A proposal for measuring photon temporal coherence in continuum radiation

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Abstract. The proposal is for a technique complementary to spectral line analysis. It would be especially useful in astronomy, where observational tools are few. As continuum radiation can be viewed as a mixture of pure states, it should be possible to measure the temporal coherence of the photons as a function of energy. Young’s Double-Slit Experiment is used to elucidate the basic physics. A small change from the standard setup is proposed, which is simply to use a screen of small energy measuring photon detectors. The quantum theoretic exposition is also similarly standard. By restricting the photon detections to just those of a particular energy, the detection screen is then effectively one of two-level atoms. Conservation of energy then implies that the interference pattern and, thus, the measured temporal coherence that is obtained in this particular way are the same as for a normal setup with a broadband detection screen, but with just this energy subset of states as the incident radiation. This would seem to constitute a counter-example to the conventional wisdom that, with continuum radiation incident, only the temporal coherence of the filter’s passband would be measured. We explain how this conundrum is resolved, introducing the notion of a detections filter as opposed to a normal light filter. Although we briefly discuss its potential for astronomy, it will, of course, have much wider application.

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1. Introduction

The measurement of spectral lines is a most important tool in scientific applications. From our personal perspective in astronomy, together with photometry, they constitute the principal observational tools. Indeed, the measurement of the redshift, $z$, of a distant source is central to cosmology. It has led to our present understanding that we inhabit a universe that is well described by the model of a Big Bang universe. More recent has been the discovery that matter is dominated by exotic dark matter, a discovery pointing towards physics beyond the standard model in particle physics. A further revelation is that our Universe is at present, instead of decelerating, actually accelerating. It has led to a universe in which, at the present epoch, as much as 70% of the total energy is dark energy, which is simplest interpreted as vacuum energy. If this is confirmed to be equivalent to Einstein’s cosmological constant, then, under the Big Bang scenario, it is an energy density that is constant back to the time of inflation and would, thus, be a relic of inflation itself, from when the Universe was younger than $\sim 10^{-32}$ secs.

On the other hand, in the case of one of the principal cornerstones of cosmology, the cosmic microwave background (CMB) does not have any spectral lines, possessing to remarkable accuracy a Planck spectrum. Its redshift is then based on its observed temperature relative to that at recombination in the context of the Big Bang model. However, without this physical insight, it would be difficult to establish its redshift, since when redshifted or blueshifted any thermal radiation remains Planckian in form. There are, also, occasions when, for an astronomical source, there is only one spectral line observable, making a misidentification a distinct possibility. Worse, if a source simply displays a continuum spectrum with no spectral lines or other significant spectral features, the technique is unable then to provide a redshift for the source.

With the insight provided by quantum mechanics, we can look upon the continuum radiation from a normal chaotic source as, actually, a mixture of pure states, with each pure state expandable in terms of the complete orthonormal set of photon number states, the Fock states. Now, just as the wavelength of a photon from a distant source is increased by $(1 + z)$, so is its temporal coherence. Thus, it was with this in mind that we considered that a technique for estimating the temporal coherence of photons in continuum radiation would be similarly useful as that of spectral line measurements. However, as we shall see, such a novel technique may prove more powerful for understanding the physical processes of the source and, as such, it would also be useful in the laboratory. Indeed, for fundamental physics, it would further promise a new empirical means of exploring the nature of continuum radiation.

Specifically, our proposal then is for an experimental technique which is able to measure the temporal coherence of a subset of states in the continuum radiation, a subset defined by photon energy. This would normally mean the use of a light filter to separate out the photons with this energy. But, for such experiments, there is the conventional wisdom that with incident continuum radiation it is only possible to measure the temporal coherence of the passband of the spectral filtering apparatus
used. Thus, it would seem that such a proposal as ours is, unfortunately, not possible. Consequently, a completely separate, yet brief, section, Sec. 5, discusses this issue.

In Sec. 2, we present the basic physics behind our experimental proposal, which we also theoretically justify in the quantum mechanical discussion in Sec. 3. This is followed in Sec. 4 with a consideration of the experimental constraints. As we have just noted, we address in Sec. 5 an apparent contradiction with the conventional wisdom about such experiments. Sec. 6 proposes an actual initial experiment, which would also constitute a ‘proof of principle’ test of our technique. We discuss some practical considerations for the technique in Sec. 7. As an illustration of its potential for astronomy, where our own personal interests lie, some interesting astronomical prospects for its use are presented in Sec. 8. Finally, Sec. 9 contains some brief conclusions.

2. The physics behind the technique

For an actual experiment, one would probably use a Michelson or similar interferometer, upon which is incident quite normal chaotic light with a continuum component in its spectrum. But, for elucidating the basic physics behind our proposal, we make use of the Young’s Double Slit Experiment, Fig. 1. Also, depicted as incident is an idealized light source. It’s a means of explanation that has been used to great effect in simple textbook treatments of such experiments and, in any case, as we shall see, the wave aspect of the experiment is no different from that for a normal Young’s Double Slit Experiment.

We have thus shown an incident photon as a wave train of wavelength, \( \lambda_s \), and length, \( l_s \), i.e., a temporal coherence of

\[
\tau_s = \frac{l_s}{c}.
\]  

We consider then our continuum source to be a mixture of such photons over a continuous range of wavelengths. The photons are detected using a screen of small photon detectors. Thus, when a photon reaches the screen, one of these detectors is triggered and its position, \( y \), at the screen recorded as being that of the triggered detector.

Now, basic to our proposal is the concept embodied by the famous quote from Dirac’s classic text[1]: “Each photon interferes … only with itself. Interference between two different photons never occurs”. It’s a statement that we now see as not applying generally, but, happily, does apply to experiments like ours[2]. Still, it has had to wait until the recent single photon interference experiments[3]–[7] for it to be firmly established experimentally, as to do so required the advanced techniques the researchers developed to ensure that the photons incident are single isolated photons. Of course, in our case we do not have single isolated photons incident; we could actually have an innumerable number incident, as, for example, when the sun is used as the light source. The importance of their results is the physical insight it gives for our own proposal. In particular, it means that we can then treat each photon separately. Now, a photon has
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Figure 1. Proposed Double-Slit Interference Experiment. The figure shows a typical setup for a Young’s double-slit experiment, however, with a modest requirement as to the form of the detection screen. Depicted, then, is a screen made up of small photon detectors capable of measuring the energy deposited by a photon in the detector.

the probability, $P(y)$, of triggering a detector at the position, $y$, on the screen in Fig. 1 with the form of $P(y)$ determined in the usual way by the wave train of the photon. Thus, if we consider incident just photons all with the same wave train, the interference pattern they would form has, of course, the same form as $P(y)$.

As is well known, returning to focus on the photon depicted in Fig. 1 when the path difference of the two paths exceed the coherence length, $l_s$, $P(y) = \text{constant}$ and there is no interference to be seen at these positions in the pattern produced by having many such photons incident. Thus, by examining where the fringes disappear in this interference pattern, the experiment provides a measure of the photon temporal coherence, since the number, $n_f$, of fringes seen is simply related to $l_s = c\tau_s$:

$$n_f = 2\frac{l_s}{\lambda_s}.$$  

Indeed, the single photon interference experiment performed by Jacques et al. (2005) also acts to confirm such a result, as they also had to account for temporal coherence effects in order to fit fully the interference pattern observed.

However, with continuum radiation incident, the interference patterns for the different wavelengths overlap to give the well-known white light fringes and the point where the fringing disappears for any individual wavelength is lost. Thus, in order to have a measure of the temporal coherence of those photons in the continuum radiation having a particular energy, we need to attempt to separate out the interference pattern due to these photons from the mixture of patterns due to all the photons in the
radiation. The obvious means for separating out the subset of photons having just energy, \( E_s = h\nu/\lambda_s \), would be to use a normal light filter. But, conventional wisdom would dictate that, with incident continuum radiation, one succeeds only in measuring the temporal coherence of the passband of the filter. Still, with our depiction here of continuum radiation as a mixture of photons, it should, in principle, be possible to separate out the interference pattern for the photons with just energy, \( E_s \). Now, so far, we have only discussed the experiment classically and we have yet to touch on this quintessentially quantum mechanical insight into the nature of continuum radiation. Consequently, if there is a solution, it must lie in the physics of photon detection, the unequivocal quantum aspect of the experiment.

A photon is detected through the deposition of its energy in a detector, triggering it off, and the position of the photon is then recorded as just that of the triggered detector. For example, in Jacques et al. (2005)\(^4\), they have used an intensified CCD camera for registering the interference pattern and the detection of a photon occurs through its absorption by a CCD pixel to excite an electron into a higher energy level. Now, it has been demonstrated that the energy of an X-ray photon absorbed by a CCD can be accurately measured\(^8\) and, indeed, it’s a procedure that is routinely carried out in X-ray astronomy to obtain the X-ray spectrum of a distant source. Thus, the energy deposited by any photon on a CCD pixel can, in principle, be measured. Then, by restricting the recording of the detected photon positions to just those photons with energy, \( E_s \), the spatial distribution, \( P(y) \), of the photon detections would be that for this subset of photons. That is, the interference pattern seen would be for just those photons with energy, \( E_s \), and, in particular, it could then provide our desired estimate of the temporal coherence of these photons through the number of fringes present. By repeating the experiment for different values of \( E_s \), a measure of the temporal coherence as a function of energy could then be obtained. Interestingly, there is, thus, the present practical possibility of using CCD detectors in an X-ray photon interference experiment for observing the temporal coherence of the incident X-ray photons. We shall later consider possible photon detectors for use with optical sources.

Thus, the possibility of measuring the temporal coherence of photons in continuum radiation is already inherent even in these single photon interference experiments, as all that is required is an accurate means of measuring the energy deposited by the photon in the detector. As this is the underlying physics, it will also be true of a normal experiment where many photons are incident, such as, for example, for light from the sun. Consequently, instead of the normal screen for viewing the interference pattern, we are proposing the use of a screen of small photon detectors which are also able to measure accurately the energy deposited by a photon in the detector, as, indeed, we have shown in Fig. 1. To obtain the interference pattern for a particular energy, \( E_s \), we simply register the positions of the detections that have measured an energy of \( E_s \) for the absorbed photon. The temporal coherence of the photons with this energy is then given by the extent of the resulting interference pattern of the registered detections; in our picture, that would be the number of fringes, Eq. 2. As a first step in exploring the
technique here, we shall propose in Sec. 6 a simple practical example of such a detection screen, but one that may not be flexible enough to provide a means of measurement over the full wavelength range of the continuum radiation.

We see now that there are two fundamental processes involved in our experimental proposal. First is that the Young’s double slit is, of course, a wave experiment. In dealing with a photon individually, we would use the appropriate quantum mechanical equation of motion to evolve its state and determine its wave character. But, in effect, this is no different from applying classical wave theory. The second is the measurement of the position, $y$, of the photon at the screen and, crucially, the additional measurement, not normally done, of its energy, $E_s$. It is a modest change in the detection aspect of the experiment, which we now make explicit with the following mathematical treatment.

3. Quantum theory of the experiment

The quantum theory behind the Young’s double-slit experiment is, of course, well established. Just as with our physical exposition above, we shall see that all that is needed here is a slight adjustment to the standard approach. Also, we would like to emphasise that no special consideration of single photon interference experiments is required for the theoretical discussion, which applies generally. Now, for our purposes, we find it convenient to follow one of the early expositions of the theory, namely, that by Glauber in his 1964 Les Houches lectures\[2\], adopting, in the main, the same nomenclature. As we have pointed out, the crucial element for our proposal is in the process of photon detection. And, indeed, the theory begins with an examination of the absorption of a photon by an atom at position, $r$, at time, $t$. For a Young’s double-slit experiment, it would be some random atom detector of the detection screen. So, in this case, only the $y$-component, $y$, of $r$ is then of significance for the experiment.

Theoretically, light, as a mixture of pure states, $|\psi_j\rangle$, is represented by the density matrix

$$\rho = \sum_j p_j |\psi_j\rangle \langle \psi_j|,$$

where $p_j$ is the probability of the radiation field being in the state $|\psi_j\rangle$. Then, to first order of perturbation theory, the electric dipole approximation for the atom electric field interaction gives the probability for the excitation of the atom from its ground state, $|g\rangle$, to the excited state, $|a\rangle$, through the absorption of a photon, as

$$p_{g\rightarrow a}(t) = \left(\frac{\alpha}{\hbar}\right)^2 \sum_{\mu,\nu} \int_{t_0}^{t} dt' \int_{t_0}^{t} dt'' e^{i\omega_{\nu\mu}(t''-t')} M_{ag,\mu}^* M_{ag,\nu} \text{Tr}\{\rho E_\mu^{(-)}(r, t') E_\nu^{(+)}(r, t'')\},$$

quoting Eq. (4.8) of Glauber’s lectures\[2\], where the reader can find the detailed definitions of the quantities in Eq. 4. What is of relevance for our discussion is the form of the electric field operator. Here, we find it more illuminating to give it as it
A proposal for measuring photon temporal coherence in continuum radiation appears nowadays in modern texts (see, for example, Loudon (2000)[9]):

\[ E(r, t) = E^{(+)}(r, t) + E^{(-)}(r, t), \]

with

\[ E^{(+)}(r, t) = \sum_{k, \lambda} C_{k\lambda} \hat{a}_{k\lambda} \exp(-i\omega t + ik \cdot r) \]

and

\[ E^{(-)}(r, t) = \sum_{k, \lambda} C_{k\lambda} \hat{a}^\dagger_{k\lambda} \exp(i\omega t - ik \cdot r), \]

where \( \hat{a}^\dagger_{k\lambda} \) and \( \hat{a}_{k\lambda} \) are the creation and annihilation operators for a photon with wavevector, \( k \), and polarisation, \( \lambda \). Of course, \( \omega = c|k| \) and \( E_\mu \) is the \( \mu \)th component of \( E \), etc.

One needs also to introduce a weight function, \( R(a) \), to account for the fact that not all transitions are registered. In fact, when it finally comes to depicting the expected interference pattern, the screen will be assumed to be homogeneous and the distribution of the atoms within the position uncertainty of the experiment means that some average \( R(a) \) will be assumed. However, this will not affect us, as it just provides a constant factor. Indeed, upon examining Eq. 4, we see that the salient features for our proposal are twofold. First, is to note the separability of the result into a purely atomic part and the factor,

\[ G^{(1)}(r, t, r', t') = \text{Tr}\{\rho E^{(-)}_\mu(r, t') E^{(+)}_\nu(r, t')\}, \] (5)

involving just the radiation and electric field operators. It is, of course, the first order correlation function. Although obvious, it is one which we would wish to emphasise here is for the incident radiation, depicted by the density matrix, \( \rho \), Eq. 3.

The second important feature for our proposal is that of the conservation of energy. For the modes with angular frequencies, \( \omega' \) and \( \omega'' \), in \( E^{(-)}_\mu \) and \( E^{(+)}_\nu \), respectively, the electric field operators provide exponential time dependencies, \( e^{i\omega't'}e^{-i\omega''t''} \), resulting in a total time dependence of \( e^{i(\omega'-\omega_ag)t'}e^{i(\omega_ag-\omega'')t''} \) for the integrand of Eq. 4. Now, following the similar argument by Glauber, with the detector open, from time, \( t_0 \), to time, \( t \), to the radiation for a time interval, \( t-t_0 \), immensely greater than a period of the radiation, the essential contribution to the integral comes from the terms for which

\[ \hbar\omega' = \hbar\omega_ag \quad \text{and} \quad \hbar\omega'' = \hbar\omega_ag, \] (6)

with \( \hbar\omega_ag \) the atomic transition energy. Eqs. 6 are, of course, what we expected, expressing as they do conservation of energy.

Now, in the standard account of the theory, there is no measurement of the energy of the absorbed photon and there is, then, a summation over all possible final excited states, \( |a\rangle \), which is the next step in Glauber’s lectures to obtain his Eq. (4.9). At the time, broadband detectors were the norm. As stated in his lectures, “In the detectors used to date, however, the final states \( |a\rangle \) of the atoms form an extremely dense set, or a continuum”. But, as we have noted above, it is, in principle, possible to determine the
energy deposited by a photon in the CCD, that is, the energy, $\hbar \omega_{ag}$, between the ground state and the resulting excited state of the atom. It is this possibility that we want to exploit. Our experimental proposal is then to impose on the usual setup this minor additional requirement, that the photon detectors also measure this energy. This would then allow us to register just those detections for which the energy the absorbed photon has deposited in the detector is the energy of interest, namely, $E_s$, implying that the excited state, $|a\rangle$, of the registered atom is such that $\hbar \omega_{ag} = E_s$. In fact, we have, for this particular measurement, turned the detection screen into an effective screen of two-level atoms, where the energy between the two levels is this energy, $E_s$. So, although this seems a small adjustment to the usual experimental setup, the difference in detector type is significant. Whereas the standard theory features broadband detectors, here, with effective two-level atom detectors, we have very narrow band detectors, albeit, rather atypical narrow band detectors, as we shall explain in Sec. 5.

Then, by just registering detections according to energy, conservation of energy, Eq. 6 implies that only the terms with creation and annihilation operators associated with angular frequency, $\omega' = \omega'' = \omega_{ag}$, can contribute to the evaluation of Eq. 4. So, consider a state, $|\psi_j\rangle$, of the mixture, Eq. 3, incident on the detection screen. Since Fock states of the electromagnetic field are energy eigenstates, it is natural to expand $|\psi_j\rangle$ in terms of Fock states. We find it expedient here to turn again to Loudon (2000)[9] and use his notation. Then,

$$|\psi_j\rangle = \sum_{\{n_{k'\lambda'}\}} c^{\dagger}(\{n_{k'\lambda'}\})|\{n_{k'\lambda'}\}\rangle,$$

where $|\{n_{k'\lambda'}\}\rangle$ is the product of orthonormal eigenstates of the modes of the electromagnetic field, with the particular orthonormal eigenstate, $|n_{k'\lambda'}\rangle$, denoting $n_{k'\lambda'}$ photons in the mode with wavenumber, $k'$, and polarisation, $\lambda'$. Now, acting on such a state in the expansion with the annihilation operator,

$$\hat{a}_{k^\prime}|n_{k'\lambda'}\rangle = \delta_{k,k^\prime}\delta_{\lambda,\lambda'} n_{\gamma_{k^\prime}}^{1/2} |n_{k'\lambda'} - 1\rangle.$$ 

Similarly, the complex conjugate relation gives the effect of the creation operator. However, because of Eqs. 6 the creation and annihilation operators we need for our calculation are those associated with energy, $\hbar \omega_{ag}$. It implies then that the state, $|\psi_j\rangle$, can only contribute to the transition probability, Eq. 4, if in its expansion, Eq. 7 there are $n_{k'\lambda'} \geq 1$ Fock states for which

$$\hbar c|k'| = \hbar \omega_{ag} = E_s.$$ 

In other words, conservation of energy implies that only those states, $|\psi_j\rangle$, that have a photon with energy, $E_s = \hbar \omega_{ag}$, can give rise to the registration of a detection for this energy.

This is a completely general result, not requiring that $|\psi_j\rangle$ is itself an energy eigenstate. In fact, as the interest here is in a photon’s finite temporal coherence, even by just considering the uncertainty principle, a state of the incident radiation field will necessarily have an energy width. As we would expect, the theory is providing a more...
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rigorous explanation of our proposal here. Generally, the energy width is due mainly
to collisional broadening and is expected to be quite narrow, as we can see explicitly in
the collisional broadening of spectral lines.

Thus, only the part of the density matrix, \( \sum_{j : E_s} p_j |\psi_j\rangle\langle\psi_j| \), is required for
calculating the transition probability, Eq. \[4\] where by \( \sum_{j : E_s} \) we mean that the
summation is to be made only over those states having a photon with energy, \( E_s \)
Indeed, in practice we would also leave out of the summation any state providing a
negligible contribution to Eq. \[4\]. Still, since the observations are of photon detections,
we shall, for simplicity, still call this the energy subset of the incident photons with
energy, \( E_s \). But, more rigorously, we, of course, need to keep in mind that, as we have
just pointed out, a state, \( |\psi_j\rangle \), in this energy subset also has in its expansion Fock states
of other energies.

With this in mind, we see then that, instead of the full density matrix for the
continuum radiation, Eq. \[3\] we can use the effective density matrix,

\[ \rho^{\text{eff}} = B \sum_{j : E_s} p_j |\psi_j\rangle\langle\psi_j|, \tag{8} \]
in Eq. \[4\], where \( B \) is just a normalisation constant. It implies that using the effective
first order correlation function,

\[ G^{(1)}_{\mu\nu}(rt', rt'') = \text{Tr}\{ \rho^{\text{eff}} E^{(-)}_\mu(r, t') E^{(+)}_\nu(r, t'') \}, \tag{9} \]
in Eq. \[4\] in place of the original factor, Eq. \[5\] will give the same result for the transition
probability. Clearly, \( G^{(1)}_{\mu\nu} \) is, in fact, just the first order correlation function for the
radiation depicted by the density matrix of Eq. \[8\]. However, for clarity we shall continue
to call it an effective first order correlation function as far as our own discussion is
concerned.

Then, following Glauber’s lectures leading to his Eq. (7.1), we conclude that the
probability, \( P(y) \), of detecting a photon of energy, \( E_s \), at position, \( y \), on the screen is just

\[ P(y) = A \text{Tr}\{ \rho^{\text{eff}} E^{(-)}(r, t) E^{(+)}(r, t) \}, \tag{10} \]
with \( y \) being the \( y \)-component of \( r \) and \( A \) a normalisation constant, with the interference
fringe pattern given by the form of \( P(y) \). The significance of the result here is that in
a normal experiment, where the usual broadband detector screen is used, we would
have the same transition probability for incident radiation with the density matrix
of Eq. \[8\] that is, with only this energy subset incident. Clearly, Glauber’s whole
exposition leading to the results for the Young’s double-slit experiment can be repeated
using this effective density matrix. It implies then that the interference pattern and
measured temporal coherence we would find in our experiment, using just the registered
detections with measured energy, \( E_s \), would be the same as in a normal Young’s double-
slit experiment when only this energy subset is incident.

To summarise, it can be seen that we have just followed, in its basics, the standard
theory. Then, for our proposed experimental setup, the theory shows that, with our
effective two-level atoms as the photon detectors, conservation of energy implies that the incident states with energies unable to excite an atom cannot contribute to the transition probability, Eq. [4]. In practice, we would also ignore any state with a negligible contribution. More specifically, with two-level atom detectors, only the part of the density matrix that is the effective density matrix will contribute to the evaluation of the transition probability, implying that it is the effective first order correlation function that determines the form of the resulting interference pattern. Thus, it will be the same pattern as we would obtain in a completely normal Young’s double-slit interference experiment, where the usual broadband detection screen is used and where, in particular, just this energy subset of states is incident, so that the first order correlation function for this normal setup is just that of Eq. [9]. Of course, it is the visibility, as a function of $y$, of the interference pattern formed by the registered photon detections with energy, $E_s$, that then provides our desired measurement of the photon temporal coherence for this energy subset.

4. Experimental constraints

In reality, the energy deposited cannot be measured exactly. Even if the detection screen does actually consist of two-level atoms, the excited level will still have an energy width, besides the effect due to the thermal motion of the atoms. Thus, there will still be a need to include the appropriate integration over the energy range, $E_s \pm \Delta E_d$, where $\Delta E_d$ is the energy resolution of the photon detectors. Indeed, for a continuum of final states, including the narrow energy range of interest here, the resulting transition probability has the familiar form of Fermi’s Golden Rule (see, for example, Loudon (2000) [9]), where conservation of energy is expressed by the Dirac delta function factor, $\delta(\omega - \omega_{ag})$, with, for our situation, $\hbar \omega$ the energy of the absorbed photon. Then, the sum in the effective density matrix, Eq. [8] becomes an integral over those states of the continuum radiation having a photon with an energy in the range, $E_s \pm \Delta E_d$.

Clearly, for any meaningful measure of photon temporal coherence, the detector bandwidth needs to be kept as narrow as possible, ideally, with

$$\Delta \nu_d \ll \Delta \nu_s,$$

where $\Delta \nu_d = \Delta E_d / \hbar$ is the frequency bandwidth of the detectors and $\Delta \nu_s = 1 / \tau_s$, with $\tau_s$, then, an ‘average’ temporal coherence for this subset of photons having energy in the range, $E_s \pm \Delta E_d$. This is in direct contrast to the normal use of broadband detectors, such as that of CCDs in the optical, for example.

Physically, there is an observable zone of the detection screen, the size of which is dictated by the effective two-level atom detectors being used. The constraint of Eq. [11] implies that, in order to obtain a measurement of the temporal coherence, it then needs to be significantly large enough so that the region where interference ceases is easily discernible. Put simply, the observable zone for interference needs to be clearly greater than the actual area of interference.
The theoretical discussion above also shows why we have insisted on having a screen of energy measuring photon detectors rather than just simply interposing an optical filter in the light path to select out the photons with the desired energy. Using an optical filter would alter the state of a photon prior to its detection and change the density matrix to be used in Eq. \[4\] So, in order to be absolutely sure that the temporal coherence we observe using our technique is, indeed, that for this energy subset of incident photons, we must make sure that the density matrix to be used in Eq. \[4\] is, indeed, that for the incident beam arriving at the detection screen affected only by the double-slit.

To summarise, it is important that an actual state, as with the idealised photon we have used for illustrative purposes in Sec. 2, arrives at the screen altered only by the presence of the double slit. We have then proposed the use of a screen of photon detectors with the ability of providing the energy of the absorbed photon. This allows us to restrict the detectors we register to just those that have absorbed an energy in the range, \(E_s \pm \Delta E_d\). It is, of course, a form of filtering, one which we will call a detections filter, so as to distinguish it from an optical filter. Then, the interference pattern that will be observed will be given by an average of the \(P(y)\)'s for just those states in this photon energy subset of the continuum radiation. The number of fringes present in the pattern or, more generally, the visibility provides then an estimate of their temporal coherence. However, if the photons in the well-defined subset have a wide range of temporal coherences, a more sophisticated analysis would clearly be needed. But, even then, the observed temporal coherence of the subset would be expected to be decidedly different from that of the whole continuum radiation without the use of such a detections filter.

5. The experiment as apparent counter-example

Of course, our energy measuring photon detectors are acting as an effective narrow band filter. But, in this case, the photon is absorbed by the detector, whereas with a normal filter the photon passes through, with, however, its state altered. As is well-known when continuum radiation is incident, in experiments with a filter the measured temporal coherence would be just that for the bandwidth of the filter and not for the photons. This is the conventional wisdom and our experiment here would seem to constitute a counter-example to that precept. But, in our case, the filtering is done, not on the light, but on the detections by selecting just those photon detections with a measured absorbed energy of \(E_s\). This results in a filtering not of the light, but of the interference patterns, to provide just the interference pattern for the particular energy of interest. Thus, our experiment here is not actually a counter-example to the conventional wisdom regarding such experiments, but could, instead, be seen as complementary to it.

Indeed, the requirement for such detectors seems imperative from our theoretical discussion above. Consider using photon detectors without this capability of providing the energy a photon deposits in a detector and placing, instead, optical filters on the face of the detectors, instead. Then, such a setup would be described by the appropriately
altered Hamiltonian for the system and it would be no different from the normal placing of a filter in the light path. In which case, the conventional wisdom would prevail and the temporal coherence measured would be just that for the filter passband. Amusingly, such an experiment could be seen as a rather graphical illustration of the extraordinary acausal nature of the ‘collapse of the wave packet’ in quantum mechanics. Conceptually, the experiment using an optical filter in the light path does not require quantum mechanics and is completely explicable classically. Thus, such an experiment would be, a priori, incapable of achieving our aim here, an aim based on an essentially quantum mechanical understanding of the nature of continuum radiation.

We can also understand why in standard theoretical accounts only the situation using an optical filter has generally been considered. Glauber himself stated in his 1964 lectures[2], “In optical experiments a narrow band sensitivity is usually reached by putting narrow band light filters in front of broad band counters, i.e., by “filtering” the correlation function $G^{(1)}$ rather than by discriminating between photoelectrons”. Since then, this has been part of the standard theory. Our modest adjustment to this approach is to also consider this possibility of “discriminating between photoelectrons” through what we have termed a detections filter.

Thus, by registering detections according to the absorbed energy of the photon and determining the interference pattern for a particular measured energy would circumvent the conventional wisdom about the use of optical filters, without contradicting that wisdom. As mentioned in the previous section, it would be natural to call the process with our setup that of a detections filter. From a practical point of view, such detections filters would, clearly, also prove useful for any observation, whether astronomical or ground based, where the results are expected to be energy dependent. It would allow with continuum radiation the observation as if only the subset of states having a photon with a certain energy were incident. The technique may even be of use for non-continuum radiation, an example of which we discuss briefly below, in Sec. 7.

6. Suggestion for an initial experiment

This argument that our proposal is just an apparent counter-example to the conventional wisdom suggests the following simple experiment, to directly show that the extent of the interference fringes in the resultant pattern is, indeed, determined by the temporal coherence of the incident photons detected and not by that of the narrow spectral bandwidth of the photon detectors. It was simplest for us to discuss the basic physical principles using the Young’s double-slit experiment. However, for an actual experiment, it would be more normal to use a Michelson or similarly modern interferometer.

For the crucial element, we propose the use of a cold screen consisting of a layer of photoluminescent particles. These may either be embedded in some transparent material or layered on a dark surface. The observed interference pattern can then only be due to the subset of photons in the incident continuum radiation that have the right energy to excite a photoluminescent particle into its higher energy level. In other
words, the interference pattern is due to just those photons having an energy in the range, $E_s \pm \Delta E_d$, where $E_s$ is the energy difference between the unexcited and excited levels of the particles and $\Delta E_d$ is the width of the energy range over which a transition can occur. Furthermore, if necessary, one could also cool the detection screen to bring $\Delta E_d$ closer to the natural width of the transition. Clearly, for the incident continuum radiation, this screen of photoluminescent particles is, to all intents and purposes, just a screen of two-level atoms. In this case, we don’t even need to “tune” a detections filter to some particular energy and the setup amounts then to a direct experimental implementation of Eq. [4]. But, as it measures only the temporal coherence for this one energy, it cannot provide the measure as a function of energy.

For the test source, the continuum radiation from a hot dense gas or plasma should prove particularly effective. The temporal coherence of the photons from such a source would be dominated by collisional broadening. Thus, for an empirical test of our proposal, the collision rate needs to be high or, equivalently, the pressure needs to be great enough that the photons have a short enough temporal coherence, such that the resulting $\Delta \nu_s$ satisfies the condition of Eq. [11]. Fig. [1] then illustrates how when the path difference exceeds the coherence length of the photon, there is no interference, even though the narrowness of the bandwidth of the detectors would allow interference fringes with greater path differences, if present, to be seen. For an even more decisive ‘proof of principle’, one would repeat the measurement for different pressures whilst keeping the hot gas/plasma at constant temperature. We should then find that, as the pressure is increased, fewer fringes are seen, giving then a shorter measured temporal coherence, corresponding to the increased rate of collisions in the gas/plasma. Also, of course, there will be a need to compare the measured temporal coherence with the theoretically expected value.

7. Some practical considerations

Once such a ‘proof of principle’ experiment has been established, there will be a need to understand the systematic effects that may be involved in such a measurement. For example, even in our test above, a photon’s energy will have a Doppler component and, in order to calculate the expected temporal coherence, it will need to be taken into account. But, for now, we have just focussed on its simplest result, that of the number, $n_f$, of fringes in the interference pattern. For the chaotic radiation we are considering here, where collisional broadening is the dominant factor for a photon’s temporal coherence, we would expect that $n_f$ will be almost equal for wavelengths close to that selected for measurement. Thus, with the successful implementation of the technique we are advocating here, observations may well show that, where Doppler broadening is having a significant effect, it is more in the form of the envelope of the interference pattern. Indeed, a sophisticated analysis of the observed envelope, that is, the visibility of the fringes, could well provide further physical insight into the source.

Interestingly, as the photon temporal coherence generally is a measure of the
collisional broadening, it is, more or less, independent of the Doppler broadening. With the observed line width incorporating both broadening mechanisms, an awkward line profile fitting procedure is used in order to separate them. Thus, even for a spectral line, it might be useful to also measure the photon temporal coherence as a complementary measure, especially when, as with the H\textsubscript{α} line in solar radiation, the spectral line is dominated by Doppler broadening.

Of course, for the most powerful implementation of the technique, effective energy measuring photon detectors would probably need to be developed. As we have seen, this would not seem to be a problem for X-ray observations\cite{8}. One such promising line of technological research for the optical band is that of superconducting tunnel junctions and similar low temperature photon detectors\cite{10}–\cite{15}. But for the possible applications we foresee we need such a device to work also at normal and even at high light levels, as well as measuring the energy of a photon accurately enough, a technological challenge for the future. However, the use of a general device such as this may prove inefficient, requiring quite intensive data analysis if the aim is to obtain the photon temporal coherence as a function of the photon energy. It would require registering, according to photon energy, the individual interference patterns for the whole range of photon energies present in the continuum radiation. Meanwhile, for a more limited approach, as we saw from Sec. 6, the use of photoluminescent particles as photon detectors would seem to constitute a very simple and cost-effective solution.

Alternatively, it may be possible to use a white screen, observing the interference pattern produced through a narrow band filter. But, as a white screen works through the scattering of the incident light, the quantum theory for this may not be as straightforward as the discussion in Sec. 3. One could, of course, put it to the test, empirically. If it were found to be effective, it would constitute not only a very simple solution, but also a flexible one for observing the dependence on energy, provided that filters with a sufficiently narrow bandwidth as to satisfy Eq. 11 can be used for viewing the interference pattern.

8. The prospect for astronomy

With the immense usefulness of spectral line measurements, our aim has been to try to exploit in a similar way the quantum mechanical insight into continuum radiation as a mixture of photons. Although the physics of continuum radiation seems much more complicated, it’s only so if one goes no further than measuring the wavelength of a spectral line. But, as with a more detailed analysis of spectral lines, it is in the investigation of the physical conditions of the source that makes such observations as the one we propose here less straightforward to interpret, but, potentially, also very interesting, as we now hope to show with the following examples from astronomy.

An obvious first astronomical application would be to the optical radiation from the sun. In standard treatments of the sun’s atmosphere, the models would imply a density of $3 \times 10^{-7}$ g/cm$^3$ at the base of the photosphere\cite{16} \cite{17}. This would then
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give rise to a coherence time of $\sim 10^{-8}$ secs. Interestingly, Smid (2006)\cite{18} proposes a model in which the photons in the sun’s radiation is calculated to have a coherence time of $\sim 10^{-12}$ secs, implying a mass density at the base of the photosphere of at least $\sim 10^{-2}$ g/cm$^3$. This illustrates how useful such an observation of the photon temporal coherence as ours would be for our understanding of the solar photosphere and, indeed, for the photospheres of other stars.

The technique could also be applied to the continuum radiation of two distant objects such as QSOs to estimate their relative redshifts on the assumption that, for a particular class of astronomical object, the physics underlying the continuum radiation is the same. But, first, one should really use the technique on QSOs with known redshifts to explore the physics. Indeed, it may be even more interesting if the technique were to reveal that different QSOs do have significantly different physics.

For a cosmologist, perhaps the most exciting prospect is its promise for a deeper understanding of the cosmic microwave background (CMB), especially as, in the Big Bang scenario, the overwhelming number of CMB photons originate from electron-positron annihilation during the ‘annihilation era’. After this era, the photons then suffer mainly Compton scattering in the cosmic plasma (see, for example, Zel’Dovich et al. (1983)\cite{19}, Peebles (1993)\cite{20}). Now, electron-positron pair annihilation has a very narrow natural width\cite{21} and the physics of Compton scattering is well understood. Thus, as there are $\sim 10^8$ times more electrons and positrons at the beginning of the annihilation era compared to the number afterwards, the collisional broadening during the annihilation era would then be the dominant factor for the photon temporal coherence. Any subsequent collisional broadening due to their passage through the plasma to the last scattering surface would only serve to shorten an already very short temporal coherence. Thus, the possible measurement of the temporal coherence of the photons in the CMB would provide further evidence of their cosmological origin. Indeed, a detailed analysis of the interference pattern might even afford a unique opportunity to probe the Universe when it was just $\sim 10$ secs old. It is, of course, a project for the future, needing the development of the technique for use at radio frequencies, as well as the theoretical work to predict the outcome of such a measurement. Similarly, it may also eventually be of use as a probe of the physics of the reionization era, when eventually the radiation from this epoch in the Universe is discovered. Obviously, we could use the technique to observe the continuum radiation of any other astronomical source, from stars to the Big Bang.

9. Conclusions

A search of the literature would show that little theoretical work has so far been done on the subject of the possible temporal coherence of the photons in continuum radiation. That is nonetheless understandable. Given the conventional wisdom that with incident continuum radiation only the temporal coherence of the spectral filter’s passband would be measured, there seemed to be no means of measuring the photon temporal coherence
A proposal for measuring photon temporal coherence in continuum radiation and little point then in pursuing the associated theoretical calculations. But, as we have shown, our proposed technique would circumvent the conventional wisdom, without, in any way, contradicting it, to offer this possibility. It does this through what we have called detections filters, as opposed to normal light filters, where a detections filter simply consists of effective two-level atom detectors, with the transition energy the energy of interest. By registering just the detections by these effective two-level atom detectors, we are able to single out the interference pattern for the subset of photons having this energy. Fundamentally, as the quantum theory shows, it is simply a consequence of the conservation of energy. Clearly, the resultant temporal coherence measured for this energy subset will be quite different from that for the continuum radiation as a whole.

In fact, for our suggested ‘proof of principle’ experiment, we propose the use of photoluminescent particles, which are, for the experiment, actually two-level atom detectors. Clearly, although they do not provide a measure of the photon temporal coherence as a function of energy, they would be generally useful if we only need the measure for the discrete energies for which photoluminescent particles are available. Of course, other two-level systems could also be similarly useful.

Thus, following the successful implementation of a ‘proof of principle’ test, the development of our proposal here, from our own personal perspective in astronomy, would provide an additional tool in a field necessarily limited in the observational tools available to it. It holds out the promise of a new and rich vein of astronomical observations for exploring the physics of distant sources. It would, clearly, also be a useful complementary tool to those already in use in the laboratory and in industry, both as one for testing theoretical calculations, as well as its use as a diagnostic tool. Even for fundamental physics, it offers a new means of experimentally examining the nature of continuum radiation. Interestingly, the observation of plasmas and gases in the laboratory should prove useful for astronomy too, not only in providing confidence in theoretical calculations, but, also, when there is the possibility of replicating an astronomical source in the laboratory. Finally, we note that we have just concentrated here on the photon temporal coherence. But, obviously, there will be further information about the source in the visibility of these energy registered interference patterns.

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