"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/

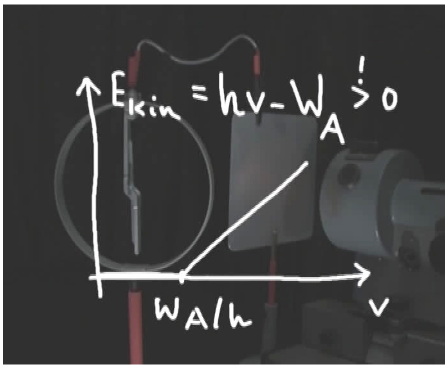
Title of scene:
The photoelectric effect

Video clip or still:
Chapter 2a, Technical Part

Author:
Stefan Heusler, Annette Lorke

Scientific keywords:
photoelectric effect, quantization of radiation, photons

Description of scene:
Our model of frogs in a prison yard is shown. Each frog represents an electron in a metal plate. If a frog wants to escape, it must jump over the wall *in a single leap*. If the height of the single lead is not sufficient, the frog will never free itself even if it jumps a thousand times. The leap energy of the frog corresponds to the photon's energy, which is converted into kinetic energy when the electron absorbs the photon.



In the following experiment the photoelectric effect is demonstrated: A metal plate is charged with electrons. The electrons can only escape from the metal plate into the air if they absorb ultraviolet radiation. Neither blue nor red light can release the electrons from the metal plate even if the light intensity is increased. Einstein was the first to find the correct explanation for the experiment:
All radiation (visible light, infrared, ultraviolet rays, etc.) is *quantized,* that means radiation consists of discrete portions of energy. These portions are called *photons.* A single photon can only have a certain portion of energy, which then can be absorbed completely by one electron. Only if the energy of the single photon is high enough, the electron can escape from the metal plate.

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Basic level

Imagine a frog in a prison yard or any other animal or person who tries to jump over the prison wall. You can even try it yourself. You can only jump over the wall if you jump high enough. If your jumps are not high enough, no matter how often you jump, you will never escape over the wall.
Albert Einstein won the Nobel price for explaining this basic idea. He understood what happens when light is shining on a metal plate. In the metal plate there are many electrons. Electrons are the negatively charged carriers of the electric current and can move freely in the metal. However they cannot escape from the metal. If light is shining on the metal, it is absorbed by the electrons. With the energy of the light, the electrons move faster. This fact was known before Einstein's explanation. Electrons absorb and emit light all the time. You can only see light because of this permanent absorption and emission. Einstein's discovery consists in the fact that this absorption and emission occurs in *jumps,* meaning that the light consists of little energy portions, the so-called *photons*, each reacting with an electron. It is like rain falling on a roof. Many raindrops together make a steady, continuous sound. But only under the first impression one hears a steady sound. After a while it becomes clear that in reality many little raindrops create single, discrete sounds.

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Advanced level

The central idea which led to the correct interpretation of the photoelectric effect is the fact that the elementary reaction between electrons and light is a discrete process: One electron reacts with one photon. Matter and radiation resemble each other because both display wave- and particle-like properties.

All electrons have the same electric charge e and the rest mass $m_0 \neq 0$. The electric current consists of many discrete electrons moving with different velocities. In 1905, Einstein discovered that a light beam features similar properties: It consists of many discrete photons with the energy E = h v. However photons do not have any rest mass ($m_0 = 0$) and therefore propagate through the vacuum always with the same velocity, $c \approx 300000$ km/s.
From classical electrodynamics, it is known that a light beam with the energy E carries a momentum p=E/c. Combining these two equations, we find:

$$E = pc = p\lambda v = hv$$

Thus, we are able to derive the relation between the photon's wavelength and its momentum p_{phot}, given by:

$$p_{phot.} = \frac{h}{\lambda}$$

A light beam shows interference effects. In 1923, de Broglie assumed that any object which has a momentum p necessarily can be assigned to a wavelength λ = h/p. An electron with the momentum p also has a wavelength through:

$$\lambda = \frac{h}{p_{elec.}} = \frac{h}{m\,v}$$

The wavelength of valence electrons has about the length $\lambda \approx 10^{-10}$ m for metals at room temperature. De Broglie postulated that electrons show interference effects.

In the case of Einstein and de Broglie it didn't take great mathematical skills to make a profound discovery. It was the courage to look at physical phenomena from an unusual perspective. Indeed, electrons show interference phenomena which are correctly described by the de Broglie wavelength. In 1929, de Broglie was awarded the Nobel price in physics for this discovery.

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Scientific level

The photoelectric effect was first observed by Heinrich Hertz in 1886. The correct interpretation was given by Einstein in 1905. It took quite a long time to overthrow the paradigm that light is a wave, maybe because all other experiments with light could be explained so well by using this assumption.

The electron was discovered by Thompson in 1897 and described as a massive, charged, elementary particle. One of science's little ironies is the fact that it took some while to overthrow the paradigm that the electron is just a particle. It was De Broglie who discovered the wave properties of the electron in 1923.

Both Einstein and De Broglie did not invent any new equation but interpreted existing equations in a new way. Max Planck had already used the relation between energy and frequency to derive his formula for blackbody radiation:

$$E = h\nu$$

In 1905, Einstein interpreted this equation correctly with his idea of the quantization of light energy. With the quantization of light it also became important to find an expression for the momentum p carried by the photon. From classical electrodynamics, the relation E = p c has been known since Maxwell's time. Combining it with the equation E = h v, we find:

$$E = pc = p\lambda\nu = h\nu$$

This leads to the relation:

$$\lambda = \frac{h}{p}$$

De Broglie postulated that this equation was not only valid for photons but was true in general. Any object which has a momentum can be viewed as a wave. Even a football has a wavelength. Why don't we see interference phenomena for a macroscopic football? This is because the wavelength is many times smaller than the size of the football. Decoherence makes the macroscopic world look classical and leads to the breakdown of interference effects. Recently, double-slit experiments with large molecules have become possible. For these experiments decoherence must be arduously decreased by minimizing the interaction between the quantum system and the environment. Thus the wave properties of larger objects can be observed. (http://www.quantum.univie.ac.at/research/matterwave/c60/index.html)

Websites about the photoelectric effect & De Broglie wavelength:

http://en.wikipedia.org/wiki/Photoelectric#Introduction
http://en.wikipedia.org/wiki/De_Broglie_wavelength