance in verifying, yet again, that the predictions of quantum mechanics are borne out. And, of course, quantum mechanics really ***is*** weird. The weirdness lies in the fact that alternative outcomes are not deterministic (there are no hidden variables) and yet, despite that, causally unconnected measurements contrive to be correlated. It's weird all right, but not as weird as popular accounts of delayed erasure generally suggest.

## 2. Quantum Erasure – A Simple Example

Recall that if we measure the path by which a photon travels in an interferometer then we destroy the interference pattern. Remarkably such a "measurement" can be undone – or erased – and the interference pattern regained. There is a caveat, though, which most sources are guilty of failing to emphasise. The caveat hinges upon exactly what is meant by "measurement". We shall return to this at the end of this section. Firstly a brief reminder of how "which path" information destroys interference.

Consider a double slit interference experiment as shown in Figure 1.

**Figure 1**




The source is assumed to supply vertically polarised light. Initially the polarisation rotator (A) and the 45° Polaroid (B) are not present. There is then an interference pattern on the screen. Algebraically this occurs as follows. The state arriving at the screen can be written,

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|U\rangle + |L\rangle\right) \tag{1}$$

Here $|U\rangle, |L\rangle$ represent the upper and lower beam paths. At the screen they will differ by a phase $e^{i\theta}$, so that, in the *x*-basis, where *x* is the position on the screen, we have,

$$\psi(x) = \frac{1}{\sqrt{2}}\left(1 + e^{i\theta}\right)\psi_U(x) \tag{2}$$

Hence,

$$|\psi(x)|^2 = 1 + \cos\theta(x) \tag{3}$$

(assuming $\psi_U(x)$ is a plane wave with $|\psi_U| = 1$) which displays the usual interference pattern.

We now insert the polarisation rotator (A), which we arrange to rotate the polarisation of the upper beam to the horizontal. (The 45° Polaroid is still not present). Since the upper and lower beams are now distinguishable by their distinct polarisations we expect the interference pattern to disappear. This is indeed the case, and the reason may be seen algebraically as follows. The polarisation part of the state will be written $|v\rangle$ or $|h\rangle$, for vertical and horizontal polarisation respectively. These are perfectly distinguishable states, so $\langle v|h\rangle = 0$. The state before encountering the polarisation rotator is $\frac{1}{\sqrt{2}}\left(|U\rangle|v\rangle + |L\rangle|v\rangle\right)$ but afterwards it is,

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|U\rangle|h\rangle + |L\rangle|v\rangle\right) \tag{4}$$

In the *x*-basis this becomes,

$$\psi(x) = \frac{1}{\sqrt{2}}\left(1 \cdot |h\rangle + e^{i\theta} \cdot |v\rangle\right)\psi_U(x) \tag{5}$$

Hence,
$$|\psi(x)|^2 = 1 \tag{6}$$

as a consequence of $\langle v|h\rangle = 0$. So the interference pattern has disappeared. From this it is algebraically transparent how the distinguishability of the two paths eradicates the interference: it makes the two terms in (4) orthogonal and hence the cross-product is zero.

Now, what about erasure? Can we undo the effects of the polarisation rotator later? We insert the 45$^o$ Polaroid. Let us write the state emerging from this Polaroid as $|45\rangle$, and the perpendicular polarisation as $|-45\rangle$. We can express the vertical and horizontal polarisations in terms of these as,

$$|v\rangle = \frac{1}{\sqrt{2}}\left(|45\rangle + |-45\rangle\right) \tag{7}$$

$$|h\rangle = \frac{1}{\sqrt{2}}\left(|45\rangle - |-45\rangle\right) \tag{8}$$

Substituting (7,8) into (4) gives,

$$|\psi\rangle = \frac{1}{2}\left(|U\rangle\left(|45\rangle - |-45\rangle\right) + |L\rangle\left(|45\rangle + |-45\rangle\right)\right) \tag{9}$$

The 45$^o$ Polaroid traps the component $|-45\rangle$ and lets through the component $|45\rangle$. So the state reaching the screen is,

$$|\psi\rangle = \frac{1}{2}\left(|U\rangle|45\rangle + |L\rangle|45\rangle\right) = \frac{1}{2}\left(|U\rangle + |L\rangle\right)|45\rangle = \frac{1}{2}\left(1 + e^{i\theta}\right)\psi_U(x)|45\rangle \tag{10}$$

Because the unique polarisation state factors out of the bracket, we now have once again,

$$|\psi(x)|^2 = \frac{1}{2}\left(1 + \cos\theta(x)\right) \tag{11}$$

So the interference fringes are regained! The "which path" information transiently provided by the polarisation rotator has been successfully erased by the Polaroid. (Note that the reason why (10) has an average of only ½ is because the Polaroid has absorbed half the photons).

Are we entitled, though, to refer to what the polarisation rotator does as being "a measurement"? I suggest not. A measurement actually consists of two things,

(i) the establishment of entanglement between the system being measured and the apparatus, and,

(ii) the "collapse of the wavepacket", i.e., the actual selection of just one of the possible outcomes.

The first of these, (i), is embodied by (4). Note that the transformation of (1) into (4) is purely unitary – and this is why it can be reversed.

The second of the measurement steps, (ii), never happens in this setup. If it had occurred in respect of our so-called measurement by the polarisation rotator, then, before reaching the Polaroid, the state would have been either $|\psi\rangle = |U\rangle|h\rangle$ or $|\psi\rangle = |L\rangle|v\rangle$ but not $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|U\rangle|h\rangle + |L\rangle|v\rangle\right)$. It would then have been quite impossible to reverse such a *true* measurement to yield an interference pattern. Instead, the polarisation rotator carries out only the first step of a measurement. The state remains coherent, with no increase in entropy, and hence is reversible.

But a partial "measurement" which stops at step (i) ***is*** sufficient to eliminate interference, because (6) follows from (4). Merely bringing the system into entanglement with a set of orthogonal pointer states is enough to eliminate interference by virtue of the above algebra. And this is reversible, unlike true measurement which is obviously irreversible once the wavepacket has collapsed.

The moral is that the term "measurement" is used ambiguously in the literature. A true measurement could not be erased. But the partial measurement of step (i) is sufficient to eliminate interference – and can also be erased, thus restoring interference.

### 3. Quantum Erasure in the Crossed SPDC Beam Setup

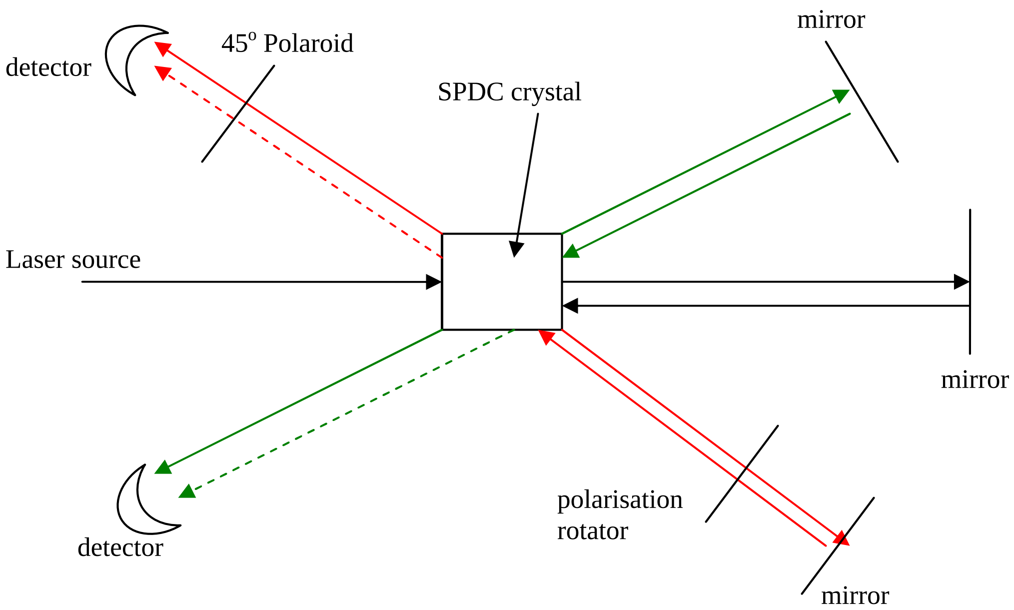
Recall the example of interference in Chapter 16 based on spontaneous parametric down-conversion (SPDC). What happens in the crossed SPDC beam setup if we introduce a polarisation rotator, and perhaps subsequently erase its effect using a $45^{o}$ Polaroid (see Figure 2)? We are assuming now that the two beams to emerge from the lithium iodate SPDC crystal are both vertically polarised. Referring to the notation in Chapter 16, but now also including the polarisation, the state entering the detectors in the absence of any polarisers/Polaroids would be,

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|G\rangle|v\rangle|R\rangle|v\rangle + |Gd\rangle|v\rangle|Rd\rangle|v\rangle\right) \qquad (12)$$

where the polarisation ket written first/second is understood to refer to the 'green' and 'red' photon respectively. We have already seen that this experiment would not produce a *local* interference pattern, but *would* produce an interference pattern provided that green and red detector correlations were taken into account – by virtue of the algebraic structure of (12).

Suppose we now introduce a polarisation rotator into the red beam at the position shown in Figure 2 so that the affected beam emerges from it with horizontal polarisation. (The $45^{o}$ Polaroid shown in the Figure is not yet present).

**Figure 2**




The state entering the detectors is now,

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|G\rangle|v\rangle|R\rangle|h\rangle + |Gd\rangle|v\rangle|Rd\rangle|v\rangle\right) \qquad (13)$$

Note that it is only the state $|R\rangle$ which is affected by the polarisation rotator. The dashed red beam does not pass through the rotator. This change is sufficient to make the two terms in (13) orthogonal and hence to eliminate any interference – even the non-local interference which might result from green/red correlations. To spell this out, if the 'green' photon hits the screen at position *x*, then, in the *x*-basis, we have $\langle x|G\rangle = \psi_G(x)$. The dashed-green path is coherent with this and has a relative phase $\theta_G(x)$ so that $\langle x|Gd\rangle = \psi_G(x)e^{i\theta_G}$. Similar remarks hold for the red and dashed-red photon paths in terms of a screen position *y*, giving,

$$|\psi(x,y)\rangle = \frac{1}{\sqrt{2}}\psi_G(x)\psi_R(y)\left(|v\rangle|h\rangle + e^{i(\theta_G+\theta_R)}|v\rangle|v\rangle\right) \qquad (14)$$

So that, $$\langle\psi(x,y)|\psi(x,y)\rangle = 1 \qquad (15)$$

because $\langle v|h\rangle = 0$ and the planes waves have $|\psi_G(x)| = |\psi_R(y)| = 1$. Consequently even the correlated interference which previously resulted from (12) does not occur.

We know, of course, that local interference cannot occur in this entangled setup because this would provide the opportunity for FTL communication (see Chapter 16). But can the correlated interference be resurrected by erasure of the effects of the polarisation rotator? Consider placing a 45° Polaroid into the red beam path as shown in Figure 2. Expressing the state (14) *before* encountering this Polaroid in terms of the 45° polarisation states (for the red and dashed-red beams only) gives, using (7,8),

$$|\psi(x,y)\rangle = \frac{1}{2}\psi_G(x)\psi_R(y)\left(|v\rangle\left(|45\rangle - |-45\rangle\right) + e^{i(\theta_G+\theta_R)}|v\rangle\left(|45\rangle + |-45\rangle\right)\right) \qquad (16)$$

Since the effect of the Polaroid is to filter the perpendicular state, $|-45\rangle$, the state entering the detectors is, (17)

$$|\psi(x,y)\rangle = \frac{1}{2}\psi_G(x)\psi_R(y)\left(|v\rangle|45\rangle + e^{i(\theta_G+\theta_R)}|v\rangle|45\rangle\right) = \frac{1}{2}\psi_G(x)\psi_R(y)\left(1+e^{i(\theta_G+\theta_R)}\right)|v\rangle|45\rangle$$

Hence, $$\langle\psi(x,y)|\psi(x,y)\rangle = \frac{1}{2}\left(1+\cos(\theta_G(x)+\theta_R(y))\right) \quad (18)$$

Thus, non-local (correlated) interference is re-introduced by the Polaroid, in the sense that if we record *x*-screen data only when photons are registered at a given, fixed *y*-position on the other screen (or *vice-versa*) then we discover an interference pattern. But if we simply look at the *x*-screen without regard for where photons arrive on the *y*-screen, then there is no interference pattern. The correlated interference is reintroduced because the effect of the $45^o$ Polaroid is to make the two terms in the wave-vector proportional, rather than orthogonal.

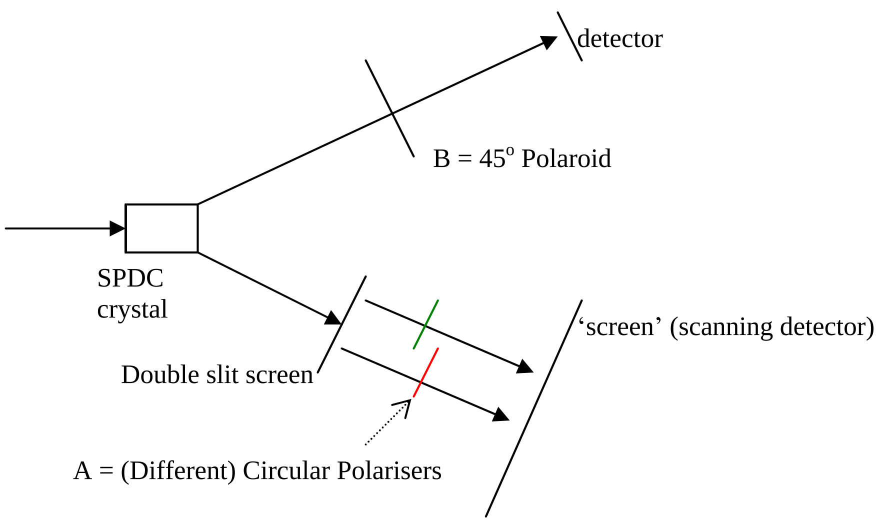
So, just as true local interference is destroyed by "which path" measurement, but can be restored by erasure of this effect, so too can non-local, correlated interference be destroyed by "which path" data obtained on one of the entangled particles alone – and this effect can also be erased and correlated interference regained by appropriate interaction with this same single particle beam alone.

Note that (18) has an average of only ½ because the Polaroid has absorbed half the photons.

## 4. Double-Slit Interference & Erasure: The Arrangement of Walborn et al

Recall the arrangement discussed in Chapter 16 where one of a pair of spin-entangled photons was incident on a double slit screen, thus producing an interference pattern. This illustrated that one of an entangled pair of particles can produce interference provided that the interfering degrees of freedom (spatial, in this case) are distinct from the entangled degrees of freedom (spin in this case). The setup is shown in Figure 3.

**Figure 3**




Supposing the circular polarisers and the $45^o$ Polaroid are not present, the state was shown in Chapter 16 to be,

$$|\psi\rangle = \frac{1}{2}\left(|Uv\rangle\left[|L1h\rangle + |L2h\rangle\right] + |Uh\rangle\left[|L1v\rangle + |L2v\rangle\right]\right) \quad (19)$$

where $U$ and $L$ refer to the upper and lower beams emerging from the SPDC crystal, and 1 and 2 refer to the upper and lower beams emerging from the double slit. This state arises because one photon emerges from the SPDC crystal in a vertical polarisation state and the other in a horizontal polarisation state, but either photon can be the one vertically polarised.

Now let's see what happens when we insert the two polarisation rotators adjacent to the two slits in the lower beam (but the $45^o$ Polaroid is not yet present in the upper beam path). These are such that an input polarisation state $|v\rangle$ becomes a clockwise polarised beam, $|C\rangle$, after passing through the 'green' polarisation rotator (aligned with the higher slit), whereas the input state $|v\rangle$ would become an anti-clockwise polarised beam, $|AC\rangle$, after passing through the 'red' rotator (aligned with the other slit). If the input polarisation state were $|h\rangle$, on the other hand, then the green rotator would produce $|AC\rangle$ and the red rotator would produce $|C\rangle$. Consequently, from (19), the state after passing through the polarisation rotators is,

$$|\psi\rangle = \frac{1}{2}\left(|Uv\rangle\left[|L1\rangle|AC\rangle + |L2\rangle|C\rangle\right] + |Uh\rangle\left[|L1\rangle|C\rangle + |L2\rangle|AC\rangle\right]\right) \quad (20)$$

It is clear that there will be no interference now because all the terms in (20) are orthogonal (because $\langle Uv|Uh\rangle = 0$ and $\langle AC|C\rangle = 0$) so all cross-terms are zero.

Why is this? Well we could carry out a measurement of the vertical/horizontal polarisation of the *upper* photon, and this would then tell us which slit the *lower* photon had travelled through via its circular polarisation. This "which path" information provided by the two polarisation rotators destroys the interference, as we would expect. Note that it is not necessary to actually obtain this information (i.e., to collapse the wavepacket to determine which path was taken). To destroy the interference it is sufficient that the first phase of a true measurement, the entanglement phase, has been done.

The interesting question which now arises is, "can we erase this 'measurement' and resurrect the interference by interacting only with the upper beam?" In popular accounts the answer is often given as an unqualified "yes". However, we shall see below that the correct answer is "yes, with a crucial proviso". The proviso is that local interference cannot be resurrected. What can be regained is only non-local, correlated interference of the type discussed previously. Regaining local interference would provide an opportunity for FTL communication, so we are wise to anticipate that it cannot occur.

Thus it is not quite accurate to refer to 'erasure' in this case. It is only partial erasure. Whereas initially we had local interference, what we regain is the weaker phenomenon of correlated interference.

To see how correlated interference arises let us now introduce the $45^o$ Polaroid into the upper beam path. This simply filters out the polarisation component $|-45\rangle$ and lets $|45\rangle$ through unimpeded. So we must first re-write the state emerging from the

SPDC crystal, $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|Uv\rangle|Lh\rangle + |Uh\rangle|L1v\rangle\right)$, in terms of the states $|\pm 45\rangle$ by substituting from (7,8). This gives,

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|U,45\rangle|L,45\rangle - |U,-45\rangle|L,-45\rangle\right) \tag{21}$$

Consequently, passing the upper beam through the 45$^o$ Polaroid causes the state to become,

$$|\psi\rangle = \frac{1}{\sqrt{2}}|U,45\rangle|L,45\rangle \tag{22}$$

Using (7,8) this can also be written,

$$|\psi\rangle = \frac{1}{2}|U,45\rangle\left(|L\rangle|v\rangle + |L\rangle|h\rangle\right) \tag{23}$$

When the lower beam passes through the double slits the state therefore becomes,

$$\begin{aligned}|\psi\rangle &= \frac{1}{2\sqrt{2}}|U,45\rangle\left(|L1\rangle|C\rangle + |L2\rangle|AC\rangle + |L1\rangle|AC\rangle + |L2\rangle|C\rangle\right) \\ &= \frac{1}{2\sqrt{2}}|U,45\rangle\left(|L1\rangle + |L2\rangle\right)\left(|C\rangle + |AC\rangle\right)\end{aligned} \tag{24}$$

We thus (apparently) get interference separately for the clockwise and anti-clockwise polarised waves, with the result that,

$$|\psi(x)|^2 = \frac{1}{2}\left(1 + \cos\theta(x)\right) \tag{25}$$

The factor of ½ is again because the 45$^o$ Polaroid stops half the photons getting through (or does it?). So we have successfully erased the effect of the polarisation rotators and restored the interference on the *x*-screen. From (25) this would appear to be local interference observable using the *x*-detector data alone – but is it?

How does the erasure happen? It is because the measurement of the polarisation at 45$^o$ forces the lower beam into a 45$^o$ state, and this is a superposition of states with vertical and horizontal polarisation. It is only these vertical and horizontal polarisation states that the polarisation rotator turns deterministically into circularly polarised states. A 45$^o$ polarisation state produces a superposition of clockwise and anti-clockwise polarisation states after passing through either rotator. Consequently knowing whether the photon at the *x*-screen has clockwise or anti-clockwise polarisation no longer tells us which slit it passed through. Either slit could result in either clockwise or anti-clockwise polarised photons, since the slits are illuminated by a superposition of vertical and horizontal polarised photons.

Fair enough - but hold on one moment. Can we really have resurrected *local* interference? Wouldn't this mean that we have a FTL communication channel? The position of the 45$^o$ Polaroid can be arbitrarily distant from the x-screen. And by inserting or removing the Polaroid we create or destroy the interference pattern at the *x*-screen. Bingo – FTL communication! Where is the snag this time?

The snag is that we have failed to notice that half the time the Polaroid will not produce a $|\psi\rangle = \frac{1}{\sqrt{2}}|U,45\rangle|L,45\rangle$ state but will absorb the upper beam photon. But in these cases the lower beam photon still gets detected at the x-screen. In this case the lower beam photon is left in the state $\frac{1}{\sqrt{2}}|L,-45\rangle = \frac{1}{2}\left(|L\rangle|v\rangle - |L\rangle|h\rangle\right)$. After passage through the double slits this becomes,

$$\begin{aligned}|\psi\rangle &= \frac{1}{2\sqrt{2}}\left(|L1\rangle|C\rangle + |L2\rangle|AC\rangle - |L1\rangle|AC\rangle - |L2\rangle|C\rangle\right)\\ &= \frac{1}{2\sqrt{2}}\left(|L1\rangle - |L2\rangle\right)\left(|C\rangle - |AC\rangle\right)\end{aligned} \tag{26}$$

Taking the absolute square gives, for the intensity at the x-screen due to those cases when the upper beam photon is absorbed by the Polaroid,

$$|\psi(x)|^2 = \frac{1}{2}\left(1 - \cos\theta(x)\right) \tag{27}$$

The only difference between (27) and (25) is the sign of the cosine term. What is *actually* observed locally at the *x*-detector is the *sum* of (25) and (27). So the cosine term cancels and we get a total signal of $|\psi(x)|^2 = 1$ at the *x*-screen, i.e., no interference pattern!

The claim that was made above regarding observing a *local* interference pattern was incorrect. Actually the interference corresponding to Equ.(25) will be observed only if coincidence counts are used. That is, only photons arriving at the *x*-screen coincident with photons successfully reaching the upper detector will result in an interference pattern. (Or, equivalently, interference is observed at the lower screen if only photons corresponding to ***no*** photon in the upper detector are counted). The interference is not local but correlated, non-local interference. There is, of course, no FTL communication.

The experiment described here has actually been carried out, by Walborn, Terra Cunha, Padua, and Monken, with results just as anticipated by the theory above, see Ref.[1].

**5. Delayed Erasure**

The term "delayed erasure" is given to experiments which involve erasure that is carried out *after* detection of the particles which produce the interference pattern. This is easily accomplished in the experimental setup of Walborn et al, Figure 3, simply by making the upper beam path long enough prior to the 45$^o$ Polaroid. Note that in §4 the analysis implicitly assumed that the Polaroid was encountered first and the double slits with their polarisation rotators encountered second. This order is easily reversed in the algebra. After the double slits and polarisation rotators, but before the 45$^o$ Polaroid, the state is given by (20), i.e.,

$$|\psi\rangle = \frac{1}{2}\left(|Uv\rangle\left[|L1\rangle|AC\rangle + |L2\rangle|C\rangle\right] + |Uh\rangle\left[|L1\rangle|C\rangle + |L2\rangle|AC\rangle\right]\right) \tag{20}$$

Using (7,8) to re-express the upper beam polarisation in terms of the $|\pm 45\rangle$ states this becomes, (28)

$$|\psi\rangle = \frac{1}{2\sqrt{2}}\left(|U\rangle\left(|45\rangle + |-45\rangle\right)\left[|L1\rangle|AC\rangle + |L2\rangle|C\rangle\right] + |U\rangle\left(|45\rangle - |-45\rangle\right)\left[|L1\rangle|C\rangle + |L2\rangle|AC\rangle\right]\right)$$

The effect of the $45^o$ Polaroid is therefore to reduce (21) to,

$$\begin{aligned} |\psi\rangle &= \frac{1}{2\sqrt{2}}|U,45\rangle\left(\left[|L1\rangle|AC\rangle + |L2\rangle|C\rangle\right] + \left[|L1\rangle|C\rangle + |L2\rangle|AC\rangle\right]\right) \\ &= \frac{1}{2\sqrt{2}}|U,45\rangle\left(|L1\rangle + |L2\rangle\right)\left(|AC\rangle + |C\rangle\right) \end{aligned} \qquad (29)$$

This is exactly as (26), and hence also produces the intensity at the *x*-screen given by (27), i.e., an apparent interference pattern (but which can actually be seen only by coincidence counting with arrivals at the upper detector, as before).

Consequently the delay of the erasure makes no difference to the results, which are the same as in §4.

Great play is made in popular accounts of the weirdness of this outcome. The lower beam photon appears to 'know' that a $45^o$ Polaroid will be inserted into the upper beam *some time after* the lower photon has already been detected. The lower photon has to 'know' this in order to know whether or not to produce an interference pattern on the *x*-screen.

But these protestations of weirdness tend to forget the crucial issue: that an interference pattern is found only when the *x*-detector counts are vetoed according to whether there is a corresponding count in the upper detector. The interference is not local, but only a correlated, non-local interference. The interference pattern is found only when those *x*-screen (lower beam) photons are counted which correspond to a photon successfully emerging from the $45^o$ Polaroid into the upper detector.

The apparent weirdness is largely the result of a conceptual error. One confuses the situation with an instantaneous effect at the *x*-screen due to the insertion of the Polaroid in the remote upper beam. This would be FTL communication and would indeed be very weird – in fact, impossible. But there is no such effect. Ask yourself, when the Polaroid is inserted what exactly is the instantaneous effect on the signal in the *x* detector? Say that you have placed your *x* detector carefully at a minimum of the potential interference pattern – and that this pattern is perfect so that no photons at all would reach this point if interference did occur. Will you detect a photon or not? You cannot tell in advance because it depends upon whether the Polaroid in the upper beam happens to pass a $45^o$ state photon or to absorb a $-45^o$ state photon – and you cannot control which will happen. So the insertion of the remote Polaroid cannot be used to propagate a FTL signal. A prediction of whether *x*-screen photons will be detected can be made only if one is first given the result from the upper detector.

Suppose the $45^o$ Polaroid is so far away that we can count large numbers of photons and develop the whole *x*-screen whilst remaining causally disconnected from the Polaroid. What do we see? We see no interference. Whether or not the Polaroid has been inserted we see a uniformly illuminated *x*-screen. Look – nothing weird at all. Only when the signal received at the upper detector is used as a mask to retain or veto individual *x*-screen counts does the interference pattern emerge. What does this mean? It means that there is a correlation between two sets of measurements which were carried out in a causally disconnected manner. How weird is this? In itself it is not especially weird.

If two sub-systems have a common source, their properties will often be correlated. This is an objective fact and does not require subsequent causal connection between the sub-systems to manifest it. For example, if a mass breaks up into two smaller masses it will surprise no one to find that the mass of one part is (inversely) correlated with the mass of the other – even if the measurements of these masses is carried out when the parts are light years apart.

However this goes rather too far in dismissing quantum weirdness. There *is* a degree of weirdness, namely non-locality in spite of the absence of hidden variables. In the classical example the matter is clear because each part can be considered as possessing a definite mass before any measurement is made. This is not the case for the polarisation of the photons – they are in a superposed polarisation state initially. So the weirdness lies in the fact that the upper and lower detectors produce correlated results at space-like separations despite being in an indeterminate state before measurement. This is exactly the same weirdness first discussed by EPR, Ref.[2]. Delayed erasure experiments with entangled particles do not expose any new or deeper weirdness, just the same tension between genuine indeterminacy and non-local correlation.

**References**

[1] Walborn, Terra Cunha, Padua, and Monken (2002), Physical Review A, (**65**, 033818, 2002).

[2] Einstein, A; B Podolsky, N Rosen (1935). "*Can Quantum-Mechanical Description of Physical Reality be Considered Complete?*". Physical Review **47,** 777–780