

From the Plum Pudding to the string theory

*Revolutionary ideas and discoveries in the 20th century for a
modern particle physics*

Outlines

- Prologue;
- **Introduction to particle physics 1**
 - From the Plum-Pudding atomic model to the Bohr model;
 - Special relativity -> general relativity (GR);
 - Quantum Mechanics (QM)
 - Quantum Field Theory (QFT)
- **Introduction to particle physics 2**
 - The standard model (SM) of forces and particles;
 - The BEH boson (Higgs boson)
- **Introduction to particle physics 3**
 - Beyond the SM: Supersymmetry (SUSY) for the electro-strong unification (GUT),
 - Beyond GUT: GR + QM : String theories?, M-theory? Loop quantum Gravity?.....

past

present

future

Prologue

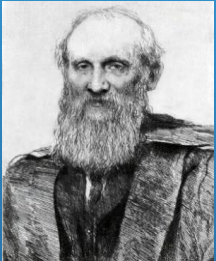
- Aim of presentations: give an overview on the particle physics and stimulate the teacher's and the student's curiosity. Feedbacks expected!
- Several revolutionary ideas and discoveries have changed the physics during the 20th century,
- hard to follow at the same time the history, the contents and their potential impact in the future developments. So, a surfing is imposed without missing to focus on important points,
- So far physicists have learned a lot, including they ignore the nature of the most part of the matter (25%) and the energy (70%) in the Universe!! (see M. Doser on Cosmology)

New ideas from young physicists are expected!

What an elementary particle is?

Matter objects without internal structure (satisfying ?)

Beginning of 20th century (credit to R. Landua CERN)



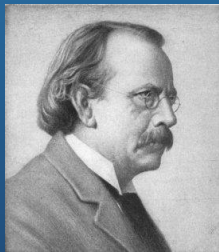
Lord Kelvin

- In the early 1900s, most physicists believed that physics was complete, described by the Newton's mechanics, gravity, thermodynamics, and the Maxwell e.m. theory.
- “There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. “ (Lord Kelvin, 1900, the father of thermodynamics).
- DARK CLOUDS:
 - 1) Blackbody radiation - Quantum Physics
 - 2) Michelson-Morley experiment - Special Relativity

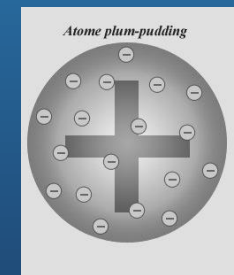
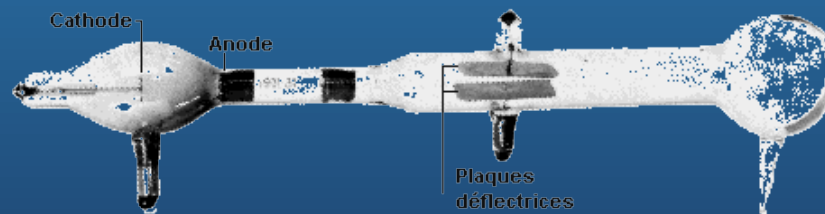
Quantum Mechanics and Special Relativity will bring revolutionary concepts in the Physics!!

“Atoms”

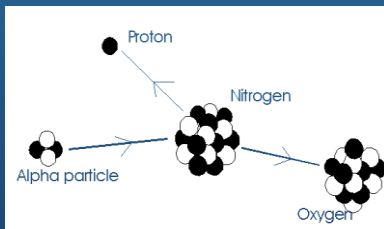
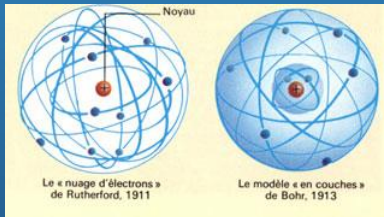
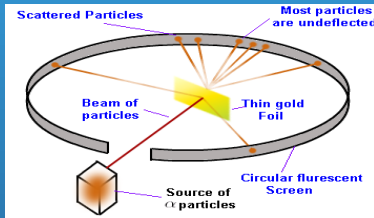
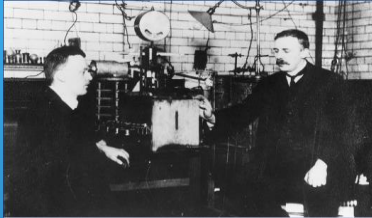
- Matter is made of “atoms”: Leucippus, Democritus... (450b.c.)
- Contribution towards the atomism (matter and lights made of atoms): Giordano Bruno, G. Galileo, I. Newton R. Boyle, J. Dalton, J.L. Gay-Lussac, A. Avogadro, R. Clausius J.C. Maxwell, D. Mendeleev, j. Perrin, A. Enstein,...
 $N=6.022 \cdot 10^{23}$ atoms/mole.
- J.J. Thomson: **1897 discovered the electron** negatively charged and for the atom suggested the Plum Pudding model: a positive charged sphere with electrons imbedded, resulting in a neutral object.



1856-1940



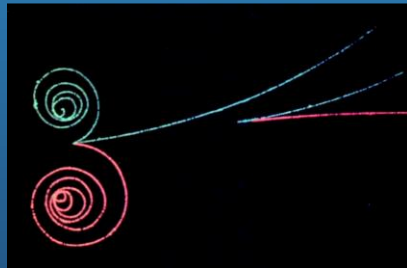
Atomic models



- 1909 Geiger and Marsden experiment: surprisingly α particles scattered through large angles on a thin gold foil. Angles not compatible with Plum-Pudding model!
- 1911 Rutherford deduced the existence of minute, positively charged nucleus where almost all the mass concentrates within an (almost) empty atom and proposed the planetary model: electrons moving on circular orbits around the nucleus.
- 1913 Bohr improved the model introducing electron shells of stationary orbits, electrons jumping from shell n to $n-1$ emit energy $\Delta E = E_n - E_{n-1} = h\nu, \dots$. Quantization of the angular momentum (\hbar unit)
- 1919 Rutherford transmuting elements produced ionized hydrogen that later took the name of **proton**, with positive charge e .

The atom as building block and more

- J. Chadwick (pupil of Rutherford) discovered the neutron n in the 1932;
- n , p and e^- the complete family of fundamental particles to build up an atom and to describe the matter, was there!
- ...1932 C. Anderson discovered a positive electron e^+ in cosmic rays!
- In additions he observed photons to transform in pair of $e^- + e^+$. Later was also observed the annihilation $e^- + e^+$ producing photons . **There was evidence of the equivalence between mass and energy!!** This tell us something, let's see later!



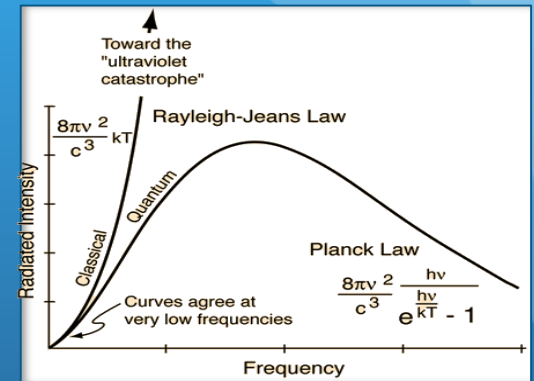
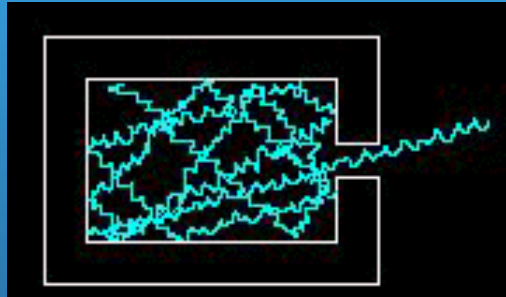
When energy converts to mass, particle and antiparticle are produced

- But as from 1900, what append to the physics in general?

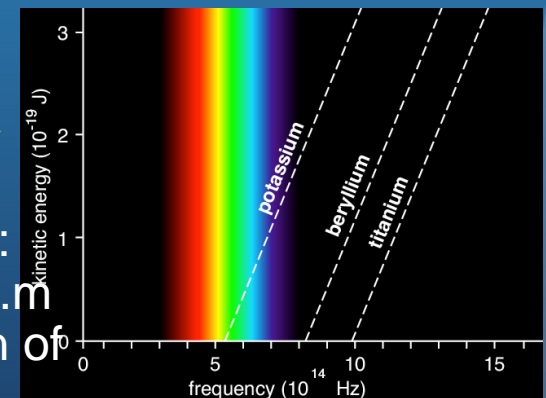
Back to 1900 !

What about the dark cloud on 1900 ?

- 1900 Blackbody radiation problem: (M. Plank) -> $E=h\nu$



- 1902: Photoelectric effect (P. von Lenard)
“The electron energy does not show the slightest dependence on the light intensity”
- 1905: Light is emitted and absorbed in quanta:
 $E_{\max} = h\nu - W$. Then Einstein interpreted the e.m radiation as propgating empty wave with grain of energy inside, later 1920 called photons



Special Relativity

- 1887 Michelson-Morley experiment: The light propagates in the vacuum with constant velocity c in all directions, no matter the velocity v of the source. No velocity composition $c' = c \pm v$ as in the Galilean relativity. No evidence of the existence of ether.

1905 A. Einstein Special Relativity (SR)

- SR Postulate1: the speed of light $c = 299792.4588 \pm 0.0002$ Km/s is constant in all the inertial reference systems;
- SR Postulate2: The physics laws have to be invariant in any inertial reference system;
- SR provide the transformation laws of space and time (Lorentz transforms) for the invariance of Newtonian mechanics and Maxwell electromagnetism, but gravity.
- From the rigid space and absolute time of Newton, the SR introduce space-time where time difference and distances aren't any longer absolute, but still flat space-time;

Special Relativity

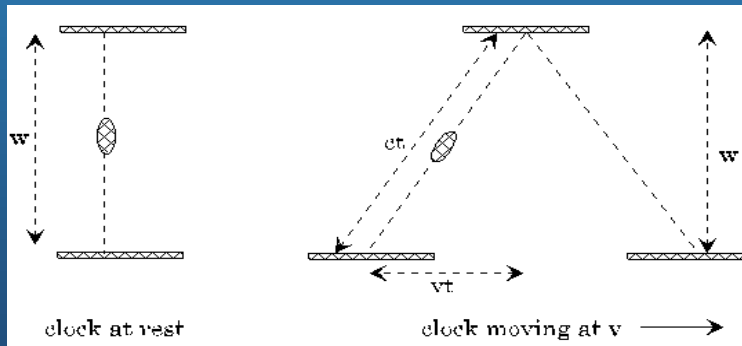
Completely new perception of the space and time came up!

New relations between energy, momentum and mass appeared:

$E^2 = m_0^2 c^4 + p^2 c^2 \rightarrow$ (at rest) $E = m_0 c^2$: Famous **mass-energy equivalence**;

$$m = m_0 \gamma$$

One of the consequences of the speed of light = constant: time dilatation (and space contraction)



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

$$t = \frac{w/c}{\sqrt{1 - \frac{v^2}{c^2}}} = g \times t$$

From SR to General Relativity (GR)

GR: the spacetime curvature

- **1915** The equivalence principle (accelerated ref. sys equivalent to to gravitational force) and the difficulties to integrate the Newtonian Gravity in the SR, brought Einstein to develop the GR.
- In GR all the physics laws (Newtonian mechanics, Maxwell e.m. and gravity, are invariant in any **accelerated reference system!**
- The space-time geometry (its metric) is deformed by the presence of energy and mass! The deformation causes mass movement that, in turn modify the deformation! This interplay brought to quite complicated solution of the Einstein equation of GR. The GR is a geometrical theory of gravitation;
- Tanks to the GR the scientific Cosmology was born, computations on black holes, collapsing stars, ... were finally possible.

2015: After several experimental confirmations, we can say Happy birthday GR!

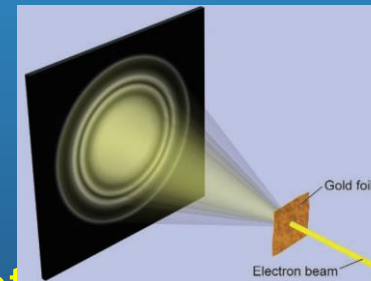
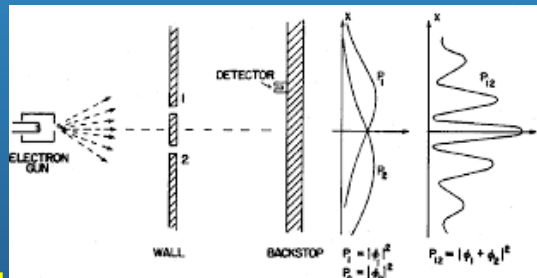
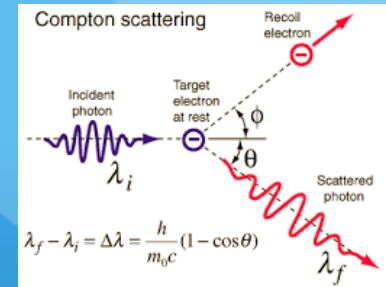
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Quantum Mechanics (Q.M.)

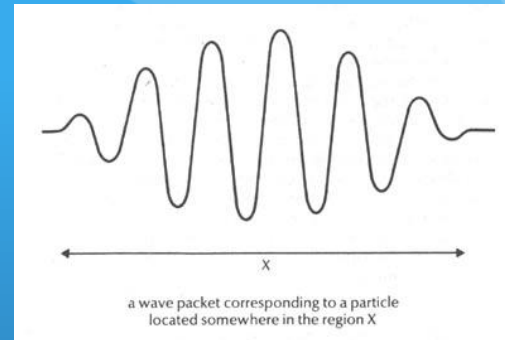
Wave-particle-duality

- Photoelectric effect (1905, Einstein), X ray scattering on electrons Compton effect(1923),... are interpreted as corpuscular behavior of the e.m. radiation: $E=h\nu$ and $p=h/\lambda$.
- **Electron, neutron diffraction** (interference patterns when crossing diffracting slits): are interpreted as wavelike behavior of particles!



- **Revolutionary and debated concept. wave-particle duality:**
 1. atomic/nuclear object have to be described as **particles OR wave** according to the studied process: (Bohr, Heisenberg);
 2. atomic/nuclear object should be described at the same time as **wave-particle !** (e.m. wave with photons embedded; particle with momentum p located in a wave with $\lambda=h/p$) (De Broglie , Einstein, Schrodinger);

Quantum Mechanics (Q.M.)



Heisenberg's uncertainty principle

- Localizing the wave packet for a particle with momentum p , the relation $\Delta x * \Delta p > h$ can be derived. The higher the precision on measurement for the position (small Δx), the higher the uncertainty on the momentum value;
- The corresponding relation for the energy and time is: $\Delta E * \Delta t > h$. Heisenberg: these relations put a limit to the knowledge we can achieve of the nuclear process.
- In addition, Heisenberg considers that in atomic/nuclear processes, for a tiny time duration t , the energy E can appear-disappear eluding the Energy conservation principle (!) according to the formula $E=h/t$ (virtual particles);

Quantum Mechanics (Q.M.)

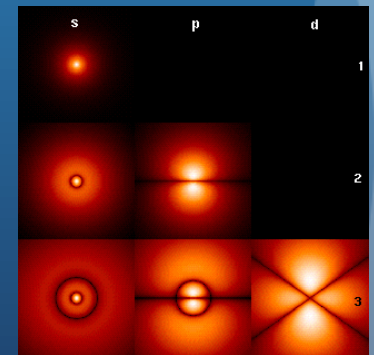
Schrodinger Equation

particles are discrete packets of energy with wave-like properties

- In the Newtonian space and time geometry, imposing that the wave packet of a particle of mass m , in a potential $V(r)$, has to solidary move with the same velocity of the particle (wave-particle approach) then the Schrodinger wave equation can be deduced:

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

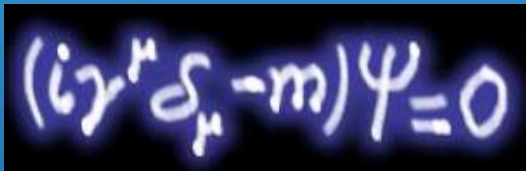
- The wave function ψ , solution of the wave equation, could be interpreted as the particle trajectory (space-time description);
- However the interpretation that affirmed with the time was the probabilistic one (Born);
- The solution of the wave equation for the Hydrogen atom is then interpreted as the probability density to find the electron in the position $p(x,y,z)$ when measured at time t .



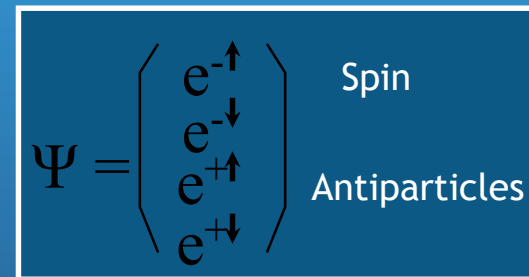
Quantum Mechanics (Q.M.)

P.A.M. Dirac 1928 : the Relativistic Wave equation

- In the relativistic space-time using the new relation $E^2=m^2+p^2$ ($c=1$) a new wave equation, invariant for Lorentz transform, describing an electron moving at close to the speed of light, can be derived :



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



$$\Psi = \begin{pmatrix} e^{-\uparrow} \\ e^{-\downarrow} \\ e^{+\uparrow} \\ e^{+\downarrow} \end{pmatrix} \begin{matrix} \text{Spin} \\ \text{Antiparticles} \end{matrix}$$

- The wave function solution is a matrix with four components, two of which with negative energy represent positrons, antiparticle of electrons;
- In 1933 Blackett and Occhialini observed with the Cavendish cloud chamber the *positron* and explicitly associate it to the particle predicted by Dirac.
- the prediction and discovery of antiparticles was a new revolution in the particle physics: an unexpected symmetry in the fundamental particles!!**

Quantum Field Theory (1927-1948)

- It was known that the electromagnetic field contains photons
- How could the interaction between electrons and photons be correctly described, respecting quantum mechanics and special relativity?
- Many people worked on this problem ...(S.I.Tomonaga, J. Schwinger, F. Dyson)
- Quantum Field Theory (QFT) treats particles as excited states of an underlying physical field, filling the universe, so the particles are called field quanta. E.g.: Photons are excited states of the e.m. field.
- In quantum field theory, quantum mechanical interactions between particles are described by interaction terms between the corresponding underlying fields.
- A mediator of the interaction, named gauge boson, is exchanged between two interacting particles

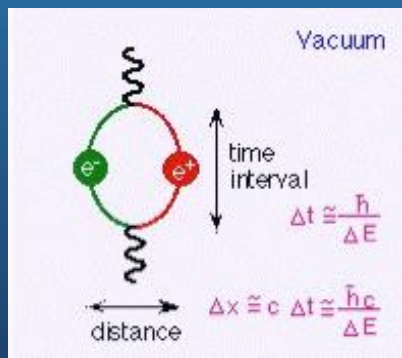
Quantum Field Theory (1927-1948)

Empty Space had become complicated!

Dirac already postulated that the negative energy levels of the vacuum were all occupied so electrons could not decay in with emission of photons (Dirac sea model)! It is not a physical explanation!

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 (identified with vacuum) can produce (virtual) electron-positron pairs: **VACUUM FLUCTUATIONS**

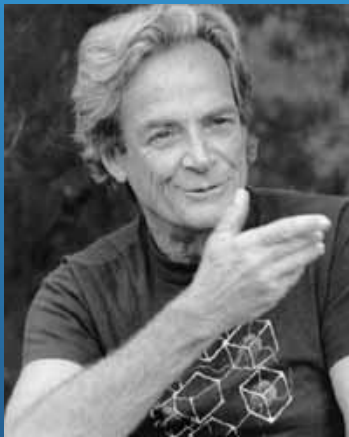


e.g. $\Delta t \cong 6.6 \cdot 10^{-22} \text{ Mev.s} / \sim 1 \text{ MeV} \cong 10^{-21} \text{ s}$

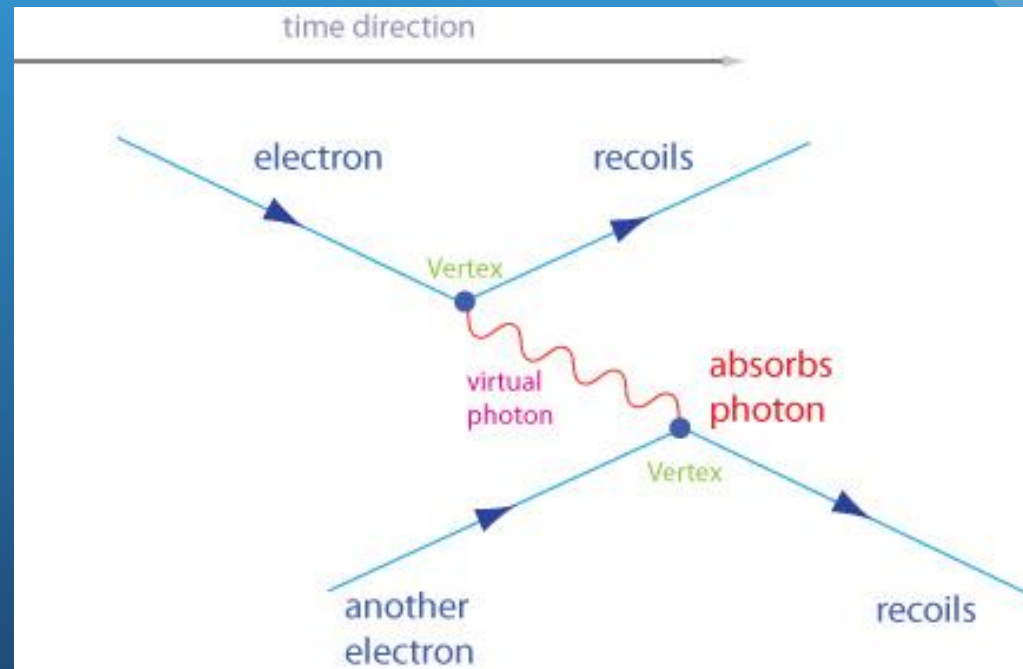
$$\Delta x \cong 3 \cdot 10^8 \text{ m/s} \cdot 10^{-21} \text{ s} \cong 300 \text{ fm}$$

Quantum Electrodynamics(QED)

QED, the master example of QFT, describe the EM interactions according to the QM+special relativity. The photon (gauge boson, see later) mediates the EM interaction.

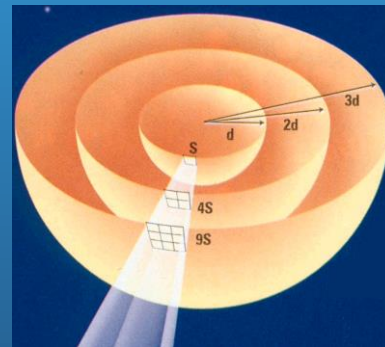
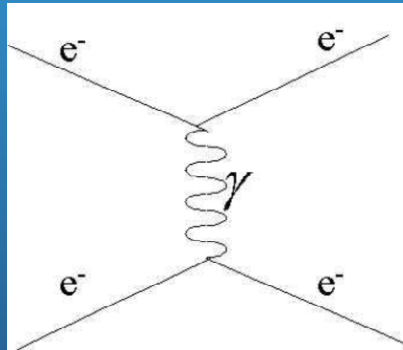


R.P. Feynman



QED: Charged particles interact by exchanging photons ²⁰

- 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

The QED became a model of QFT for the other interaction as the strong nuclear interaction (nuclear stability) and the weak interaction (nuclear fusion, radioactivity).

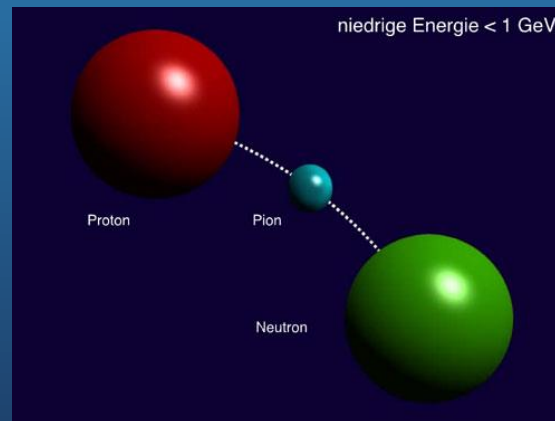
“Strong Interaction” - Nuclear forces

What keeps the protons and neutrons together in the nucle

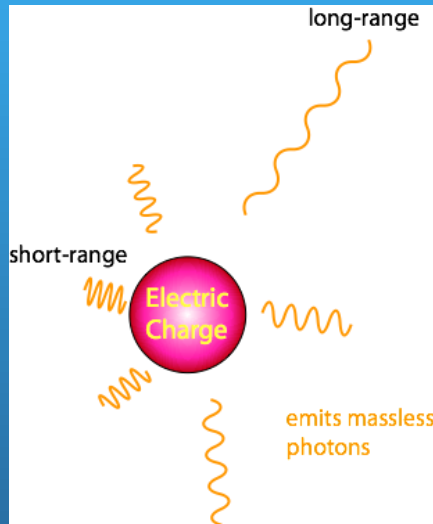
- 1) This force must be stronger than the electromagnetic repulsion
- 2) It must be of short range ($\sim 1\text{-}2\text{ fm}$) to explain the size of nuclei

Yukawa's idea (1934):

a massive particle (“pion”) is exchanged between two nucleons that mediates the strong interaction

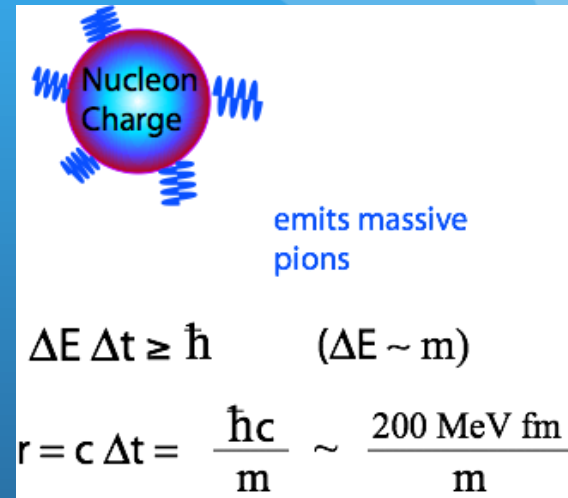


Electromagnetic vs Nuclear



$$V(r) = -e^2 \frac{1}{r}$$

Coulomb law



$$V(r) = -g^2 \frac{e^{-mr}}{r}$$

Yukawa potential ~ Modified "Coulomb" law

Indeed the pion p will be discovered in 1943 $m=140$ MeV

part I Summary

- 1897-1913: Thomson->Rutherford->Bohr from the Plum-pudding model to the planetary model of the atom;
- From rigid space and time (Newton) to the spacetime of Einstein for the invariance of mechanics and e.m. but gravity. GR a geometric theory of gravitation ensuring the invariance of all the interactions in accelerated ref. sys. . The scientific Cosmology can begin.
- Energy quanta $E=h\nu$, wave-particle duality $\lambda=h/p$ and Heisenberg uncertainty relations => Quantum Mechanics (QM). For the solution of the Schrodinger wave equation (wave function) the probabilistic interpretation affirmed...but...
- Special relativity + QM for a fast moving electron => Dirac equation => antimatter and electron spin, for the vacuum postulated the existence of Dirac sea to account for the matter was not collapsing !
- QED, the first example of QFT, the photon as mediator of E.M. interaction, the quantum vacuum as ground state of EM field (virtual particles). QED: a successful model used for the strong (Yukawa model) and weak interactions.