

A Review of the ZWM Study; What Destroys the Interference?

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In 1991-1992 three papers were published by the same authors referred to as the ZWM study^{1,2,3} concerning the subject of induced coherence in photon downconversion. We present a review of these papers which all concern the same experimental arrangement. The central conclusion made by the authors is that interference is destroyed by the in principle knowability of path, that path indistinguishability is fundamental to interference effects. We review these papers with an emphasis on validating this conclusion and attempting to understand the action that is taken in the preparation of the "idler" photon and the subsequent affect that this action has on the interference visibility of the entangled "signal" photon.

The ZWM Paper

The first paper published in this study, reference 1, is an experimental paper which takes its naming from the ordering of the authors; Zou, Wang and Mandel. This paper presents an experiment with induced coherence between the outputs of two separate photon downconversions, typically referred to as signal and idler photons, which is demonstrated by the presence of single photon interference between the two possible sources of signal photon. The experimental setup is illustrated in Figure 1 where a pump wave is beam split (BS_p) into two coherent pump beams that are made incident upon the two separate non-linear optical crystals (DC1 and DC2). The pump photon is an Argon-Ion laser with wavelength 351.1nm and the downconversion crystals are non-linear $LiIO_3$ crystals which occasionally convert the laser pump photons into a signal and idler pair. The signal (788.7nm) and idler (632.8nm) photons created in downconversion obey a wave vector conserving process so that their frequencies add to the pump frequency. The output idler beams are setup to be in exact alignment which requires that the first idler i_1 be transmitted through the second crystal DC2 where it comes into alignment with i_2 and both beams are incident upon a time resolved detector D_i . The signal outputs are added at second beam splitter (BS_o) beyond which they fall on a time resolved detection system D_s . The experimental arrangement is setup so that the optical paths from the pump beam splitter to the second crystal (BS_p to DC1 to DC2) and (BS_p to DC2) is less than the coherence length of the pump light (5cm). Also the optical path lengths of (DC1 to BS_o via s_1) and (DC1 to DC2 to BS_o via i_1 and s_2) are made to differ by no more than a coherence length of the downconverted light (0.33mm). There is also a coincidence counter (CC) which is used to compare the counts registered by the two detectors to check for coincidence counts.

With this setup the authors conduct interference experiments by varying the path difference of the signal paths and collecting the counting rate at D_s as a function of path difference. They perform this interference experiment for several different values of transmissivity of the filter which is placed in the path between DC1 and DC2. This filter is actually a set of neutral density filters which can be added to reduce transmissivity.

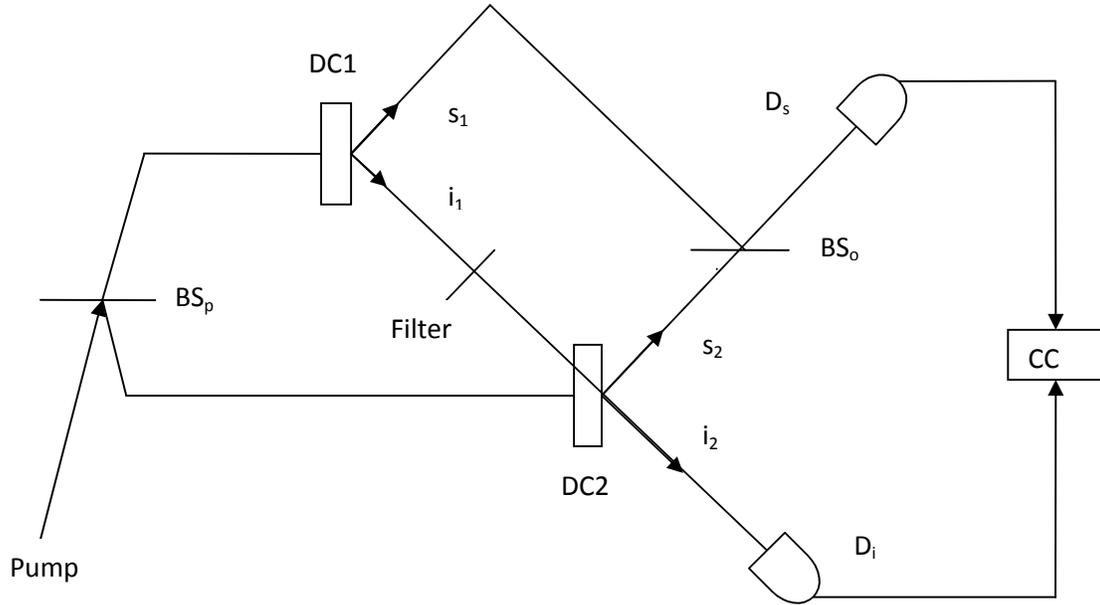


Figure 1 The ZVM : Two downconversion crystals (DC1 & 2) are commonly pumped. Their outputs, signal and idler photons labelled s and i , are arranged so that i_1 transmits through DC2 and comes into exact alignment with i_2 . The combination of s_1 and s_2 only results in interference when the idler i_1 is not attenuated at the filter.

By performing the interference experiment for several different values of transmissivity they find a linear relationship between the visibility of the interference and the transmissivity. One is lead to the obvious question, why would the interference between the possible sources of signal have a dependence upon the preparation of the idler? The quick answer is to simply state that the knowledge of the path of the signal is made available to the experimenter if the idler is blocked. If there is downconversion at DC1 and idler i_1 is blocked then there should be a signal photon detected at D_s which came from DC1 and there should be no detection at D_i because the idler was blocked. If there is downconversion at DC2 then we get detection at both detectors D_s and D_i in coincidence. So when the idler is being blocked the idler detector gives us information of the path of a signal photon detected at D_s ; the path is s_1 if there is no coincidental detection at D_i and the path is s_2 if there is a coincidental detection at D_i . This is the conceptual account of the experiment provided by the authors but we must also understand the experiment in the context of a mathematical analysis provided by the authors.

We will limit our statement of the mathematics to the relevant material, but the interested reader is directed to references 1 and 2 for the complete calculation. In reference 1 the calculation is limited to the assumption of monochromatic signal and idler fields but in reference 2 the calculation is generalized to a multi mode treatment. The analysis begins in reference 1 with the calculation of the time dependent state vector using the interaction Hamiltonian at crystal j as,

$$H_j = \hbar g_j V_j(t) \hat{a}_{ij}^\dagger \hat{a}_{sj}^\dagger + \text{Hermitian conjugate}$$

where g_j is a susceptibility function, $V_j(t)$ is the classical pump amplitude and \hat{a}_{ij}^\dagger and \hat{a}_{sj}^\dagger are the idler and signal photon annihilation operators respectively. However, in order to evaluate the preparation of the neutral density filter one would require a second interaction for the absorption, so the authors simplify

the treatment by considering the filter to be a beam splitter with an empty input port and similar transmissivity to the filter. This allows for a simple mathematical transform of the creation operators,

$$\hat{a}_{i2} = \mathcal{T}\hat{a}_{i1} + \mathcal{R}\hat{a}_o$$

where \mathcal{T} and \mathcal{R} are the transmissivity and reflectivity of the beam splitter (filter) and \hat{a}_o is the creation operator for the empty input port. With this transform to the interaction Hamiltonian the authors calculate the time dependent state vector as

$$|\psi\rangle = |0\rangle_{s1}|0\rangle_{i1}|0\rangle_{s2}|0\rangle_o + f_1V_1(t)|1\rangle_{s1}|1\rangle_{i1}|0\rangle_{s2}|0\rangle_o + f_2V_2(t+t_o)e^{-i\theta}\{\mathcal{T}^*|0\rangle_{s1}|1\rangle_{i1}|1\rangle_{s2}|0\rangle_o + \mathcal{R}^*|0\rangle_{s1}|0\rangle_{i1}|1\rangle_{s2}|1\rangle_o\}$$

where f_1 and f_2 are functions which define the fraction of light that is downconverted at the two crystals and the modes are labelled for s_1, i_1, s_2 and o (the empty input port). The exponential has the phase shift, θ , that is associated with propagation from DC1 to DC2 and t_o is the time of this propagation. The observant reader might notice that there is no mode for the second idler, i_2 . This is because the first and second idler modes have been treated as one, which is justified by the perfect alignment of the idler beams. With this assumption we might imagine that the absence of a second signal mode in the state vector will allow for a calculation of interference in the correlation function at the signal detector, and such is the case. The authors calculate the counting rate at the signal detector, R_s , as a varying function of the phase difference with θ_1 and θ_2 as the phase associated with propagation from DC1 to D_s and DC2 to D_s respectively.

$$R_s \propto |\mathcal{T}| \cos(\theta + \theta_2 - \theta_1 + \dots)$$

The authors also calculate the visibility of the interference which is shown to be directly proportional to the transmissivity amplitude $|\mathcal{T}|$. This explains the linear dependence of the visibility of interference on the transmissivity which we earlier explained as being due to the availability of path information measurement in the preparation of the idler. One might question whether the availability of path information, distinguishability, is directly relatable to the visibility of interference. Indeed this is the case, as one of the authors, Mandel, shows in a later paper⁴ that for an interference effect with two sources that equally contribute to the interference there is a direct equitability between the visibility of interference and the degree of indistinguishability. Mandel does this calculation by performing a decomposition of the state operator for a mixed state with a portion of distinguishable light and a portion of indistinguishable light. In the ZWM study, we also have a mixed state with part distinguishable (the reflected portion at the filter) and part indistinguishable (the transmitted portion at the filter) and the degree of indistinguishability is the complex transmissivity coefficient amplitude $|\mathcal{T}|$.

In reference 1 we also have an additional calculation intended on highlighting the dependence upon $|\mathcal{T}|$. The authors use the state operator to trace out the reduced density matrix of the signal photon, ρ_s , for which they calculate an expression with four terms, one with the vacuum state, one for each single photon state (s_1 and s_2), and the final term is shown below,

$$\mathcal{T}f_1f_2^*V_1(t)V_2(t+t_o)e^{-i\theta}|1\rangle_{s1}|0\rangle_{s2s2}\langle 1|_{s1}\langle 0| + \text{Hermitian conjugate}$$

This is a coherent combination of cross-over terms which yields interference, and there is a linear proportionality to the transmissivity \mathcal{T} .

Conclusions

Having reviewed the analysis of this paper we still might wish to question the assumption made by the ZWM authors which allows for them to make their calculation of interference, the dropping of an idler mode in the calculation of the state vector. Without this assumption surely we will not be able to calculate interference in the correlation function. The assumption for the mode assessment is that the two modes may be treated as one on the condition of exact alignment of the idler beams. But is there another condition here which the authors do not mention. We might ask how this assumption is justified when we consider that the two idler modes are definitely distinguishable by virtue of a signal photon detection at times prior to the combination of the signals. Surely the signal photons could be measured prior to combination and these detections would infer distinguishability of the idlers, so the idlers are distinguishable up to and until the signals are combined and detected. It is the combination of the signal beams and their subsequent detection which is also necessary for the assumption made in the calculation of the state vector, the dropping of an idler mode.

This gives the ZWM study a distinction as an interference effect of quantum mechanics, whereas most interference effects simply require the eventual combination and detection of beams to adequately prepare indistinguishability of path, the ZWM study requires the signals to be combined and detected but it also requires the idlers to be prepared in a manner that they cannot be distinguished prior to or after the detection of the signal photons. Even though one could in principle distinguish the idlers with a signal detection prior to the combination of signals, as long as this is not done the assumption is valid. The idlers must be prepared in a manner that the first idler is transmitted through the region of emission of the second idler while the second idler is being emitted. For reasons not exactly known, this type of combined indistinguishability is enough to warrant the dropping of one of the two modes in the calculation of the state vector.

This distinction might be added to the historical fact that the ZWM study is the only such study in the history of quantum mechanics which produces a single particle interference effect between possible sources of a particle while measuring coincidence detection of its entangled partner particle.

In finishing our review of reference 1 we should state the conclusions that have been reached in this paper by the authors, with specific emphasis on the action that is being taken in the preparation of the idler that destroys or creates interference of the entangled signal. The conclusions that the authors do make can be stated in the form of principles:

- 1) Induced coherence does not require induced emission.
- 2) The destruction of the interference is not a result of an uncontrollable disturbance to the system but rather due to the intrinsic distinguishability of path.
- 3) Distinguishability of path need not actually be measured in order to destroy interference, but it is the mere fact that the measurement of path could in principle be performed that is sufficient to destroy interference.

With regards to our intended purpose of this review, we would note that the authors conclude that there is no such causal driving force or action in the preparation of the idler which causes the change in the measurable statistics of the signal. However they do not seek such an explanation of a driving force, they merely note that there is no such disturbance present.

The WZM1 Paper

The second paper in the study, reference 2, is one which presents the exact same experimental setup to the ZWM except with a more thorough theoretical analysis. The authors perform the calculation of the state vector with a full multi mode treatment rather than the simple monochromatic case. This paper also presents a calculation of the rate of detection of the idler detector and the rate of coincidence detection between the signal and idler detectors. There is also a restatement of the experimental results in reference 1 along with results of interference in the rate of coincidence measurements. The calculation of the state vector with multi mode treatment offers little new information for our review so we do not state these calculations here. The calculation of the detection rate however will provide us with much new information regarding our inquiry. The authors calculate that of the counting rate of the signal detector, R_s , which is done by evaluating the correlation function at the signal detector. The final expression calculated for R_s is

$$R_s = \frac{1}{2} \alpha_s \{ |f_1|^2 \langle |V_1|^2 \rangle + |f_2|^2 \langle |V_2|^2 \rangle + 2 g(V_1, V_2) |T| |f_1 f_2| |\mu(t_o + t_2 - t_1)| \cos[\omega_i(t_o + t_2 - t_1) + \omega_i \delta t_o + \omega_s(\delta t_1 - \delta t_2) + \dots] \}$$

where α_s is the efficiency of the signal detector, $g(V_1, V_2)$ is an algebraic function, $\mu(t_o + t_2 - t_1)$ is a normalized correlation function for the signal and idler, t_1 and t_2 are the propagation times from DC1 to D_s via s_1 and DC2 to D_s via s_2 respectively. The times δt_o , δt_1 and δt_2 are increments of times t_o , t_1 and t_2 respectively that are much smaller than the coherence time of the signal and idler, and ω_s and ω_i are the average frequencies of the signal and idler respectively. Looking at this detection rate for the signal detector we can see that the interference will manifest in the cosine function. There is two distinct arguments in the cosine function which will dictate the modulation of the interference pattern, the $\omega_i \delta t_o$ and $\omega_s(\delta t_1 - \delta t_2)$ arguments. If we vary the path length of the signal s_2 between DC2 and BS_o or signal s_1 between DC1 and BS_o in increments of $c\delta t_2$ and $c\delta t_1$ respectively then we would measure a modulation of R_s with period $2\pi c/\omega_s$. This is exactly the effect which is observed in reference 1, the varying of the signal path length to produce interference with optical path difference.

The second possibility arises in varying the path length that i_1 traverses, if we choose to vary the path length of the idler i_1 between DC1 and DC2 which would be varied in increments of $c\delta t_o$ then we would measure a modulation of R_s with period $2\pi c/\omega_i$. This is a truly astonishing result, as varying the path length of the idler between DC1 and DC2 will sweep out an interference pattern in the signals, or will it? Looking closely at the preparation of the experiment we might conclude that by varying this i_1 path length we are in fact moving the whole of the signal interference pattern while the relative path lengths of the signal are held fixed, which would give the appearance of sweeping out an interference pattern. The explanation we provide here is that the optical path length between DC1 and DC2 determines where the center of the interference pattern occurs because the full requirement of interference involves the transmission of i_1 through DC2 in exact alignment with i_2 and the timing of this transmission determines the center of the interference pattern. It is the transmission of i_1 through DC2 which induces coherence between the two crystals and so allows for interference between the signals. This point is highlighted by one of the criteria of the experiment that we have mentioned earlier, that "the optical path lengths of (DC1 to BS_o via s_1) and (DC1 to DC2 to BS_o via i_1 and s_2) are made to differ by no more than a coherence length of the downconverted light (0.33mm)." The obvious question is, if we vary the path length of i_1 between DC1 and DC2 would we sweep out the interference of the signals over the

coherence length of 0.33mm or would we be moving the center of the interference pattern relative to the fixed paths of the signal?

We speculate here that if the path length of i_1 between DC1 and DC2 is changed, that this change in preparation only moves the center of the interference pattern so an equal but opposite change in the path length of s_2 between DC2 and BS_o will keep the detection rate R_s constant. This would imply that the two signal path lengths need not be identical to get the center of the interference pattern, which is correct. The total signal path is also partially determined by the path of the pump photon as the one path goes from BS_p to DC2 to BS_o (the signal path of s_2) and the other path goes from BS_p to DC1 to BS_o (the path of s_1). Actually, these two paths only need to be identical to within the coherence length of the pump (5cm). So it would be possible to have an interference pattern that has these two paths differing by up to 5cm, but the interference pattern only sweeps out over the coherence length of the signals (0.33mm) and is centered about a point that has our initial assumption satisfied, that paths DC1 to BS_o via s_1 and DC1 to DC2 to BS_o via i_1 and s_2 are identical.

Another calculation is performed for the counting rate of the signal detector except with only the contribution from the s_2 beam as input, R_{s2} , which is calculated as

$$R_{s2} = \frac{1}{2}\alpha_s |f_2|^2 \langle |V_2|^2 \rangle$$

This describes the spontaneous emission of signals from crystal DC2. The detection rate at the idler detector, R_i , is also calculated as

$$R_i = \alpha_i \{ |T|^2 |f_1|^2 \langle |V_1|^2 \rangle + |f_2|^2 \langle |V_2|^2 \rangle \}$$

where α_i is the efficiency of the idler detector. This detection rate describes spontaneous emission of idlers as are contributed from DC1 and DC2.

This now gives the necessary proof to the authors to conclude that indeed there is no “induced emission” which is accompanying the induced coherence between the signal outputs of the two downconversion crystals. If there was an induced emission we would expect to see an additional term in the counting rate at the signal detector, R_{s2} , that is dependent upon the first idler i_1 . We would also expect to see a similar term in the detection rate at the idler detector, R_i , so because we see neither we can assume that there is no such induced emission at DC2 that results from the transmission of i_1 through DC2.

The final calculation performed in reference 2 is the coincidence detection rate, R_{s_i} , which is shown to have exponential functions with the arguments that are also present in the counting rate at the signal detector. The interference in R_{s_i} can be collected by varying the displacements of $c\delta t_0$, $c\delta t_1$ and $c\delta t_2$.

So we might ask if there are any additional conclusions that were not presented by the authors in reference 1 but are presented in reference 2 which are relevant to our central question concerning the action that is being taken in the preparation of the idler that destroys or creates interference of the entangled signal. The answer is no, however when we consider what conclusions we might come to as a result of reviewing these papers then we do see one important result that comes exclusively from the detailed analysis of reference 2. We were brought to the speculation that by varying the i_1 path length between DC1 and DC2 we are in fact moving the whole of the signal interference pattern. This is a relevant detail that is not obvious in the monochromatic calculation of the signal detection rate that is presented in reference 1 where the cosine function in R_s has an argument θ (the phase associated with propagation between DC1 and DC2). If the authors are correct in their calculation then the i_1 path length preparation can be varied to change the measurable statistics of the signal, it can be varied to

create interference in the signal detection rate. It is well understood that the preparation of the idler can be modified by mis-alignment to destroy interference, but to actually have the preparation of the idler as the varying change which causes interference in the signal is another effect entirely.

The WZM2 Paper

This paper, reference 3, is the third of the series that considers the same experimental setup to the other two and is published by the same authors. Reference 3 is only a theoretical paper but it considers the possibility of a small modification to the preparation of Figure 1, instead of a normal filter it uses a filter with a time dependent transmissivity. The intended goal of reference 3 is to understand the exact affect of the action of attenuating the idler between DC1 and DC2 on the detection rate of the signals, and to calculate this affect with exact time information.

The analysis in this paper begins with the calculation of the time dependent state vector which differs from the other references because it takes into account a time dependent filter which modifies the amplitude of the idler that passes the filter. This difference does not lead to a substantial change in the calculation of the signal detector counting rate, R_s , as it still exhibits interference that is identical to that of the other references. However, the visibility of the interference now has a time dependent factor which results from the time dependent transmissivity, $\mathcal{I}(t)$, which is in direct proportion to the visibility, $\mathcal{V}(t)$.

$$\mathcal{V}(t) \propto |\mathcal{I}(t-t_2-t')|$$

Where t_2 is the time of propagation from DC2 to D_s via s_2 and t' is the time of propagation from the filter to DC2. So the temporal argument in brackets is the time of detection, t , minus the time from the filter up to the detector, which is equal to the time at the filter. This has shown that the visibility of interference in the rate of detection at the signal detector is directly proportional to the transmissivity of the filter evaluated at the time the detected photons passed the filter. We could say that the interference depends upon the preparation of the idler at the filter which is at a specific point on the past light cone emanating from the moment of detection of the photon.

With this argument in place, the authors may now conclude that there is a local explanation for the disappearance of interference in the event of the attenuation of the i_1 path. The authors further consider the possible arguments that could be made concerning an “uncontrollable disturbance” to the system which would cause the loss of interference. These arguments must fail because there is simply no way to explain there being a disturbance to the signal system by virtue of an attenuation of the idler, unless we consider the possibility of DC1 and DC2 emitting photon pairs at the same time in which case the DC1 emission would be blocked from inducing coherence with the emission from DC2. This argument fails because the two downconversions almost never have simultaneous emission. There simply is no explanation for the loss of interference being due to a physical disturbance to the system. The conclusion of the authors is the same as in the other two references; the loss of interference is due to the availability of distinguishing information of the signal photon’s path.

Discussion

Having completed a review of the three papers that are relevant to the ZWM study, we are now in a position to put forth the question which is central to this review, what is the physical driving force which accounts for the change in measurable statistics of the signal (the destruction of interference) that is present in the experimental arrangement of the ZWM study when we take the simple action of attenuating the idler photon between DC1 and DC2. According to the authors, the interference of the signal is destroyed due to the mere possibility in principle of being able to measure the signal path, path distinguishability. If we are to accept this as principle, which of course we do, then we must surely also ask what physical mechanism is also present in the preparation which may account for the change in the measurable statistics of the signal? What is the driving force which causes this measurable change which we refer to as the destruction of interference? To which we must answer (considering what we have now accepted as principle), there simply is no such causal mechanism or driving force. The interference is allowed in the one preparation because of the induced coherence which is solely due to the possible presence of i_1 at DC2, at a time while the idler could have been emitted from DC2, which would imply that it is not i_1 but i_2 . It is this indistinguishability which is the reason for the allowance of interference, so the destruction of interference is due to the distinguishability alone. There is no actual interaction between the idler and the signal in either preparation and there is no such driving force.

Having gone this far in our reasoning we must now ask if indeed this action in the experimental arrangement, the destruction of interference in the ZWM, is a violation of the laws of conservation of energy and momentum. In the one preparation which allows interference ($|\mathcal{T}|=1$) we have a specific statistical arrangement of measurements which we may predict with great certainty, and in the other preparation which does not allow interference ($|\mathcal{T}|=0$) we have a different statistical arrangement of measurements which we may predict with a similar certainty. There is a displacement of the positions of the measured statistics when going from one preparation to the other. Surely when we change an experimental preparation in such a manner that we cause a predictable displacement in the positions of a statistically relevant set of measurements then there must be an explanation as to how this change in preparation caused a driving force which lead to the change in position of the measurements. Apparently, in the experimental arrangement of the ZWM there is no such explanation and the driving force is the presence of distinguishing information of path. At this point we may only conclude that indeed there is a violation of the laws of conservation occurring in the ZWM experiment when we destroy or recreate interference. "Distinguishing information of path" does not constitute a driving force. It merely constitutes a change to the state description of the system. If indeed we are correct about this occurring for the ZWM experiment, we may also conclude that there is a violation of conservation occurring in all experiments of quantum mechanics where there is a destruction or recreation of interference by virtue of change in preparation which only causes distinguishing information of path, which is the case for all interference effects of quantum mechanics.

References

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