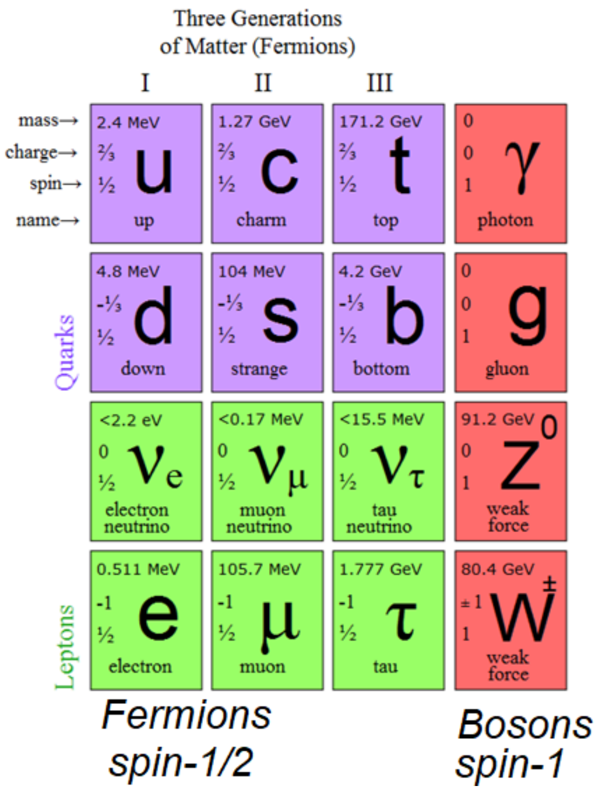
MIDDLE EAST TECHNICAL UNIVERSITY

Particle Data Analysis in High Energy Physics

Lecture 2

Overview of Particle Physics



Ahmet Bingül

METU, Physics

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Introduction

- Particle Physics deals with the study of elementary constituents of matter and interactions.
- More than 300 of particles are discovered so far.
- Most of them decays rapidly after beeing produced in reactions.
- **Elementary** means particle has no known stucture or **pointlike**.
  How pointlike is pointlike? This depends on the spatial resolution of the probe used. Resolution (Δr) is limited by de-Broglie wavelength.

$$\Delta r \sim \lambda = \frac{h}{p}$$

h = 6.63×10^{-34} J.s Plank Constant

p = particle momentum

e.g, to resolve Δr ~ 1 nm using electrons the required momentum is

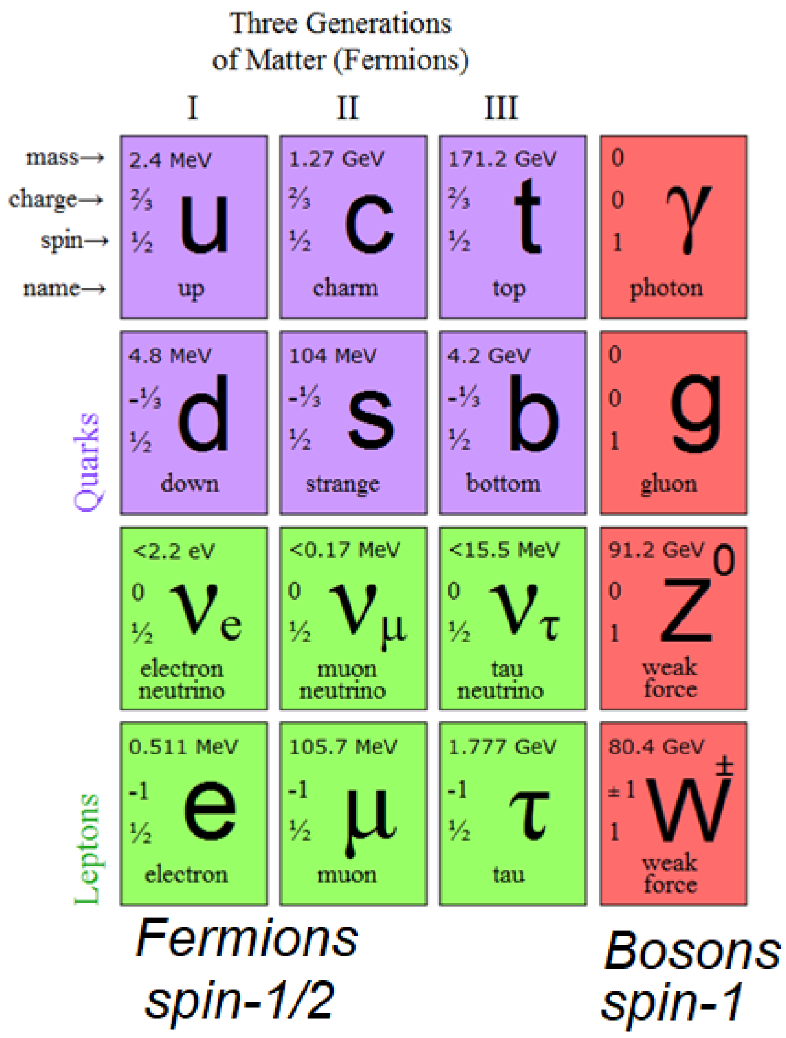
$$p = \frac{h}{\Delta r} = 6.63 \times 10^{-25}\ \mathrm{kg.\,m/s} \rightarrow E = 1.5\ \mathrm{MeV}$$

Standart Model

Today we know that matter is composed of atoms and atoms are composed of fundamental particles.

The standart model is a theory that explains how different fundamental particles are arranged and how they interact with each other.

- We have 3 families of **quarks** and **leptons**.
- Stong interactions are mediated by 8 **gluons**.
- Electromagnetic interactions are mediated by **photons**.
- Weak force is mediated by **W** and **Z bosons**.
- **Higgs boson** is an elementary particle transmitting the Higgs field giving particles mass.



Fundamental Forces (Interactions)

The four interactions we already know are **apparently** enough to account for all the physical processes and structures in the universe on all scales of size from atoms and nuclei to galaxies of stars.

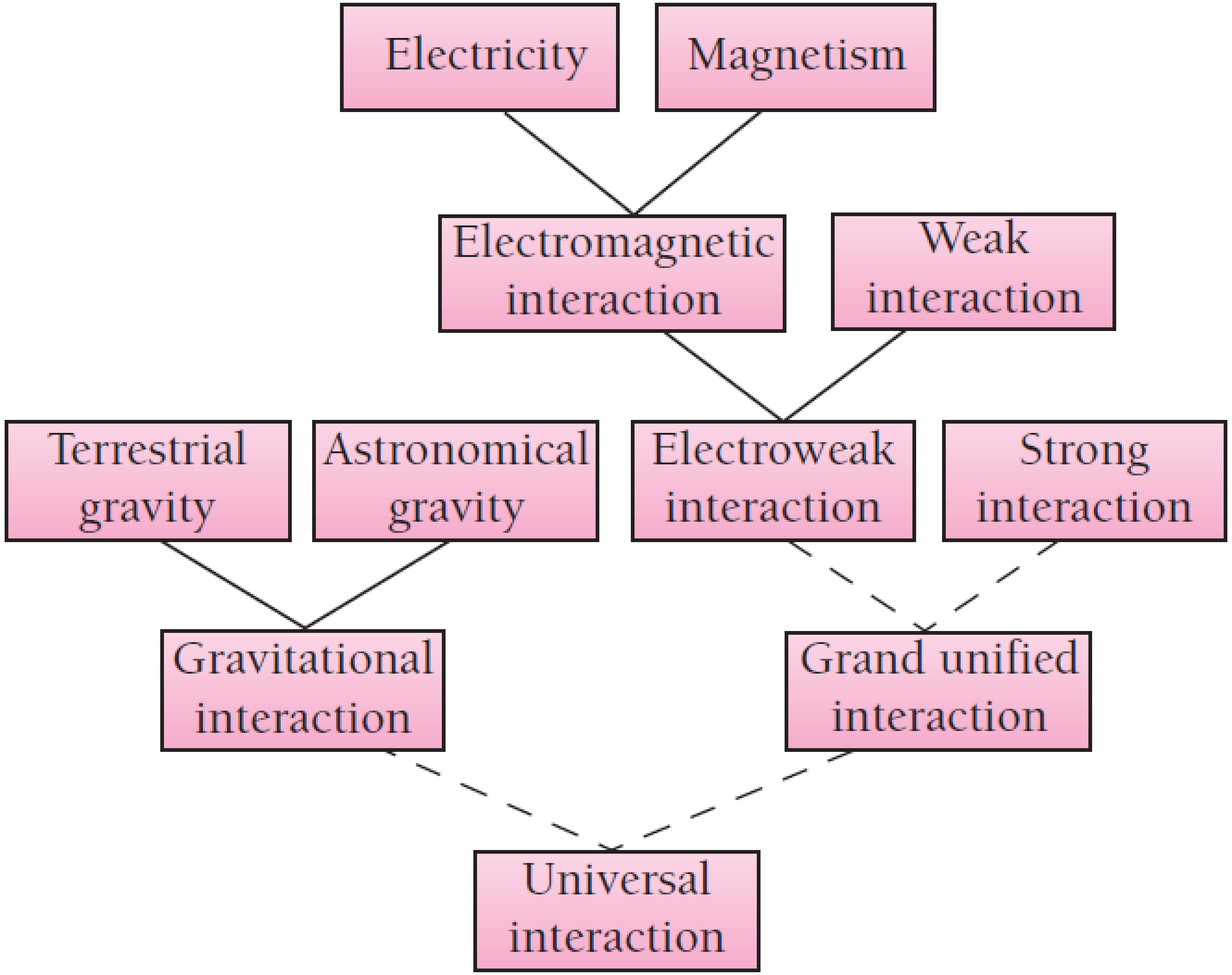
The Four Fundamental Interactions. The graviton has not been experimentally detected as yet.

Interaction	Particles Affected	Range	Relative Strength	Particles Exchanged	Role in Universe
Strong	Quarks	$\sim 10^{-15}$ m	1	Gluons	Holds quarks together to form nucleons
	Hadrons			Mesons	Holds nucleons together to form atomic nuclei
Electromagnetic	Charged particles	∞	$\sim 10^{-2}$	Photons	Determines structures of atoms, molecules, solids, and liquids; is important factor in astronomical universe
Weak	Quarks and leptons	$\sim 10^{-18}$ m	$\sim 10^{-5}$	Intermediate bosons	Mediates transformations of quarks and leptons; helps determine compositions of atomic nuclei
Gravitational	All	∞	$\sim 10^{-39}$	Gravitons	Assembles matter into planets, stars, and galaxies

Fundamental Forces (Interactions)

One of the goals of physics is a single theoretical picture that unites all intearactions.

Much progress has been made, but the task is not finished.



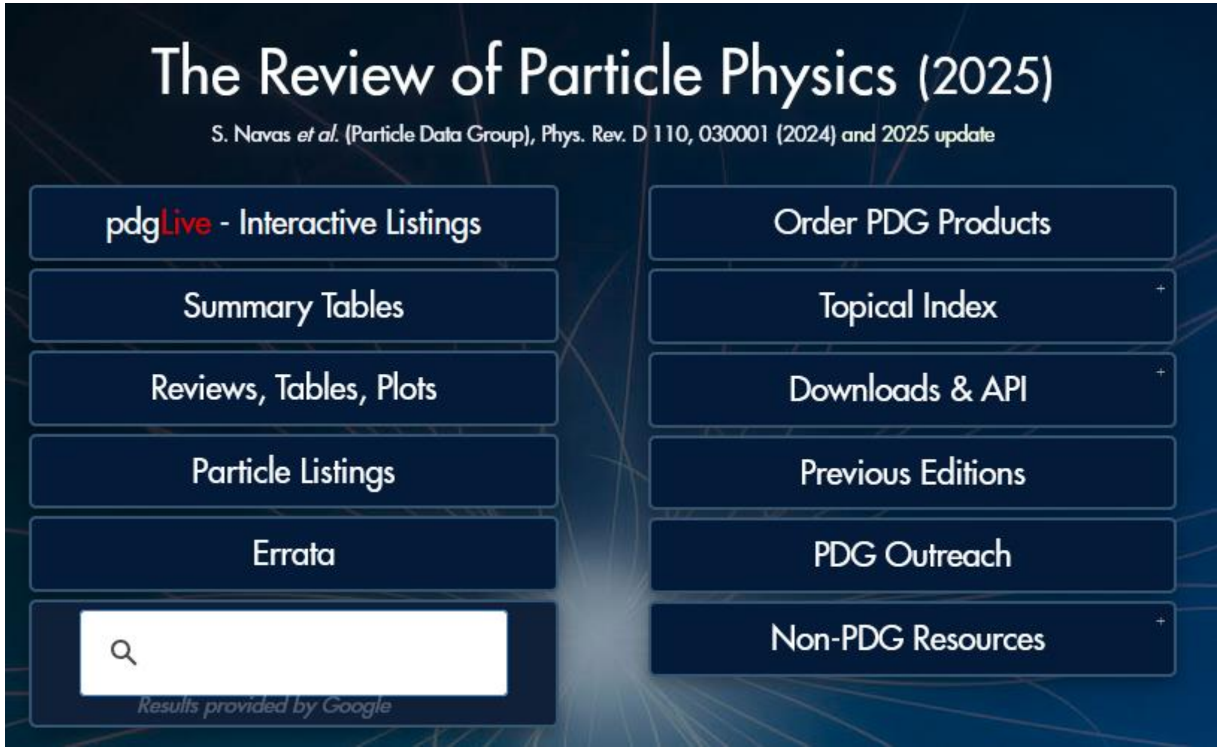
Particle Data Group (PDG)

PDG is an international collaboration of particle physicists that compiles and reanalyzes published results related to the properties of particles and fundamental interactions.

Home Page:

https://pdg.lbl.gov

https://pdglive.lbl.gov



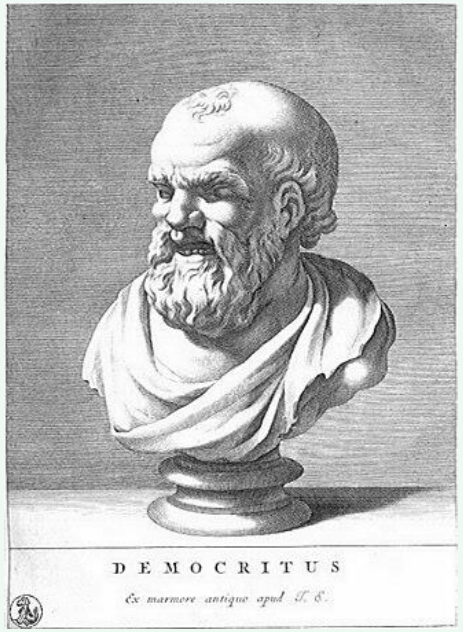
Electron , Proton, Neutron and Photon

Ancient Times

There were various ideas to explain the nature of matter.

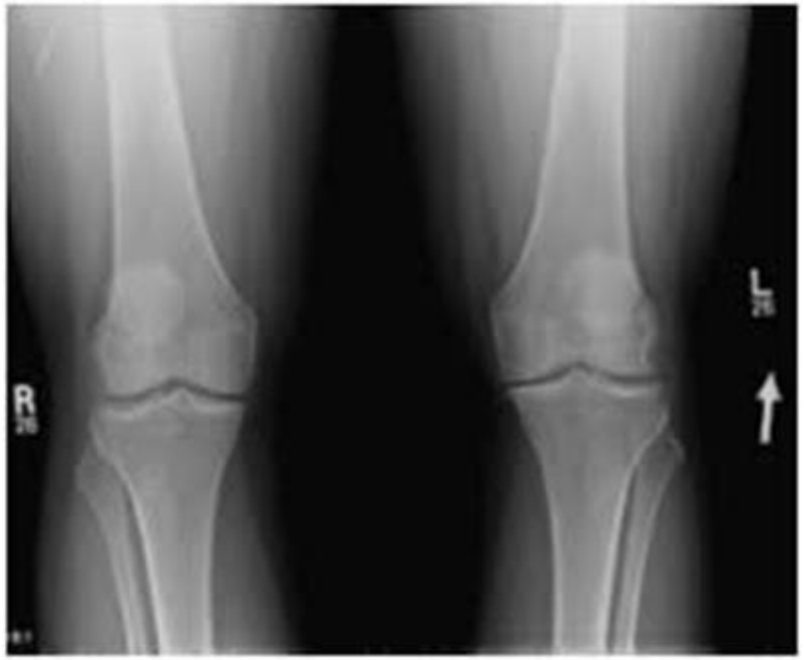
Empedocles proposed the four classical elements:
Air – Fire – Water – Earth

Democritus’s said:
"Everything is composed of atoms that are physically indivisible"



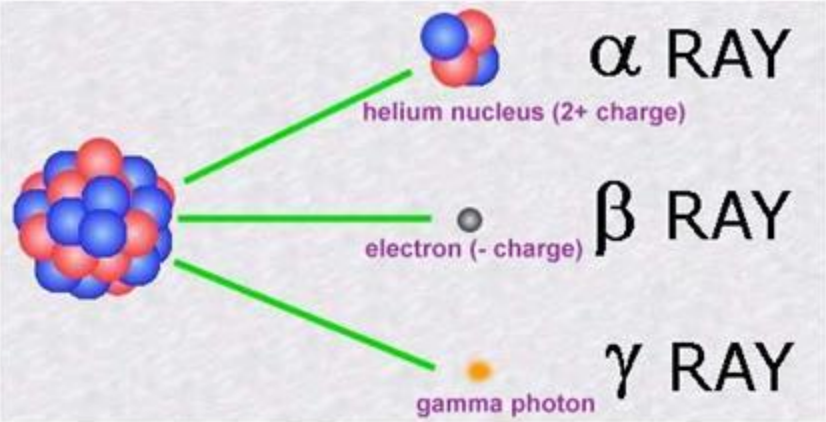
X-Ray

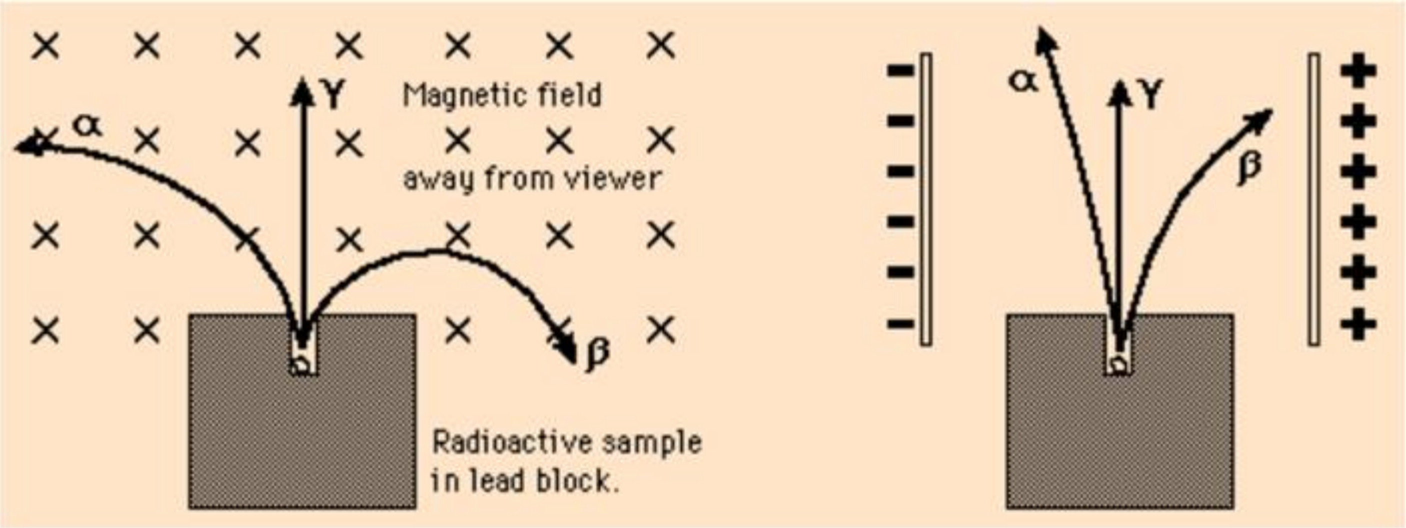
In 1895, X-rays are discovered by *W.C. Röntgen*

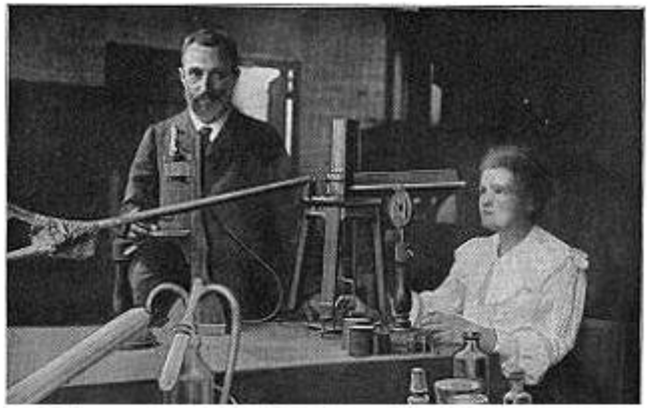


Radioactivity

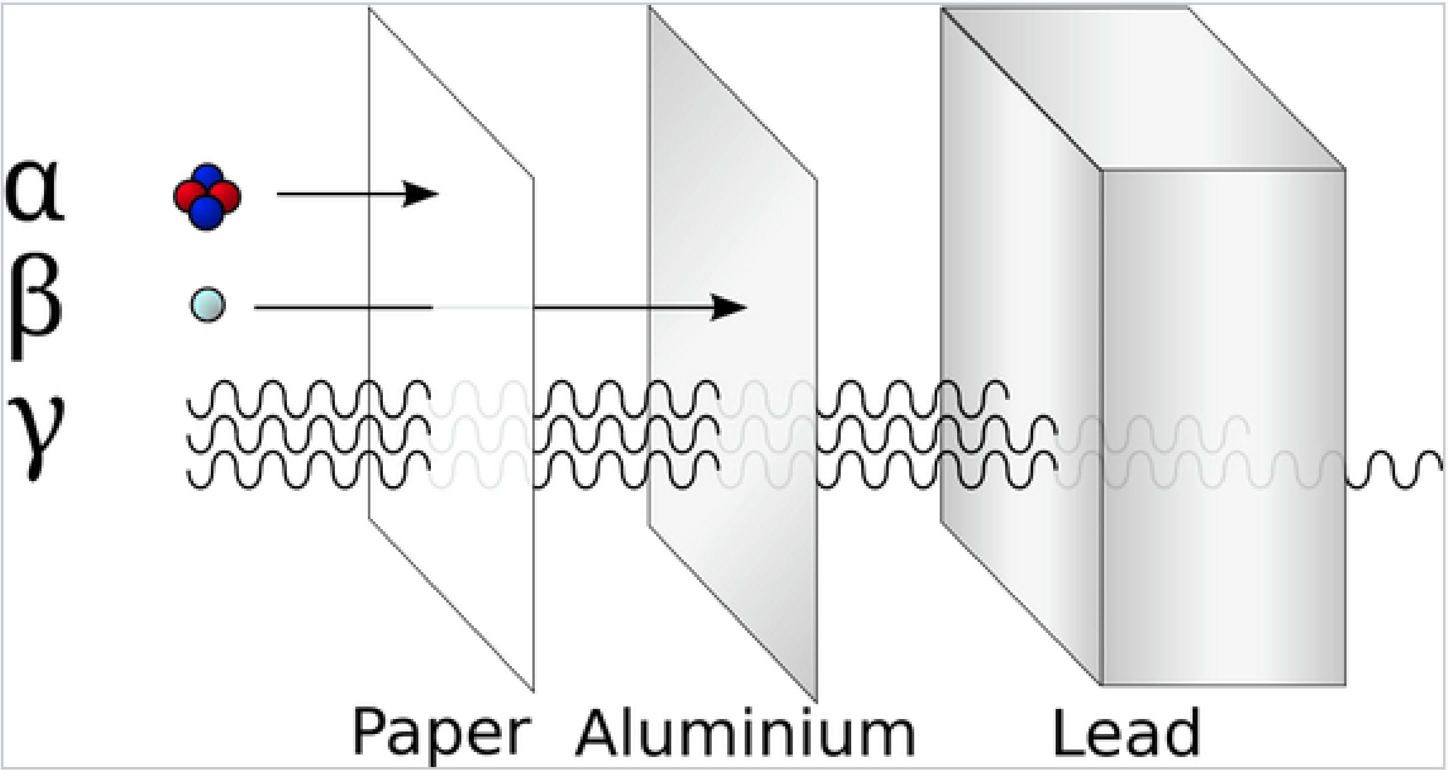
In 1896, it was found that several atomic nucleus radiates particles.
A material containing unstable nuclei is considered radioactive.
Radioactivity is first studied by H. Becquerel, M.Courie.







Pierre and Maria Curie
in their first laboratory



An illustration of the relative abilities of three different types of ionizing radiation to penetrate solid matter. Typical alpha particles (α) are stopped by a sheet of paper, while beta particles (β) are stopped by 3mm aluminum foil. Gamma radiation (γ) is dampened when it penetrates lead. Note caveats in the text about this simplified diagram.

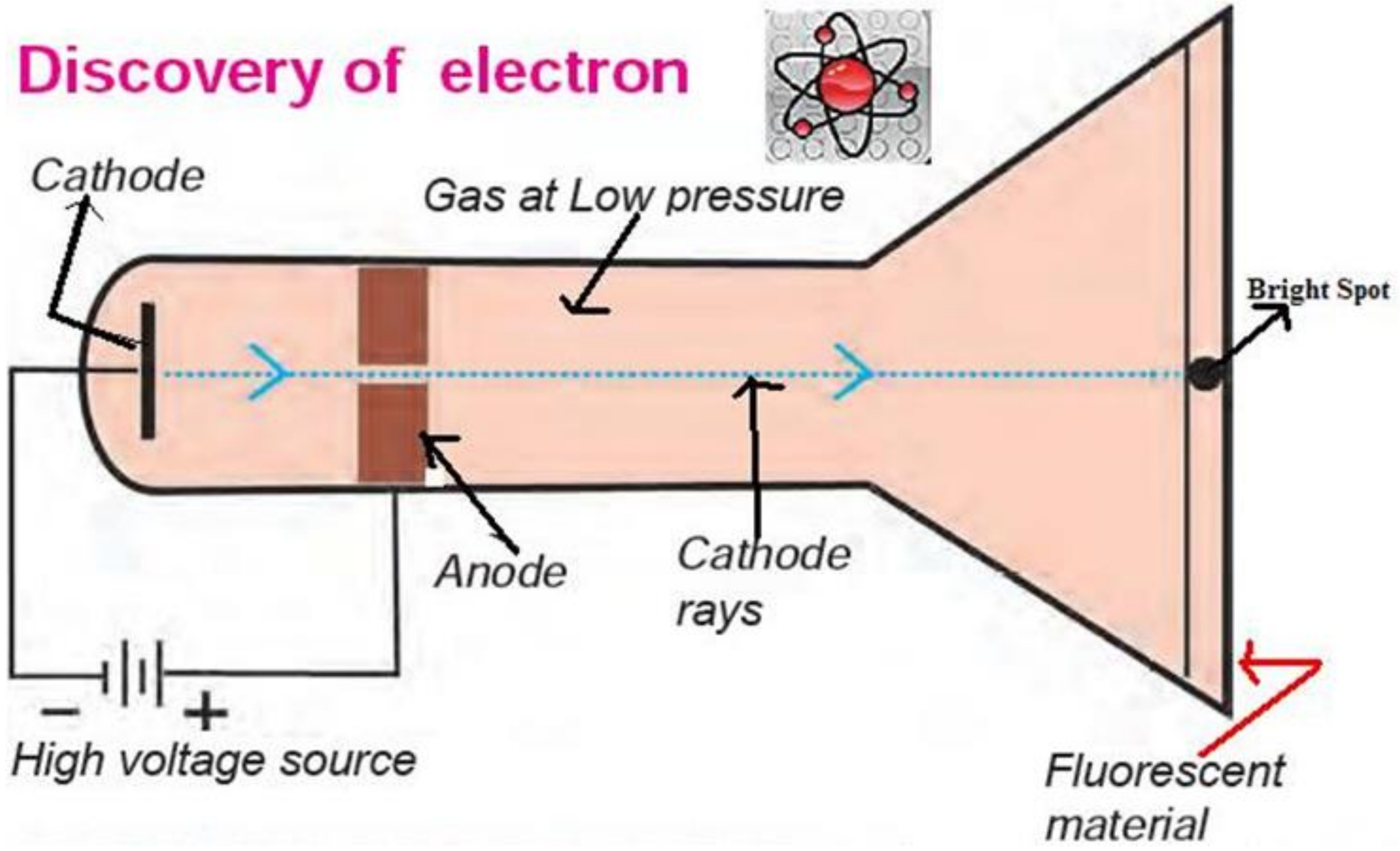
Electron

Particle Physics was born in 1897,
with J. J. Thomson's discovery of the electron.

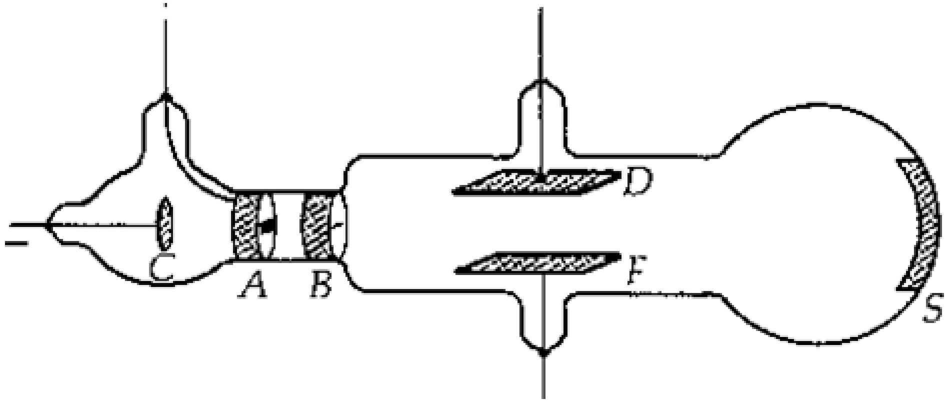
Thomson knew that "cathode rays" emitted by a hot filament could be deflected by a magnet.

These were not rays at all, but rather streams of particles interacting with electric and magnetic field.

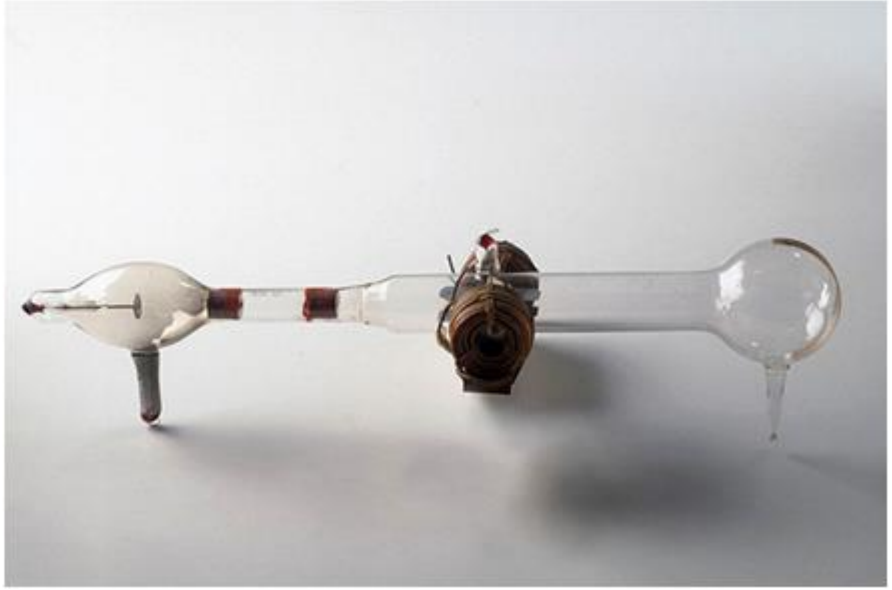
This is a negatively charged particle.


Discovery of electron
Cathode
Gas at Low pressure
Bright Spot
Anode
Cathode
rays
High voltage source
Fluorescent
material

Original Cathode Ray Tube

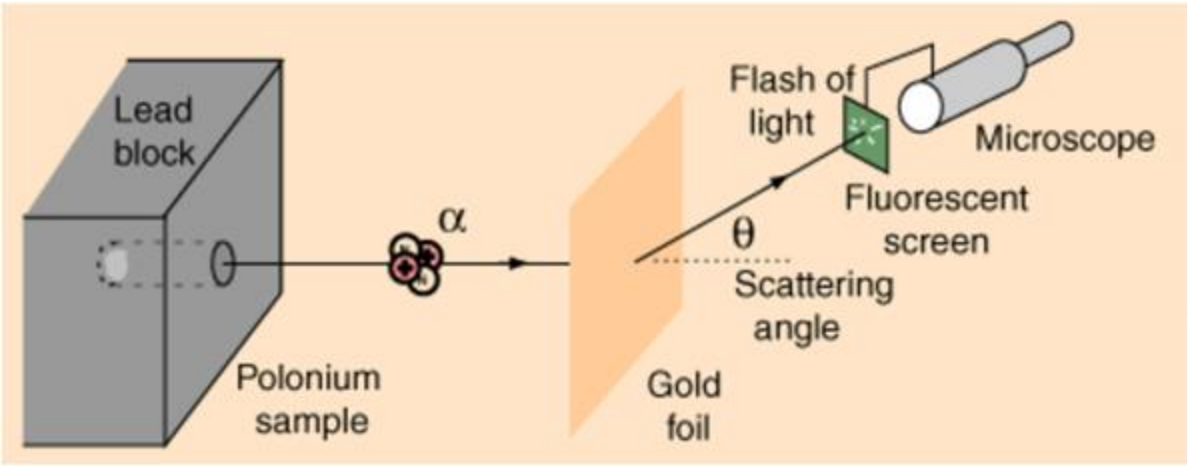


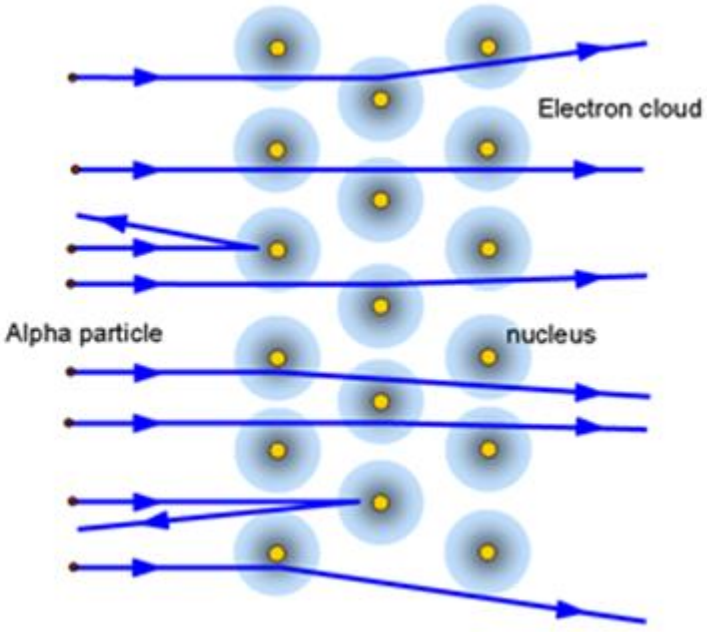
Thomson's tube for measuring q/m for the particles of cathode rays (electrons). Electrons from the cathode C pass through the slits at *A* and *B* and strike a phosphorescent screen *S*. The beam can be deflected by an electric field between plates *D* and *F* or by a magnetic field (not shown).



Rutherford Scattering Experiment (1911)

This experiment showed that the positive charge, and most of the mass, was concentrated in a tiny core, or nucleus, at the center of the atom.





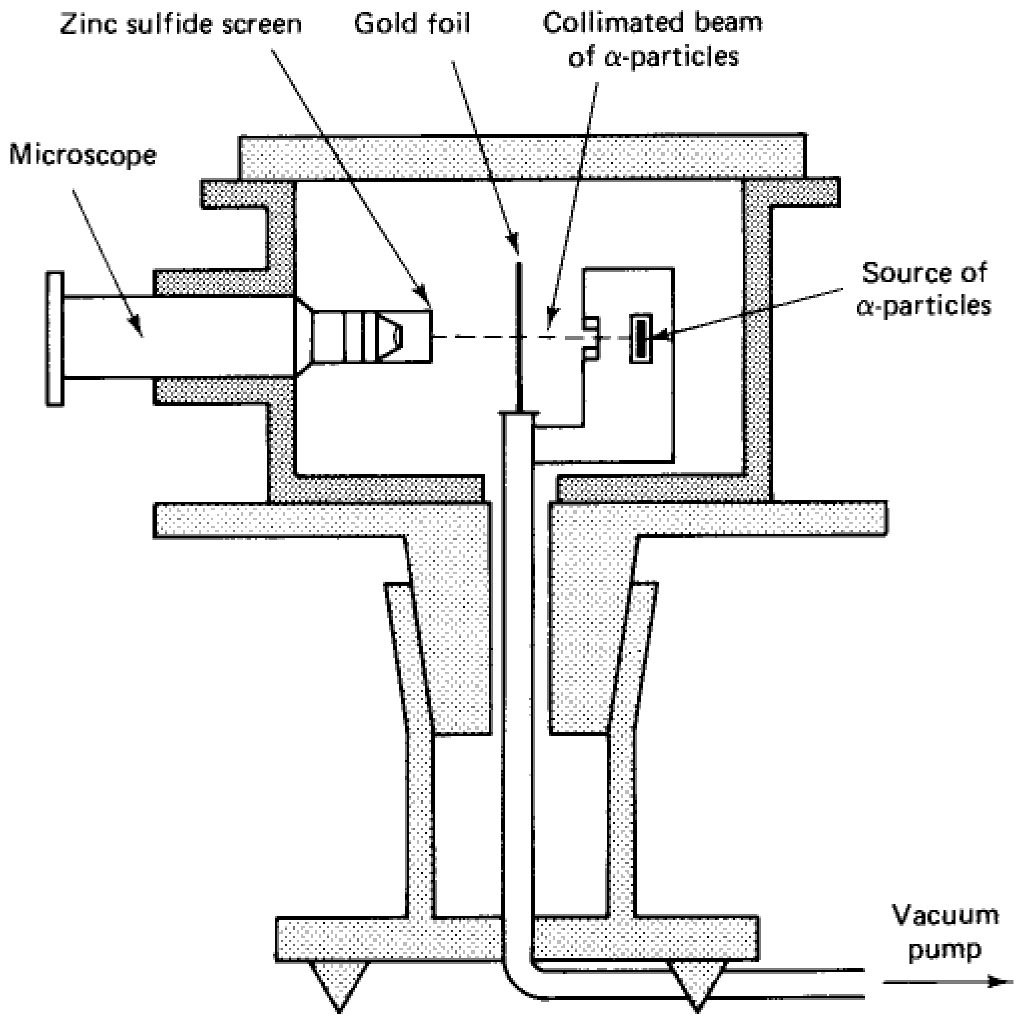


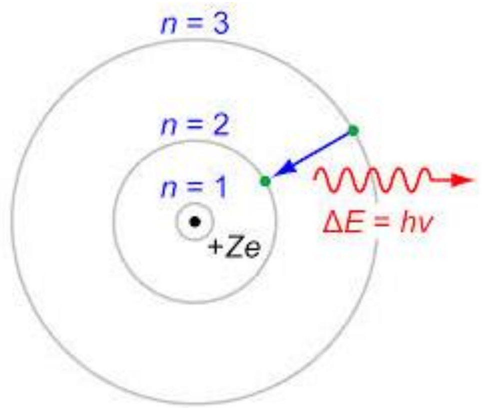
Figure 1.2 Schematic diagram of the apparatus used in the Rutherford scattering experiment. Alpha particles scattered by the gold foil strike a fluorescent screen, giving off a flash of light, which is observed visually through a microscope.

Proton

- The nucleus of the lightest atom (hydrogen) was given the name **proton** by Rutherford.

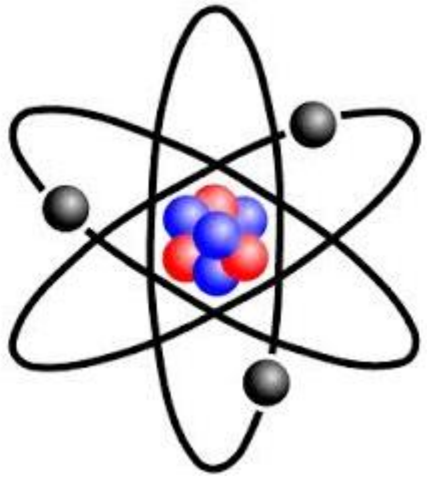
- In 1914 Niels Bohr proposed a model for hydrogen consisting of a single electron circling the proton, rather like a planet going around the sun, held in orbit by the mutual attraction of opposite charges.

- Using a primitive version of the quantum theory, Bohr was able to calculate the spectrum of Hydrogen.



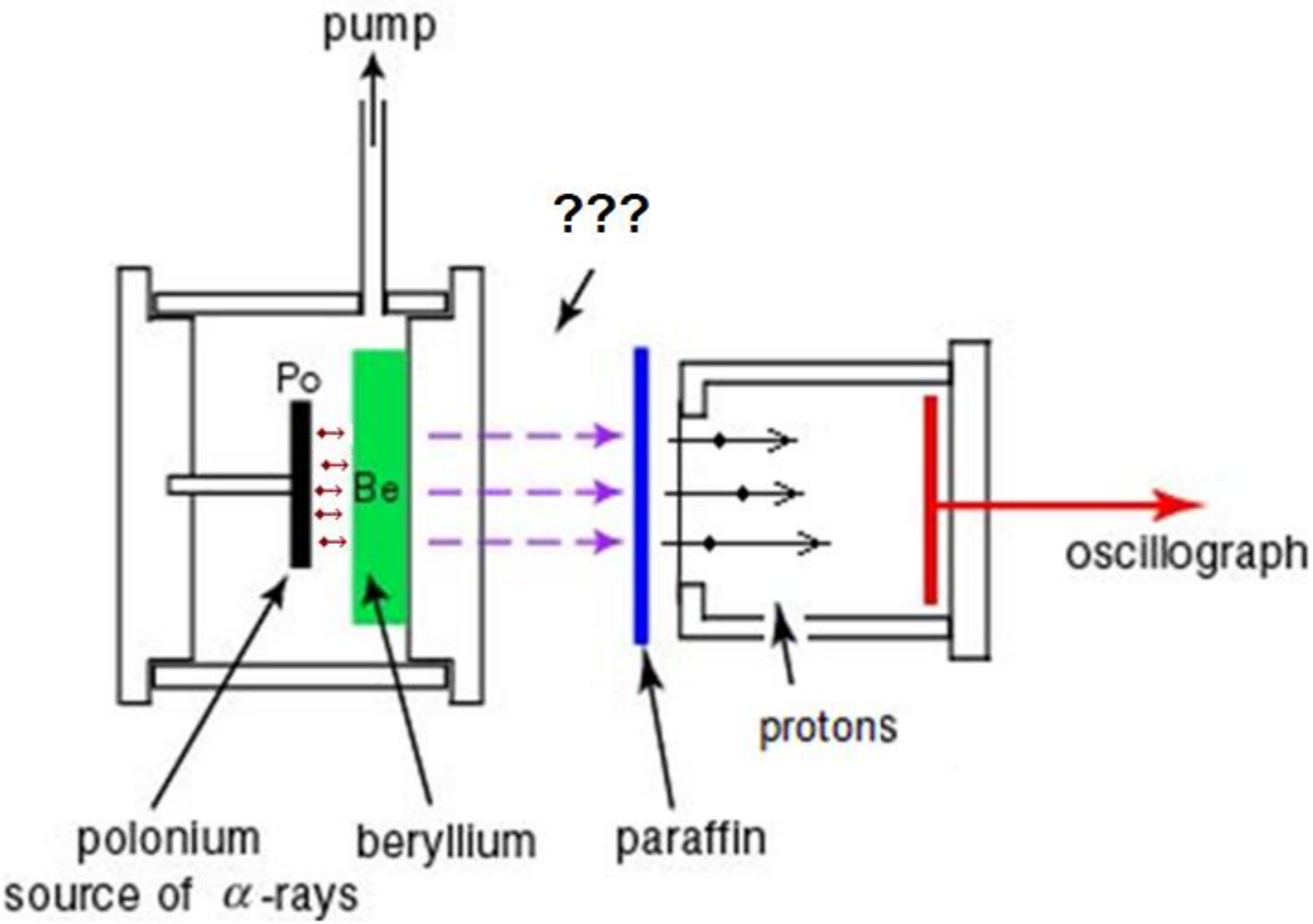
Neutron

- In 192x a lot of isotopes have been found by W. Aston and others.
- In 1932, the discovery of the neutron by J. Chadwick put the final touch on the classical period in elementary particle physics.
- "What is matter made of?."
  In 1932, it was all just protons, neutrons, and electrons.
  Proton and neutron are collectively known as **nucleons**.



Discovery of Neutron

Chadwick applied conservation of energy and momentum to predict the mass of unknown neutral particles outgoing from **Be** target.

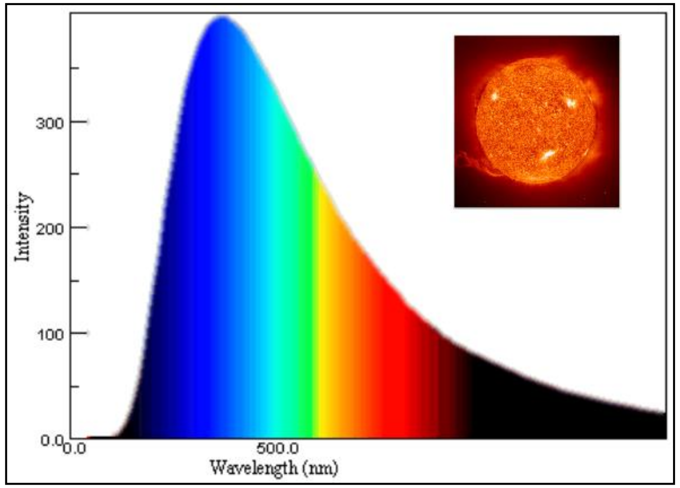


$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}C + n$$

Photon (1900-1924)

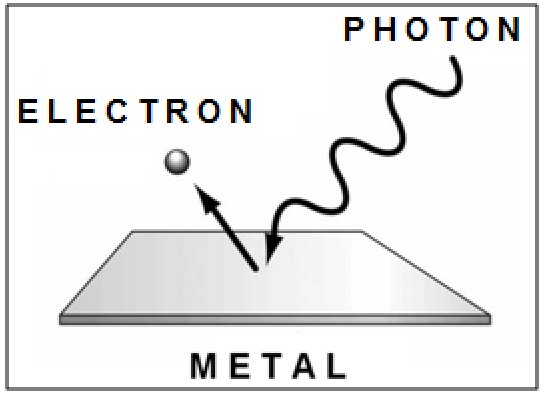
- **1900 Photon (*M. Planck*)**
  Photon energy is given by:

$$E = h\nu$$



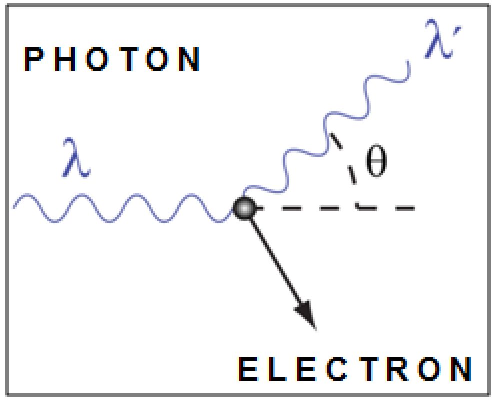
- **1905 Photoelectric Effect (*A.Einstein*)**
  Kinetic energy of the ejected electron:

$$K < h\nu - w$$



- **1923 Compton Scattering (*H.Compton*)**
  Wavelength of the scattered photon:

$$\lambda' = \lambda + \frac{h}{m_e c}[1 - \cos\theta]$$



Leptons

Leptons - *Three pairs of truly elementary particles*

The list of the six known leptons and their antiparticles.

Table 13.2 Leptons. All are unaffected by the strong interaction and are fermions. The neutrinos are uncharged; their masses are unknown but unlikely to exceed a few eV/c^2.

Lepton	Symbol	Antiparticle	Mass, MeV/c^2	Mean Life, s	Spin
Electron	e^-	e^+	0.511	Stable	$\frac{1}{2}$
e-neutrino	ν_e	$\bar{\nu}_e$	Very small	Stable	$\frac{1}{2}$
Muon	μ^-	μ^+	106	2.2×10^{-6}	$\frac{1}{2}$
μ-neutrino	ν_μ	$\bar{\nu}_\mu$	Very small	Stable	$\frac{1}{2}$
Tau	τ^-	τ^+	1777	2.9×10^{-23}	$\frac{1}{2}$
τ-neutrino	ν_τ	$\bar{\nu}_\tau$	Very small	Stable	$\frac{1}{2}$

Antiparticle

Every type of particle of "ordinary" matter is associated with an antiparticle with the same mass but with opposite physical charges (such as electric charge).

Antiparticle of the electron (e^-) is the positron (e^+)

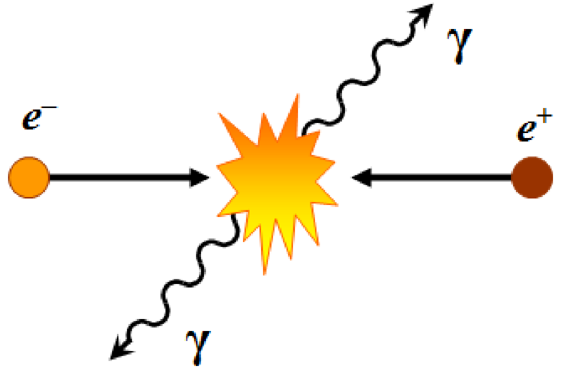
Antiparticle of the proton (p) is the positron ($\bar{p}$)

Antiparticle of the neutron (n) is the positron ($\bar{n}$)

Some particles, such as the photon, are their own antiparticle.

$e^- - e^+$ pairs can annihilate each other, producing photons.

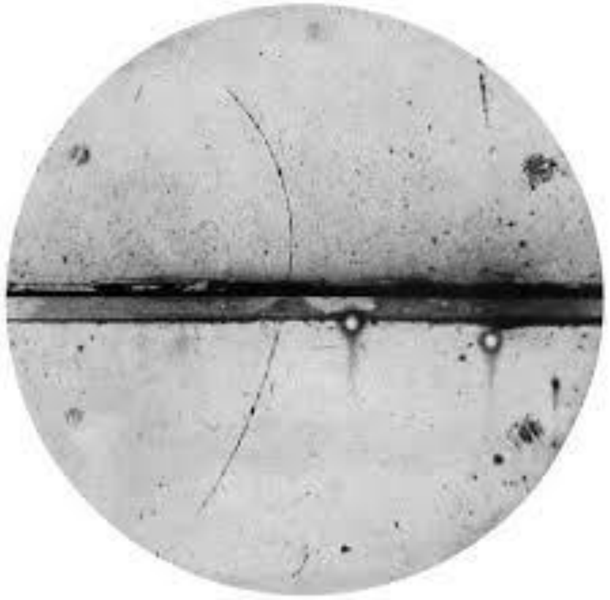
Electron
charge = -e
Mass = m_e
Spin = 1/2



Positron
charge = +e
Mass = m_e
Spin = 1/2

This is the fundamental principle of PET in Medicine.

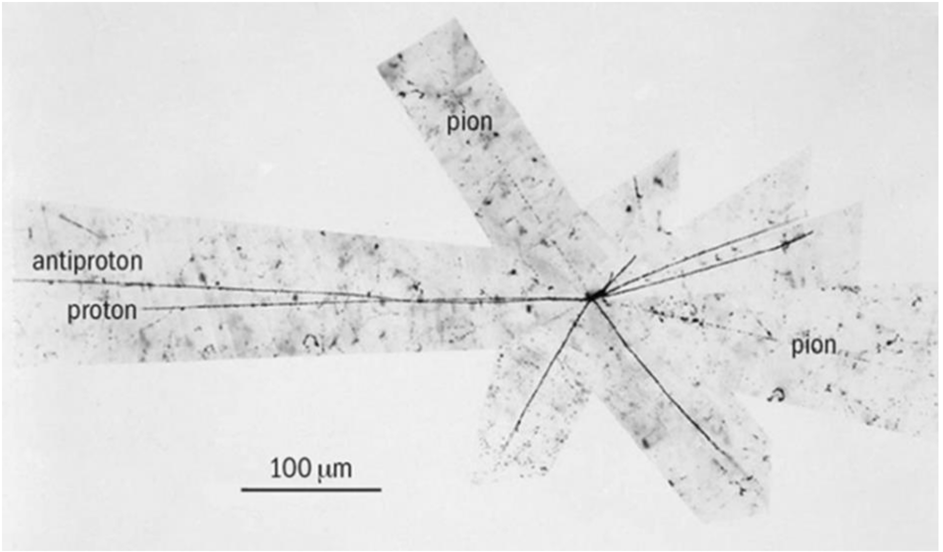
In 1932 P. Dirac predicted the existance of positron (see Appendix A). In the same year, C. D. Anderson found that cosmic-ray collisions produced these particles in a cloud chamber.



In 1955 Anti-proton discovered at the Bevatron particle accelerator.

1979 antiprotons have been detected in cosmic rays via the the reaction where *N* is nucleus:

$$p + N \rightarrow p + p + \bar{p} + N$$



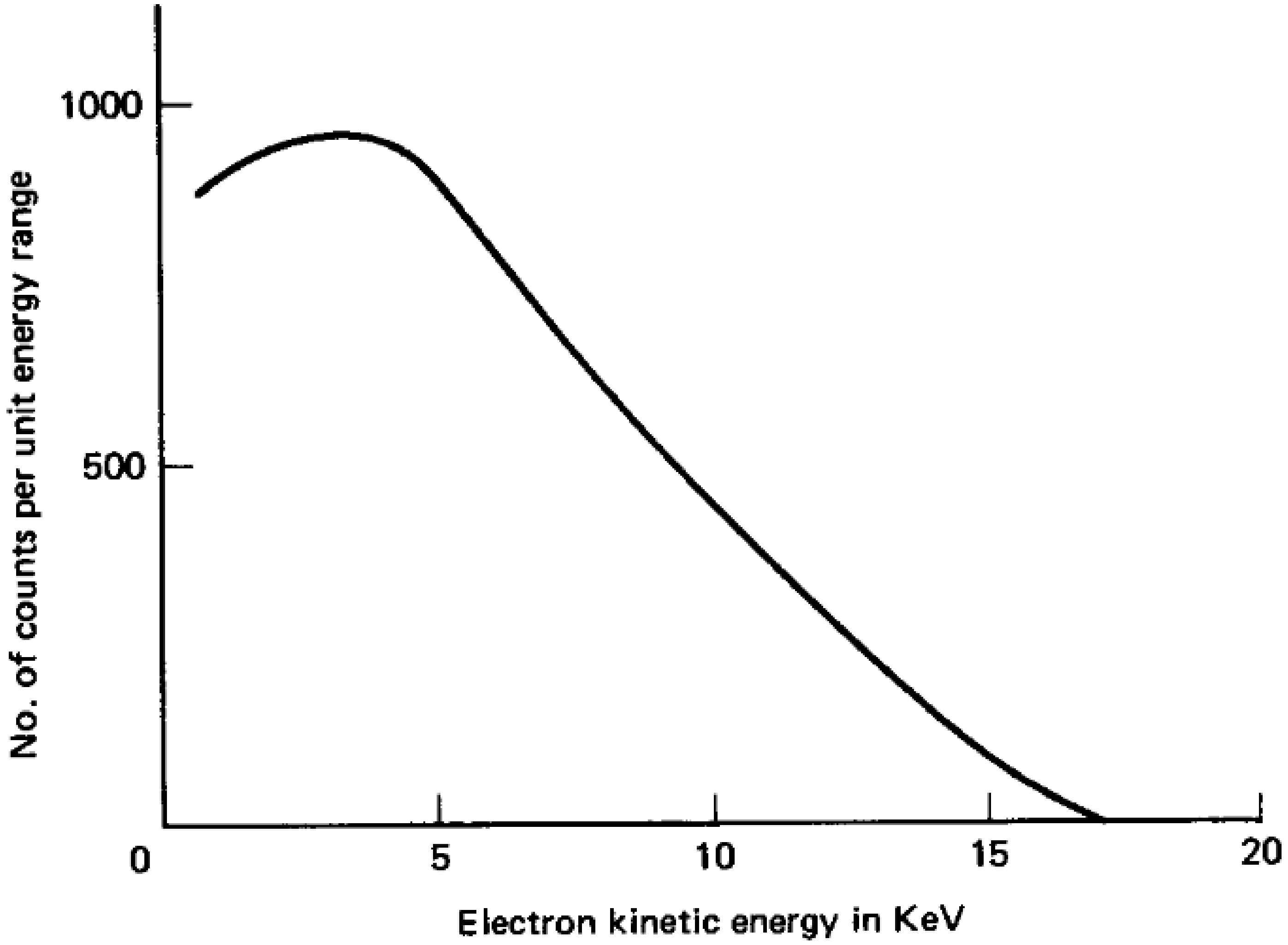
Neutrinos (1930-1962)

Nuclear beta decay:

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$$

$${}^{3}_{1}H \rightarrow {}^{3}_{2}He + e^{-}$$

$$A \rightarrow B + e^{-}$$

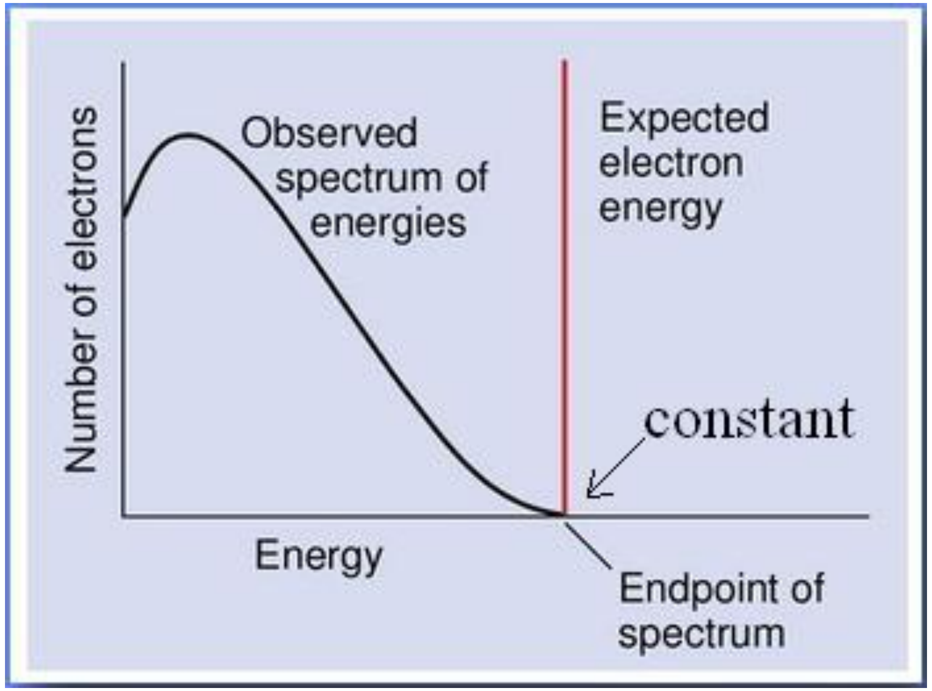


The beta decay spectrum of tritium (${}^{3}_{1}H \rightarrow {}^{3}_{2}He$).

Characteristic of two-body decay:

$$A \rightarrow B + e^-$$

$$E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A}\right)c^2 \equiv \text{constant}$$



Hovever, the observed energy spectrum of electrons
are distributed from zero to *E*. So we have missing energy!

In 1931, Pauli proposed an hypothetical particle which conserves the energy.

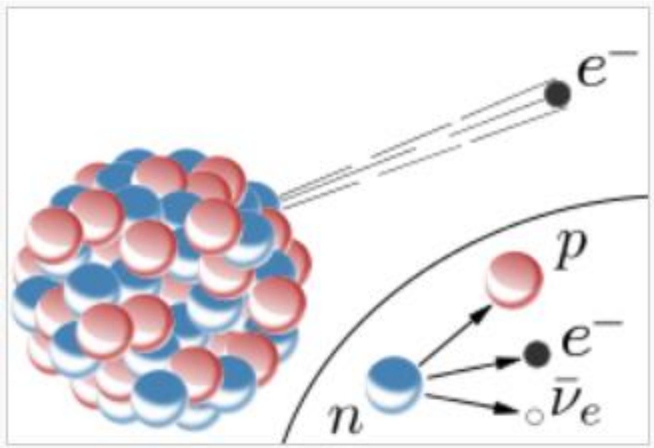
Observed reaction:

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$$

Correct reaction:

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \bar{\nu}_e$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



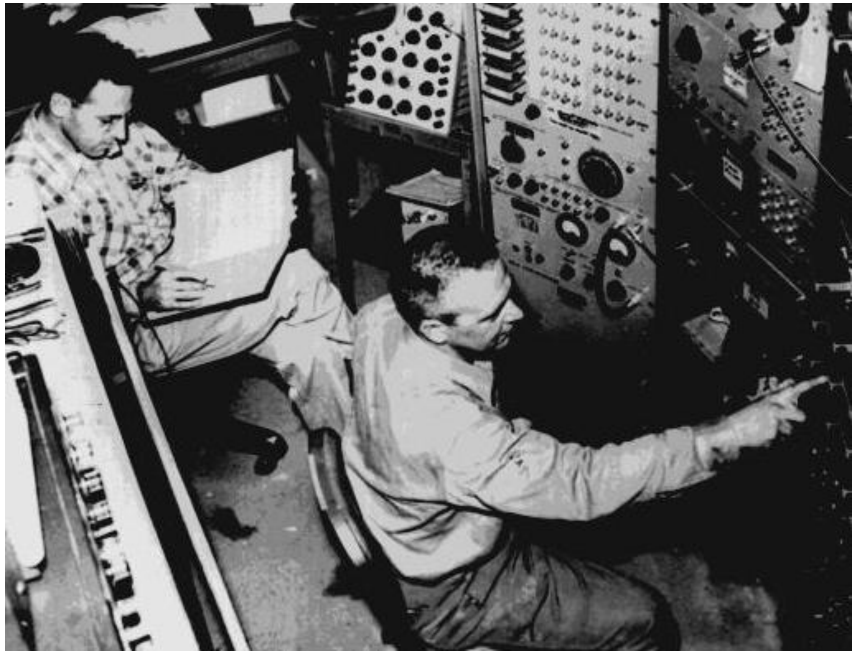
Observation of Neutrino

The difficulty of observing the neutrino is that it interacts so weakly with matter.

In 1956, neutrino has been discovered *by Cowan and Reines.*

They set up a large tank of water and watched for the "inverse" beta-decay reaction (See Appendix B)

$$\bar{\nu} + p^{+} \longrightarrow n + e^{+}$$



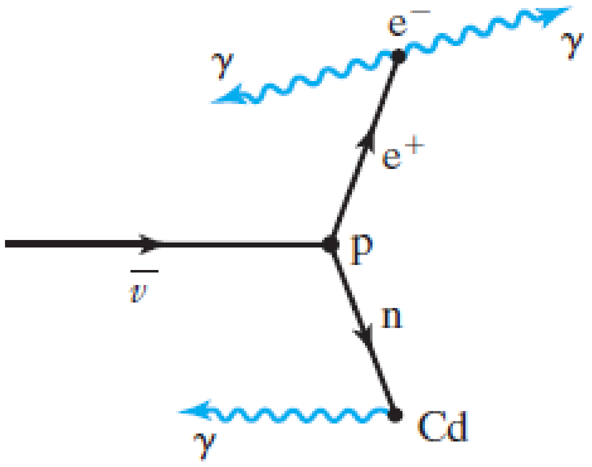
Experimental Setup

Reactions:

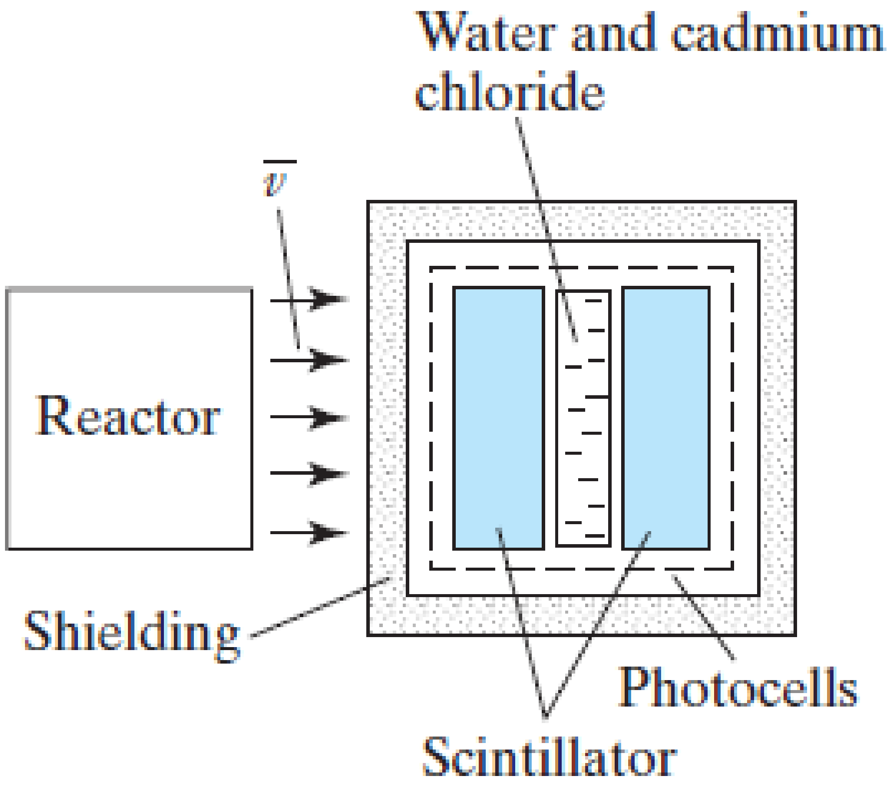
$\bar{\nu} + p \rightarrow e^+ + n$

$e^+ + e^- \rightarrow \gamma + \gamma$

$n + {}^{113}\mathrm{Cd} \rightarrow {}^{114}\mathrm{Cd} + \gamma$



- Flux = 5×10^{13} neutrinos/cm^2/s
- They could observe only two or three events every hour.



Other Leptons

The muon, and its associated neutrino were first discovered in the decays of charged pions:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \bar{\upsilon}_\mu$$

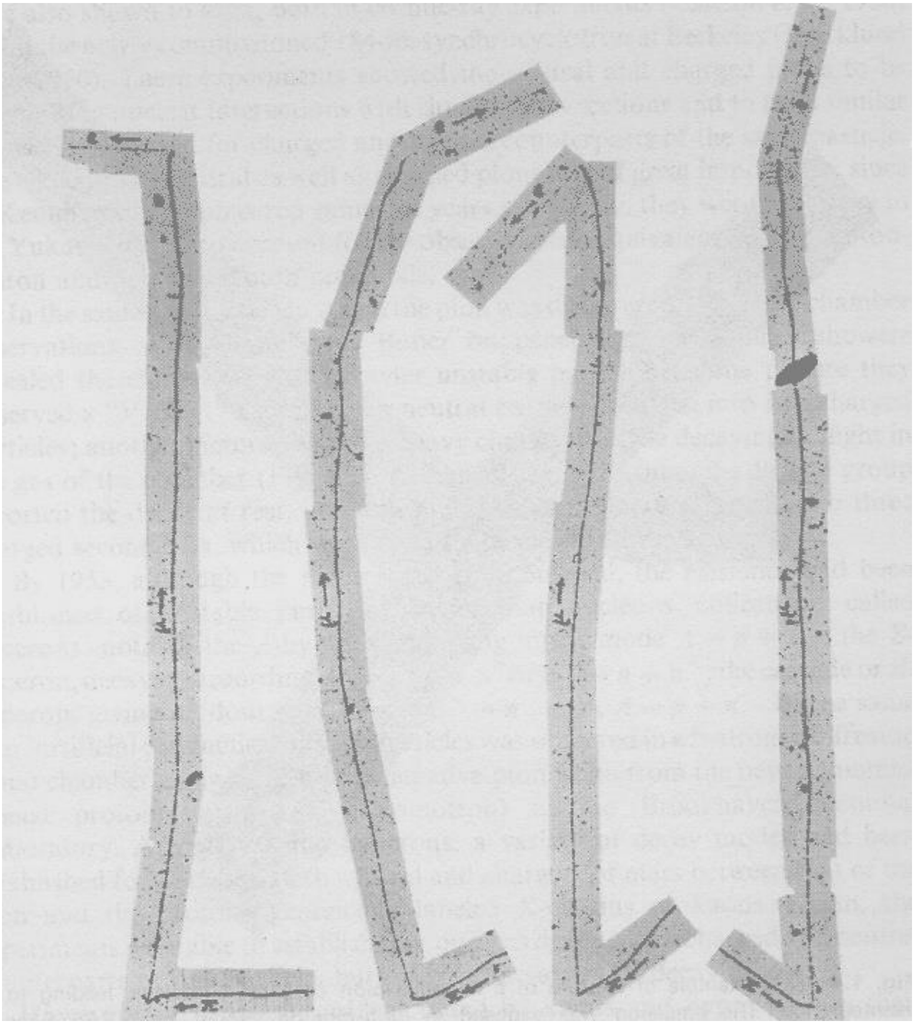
and muons decays to electrons*:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\upsilon}_\tau \qquad \mu^- \rightarrow e^- + \bar{\upsilon}_e + \nu_\mu$$

Why do we see two neutrinos in the last two reactions?

In 1975, the final pair of leptons are found:

$$\tau^+ \rightarrow \mu^+ + \bar{\upsilon}_\tau + \nu_\mu \qquad \tau^- \rightarrow \mu^- + \bar{\upsilon}_\mu + \nu_\tau$$



** The neutrinos involved in pion decays are not the same as those involved in beta decay.*
The existence of another class of neutrino was established in 1962.
A metal target was bombarded with high-energy protons, and pions were created in profusion.
Inverse reactions traceable to the neutrinos from the decay of these pions produced muons only, and no electrons.
Hence these neutrinos must be different in some way from those associated with beta decay.

Neutrino is electrically neutral, weakly interacting elementary subatomic particle with half-integer spin.

Upper limit for masses of neutrinos see PDG web page:

$$m(\nu_e) = m(\bar{\nu}_e) < 0.8 \text{ eV}$$
$$m(\nu_\mu) = m(\bar{\nu}_\mu) < 0.19 \text{ MeV}$$
$$m(\nu_\tau) = m(\bar{\nu}_\tau) < 18.2 \text{ MeV}$$

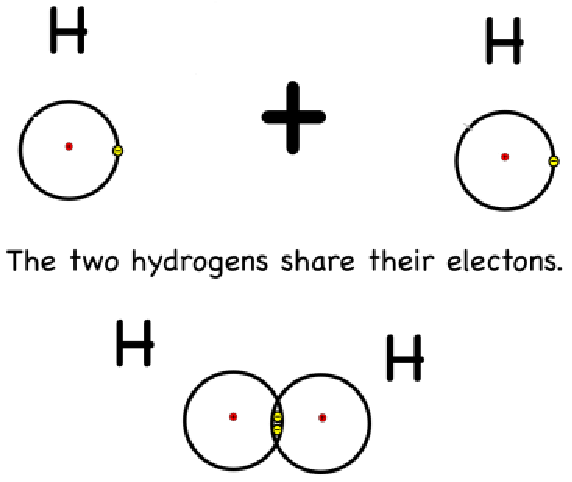
Hadrons

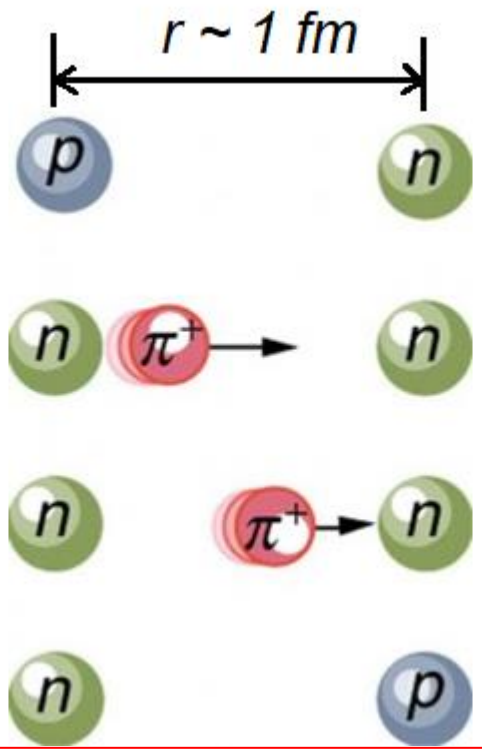
Meson Exchange Model

- Exchange of electrons between atoms holds a molecule together.
- A similar mechanism may operate inside a nucleus.
  In 1935 H. Yukawa proposed a new particle which is exchanged by nucleons. Today these particles are known as pions (π^+, π^-, π^0)
- According to this model every nucleon emits and absorbs pions. The associated momentum transfer is equivalent to the action of force.The mass of the pion can be predicted via uncertainty principle:

$$\Delta E \Delta t \sim \hbar/2$$
$$(mc^2)(r/c) \sim \hbar/2$$
$$mc^2 = \frac{\hbar c}{2r} \approx 100 \text{ MeV}$$

- Pions are discovered in 1947 with observed values:
  $m(\pi^+) = m(\pi^-) \approx 140 \text{ MeV}$ and $m(\pi^0) \approx 135 \text{ MeV}$





Hadrons - *Particles subject to the strong interaction*

Unlike leptons, hadrons are subject to the strong interaction. Table lists some hadrons with the longest lifetimes against decay into other particles.

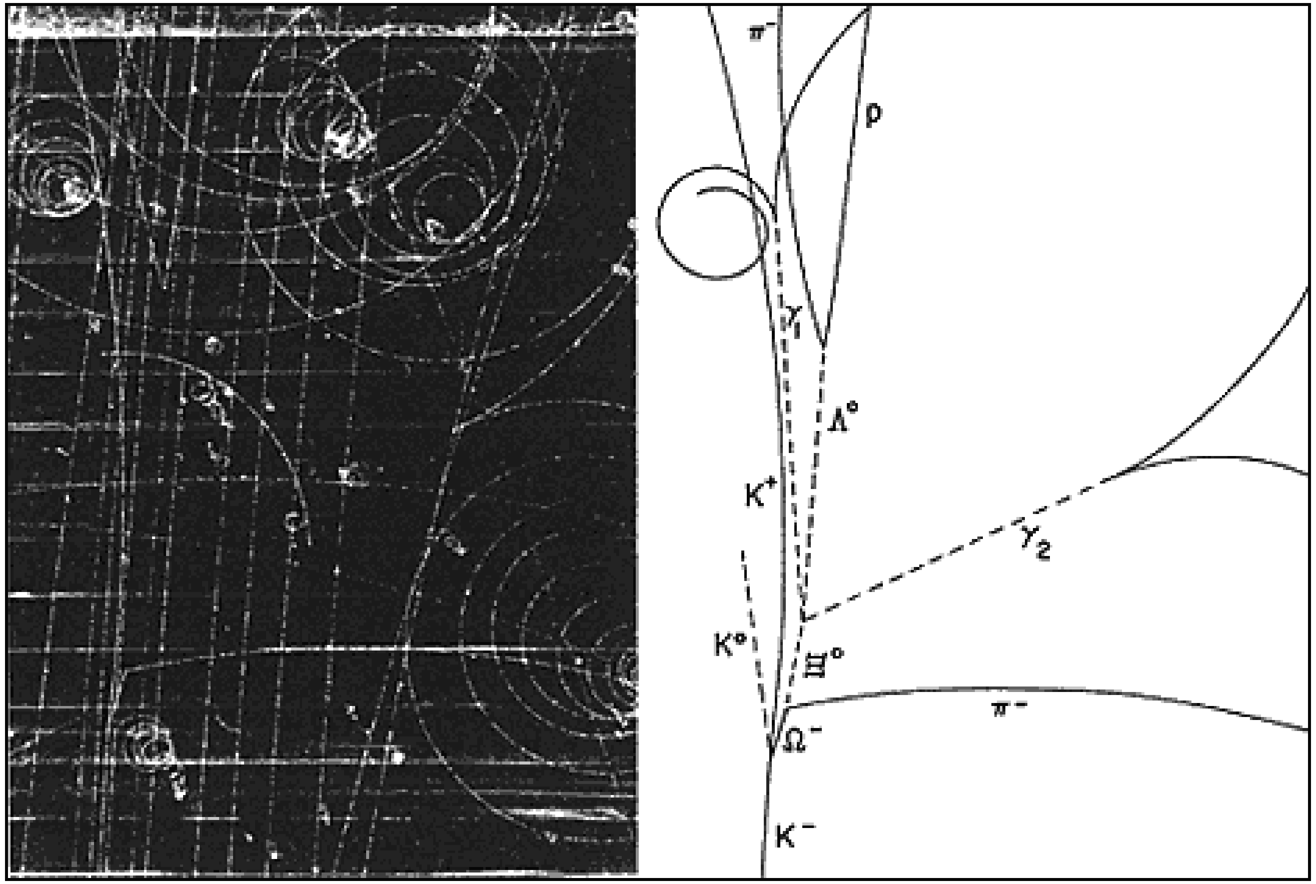
Table 13.3 Some hadrons and their properties. The symbol S stands for strangeness number, discussed in Sec. 13.4. Antiparticles have strangeness numbers the negative of those shown.

Class	Particle	Symbol	Antiparticle	Mass, MeV/c^2	Mean Life, s	Spin	S
Mesons	Pion	π^+	π^-	140	2.6×10^{-8}	0	0
		π^0	Self	135	8.7×10^{-17}		
		π^-	π^+	140	2.6×10^{-8}		
	Kaon	K^+	K^-	494	1.2×10^{-8}	0	+1
		K_S^0	$\overline{K_S^0}$	498	8.9×10^{-11}		
		K_L^0	$\overline{K_L^0}$	498	5.2×10^{-8}		
	Eta	η^0	Self	549	5×10^{-19}	0	0
		η'	Self	958	2.2×10^{-21}		
Baryons	Nucleon: Proton	p	$\overline{p}$	938.3	Stable	$\frac{1}{2}$	0
	Nucleon: Neutron	n	$\overline{n}$	939.6	889		
	Lambda	Λ^0	$\overline{\Lambda^0}$	1116	2.6×10^{-10}	$\frac{1}{2}$	−1
	Sigma	Σ^+	$\overline{\Sigma^-}$	1189	8.0×10^{-11}	$\frac{1}{2}$	−1
		Σ^0	$\overline{\Sigma^0}$	1193	6×10^{-20}		
		Σ^-	$\overline{\Sigma^+}$	1197	1.5×10^{-10}		
	Xi	Ξ^0	$\overline{\Xi^0}$	1315	2.9×10^{-10}	$\frac{1}{2}$	−2
		Ξ^-	$\overline{\Xi^+}$	1321	1.6×10^{-10}		
	Omega	Ω^-	Ω^+	1672	8.2×10^{-11}	$\frac{3}{2}$	−3

All baryons other than nucleons (p, n) decay with mean lives of less than 10^{-9} s in a variety of ways, but the end result is always a proton or neutron.

For example, here is one sequence which the Ω^- baryon can follow in its decay:

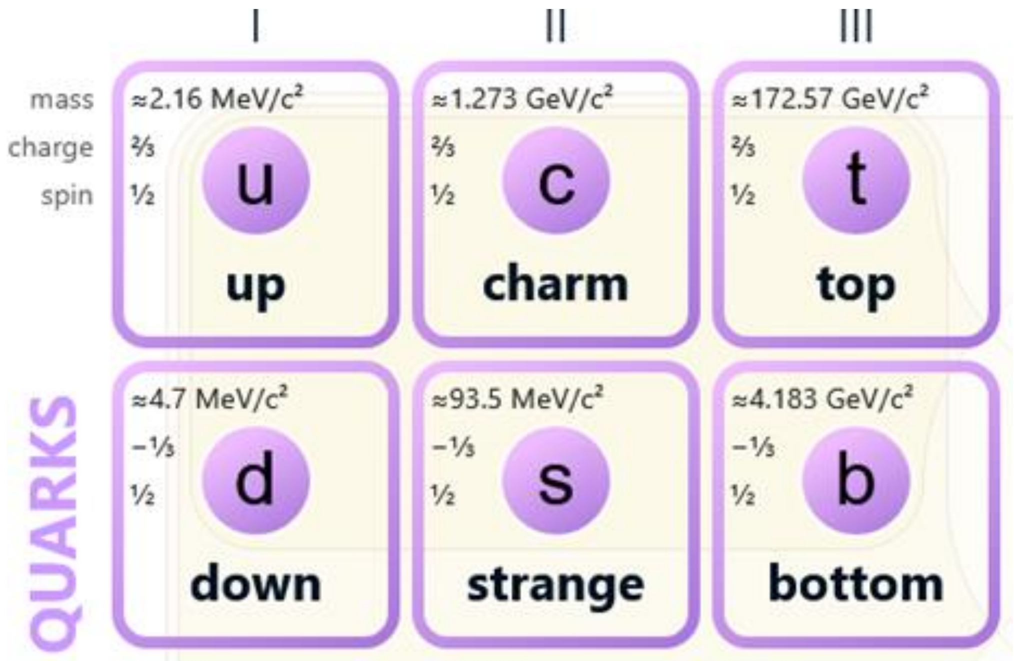
$$\Omega^- \rightarrow \Xi^0 + \pi^-$$
$$\Xi^0 \rightarrow \Lambda^0 + \pi^0$$
$$\Lambda^0 \rightarrow p^+ + \pi^-$$

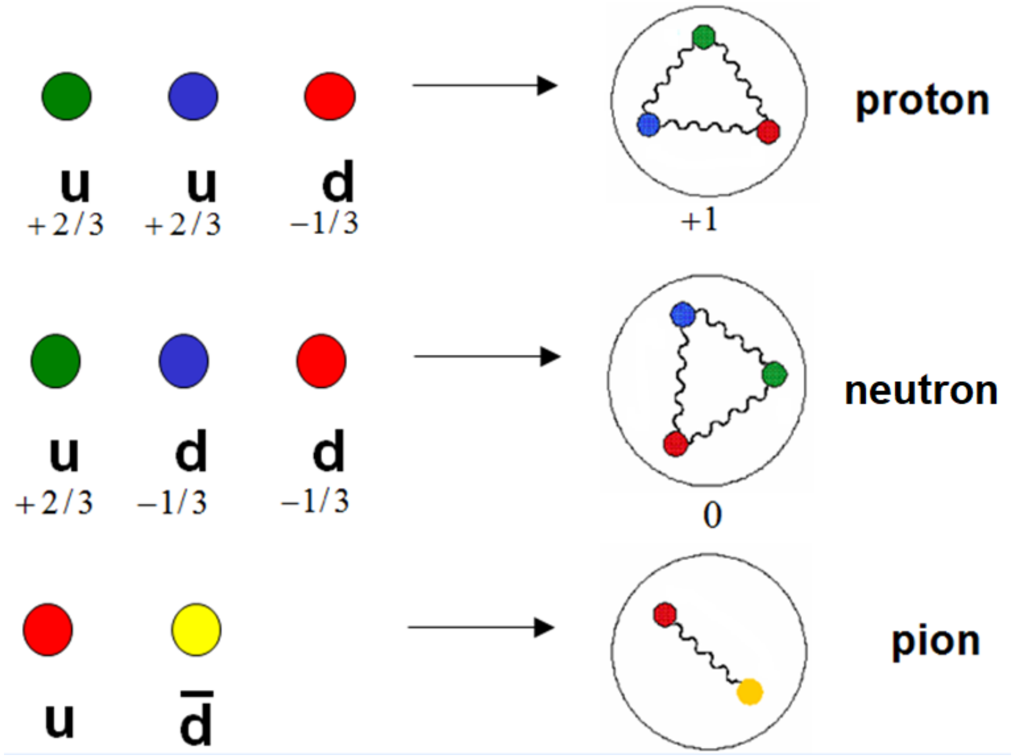


Quark Model

The quark model is a classification scheme for hadrons in terms of their (valence) quarks.

1. All baryons are composed of three quarks.
2. All antibaryons are composed of three antiquarks.
3. All conventional mesons are composed of one quark-antiquark pair.
4. Quarks interacts via gluons.
5. Quarks have fractional electronic charge.





In 1968, quarks are discovered in *SLAC lab*

electron - proton collision …

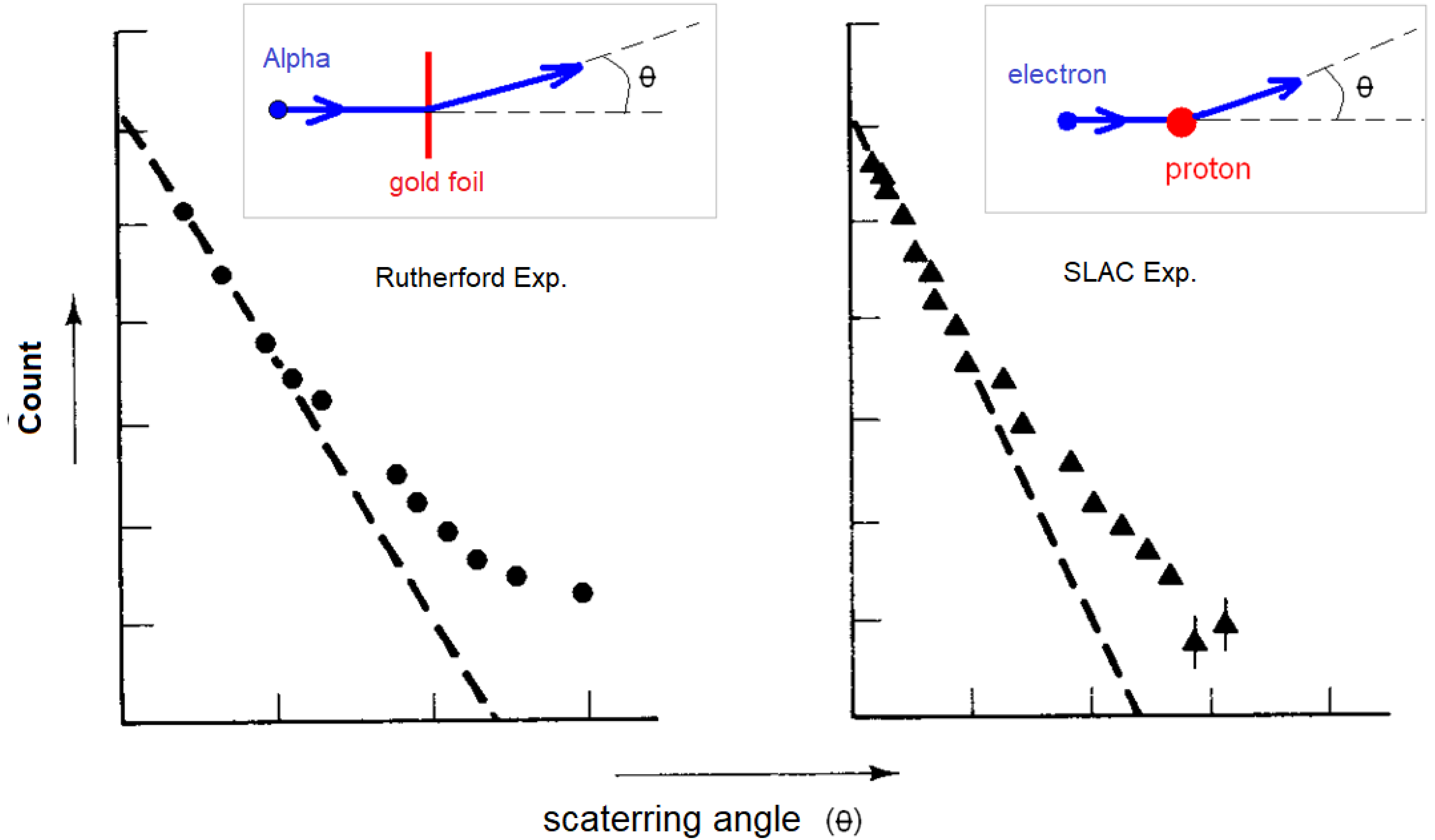

Alpha
gold foil
θ
Rutherford Exp.
electron
proton
θ
SLAC Exp.
Count
scaterring angle (θ)

Table 13.5 Compositions of some hadrons according to the quark model

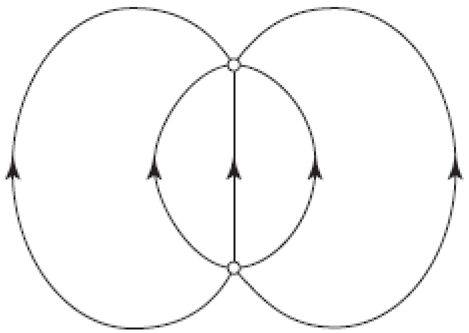
Hadron	Quark Content	Baryon Number	Charge, *e*	Spin	Strangeness
π^+	$u\bar{d}$	$\frac{1}{3} - \frac{1}{3} = 0$	$+\frac{2}{3} + \frac{1}{3} = +1$	$\uparrow\downarrow = 0$	$0 + 0 = 0$
K^+	$u\bar{s}$	$\frac{1}{3} - \frac{1}{3} = 0$	$+\frac{2}{3} + \frac{1}{3} = +1$	$\uparrow\downarrow = 0$	$0 + 1 = +1$
p^+	uud	$\frac{1}{3} + \frac{1}{3} + \frac{1}{3} = +1$	$+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$	$\uparrow\uparrow\downarrow = \frac{1}{2}$	$0 + 0 + 0 = 0$
n^0	ddu	$\frac{1}{3} + \frac{1}{3} + \frac{1}{3} = +1$	$-\frac{1}{3} - \frac{1}{3} + \frac{2}{3} = 0$	$\downarrow\downarrow\uparrow = \frac{1}{2}$	$0 + 0 + 0 = 0$
Ω^-	sss	$\frac{1}{3} + \frac{1}{3} + \frac{1}{3} = +1$	$-\frac{1}{3} - \frac{1}{3} - \frac{1}{3} = -1$	$\uparrow\uparrow\uparrow = \frac{3}{2}$	$-1 - 1 - 1 = -3$

Strong Force and QCD

The strong force was originally introduced as the force between any two nucleons in a nucleus. The strong force must actually be a force between quarks since nucleons are bound states of quarks. **No quark has ever been isolated! → quark confinement**

Electromagnec force originates from electric charges (+,-)
Strong force originates from strong (color) charges (red,green,blue)

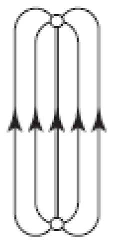
Field lines between two charges



QED: the quantum theory of the force between electric charges
QCD: the quantum theory of the force between color charges

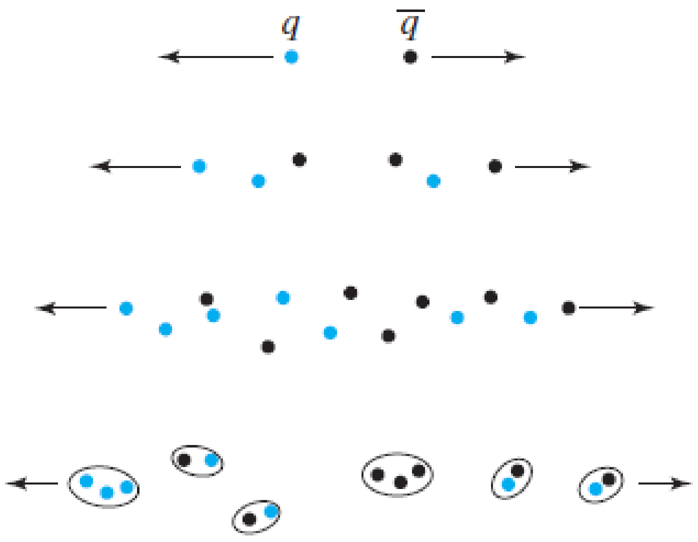
Potential energy between electric charges: $U(r) = -k/r$
Potential energy between color charges: $U(r) = ar - b/r$

Field lines between two quarks



The explanation for quark confinement begins with the idea that, as though they were connected by a spring, the attractive force between two quarks goes up as the quarks move apart from their normal spacing. This means that more and more energy is needed to increase their separation.

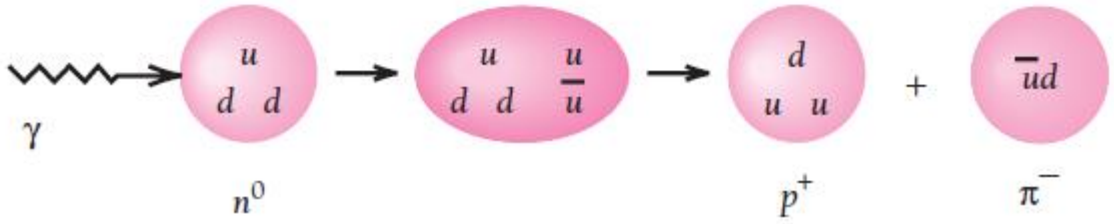
But, with enough energy added, instead of a quark breaking free from the others in a hadron, the excess energy goes into producing a quark-antiquark pair.



Example:

Energy is given to a neutron by a photon, and the result is a quark-antiquark pair created inside the neutron.

$$\gamma + n^0 \rightarrow p^+ + \pi^-$$



Conservation Laws

All particle reactions and decays obey certain conservation laws:

- Conservation of total energy
- Conservation of linear momentum
- Conservation of angular momentum (spin)
- Conservation of invariant mass (for all inertial coordinates)
- Conservation of charge
- Conservation of lepton number
- Conservation of baryon number
- Conservation of Strangeness (there is an exception for weak interactions)

For any decay: $X \rightarrow Y + Z$ $m_X > m_Y + m_Z$ (mass is not conserved)

For any collision: $1 + 2 \rightarrow 3 + 4$, may be $m_1 + m_2 \neq m_3 + m_4$ (mass is not conserved)

Some quantum numbers are assigned to fundamental particles:

Conservation of lepton number	*Conservation of baryon number*	*Conservation of Strangeness*
L_e = +1 for e- and ν_e L_e = -1 for e+ and $\overline{\nu_e}$ L_e = 0 for all other particles L_μ = +1 for μ- and ν_μ L_μ = -1 for μ + and $\overline{\nu_\mu}$ L_μ = 0 for all other particles L_τ = +1 for τ- and ν_τ L_τ = -1 for τ+ and $\overline{\nu_\tau}$ L_τ = 0 for all other particles	B = +1 for all baryons B = -1 for all anti-baryons B = 0 for all other particles	Strangeness (S) is conserved in strong and electromagnetic interactions but it may not be conserved in weak interactions. ΔS = 0 for strong interactions ΔS = 0 for em interactions ΔS = 0 or 1 for weak inter.

Note that

- There is no conservation law for mesons
- There is no conservation law for photons

Example 1

Consider a neutrino originating from the decay $\pi \rightarrow \mu + v$.

What is the type of the neutrino if pion is positively charged?

Example 2

Determine the unknown particles denoted by X:

$$X + p \rightarrow p + p + p + \bar{p}$$

Example 3

Explain why the following reactions are forbidden

$$\mu^- \rightarrow e^- + \gamma \qquad \bar{\nu}_\mu + p \rightarrow e^+ + n$$

Strangeness

A number of particles were discovered that behaved so unexpectedly that they were called "strange particles." They were only created in pairs, and decayed only in certain ways but not in others that were allowed by existing conservation rules. To clarify the observations, M. Gell-Mann and K. Nishijina introduced the strangeness number S. Strangeness (S) is conserved in strong and electromagnetic interactions but it may not be conserved in weak interactions.

$$\begin{array}{lcccccccccccc} & p^+ & + & p^+ & \rightarrow & \Lambda^0 & + & K^0 & + & p^+ & + & \pi^+ \\ S: & 0 & & 0 & & -1 & & +1 & & 0 & & 0 \end{array}$$

$$\begin{array}{lccccc} & \Xi^- & \rightarrow & n^0 & + & \pi \\ S: & -2 & & 0 & & 0 \end{array}$$

$$\begin{array}{ccccc} \Lambda^0 & \rightarrow & n^0 & + & \pi^0 \\ -1 & & 0 & & 0 \end{array}$$

Multiplet	Particle	Quark content	Mean life (s)
$\pi(138)$	$\pi^+(139.6)$	$u\bar{d}$	2.6×10^{-8}
	$\pi^\circ(135.0)$	$u\bar{u}$ and $d\bar{d}$	8.4×10^{-17}
	$\pi^-(139.6)$	$d\bar{u}$	2.6×10^{-8}
K(496)	$K^+(493.6)$	$u\bar{s}$	1.2×10^{-8}
	$K^\circ(497.7)$	$d\bar{s}$	5.2×10^{-8} and 8.9×10^{-11}
$\bar{K}(496)$	$\bar{K}^\circ(497.7)$	$s\bar{d}$	5.2×10^{-8} and 8.9×10^{-11}
	$K^-(493.6)$	$s\bar{u}$	1.2×10^{-8}
$\eta(549)$	$\eta^\circ(548.8)$	$u\bar{u}$, $d\bar{d}$, and $s\bar{s}$	6.1×10^{-19}

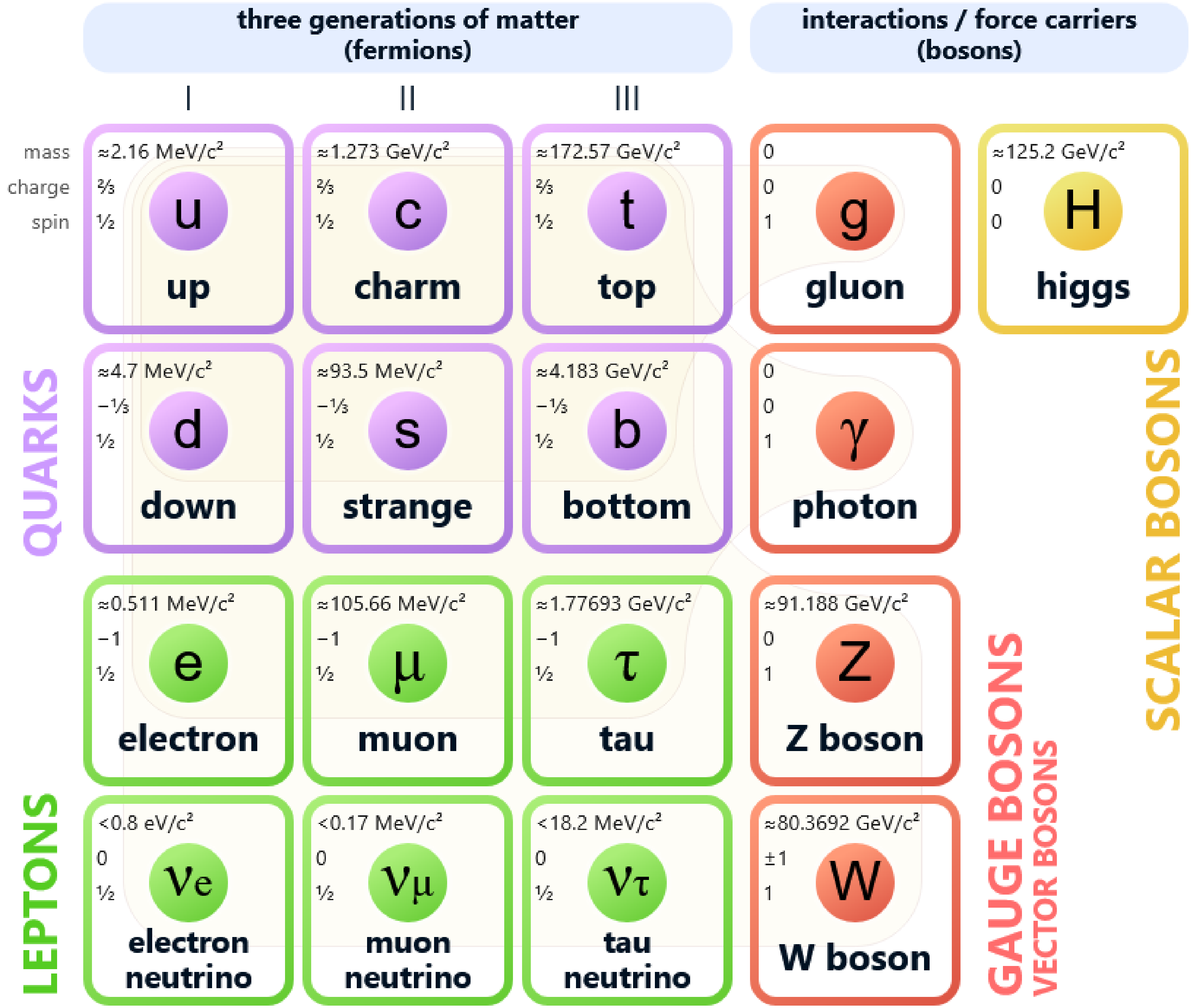
Multiplet	Particle	Quark content	Mean life (s)
N(939)	p(938.3)	uud	∞
	n(939.6)	udd	896
$\Lambda(1116)$	$\Lambda(1115.6)$	uds	2.63×10^{-10}
$\Sigma(1193)$	$\Sigma^+(1189.4)$	uus	7.99×10^{-11}
	$\Sigma^\circ(1192.5)$	uds	7.4×10^{-20}
	$\Sigma^-(1197.4)$	dds	1.48×10^{-10}
$\Xi(1318)$	$\Xi^\circ(1314.9)$	uss	2.90×10^{-10}
	$\Xi^-(1321.3)$	dss	1.64×10^{-10}

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	−1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	−1	−1	K^-
$s\bar{d}$	0	−1	$\bar{K}^0$
$s\bar{s}$	0	0	??

qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^+
udd	0	0	Δ^0
ddd	−1	0	Δ^-
uus	1	−1	Σ^{*+}
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	Ω^-

- **1974** **J/ψ (charm quark)** **SLAC**
- **1977** **Bottom quark** **Fermilab**
- **1983** **W and Z bosons** **CERN**
- **1995** **Top quark** **Fermilab**
- **1995** **Anti-Hidrogen atom** **CERN**
- **2010** **Neutrino Oscillation** **CERN**
- **2012** **Higgs Boson** **CERN**
- **2024** **GlueBall** **BESIII**

Standard Model of Elementary Particles



Appendix

Appendix A – Dirac Equation and Positron

In NRQM we describe the dynamics of a system with the Schrödinger equation, which for a particle moving in one dimension with a potential $V = V(x)$ is

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi = i\hbar\frac{\partial\psi}{\partial t}$$

Relativistic of QM version for spin ½ particles is the Dirac Equation:

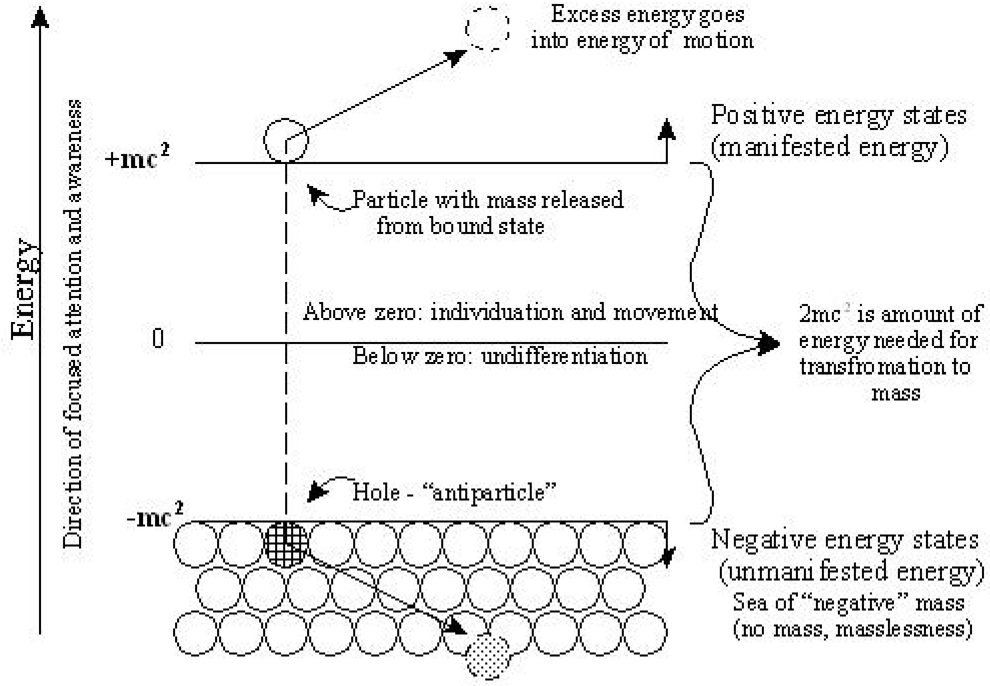
$$i\hbar\frac{\partial\psi}{\partial t} = -i\hbar c\vec{\alpha}\cdot\vec{\nabla}\psi + \beta mc^2\psi$$

Here α and β are actually matrices. Solution of this equation allows for negative energy states:

$$\boldsymbol{for\ e^-}: E = +\sqrt{p^2c^2 + m^2c^4} \qquad \boldsymbol{for\ e^+}: E = -\sqrt{p^2c^2 + m^2c^4}$$

Dirac postulated that the negative energy states are all filled by an infinite "sea" of electrons. What happened when we impart to one of the electrons in the "sea" an energy sufficient to knock it into a positive energy state?

The absence of the "expected" electron in the sea would be interpreted as a net positive charge, **the positron.**



Pair Production from sea of "negative" mass

Appendix B: Crossing Symmetry

Suppose that a reaction of the form is known to occur:

$$A + B \rightarrow C + D$$

Any of these particles can be "crossed" over to the other side of the equation, provided it is turned into its antiparticle, and the resulting interaction will also be allowed:

$$A \rightarrow \bar{B} + C + D$$
$$A + \bar{C} \rightarrow \bar{B} + D$$
$$\bar{C} + \bar{D} \rightarrow \bar{A} + \bar{B}$$

Compton scattering : $\gamma + e^- \rightarrow \gamma + e^-$

pair annihilation : $e^- + e^+ \rightarrow \gamma + \gamma$