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REMARKS ON OBSERVED SUPERLUMINAL LIGHT PROPAGATION

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A recent experiment [1] shows evidence for strong superluminal group and energy propagation, albeit not for superluminal signal velocity, in light pulses. A few remarks are in order about its implications on the quantum theory of light.

Key words: superluminality, wave-particle duality, photon.

1. INTRODUCTION

In a recent paper [1] the results of an experiment are discussed which show strongly superluminal group velocities for light pulses propagating through atomic caesium gases at 30 $°C$ in the spectral condition of anomalous dispersion. In fact a near gaussian light pulse of 3.7 μs width and 120 KHz bandwidth is seen to cross a 6 cm caesium cell with a group velocity index of about 310 (negative), so that a forward time shift of 62 ns of the pulse is obtained. This practically means that "a light pulse propagating through the atomic vapour cell appears

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at the exit side so much earlier than if it had propagated the same distance in a vacuum that the peak of the pulse appears to leave the cell before entering it". This paradoxical phenomenon was predicted by the proponents of this experiment [2, 3, 4, 5] on the basis of classical optics and was explained as the result of a reshaping of the light pulse due to classical interference between its different frequency components in an anomalous dispersion region. It is also claimed that these results are not at odds with causality or special relativity for two main reasons: first because they are the result of the Kramers–Kronig relations which are based on the causality requirements of electromagnetic responses; second because the information propagation velocity seems to be best defined as the *frontal* velocity of a step–function signal which has been shown not to exceed c [6, 7]. However in the opinion of the authors these rather counterintuitive results suggest also further remarks about the quantum nature of the light that will be briefly discussed in this letter.

2. WAVES, PHOTONS, AND CAUSALITY

The calculations involved in the prediction of these effects [2, 3, 4, 5] are completely classical in the sense that they make use of the theory of electromagnetic wave propagation as was essentially known since Maxwell times [6]. In fact the concept of photon seldom surfaces in these papers and is never instrumental to explain these experiments. This was also clearly acknowledged by one of the proposers of the experiment [2] by saying that "an open theoretical issue is how to provide a microscopic description of these effects by means of a fully second–quantized treatment, which could predict the behavior of off–resonance *single–photon* wave packets interacting with the inverted atomic medium". However in the opinion of the authors one of the interesting aspects of these results lies in what can be gained from them about the wave-particle nature of the light.

A first remark is that the showed effects can not be explained only in terms of photons as localized particles, without use of the concept of waves, in a way which is reminiscent of the two slit interference. In fact we are said that [1] the atomic caesium vapour constituting the dispersive medium is confined in a 6 cm long cell. If the photons were only particles going through this cell they could gain, on twin photons traveling in vacuum, no more than a 0.2 ns advance, since this is the time taken to cross 6 cm at the velocity $c = 3 \times 10^{10}$ cm/sec. On the other hand the main result of the experiment consists in the fact that the electromagnetic pulse undergoes a forward time shift of 62 ns: hence it is apparent that it would be impossible to explain these results only on the basis of what happened to the velocity of a corpuscular photon along a 6 cm path. In fact this requires a modification of the fields all around the caesium cell with the corresponding deformation of the waves predicted by the anomalous dispersion theory. In the opinion of the authors this shows that we are in presence of an essentially *wave* (as contrasted with *corpuscular*) phenomenon as in the case of the two slits experiment. However the corpuscular aspect of this experiment is not irrelevant since it has been pointed out [4] that the proposed amplification scheme "is faithful even at the single–photon level", and hence that the present experiment "will be further analyzed, particularly for the case when the light pulse consists of only a few photons" [1] in a way similar to both that of the previous tunneling experiments [8] and that of the classical two slits interference.

The wave explanation of the results is based on the ideas of the *pulse reshaping* which is discussed at length in the proponent papers [2, 3, 4, 5], and which can be made compatible with causality. In fact the speed at which the information seems to be carried by a light pulse should correspond to the so–called *frontal velocity* (the speed at which a step function shaped pulse travels), and that has been shown [6, 7] not to exceed c. Here on the other hand the pulse is gaussian and the forward time shift of 62 ns has been measured with reference to the peak location of the gaussian envelopes, so that it is the *group velocity* which is superluminal. It is known indeed [4] that in a Lorentz-model dielectric there exist spectral regions where the group velocity exceeds c, also if despite these effects no real signal can be transmitted faster than c. Of course the conceptual difficulty is here compound with the fact that a gaussian pulse has no evident *front* to show, but it is also clear enough that "all the information about the shape of an analytic pulse is contained in any finite interval along, for example, its leading edge". This leads to paradoxical, but not absurd, consequences since in the said spectral regions the peak of a gaussian pulse can come out of the cell *before entering it*: of course this is the origin of the superluminal propagation put in evidence in the present experiment. This can be made more intuitive by saying that (from the behaviour of the leading edge) the cell *knows* the form of the pulse and the location of its peak well before the actual arrival of it, and hence it can also emit it in advance with little deformation. It is clear enough that this can only be understood as a wave phenomenon which pertains to the boundary conditions to be imposed to the wave equation. Finally it is remarkable, albeit unusual, that this behaviour is also reproducible for ordinary electronic signals with a simple bandpass amplifier [9].

What can be said now about the possible superluminal propagation of photons themselves? Let us suppose that the results of the experiment can be reproduced also with single photon packets: are we entitled to say that every single photon (or also a few of them) traveled faster than c? Remark first of all that the wave packet has a time width of 3.7 μs corresponding, at the velocity c, to a space width of about $10^5\ cm = 1\ Km$, namely it is spatially very wide with respect to che 6 cm cell. Moreover the time separation between the incoming and the outgoing peaks is 62 ns corresponding to about 1800 $cm = 18\ m$.

Hence the spatial situation of ordinary (traveling at c) and advanced pulses seems to be that of two very wide (about 1 Km) gaussian envelopes, with peaks slightly apart (about 18 m) and hence almost completely superposed. In the present experiment the pulses contain a lot of photons and the intensity of pulses is recorded in time. If the experiment can be made also with single–photon packets the intensity will be slowly recovered by addition of photon by photon arrivals, still once in a way reminiscent of a single–photon two slits interference. Now we can compare the arrival times of photons traveling in vacuum or through the caesium cell: since the packets are superposed we will record every possible pair of arrival times and we will recover the shifted intensity curves only as a final average. Moreover, because of the uncertainty about the emission location of these photons, nothing could be said about the individual velocity of every photon and hence on the comparison between the velocities of photons traveling in vacuum and of photons traveling in the caesium cell. As for the two slits single–photon interference, where you *see* the interference pattern not on the single photon but only at the end of the experiment, here too we can not *see* the effect of superluminal propagation on every single photon, but we can only recover it in average at the end of the experiment. In some way the reshaping of the packet influences the motion of the photons, but it seems impossible to associate a superluminal velocity to every (or also some) single photon.

Of course different questions would be raised is if the experience could be so modified to put in evidence a superluminality of individual photons. Can we do that, or the situation is once more similar to the case of the two slits interference, where every modification which lets us to know which slit the photon is going through also leads to the disappearance of the interference pattern? In the opinion of the authors a way to do that could be to narrow the spatial width of the wave packets to a level such that the normal (traveling at velocity c) and the superluminal can be clearly separated. If we can manage to have that we could say that almost every photon in the superluminal packet traveled faster than the photons in the ordinary packet. Since the measured velocity ratio in the caesium cell is about 300, this situation would be macroscopically in violation of usual causality. Because of this the author think that for some reason it should be impossible to cut down the width of the pulses to the said length. For example it is remarkable that there is no incurable conflict in principle between this requirement and uncertainty principle or practical monochromaticity of the packet. In fact, since the peaks are about 18 m apart, the width of the packets should be reduced to a few meters, or correspondingly the time width should be reduced do about 10 $ns = 10^{-8} sec$. The frequency/time uncertainty relations $\Delta\nu \cdot \Delta t \simeq 1$ would then in principle allow frequency uncertainties as small as 10^8 Hz or greater. Since in the microwave spectrum the frequency is of the order of magnitude of 10^{10} Hz, and in the visible of 10^{15} Hz, in principle there could be room enough to satisfy both the uncertainty requirements and a good frequency definition. But since the separation of the two gain lines of the caesium is of only 2.7 $MHz = 2.7 \times 10^6$ Hz the new narrow packet would spectrally spread well beyond experimetally permitted bounds. We feel moreover that the cutting down of the spatial (or time) pulse width should also come in conflict with all the approximations made in [2, 3, 4, 5] in order to predict the effect, and hence that it should be impossible to detect both: the reshaping of the light pulse and the single photon superluminality.

3. CONCLUSIONS

In the opinion of the authors, this experiment clearly shows the essentially wavelike nature of light: it can not be justified only in terms of localized properties of photons as particles. Moreover it is apparent that no conflict with the causality is actually implied and the authors conjecture also that no such a conflict can arise from future modification of this experiment. However, since it is an effect which is strictly connected with the quantum behaviour of the microscopic world, and which could in principle be done also with single–photon pulses (as the similar experience on tunneling [8] has shown a few years ago) it would also be very interesting try to elaborate a description of it not only in a second quantized approach, but also in terms of particle trajectories, either in the framework of the Bohmian Mechanics [10] or in that of the Nelson stochastic mechanics [11]. In fact it has been rightly remarked that "the central problem is not the absence of an appropriate Hermitian operator [for the time in quantum mechanics], but rather the absence of well-defined histories (or trajectories) in standard quantum theory" (see [7], p. 383); but until today, at the knowledge of the authors, along this line of thought only a preliminary discussion for the tunneling times by means of Bohm trajectories (see [7], p. 358 and references quoted therein) has been developed.

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