Research Article

Aristotle, Heisenberg, and the Non-Locality and Non-Temporality of a Single Photon

Alfred Driessen[1]

1. Emeritus Professor, University of Twente, Netherlands

Within the framework of Aristotelian philosophy, the author presents an analysis of the exchange of energy by photons. These massless particles exhibit the most pronounced quantum behavior and pose serious challenges to classical physics. The arguments are based on the Heisenberg Uncertainty Principle and a number of Gedanken experiments on single photons. For illustration, experimental and numerical work on optical microresonators is discussed. These allow to assess the validity of Maxwell's equations and to verify some of the Gedanken experiments. As a result of the discussion, one has to accept that the photon trajectory is causally influenced by the final state, which is separated in time and space from the initial state: non-locality and non-temporality.

1. Introduction

In earlier studies, the authors sought to develop a philosophical framework for understanding the foundations of the major new theories in physics: Quantum Mechanics (QM) and Relativity. In *Aristotle and the Foundation of Quantum Mechanics*[1], it is shown that the Aristotelian approach to change and motion unexpectedly makes QM comprehensible. The following study, *Philosophical Aspects of Time in Modern Physics*[2], focuses on time and includes Relativity in addition to QM.

In the Aristotelian tradition, empirical observations serve as illustrations of philosophical statements. However, a major change had occurred. Aristotle could use knowledge available to the educated intellectuals of his time. But now, the scientific background is only available to specialists. Nevertheless, it makes sense to confront philosophy with science, resulting in a challenging mix of disciplines. In the following, concepts of the Aristotelian philosophy are illustrated by the physical theory of light and the photon, the particle of light. The photon, a massless particle, exhibits the strongest quantum and simultaneously the most relativistic character. Its properties would serve as a suitable illustration for the philosophical concepts discussed in the studies of[1] and[2]. A drawback, however, might be the technical nature of the argumentation. The collection of articles *What is a photon?*[3] may serve as a good introduction to the following.

The role of Heisenberg and his uncertainty principle (HUP)[4],[5] is fundamental in our discussion. It relates the uncertainties in energy and time in a way so that the product of both has a minimal value. For the majority, the principle is accepted as a law of nature arising due to the finite information in any physical system, whereas for others, it is an expression of the insufficient knowledge of the system under study. They believe hidden variables or some new physical insight could circumvent this deficiency. Related to the HUP is the exclusion of strict determinism in nature. Aristotle did not foresee Heisenberg, but offers a framework where the findings of Heisenberg about non-deterministic laws in nature could be embedded[6].

The author intends to show, that non-local and non-temporal correlations occur in the trajectory of a single photon. Within the Aristotelian approach, the trajectory of any movement is considered a whole; see[1]. In that case, non-local and non-temporal correlations are not astonishing. The physical analysis, however, needs a set of Gedanken experiments to confirm the proposition. A first version of the analysis can be found in[7], see also[2]. Especially relevant for our argumentation will be experimental studies with photons, for example, the propagation of short (femtosecond) pulses in microring resonators[8] and[9].

In the following, we first start with a section about light and, when considered as a particle, the photon. We specify what is meant by non-local and non-temporal correlations. We also introduce the HUP for a photon. Thereafter, we present the photon's analysis with physical terms. Then it is time to apply the Aristotelian philosophical concepts to our photon experiments. The last section will summarize and discuss the results.

2. What do we know about the photon?

The basic idea of a photon can be summarized as follows: a photon is a transfer of a quantum of energy E emitted at place *A* and absorbed at another place *B*. The speed of energy transfer is finite and has a constant value in a vacuum for all energies. The speed of light is approximately 300.000 km/s. This may seem extremely high, but when working with light pulses, it can be easily handled in the laboratory. A picosecond, ps (1 millionth of a millionth of a second) is a convenient measure of ultrashort light pulses, which we will discuss below. The intensity profile of a 1 ps light pulse is about 0.3 mm in space and can be easily manipulated with precision mechanical translation stages.

The positions of all possible final places *B* at a given time define a surface around the source *A* expanding with the speed of light. The volume enclosed by this surface is related to the concept of the so-called “wavefunction” that “collapses” eventually at a single site *B*. Objects' geometry and optical properties determine this volume which may be highly a-symmetric and bizarre.

The trajectory of a single photon from *A* to *B* is not directly accessible by any experimental method and can only be approached by statistical methods. There is no *which-way information,* as any attempt to achieve this information will change the trajectory. In the case of large numbers of photons, approximate models like the ray-picture or Maxwell Equations solved by, e.g. Beam propagation algorithms, give good results[10]. In the individual case one can work only with wavefunctions, whose squared amplitude is proportional to the probability to detect a photon at that specific position. Single photon experiments show that photons can follow, in a certain sense, simultaneously parallel paths and have an extension, the coherence length. According to Dirac, *photons interfere with themselves*, a statement quoted in[11]. Photons show particle properties different from those of macroscopic objects.

Non-locality and non-temporality refer to phenomena where one encounters correlations or influences of events peculiarly separated in space and time. Fig. 1 shows an *x*-*y*-*t* diagram (two space- and one time-coordinate) with the present-time plane and the future and past light cones of an event located at the origin. In classical physics and relativity, the causes of the event lie in the past light cone; a time-like interval connects them with the event. Non-locality means that causes are located in the past half space or in the generalized present but outside the past light cone; the interval connecting cause and event is spacelike. As a consequence faster than light correlations are involved or action on a distance. Non-temporality means that events in the future light cone have a certain influence on the present state of the origin; the interval connecting cause and event is timelike but with the arrow of time reversed. In the case of non-temporality faster than light effects would not solve the occurrence of these striking correlations.

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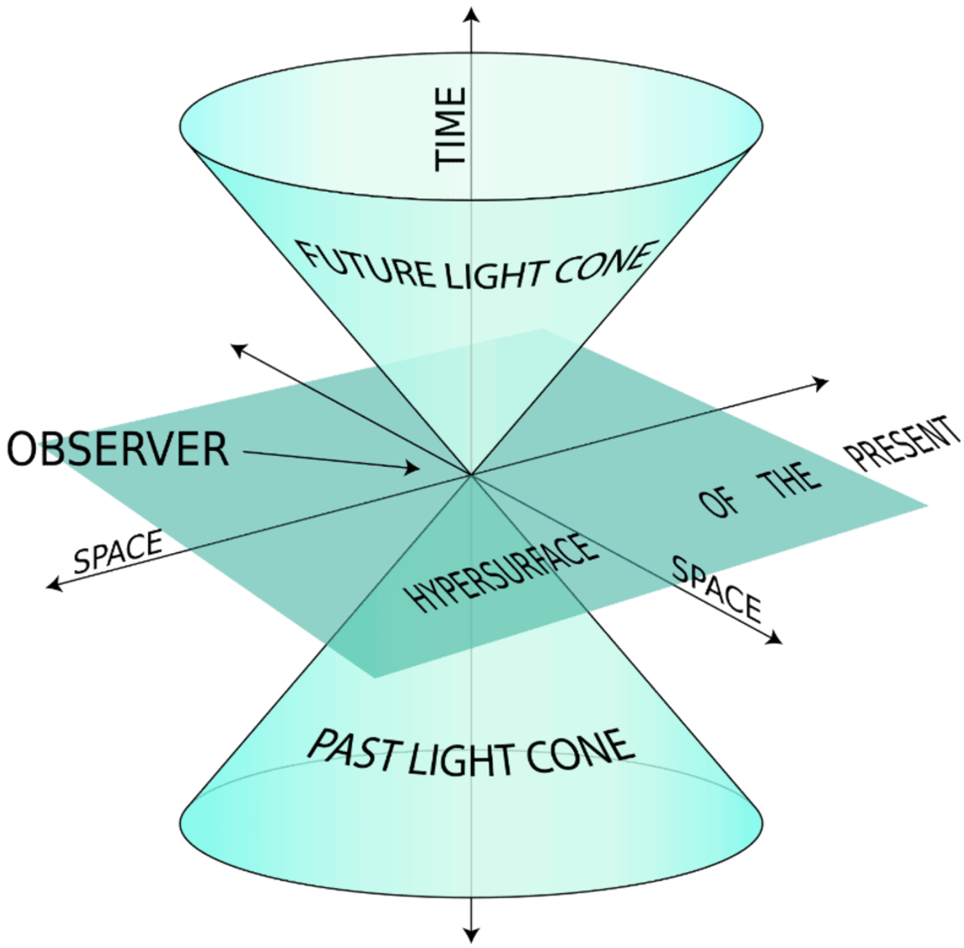

Figure 1. Diagram of the future and past light cones. A light cone is the path that a photon emanating from a single event in the origin (or arriving at the origin) would take when traveling in all directions through space-time. Taken from[12]

In the following argumentation about the peculiar properties of the photon often the Heisenberg uncertainty principle (HUP) will be applied. This principle can be stated as, see e.g.[13]:

$$\Delta E \cdot \Delta t \geq h/(4\pi) \tag{1}$$

where ΔE and Δt are the uncertainties in energy and time, respectively, of the photon and h the Planck constant. According to Planck, one can express E in terms of the frequency ν of the photon

$$E = h\nu \tag{2}$$

In this way the HUP can be written:

$$\Delta v \cdot \Delta t \geq 1/(4\pi) \tag{3}$$

In the case of a transform-limited optical pulse, the product of the full-width-at-half-maximum (FWHM) of the pulse spectrum (the bandwidth, $\Delta\nu$) and the temporal profile, Δt, is equal to a constant *k*. Its value depends on the definition of the uncertainties and the pulse shape and amounts to 0.441 for a Gaussian-shaped pulse[14]. In a good approximation, therefore, Eq (3) can be rewritten:

$$\Delta v \cdot \Delta t = 5/(4\pi) \tag{4}$$

In the HUP, as formulated in Eq. (4), the uncertainty in time Δt can also be expressed as the uncertainty in the coherence length $l_c = c\Delta t$. It is referred to as the pulse duration or the FWHM of the source. In the next section, we present evidence that the l_c of a photon firstly is determined by any principal time uncertainty in the whole trajectory, including source, single, multiple, or parallel paths, and the detector arrangement, and secondly is unchanged during the total trajectory from source *A* to endpoint *B*.

3. Non-local and non-temporal temporal processes involved in the interaction by photons

In the following, it will be shown that non-local and non-temporal processes play an important role in the energy exchange by photons; for related work, see, e.g.[15][16]. The argumentation is based on three main ideas:

i. the coherence length of a photon remains unchanged during the complete lifetime from emission to absorption;
ii. the coherence length is dependent not only on the source properties but on the characteristics of the whole trajectory
iii. the trajectory of a photon is dependent on the coherence length.

The consequences are dramatic, as photons of astronomical light sources connect events separated in space and time by billions of light-years and billions of years, respectively. To support the argumentation, Gedanken experiments are performed that exclude some straightforward but probably too naïve conclusions.

Before starting the discussion, one must clarify whether the photon is an object of physical reality. In the case of a full no, one is confronted with the experimental fact that at one place *A* and initial time t_i energy vanishes, and later at place *B* and final time t_f energy is generated. If no physical reality

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connects those two events in space and time, one is forced to accept action-at-distance in space and in time. Also, the energy conservation law would not be obeyed during the time between emission and absorption. At astronomical distances between places *A* and *B*, the timescale of missing energy could be as large as millions of years. Therefore, one must accept the photon as an object of physical reality. It is relevant to note that also in the classical view, as expressed in Maxwell's equation, there is a physical reality connecting the time and place of emission and absorption of electromagnetic radiation, namely the electromagnetic field.

The argumentation leading to evidence for the nontemporal character of a single photon is not trivial and requires a series of argumentations with side branches and direct and indirect proofs. Central in the discussion is a series of Gedanken experiments with single photons. In the case of linear optics, this is not a real restriction as there is, in that case, no interaction between photons. All experiments are repeated sufficiently to arrive at meaningful results so that statistical noise can be neglected. The photon source could be the spontaneous emission of a dilute cold gas producing photons with energy $E = h\nu_0$. The spread in frequency $\Delta\nu$ is only determined by the natural line width and is related to the lifetime τ_R of the excited state by the HUP (4), which reads in this case:

$$\Delta v \cdot \Delta t_R = 5/(4\pi) \tag{5}$$

The following ideal apparatuses can do the analysis of the photons:

i. the ideal high-speed photodetector with 100% quantum efficiency at all wavelengths of interest having a small detection area;
ii. the ideal, loss-less spectrometer, based on, e.g. a prism with *N* output channels;
iii. the ideal, loss-less Michelson interferometer with one of the mirrors placed on a translation stage to determine the coherence length.
iv. the ideal loss-less single-mode fiber with non-zero dispersion.

With this equipment, we start our first experimental analysis of the photon source. The spectrometer, together with a detector array, allows the determination of ν_o and $\Delta\nu$ of the photon source. In addition, by measuring the output intensity of the Michelson interferometer as a function of the translation of the interferometer mirror, the coherence length or coherence time $t_c = l_c/c$ of the photon source can be determined. The coherence time measured is related to a characteristic time scale of the photons arriving at the detector. In this specific experiment, the only relevant time scale for the photon is the

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photon's lifetime at the source τ_R. The experiment gives, therefore, $t_c \approx \tau_R$. One finds that Eq. (5) is fulfilled.

In the next Gedanken experiment, photons of the above-described source are passed through a spectrometer to separate in-space photons with different frequencies. Each photon is directed to one of the N output channels. Connecting each channel with a photodetector, the frequency ν_o and spread in frequency $\Delta\nu$ can be measured with the same result as in the first experiment. When the Michelson interferometer is used to measure the coherence length of the photons at any of the output channels of the spectrometer, one finds a much larger coherence length l_c' than in the first experiment. Putting an additional spectrometer at any of the output ports of the first spectrometer one can measure a much reduced spread in frequency $\Delta\nu$' and the Heisenberg uncertainty relation, Eq. (4), now becomes (with t_c' the new coherence time):

$$\Delta v' t_c' = 5/(4\pi) \tag{6}$$

The characteristic time scale of the photon has changed, as in addition to the lifetime of the source, an additional time uncertainty occurs in any spectrometer due to the uncertainty in the geometrical path length of the photon. This point is discussed in section 2.3 of[9]: *The role of the Heisenberg uncertainty principle in wavelength selecting structures.*

We can, therefore, conclude that the same source can, depending on the experiment, provide groups of photons with different intrinsic properties, namely a different coherence length and a different frequency spread. The question now is whether we are really dealing with different properties. Is it not possible that in the second experiment the photons are selected according to their frequency? Such a subgroup would automatically have a larger coherence length and reduced $\Delta\nu$. In the first experiment we could not detect the larger coherence length as the interference pattern at the output Michelson interferometer has been smeared out due to the spread in frequency. If this assumption were true, our photon source would emit individual monochromatic photons. The spread in frequency would only appear in a group of photons. In this picture, we could not observe the longer t_c' as each photon had its individual longer coherence length, which our measurement could not observe. This was because our statistical method always treated photons with a rather large spread in frequency $\Delta\nu$.

This assumption can be reduced to a hidden variable theory, as it ascribes precise but not measurable values to the single photon. Consequently, one has to give up the HUP for the individual photon. If the photon source would emit photons with each photon having a very low spread in frequency and consequently a large coherence time, then Eq. (5) is not fulfilled. Accepting quantum mechanics as a valid theory, the hidden variable approach has to be rejected.

Two other possibilities are left to explain that two different values for the coherence length can be obtained with photons from the same source. The first is that a spectrometer acts as a coherence length transformer. The alternative is that the properties of the photon emanating from the photon source depend on the circumstances the photon will encounter on its trajectory. We perform a third Gedanken experiment to gain deeper insight into these alternatives. Our light source is now directed to a single-mode fiber with a certain finite dispersion. The length of the fiber is chosen long enough so that the dispersion induced spread in transmission time Δt_{fiber} exceeds by far the source's lifetime, i.e. $\Delta t_{fiber} >> \tau_R$.

After transmission through the fiber, the photons are directed to a spectrometer, whose N output channels are each connected with a photodetector. Measurements like those in the second experiment are now performed. In addition, the time t_N between the excitation of the source and detection at the photodetector for all channels N is measured. Within the coherence length transformer picture, one would expect nearly the same $<t_N>$ for all N. In the other case one would see a spread in $<t_N>$ nearly equal to $\Delta t_{fiber}(\nu)$. Experimentally one finds that the photons of each channel N have their $t_{fiber}(\nu)$ in accordance with the fiber dispersion for a photon with frequency ν and the reduced spread in $\Delta\nu$. As a conclusion, there is no coherence length transformation. The photons entering the fiber already have a coherence length different from the bare source photons that are not connected to a spectrometer. This is in accordance with an everyday experience in linear optics: an optical filter (like the spectrometer) can be placed directly behind the source or just in front of the detector without changing the result.

Are we not contradicting our argument given above that the spectrometer is just distributing the photons that already had their individual long coherence length in space? We rejected that argument by claiming that the HUP should be fulfilled. The only explication could be that the HUP Eq. (4) does refer not only to principal uncertainties in time at the source but also to any part of the whole trajectory. The trajectory has to be considered as a whole. The photon has a unique and unchanged coherence length and energy uncertainty all over the trajectory from source to absorber. The values of these, however, are not determined by the source alone, but also by any part of the trajectory that introduces a principal time uncertainty. In the third Gedanken experiment, for example, the coherence length determining the duration of the photon transmission through the fiber also depended on the apparatus - the spectrometer - placed nearly at the end of the trajectory. The photons probe the presence of the spectrometer only in the last phase of the trajectory, the influence, however, is already present in the first phase of the trajectory. Therefore, with the observation of the Gedanken experiment that the photon trajectory depends on the basic photon properties, i.e. the coherence length and the spread in energy, one arrives at the conclusion that the transmission of a photon is connected to a non-temporal process.

After going through the branches of the argumentation, the conclusion becomes obvious: in the case of energy exchange by photons, non-temporal processes play a decisive role. In the special case that one considers photons as objects of reality, evidence is given that the coherence length is unchanged along the photon trajectory and is determined by the fundamental time uncertainty in the trajectory as a whole.

4. Aristotle's vision of movement

After the previous chapter's technical character, it is time to consider a suitable philosophical framework to make our results understandable. The proverbial weirdness of QM seems to be an appropriate qualification also for the properties of a photon. The question, however, is whether one should blame QM or, alternatively, the framework of the metalevel. In the 30s and 40s of the last century, Peter Hoenen evaluated QM in terms of the physics and metaphysics of Aristotle[17][18]. In a recent study, we have updated his vision and illustrated our approach with examples from modern physics, including a section on photons[1].

Aristotle's philosophy focuses on movement and change. The everyday experience of continuous change in nature strongly contradicted the logical conclusions of his predecessor, Parmenides, of an unchanging, eternal, and indivisible being. The atomists and their modern representatives, the mechanicists, try to solve the logical challenge of Parmenides by allowing a large or even infinite number of indivisible beings, the atoms. Change, however, is limited to the geometric rearrangement of these tiny particles. This framework may be appropriate for classical mechanics but not for QM.

Aristotle would know the ideas of Democritus about atoms and replaced the physical concepts of atoms and geometry with metaphysical concepts of matter and form, the hylomorphism. Simultaneously, he allowed a further subtlety: besides being and not being at all, there is potential being.

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Heisenberg explicitly considered this point[19]:

> The probability wave of Bohr, Kramers, Slater, however, meant more than that; it meant a tendency for something. It was a quantitative version of the old concept of ***potentia*** in Aristotelian philosophy. It introduced something standing in the middle between the idea of an event and the actual event, a strange kind of physical reality just in the middle between possibility and reality.

Let us focus again on the photon emitted at the initial point *A* and absorbed in the final point *B*. The central point of Aristotle's discussion on movement is a correct understanding of its nature: movement is a fluent continuum that has to be considered as a whole, a quantum. The question now arises as to whether this continuum has parts. Actually, there are no parts at all; otherwise, it would not be a continuum but an aggregate. Potentially, there may be parts, but this would depend on the movement's nature (in Greek, the physis). Known already in Greek antiquity, a lyre string, for example, allows only discrete steady states of movement. For the movement of a photon, the important question arises of whether there are natural minima. This a challenging question, as the trajectory of a classical object, like a stone, can be easily divided. The astonishing thing about the photon trajectory is the occurrence of a natural minimum. Like other phenomena in QM, the natural minimum is identical to the whole. The division is impossible without changing the movement's nature or the physics. The nature of the photon does not allow movement's division; see the previous section. It ended with the bold statement that basic properties like the coherence length remain unchanged along the photon's trajectory.

Above, we mentioned non-local and non-temporal processes involved in the interaction by photons. Within the Aristotelian framework we could clarify the striking weirdness of correlations of future events back to the present now. In Fig. 1, it would be the causal effect of an event in the future light cone directed to the now at the origin. In the classical world, we easily accept that the trajectory from city *A* to city *B* is only completely fixed after arrival at city *B*. There are so many unforeseen obstacles and events midway and even at the endpoint. Detailed knowledge about the trajectory is needed to assess its characteristics if the movement is a whole. In the classical world, however, any future intervention at point *C* between *A* and *B* does not change the trajectory from *A* to *C*.

In an Aristotelian approach, the situation is different. The movement from *A* to *B* can be stopped at *C*; one would say that the photon is absorbed at *C*. In the other case, the photon would continue, but its properties may be different, but also across the trajectory from *A* to *B*. The movement of a photon is not traceable, no *which way* information is possible without changing the movement itself.

It may be useful to confront the Aristotelian framework with calculations and experiments on optical microresonators[20][21]. These are circular waveguides with two attached waveguides that allow coupling from and to the resonator (see Fig. 2a. Let's consider the trajectory of a photon. It has a natural minimum, and the number of potential parts of the trajectory is exactly one. There is no intermediate point *C* between source *A* and detector *B*. Treating a photon classically as an electromagnetic wave, one avoids any quantum weirdness. In the time-dependent beam propagation method (TDBPM), based on Maxwell's equations[22], the potential trajectories of the photon can be accurately followed in time. The result of the calculation, however, gives only the probability that the photon reaches a certain point. For a large number of photons, this would give the intensity. Delayed choices and multiple path structures are no problems; as for the TDBPM, the calculation develops in time and always considers the actual time-dependent geometry.

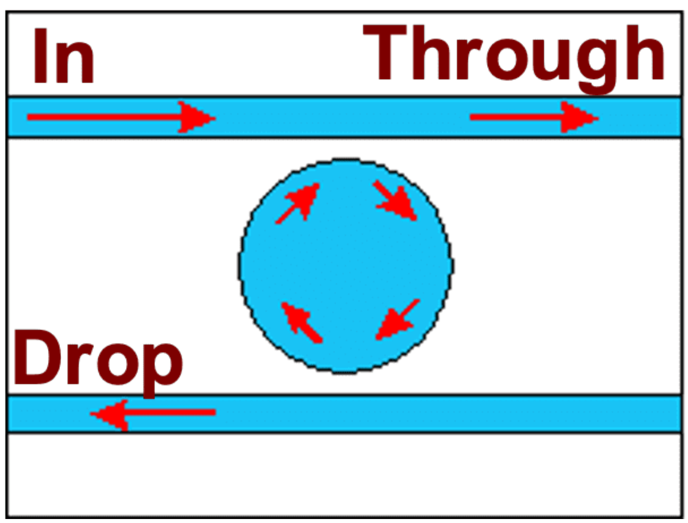

Figure 2a. Schematic view of an optical microresonator based on planar waveguides. It consists of a ring resonator and two adjacent single mode optical waveguides.

For illustration, Stoffer presents in Fig. 2b the evolution in time of the electromagnetic field of a light beam entering a microresonator. Like the wavefunction, the square of the electromagnetic field gives the normalized intensity, whereas the square of the wavefunction gives the probability of absorbing

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the photon at this position. With the aid of Maxwell's equations, one calculates the probability of reaching a certain point *B* at a given time. Looking at the two alternatives in Fig. 2b, one sees that the field develops in the beginning (in the first two timeframes) in the same way for the microresonator in-resonance or otherwise off-resonance. Only after the first roundtrip and multiple paths the difference becomes visible. When detecting after some time the photons at either the through or drop port, different spectra, and pulse forms can be measured, even when the same photon source is chosen, see[9] for a number of experimental results.

By way of illustration, Stoffer shows in Fig. 2b the time evolution of the electromagnetic field of a light beam entering a microresonator. The square of the electromagnetic field gives the normalized intensity, while the square of the wave function gives the probability of absorbing the photon at that position. Using Maxwell's equations, one can calculate the probability of reaching a given point *B* at a given time. Looking at the two alternatives in Fig. 2b, we can see that initially (the first two time periods) the field evolves in the same way whether the microresonator is in resonance or not. Only after the first roundtrip and multiple paths the difference becomes visible. If the photons are detected after some time either at the through port or at the drop port, different spectra and pulse shapes can be measured, even if the same photon source is chosen, see[9] for a number of experimental results.

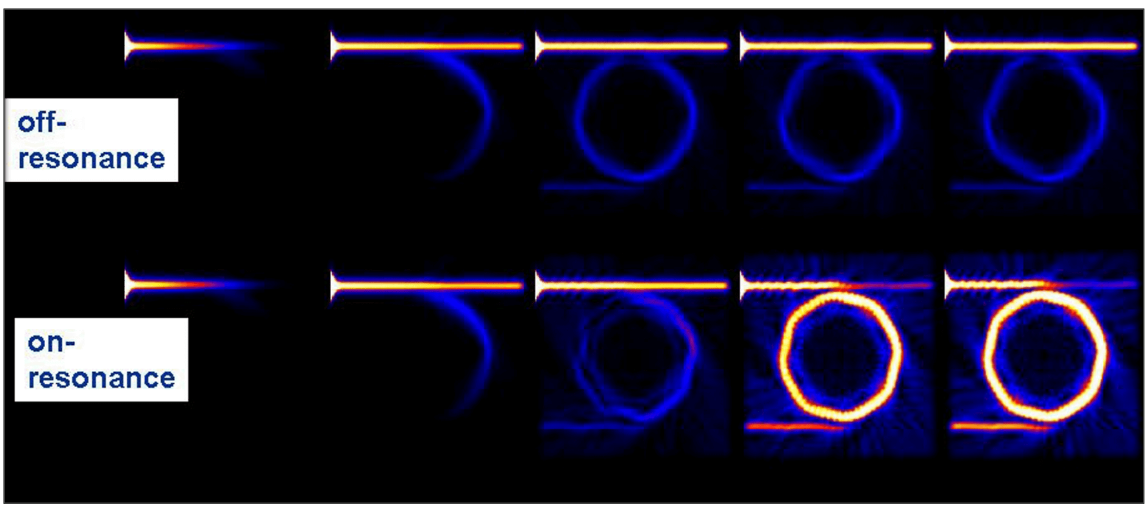

Figure 2b. Evolution of the numerical solution of the Helmholtz Equation for a microresonator being off- and on-resonance[22].

Now, an important observation can be made regarding a possible backward causality. The TDBPM calculation takes all the photon's potential trajectories into account. At point *B* no trajectories are changed, even in the case of a large number of roundtrips within the resonator. Only a selection of the potential endpoints within a certain time window is made. No law of nature determines which endpoint is eventually chosen; only the probability is according to Maxwell's Equations. Considering a single photon detected at point *B*, one can state that the actual probability of absorption for that point had been one, and simultaneously zero at all other points. That means that there are non-local correlations between the endpoints.

The phase and intensity of the electromagnetic field at point *B* at a given time are the result of calculations of the TDBPM, which needed a computer with high processing speed and large memory. In the quantum world, this information of the photon is present at point *B*. The detailed information about the photon in TDBPM is in the computer memory outside the time framework of the calculation. In the quantum world, this information is outside space and time.

5. Discussion

The conclusion about non-temporality in quantum processes is not new; Sommerfeld already stated in 1930[23]:

> *When I sometimes spoke about a new and conditioned causality, it was based mathematically on the fact that we had to calculate the radiation of an atom on the basis of a formula where the initial and final states were included equally and symmetrically. That means that in the case of radiation a foresight on the final state together with a memory of the initial state is present as a mathematical fact.*

What is new in the present contribution is the argumentation demonstrating that the influence of the final state applies to time-like intervals in photon trajectories. We also show that no backward causality is involved. The trajectory from *A* to *B* is a continuum with a natural minimum of parts that is exactly 1. The laws of nature consider all relevant circumstances at any point of the trajectory at the time the photon is passing. At point *B* and the final time t_f the photon is absorbed, and the trajectory is fixed. No changes were made in the past; the trajectory actualized was one among the many possible routes. The other possibilities are then discarded.

An experimental paper on quantum correlations with photons[16] concludes that the observed quantum correlations are *not only independent of the distance, but also it seems impossible to cast them in any real-time ordering*. This agrees with Sommerfeld's comment and our observation in the fiber Gedanken experiment that a change at the end of the photon trajectory also influences the part already completed. It is not difficult to work out delayed-choice Gedanken experiments where the detector arrangement is changed after the emission of the photon. For an experimental realization of such an experiment, see[24]. Even in that case, the new arrangement will not work as a "coherence length transformer," as the above-given argumentation of the "static" Gedanken experiments is still valid in the case of delayed choices.

Meanwhile, experiments confirm single photons' non-local and non-temporal behavior. Experiments by[8] and[9] with ps and fs pulses in microresonators and time-resolved detection indicate a difference in the resonator's response depending on a principle time uncertainty in the detector.

In conclusion, evidence is given that energy exchange by photons involves non-local and non-temporal processes. The evidence is only indirect but based on experimentally supported principles, like Heisenberg's uncertainty principle. The acceptance of non-temporality is not against any experimental fact. There is no backward causality. Instead, information about all possible trajectories remains available until the selection and consequent absorption at the final point *B*.

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