The myth of the down converted photon

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Abstract

Parametric down conversion (PDC) is widely interpreted in terms of photons, but, even among supporters of this interpretation, many properties of the photon pairs have been described as “mind-boggling” and even “absurd”. In this article we argue that a classical description of the light field, taking account of its vacuum fluctuations, leads us to a consistent and rational description of all PDC phenomena. “Nonlocality” in quantum optics is simply an artifact of the Photon Concept. We also predict a new phenomenon, namely the appearance of a second, or satellite PDC rainbow. (This article will appear in the Proceedings of the Second Vigier Conference held in York University, Canada in August 1997. A somewhat more formal version has been submitted to Phys. Rev. Letters, and may be found at http://xxx.lanl.gov/abs/quant-ph/9711029.)

1 Introduction

In an article for the last conference in this series[1] we gave a description of the Parametric Down Conversion (PDC) process based on the real vacuum electromagnetic-field fluctuations. We indicated that there was a serious unsolved problem, in that detectors must somehow subtract away these fluctuations; such a mechanism must come into play in order to explain the very low dark rates actually observed. We have since published a series of articles[2, 3, 4, 5] in which a great variety of PDC phenomena have been analyzed using this description. Since we have been able to establish a formal parallel, through the Wigner representation, between the new (or rather the old!) field description and the presently dominant Photon Theory, it is clear
that, once the reality of the zeropoint field has been accepted, there are no PDC phenomena which require photons. Furthermore we have made considerable progress on the subtraction problem\[5\]; all that is needed to explain the low dark rates of detectors is the recognition of their extremely large time windows (5ns is a very large number of light oscillations).

The approach of the above series of articles was a kind of compromise between the standard nonlocal theory of Quantum Optics, where the interaction of the various field modes is represented by a hamiltonian, and a fully maxwellian theory, which would be both local and causal. In this latter case the nonlinear crystal would be represented as a spatially localized current distribution, modified of course by the incoming electromagnetic field; the outgoing field would then be expressed as the retarded field radiated by this distribution. A preliminary attempt at such a theory was made\[6\], using first-order perturbation theory. However, we showed, in the above series of articles, that a calculation of the relevant counting rates, to lowest order, requires us to find the second-order perturbation corrections to the Wigner density, and the close formal parallel between these two theories means that the same considerations will apply to the maxwellian theory.

2 What is PDC?

It is necessary to pose this question, because, depending on the answer given, PDC may be described as either a local or a nonlocal phenomenon.

An example of the modern, nonlocal description is provided by Greenberger, Horne and Zeilinger\[7\]. A nonlinear crystal, pumped by a laser at frequency \(\omega_0\), produces conjugate pairs of signals, of frequency \(\omega\) and \(\omega_0 - \omega\) (see Fig.1). Since light is supposed to consist of photons, this means that an incoming laser photon “down converts” into a pair of lower-energy photons. Naturally, since we know that \(E = \hbar \omega\), that means energy is conserved in the PDC process, which must be very comforting. However, the above authors themselves refer to the PDC photon-counting statistics as “mind-boggling”, and a more recent commentary\[8\] even uses the term “absurd”.

There is an older description, which I suggest is more correct than the modern one. It had only a short life. Nonlinear optics was born in the late 1950s, with the invention of the laser. Up to about 1965, when Quantum Optics was born, the PDC process would have been depicted\[9, 10\] by Fig.2; an incoming wave of frequency \(\omega\) is down converted, by the pumped crystal, into an outgoing signal of frequency \(\omega_0 - \omega\). The explanation of the frequency
Figure 1: PDC - the modern version. A laser photon down converts into a conjugate pair of PDC photons with conservation of energy.

Figure 2: PDC - the ancient version. When a wave of frequency $\omega$ is incident, at a certain angle $\theta(\omega)$, on a nonlinear crystal pumped at frequency $\omega_0$, a signal of frequency $\omega_0 - \omega$ is emitted in a certain conjugate direction. The modified input wave is called the idler.

relationships lies in the multiplication, by the nonlinear crystal, of the two input amplitudes; we have no need of $\hbar$! This process persists when the intensity of the input is reduced to zero, because all modes of the light field are still present in the vacuum, and the nonlinear crystal modifies vacuum modes in exactly the same way as it modifies input modes supplied by an experimenter. What we see emerging from the crystal is the familiar PDC rainbow. This is because the angle of incidence $\theta$, at which PDC occurs, is different for different frequencies on account of the variation of refractive index with frequency.

We depict the process of PDC from the vacuum in Fig.3, but note that this figure shows only two conjugate modes of the light field; a complete picture would show all frequencies participating in conjugate pairs, with varying angles of incidence. In contrast with Fig.2, where we showed only the one relevant input, we must now take account also of the conjugate input
mode of the zeropoint, since the first mode itself has only the zeropoint amplitude.

The zeropoint inputs, denoted by interrupted lines in Fig. 3, do not activate photodetectors, because the threshold of these devices is set precisely at the level of the zeropoint intensity, as discussed in Ref. [3]. However, the two idlers have intensities above that of their corresponding inputs. Also there is no coherence between a signal and an idler of the same frequency, so their intensities are additive in both channels. Hence there are photoelectron counts in both of the outgoing channels of Fig. 3.

The question we have posed in this section could be rephrased as “What is it that is down converted?”. According to the thinking behind Fig. 1, the laser photons are down converted, whereas according to Fig. 3 it is the zeropoint modes; they undergo both down conversion, to give signals, and amplification, to give idlers.

3 Photon production rates in PDC

There is a small, but important difference between the maxwellian theory and the theory outlined in our Wigner series [2, 3, 4, 5], though both of them could be said to be based on Fig. 3. The Wigner series gave us the undulatory version of quantum optics, but its starting point is a hamiltonian which takes the creation of photon pairs as axiomatic. The maxwellian theory, whose details are given elsewhere [11], starts from a nonlinear expression for the induced current and deduces a coupling between the field modes. This coupling is very similar, but not identical, to that deduced from the Wigner-based theory. As we have emphasized, there are no photons in the maxwellian theory, but if we translate the intensities of the outgoing signals

\[
\text{zeropoint input}(\omega) \rightarrow \theta(\omega) \\
\text{zeropoint input}(\omega_0 - \omega) \rightarrow \theta(\omega_0 - \omega)
\]

\[
\begin{align*}
\text{signal}(\omega_0 - \omega) + \text{idler}(\omega_0 - \omega) \\
\text{idler}(\omega) + \text{signal}(\omega)
\end{align*}
\]

Figure 3: PDC from the vacuum. Both of the outgoing signals are above zeropoint intensity, and hence give photomultiplier counts.
in Fig.3 into photon terms, we obtain the result
\[
\frac{n_i(\omega) + n_s(\omega)}{n_i(\omega_0 - \omega) + n_s(\omega_0 - \omega)} = \frac{\cos[\theta(\omega_0 - \omega)]}{\cos[\theta(\omega)]}.
\]

So we conclude that the photon rate in a given channel is inversely proportional to the cosine of the rainbow angle. In the Photon Theory, the above ratio is one.

There seems little chance of finding out directly which of these theories is correct; the difference between the two ratios is small, since the rainbow angles are typically around 10 degrees, and it is not possible to measure at all accurately the efficiency of light detectors as a function of frequency. It is true that some of the experiments we have analysed, using the standard theory, in Refs.\[2, 3, 4, 5\], have slightly different results in the present theory, for example the fringe visibility in the experiment of Zou, Wang and Mandel\[12\]. Some details will be published shortly, but we can say that an experimental discrimination will be very difficult.

4 Parametric up conversion from the vacuum

There is, however, at least one prediction of the new theory which differs dramatically from the standard theory. An incident wave of frequency $\omega$, as well as being down converted by the pump to give a PDC signal of frequency $\omega_0 - \omega$, may also be **up converted to give a PUC signal of frequency $\omega_0 + \omega$.** We depict this phenomenon, which is well known\[9, 10\] in classical nonlinear optics, in Fig.4. Note that the angle of incidence, $\theta_u(\omega)$, at which PUC occurs is quite different from the PDC angle, which in Fig.2 was denoted simply $\theta(\omega)$, but which we should now call $\theta_d(\omega)$.

Now, following the same argument which led us from Fig.2 to Fig.3, we predict the phenomenon of PUC from the Vacuum, which we depict in Fig.5.

When we come to calculate the intensity of the PUC rainbow, there is an important difference from the PDC situation, because we find that the idler intensities are now less than the input zeropoint intensities. The signal intensities in both channels almost, but not quite, cancel this shortfall, so that the PUC intensities are only about 3 per cent of the PDC intensities, which may explain why nobody has yet observed them. Also, note that there is a detectable signal only in the lower-frequency channel, because the
relation corresponding to eq.(1) is

$$\frac{n_i(\omega) + n_s(\omega)}{n_i(\omega_0 + \omega) + n_s(\omega_0 + \omega)} = \frac{\cos[\theta_u(\omega_0 + \omega)]}{\cos[\theta_u(\omega)]},$$

which means that in one of the channels (actually the upper-frequency one), the total output intensity is less than the zeropoint, so nothing will be detected in this channel. My prediction therefore is that, as well as the main PDC rainbow $\theta_d(\omega)$, there is also a satellite rainbow, whose intensity is about 3 percent of the main one, at $\theta_u(\omega)$. An approximate calculation\[11\] shows that $\theta_u(\omega)$ is about 2.5 times $\theta_d(\omega)$.

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Figure 4: PUC. In contrast with PDC the output signal has its transverse component in the same direction as that of the idler.
Figure 5: PUC from the vacuum. Only one of the outgoing signals is above the zeropoint intensity. The other one, depicted by an interrupted line, is below zeropoint intensity.

5 Conclusion

Our contribution to the previous conference in this series was entitled “The myth of the photon”. The present article repeats this theme, but covers a narrower range of phenomena. This is because the local theory of nonlinear crystals is now very much more complete than the corresponding theory for atoms. In retrospect, the word “obsolete”, which we used in the previous article, for all photon theories, was excessively triumphalist. Of course one could argue that they became obsolete once their nonlocal nature was revealed, that is a quarter of a century ago, but there was nothing local on offer at that time. The claim we made, maybe prematurely, was based on having demonstrated, by the use of certain model theories with very limited fields of application, that local theories were, in all cases possible. Now we have passed into a new phase of the programme; we now have, for a very wide and growing area of investigation, a well defined alternative theory which makes certain new predictions. If and when such predictions are verified, I think that down-converted photons, for example those depicted in our Fig.1, will be very definitely obsolete.

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