The Size and Energy of a Wave Packet

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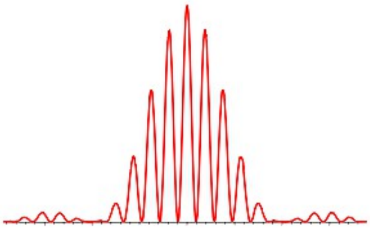
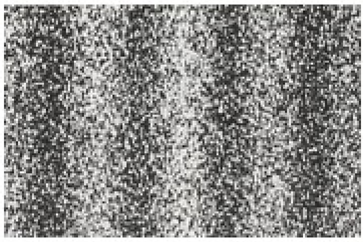
Abstract: After the spin-flip a Hydrogen atom emits a photon, but radio astronomers measure electromagnetic waves at 1420 MHz. How and where is the photon converted into an electromagnetic wave? Do photons really exist? This question is discussed in great detail with reference to the differences between energy measurement and amplitude measurement. The combination of formulas of Quantum mechanics and the wave theory gives the diameter of a wave packet of circularly polarized light. This allows the calculation of the energy loss during the traversal of a thin plasma.

Introduction



What is light? Depending on the experimental set-up visible light ($f \approx 10^{15}$ Hz) may be interpreted either as a wave phenomenon with interference phenomena or as a swarm of tiny photons that causes tiny hits on photosensitive material. Each of the two models can explain certain observations well, but fails in others. None can explain all observations consistent. At different frequencies, the double-slit experiment shows that the result, and thus the choice of the "right" model depends very much on the detection method (of course, the distance and width of the slits must be adapted to the particular wavelength):



- With intense light ($f \approx 10^{15}$ Hz) and with radio waves ($f \approx 10^{10}$ Hz) of any intensity you measure a continuous profile of the intensity (upper panel).
- At very low light, a dot pattern is formed whose density is predictable (lower picture). Radio waves do not generate dot patterns, even at very low intensity.

Either the photons at 10^{10} Hz are much larger (improbable, the QM does not mention a radius) or the difference is caused by the detection method. In the field of light "energy packets" are counted, the result is a digital yes / no distribution. For radio waves the amplitude is measured and you *always* get a continuous distribution. This is true not only for the double-slit experiment, in the focal plane of large parabolic mirror one observes the same principle differences:

In the optical astronomy the sensitivity of the receivers is relatively low because of the "square-law" detectors and the frequency can be determined only inaccurately. Low-noise amplifiers do not exist and there is no viable method for reducing the frequency of weak signals.

Reducing the frequency by several orders of magnitude to the range of the radio waves ($f \approx 10^9$ Hz), the wave character is only apparent, there is no method for detection of photons. Instead of measuring directly the energy of the received radiation (as in the optical domain), sophisticated electronic devices are used to amplify the alternating current (an analog signal) of a dipole antenna. The frequency is reduced by mixing, because at low frequencies the amplification of signals is easier. Finally, the amplitude and phase of the signal is registered with rectifiers. Thanks to sophisticated technology, all wave properties, in particular the frequency, can be determined with high precision. For these reasons, the angular resolution of the radio astronomy exceeds that of optical telescopes by orders of magnitude.

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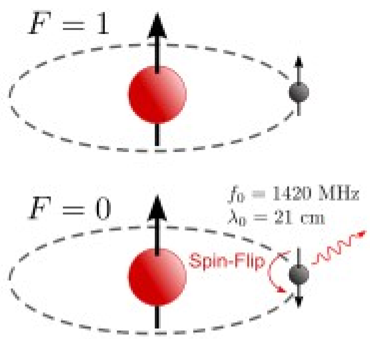
At much higher frequencies beyond the X-ray range ($f \approx 10^{22}$ Hz), the opposite is true: In this area, parabolic mirrors do not exist, the energy of the photons is measured relatively imprecise, the angular resolution is insufficient. We observed no interference phenomena and can not even determine the basic properties of waves such as frequency and wavelength.

The following discussion does not deal with race, how to generate extremely high power, but of isolated atoms, which emit low-frequency electromagnetic waves of very low power without interaction with the ambient. From a technical point of view, atoms are very inefficient radiators, because their dimensions are substantially smaller than the wavelength of the radiated electromagnetic waves. It is unclear how and where the energy *hf*, which is provided by an atom, is converted into a very good monochromatic wave with remarkable coherence length. Therefore, the statements of quantum mechanics (QM) and wave theory are compared in detail.

How is the energy released?

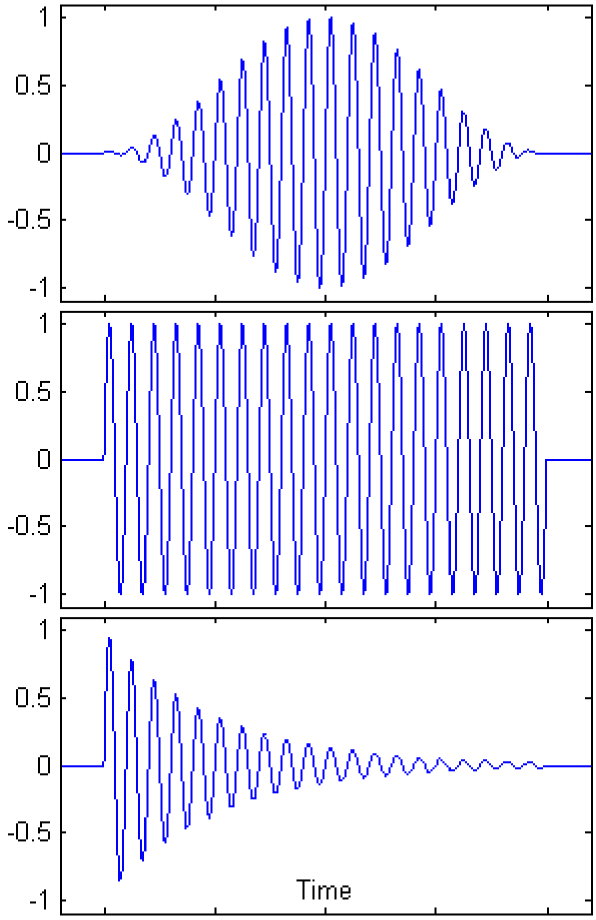
The QM describes the entire transmission as follows: The light source generates photons and in the receiver many electrons are detached from their atomic bonds. The intensity of the light is calculated from the number of collected electrons within a defined period of time. This brief description may be sufficient in the field of gamma radiation. The laws of QM must also be true, if the binding energy is not achieved and hence there is no instrument to detect photons. For this reason, visible light is not discussed, but the generation, propagation and detection of spectral line 1420 MHz. The receivers of radio astronomy are built on to the same principles as radios. The hardware is sensitive only to electromagnetic waves and requires no rules of quantum mechanics. Where and how a photon converts into an electromagnetic wave?



In very distant gas clouds, excited hydrogen atoms reduce spontaneously their inner energy and emit the difference. Because of the low density, the atoms are therefore almost undisturbed, because they are about 10 mm apart. In the excited state that is generated by random inelastic collisions, the spins of the proton and electron are in parallel, the total angular momentum of the atom is $\hbar = h/2\pi$. After a very long time, one of the two spins turns (spin-flip) and then both spins are antiparallel, the total angular momentum is zero. Because of conservation of angular momentum, the electromagnetic wave must be circularly polarized and the rules of QM yield the energy released 5.87433 μeV. What follows is described very differently by QM and wave theory and often mixed unsystematic.

According to QM, a photon with this energy and the spin $\hbar$ is released and flies away at light speed. The QM has no measurable frequencies and wavelengths, the terms coherence time and coherence length also not part of their vocabulary. For the "production time" Δt of the photon, the QM does not mention any time frame. Usually, it is assumed that the (dot-shaped?) photon leaves the atom at a time point. If Δt is shorter than 704 ps (this oscillation period corresponds to the frequency 1420 MHz) or even zero, a possible motion of the atom can no longer influence the energy of the photon. It is also assumed that the receiver absorbs the photon at a time point and the receivers position a few picoseconds before is irrelevant. The Doppler effect can in principle not be explained by means of QM.

The wave theory describes how the circularly polarized electromagnetic wave spreads and how the frequency may be modified during generation, propagation and reception. The wave theory does not describe how this wave packet is constructed. From the very short half-width of the HI line of hydrogen[1] from only $\Delta f \approx 5\,kHz$ follows with the formula $\Delta\lambda \cdot L \approx \lambda^2$ a coherence length of about $L \approx 60\,km \approx 280 \cdot 10^3\,\lambda$.



The wave packet is built during a remarkably long period of 200 µs. During this period, all changes in position of the atom affect the generated wavelength and the Doppler effect can be simply explained. Since a circularly polarized wave can not be a spherical wave, the wave packet has a preferred direction. Below it is shown that the diameter of the wave packet is finite.

Puzzling is the time dilation: The QM makes no mention of time it takes for the spin-flip. Most physicists will probably suggest $\Delta t < 10^{-15}\,s$, then the atom should be in peace again. Measurement results are lacking. From the perspective of the wave theory, an unknown mechanism must ensure that a wave of circular polarization is produced with the utmost precision. Direction and frequency must be stable over time, the amplitude must end on time. It is unknown whether the amplitude is constant or, for example, decreases exponentially. The image shows the time course of a few envelopes based on linear polarization, as a circularly polarized wave is hard to draw.

If you wanted to create the wave train with technical means, you need at least an energy storage, which is slowly "emptied" and an accurate timer. In a hydrogen atom, you will not find these building blocks. The extent of an effective "transmitting antenna" transverse to the emission direction of the wave should be λ/2. The diameter of a hydrogen atom, however, is smaller at least by a factor of 10^9. Perhaps from the moment at which the energy *hf* is released, an electromagnetic near-field is formed, containing virtual photons, which act as an energy storage. The volume of the near-field does not depend on the size of the transmission antenna, as long as the length is much shorter than the wavelength.

The transfer of energy to the Earth

In the QM-model, some photons are probably flying toward earth. Since they do not "age" or expand, all the properties as spatial extent, direction of propagation and speed should remain constant. An experimental confirmation or refutation is impossible in principle, because the QM makes no statement about the location, movement and size of photons. The de Broglie-Bohm theory as QM-variant, which also describes the path of the photon is considered to be refuted. The QM describes some ways to change the energy of a photon, none of which applies in the range about 5.87 µeV. This energy is smaller than the rest energy of the electron by a factor of 10^{11}, which is why the Compton scattering can *not* cause any loss of energy. According to the QM Doppler effect and Redshift do not exist! The laws of QM do *not* allow any change of energy of photons produced by lone hydrogen atoms in gas clouds in our own or in distant galaxies. But radio astronomers do measure systematic energy deviations! Are photons a suitable model to explain these astronomical observations?

The QM makes surprisingly accurate statements about the interaction of energy and matter, if the dimension is limited to the atomic and subatomic scale. Given the relatively large wavelength of 0.21 m, the QM does not provide meaningful answers to all questions *between* start and finish. QM can not explain how a parabolic mirror works and knows no answer, why its reflection properties not deteriorate when holes are drilled in the metal surface with a few centimeters in diameter to reduce wind load. The assumption that the energy packets of the hydrogen atoms were tiny photons can not even answer such simple questions.

The wave theory is well suited to describe the spread (not the generation and detection) of electromagnetic waves, as well as phenomena such as refraction and diffraction in detail. It provides accurate and experimentally verified statements about the permissible size of the holes in a parabolic mirror at the wavelength of 0.21 m and the accuracy with which the surfaces must be formed. It is the basis of all astronomical instruments and need not be presented here in detail. Wave theory describes the cause and measurement of the polarization simply and correctly. Extrasolar planets are sought by high-resolution spectroscopy, the function of which can be explained only with waves. The HBT effect was predicted using classical wave theory and can therefore be explained far easier and better than be with QM. Quantum mechanics originally doubted its existence[2] and could provide a rather complicated explanation until years after the experimental confirmation.

Overall, the QM can contribute remarkably little to explain astronomical observations. Their laws are manifestly inappropriate to describe the propagation and transformation of electromagnetic radiation over long distances. The QM was indeed designed to describe details of energy transformations in atomic dimensions. Here they achieved astonishing precision and is considered to be error-free.

How is the energy detected?

There is no detector device for very low-energy photons. From QM perspective, the signal of the hydrogen line can not be measured. Neither of earth-bound nor of astronomical sources. Although there may arrive billion photons of this energy here, not a single one can be detected. Even a two-photon absorption is very unlikely and would not be detectable even with cooled receivers. Radio astronomy would not exist.

For wavelengths less than 100 microns (the region between the IR light and gamma radiation), today's technology does not have any components in order to evaluate the amplitude and phase of electromagnetic waves. One must therefore use energy sensitive detectors. These are - technically correct - known as Square-law detectors, because their output is not proportional to the amplitude of the incident wave, but to the square of the amplitude. There is no output signal when the detected power is smaller than the band gap respectively the work function.

The disadvantages of the process are known: A low sensitivity, also referred to as detection probability, strong shot noise and 1 / f noise. These side effects do not depend on whether the detector is a photo emulsion or a semiconductor. If you would have to receive electromagnetic waves in the MHz range with energy sensitive detectors, you might not receive the signals from communications satellites and GPS. Phones could receive messages from a distant base station, if the base station had enough power. A signal transmission in the opposite direction would overload any mobile phone.

In the wireless technology you do not measure the intensity of radiation and therefore you do not have to remove electrons from their bonds and count them. Instead, one uses the fact that in any metal electrons are unbound and can move freely. Even at very low intensity, the electric field component of the wave accelerates many billions of electrons, causing electrical current that can be amplified and measured. There are no problems with minimum energy and statistical noise. All signal processing is performed by linear laws and the phase of the electromagnetic wave is preserved, because the amplitude is not squared. The outstanding good angular resolution of the radio astronomy is based on precise measurement of amplitudes and phases of electromagnetic waves.

To observe faint radio waves in the vicinity of 1420 MHz, a sufficient number of wave packets must reach the antenna. The electric fields are superimposed constructively inducing an alternating current in the dipole. The receiver displays (after strong amplification) a signal which is proportional to the amplitude of the resultant wave. This is not an energy measurement and has nothing to do with QM, because in QM amplitudes can not be measured. A divergent signal frequency is usually explained by the Doppler effect as a typical wave phenomenon. But there are also other explanations.

A comparison with the intensity measurement in the optical range shows the principal shortcomings of the energy measurement:

1. Already in the detector, the amplitude of the electromagnetic field is squared, wherein the phase information is lost (the energy as a scalar does not have phase).
2. Individual electrons have to be removed from their atomic bonds. This energy threshold is a non-linearity, producing a digital output signal: No photoreceptor can provide a fraction of an electron.
3. With a decreasing intensity, the number of countable electrons decreases and the statistical noise increases.

These disadvantages have to be (yet) taken into account, because there are (still) no suitable electronic devices that can process electric currents at frequencies around 10^{14} Hz. The previous progress is remarkable:

- In 1925, the broadcast receivers could only handle frequencies up to 10^6 Hz. Higher frequencies were unusable shortwave.
- 1950, the limit sensitive radars was 10^9 Hz
- 1980, one could receive the signals of low-power communications satellite at 10^{10} Hz
- 2010 CBM radiation could be measured up to 10^{11} Hz
- 2014 HEMT laboratory samples can already amplify 10^{12} Hz

On average, the frequency limit of sensitive receivers has increased tenfold every 17 years. If this trend continues, the sensors of optical astronomy are no longer photon counters, whose data must be smoothed with statistical tricks. Around 2060, the *amplitude* of light waves will be processed with *linear* electronic devices such as in the current radio astronomy. Maybe the technical breakthrough is earlier, because transistors and interconnects in computer chips already are smaller than 50 nm and will shrink further. A linear amplifying input stage for wavelengths around 1000 nm should be constructible. Today's tiny transistors are optimized for digital signal processing in computers - the signal processing in the optical domain requires however analog-working, low-noise transistors.

Occasionally it is claimed that the antenna current is caused by very many simultaneous incoming photons. Since you can not count them in the frequency range around 1420 MHz, that's at least an unprovable and therefore unscientific opinion. Above all, the mechanism is unclear how irregular incoming packets of energy (energy is a scalar quantity) can produce an alternating current with a defined frequency (vector quantity) in a piece of metal. This mechanism must also explain why the oscillation direction of the alternating current is orthogonal to the direction of reception, although the momentum of the incoming photons is oriented parallel to the direction of propagation.

It is usually referred to as a proof for photons that at low intensity, Square-law detectors provide no constant output signal, but an irregular sequence of charge pulses. This is no compelling reason, because Max Planck showed that a thermal source emits energy only in multiples of the minimum energy *hf*. It does not necessarily follow that this energy is transported in the form of particles, called photons. A wave packet can also carry a defined amount of energy. If this wave packet is fully absorbed, an energy-sensitive detector must display this energy *hf*. But it is unclear why the energy detector indicates either the full energy of the wave packet or nothing. This may be caused by the principle of Square-law detectors, which do not measure the amplitude of the electro-magnetic wave, but the square of the amplitude. The solution to this problem is not a task for the wave model, which was primarily designed for processing of interference phenomena.

There is no wave-particle duality..

..because wave theory and QM were designed to solve different problems. Both themes comple-ment, they do not overlap. The object of the wave theory is not description of the production, but the spatial and temporal propagation of waves. The good observable phenomena such as inter-ference and Doppler effect can be explained with real, measurable amplitudes and phases. In the wave theory, any indication is missing why electromagnetic waves are not generated with arbitrarily low energy and arbitrary angular momentum. This is not a task of the wave theory.

In the QM one has to calculate with complex amplitudes which are experimentally undetectable. It remains unclear what the waves in the QM-formulas mean exactly.

If an electromagnetic wave of energy *hf* is created, the wave theory differentiates between near field and far field. In the immediate vicinity of the transmitting station, the near field, there are surpris-ingly strong electric and magnetic components of the wave, which differ in principle from those in the far field. In the near field of the phase shift between the electric and magnetic field is about π / 2, the energy contained in this region is much higher than *hf*. The Poynting vector, which describes the energy flow depends on place and time, points sometimes back to the source. This surprising statement means that the source not only emits energy, but at times also absorbs energy. The sen-tence "The source breathes in the near field" vividly describes the complex relationships in this volume, which can be described approximately by a sphere of radius 3λ . Very far from the source, the phase shift between the electric and magnetic field disappears, the Poynting vector in the far field points away from the source.

The near-field contains significantly more energy than the far-field subsequently transports. The flow of energy in the energy-rich "breathing" near field must be quantized. Are these the virtual particles that appear and disappear spontaneously and are previously known as spontaneous fluctu-ations of a quantum field? So far there is no quantization of the near field, because the wave theory knows no energy quanta and the QM has no near field.

The radiated wave is "connected" with the source during the duration of the coherence time and reacts to any changes in location, which explains the Doppler effect.

QM does not describe the generation and propagation of electromagnetic waves. The QM defines very precisely the minimum energy *hf* and the angular momentum. The statements of QM, how the energy of A passes to B, are very poor and totally useless for the construction of astronomical instruments. In QM, the near field does not exist (allegedly) and can not be described, because QM has neither electric nor magnetic vector fields and can not describe their phase shift. According to the QM, the source "passes" energy to the photon energy and this departs at the speed of light. Because the photon has no spatial extension, the contact time is zero, there is no subsequent energy exchange between source and photon. The same applies if the photon is absorbed. As a point-like object it "notices" the receiving site only in the moment in which it is absorbed. Therefore, any movement of A and B do not affect the photon, the Doppler effect can not be explained in principle. Why are flying photons assumed, although they can not even explain the interference phenomena, known for centuries? Perhaps the simplest explanation is true: If no interference is expected in the experimental setup, a particle is invented and named photon, whose values for the energy and angular momentum are defined by QM. This is an elementary particle that we must not imagine as a particle. Photons cover large distances at the speed of light, but they have no trajectory. Speaking of photons is saving lot of work with spatially extended fields and space-dependent phases. Dealing with particles is such a great saving of labor that the phonon has been invented in solid state physics. Here, everybody remembers that this "particle" does not really exist, it facilitates the processing of some problems. For photons this caution is unknown, although photons have never been detected.

A photon can perhaps be understood as a summary of characteristic information like a record or data set in computer science.

- If a record contains elements such as name, address, date of birth and phone number, it identifies a person. The record, however, is not a person.
- If a record contains elements such as height, width, depth, price and power consumption, it describes for example a washing machine. With this data set you can not wash socks.
- If a record contains elements such as charge, angular momentum, energy and rest mass, it describes, for example, the difference between two atomic energy levels. This record is not a particle moving at the speed of light.

If an enigmatic machine (perhaps a quantized near field) should produce a wave packet it receives a record from the atom with all the necessary information from which it can determine the frequency. This machine produces the wave packet. Once this machine is disturbed, it stops production resulting in decreased coherence length and increased half-width of the spectral line. In spectroscopy this is called pressure broadening.

As soon as the wave packet arrives at the receiver, the local machine creates another record, which may not match the original, because some data may have been changed en route. The records of the manufacturer and supplier may be different: The hydrogen atom emits energy (and angular momentum), the dipole receives electromagnetic waves having a frequency corresponding to a different energy.

In summary it can be said that QM and wave theory are independent areas that are specialized for different tasks:

- QM includes formulas to calculate energy levels and angular momenta very precise atomic scale. QM is inadequate to describe the propagation of electromagnetic energy and fails even at the simplest experimental arrangements such as the double slit experiment. The main reason is that the QM knows no no (linear) superposition measurable amplitudes. The spatial extent of quantum mechanical problems is essentially limited to the size of molecules.
- The wave theory explains excellently all interference experiments, because for amplitudes of electric and magnetic fields, the linear superposition principle applies. Nothing depends on the absolute value of the amplitudes. The wave theory does not prescribe any discrete values for amplitude, the energy of the waves is incidental. The spatial dimension of typical applications is considerably larger than the extension of molecules.

Linking the formulas for momentum and energy density

Electromagnetic waves and photons have the (linear) pulse $\vec{p}$, whose direction coincides with the direction of propagation. Limiting to the amount of the pulse, in QM the formula $p=\frac{h}{\lambda}=\frac{h\,f}{c}$ describes a single photon. This formula contains no indication for the volume of a photon, so far there are no corresponding measurement results. From the perspective of the electromagnetic waves is amazing that the QM makes no distinction between near and far field, ie ignoring the distance between the radiation source and observation. That may be the missing link.

For an electromagnetic wave $\vec{p}=\varepsilon_0\int_V \vec{E}\times\vec{B}\,dV=\varepsilon_0\mu_0\int_V \vec{S}\,dV$ holds, where $\vec{S}$ is the Poynting vector. In the near field, the relationship between $\vec{E}$ and $\vec{B}$ is location-dependent, difficult to describe, and completely different than in the far field. Only at large distances from the source, ie in the far field, $\vec{E}$ and $\vec{B}$ are proportional and always include a right angle, the momentum is pointing in the direction of propagation. Therefore, in this area the formula can be simplified $p=\frac{\varepsilon_0}{c}\int_V E^2\,dV$. Since QM and Maxwell's equations both describe light, $h\,f=\varepsilon_0\int_V E^2\,dV$ must apply. A calculation using the energy density $u=\varepsilon_0 E^2$ has the same result.

A key element of this formula is the spatial extent and the volume of the wave packet. At this point it should be noted that the conventional representation of a wave is very problematic: The amplitude is usually described with the formula $A=A_0\sin\left(2\pi f\left(\frac{x}{c}-t\right)+\varphi\right)$, without limiting the allowable values of *x* and *t*. While this is mathematically convenient and simplifies the work, it describes an infinitely extended wave with infinite energy content. Thus, it can not describe the emission of a defined amount of energy in atomic processes. Only if the integration volume is limited, the electric field strength *E* can be measured and is not infinitesimally small. For this reason, a wave packet of finite extension is always assumed.

Linking the formulas for the angular momentum

For the angular momentum, both theories provide different formulas. In QM, each photon has the spin $s=h/2\pi$ that is oriented parallel or antiparallel to the direction of propagation. The angular momentum of the electromagnetic field is calculated again by integration over the total volume of the wave packet $\vec{J}_{Classic}=\pm\varepsilon_0\int_V \vec{r}\times(\vec{E}\times\vec{B})\,dV$. The use of the Poynting vector $\vec{S}$ simplifies this formula $\vec{J}_{Classic}=\pm\varepsilon_0\mu_0\int_V \vec{r}\times\vec{S}\,dV$. The sign decides the direction of rotation, whose axis is parallel to the propagation direction. It should be noted that the spin of the photon and the classical angular momentum are related by the formula $J_{Classic}=\sqrt{2}\cdot s$.

In the far field the wave packet of a circularly polarized electromagnetic wave is rotationally symmetric and a (finite) sequence of planar, circular wavefronts (of finite extent) transverse to the wave vector. The local area power density $S=\varepsilon_0 c\,E^2$ may have a different value at any point of the wave packet.

Cylindrical wave packet

Each wave packet has a limited length, the course of the intervening envelope is unknown, however. Common but unproven assumptions are bell-shaped and exponential decay of the amplitude.

Hereinafter, it is assumed the wave packet is a cylinder of radius R and length L, whose axis of symmetry coincides with the direction of propagation. The two integrals for momentum and total energy and angular momentum of the wave must have finite values. If the intensity of the wave has the constant value S everywhere in the interior of the cylinder and disappears in the outer space, the calculation with cylindrical coordinates is very simple and leads to

$$J=\pm\varepsilon_0\mu_0 S\int_0^L\int_0^R\int_0^{2\pi} r^2\,dz\,dr\,d\varphi=\frac{\pm 2\pi}{3}\varepsilon_0\mu_0 S L R^3=\frac{\pm 2\pi\varepsilon_0 E^2 L R^3}{3c} \quad .$$

Since QM and Maxwell's equations describe the same physical phenomenon,

$$3\sqrt{2}hc=4\pi^2\varepsilon_0 E^2 L R^3 \qquad (1)$$

must apply for the angular momentum and

$$hf=\varepsilon_0\int_V E^2\,dV=\varepsilon_0 E^2\pi R^2 L \qquad (2)$$

to the energy. These two equations are conserved quantities of a cylindical wave packet, from which one can calculate the radius $R=\frac{3\sqrt{2}c}{4\pi f}=\frac{3\sqrt{2}\lambda}{4\pi}$. Interestingly, a similar value was calculated in a completely different way and interpreted as the radius of a sphere[3].

Usual receiving antennas confirm this value. λ / 2 dipoles correspond approximately to the calculated diameter of a wave packet. Shortened dipoles cover only a fraction of the cross-sectional area of the cylinder and withdraw less energy from the wave packet. Extended dipoles hardly bring additional gain, because the parts far outside radiate more energy than they absorb. The diameter of the wave packet can also be an indication of the minimum diameter of photodiodes.

The formulas contain no indication of the length of the wave packet, which is why the coherence length L is used. Depending on the line width of the spectral line, L assumes values from the range $10^3\cdot\lambda<L<10^8\cdot\lambda$. Thus, the energy density $u=\frac{8\pi h f^3}{9c^2 L}$ and the electric field strength $E^2=\frac{8\pi h\mu_0 f^3}{9L}$ of the cylindrical wave packet are calculated. The value of the coherence length effects none of the subsequent results and may be selected as desired. The natural line width of optical spectral lines is very low when surrounding atoms interfere only slightly.[B]

Examples: The natural line width of the sodium D-line is about 10 MHz. Each wave packet contains about 10^7 oscillation periods, is 6 m long and carries the energy *hf*. At a wavelength of 600 nm, the wave packet is a very thin cylinder with 400 nm diameter and 6 m in length. The electric field strength inside the wave packet is about 226 V / m.

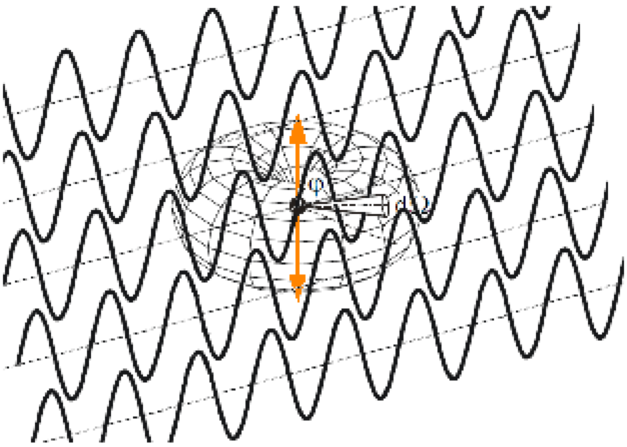
(B)Link: Natural line widths for spectral lines in the visible spectral range are approx. 10^{-14} m . This corresponds to a coherence time of approx. 10^{-8} s or a coherence length of 30 m. In commercial spectral lamps the temperature and pressure situation will, however, lead to a noticeable broadening of the spectral lines. The dominant effect of the line broadening in spectral lamps is pressure broadening. If during the light emission, impact with a further atom occurs, this leads to a change in the photon energy and/or the phase of the emitted wave and therefore to a change in the line width. This effect is linearly associated with the gas pressure and leads to additional shifting of the spectral lines. A further part of line broadening is based on the Doppler effect because the atoms move statistically in space during the emission. This broadening mechanism increases linearly with the translation speed of the atoms and therefore with increasing temperatures T . In the visible spectral range the Doppler broadening exceeds the natural line width by approximately two orders of magnitude.

The HI-line of hydrogen at 1420 MHz has a half width of about 5 kHz. The distance between the hydrogen atoms in the gas cloud is so large that independent wave packets are generated. The formula $\Delta\lambda \cdot L \approx \lambda^2$ gives a coherence length of 60 km and a volume of 960 m³. The energy density is very low and the electric field strength is only 10^{-8} V / m. Under optimal conditions, each wave packet induces a voltage of 1 nV in a λ / 2 dipole. This is below the detection limit of radio telescopes, so a signal can only be registered when the amplitudes of several wave packets add up. This is obviously not a problem, given the large coherence length.

In the X-ray range the wavelength is at 1 pm, the coherence length shrinks to $L \approx 1000\,\lambda$ and the electric field strength increases to about 10^{16} V / m. This means that all atoms can be ionized.

The red shift at low energy loss

A right-circularly polarized wave has the electric component $\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = E_0 \begin{pmatrix} -\sin(\omega t) \\ \cos(\omega t) \\ 0 \end{pmatrix}$ and the magnetic component $\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = B_0 \begin{pmatrix} -\cos(\omega t) \\ -\sin(\omega t) \\ 0 \end{pmatrix}$. The Poynting vector $\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} = \frac{E_0 B_0}{\mu_0} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$ is constant, pointing in the direction of wave propagation and has the value $S = \frac{8\pi h f^3}{9 c L}$. *L* is the length of the wave packet. Because the wave packet carries finite energy, the field strength and the magnetic field are zero outside the period $0 \le t \le L/c$.



On the way to Earth, the light passes through the interstellar medium (ISM), a "warm ionized gas" temperature of 8000 K, about 20% to 50% of all atoms are ionized. With the help of radio astronomy, the mean density of free electrons of $4 \cdot 10^5$ per m³ was calculated, resulting in an average distance of electrons of d ≈ 14 mm[4 5]. In the intergalactic medium (IGM), the average distance is estimated to be about 10 m. Each unbound electron that is "touched" by the wave packet, absorbs a tiny amount of energy

$$e_1 = \sigma_{Elektron} \int_0^{L/c} S\, dt = \sigma_{Elektron} \frac{8\pi h f^3}{9 c^2}$$, where

$\sigma_{Elektron} = 6.65 \cdot 10^{-29}\, m^2$ is the classical scattering cross section of the electron. An unbound electron is structureless and is not in a potential well. Therefore, it can not store energy and radiates symmetrically, as shown in the picture for a vertically accelerated electron.

Below it is shown that the tiny energy loss reduces the frequency of the wave packet. At a frequency of 1420 MHz, no electron can absorb all the energy of the wave packet because the apparent cross-section much, much smaller than the cross-sectional area of the wave packet (0.016 m²). For this reason, the electron can not scatter the wave packet and change its direction. Only in X-rays at much higher frequencies, the areas are comparable and you are in the region of Compton scattering.

Each unbound electron takes away a tiny fraction e_1 from the the wave packets total energy *hf*. Planck's theory describes the smallest possible change of energy of a physical system that can oscillate harmoniously. Only then applies $W_{min} = hf$. An unbound electron experiences no restor-

ing force into a rest position and is therefore not an oscillator. Hence an unbound electron can take away an arbitrarily small amount of energy from the wave packet and emit it immediately.
If the wave packet comes from the distance *D*, traversing a region with the average electron density n_e, it affects $N = n_e \cdot V = n_e \left(\frac{3\sqrt{2} c}{4\pi f} \right)^2 \pi D$ electrons. These electrons reduce the energy of the wave packet by the energy $V = N e_1 = n_e \left(\frac{3\sqrt{2} c}{4\pi f} \right)^2 \pi D \sigma_{Elektron} \frac{8\pi h f^3}{9 c^2} = n_e \sigma_{Elektron} h f D$. Because every electron radiates symmetrically, as shown in the picture for a vertically polarized electromagnetic wave, the wave packet undergoes no transverse momentum, its direction is not changed.

Reduced electric field strength or reduced frequency?

For small distances, the condition $V \ll hf$ is satisfied and it can be assumed that the diameter of the wave packet is constant. *Before* the wave packet touches the free electrons, the above derived formulas $3\sqrt{2} h c = 4\pi^2 \varepsilon_0 E_1^2 L_1 R_1^3$ and $h f_1 = \varepsilon_0 E_1^2 \pi L_1 R_1^2$ apply. *After* the wave packet has passed all the electrons and lost some energy, the formulas $3\sqrt{2} h c = 4\pi^2 \varepsilon_0 E_2^2 L_2 R_2^3$ and $h f_2 = \varepsilon_0 E_2^2 \pi L_2 R_2^2$ apply. These four equations must be satisfied. That is a law of conservation.

From the classical point of view, any energy loss is equivalent to a reduction of the amplitude and the electric field strength of the wave packet. The frequency should be constant.

As QM does not deal with the electric field strength of the wave packets, any energy loss is equivalent to a reduction of the frequency.

QM and classical wave theory contradict each other−who wins, because the formulas of both areas are linked?

From the assumption of a constant frequency $f_1 = f_2$ follows $R_1 = R_2$ and $E_1^2 L_1 = E_2^2 L_2$.
Then neither energy nor angular momentum of the wave packet would change, a contradiction to the previously calculated energy loss. That would mean that there is no Thomson scattering - incompatible with the experimental experience.
If a frequency change is *not* excluded, the energy loss $\frac{3\sqrt{2} c h (R_2 - R_1)}{4\pi R_2 R_1} = h(f_1 - f_2)$ is the only solution of these four equations. QM is the winner. The frequency decreases, the radius of the wave packet increases. With low energy loss, the relative frequency shift[C 6] has the value

$$\frac{\Delta f}{f} = z = n_e \sigma_{Elektron} D \quad . \qquad (3)$$

This formula satisfies some astronomical observations:

- z does not depend on frequency or wavelength
- z does not depend on the coherence length or intensity of the wave packet
- at small distances ($\sigma_{Elektron} n_e D \ll 1$), z is proportional to the distance *D*

(C)The calculation of the energy loss in the comparatively much larger Fresnel zones leads to a similar result. Because of the lower energy density of the calculated factor $w = \frac{3 q_e^4 \mu_0^2}{512 \pi m_e^2} = 2.33 \cdot 10^{-30} m^2$ is smaller than $\sigma_{Elektron} = 6.65 \cdot 10^{-29} m^2$.

The comparison of the above approximation $z = n_e \sigma_{Elektron} D$ with the Hubble formula $c z = H_0 D$ yields $c \sigma_{Elektron} n_e = H_0$. Using the currently accepted value of the Hubble constant $H_0 \approx 70 \frac{km}{s \cdot Mpc}$, the average electron density in vicinity of our galaxy is $n_e = \frac{H_0}{c \sigma_{Elektron}} \approx \frac{114}{m^3}$.

The redshift at large energy loss

If the distance or the density of free electrons is very large, the total energy loss increases and the condition $V \ll hf$ is not met, the radius of the wave packet increases markedly with decreasing frequency and the above assumption of a long cylinder with constant diameter is no longer acceptable. To calculate the total energy loss, the overall Distance *D* is divided into successive short cylinders of length $dx = \frac{\Delta f}{f n_e \sigma_{Elektron}}$. Integrating both sides and using the definition $f_{observed}(1+z) = f_{emit}$, one obtains

$$D = \frac{\ln(z+1)}{n_e \sigma_{Elektron}} \quad . \qquad (4)$$

This non-linear equation is valid for very large values of the redshift. The assumed Hubble linear relationship between redshift and distance is only an approximation for $z \approx 0$.

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