"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:
Scienc*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 virtual in the void

Video clip or still:
Chapter 5, Artistic part

Author:
Stefan Heusler, Annette Lorke

Scientific keywords:
quantum vacuum, anti-particles

Description of scene:

Prof. Ethereal and his assistant Nick look at a mammoth which is over 18000 years old. They discuss Dirac's theory of the electron which was developed in 1928. Models and theories in physics have much in common with biological evolution: As time goes by they compete with each other and either improve or become extinct. Metaphorically speaking only bones remain of the old ideas. But at its time each model had its reason to exist. Each step in the evolution of scientific knowledge is a great adventure.

Dirac's theory of the electron turned out to be incomplete when Lamb's experiments proved that the energy staircase of the hydrogen atom did not fully coincide with the mathematical predictions of Dirac's equation. Thus, the theory had to evolve further, with quantum electrodynamics as final result for the time being. The key idea which was missing in Dirac's theory was the self-interaction of the electron, the positron and the photon. This means that electrons, positrons and photons permanently interact with the *void*. Therefore a free electron, a free positron or a free photon simply does not exist.

Prof. Ethereal and Nick try to create the void which turns out to be quite difficult. Then, the professor develops his last model in order to explain what might happen to electrons, positrons and photons in the quantum vacuum.

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Movie clip: Chapter 5, Artistic Part
Director: Stefan Heusler
Film Studio: Science*e*motion, www.sciencemotion.de

Basic level

Imagine thousands of polished metal balls. In each of these balls all the other balls are reflected and can be seen. One real ball "contains" all the other balls as a virtual image. The virtual image of all the other balls in the real ball serves as a metaphor for the state of "nothingness" or the "void". Actually, nobody knows what nothingness is. In physics, we use a similar model of the void which behaves like the reflected metal balls that are *invisible* for our eyes and instruments. We cannot see these virtual balls directly. Only if a real, that is, a *visible* metal ball is used, can we detect the invisible balls by the reflection on the real ball. The void unfolds its effect only if we put a real metal ball into it. The void couples to the real ball by making thousands of invisible, virtual balls reflect themselves on the real ball.

You might wonder whether a *virtual* and thus invisible ball might become a *real* one under certain circumstances. The virtual electrons, positrons and photons store all possibilities, but only one of these becomes real and observable. It is a good question *which* of the virtual possibilities becomes real. But nobody really knows. The modern interpretation given by quantum mechanics is that each possibility has a certain *probability.* For a single reaction it is impossible to predict what the outcome will be. Throwing a dice is a similar thing. You only know that the result will be a number between one and six. However you cannot foretell which of the numbers will be seen after your throw. Each of the six numbers has a certain probability to show up.

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Advanced level

At the famous Shelter Island conference in 1947 the most important American physicists of that time gathered to discuss the status of quantum electrodynamics. During the Second World War Willis Lamb and Robert Retherford had improved radar technology for military purposes. After the war, when fundamental research could focus on non-military questions again, the improvements in radar technology proved to be very useful for experiments with the hydrogen atom. Just before the conference Lamb and Retherford had gathered enough data to prove that Paul Dirac's theory of the hydrogen atom was not completely correct. Their highly important results showed a minute deviation from Dirac's predictions. At the Shelter Island conference, this was one of the hottest topics to be discussed.

In Dirac's theory, the electron is assumed to be a point-like particle which feels the Coulomb force in the potential created by the atomic nucleus. An electron and its atomic nucleus interact with each other by exchanging virtual photons. However, in his theory Dirac neglected the potential which is created by the electron itself. In other words, the interaction of the electron with itself is neglected. This self-interaction can also be regarded as a virtual photon, which is emitted and reabsorbed by the electron. For this reason, a free electron simply does not exist. It is surrounded by a cloud of *virtual* particles which are in permanent interaction with the electron. In this manner, the electron interacts with the quantum vacuum even if there are no other real particles than the electron.

The virtual particles can have any amount of energy. But if you want to create e.g. a virtual photon with the energy $\Delta E = h^*v$, you need at least the time $\Delta t = h/\Delta E$. Therefore, the energy-time uncertainty relation must be fulfilled.

$\Delta t \geq h / \Delta E$ $\quad\quad$ $\Delta E \, \Delta t \geq h$

For very short times a huge amount of energy can be created in the quantum vacuum. Virtual particles cannot be observed directly but only indirectly due to their interaction with real particles.

In the language of classical electromagnetism, the self-interaction of the electron leads to a correction term of the 1/r Coulomb potential. For the electron in the hydrogen atom, r is the distance between the electron and the nucleus. The experimental data are explained very well if this correction term is included in the theory.
Permanent interaction with the quantum vacuum leads to a superposition of a free electron with virtual photons and electron/positron pairs. The state with virtual particles is suppressed compared to the single-particle state by the factor $\alpha \approx 1/137 \approx 0.0073$ (the 'fine structure constant'), which is a small number. Since the interaction with the quantum vacuum is small, the correction of Dirac's theory, which only considers the single-electron state, leads only to a minute change in the energy levels of the hydrogen atom.

Websites about the Shelter Island conference and the Lamb Shift:
http://en.wikipedia.org/wiki/Shelter_Island_Conference
http://en.wikipedia.org/wiki/Lamb_shift

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Scientific level

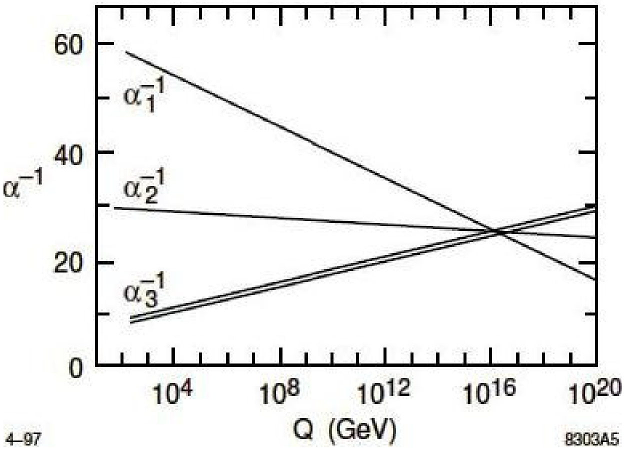
In particle accelerators, electrons are sped up close to the speed of light and gain an enormous energy. The higher the energy of the real electron gets, the more virtual particles become important. The fact that virtual particles change the 1/r-Coulomb law has been the key for the theoretical description of the Lamb shift in the hydrogen atom. It can be expected that the deviations from the Coulomb law become stronger and stronger, the higher the energy of the electron gets. The coupling strength between electrically charged particles depends on their energy. The fine structure constant $\alpha/(2\pi) = e^2/(h^*c)$ has the numerical value of roughly $\alpha = 1/137$ only at low energies. The *renormalized* electric charge e_R is a function of the energy on account of increasing fluctuations of the quantum vacuum at a higher energy. Therefore, the fine structure constant reveals itself to be a function of the energy $\alpha(E)$ („running coupling") and not a constant which is directly observable in particle accelerators. At the energy scale of weak interaction the electromagnetic coupling becomes stronger, $\alpha(90\ \text{GeV}) \approx 1/127$ (the resonance energy of the W^+, W^- and Z-bosons, $E \approx 90$ GeV).

The higher the energy, the stronger the coupling of the real electron becomes. It looks as if more and more virtual states from the quantum vacuum "wake up" and intensify the electric coupling.

The "running coupling" emerges also for the other interactions. In the standard model, the weak and strong interaction are described with quantum field theories which are deduced by using similar methods as in QED. The most important principles for the derivation of the corresponding field theory are (gauge) symmetries and relativistic invariance. It is not possible to predict theoretically *which* symmetry our world has. In the standard model, the symmetry is introduced so it corresponds to the experimental data.

In QED the "running coupling" becomes larger for high energies whereas for strong interaction it becomes smaller (the so-called asymptotic freedom). In contrast to photons, which are *neutral*, the strong interaction is mediated by charged particles. These coupling particles consist of eight different types of gluons which carry colour charge and attract or repulse each other.
In the case of weak interaction, three different coupling particles exist, namely the W^+, W^- and Z-bosons.
All coupling particles (the so-called 'gauge bosons') may not only carry electric charge, but also "hypercharge" and colour charge. Let's call α_1, α_2, α_3 the three running coupling parameters of the hypercharge (α_1), the electroweak (α_2) and the strong coupling (α_3).
At low energies, the hypercharge and electroweak gauge bosons orientate towards the electromagnetic interaction mediated by the massless photon, and towards the weak interaction mediated by the massive W^+, W^- and Z-bosons. This is related to the so-called "spontaneous symmetry breaking".
At energies much higher than 90 GeV, the electromagnetic and weak interaction can be unified in the electroweak theory, described by the two coupling parameters α_1, α_2. In the standard model, all three coupling parameters α_1, α_2, α_3 almost meet at one point at an extremely high energy (at about 10^{16} GeV). This is already a fascinating

hint towards the possibility that all these interactions stem from a single, *unified* theory, called GUT (grand unified theory). It was a fantastic discovery published in 1991 (Amaldi et. al.) that in a super-symmetric generalization of the standard model, all three couplings do meet at exactly one point. “Super-symmetry” simply means that each particle with a half-integer spin must have a “partner particle” with an integer



spin. Super-symmetry predicts the existence of an integer-spin partner particle of the electron, which has not been discovered yet.

The energy scale on which all couplings exactly unify is the so-called GUT-scale ($Q \approx 10^{16}$ GeV). At this enormous energy all forces, except for gravity, are unified according to this model. It is still an open question whether our world is super-symmetric or not. The next generation of particle accelerators (ATLAS at CERN) might give an answer to this fascinating question, hopefully by detecting super-symmetric partner particles of electrons, positrons....

Websites about gauge bosons

http://en.wikipedia.org/wiki/Fine_structure_constant
http://en.wikipedia.org/wiki/Running_coupling
http://en.wikipedia.org/wiki/Landau_pole
http://motls.blogspot.com/2004/10/gauge-coupling-unification.html