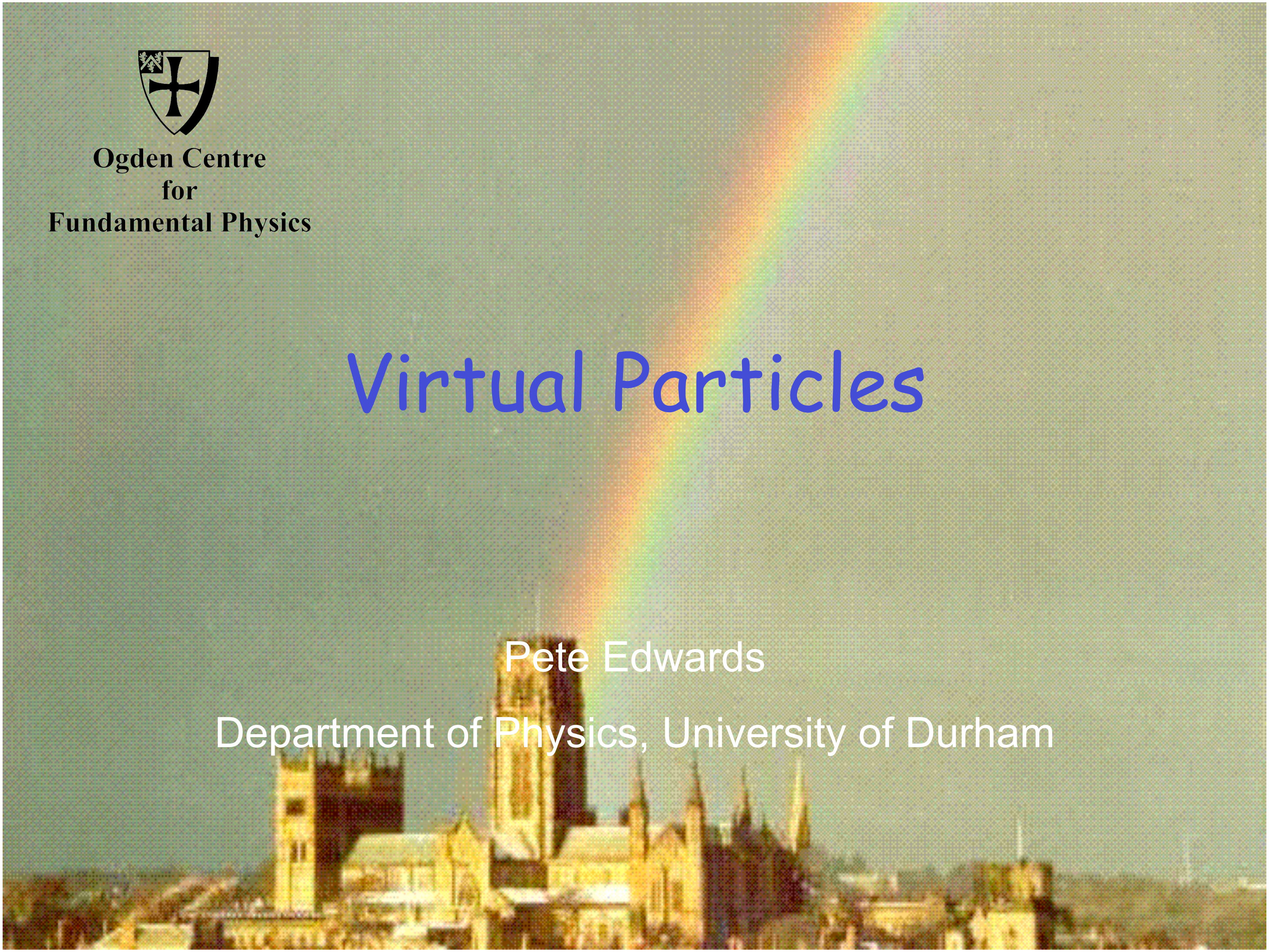


Ogden Centre
for
Fundamental Physics

Virtual Particles

Pete Edwards

Department of Physics, University of Durham

Uncertainty and virtual particles

In 1927, Heisenberg formulated a fundamental property of quantum mechanics which said that it is impossible to measure both a particles position AND its momentum exactly.

The more precisely we determine one, the less we know about the other.

This is called the Heisenberg Uncertainty Principle.

$$\Delta x \, \Delta p \geq \hbar / 2$$

Uncertainty and virtual particles

The principle can also be written in terms of energy and time:

$$\Delta E \, \Delta t \geq \hbar / 2$$

This means that the uncertainty in the energy of a particle multiplied by the uncertainty of time is greater than or equal to a constant.

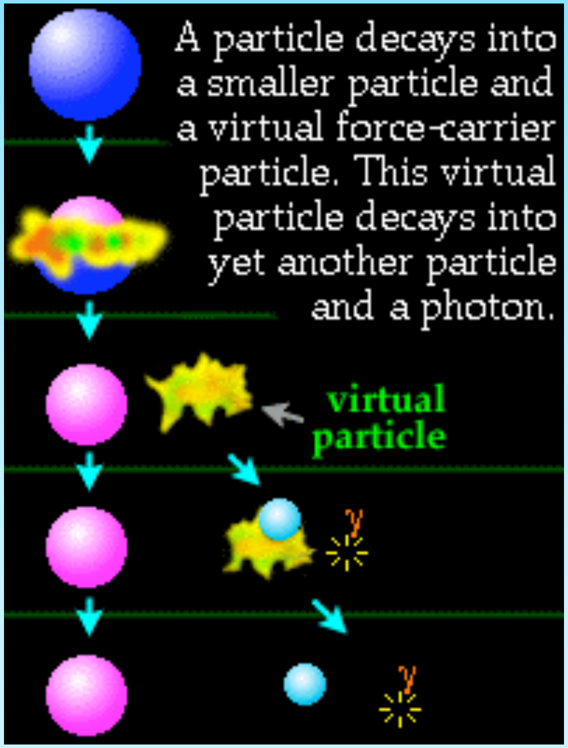
So for a very short time, the uncertainty in the energy can be large.

This leads into the idea of …………………

Virtual particles

In many decays and annihilations, a particle decays into a very high energy force carrier particle which almost immediately decays into a low energy particle.

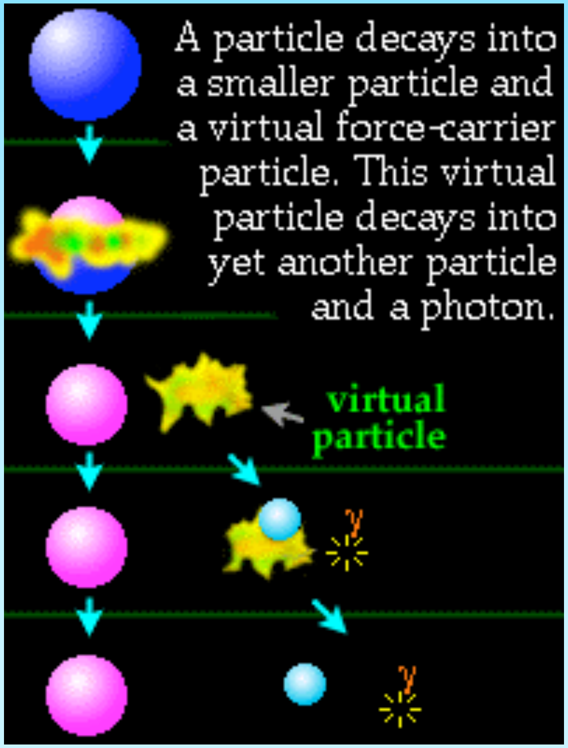
The conservation of energy seems to be violated by the apparent existence of these very energetic particles.



Virtual particles

However, according to the above principle, if the time for a process is exceedingly short, then the uncertainty in energy can be very large.

These high energy force carrier particles may exist if they are short lived. In a sense, they escape reality's notice.



Virtual particles

We can 'borrow' energy from the vacuum as long as we do it for a given time.

The more energy we 'borrow' the shorter the time we can have it.

Virtual particles

The bottom line is that energy is conserved.

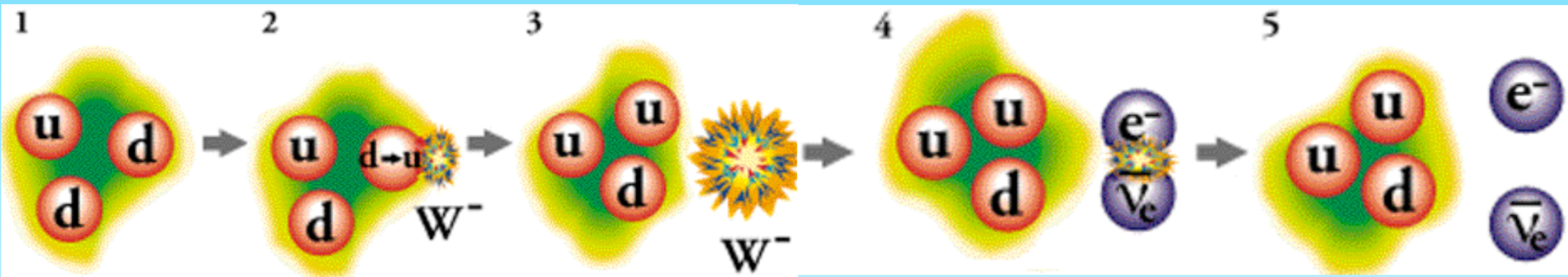
The energy of the initial decaying particle and the final decay products is equal.

The virtual particles exist for such a short time that they can never be observed.

Most processes among fundamental particles are mediated by virtual carrier particles.

Neutron beta decay

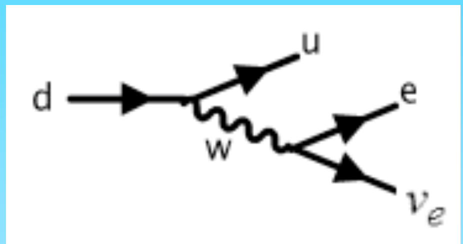
In beta decay a neutron (udd) decays to a proton (uud), an electron, and an anti-neutrino via a virtual (mediating) W boson.



The intermediate stages of this process occur in less than a billionth of a billionth of a billionth of a second, and are not observable.

Neutron beta decay

The Feynman diagram for this process is



Feynman diagrams have lines that represent mathematical expressions, but each line can also be thought of as representing a particle.

However, in the intermediate stages of a process the lines represent the virtual particles that can never be observed.

These particles do not obey the required Einstein relationship between their energy, momentum and mass.

$$E^2 = p^2c^2 + m^2c^4$$

Electromagnetic Force

Most processes among fundamental particles are mediated by virtual carrier particles.

This includes the forces between particles.

For example, the electromagnetic interaction between two charged particles (say two electrons) is understood to be due to the exchange of virtual photons.

This idea of force carrying virtual particles can be extended to the other fundamental forces.

The Casimir Effect: a force from nothing

According to quantum theory, the space inside a vacuum is not empty but is filled with a 'sea' of virtual particles.

Virtual photons are the most numerous as they are the easiest to 'make', since they have no rest mass.

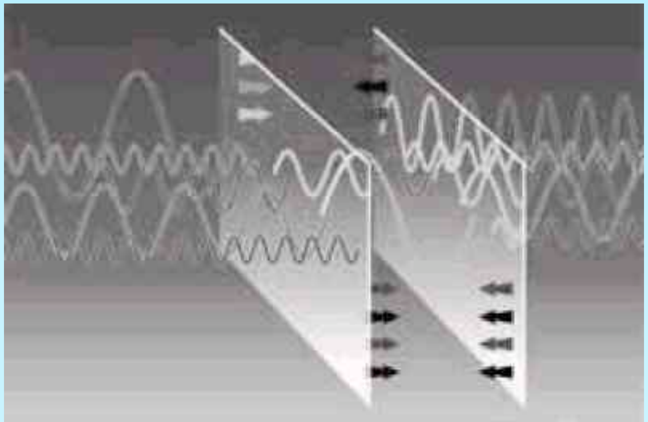
In the 1940s the Dutch physicist Hendrik Casimir suggested a way in which these quantum fluctuations could be detected.

The Casimir Effect: a force from nothing

Think of virtual photons as electromagnetic waves, then there is an infinite number of possible modes in all frequencies and directions in empty space.

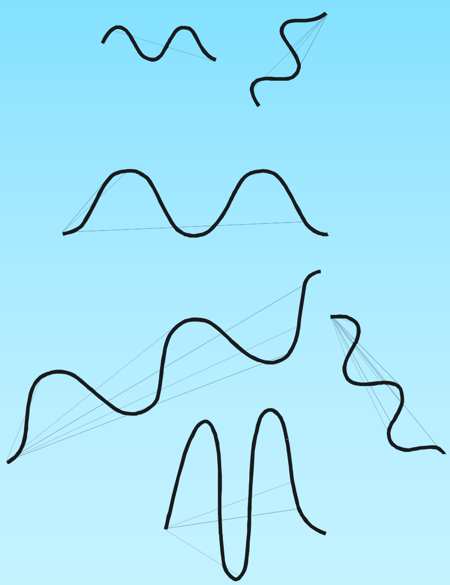
Suppose we place two highly reflective metal plates close to each other.

Inside the space between the plates, photons will be reflected from the walls and only virtual waves with certain wavelengths will 'fit' in the gap; all other modes will be excluded.

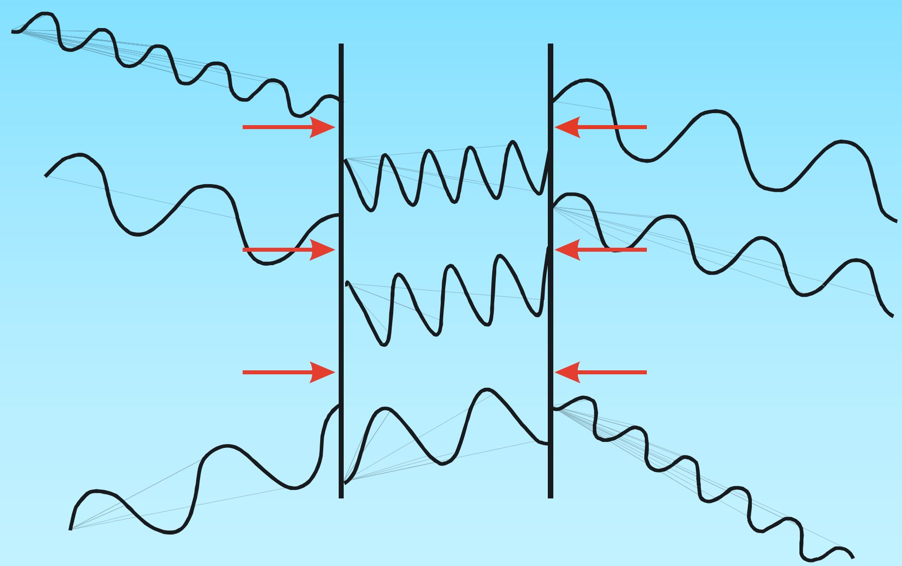


The Casimir Effect: a force from nothing

The number of vibrational modes of the virtual waves (all of which carry momentum and energy) is now greater outside the plates than between them.



In the vacuum, an infinite number of virtual photons can exist in all directions and with all frequencies.



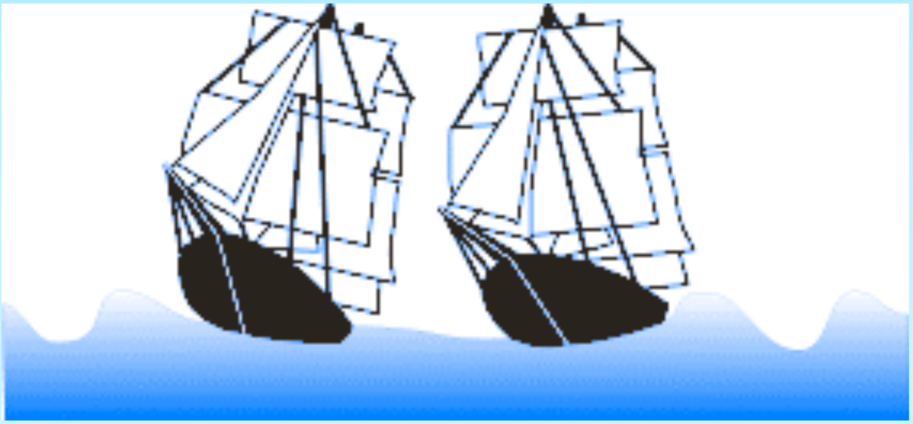
Only photons that 'fit' between the plates with an integral number of wavelengths are allowed. There are fewer virtual photons between the plates than outside.

The Casimir Effect: a force from nothing

There are fewer photons existing between the plates than outside them.

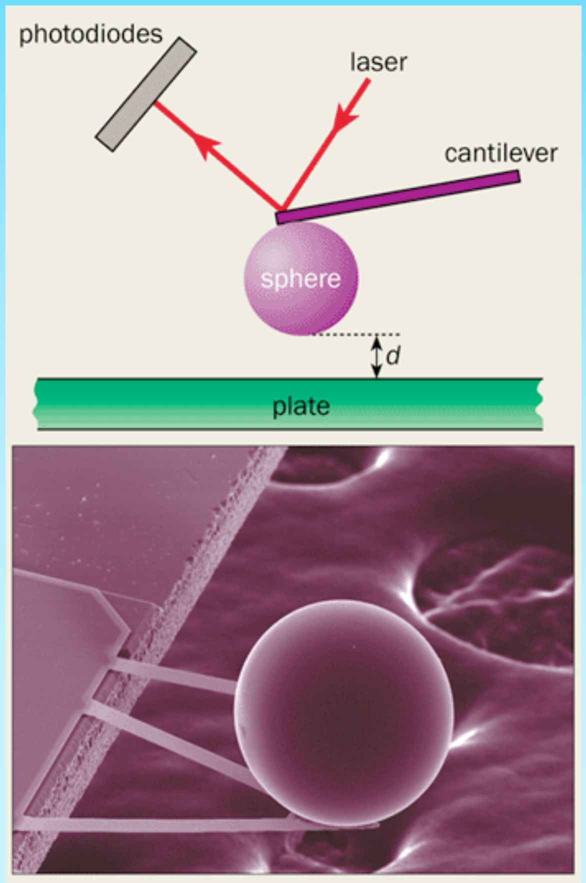
This imbalance means the plates have a net force or an excess 'vacuum fluctuation pressure' exerted on them externally.

This force pushes the plates together!



The Casimir Effect: a force from nothing

Experiments have shown the Casimir Effect does exist – we are surrounded by a sea of virtual particles.



A recent experiment used a polystyrene sphere 200 μm in diameter coated in gold. This was brought to within 0.1 μm of a gold coated flat disc.

The resulting attraction between them was monitored by the deviation of a laser beam.

The Casimir force was measured to better than 1% of the expected value.

Something from nothing

The idea of virtual particles came from the Heisenberg Uncertainty Principle which describes a fundamental property of nature on its smallest scale.

Most processes amongst fundamental particles are mediated by virtual carrier particles.

This includes the forces between particles.

Experiments to measure the Casimir Effect show that virtual particles do exist.

The space inside a vacuum is not empty, we are surrounded by a sea of virtual particles!

Credits

Thanks to the following sources for providing images:

Particle Data Group –
http://pdg.web.cern.ch/pdg/cpep/unc_vir.html
slides 4,5,8.

SLAC Virtual Visitor Centre –
http://www2.slac.stanford.edu/vvc/Default.htm
Slide 9.

PhysicsWeb –
http://physicsweb.org/article/world/15/9/6
Slides 11,15.

Animation on slide 10 © J.Eric Slone –
http://www.FeynmanOnline.com