

# **PARTICLE PHYSICS AND COSMOLOGY**

in the 20<sup>th</sup> century

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CERN

## **DISCLAIMER**

**This is a lecture about particle physics and cosmology.  
It covers about 100 years of ideas, theories and experiments.**

More than 50 Nobel prize winners on particle physics

Very difficult to be comprehensive, exact or in-depth

**This is a broad overview about the main discoveries.**

All that remains to do in physics is to fill in  
the sixth decimal place

(Albert Michelson, 1894)



Kinetic theory,  
Thermodynamics

Boltzmann

Maxwell

Newton

## Particles

## Fields

## Universe

## Technologies

Electromagnetic

Weak

Strong

Detector

Accelerator

1895

$e^-$

Brownian  
motion

Photon

Radio-  
activity

1900

1905

Atom

Special  
relativity

1910

Nucleus

Quantum mechanics  
Wave / particle  
Fermions / Bosons

1920

$p^+$

1930

$e^+$

$n$

Dirac  
Antimatter

Fermi Beta-  
Decay

Yukawa  
 $\pi$   
exchange

Galaxies; expanding  
universe

General  
relativity

Geiger

Cloud

1940

$\mu^-$

Dark Matter

Nuclear fusion

1950

$\tau^-$

$p^-$

$\pi$

Particle  
zoo

QED

P, C, CP  
violation

Big Bang  
Nucleosynthesi  
s

Bubble

Synchrotron

1960

$\nu_e$

$u$   $d$   $s$

Higgs

W bosons

Cosmic Microwave  
Background

$e^+e^-$  collider

1970

$\nu_\mu$

$c$

GUT

EW unification

QCD  
Colour

Wire chamber

Beam cooling

1975

$\tau^-$

STANDARD MODEL

SUSY

Superstrings

Inflation

1980

$\nu_\tau$

$b$

$W$

$Z$

$g$

Modern  
detectors

$p^+p^-$  collider

1990

$t$

3 generations

CMB Inhomogeneities  
(COBE, WMAP)

WWW

2000

$\nu$  mass

Dark Energy (?)

GRID

2010



Kinetic theory,  
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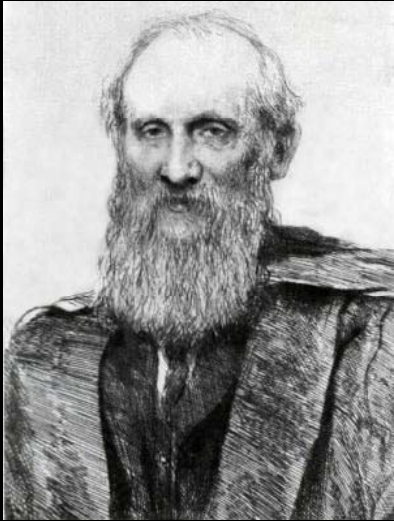
Dark Energy (?)

GRID

2010



**In the early 1900s, most physicists believed that physics was complete, described by classical mechanics, thermodynamics, and the Maxwell theory.**



**William Thomson  
(Lord Kelvin)**

Address to the British Association for the  
Advancement of Science, 1900

There is nothing new to be discovered in physics  
now, All that remains is more and more precise  
measurement.  
(Lord Kelvin, 1900)

But Lord Kelvin also mentioned two 'clouds' on  
the horizon of physics:

- 1) Blackbody radiation
- 2) Michelson-Morley experiment

1900

Universe = solar system and the stars of our galaxy

Nobody knew how the sun produced its energy

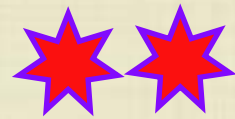
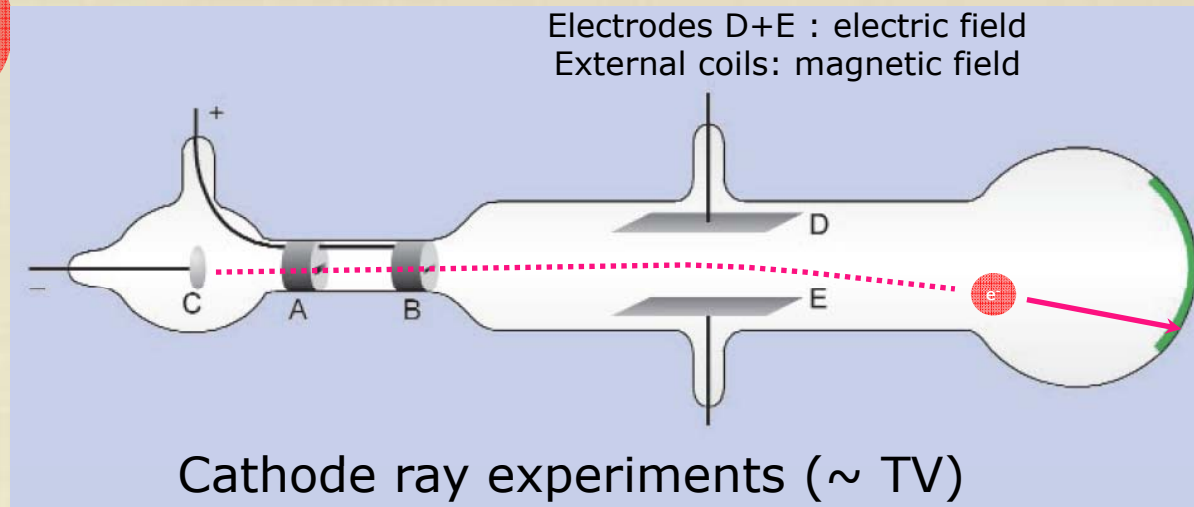
Nothing was known the structure of atoms and nuclei

Only two known fields: gravitation, electromagnetism

Nobody anticipated the incredible journey of physics in the next 100 years

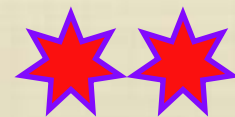
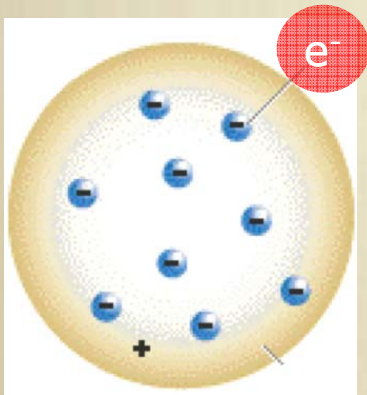


J.J. Thomson

 $e^-$ 

**'Rays' are charged corpuscles\*  
with unique charge/mass ratio**

**\*later called 'electrons'**



**Electrons are sub-atomic particles!**

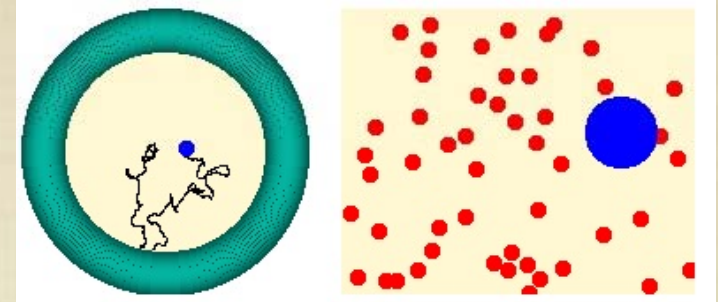
His 'plum pudding' model  
of the atom (1904)



Robert Brown (1827) observes random walk of small particles suspended in a fluid



Albert Einstein (1905) explains by kinetic theory that the motion is due to the bombardment by molecules

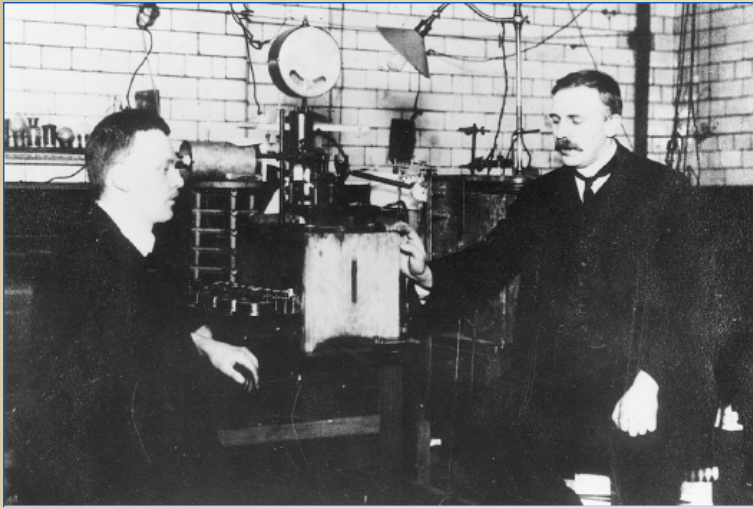


Francois Perrin (1907) uses Einstein's formula to confirm the theory and measure Avogadro's number

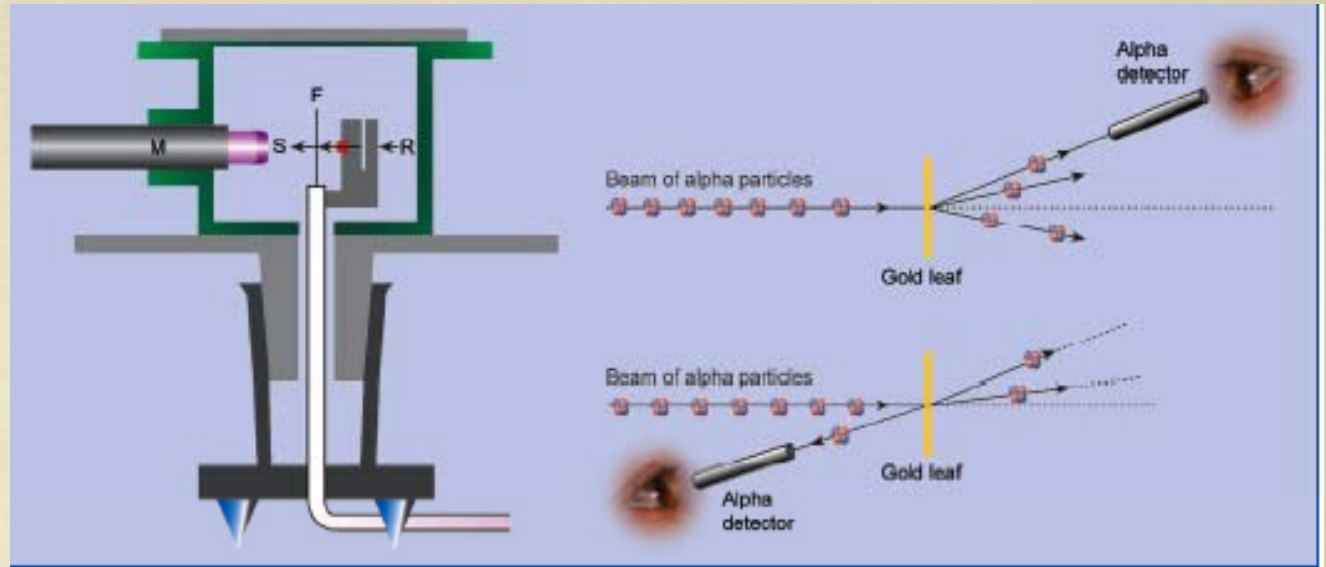
$$\langle x^2 \rangle = \frac{2kTt}{\alpha} = \frac{kTt}{3\pi\eta a}$$



**The existence of atoms was proven**



Ernest Rutherford (r) and Hans Geiger (l)  
in Manchester



Geiger and Marsden fired alpha particles (He nuclei) on gold foils  
1 in 8000 alpha particles were backscattered ( $> 90^\circ$ )

This could not be explained by the 'plum pudding model'

Rutherford's explanation: all the mass of the atom is concentrated in the nucleus

Size: At minimum distance, Coulomb repulsion = kinetic energy:  $\sim 27 \times 10^{-15} \text{ m}$  (true value: 7.3)



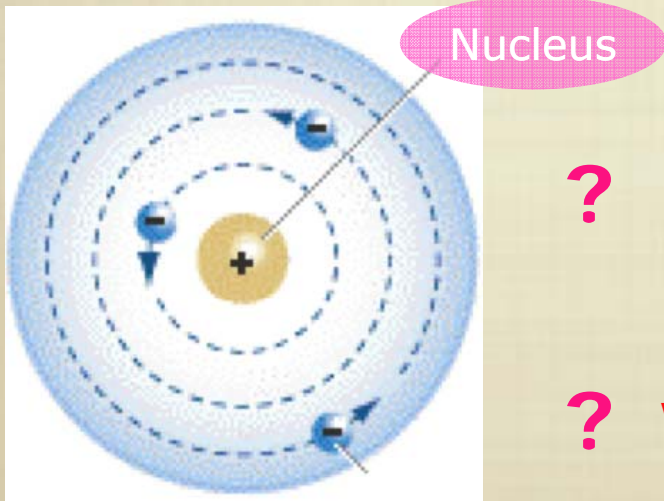
**Discovery of the nucleus**



Analogy with solar system:

If the nucleus had the size of the Sun

**the electrons would orbit in 1000 x the distance of Sun-Earth**



Rutherford's model  
of the "empty" atom

? How can electrons orbit a nucleus without radiating their energy?

? What is the nucleus made of ?

# PARTICLE SPECTRUM

1913



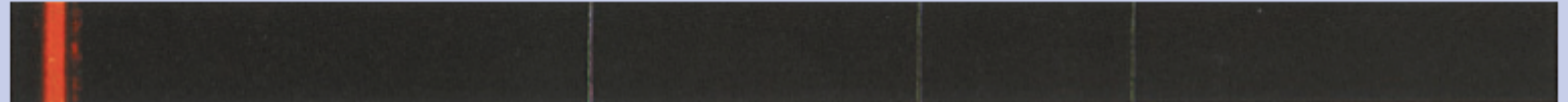
J. J. Balmer (1885) observed the emission spectrum of hydrogen

656.210 nm

486.074 nm

434.010 nm

410.12 nm



His empirical formula:

$$\lambda = \frac{hm^2}{(m^2 - n^2)}$$

Niels Bohr visited Rutherford in 1913

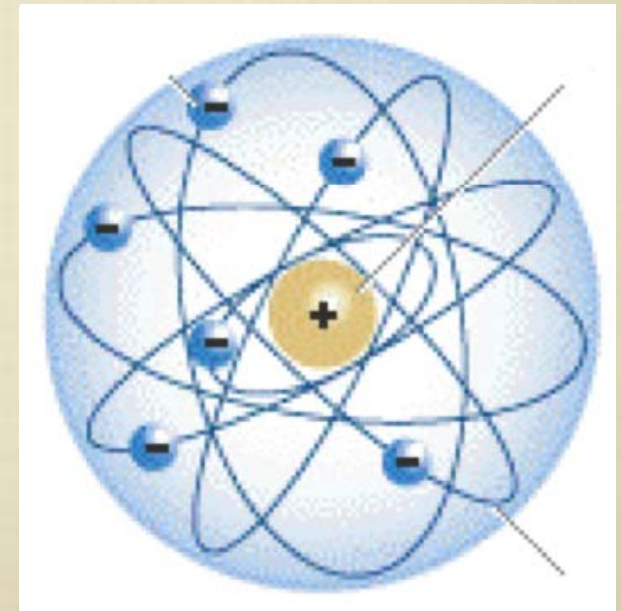
*he was the first to apply quantum ideas to atoms*

- Quantization of angular momentum -> energy levels

$$\mathbf{L} = n \cdot \hbar = n \cdot \frac{h}{2\pi}$$

$$E_n = \frac{-13.6 \text{ eV}}{n^2}$$

- Emission of radiation only during transitions
- Energy of photons = difference of energy levels





# PARTICLE SPECTRUM

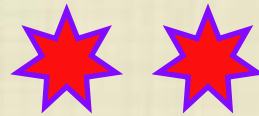
1923-1927

**It took 10 more years to understand the mysterious rules governing the atomic world: quantum mechanics.**

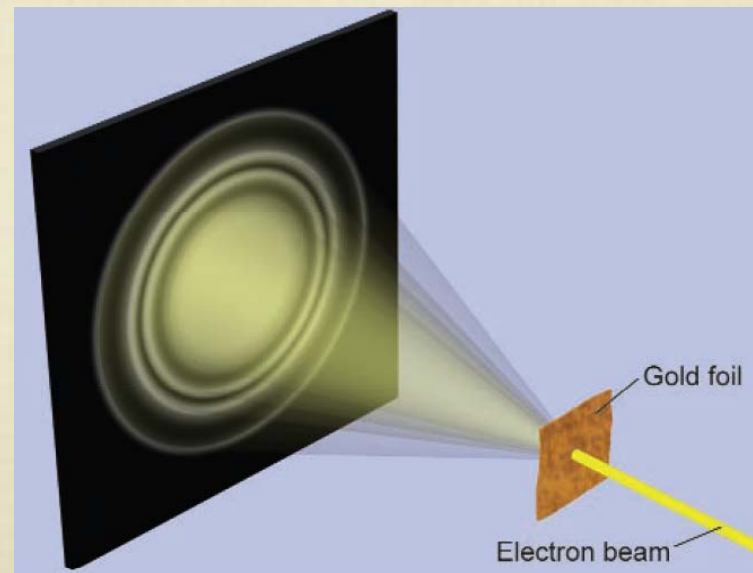


Louis de Broglie (1924)

Particles behave like waves



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



\*this hypothesis was confirmed in 1927  
by electron diffraction (Davisson/Germer)



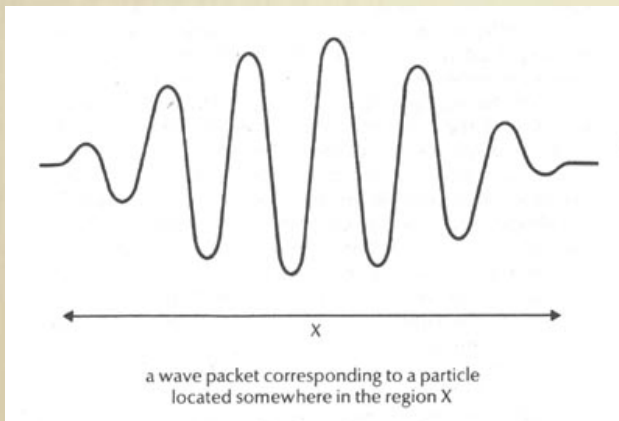
## Uncertainty relation

If particles are waves (of finite size), then there must be a limit to the precision of measurement between:

Heisenberg (1925)

Position and momentum

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$



Analogy:

Measurement time  $\Delta t$  of a signal leads to uncertainty of frequency (Fourier transform):

$$\Delta f \Delta t \sim 1$$

Energy and time

$$\Delta E \Delta t \geq \hbar$$





Schrödinger  
1926

## Probability wave function

Excellent description  
if  $v \ll c$

If particles are waves  $\rightarrow$  describe by a wave equation

$$H\psi(\mathbf{r}, t) = (T + V)\psi(\mathbf{r}, t) = \left[ -\frac{\hbar^2}{2m} \nabla^2 + V(\mathbf{r}) \right] \psi(\mathbf{r}, t) = i\hbar \frac{\partial \psi}{\partial t}(\mathbf{r}, t)$$

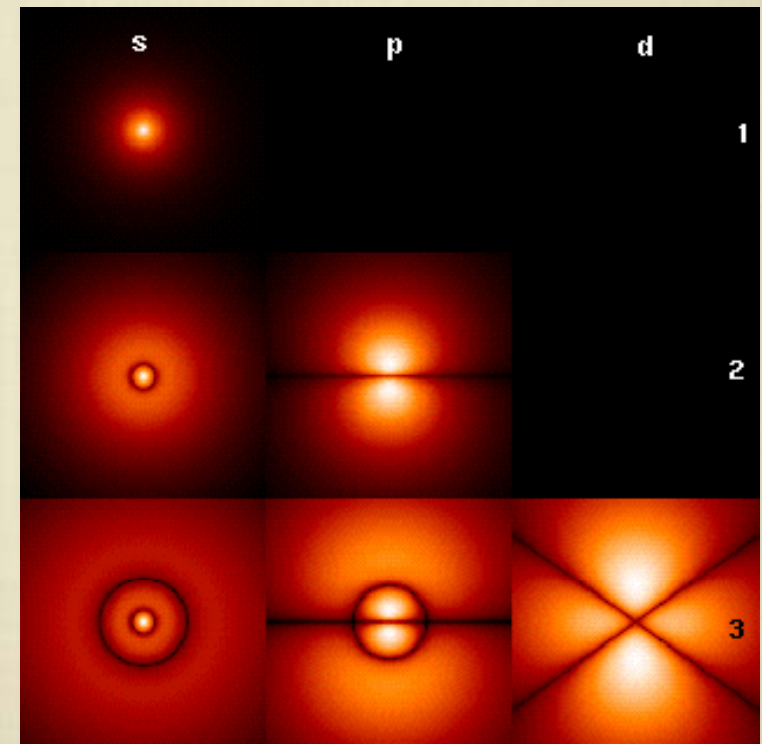


Interference:  $\psi$  = complex function

**Interpretation** (Bohr, 1927):

$\psi$  = probability amplitude

$|\psi|^2$  = probability



Electron wave functions in hydrogen atom  
(‘standing 3-dim waves’)

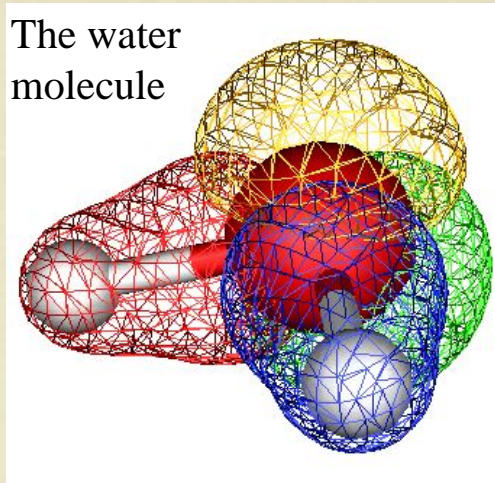
**Quantum physics explained the existence of 'structure' in nature**



Linus Pauling (1928)

## The nature of chemical bonds

The water molecule



Atoms, Molecules and the origin of structure were understood.

**And the atomic nucleus? Not much progress between 1911 - 1932.**

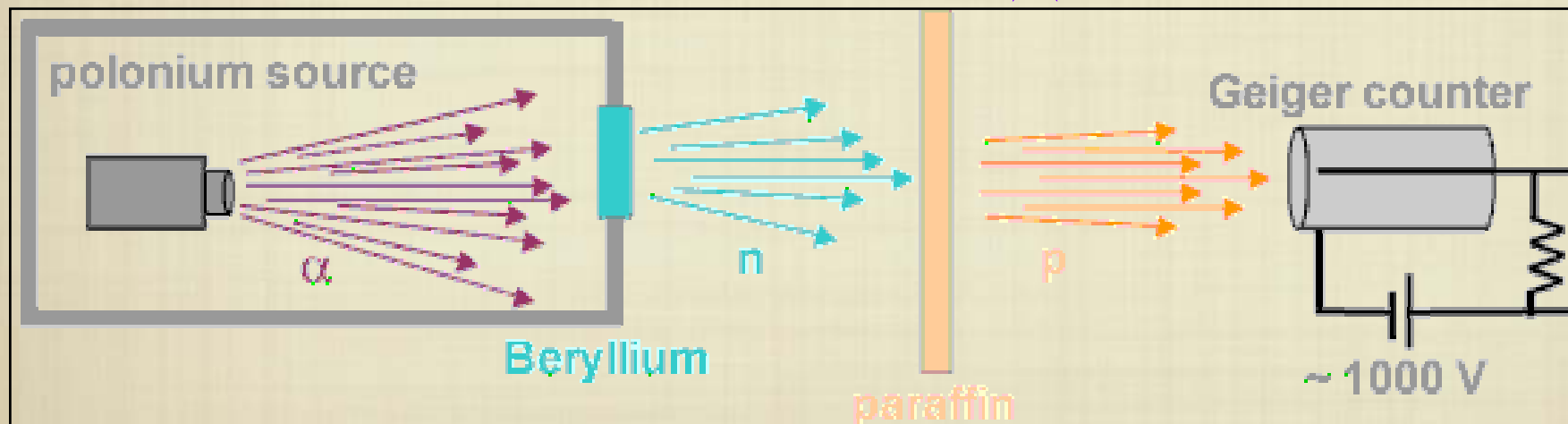
**What is the nucleus made of ?**

For example: He-4 has only  $Z=2$ ; what are the other two units of mass due to ?

**Heisenberg: Protons and electrons (4 protons and 2 electrons)?**

Did not work - the uncertainty relation forbids the presence of electrons in the nucleus!

**Chadwick (1932): The neutron**



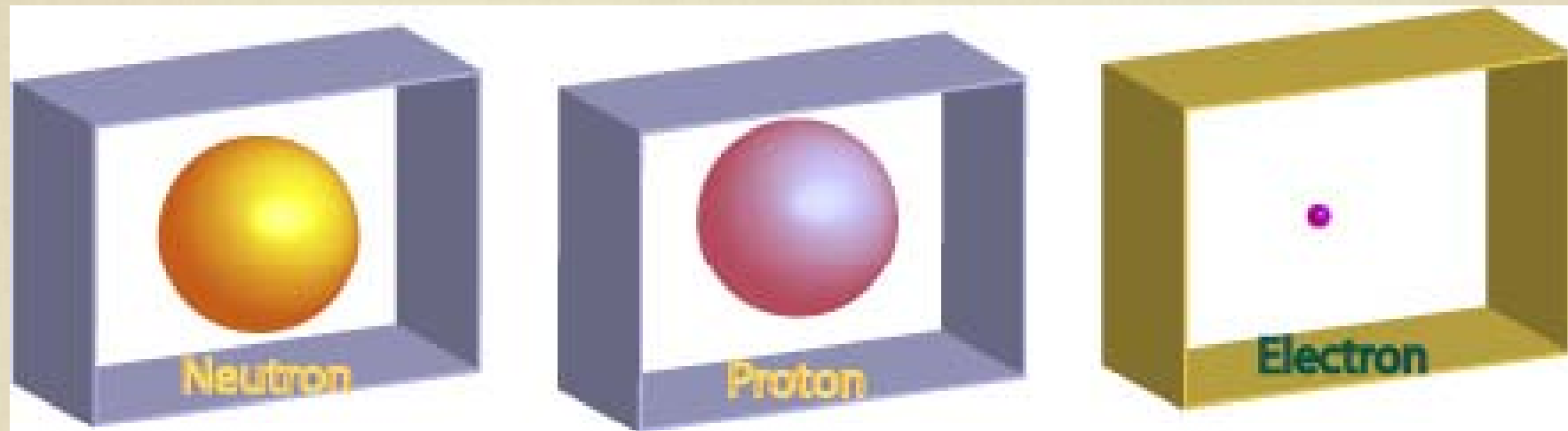
From kinematics: Mass of neutron  $\sim$  mass of proton

**What keeps everything together? Strong short-range interaction?**



# PARTICLE SPECTRUM

## Fundamental particle spectrum (1932)



**Simple, easy to remember  
Still taught at schools  
(usually in chemistry lessons)**

**What holds atoms and nuclei together?**

**1900: two fundamental interactions were known:**

$$F_G = G m_1 m_2 \cdot \frac{1}{r^2}$$

$$F_C = Q_1 Q_2 \cdot \frac{1}{r^2}$$



Gravitation

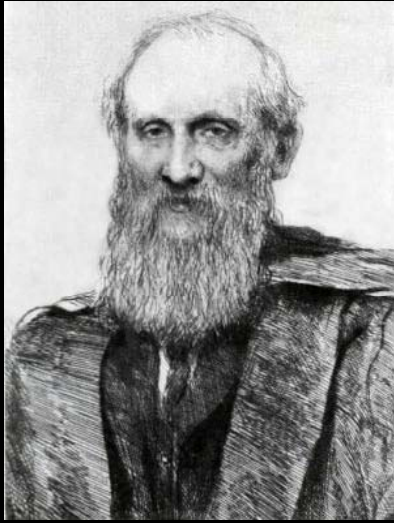


Electromagnetism

Similarities: both have inverse square dependence on radius

Differences: the strength of the forces is vastly different (38 orders of magnitude!)

**Remember: in 1900, there were two 'clouds' on the horizon of physics:**



**William Thomson  
(Lord Kelvin)**

**Two clouds:**

- 1) Blackbody radiation**
- 2) Michelson-Morley experiment**

**Their understanding would lead to**

- quantum theory**
- relativity**

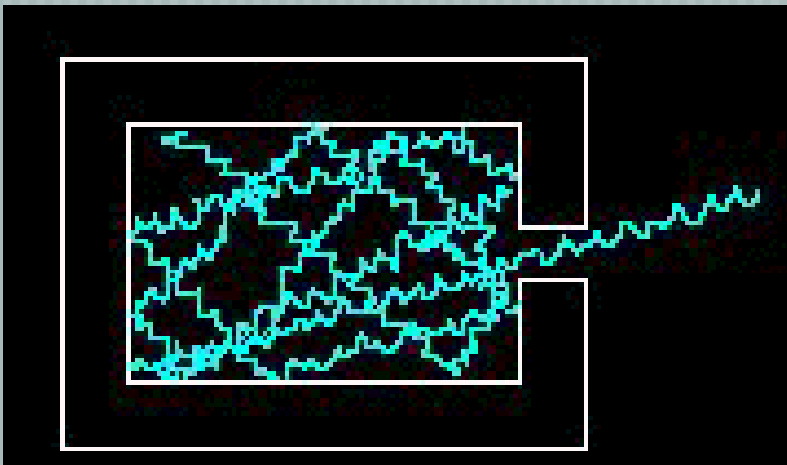


# Fields

'Electromagnetic' interaction

Photon

## Blackbody radiation

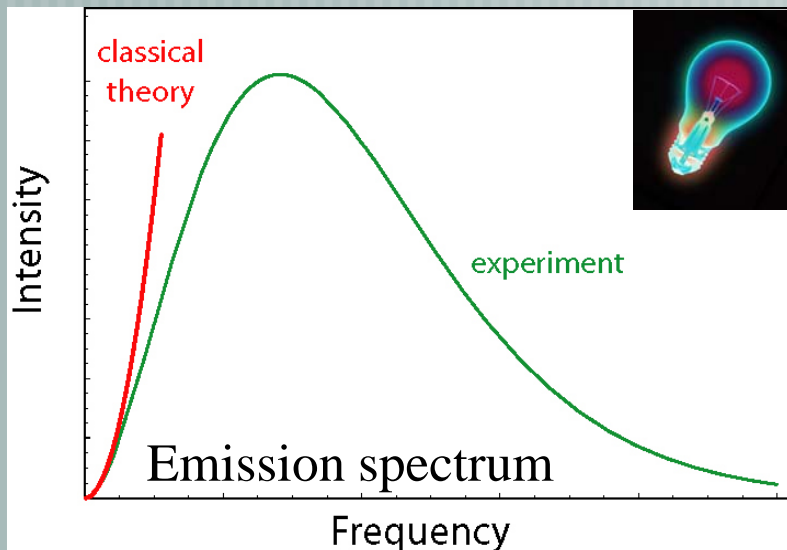


"Black body" absorbs all incoming light;  
re-emits thermal equilibrium radiation

"Radiation function" =  $f(T)$  only

$$I(\nu) \sim \nu^2 \langle E \rangle$$

average energy of oscillators  
(proportional to temperature)



Ok for 'low' temperatures (Jeans law)

# Fields

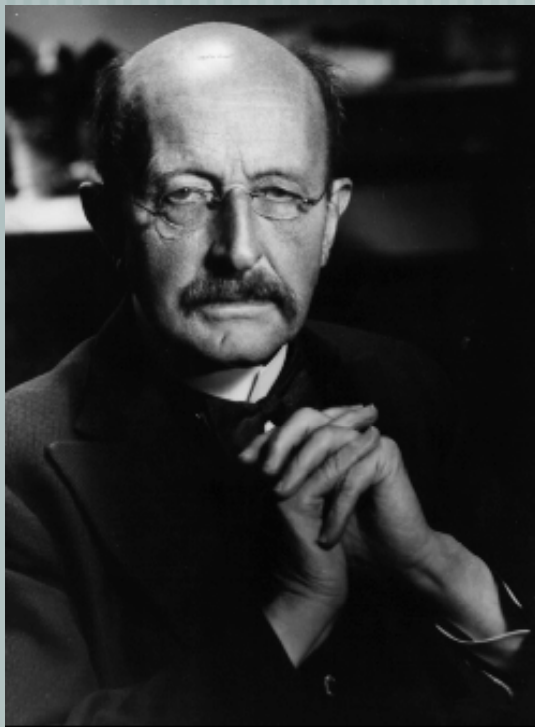
'Electromagnetic' interaction

Photon

## An “Act of Desperation”

Oscillators (in the wall of the black body)  
emit ‘finite energy elements’  $\epsilon = h \nu$

14 December 1900



Max Planck

*Higher frequency means bigger chunks, so it is less likely to find  $E \gg kT$*

$$I(\nu) \sim \nu^2 \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$

average energy  
of oscillators

$h$  = new fundamental constant

# Fields

'Electromagnetic' interaction

Photon

1902

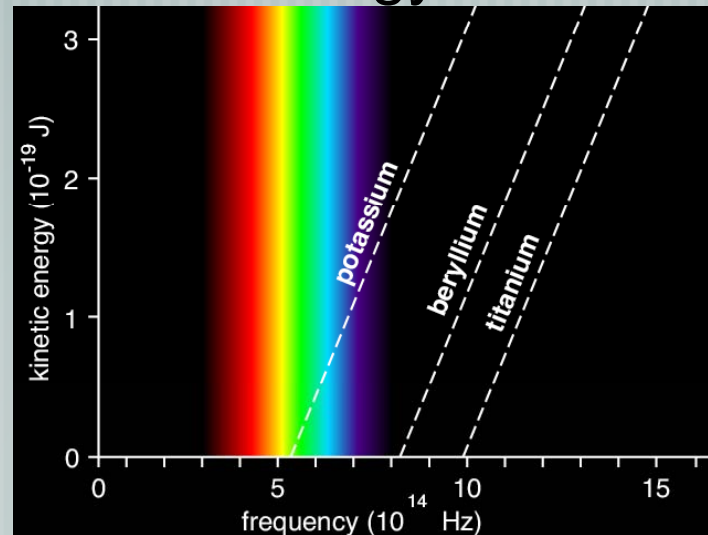


Philipp von Lenard

## The photoelectric effect

Cathode rays (electrons) are produced by shining light on metal surfaces.

Classical expectation: Energy of light proportional to square of its amplitude  $\sim$  electron energy



Energy proportional to light **frequency** (slope = "h")

*"The electron energy does not show the slightest dependence on the light intensity"*



# Fields

'Electromagnetic' interaction

Photon

“My only revolutionary contribution”

17 March 1905



Albert Einstein

Light is **emitted** and **absorbed** in **quanta**

★ ★  $E_{\max} = h\nu - W$

*“A **light quantum** gives all its energy to a **single electron**.”*

*(Compton, 1917, proved it)*

# Fields

Special relativity

## Special relativity



Einstein had thought about the 'medium' for electromagnetic waves and concluded that there was none.

*But how could the speed of light be the same in all inertial frames?*

### His postulates:

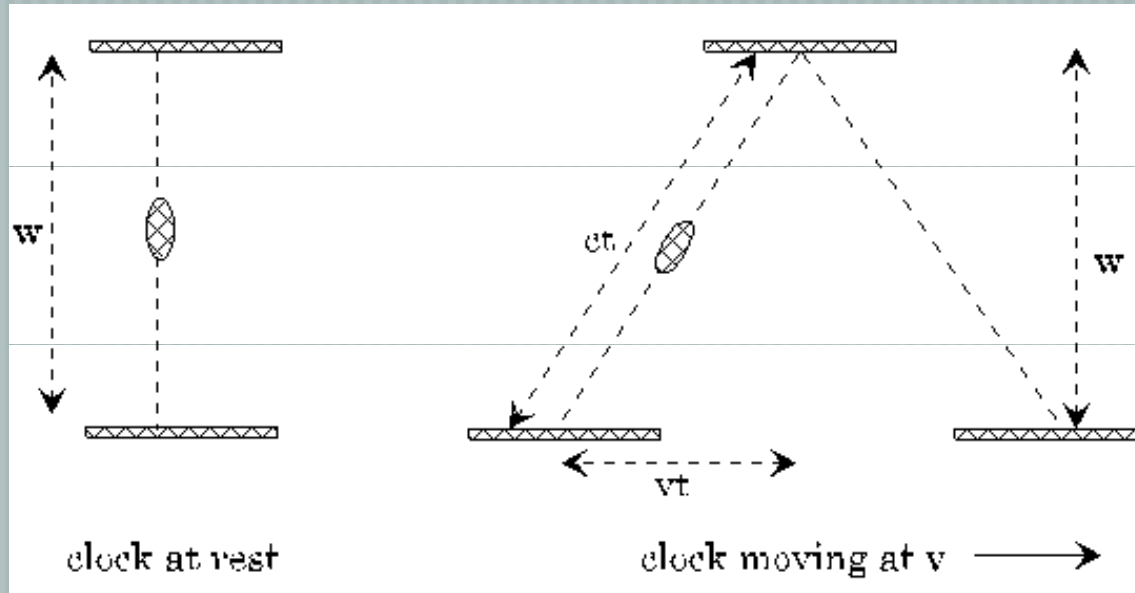
- 1) Speed of light = constant =  $c$  (in vacuum)
- 2) all inertial frames are equivalent ("relativity principle")

### His conclusions:

Since  $c = \text{const}$ , and speed = (space interval/time interval) -->  
space and time cannot be absolute!

# Fields

## Special relativity



$$c^2 t^2 = v^2 t^2 + w^2$$

$$t^2 (c^2 - v^2) = w^2$$

$$t = \frac{w/c}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma \cdot \tau$$

1) Time dilation, space contraction

2) Modification of Newton's laws, relativistic mass increase.

$$E = mc^2$$



# Fields

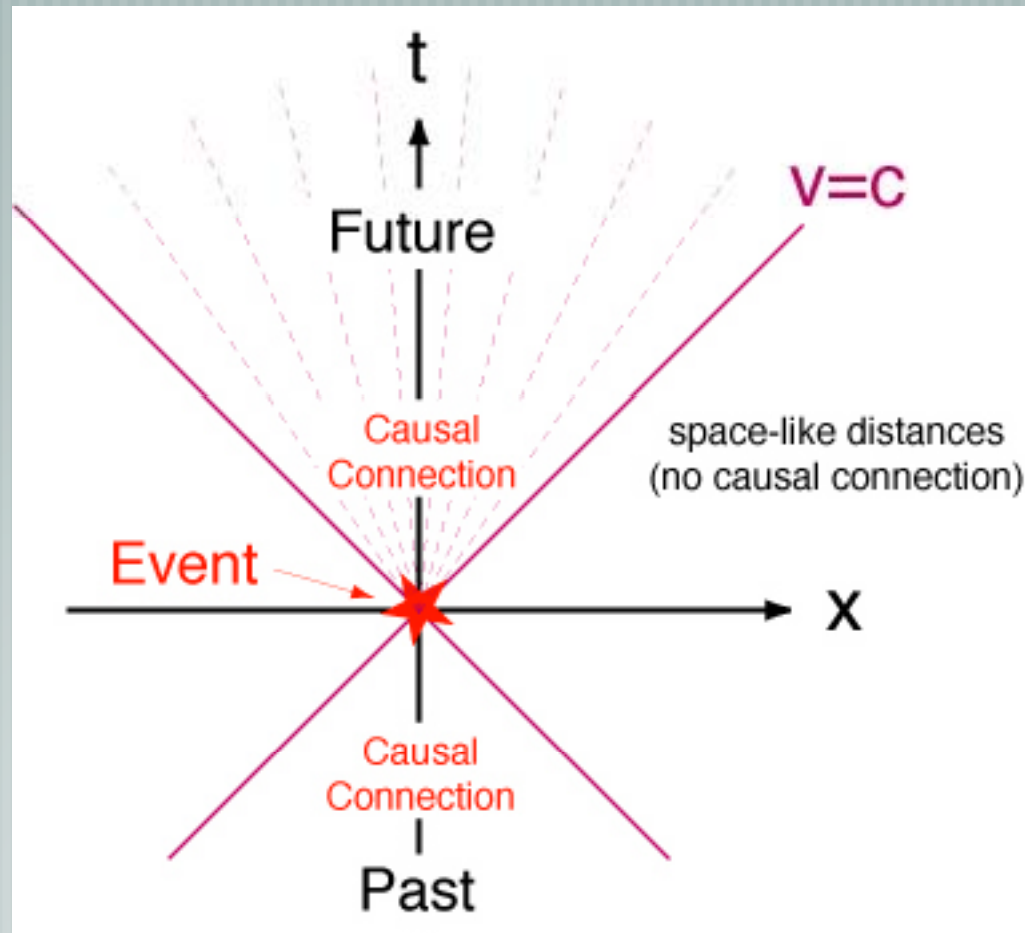
Special relativity

**Relativity allowed to define "CAUSALITY" in a consistent way**

**Nothing can move faster than light**



**Only events in the "light cone" can be causally connected**



# Fields

'Electromagnetic' interaction

How could special relativity and quantum physics be united ?

Dirac's guess:



Paul A.M. Dirac  
(1928)

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

Compare with (non-relativistic)  
Schrödinger equation

$$E^2 = p^2 + m^2 \rightarrow$$
$$E = \pm(\alpha \cdot p) + \beta m$$

$$E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi$$

## CONSEQUENCES:

**ELECTRON SPIN EXPLAINED**

**ELECTRONS OBEY 'PAULI PRINCIPLE' (1940) - FERMIONS**

**ANTIPARTICLES MUST EXIST !**

# Fields

'Electromagnetic' interaction

Two crucial (theoretical) **predictions** by Dirac

The wave function has 4 components (two spin  $1/2$  particles)

2 components for particle - and 2 components for antiparticle!

Every particle has an antiparticle ! ★★





$e^+$

# Fields

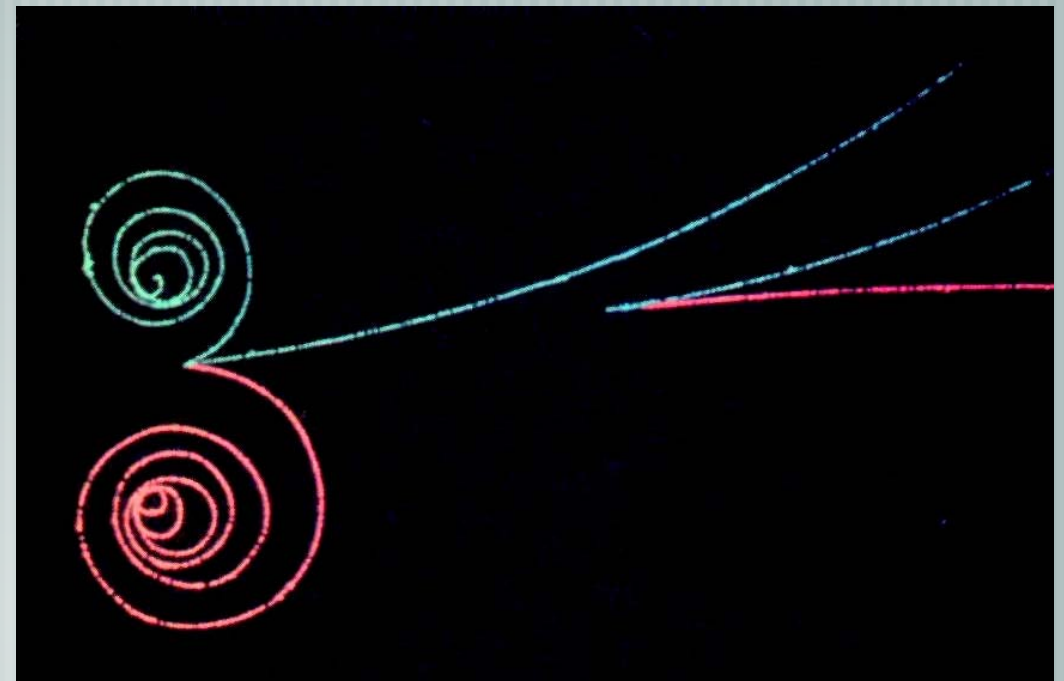
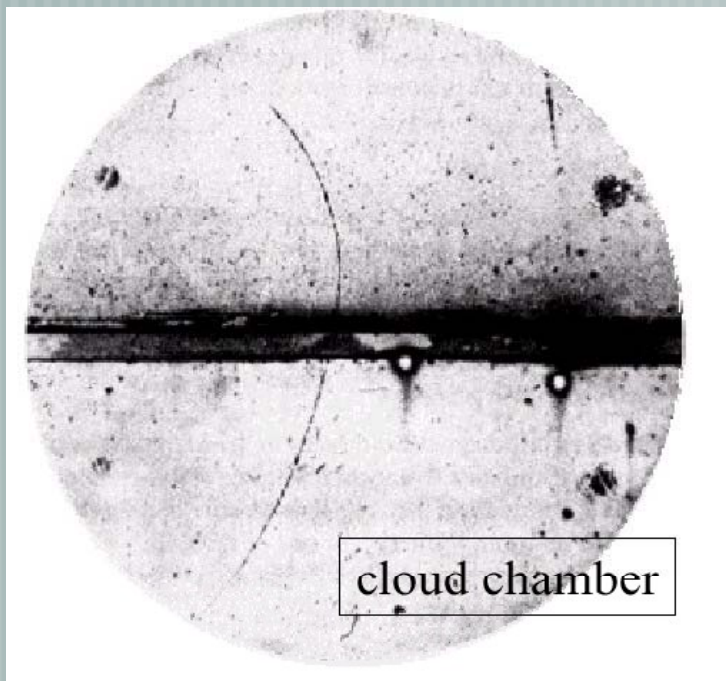
'Electromagnetic' interaction



## Discovery of the positron

*Dirac was right!*

Anderson (1932)



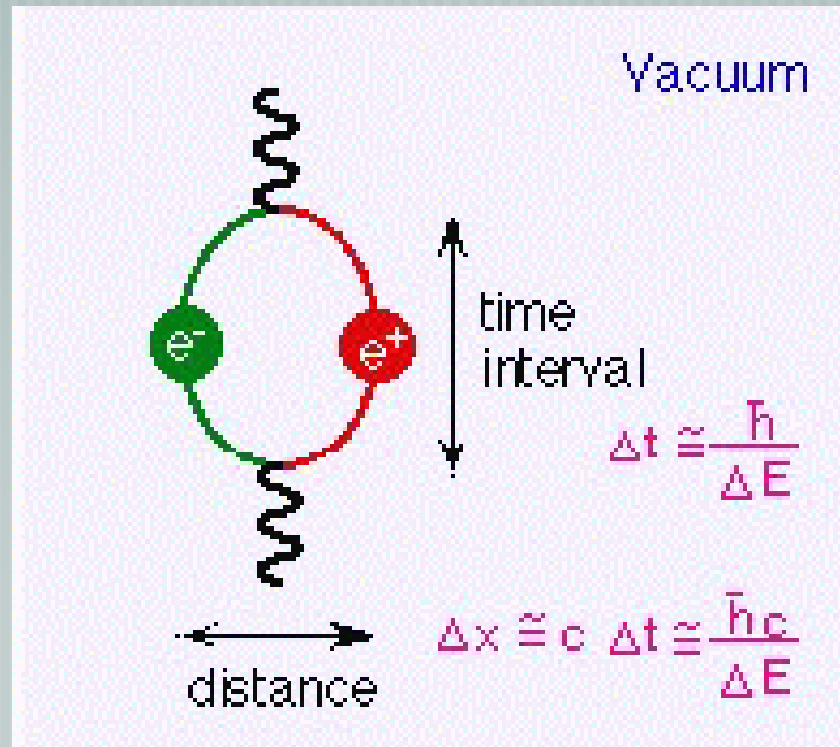
# Fields

'Electromagnetic' interaction

## NOW THE VACUUM HAD BECOME REALLY MESSY

Quantum physics says that 'oscillators' (e.g. field quanta) cannot be at absolute rest (uncertainty relation)

The lowest energy states of e.g. electromagnetic fields can produce (virtual) electron-positron pairs: **VACUUM FLUCTUATIONS**

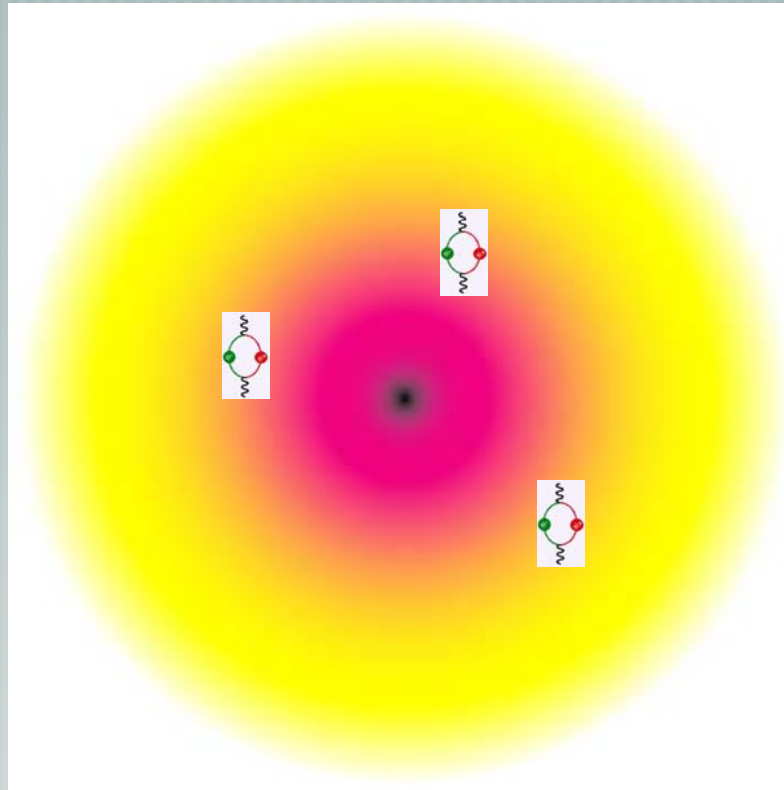
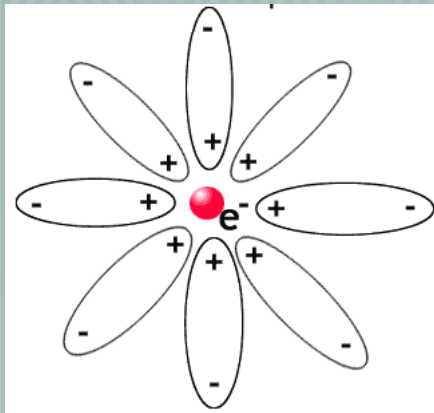


# Fields

'Electromagnetic' interaction

**How to calculate the interaction of photons and electrons?**

a new picture of the **"dressed" electron** emerged:



vacuum fluctuations modify its charge and mass ('Debye shielding')



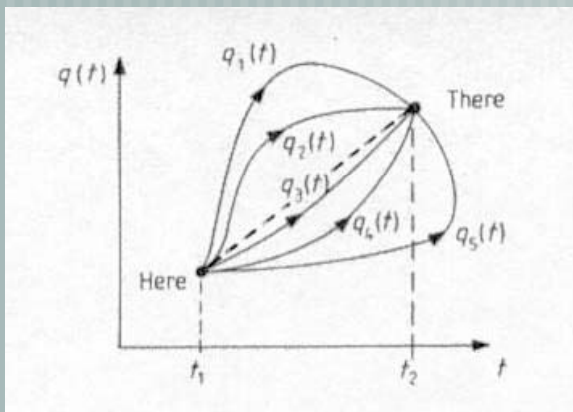
# Fields

1934 - 1948



R. P. Feynman

All paths are possible  
(‘multiple slit experiment’)



## Quantum Electrodynamics

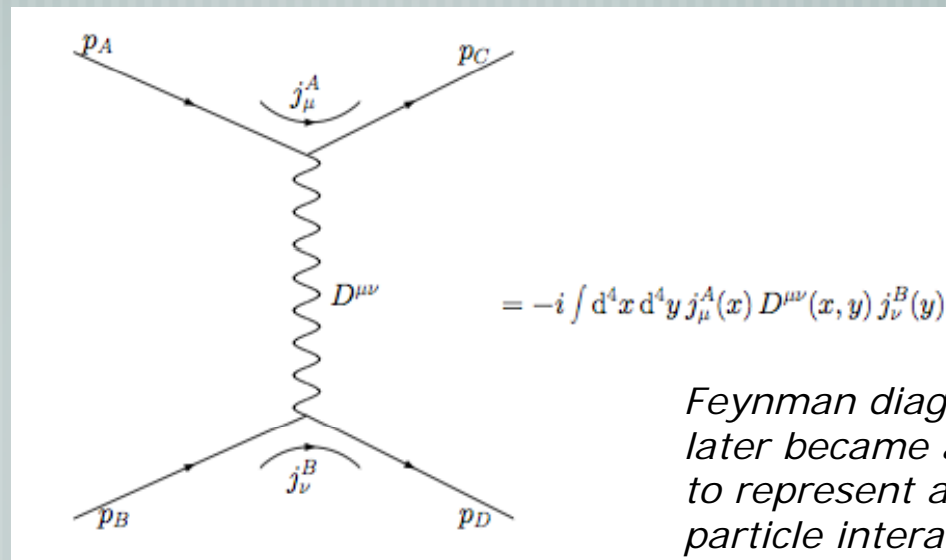
Feynman, Tomonaga, Schwinger

### “Renormalization”

The ‘naked’ electron + vacuum fluctuations = measured electron  
(“infinite” - “infinite” = “finite”)

### Feynman diagrams

Precise computation rules - in graphical form



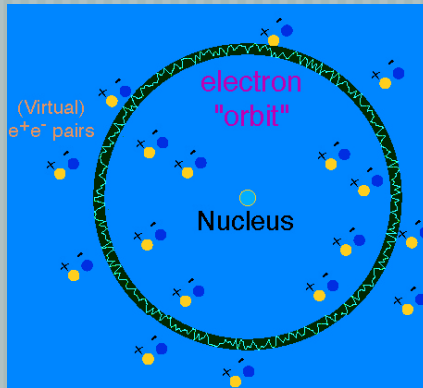
*Feynman diagrams  
later became a graphical way  
to represent all kinds of  
particle interactions*

# Fields

1948

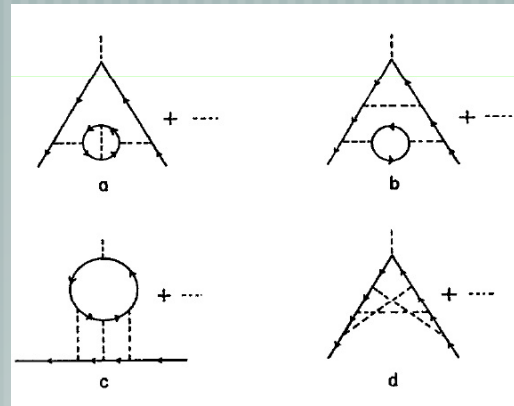
**Vacuum fluctuations have observable effects**

... and Quantum Electrodynamics allowed to calculate them precisely



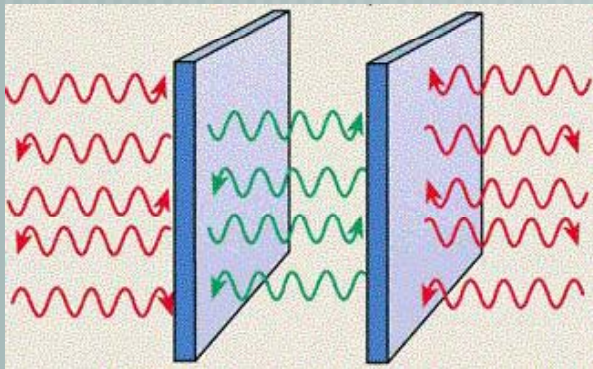
## Lamb Shift

(shift of atomic energy levels)



**Electron (anomalous) magnetic moment**

$$\frac{1}{2}(g - 2) = \frac{1}{2}\frac{\alpha}{\pi} - 0.32848 \left(\frac{\alpha}{\pi}\right)^2 + (1.183 \pm 0.011) \left(\frac{\alpha}{\pi}\right)^3.$$



## Casimir effect

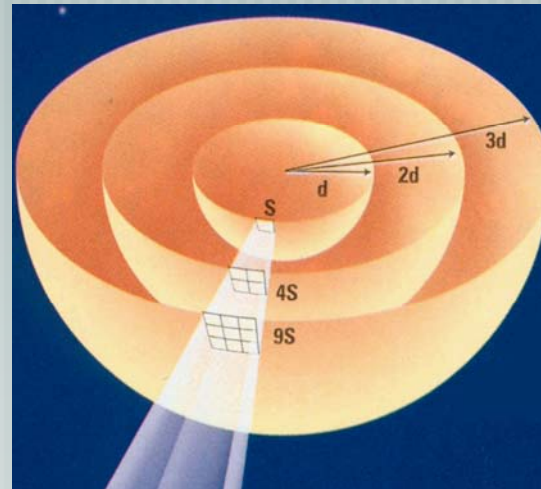
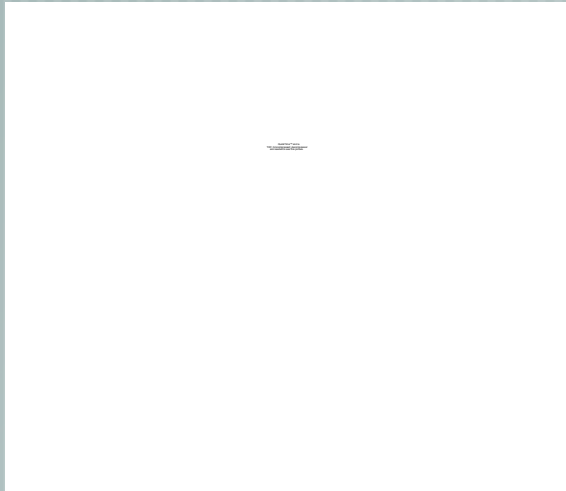
(force on two uncharged metal plates)

# Fields

'Electromagnetic' interaction

**QED: Charged particles interact by exchanging photons**

- 1) **Massless virtual photons are continuously emitted by electric charges**
- 2) The  **$1/r^2$  law** comes from the probability to hit another particle at distance  $r$   
(directly connected with the 3 dimensions of space)



**$1/r^2$  law**

**Could that become a model for other interactions?**