"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 4a

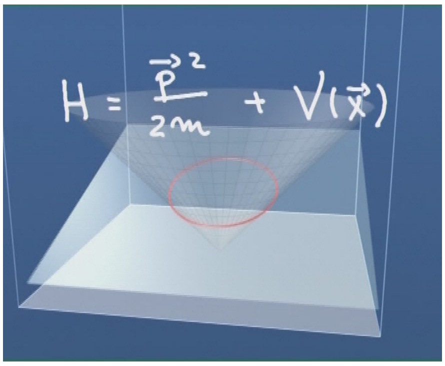
Title of scene:
The atom and the solar system

Video clip or still:
Chapter 4a, Technical Part

Author:
Stefan Heusler, Annette Lorke

Scientific keywords:
solar system, atomic model, Kepler and Newton, ellipses

Description of scene:



We show that an ellipse is obtained by intersecting a cone with a plane. According to Newton the equations of motion for the earth moving around the sun is solved by an ellipse. The gravitational force between the earth and the sun depends only on their distance r to each other and is proportional to $1/r^2$.

In classical physics, Newton's theory of gravitation has a striking analogy to Coulomb's law which was developed for electricity: Two electrically charged particles also feel a force which depends on their distance r and is proportional to $1/r^2$. For an atom which consists of a positively charged nucleus and negatively charged electrons, Newton's classical equations of motion provide the same solution as in the case of gravity. From the perspective of classical physics the atom would be similar to the "solar system" in which the atomic nucleus would play the role of the sun and the electrons would take over the part of the earth and other planets.

In contrast to the solar system Newton's classical theory does not work for the atom. The energy of the electron in the atom can change only in steps and not continuously. The portioned change of the electron's energy corresponds to the quantized energy of photons. For this reason, a new theory for the atom had to be developed, a theory which is called *quantum mechanics*.

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

Movie: QED – Matter, Light and the Void
Movie clip: Chapter 4a, Technical Part
Director: Stefan Heusler
Film Studio: Science*e*motion, www.sciencemotion.de

Basic level

Astronomy is the oldest science. More than 350 years ago, Johannes Kepler was able to find simple laws which describe the motion of the planets. The most important of Kepler's laws says:
The planets circle the sun in elliptical orbits. The sun is situated in one focus of the ellipse.

If you don't know what an ellipse is, go into a dark room with a pocket torch. The light which shines onto the wall has an oval shape. The boundary of this oval is an ellipse.

Even more important than the fact that planets circle the sun in ellipses is the statement that planets really orbit the sun! At Kepler's time, most people had not come to believe that the sun is the centre of our solar system.

Isaac Newton made a very great discovery in the history of science by *calculating* the motion of the planets. With this calculation, he showed that mathematical formulas and the observations of nature were deeply related. Due to Newton's success, science rapidly developed. Many more relations between observations of nature and mathematical formulas have been discovered since then.

Mathematical formulas are the *language* to describe the laws of nature. For example, Newton discovered that the force between the earth and the sun is in inversely proportional to the square of their distance. This allowed him to *calculate* the motion of the earth around the sun. Ellipses are the result of this calculation and show the motion of all the planets around the sun.

However, about 200 years later, some observations were made which could not be explained with Newton's laws. The atom cannot be depicted as a tiny solar system, with electrons orbiting the nucleus on ellipses.

If a "law of nature" (a mathematical model) is in contradiction to an experiment we have to refine our model and try to come closer and closer to the "true" law of nature. For this reason, quantum mechanics was developed at the beginning of the 20th century and generalized Newton's classical mechanics. Using quantum mechanics, the atom can finally be described mathematically and the calculated properties of the atom coincide with the experiment.

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

Movie: QED – Matter, Light and the Void
Movie clip: Chapter 4a, Technical Part
Director: Stefan Heusler
Film Studio: Science*motion*, www.sciencemotion.de

Advanced level

Newton had two surprisingly simple but essential ideas which allowed him to calculate the orbits of the planets around the sun:

A. A force F accelerates the earth with the mass m. The acceleration of the earth is directly proportional to this force and points in the same direction as this force.

B. The gravitational force between the earth and the sun is inversely proportional to the square of their distance.

Translated into mathematical equations, this gives:

$$\text{A.} \quad \vec{F} = m \frac{d^2 \vec{r}}{d t^2}$$

$$\text{B.} \quad \vec{F} = G \frac{m M}{|\vec{r}|^2}$$

Here, m is the mass of the earth, and M is the mass of the sun. We assume that all the mass of earth and all the mass of the sun are accumulated at one point. As origin of the coordinate system, we choose the centre of mass of the system "sun and earth". Since the sun is a great deal heavier than the earth, we may well approximate the centre of mass to the position of the sun itself. Then, |r| is the distance between the earth and the sun. With the equations A. and B. it is possible to find the time development of the distance vector between the earth and the sun while the earth is orbiting the sun. Newton did not only guess these equations, he also solved them and found an ellipse as the orbit! Moreover, he discovered that the sum H of the kinetic energy (1/2*mass* velocity^2) and the potential energy (V = -G*M/|r| at the position |r|) of the earth is preserved.

$$H = \frac{m}{2} \left(\frac{d \vec{r}}{d t} \right)^2 + m V(|\vec{r}|)$$

$$\frac{d H}{d t} = m \left(\frac{d \vec{r}}{d t} \right) \left(\frac{d^2 \vec{r}}{d t^2} \right) + m \left(\frac{d \vec{r}}{d t} \right) \frac{dV(|\vec{r}|)}{d \vec{r}} = 0$$

Mathematically, this is expressed by the fact that the derivative of the total energy H with respect to time vanishes. Therefore, the total energy H is a constant of motion. Indeed, we can demonstrate this in general by rediscovering Newton's law A:

$$m \left(\frac{d^2 \vec{r}}{d t^2} \right) = - m \frac{dV(|\vec{r}|)}{d \vec{r}} = \vec{F}$$

The force points towards the steepest gradient of the potential (see chapter 4a for the gradient field).
Actually, all these ideas and equations developed for the motion in our solar system are also valid in classical electromagnetism. We simply have to replace
(1) the gravitational charge "mass" with the electric charge, which can be positive or negative;
(2) the gravitational constant G with the corresponding constant for the electric force.

In particular, the force between electric charges is inversely proportional to the square of the distance, similar to the case of gravity.

However, Newton's theory completely fails for the description of the electron "moving" around the positively charged nucleus in the atom. In contrast to the orbits of the solar system not all values for the energy H are possible for the electron in the atom.
Only very specific values for H are allowed which depend on the kind of atom. As a model of H we have to choose an energy staircase as a discontinuous function, because H is not a continuous function any more.

How can we transform the energy H, which is a continuous function in classical physics, into a discontinuous energy staircase? What is necessary to jump from classical mechanics to quantum mechanics? The answer is related to the *commutator* between position and momentum.

Websites about Kepler & Newton and the scientific revolution
http://en.wikipedia.org/wiki/Isaac_Newton
http://en.wikipedia.org/wiki/Johannes_Kepler
http://en.wikipedia.org/wiki/Scientific_revolution

Website about the atom
http://en.wikipedia.org/wiki/Atom

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

Movie: QED – Matter, Light and the Void
Movie clip: Chapter 4a, Technical Part
Director: Stefan Heusler
Film Studio: Science*e*motion, www.sciencemotion.de

Scientific level

The classical description of the electron in the atom fails for two reasons:

1. If the electron was a point-like particle moving around the atomic nucleus, it would be *accelerated.* According to classical electromagnetism, accelerated electrons permanently radiate (like the Hertz dipole). Thus, the atom would be unstable.
2. Electrons in the atom could take on any energy according to classical mechanics. However, the spectrum of an atom is discrete. Only certain energy values are allowed.

It is fascinating that just *one* idea is sufficient to cure these problems. All we have to do is to introduce non-commutative variables for position and momentum.
The postulate that the commutator between position and momentum is proportional to Planck's constant h leads to an energy staircase with discrete energy levels.

$$H = \frac{\vec{p}^{\,2}}{2\,m} + m\,V\left(|\vec{r}|\right), \qquad \vec{p} = m\left(\frac{d\,\vec{r}}{d\,t}\right)$$

$$[r_k, p_l] = i\,\frac{h}{2\,\pi}\,\delta_{kl}$$

The step heights of the staircase in the hydrogen atom coincide very well with experimental measurements.