

Single photons cannot be extracted from the light of multi - atom light sources

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ABSTRACT

Throughout the development and confirmation of the photon concept, „Gedankenexperiments“ have been invoked where a light source is attenuated until „only one photon is in the apparatus“. Such a statement requires, however, knowledge on details of the light generation process, which were not known until the advent of true single - photon light sources such as isolated single atoms or molecules. Here, starting from a two atom light source, it is shown that probably multi - atom or multi - molecule light sources do not generate, even not in small fractions, antibunching photons and that attenuation down to one photon per time unit is not reliably possible. Thus, one of the strongest arguments in favour of the existence of single “photons” in free space, the accumulation time argument, which discusses the absorption of a single photon by a single atom or molecule, becomes questionable

KEYWORDS:

Light sources, energy quantum of light, photon, bunching, double slit experiment, Michelson experiment, entangled photons

INTRODUCTION

In the following text, the term photon will be used for an energy quantum $h\nu$, which is exchanged in interactions between light and matter. In contrast, when a non - dividable particle like light quantum is meant which freely travels in space, the term “photon” (in quotation marks) will be used.

In the development of the model of light essentially three effects and properties have been thought to make it necessary to invoke a particle aspect of light, i.e. to postulate a “photon”:

- i) The photo effect.
- ii) The Compton effect.
- iii) The accumulation time argument.

The first two arguments have turned out not to be sufficiently stringent to postulate the “photon”. The photo effect only shows the quantisation of energy exchange between light and matter¹. The Compton effect can be well described with wave packets. Finally, for the accumulation time argument it will be shown below, that it's experimental basis is missing.

One major reason for an over - interpretation of experiments in favour of a “photon” is the fact that, until recently, the process of light generation in multiatom light sources was not understood to sufficient detail. As will be shown below, multiatom light sources comprise all classes of light sources except single atoms or molecules.

Only with the advent of single atom or single molecule techniques, it has become possible to understand an important aspect of light emission. Below it is shown that it is extremely difficult to satisfy a mandatory prerequisite of many experiments, which were crucial in the formulation of the concept of the “photon”. It is not possible to generate isolated “photons” in a multiatom light source and to attenuate light from such a source with such an accuracy that exactly one “photon” is in the apparatus.

THE UNDERESTIMATED DETECTOR PROBLEM

In experiments addressing the nature of light the optical signal is converted into a free electron essentially by an atom or a group of atoms. Subsequently this tiny signal is converted into a detectable signal either by a photographic process or by electron amplification with a sort of photo-multiplier. The fastest detectors have a time resolution of 70 ns^2 , i.e. they are a factor of 50 000 000 slower than two photons in a wave - train can follow each other. Thus, when a detector is claimed to be a “single photon” detector, this means that it can register light down to one $h\nu$ quantum. It does, however, not mean that one “click” in the detector means that exactly one photon is counted. Millions of additional photons may fall on the detector until it is able to really count the next one. In that sense, Richard Feynman’s statement : *“We know that light is made of particles because we can take a very sensitive instrument that makes clicks when light shines on it “*³ and similar statements on clicks in a photo - detector in connection with “photons” do not completely reflect the experimental situation.

DETECTORS AS A TECHNICAL SOURCE OF WAVE - PARTICLE DUALITY

The following arguments make it plausible that our impression of a wave – particle duality of light may have a technical origin rather than being a basic physical phenomenon. In order to trigger a detector, not only the energy must be sufficiently high, but also the energy density. If the energy density of a detector is much higher than that of the corresponding photon, a large number of photons need to co-operate in order to trigger the detector. This is perceived as wave like behaviour. If the energy density of a detector is much smaller, a single photon can trigger the detector. This is perceived as particle like behaviour. The energy density of a photon at a given wavelength is, over the whole electromagnetic spectrum, $hc / (\lambda * \text{volume})$. Due to the Heisenberg uncertainty principle, the photon, independent whether it is described as a wave packet or a point like particle, needs a space with linear dimensions of λ . Thus, its energy density is proportional to λ^{-4} .

Determining the energy density of a detector is somewhat difficult, since that would require a very detailed knowledge on the detection process. For the following consideration, however, only a very crude knowledge on the order of magnitude is required. The detector may be an atom, for example a hydrogen atom. Since we know the energy and the radius of the first excited state ($n = 2$) of hydrogen, the calculation is straightforward (see fig.1). Other detectors may be solid state devices where a few eV have to be deposited in a volume of the order of the wavelength. Fig. 1 illustrates these energy densities:

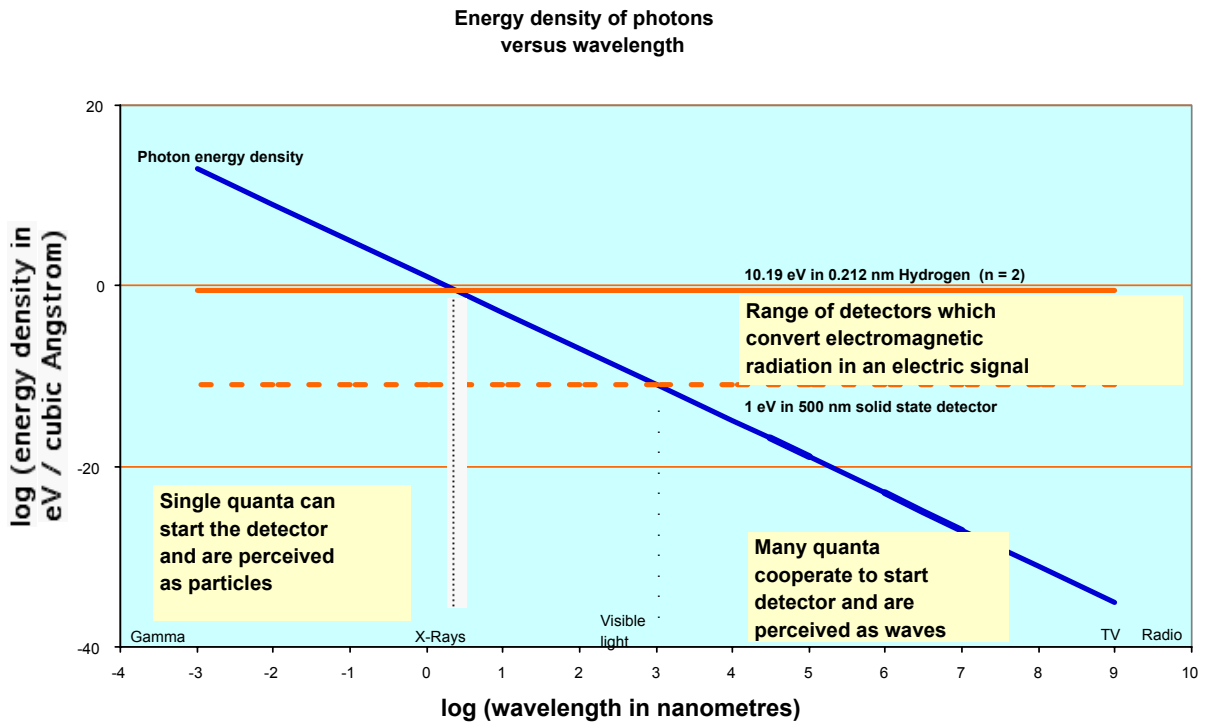


Fig 1: Double logarithmic plot of the energy density of photons at different wavelengths. The slope of the line is - 4. The solid horizontal line represents approximately the upper limit of energy densities available in single atoms (here for the example of the hydrogen atom). The broken horizontal line represents the lower limit of energy densities in solid state detectors. The error in the lower limit may be one order of magnitude, depending on the detailed mechanism of function of this type of detectors.

The figure shows that the energy densities starting from X rays towards shorter wavelengths for photons are higher than those of the detectors. Thus, one perceives this electromagnetic radiation as particle - like. Above the visible range towards longer wavelengths, the photon energy densities are small, i.e. this range of electromagnetic radiation is perceived as wave - like. Between approximately the X ray and the visible regime it depends on the type and on functional details of the detector, whether the radiation is perceived as particle - like or as wave - like. Thus, it is not the property of the radiation, but the ratio of energy densities, which cause a sort of wave - particle duality. Note that this argument nicely explains the transition from particle like electromagnetic radiation in the range of gamma radiation to the wave like electromagnetic radiation in the range of radio waves. Invoking a particle like “photon” solely for the short to optical range cannot explain this transition and thus contradicts the well accepted view resulting from the Maxwell equations that electromagnetic radiation has the same physical basis over all wavelengths.

SINGLE ATOM / MOLECULE LIGHT SOURCES: ANTIBUNCHING LIGHT

If a spatially isolated atom or molecule is excited and subsequently emits light, for energetic reasons this will be one energy quantum $h\nu$, where ν is a characteristic frequency of the emitting atom or molecule. It is easily conceivable that this light is antibunching, since after the atom has emitted a photon, it takes some time until it can re-absorb and emit a further one. This has been confirmed experimentally^{4,5,6} and for a plethora of single photon light sources^{7,8}. One should, however, keep one important experimental detail in mind: antibunching is usually measured with a time resolution of nanoseconds. The femtosecond bunching of photons in a wavetrain cannot be seen directly. It is tacitly assumed that, when bunching is seen on the nanosecond time scale, this is a hallmark of bunching on the femtosecond time scale.

Apart from this energetic aspect, surprisingly little is known on details of light absorption and emission by single atoms or molecules. Particularly, the internal structure of such a photon has so far escaped experimental tests. An attempt has been made to characterize theoretically this “birth of a photon”^{9,10}. However, so far, no suitable experiment is available to clarify, whether such a single photon i) remains point like, ii) finally adopts a limited volume or iii) is diluted out over large travelling distances. All experiments where single photons have been detected after their birth from single atoms or molecules have so far done this with a detector distance of a few tens of centimeters. This is short enough to re-gather the whole photon energy in a typical detector, even if it is already diluted out to some extent. At least one feature of such single photons originating from single emitters is known: They are able to interfere¹¹.

THE ACCUMULATION TIME ARGUMENT IS INVALID

The accumulation time argument postulates that, if the photon were significantly extended in space, the time for a single atom or molecule were too short to accumulate a whole energy quantum $h\nu$ during the flyby along a single atom or molecule (see for example¹). This theoretical reasoning is correct. However, the required experiment has so far remained a “Gedankenexperiment”. Presently, only two types of experiment with single atoms or molecules are really possible: The absorption of a single photon by a solid state (multiatom) detector. Alternatively, a single atom or molecule can be excited in a multiphoton field of light. In the latter case, cw fields of the order of 10 mW or pulses of nJ / fs or $\mu\text{J} / \text{ns}$, i.e. with peak intensities of kW are required. That means that in any practical experiment a very large number of photons are simultaneously available to excite a single atom or molecule. Until the unambiguous proof, that a single isolated atom or molecule can be excited by a single, isolated photon, the accumulation time argument cannot be invoked to postulate a “photon” and is thus, for the time being, obsolete.

BUNCHING IN A TWO - MOLECULE LIGHT SOURCE

In order to understand, how a multi atom / molecule light source works, it is useful first to have a look on a two - emitter light source. Such data have recently become available, although the corresponding experiments have been performed for other purposes¹². Two terrylene molecules are embedded in a para - terphenyl crystal at a distance of 12 nm. Due to slight differences in their microenvironment their excited state occupation probabilities and the resulting fluorescence peaks are slightly different (approx. 3 GHz), so that the excitation source could be tuned to generate fluorescence either from molecule 1 or from molecule 2. After tuning for molecule 1, it behaves like an isolated single molecule, i.e. it emits anti-bunching light as expected. Correspondingly, molecule 2 behaves “correctly”. However, the optical properties of this molecule - pair are not just the sum of each of the parts, but reveal a cross peak at half the wavelength between the absorption peaks of the individual molecules. If the excitation source is tuned to this cross - peak, a surprising effect occurs: the emitted light is bunching ! Bunching and the existence of a cross - peak indicate, that both molecules co - operate and do no longer emit strictly anti-bunching light. This result was explained via dipole - dipole coupling¹² and was essentially confirmed in a completely different type of experiment¹³.

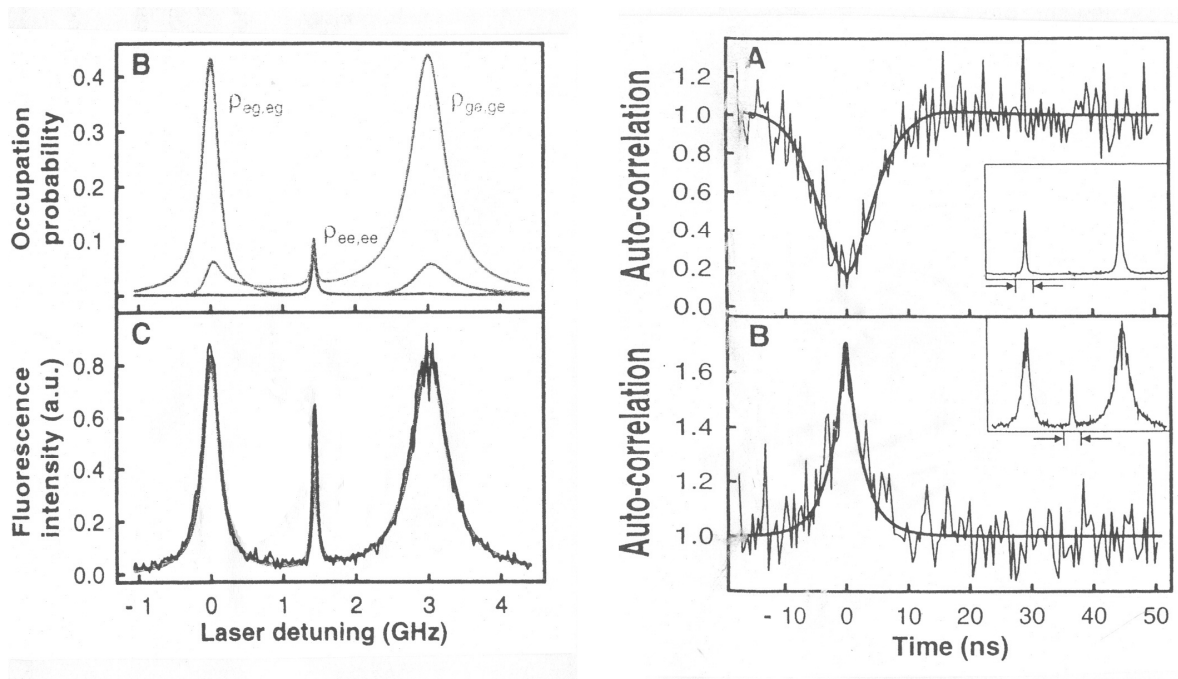


Fig.2 (Reproduced from Hettich et al 2002 , Ref 12):

Left panel: B: Occupation probability and C: fluorescence intensity at slight de-tuning of a laser source for two emitters at a distance of 12 nm.

Right panel: A: Antibunching when the laser is tuned either to molecule 1 or to molecule 2. B: Bunching when it is tuned to the cross peak.

MULTIATOM LIGHT SOURCES

In any multiatom light source, the average distance between single emitters is much smaller than 12 nm: in solid state sources almost two orders of magnitude, and even in a 1 atmospheric gas source this distance is of the order of 1 - 2 nm. Thus it is impossible to generate isolated, non co - operating photons from such a source. The following estimate shows that the number of co - operating photons is very large: In a classical light source, at least a volume with linear dimensions of half a micrometer needs to co - operate. Otherwise the spatial coherence would not be sufficient to generate interference in classical experiments such as Young's double slit experiment or the Michelson interferometer. In a solid state light source such as the wire of a light bulb, this means that at least 10^{11} - 10^{12} atoms co - operate to generate the light, in a 1 atmospheric gas light source this number is of the

order of at least $10^7 - 10^8$ atoms.

THE POSSIBLE EMISSION PATTERNS OF A MULTIATOM LIGHT SOURCE

As mentioned in the chapter on detectors, one has to regard time windows of at least 70 ns (or longer) as one time unit. Also, for a single photon, independent of describing it as a particle or as a sort wave-packet, it is mandatory that it exactly carries one energy quantum $h\nu$ within an optical cycle of approx. 1.5 fs. If, within the 70 ns interval many (starting from 2) photons are emitted, essentially three emission patterns are possible:

- a) The $h\nu$ quanta follow immediately each other. This is essentially already a short wave – train with some degree of temporal coherence.
- b) The $h\nu$ quanta are separated from each other. The process will be statistical, i.e. these quanta cannot interfere, except if one invokes a guiding wave which organises this emission. Invoking such a wave means however to secretly come back to the classical wave picture. This step is solely necessary to save the “photon”. When approaching this point more open minded, a classical wave interpretation cannot be experimentally distinguished from the guiding - wave model. As a consequence, a pure wave description is at least equally adequate.
- c) More than one $h\nu$ quantum can be emitted within one optical cycle. The quanta can be split at a beam splitter, mirror or slit to travel two different paths. Any interference in that case is purely textbook interference in the sense of the classical Young or Michelson interpretation.

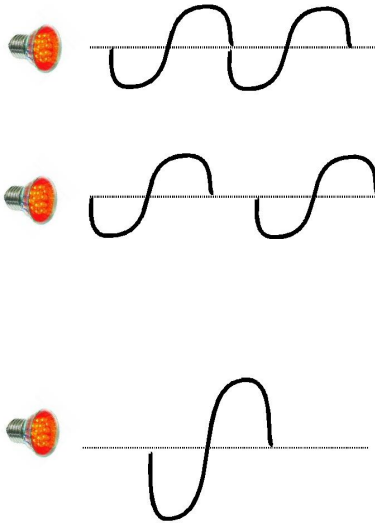


Fig 3: Emission patterns from a multiatom light source: In the upper two cases, the energy is $1 h\nu$ per optical cycle (approx. 1,5 fs). Attenuation can probably only occur via removing a whole wave – train. Shortening a wave-train is improbable since that would have an effect of attenuation on temporal coherence, which has so far not yet been observed. In the lower panel the energy per optical cycle is an integer multiple of $h\nu$. This can be probably attenuated by reducing the number of quanta per optical cycle and can be split at a beam splitter or directed into different paths in a double slit or Michelson experiment. An experiment based on the lower scheme is completely classical, since always more than one photon is available.

WHY GAMMA SOURCES APPEAR TO EMIT „PHOTONS“ BUT RADIO ANTENNA DO NOT

For an estimate on a reasonable distance, over which dipole - dipole interaction occurs, the Foerster theory states that dipole - dipole coupling occurs over a distance of R_0

$$R_0 = 8.79 * 10^{-5} * (k^2 * n^{-4} * f_D * \int e_A(\lambda) * f_D(\lambda) * \lambda^4 d\lambda)^{1/6}$$

where k describes the mutual orientations of the dipole vectors of the two molecules coupling by dipole - dipole interaction, n is the index of refraction of the environment and the integral is the overlap of the emission spectrum of the donor molecule which acts as sender and the absorption spectrum of the acceptor molecule which acts as receiver. Note that with the crude assumption of a rectangular excitation peak $e_A(\lambda)$ and fluorescence peak $f_D(\lambda)$ the integral becomes proportional to $\lambda^{5/6}$, or approximately proportional to λ .

This relationship is known as Foerster resonance energy transfer (FRET) and is often used in biological microscopy for measuring distances between fluorescence - labelled molecules in biological cells. The typical distances are of the order of 10 nm, indicating that the aforementioned assumption of dipole - dipole coupling in the two molecule light source is correct. At otherwise identical conditions is

$$R_0 \text{ proportional to } \lambda$$

Thus, for small wavelengths R_0 becomes smaller than the atom to atom distance in a solid state emitter such as a piece of radioactive material. As a consequence, no dipole - dipole coupling is possible and all emitters behave as if they were isolated. For this reason, in addition to the detector aspect discussed in fig. 1, radioactivity is antibunching and appears to be particle - like. In contrast, for radio antenna the Foerster distance is always larger than any atom - atom distance and thus dipole - dipole coupling and co - operation of emitters is unavoidable.

THE STATISTICAL IMPOSSIBILITY OF ATTENUATION OF A MULTIATOM LIGHT SOURCE TO ONE “PHOTON”

Even if the large number of photons generated in a suitable volume of a multiatom light source were independent of each other, a purely statistical argument would make it almost impossible to retrieve single “photons” with sufficient accuracy. As mentioned above, even a micrometer sized multiatom source would generate millions of “photons” per 70 ns, which has already above been discussed as the measuring time unit for fast photo - detectors. This number has to be reliably reduced to exactly one photon in order to allow experiments as they are postulated in “Gedankenexperiments”, which have led to the “photon” concept of light. Any claim on such a precise attenuator needs to be proven in detailed experiments. Until such a proof is given, a Gaussian statistics for the attenuation process has to be assumed. This means that the error is of the order of 1000 - 10 000 “photons” per 70 ns, far away from 1 photon, as it is assumed in the corresponding “Gedankenexperiments”.

THE DOUBLE SLIT EXPERIMENT WITH SINGLE PHOTONS REMAINS A “GEDANKENEXPERIMENT”

In quantum mechanics the Young double slit experiment is often used to explain the concept of probability amplitude. For that reason it is argued that, if a light source is attenuated so far that precisely one “photon” is in the apparatus, one still would see interference. Even the early discussions between Bohr and Einstein were based on such an assumption. However, with the impossibility to extract single photons from a multiatom light source,

these experiments have remained “Gedankenexperiments”. With the advent of single photon light sources, it has at least in principle become possible to perform such an experiment.

THE INTERPRETATION OF EXPERIMENTS ON ENTANGLEMENT IS QUESTIONABLE

In experiments on quantum encryption, entanglement and quantum information transfer it is crucial that one deals with one single quantum state. This requires that such a quantum state can be prepared and that it can be detected, Both is questionable. As long as entangled states are prepared with multiatom regions of an extended source there are similar problems as for the single – photon - double slit experiment. More seriously, in order to interpret coincidences of the two parts of an entangled pair as quantum information transfer, the two detectors would need a temporal accuracy of 1 - 2 fs, which have to be synchronised within this accuracy. This is far from any experimental reality.

DISCUSSION

The present discussion has given a number of arguments against particle like “photons” and thus against a wave - particle dualism of light. Each of them raises doubts on the existence of ”photons” and in combination they all together make it almost impossible that such “photons” are needed to understand light.

In conclusion, there is presently no need to invoke a particle like “photon”. A pure wave description of light is completely adequate. Even the antibunching light of a single emitter can be described as a sort of spatially extended wave packet and needs no non – dividable particle like “photon”. Thus, the wave – particle dualism of light appears to be a technical dualism of light sources and their relationship to their detectors, not a physical principle. Only when new arguments in favour of a particle like “photon” emerge, the discussion will have to be resumed, Then, however, it will be equally necessary as for the arguments above to check down to the last detail, whether the experimental basis for such an argument is really given.

NOTE ADDED IN PROOF:

Once the need for a highly localized particle - like photon has become less stringent, it is possible to formulate a photon model with a spatially extended photon. A final photon model will probably be represented as a three dimensional wave similar to the hydrogen atom, i.e. as the solution of a sort of Schrödinger equation. In analogy to the development of the Schrödinger equation, one may, as a preliminary step towards reaching that goal, formulate a semi - classical model which quantitatively predicts a few properties of the photon.

Such a model may be a self similar and self driving LC oscillator, consisting of a capacitor with cross section $F = r^2 \pi$ and a length $d = 2\pi r$, and a coil with one turn with the same cross section ($A = F$) and the same length $l = 2\pi r$ per turn.

The capacity is $C = \epsilon_0 F / d = \epsilon_0 r$ The inductivity is $L = \mu_0 A / l = \mu_0 r$

The frequency of this oscillator is

$$f = 1 / 2 \pi \sqrt{LC} = 1 / 2 \pi \sqrt{\epsilon_0 r \mu_0 r} = 1 / 2 \pi \sqrt{\epsilon_0 \mu_0} r = c / 2 \pi r \quad (\text{using } c = 1 / \sqrt{\epsilon_0 \mu_0})$$

Note that so far the only assumption was self - similarity. One can achieve any wanted oscillation frequency by just varying the radius (and because of $d = l = 2\pi r$ the length) of the capacitor and the coil.

In order to describe light with the wavelength λ , $f = c / \lambda$ needs to be satisfied. From this it follows that the self - similar LC oscillator, which describes light, needs to have the linear dimension

$$r = \lambda / 2 \pi$$

i.e. we have derived the transversal spatial dimensions of a photon.

For such an LC oscillator, at a given time, all energy is in the coil. The speed of the current is

$$v = 2 \pi r f = 2 \pi (\lambda / 2 \pi) (c / \lambda) = c$$

This can now be used to calculate the spin of the photon as the angular momentum M of the relativistic mass $m_{\text{photon}} = h / (c * \lambda)$ of the photon from its (longitudinal) wavelength,

$$M = m_{\text{photon}} * r * v = h / (c * \lambda) * (\lambda / 2 \pi) * c = h / 2 \pi$$

i.e. the angular momentum can be calculated as $1 * (h / 2 \pi)$, i.e. the origin of the spin 1 of the photon becomes immediately clear.

In conclusion, modelling the photon as a self - similar LC oscillator results in linear transversal dimensions, which are reflected by its wavelength and a wavelength independent spin 1, in spite of the fact that a priori an angular momentum is dependent on spatial dimensions. Assuming an LC oscillator requires that some charged matter is oscillating in a spatially self - confining, self - propelling manner. Describing a photon as a cloud of such matter may appear, at a first glance, to be very speculative. However, it is in full agreement with the Maxwell equations, which imply that any electric field can only be generated by a true physical charge and a magnetic field by a true physical current.

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