Lamps, lasers and detectors - Misconceptions in the interpretation of classical experiments on light

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The edifice of quantum mechanics (of quantum objects travelling freely in space) is not based on physical reality

A popular statement (starting from the classical discussions between Einstein and Bohr via Feynman to very recent textbooks on quantum mechanics) **is:**

If one attenuates the light impinging on the beam splitter, double slit, Mach Zehnder or Michelson interferometer so far **that only one photon** (particle) **is in the apparatus we still see interference** (waves)

This talk will show, on the basis of recent single molecule experiments that this assumption does not reflect physical reality !

Several slides below will reproduce a discussion with an influential main stream physicist There, all the classical and „well accepted" experiments are defended, which have led to the edifice of wave particle dualism

The statistical impossibility of attenuating a multiatom light source to one photon

Even a micrometer sized multiatom source would generate millions of ”photons” per 70 ns, the measuring cycle for fast photo - detectors.

This has to be reliably reduced to exactly one photon

Any claim on such a precise attenuator needs to be proven in detailed experiments.

Probably, attenuators act by removing, not shortening, wavetrains (since attenuators do not change the coherence length of the light). Thus, even highly diluted light comes in a femtosecond - bunched version.

- *** *
- *** are not attenuated to * but ***
- *** *

The photon is fundamentally a quantum mechanical object, and any model that fails to take this into account is very badly flawed. There is a huge body of research in quantum optics that demonstrates this (the mainstream physicist)

Essentially all of this "huge body" are experiments with multi atom light sources where a single photon situation is assumed

In such experiments either
cw light sources with approx.10 mW (10^{16} photons / sec or 10^{7} photons / nsec)
or pulsed lasers with kilowatt peak powers (probably saturation of the emitters)

are focused into a volume of at the very **least (1 µm)^3 = 10^9 emitters**
(probably even a few orders of magnitude more in a one atmospheric gas source. In solid state sources the number of emitters is even higher).

The physical reality is, that millions of photons, not just a few which might finally be attenuated to one, **are emitted within a physically realistic** (see later) **time interval**

Its not a nobody, who doubts the validity of these classical and „well accepted“ experiments - its the Aspect / Grangier group, who have published these experiments earlier

There is a long history of papers, which were optimistic to give the ultimate information on single photon experiments just to be invalidated by later papers.

1986: none (of the earlier papers) have been performed with single photon states of light (Grangier et al in Europhys Lett 1986)

2007: none of the experiments fully followed the original scheme, which required the use of the single particle quantum state....J

Jacques et al, 2007 Science 315, 966 968, - the Grangier / Aspect group.

Neither light generation nor photon detection is described with sufficient detail to really estimate how many photons are passing the apparatus during one measuring cycle of the detector (see later).

What have we learned so far

Classical and “well accepted” experiments or lines of arguing, including those of the Bohr / Einstein discussion, those of Feynman and those of the Grangier / Aspect group are obsolete.

Experiments with many photon states have been interpreted as if they were performeded with single photon states

The next step

Only with true single photon states the conclusions can be drawn which led to the edifice of wave parrticle dualism and to models of light

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 hn,**

- **. 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.**

- **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.**

Preparing single photon states is even more difficult than originally thought: even two single molecules emit bunches

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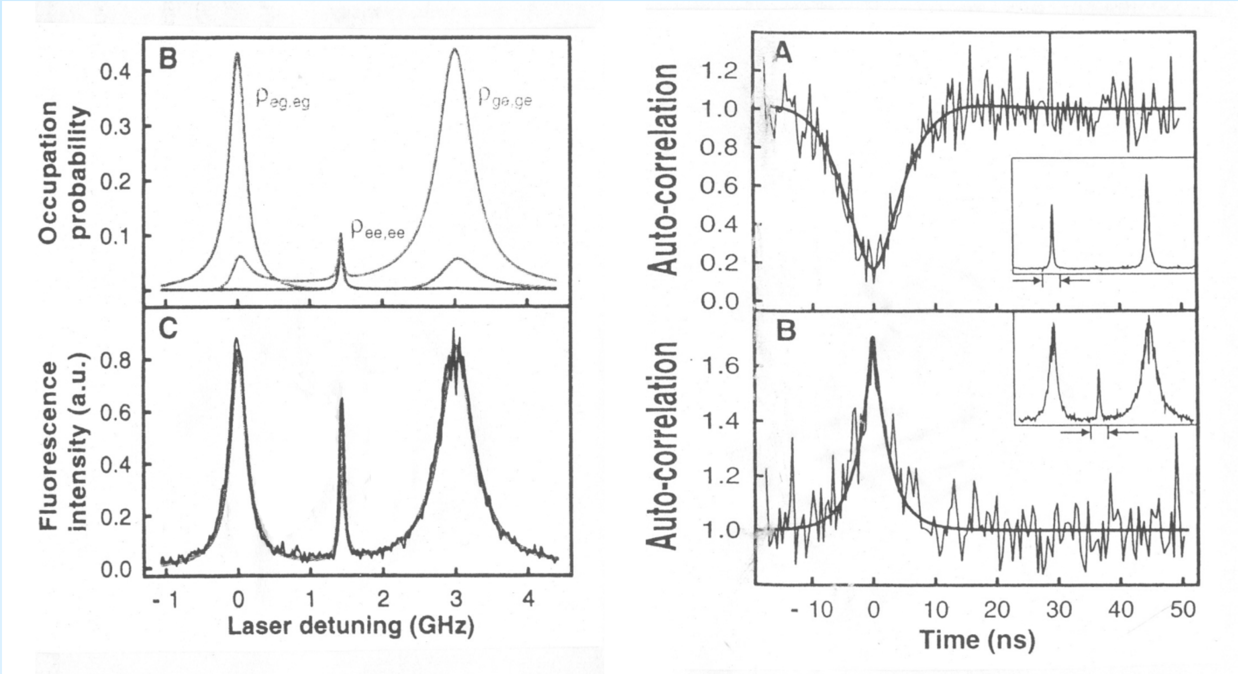
but

Two terrylene molecules embedded in a para - terphenyl crystal at a distance of 12 nm reveal first signs of bunching.



If two atoms or molecules as distant as 12 nm are excited at once, they reveal already a cooperative spectral signature and their photons bunch.

C.Hettich, C.Schmitt, J.Zitzmann, S.Kühn, I.Gerhardt, V.Sandoghdar. Nanometer resolution and coherent dipole optical coupling of two individual molecules 2002 Science 298, 385 - 389)

Two photons in a cavity bunch

M.Hennrich, A.Kuhn, G.Rempe Transition from antibunching to bunching in a cavity 2005 Phys.Rev.Lett 94, 053604

Multi - atom / molecule sources have linear dimensions of at least 0.5 μm and interatom distances of 1.5 nm (gas at 1 atm) or less (solid body). This means that billions of atoms / molecules co - operate in light generation

Micro coherence in any multi – atom light source

The average distance of two atoms in a 1 atm gas light source is approx. 1.5 nm.

At no circumstance, such a light source behaves like a single atom source. It does not emit isolated photons.

Single atom or molecule light sources emit one hv portion / photon at a time, up to every 10 ns a new one.

The volume of origin has a linear dimension of an Angstrom. Assuming a plane wave A = Ao * exp(ikx – ωt) is not adequate. The "birth" of a photon is a complex process see for example O.Keller Single Molecules (2002) 3, 5 - 18

Multi – atom light sources emit cooperatively a large number of photons a given time.

The volume of origin has a linear dimension of a few hundred nanometres (see next slide) or of the order of a million atoms in a gas source of atmospheric pressure. Assuming a plane wave is adequate.

A quantitative description of dipole dipole coupling

- The distance, over which dipole - dipole interaction occurs is given by the Foerster theory

- $R_o = 8.79 * 10^{-5} * k^2 * n^{-4} * f_D * \int e_A(\lambda) * f_D(\lambda) * \lambda^4 d\lambda)^{1/6}$
  - = for our purposes const * overlap integral $^{1/6}$
  -

- $e_A(\lambda)$ and $f_D(\lambda)$ are by their nature an emission and an absorption peak, for our purposes almost identical and can be approximated by rectangular peaks

- Then the integral becomes proportional to $\lambda^{5/6}$, or approximately proportional to λ.

-

Why Gamma sources appear to emit particles, radio antenna waves and optical sources reveal wave - particle dualism

From the equation of the previous slide fit ollowed

At otherwise identical conditions the Foerster distance is

R_o approximately proportional to λ

Small λ — **R_o << atom to atom distance**

No dipole – dipole coupling in a solid state emitter such as a piece of radioactive material. All emitters behave as if they were isolated,
radioactivity is appears to be particle - like.

Large λ — **R_o >> atom - atom distance**

dipole – dipole coupling over large distances,
cooperation of essentially all emitters

Radio radiation appears as wave like

Optical λ — **Foerster distance approx atom - atom distance**

"Dual" situation

Two (many) photons can be emitted one after each other or one upon the other

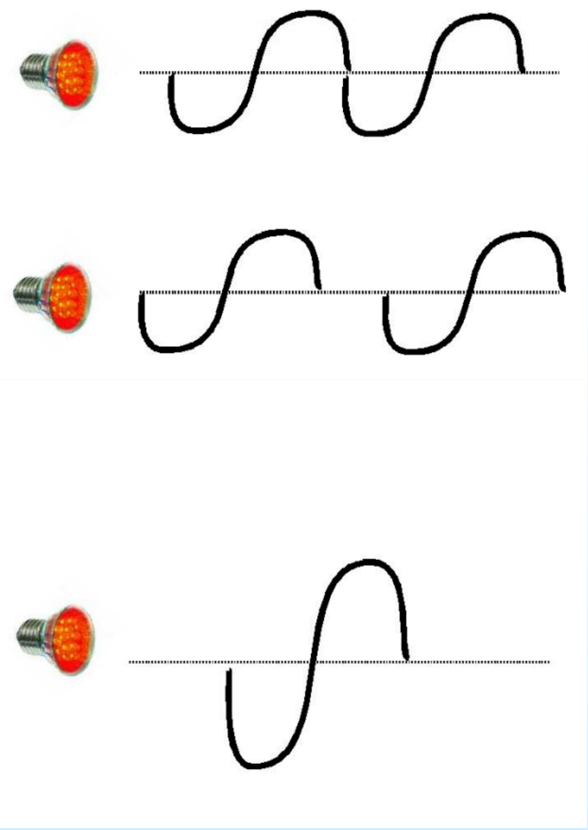


Fig 3: Emission patterns from a multiatom light source: In the upper two cases, the energy is 1 hν per optical cycle (approx. 1,5 fs). Attenuation can probably only occur via removing a whole wave – train. Shortening a wave-train is improbable since that would have an effect of attenuation on temporal coherence, which has so far not yet been observed. In the lower panel the energy per optical cycle is an integer multiple of hν. 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.

Only experiments with true single photon emitters can provide experimental information on the behaviour of single photons

Single atoms and molecules are single photon emitters

Only very recently (in principle after 1990, practically after 2002 ... 2004) it became possible to perform experiments using true single photon sources

perhaps also quantum dots or colour centres in a solid state body,

it has to be thoroughly proven that they really emit individual photons and not photon bunches

The 2007 experiment of the Aspect / Grangier group uses colour centres in a solid state body as single photon source to perform "Wheelers delayed choice experiment", essentially a beam splitter / double slit experiment (Jacques et al, 2007 Science 315, 966 968, - the Grangier / Aspect group).

They are cautious enough to speak of "single photon pulses" and not of "single photons"

This experiment will be discussed in more depth during the talk on the photon

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Experiments with many photon states have been interpreted as if they were performeded with single photon states

Microcoherence makes it even more difficult to isolate single photons from any light source. Even quantum dots or color centers in a solid state body may not be suitable. Only with true single atoms or molecules one is on the safe side.

The next step

Detectors are even less understood than the light sources and may be another reason for our perception of wave paricle duality

DETECTORS AS A TECHNICAL SOURCE OF WAVE - PARTICLE DUALITY

- **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).**

- **Other detectors may be solid state devices where a few eV have to be deposited in a volume of the order of the wavelength. The figure in the next slide illustrates these energy densities:**

THE UNDERESTIMATED DETECTOR PROBLEM

- **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 (1.5 fs). Thus, when a detector is claimed to be a ”single photon” detector, this means that it can register light down to one hv quantum. It does, however, not mean that one ”click” in the detector means that exactly one photon is counted.**

- **Many 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 reflect experimental reality.**

An estimate on the energy density of a photon

In order to trigger a detector, not only the energy must be sufficiently high, but also the energy density.

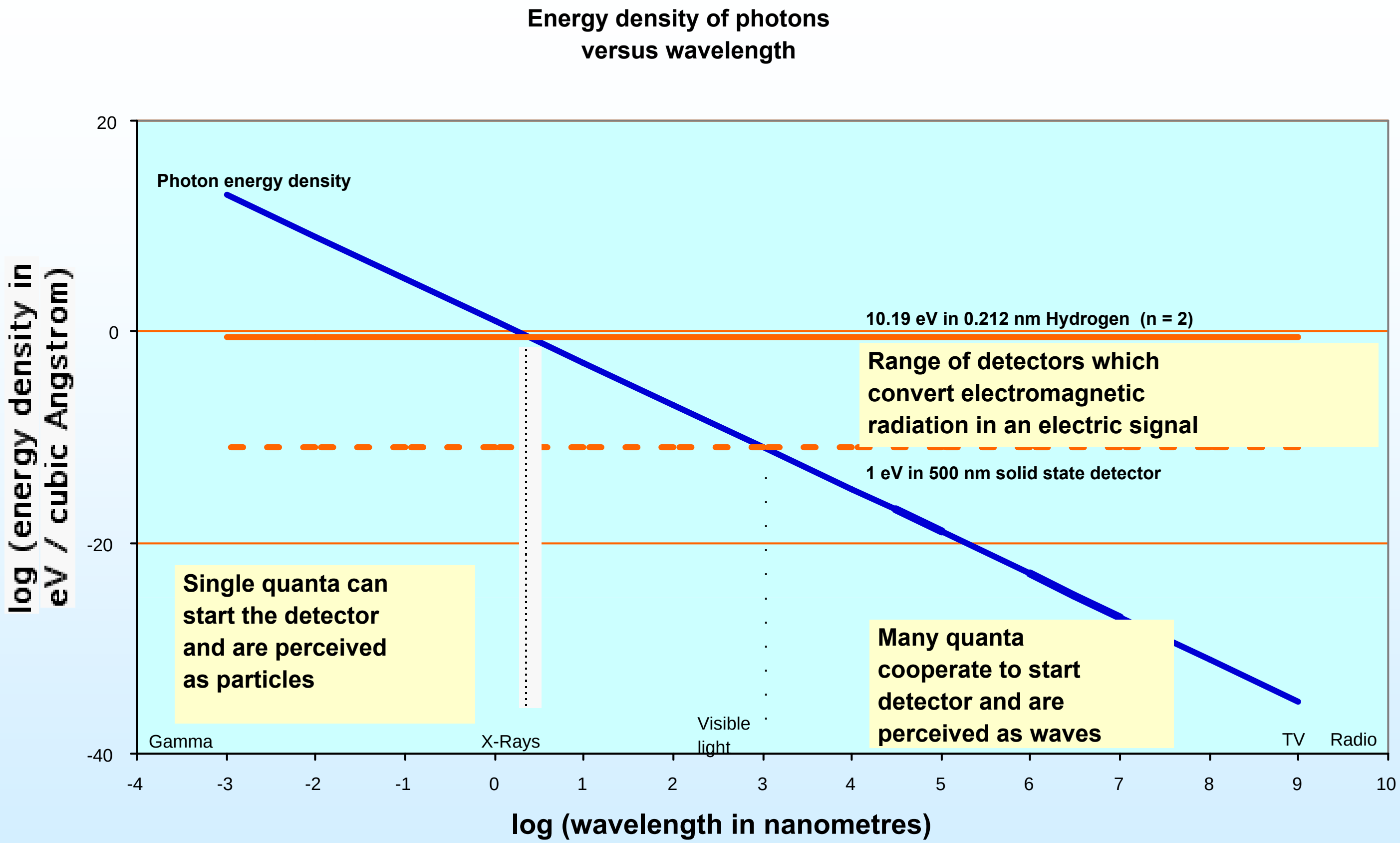
If the energy density of a detector is much higher than that of the corresponding photon, a large number of photons need to co-operate in order to trigger the detector. This is perceived as wave like behaviour.
If the energy density of a detector is much smaller, a single photon can trigger the detector. This is perceived as particle like behaviour.

The energy density of a photon at a given wavelength is, over the whole electromagnetic spectrum, hc / (λ * 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, the energy density of a photon is proportional to λ^{-4}.

Wave or particle - Is it just the detector ?

Solid horizontal line: upper limit of energy densities available in single atoms.
Broken horizontal line: lower limit of energy densities in solid state detectors.
Error in lower limit : one order of magnitude, depending on the detailed mechanism of detector type



This nicely explains the transition from gamma radiation (particle like) to radio waves.

Invoking a particle like ”photon” solely for the short optical range cannot explain this transition

and thus contradicts the view that electromagnetic radiation has the same physical basis over all wavelengths.

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Detectors may cause a technical wave particle duality

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- 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.

A single photon ..... has a definite spin, and thus a definite polarization. How, then, can a pair of correlated photons violate Bell's inequality
(for example, Ou and Mandel, Phys. Rev. Lett. 61 (1988) 50; Tittel et al., Phys. Rev. Lett. 81 (1998) 3563
(the mainstream phycisist)

- **EPR experiments or tests of Bells inequality definitely require photon pairs which comprise a quantum system.**

- **If in such an experiment only two atoms are excited within one detection cycle of the used detector (i.e. if on each side of the experiments two photons arrive within one detection cycle) the probability is 1 / 2, that the two detected photons are not representing a quantum system. With millions of photons this probability is close to zero.**

- **Thus, the validity of Bells inequality has not yet really been shown for single photon pairs.**

Summary

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