"QED – Matter, Light and the Void"

Scientific subject and topic:
Physical properties of light

Title / year:
"QED – Matter, Light and the Void" (2005)

Movie producer:
Science*e*motion

Director:
Stefan Heusler

Website of movie:
http://www.sciencemotion.de/

Description of movie:
In the first part of the DVD, the properties of light are shown in a puppet animation movie (30 Min.). Prof. Ethereal and his colleague Nick perform experiments about the physical properties of light and try to explain their results by using models. Not all of their explanations are complete, and not all of their ideas lead to correct conclusions. But their discussions and experiments impart methods of scientific research in a humorous way: A scientist should not be satisfied with just one theory and a corresponding experiment but should try to refine his methods of understanding nature, in this case with the final goal to comprehend the fascinating properties of light better and better.

In the second part of the movie, all the models and experiments are explained on a scientific level using mathematical formulas. In this part, facts of modern research are presented, culminating finally in the theory of quantum electrodynamics (QED). The level of the scenes (about 30) varies between high-school and university level, depending on the difficulty of the specific topic related to the question "What is light?"

Link to Trailer Site:
http://www.sciencemotion.de/

Buy DVD:
Order the DVD for EUR 20.00 plus shipping charge on the website
http://www.sciencemotion.de/

Technical Part, Chapter 2b

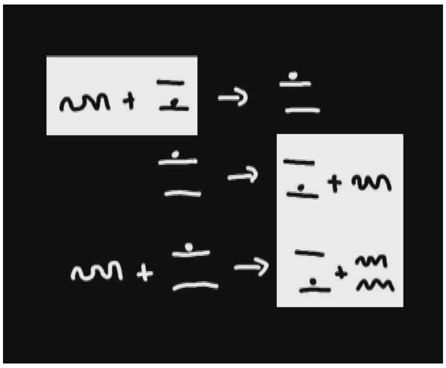
Title of scene:
Blackbody radiation

Video clip or still:
Chapter 2b, Technical Part

Author:
Stefan Heusler, Annette Lorke

Scientific keywords:
blackbody radiation, photons, quantization of radiation, Planck's constant

Description of scene:
We derive the formula for blackbody radiation on the basis that light is quantized in energy portions (photons) and electrons in the atom change their energy in steps. If the energy difference between two energy steps of an electron coincides with the energy of the photon, two different processes are possible. In the first reaction, the electron absorbs a photon and then jumps to a higher or excited energy level. In the second reaction, the electron emits a photon and falls down to a lower level.



It is crucial to note that the emission of the photon can be either "spontaneous" or "stimulated". These two ways of emission was an idea first introduced by Einstein. The idea gave the clue for one possible derivation of the formula describing blackbody radiation.

Author: Stefan Heusler, Annette Lorke
E-mail: sciencemotion@web.de

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Basic level

Light consists of many, many small portions of energy, called *photons*. These photons vary in their energy. For example, photons in blue light have more energy than in red light. These energy portions are absorbed and emitted by electrons in the atoms. An atom consists of a positively charged, very small nucleus and a big cloud of negatively charged electrons around the nucleus. If an electron absorbs a photon, it gains energy. If the electron emits a photon, it loses energy. We visualize this process of losing and gaining energy with a big staircase on which the electron jumps up or falls down the steps. The jump heights depend on the energy of the photons. Only if the photon's energy corresponds to the energy difference between the two steps the electron uses, can the electron manage to move on the energy staircase of the atom.

In each atom, the steps of the energy staircase have their specific height. Thus, only very specific light energy can be absorbed and emitted by each atom, depending on the height differences of its staircase. That's why for example cooking salt (NaCl) has a very specific colour if you burn it. The specific colours characterize an atom and occur because photons of a characteristic energy are emitted.

A *blackbody* is an object which can absorb *all* kinds of photons and therefore consists of many different atoms with all possible kinds of step heights on different staircases. *Blackbody radiation* is called the mixture of different kinds of photons which are permanently emitted and/or absorbed by the blackbody depending on its temperature.

Blackbody radiation serves as a good approximation for the radiation emitted by materials which consist of several different atoms. Therefore, scientists don't need any details about such an object to describe the nature of its radiation. Only the object's temperature must be known. For example, the radiation emitted by the surface of the sun can be described very well as blackbody radiation. For a hot coffee you needn't any details about the coffee's ingredients to explain the characteristics of its radiation. The only difference between the radiation of the sun's surface and the hot coffee is the temperature: The sun's surface has a temperature of about 5000° C, thus emitting photons in the visible range. The hot coffee has a temperature of about 50° C, thus emitting photons in the invisible infrared range (heat radiation).

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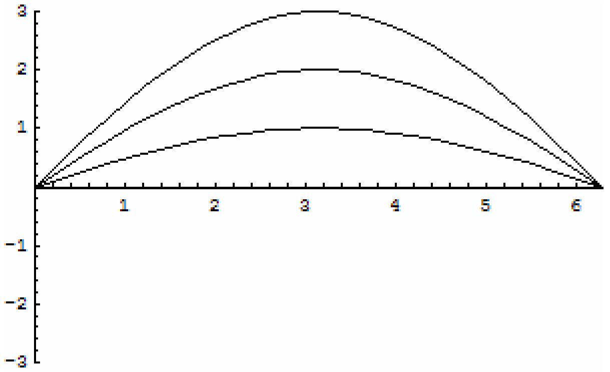
Advanced level

At the beginning of the 20th century, blackbody radiation was an important topic in physical research. It caused a big problem because the experimental results did not match the classical theory of light and, more general, of electromagnetism. Max Planck and Albert Einstein found the solution to this problem, which became a cornerstone to the theory of quantum mechanics.

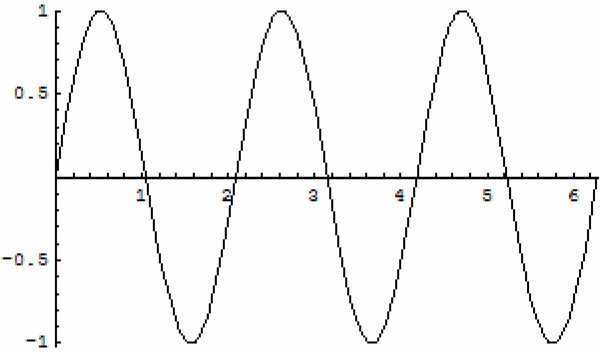
For simplicity we assume the blackbody to be a one-dimensional object of the length $L = 2\pi \approx 6.28$. In classical physics, light is understood as a continuous electromagnetic wave. In the one-dimensional object, we consider electromagnetic waves which vanish at its boundaries, $x = 0$, $x = L$. We describe the electric field $E[x]$ as

$$E[x] = E_0 \, \text{Sin}\left[\frac{2\pi}{\lambda} x\right]$$



In the opposite illustration, we show the electric field with the wavelength λ which is twice as large as the object. $\lambda = 2{*}L$ is the longest possible wavelength which fulfils the boundary conditions, $E[0] = 0$, $E[L] = 0$. The figure illustrates the amplitude with three different values $E_0 = 1, 2, 3$. In classical electromagnetism, the *energy* depends on both the wavelength λ and the amplitude E_0. The larger the amplitude E_0, the higher is the energy contained in the electric field.
For $E_0 = 0$, there isn't any wave. Therefore the energy must be zero. The crucial point is that in classical electromagnetism *any value* for the amplitude E_0 is allowed. This turns out to be wrong in quantum mechanics as the energy is quantized. E_0 can only change in steps.

There are more solutions to the electric field $E[x]$ which fulfil the boundary conditions, $E[0] = 0$, $E[L] = 0$.



In this figure, exactly 3 wavelengths ($\lambda = 1/3{*}L$) fit into our one-dimensional object. The corresponding electric field reads:

$$E_6[x] = E^6{}_0 \, \text{Sin}[3\,x]$$

On the right hand side of the equation, we call $E^6{}_0$ the amplitude corresponding to the wavelength $\lambda = 1/3*L = 2/6*L$. In the figure, we have chosen the example $E^6_0=1$. The shorter the wavelength λ, the higher is the energy of the electric field. In general, we may write:

$$E_n[x] = E^n{}_0 \, \mathrm{Sin}\left[\frac{n}{2}\, x\right], \quad n = 1,\ 2,\ 3,\ 4,\ \ldots$$

By definition *all* possible wavelengths which fulfil the boundary conditions E[0] = 0, E[L] = 0 occur in a blackbody ($\lambda = 2L/n$, n = 1, 2, 3...).
If we sum up the energy of all these possible wavelengths, the resulting field energy diverges since an infinite number of wavelengths, which become smaller and smaller, increase the energy. This is the so-called ultraviolet catastrophe because infinite field energy has nothing to do with the measured radiation spectrum.

To cure this problem, scientists argued that the amplitude $E^n{}_0$ of radiation with very high energy ($n >> 1$) must be small. In classical thermodynamics, this can be described by using the so-called Boltzmann factor. This assumption is correct for very high energy ($n \rightarrow \infty$). However, nobody was able to derive the correct formula for finite n ($1< n < \infty$) within classical mechanics.

It was Max Planck who finally found the correct formula. He had to introduce a new constant to derive it: *Planck's constant* $h = 6.6*10^{-34}$ J*s. The unit of this new constant is "Energy times Time".
It was Einstein who finally found the correct *interpretation* of Max Planck's result: Light energy (in general, any radiation) is *portioned* or *quantized*. For example, a beam of red light consists of many, many photons with the energy E = h*v. The frequency of red light is given by about $4.3*10^{14}$ oscillations per second. The energy contained in one red light quantum therefore is given by:

$$E_{red} = h\,\nu_{red} = \left(6.6 * 10^{-34}\ J\ s\right)\left(4.3 * 10^{14}\ \frac{1}{s}\right) = 2.8 * 10^{-19}\ J$$

In contrast to the classical theory, the amplitude E_0^n for the red light wave cannot change continuously in the quantum field theory but changes in portions. The smallest possible portion is given by E_{red}, corresponding to the energy of one photon.

Websites about Blackbody radiation and Max Planck
http://en.wikipedia.org/wiki/Blackbody
http://en.wikipedia.org/wiki/Planck

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Scientific level

Max Planck derived the correct formula for the blackbody radiation in spite of his using the paradigm that light is a classical electromagnetic wave: The radiation energy is proportional to the frequency and the square of the amplitude. Since the amplitude is allowed to have any value, the classical radiation energy can be changed continuously. Considering the *entropy* of the radiation field, Max Planck was able to find the correct formula. However, in the derivation, Max Planck was forced to introduce a new constant, and by comparing the experimental results for the blackbody radiation with his theory, he found $h = 6.6 \cdot 10^{-34}$ J*s, hence called Planck's constant.

The discovery of this constant was the birth of quantum mechanics. Max Planck was aware of the importance of his discovery, yet he couldn't foresee its consequences. Planck's constant indicates the scale on which the discontinuous structure of matter and light is observed. Any radiation is quantized according to E = h*v.

For any matter the position x and the momentum p cannot be observed simultaneously. Instead, both x and p are operators fulfilling the commutator

$$[x, p] = xp - px = i \frac{h}{2\pi}$$

The history of discoveries leading to quantum mechanics started with Planck's derivation of the blackbody radiation, continued with Einstein's quantization of light and finally ended up in atom physics with the discovery of the commutator of position x and momentum p. In combination with Newton's classical mechanics, this commutator facilitates the correct derivation of the quantized spectrum of atoms.