Light on the Models of Photon and Electromagnetic Wave

Herbert Weidner[A]

Abstract: The idea that electromagnetic radiation is a stream of punctiform "photons" proves to be a well-suited model at wavelengths below a few nanometers. This picture is worthless at wavelengths beyond a few millimeters, because only the wave model can explain the observations. The question of how to imagine the generation of a photon is discussed using examples from the metrologically easily accessible radio area.

Introduction

Physics is based on an interplay of observations and theory. The observations do not resemble the notes in a diary, they rather record the results of targeted experiments. As a rule, a special experimental setup is made in order to reduce disturbing influences and to focus on the desired effect. The task of the theory is to work out coherent and consistent principles from a large number of similar observations and to provide *at least* one verifiable prediction. All conclusions must be checked by further experiments.

The most famous example is associated with the name Maxwell. This genius was able to summarize the results of numerous experiments in the field of electricity and magnetism in only four differential equations and predict the existence of electromagnetic waves. His highly surprising prediction that light is a special case of these waves has long been confirmed.

Due to their low mass, electrons react to very weak electric fields and are therefore − without exception – the key element of *all* sensors for electromagnetic waves. That's the first puzzle: There is no physical reason why electrons should react to the flyby of *uncharged* particles like photons. Does it make sense to call light a stream of uncharged particles?

Predicted by Maxwell, the experimental confirmation of electromagnetic waves by Hertz started an incomparable advancement of the telecommunications technology, which became an indispensable part of our life. The intensive research has led to many surprising new developments of devices and transmission methods and to the fact that there are no knowledge gaps below about 10^{11} Hz. Therefore, high-frequency technology is no longer a part of physical research and problems are solved with engineering techniques. In this area, photons are useless; they are neither helpful nor necessary to solve technical questions and that is how it will probably stay.

Where does the idea of photons come from?

In 1905, Einstein invented photons to explain the photoelectric effect at optical frequencies near $5 \cdot 10^{14}$ Hz. Five years earlier, Max Planck had shown that oscillators (in the field of optics) can not transmit electromagnetic waves with arbitrarily small energy. The energy transfer takes place in packets, whereby the total energy is always divided into integer multiples of the minimum energy *hf*. It should be noted that only the energy exchange between *oscillators* is the basis of Planck's law of radiation. However, electromagnetic waves can also be generated in other ways (examples below) and it is questionable whether in these cases too the assumption is true that there is a minimum energy for the radiation.

Einstein replaced the electromagnetic waves with tiny, electrically neutral “light quanta” that have a single task: They transport a defined amount of energy. To solve the puzzle of the photoelectric

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[A] 31.Jan 2018, email: herbertweidner@gmx.de effect, a size specification of the light quanta or alternating electric / magnetic fields was irrelevant. Einstein never claimed that photons are particles. Later, the term photon was coined and few other properties such as the spin were added.

Although Einstein was able to convincingly explain the photoelectric effect, he also created a new puzzle: how can uncharged photons influence electrons? (And how can an electric current affect the photons? This will be discussed below.) Einstein's proposal divided the realm of electromagnetic waves: radio waves with frequencies below 10^7 Hz retain their known properties and are described by the Maxwell equations as before. Although the energy content of individual photons in this wavelength range is far below the detection limit of any instrument, some physicists use the term photon when they discuss certain problems (for example in NMR). The handling of light ($f > 10^{14}$ Hz), however, is complicated: Some phenomena, such as diffraction, which have nothing to do with energy, are interpreted as wave phenomena as before. But as soon as energy is involved, light is understood as a collection of photons and it is not allowed to interpret them as massive particles.

Hundred years ago, there was no way to detect energy levels in the field of radio waves, because the technical limit was as low as 10^7 Hz and the available measuring instruments were far too insensitive. By now, electronic circuits can handle frequencies in excess of 10^{11} Hz, and the components generate significantly less noise. As soon as it is feasible to build rectifiers at frequencies around 10^{14} Hz, field strengths (and not just energies) will be measurable in this frequency range. This will change the physics thoroughly, because − with very few exceptions − all radical changes in physics were triggered by surprising measurement results.

In the current state of the art, energy measurements in the optical domain do not provide analog results, they only provide pulses when a certain threshold (defined by the material) is exceeded. This digital behavior corresponds to a Geiger counter in the field of radioactive radiation. In both cases, no physical quantities are measured, but events are counted. “Photon counting” especially at low optical frequencies ($<10^{14}$ Hz) is an inaccurate method because nobody can distinguish whether a count was triggered by a photon or by thermal noise. Although the sensors are cooled, infrared measurements remain very problematic. An analog measurement of the electric field amplitude of light would be a pioneering invention.

Defining a photon

In physics, the term *photon* has a fixed meaning and is used to characterize certain properties of electromagnetic waves. This term adds a few details to the well-known properties of electromagnetic waves that were not known at the time of Maxwell and were not needed then. The additions are:

- Electromagnetic waves *generated by oscillators* with frequency *f* can not carry any amount of energy, but only multiples of the minimum quantity *hf*, where *h* is the Planck Constant. This statement does *not* apply if the electromagnetic waves are generated in any other way than by resonators, for example by accelerating electrons in the FEL. The reason: The frequency of a photon emitted during an electronic transition is related to the energy difference (ΔE) between the two energy levels involved in the transition. The unbound electrons that are transversely accelerated in the undulator do not switch between energy levels.
- The minimum amount of energy is transmitted by a spatially and temporally limited wave packet, which is always circularly polarized and has the angular momentum $h/(2\pi)$. An unlimited wave would carry infinite energy.
- One wave packet may be called photon; it can not be broken down into fractions. In a vacuum, it moves at the speed of light. Photons are “born” in one place and absorbed in another. In between, they can not be observed and it is forbidden to describe their trajectory. The cause is not of a fundamental nature, but the current construction of quantum mechanics:

QM can describe properties of stationary states, but not the motion of atomic particles.

- Since a wave packet consists only of electric and magnetic fields and does not contain or transport solid particles, it has no rest mass. As the average value of the electric and magnetic fields is zero, the wave packet is uncharged. A wave packet always has a spatial extent and shape and can not be reduced to one point. The more precisely the frequency is defined, the longer the wave packet must be.
- If many wave packets carry energy into roughly the same direction like inside a laser, they obey the Bose statistics due to their angular momentum and may produce surprising phenomena.

Perhaps it is a good idea to look at a photon like the center of gravity of an extended body such as the moon. Some calculations are simplified and some answers easier to understand by symbolizing this voluminous celestial body by a dot which is attracted by the sun and the earth. It makes no sense to ask about the shape or volume of the center of gravity, it is nothing more than an idealization to simplify certain tasks − it is *not* the perfect solution for all tasks. When speaking of the moon orbit, one means the path of the center of gravity. When preparing a moon landing, one should not focus on this dot, but on the mountains and valleys of the surface.

So, what is light? What are photons? What are radio waves? Regardless of the total energy transported, all are special aspects of electromagnetic waves that differ in their wavelength. They remain invisible unless they interact with matter. If the wavelength is shorter than the resolving power of the instruments, it may make sense to symbolize such a tiny wave packet through its central point and call it photon. Since electrons react particularly strongly to the electric field, the magnetic component of the wave is usually ignored. This inaccuracy may be sufficient to explain the vast number of observations, but it also causes subtle effects to be overlooked[1].

Unproven claims to the term “photon”

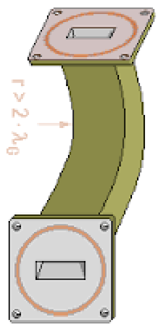
Undoubtedly, some phenomena in the field of optics can be well explained by photons, in particular those in which the spatial arrangement or extent of the relevant effects does not matter. A prime example is the photoelectric effect, which is all about energy. But there are also phenomena in which photons offer no explanatory approach − such as zone plate, total internal reflection, Snell's law or the double-slit experiment (We are talking *only* about the double slit and *not* about the measurement by non-linear (square-law) energy detectors! A photodiode detector reacts to energy; this is proportional to the square of the amplitude of the electromagnetic field.) In many wikipedia articles such as Arago spot, the term “photon” is not even mentioned, because it would only confuse and explain nothing.

Wrong claim: the photon is an uncharged particle.

- Neutrons can easily penetrate thin metal foils; the supposedly uncharged photons can not do that. Do we have to differentiate between “uncharged” and “super-uncharged”?
- When high-power lasers “cut” metal, that's just because the *electric field* of light swirls the electrons in the metal so much that it melts and is blown away. “Neutron cutting” or “Neutron heating” are unknown.
- Photons in the frequency range 3 MHz to 30 MHz, which are emitted by terrestrial transmitters, usually remain in the near-earth space because they are reflected (not absorbed!) by the electrically conductive ionosphere. Why do the electric currents in the ionosphere influence uncharged particles in the radio range? Why do they not affect the photons in the optical range?
- When photons pass through a glass plate (air − glass − air), the first interface decreases their velocity abruptly from $3 \cdot 10^8$ m/s to $2 \cdot 10^8$ m/s. As soon as they leave the glass plate, the

speed increases abruptly to $3\cdot10^8$ m/s. Which mechanism accelerates the electrically neutral photons? (we ignore the possible change of direction)

- A waveguide bend must be made of metal, plastic does not enforce the desired direction change. How do the uncharged photons distinguish whether the environment conducts electricity or not?
- The light beam of a laser pointer can be transmitted without loss through a 50 m long copper tube (diameter = 100 cm), filled with air. The photons of a 100 MHz transmitter (below the cutoff frequency) do not get far, they are no longer detectable after a few meters. How so? What forces the uncharged photons to turn back because they are not absorbed? Strange: If you cut the copper tube in the right places, almost all 100 MHz photons can pass through the slotted waveguide (with maxwell's equations one can calculate, where the waveguide must be slotted. Quantum mechanics has no tools to perform these calculations!). How do the point-like photons notice if the copper tube 50 cm away is cut or not? Replacing the copper tube with a plastic tube results in deviating results. Does each photon have a sensor to distinguish metal from non-metal?



Solution: The claim that light consists of uncharged particles is caused by insufficient measurement technology 90 years ago, when quantum mechanics was invented. At that time, it was only possible to measure the time dependence of the field strength with radio waves below 10^6 Hz (meanwhile the limit was pushed to 10^{10} Hz). In this frequency range, there was no reason to even mention the mean value of electromagnetic waves (zero).

At frequencies above 10^{14} Hz, nothing has changed during the past 90 years. You still can not measure the electric field strength of light. (But all physicists are convinced that it exists. Count how often the term “electric field strength” is used in the discussion of nonlinear optics. Also, count how often photons are used to *explain* the facts.) Long time ago, when the physicists were asked if the newly invented “photons” were electrically charged, they could only mention the mean zero − and it has remained so to this day. Sure, it is not wrong to mention the average value of the electric field strength. But it does not provide any valuable information when solving Maxwell's equations.

Wrong claim: the photon is a point-like particle.

- Let us stay with a 100 MHz signal through the waveguide made of copper. Are the supposedly point-shaped photons too thick? Does their diameter change when the copper tube is slotted? The simplest explanation is to assume that the cross section of photons increases with increasing wavelength − this is denied by QM without any experimental evidence ever being presented. Is any problem solved by the unproven claim that photons have no volume?
- A microwave oven contains two very different sources of photons: a 20 W lamp for visible light and a 900 W magnetron producing 2.4 GHz radiation. The door is a metal screen with many 1 mm holes. Why does the light penetrate through these holes, but the microwave radiation does not, although all photons are dots − regardless of the wavelength?
- Why can no radio waves (0.1 MHz < f <10 GHz) be conducted through optical fibers, even though the core diameter (d > 10 µm) exceeds by far the thickness of the point-like photons (d = 0)? The fibers absorb neither light nor radio waves.

The above examples show that no problem (in the field of radio waves) can be solved with the assumption of punctiform photons. Why does it work only with wavelengths smaller than 5 µm? The most obvious answer is: with radiowaves, the structure of the problem can be conveniently examined; as soon as the structure can no longer be examined with optical microscopes, it is no big mistake to replace electromagnetic wave packets with expansion-free points. Calculations indicate that photons are cylinder-like electromagnetic wave packets whose diameter corresponds approximately to a wavelength[2]. The length of a photon is discussed below.

Wrong claim: the photon is a an elementary particle. With the help of a nonlinear crystal, one photon may be split into two photons. The process is called Spontaneous parametric down-conversion. To this day, no conclusive explanation has been found as to how this division occurs. However, the existence of SPDC proves that photons are *not* indivisible elementary particles.

How to deal with photons?

Since a high-energy wave is always composed of a large number of photons, it is impossible to investigate the existence and behavior of *single* photons with a laser. Therefore, the focus will be on low-energy and low-intensity electromagnetic waves. But lone wave packets are rare and it is not easy to produce and to examine them in the lab. If the wave length is large enough, the electric field strength of the waves can be measured, details can be resolved more accurately and proven instruments of the telecommunications industry can be used. This simplifies discussions as to whether and how much the observer influences the measurement result.

Whenever a student asks "What is a photon? How is it created or absorbed? What is the mechanism of this process and how long does it take?" , the standard answer sounds like: "*There are quantum systems like atoms with different energy states. When the energy state decreases, a photon is emitted whose energy corresponds exactly to the energy difference of the two states. A photon can be absorbed by a quantum system if its energy exactly matches the difference between the current energy state and an allowed higher energy state. Since both processes take place instantaneously, no mechanism needs to be described.*"

These doctrinaire-sounding statements may apply to some physical processes and it is difficult to confirm or disprove them by experiment in the optical range. However, some reproducible phenomena are described incorrectly. A small selection:

- If you look at the descriptions of cyclotron radiation and bremsstrahlung, electromagnetic radiation is generated with a very wide spectrum without the involvement of any energy levels (no spectral lines!). These are probably common mechanisms for generating photons in the hot interior of stars.
- The single-anode magnetron generates radio waves without resonant circuits and without quantum-mechanical energy levels. The resonant circuits of modern magnetrons improve the efficiency, but do not change the principle of generating electromagnetic waves.
- A FEL partially converts the kinetic energy of electrons into very intense electromagnetic radiation, the wavelength of which is defined by the undulator geometry and not by any energy differences.
- In NMR, precessing atomic nuclei in a magnetic field generate or absorb electromagnetic energy at wavelengths that exceed the size of the nucleus many billions of times. Again, there is no jump between energy levels, because the frequency of the wave equals the rotation speed of the larmor precession. The generated radiation (called FID) can be measured for many seconds and is the opposite of a "sudden jump". In the technically accessible range between a few microTesla and 25 T, the frequency is proportional to the strength of the magnetic field and is infinitely variable (MRI).

The sentence "*The generation and absorption of photons takes place instantaneously, no mechanism needs to be described*" is proved by no experiment and corresponds to a religious doctrine, which must be questioned. It explains nothing, the only task is to cover up knowledge gaps. One knowledge gap is caused by quantum mechanics, which was developed to handle stationary states, energy levels, statistics of many-body systems and calculation of probabilities. QM was never conceived to describe mechanisms that are difficult to observe.

Heisenberg's uncertainty principle allows us to estimate the permitted limits of a process without knowing the mechanism; but it prevents a conceptual understanding of the process[B]. This made people believe that a transition from one energy level to another cannot proceed through any observable intermediate levels. If photons of very high frequency ($f > 10^{14}$ Hz) are generated (or absorbed), the corresponding process is usually very fast. With today's measurement technology, it is not very promising to investigate such processes for possible intermediate steps. The chances of success increase if one studies processes in which the participating photons have sufficiently low frequencies ($f < 10^9$ Hz). NMR is particularly well-suited to seek intermediate steps in the generation and absorption of electromagnetic waves: the frequencies are very low (between 2 kHz and 900 MHz) and radio-frequencies have the great advantage that amplitudes and phases can be recorded directly, while at optical wavelengths typically only cycle averaged intensities can be detected. And: In this frequency range one may think of photons, but one can not measure photons. All measurable phenomena can only be explained by the interaction of electromagnetic waves and electrons (on the basis of Maxwell's differential equations).

For several reasons, the waves used in radio technology are never called photons: photons are likely to be counted with semiconductor detectors if the photon energy exceeds a certain material-specific threshold and if both values exceed the mean kinetic energy kT of the detector molecules. Cooling can lower the detection limit to the infrared range. Below the terahertz gap, it does not make sense to talk about photons because you can no longer detect them. At lower frequencies, one can directly measure the components of an electromagnetic wave and compare them with the results of Maxwell's theory. This proven combination of theory and metrology has been confirmed millions of times and provides incomparably more detailed results than the counting of photons.

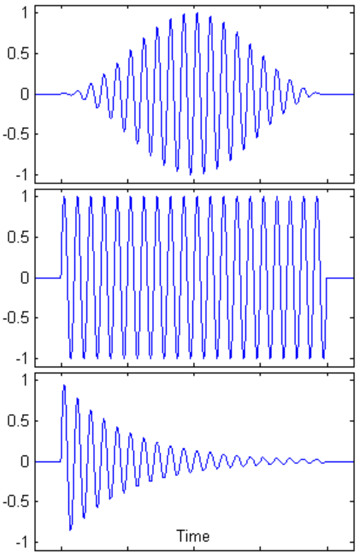
Probably, the energy content of electromagnetic waves is quantized in *every* frequency range. But this does not force us to invent a new elementary particle. In the range of radio waves, one can measure amplitude differences and phase shifts and there is no reason to symbolize a wave packet by an uncharged, point-shaped particle called photon. On the other hand, if you only need energy and spin in the area of light and you have no instruments to measure amplitudes and phases, it makes sense to think of a wave packet as the quasiparticle photon. The same is done in solid state physics, where a limited bundle of sound waves is treated a “particle” named phonon. Phonons can be reflected, bundled or scattered. But no physicist would seriously assume that “sound particles” fly through the crystal. The behavior of a rotating body can also be described more simply if it is symbolized by a pseudo-vector. This is all right, as long as you are aware that these fictitious particles are not real but were invented to simplify certain calculations. Only in the subject of light, many researchers confuse the symbol “photon” with the more complex physical reality.

Properties of an electromagnetic wave packet

A photon carries the energy hf and must therefore be limited in time and space; a photon symbolizes the center of an electromagnetic wave packet; it must have a beginning and an end. No real wave consists of infinitely extended wavefronts, as is often assumed to simplify the formulas. Since a photon transports the spin $h/2\pi$, it can not propagate isotropically (no spherical wave), as it is sometimes mistakenly assumed. Only when a light source generates a large number of photons and no special precautions provide for a certain directivity, there will probably be no direction in which no photons fly. But that's not our topic. A single photon always has a propagation direction that does not change without external cause. A photon does not spread, because it is massless.

[B] The uncertainty principle is a similarly important framework condition as the law of conservation of energy. Both allow an assessment of whether a particular physical process is possible without having to go into detail. A perpetual motion machine of any design can be rejected with with a note on energy conservation, without knowing the internal mechanism.

Modeling the envelope of a wave packet



We focus on the movement in the z-direction, in which the wave-packet moves at the speed of light. We need a factor *C*(*t*) to limit the period of time in which the wave affects a resting (or slowly moving) particle like an unbound electron. The formula $E=C(t)\cdot E_0 e^{i(kr-\omega t)}$ describes the electric field strength of a linear polarized wave along the z-axis as a function of location and time. A circularly polarized wave can be described more simply because the electric field vector rotates around the z-axis with the frequency $2\pi f=\omega$. The handedness of the circularly polarized electromagnetic waves corresponds the direction of spin of a photon in quantum mechanics. Since we are only interested in the envelope, we ignore the periodic change in direction of a measurable quantity and focus on the amount of the field strength. For this applies: $|E|=C(t)\cdot E_0$

The envelope *C*(*t*) must be continuous and assume the value zero outside of a certain interval. In the optical domain, the shape of the envelope could not be measured yet. Each of the three variants in the plot above has advantages and disadvantages, some have discontinuities that complicate the mathematical treatment. We assume that the envelope resembles a bell curve and choose the function $C=½(1-\cos(W\cdot t))$ with the range $0\le W\cdot t<2\pi$. Outside this range, $C = 0$. Numerical checks show that the exact shape of the envelope has little effect on the results of this work, provided that the shape is sufficiently smooth and without discontinuities.

Technically, the envelope *C*(*t*) is caused by an amplitude modulation of a carrier with a frequency mixture (focus is the modulation frequency *W*). Each modulation produces so-called sideband frequencies in the immediate vicinity of the center frequency, the amplitudes of which usually decrease with increasing frequency spacing. The frequency range occupied by the sideband frequencies is called *natural line width*. Some examples show the magnitude of natural line widths.

1. (Optics) One of the strongest atomic transitions is the Na D line at 589 nm and a line width of 9.8 MHz. This results in $\Delta f/f=\Delta\lambda/\lambda = 1.9\cdot10^{-8}$.
2. (Optics) The natural line width of the 852 nm transition in ^{133}Cs atoms is 5.09 MHz. This results in $\Delta f/f=\Delta\lambda/\lambda = 1.4\cdot10^{-8}$.
3. (Gamma rays) The famous 14.44 keV line of Fe^{57} (Mössbauer effect) ($\lambda = 86.1$ pm) has a natural line width of only $4.66\cdot10^{-9}$ eV. This corresponds to a fractional bandwidth of $\Delta f/f= 3.3\cdot10^{-13}$.
4. (Radio) Conventional NMR spectrographs measure frequencies around 400 MHz and achieve a line width of 0.5 Hz. The resolution is limited because the FID signal disappears in the noise about four seconds after the impulse excitation, resulting in $\Delta f/f\approx 10^{-9}$.

If the intensity is very low, the radiation is formed from independent wave packets that do not overlap. Nevertheless, it retains all the characteristics of an electromagnetic wave and does not turn into a particle.

Linking the emission coefficient and the length of a photon

If there is no stimulated emission and if we measure enough wave packets, the natural line width is based on the following statistics: A quantum mechanical system waits for some time in the excited state (2), before it jumps into a lower energy state (1) by emitting a wave packet (a photon). The average waiting period is the reciprocal of the Einstein coefficient A_{21}, which is tabulated here. Heisenberg's uncertainty principle allows to calculate the average inaccuracy of the emitted radiation, resulting in $$\frac{\Delta f}{f}=\frac{\Delta\lambda}{\lambda}=\frac{A_{21}}{2\pi f} \qquad (1)$$

For undisturbed atoms, the waiting period for forbidden transitions can take years. This leads to extremely low half-widths, which are responsible for the extreme precision of atomic clocks. If a signal consists of too few oscillations, the frequency can only be determined inaccurately. A lone delta pulse has no definable frequency at all. Very short wave packets consist of few oscillations and therefore have an extremely broad spectrum (in optics: white light, in radio transmission: UWB signals). A high accuracy (low Δf) can only be achieved by counting a very large number of individual oscillations occurring within a specific period of time Δt. Both magnitudes are linked by a uncertainty relation. There are different definitions of these quantities, leading to slightly different results for the time-bandwidth product.

- Küpfmüller was the first to discover a connection between the minimum duration Δt of a signal and the measurable spectral bandwidth Δf. Depending on the exact definition, one can choose between the two formulas $\Delta t\cdot\Delta f=1$ and $\Delta t\cdot\Delta f=0.5$
- For the time-bandwidth product of a Gaussian-type wave packet applies $\Delta t\cdot\Delta f\approx 0.44$
- With a more precise definition, Rohling derived the relationship $\Delta t\cdot\Delta f\geq\sqrt{1/8\pi}\approx 0.2$
- Using Heisenberg's uncertainty principle $\Delta E\cdot\Delta t\geq h/4\pi$ gives $\Delta f\cdot\Delta t\geq 1/4\pi\approx 0.08$. This value seems to be far too small.
- Using Heisenberg's original formula $\Delta E\cdot\Delta t\geq h/2$, you get $\Delta f\cdot\Delta t\geq 0.5$

Choosing $\Delta t\cdot\Delta f=0.5$, the typical length of a wave packet (= coherence length) is:

$$L=c\cdot\Delta t=\frac{c}{2\Delta f}=\frac{c}{2f}\cdot\frac{f}{\Delta f}=\frac{\pi c}{A_{21}} \qquad (2)$$

The length of a wave packet depends *only* on the transition probability and not on the wavelength. Due to the selection rules, there are at least two clearly distinguishable groups of wave packets. Almost all known spectral lines in the optical range are “allowed” transitions with $A_{21}\approx 10^8$ s^{-1} . In this range, a wave packet is typically several meters long.

The forbidden transitions with mostly very low intensities are difficult to produce in the lab, they have Einstein coefficients between $A_{21}\approx 10^{-2}$ s^{-1} and 10^{-7} s^{-1}[3][4], which is why each wave packet is many kilometers long. But that is far from the upper limits, because the famous 21 centimeter line of hydrogen, the favorite frequency of radio astronomers, has the remarkably low transition probability of $A_{21}=2.85\cdot 10^{-15}$ s^{-1}. This corresponds to a fractional bandwidth of $\Delta f/f=3.2\cdot 10^{-25}$ [C]. According to formula (2), one wave packet is 35 million light-years long − more than ten times further than the Andromeda galaxy. The beginning of the elongated wave packet already passes through the receiver stages on earth while in the Andromeda HI clouds, the emission of the same packet has not yet ended. It takes 35 million years to *fully* receive a photon with the energy content *hf*. But the radio astronomers have to limit themselves to a few hours and still receive signals. So are photons divisible?

This surprising and bizarre result is a direct consequence of the definition of the Einstein coefficient A_{21} . All Einstein coefficients are calculated on the basis of the atomic properties of the atom and not determined experimentally.

What is wrong? How can the problem of the excessive length of wave packets be solved? Perhaps the formula $T_{21}\cdot A_{21}\approx 1$ is not general, maybe it only applies to allowed transitions, but not to forbidden transitions. Perhaps the half width of a spectral line does *not* depend on how much time

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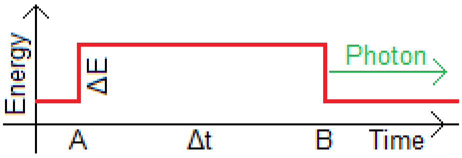
[C] Since the gas clouds move quickly and irregularly, the received signal is a wide frequency mix of many Doppler-shifted lines. The bandwidth of the receivers must be chosen accordingly. A standard value is 5 kHz.

the atom has previously spent in the higher energetic state. In other words, even if an atom has been waiting several million years in the higher energy state, the wave packet is produced in a much shorter time (a few milliseconds?). When does the generation of the photon start, when does it end? In textbooks, the relationship between the lifespan Δt of an excited state and the width of the emitted spectral line is presented contradictorily.

The first version is more commonly read[5][6]: *By colliding with another atom, an atom gets into an excited state. During a certain period Δt (average lifetime) nothing happens (no subsequent collision!); then the atom decays by spontaneous emission into a deeper state and emits a photon. Photons emitted thereby do not all have exactly the same energy. Instead, the observation shows that the spectral line has a certain width ΔE, even if all other disturbing influences are switched off. This natural line width is linked to the finite lifetime of the excited state.*

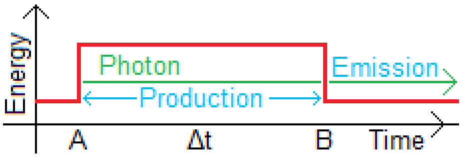


The figure shows the energy content of an atom as a function of time. At time A, the atom absorbs energy ΔE, then nothing happens during the period Δt. At time B, the atom drops spontaneous into the lower energy level it had before time A and generates a photon of energy $\Delta E = hf$, which escapes at the speed of light.

The average waiting time Δt is the reciprocal of the Einstein coefficient A_{21}, which is tabulated here. A_{21} is fixed by the intrinsic properties of the relevant atom for the two relevant energy levels. In the case of the two yellow sodium lines near 589 nm, the atom spends $\Delta t \approx 16.3$ ns in the excited state before it emits a photon. The photon does not exist before the jump, it is generated during the jump (or femtoseconds later?). This caesura at point B leads us to a problem of understanding, because the formula $\Delta E \cdot \Delta t \geq h/4\pi$ is used to join two values that are assigned to different non-overlapping periods. The period Δt applies *before* the generation of the photon, while ΔE denotes the energy uncertainty of the photon, which can only be measured *after* the photon is created. Does the atom have a clock and a memory so that it can link two values that can not be measured simultaneously?

Almost all textbooks describe the creation of a photon as in the above pattern and do not mention the inconsistent scopes of ΔE and Δt.

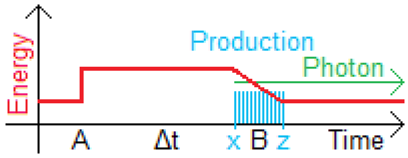
Occasionally, the process is described completely differently[7]: *Exercise 3.15: What is the difference between the lifespan of an excited state and the emission time? Solution: The lifespan* ***is****(!) the emission time. In quantum physics it takes the place of the decay time of an oscillator in the classical radiation model. It is assumed that the quantum jump takes place arbitrarily fast. The jump is therefore a digital process in which the lifetime of the excited state is large compared to the time of the quantum jump.*



Unfortunately, the author does not explain why he assumes that the formation of the photon starts at time A, simultaneously with the excitation of the atom. This proposal has the great advantage that the Heisenberg uncertainty principle can be applied without contradiction. This would underpin the known experimental results of the allowed transitions. However, this proposal does not solve the problem of excessive long wave packets in forbidden transitions.

Although this proposal eliminates the problem of applying the Heisenberg uncertainty principle, it contains a much more serious problem: Stimulated emission is impossible because there is no time window for it. The production time of a photon *must* be much smaller than Δt! Since stimulated emission undoubtedly exists (it is the basis of all lasers), this proposal is probably wrong.

The spontaneous production of a photon in the near field



The two variants discussed above are extreme cases. Perhaps the physical reality is better described by the following compromise: The wave packet arises within a defined period t_{x-z}, shorter than Δt, but not instantaneously, as claimed by QM. This proposal avoids the problems just discussed.

- This process is no extremely short process, because short electromagnetic pulses *always* produce a very broad spectrum. In fact, the opposite is true: Only if the generation of the wave packet is *not* a short process and the time span t_{x-z} is long enough, spectral lines of remarkably narrow bandwidth can be generated.
- According to Küpfmüller's theorem, the wave packet evolves slowly within an extended oscillation period t_{x-z}. As a result, the wave packet contains the necessary number of oscillations to explain the experimentally observed narrow line width. If t_{x-z} is significantly shorter than Δt, there is plenty of time left for stimulated emission. For forbidden transitions, t_{x-y} is considerably shorter than Δt and the problem of overly long wave packets does not exist.
- As with other spontaneous processes, nobody knows a deeper cause that triggers the emission of a wave packet at time x.
- When the atom drops into the lower energy state, the released energy ΔE generates an electromagnetic field in the vicinity of the atom, the so-called near field. This does not happen suddenly because electromagnetic alternating fields of defined frequency require some time to build up and to decay. This can be seen particularly well at the low frequencies of NMR spectroscopy: it takes many microseconds to excite the larmor precession (to be exact: to tilt the magnetization vector away from its equilibrium position). Then you can measure the FID signal for a few seconds.
- If this suggestion is correct, the energy uncertainty of the generated photon is determined by the formula $\Delta E \cdot t_{x-z} \geq h/2$.

It is noteworthy that the beginning of the FID signal is already measured while the electromagnetic wave is being generated. In NMR spectroscopy, this is done by default and no one is surprised that the beginning and end of the wave packet (period x-z) are clearly separated. This slow-motion effect is made possible by the comparatively low frequency ($f \approx 50$ MHz). For various reasons, there are (still) no comparable measurements in the optical range: Above 10^{14} Hz, the time span t_{x-z} is considerably shorter and there are no suitable instruments. The usual photodetectors generate a pulse when the total energy exceeds a device-specific limit. This crude method is unsuitable for measuring tiny time differences caused by a *single* photon.

Since atoms are always smaller than the wavelength of the emitted photons in the optical range, they can be considered, with good approximation, as point antennas ($r \ll \lambda$), centered in the reactive near field that surrounds the atom during the emission. So far, details of the near field have hardly been researched, because in telecommunications, it is all about bridging long distances. The electrical and magnetic fields within the reactive zone are very difficult to describe, as is the energy exchange between the atom and the near field. The energy that is carried back and forth between the atom and the reactive near field is much stronger than the energy emitted by the far field. This energy exchange also ensures that the atom does not come to rest immediately after it has begun to release its energy into the near field. On the contrary – the “energy swing” forces the atom again and again to temporarily store and release energy. In the meantime, a small part of the total energy is constantly radiated in the far field.

A very similar process can be observed when a calm water surface is disturbed by a stone throw (where is the location of the atom): not a single, circular wave is created, which moves away from the atom. Rather, a whole series of circular waves is generated and the center comes to rest only after some time. As you can see in the photo, the waves briefly supply enough energy to push up a drop of water in the center.

The atom does not experience a single, very short "quantum leap", but it oscillates until all the excess energy is radiated. That can take a long time, because the atom represents an extremely short transmitting antenna, compared to the radiated wavelength. The less efficient the radiator, the longer it takes to emit a defined amount of energy (We are talking of the smallest energy unit *hf*). That is expressed by the quality factor Q, which is defined as the ratio of the energy stored in the oscillating resonator to the energy dissipated per cycle by the radiating process. An extreme example is the decay of the FID signal in NMR. Since the atomic nucleus is much, much smaller than the radiated wavelength ($\lambda \approx 1$ m), the FID signal can be measured for several seconds. If the signal could be measured in the far field, the transmitted FID wave packet would be at least 600,000 km long.

In the optical range, the wave packets are much shorter. As mentioned above, the sodium atom spends about 16.3 ns in the excited state before it emits a wave packet with $\lambda = 589$ nm. If the photon production takes 1% of this time, the wave packet consists of 83,000 oscillations and is 5 cm long. The exact length has not been measured yet.

It is puzzling how a single tiny atom can produce such elongated waves with the highest precision. Of course, any discussion about this incredible result can be avoided by symbolizing each electromagnetic wave packet with a dot-shaped photon. But: Does that ease the understanding of light? Einstein told us: Make things as simple as possible, but not simpler!

> *"All these fifty years of conscious brooding have brought me no nearer to the answer to the question, 'what are light quanta?' Nowadays, every Tom, Dick, and Harry thinks he knows it, but he is mistaken."*
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> Albert Einstein, letter to Michael Besso 1954.

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