Particle Physics

- 1897 – Thomson – electron (Nobel Prize in Physics 1906)
- 1905 – Einstein – photon (Nobel Prize in Physics 1921)
- 1911 – Rutherford (Thomson's student) – atomic nucleus – hydrogen (lightest nucleus) → proton (Nobel in Chemistry 1908 ↓ radioactivity)
- periodic table : atomic mass increases more-rapid than nuclear charge
- 1932 – Chadwick (Rutherford's student) – neutron (Nobel in Physics 1935)

(!) **Marie Curie**

↓

theory of radioactivity → Nobel Prize in Physics 1903 (Becquerel, Pierre Curie, Marie Curie)

radium, polonium } Nobel Prize in Chemistry 1911 (Marie Curie)

∘) Walter Bothe and Herbert Becker (1928)

(Po) $\xrightarrow{\alpha}$ (Be) $\xrightarrow[\text{neutral radiation}]{\text{electrically}}$ (?)

bombarded beryllium with α particles (↙ used in Rutherford's experiment (nucleus of He)) emitted from polonium. Be then gave off a penetrating electrically neutral radiation.

(!)

∘) **Irene Joliot-Curie** and Frederic Joliot-Curie (1932) → Nobel Prize in Chemistry 1935 } for artificial radioactivity NOT this experiment

continued Bothe's experiment

this radiation emitted protons from paraffin (hydrogen atoms) { analogy with Compton effect, in which x-ray photons in metal eject e^-; they concluded this radiation was γ-rays ejecting protons

•) Chadwick repeated the experiment (Nobel Prize in Physics 1935)

bombarded not only H in paraffin

but also He, N and other elements

proved beryllium emissions had <u>mass</u> ~ mass of proton

<u>neutron</u>

<u>Neutron</u> – imptt role in nuclear reaction – easier to penetrate nucleus – no Coulomb repulsion

fission (↓ of uranium) $^{235}U + n \rightarrow {}^{92}Kr + {}^{142}Ba + 2n + 179.4\ MeV$

1938 by Otto Hahn (Rutherford's student) and Fritz Shassmann

↑ only he got the Nobel Prize 1944

↓ experiments started with [Lise Meitner] (!) who gave the interpretations from Sweden

Side Note

(!) [Maria Goeppert-Mayer]

Nobel Prize in Physics 1963

shell model

worked for many years with no salary

For a brief time:

e^-, p, n, photons – elementary particles

But soon with particle accelerators producing greater and greater energies an enormous amount of particles were discovered

which are the <u>elementary</u> <u>particles</u>?

(p) and (n) – known as <u>nucleons</u> are not

↓

scientists tried to put together the pieces of the puzzle in what they called <u>Standard model</u>

Side note

•) Rutherford was Thomson's student

•) Bohr, Chadwick, Geiger, Hahn, etc. were Rutherford's students

Elementary Particles → (Standard Model)

↙ they are either **bosons** or **fermions** depending on their spin

- bosons ↑ integer spin (particles associated with fundamental forces)
- fermions ↑ half-integer spin { Pauli exclusion principle (particles associated with matter)

⇒ **Fermions**: (Table 12-1)

leptons (spin 1/2)		(charge)	quarks (spin 1/2)		(charge)
electron	e	-1	up	u	$2/3$
electron neutrino	ν_e	0	down	d	$-1/3$
muon	μ	-1	charm	c	$2/3$
muon neutrino	ν_μ	0	strange	s	$-1/3$
tau	τ	-1	top	t	$2/3$
tau neutrino	ν_τ	0	bottom	b	$-1/3$

(u, d, c, s, t, b: flavors)

strength	range (m)		leptons	quarks	
1	∞	gravitational force	✓	✓	
10^{36}	∞	electromagnetic force	✓	✓	
10^{25}	10^{-18}	weak interaction	✓	✓	{ associated with radioactivity } Ex: beta decay
10^{38}	10^{-15}	strong interaction	✗	✓	{ attractive force that holds nucleons together

→) Quarks and antiquarks have never been detected as free particles

↳ evidence for their existence:

high energy electrons are deflected by protons through large angles

→) Analogous to electric charge, quarks have COLOR CHARGE : red, blue, green (3 possible values)

Ex: there are 3 different u quarks: u_r, u_b, u_g

Every particle has a corresponding <u>antiparticle</u> with the same mass but opposite electric charge } <u>QED</u> quantum electrodynamics

Feynman, Schwinger, Tomonaga
Nobel Prize 1965

- photon is its own antiparticle
- particle + antiparticle may annihilate
- antineutron is made of antiquarks
- antiproton + positron → antihydrogen atom

→) why is the universe almost entirely made of matter and not antimatter ?

↳ ongoing research
CP violation helps understanding it (Nobel Prize 1980 James Cronin, Val Fitch)
(C = charge, P = parity)

Therefore,

leptons → anti leptons
quarks → antiquarks

<u>Hadrons</u> → bound states of the quarks and antiquarks

- <u>Baryons</u> (3 quarks)
  - proton: uud
  - neutron: udd
  - Λ, Σ,
- <u>Mesons</u> (quark + antiquark)
  - pion: $\pi^+ (u\bar{d})$, $\pi^0 (d\bar{d}, u\bar{u})$, $\pi^- (d\bar{u})$
    - spin 0
    - Yukawa predicted their existence
    - Nobel in Physics (1949)
    - was thought to be carriers of strong interaction
  - Kaon
  - eta

Pions were thought to be strong force mediators

Strong force mediators: gluon

⇛ **Bosons** ⟶ mediators of fundamental forces
↓
process by which elementary particles interact with each other

interaction – described as a physical field mediated by exchange of virtual particles { detectable as forces not as real particles }
↓
(gauge bosons)

Elementary Bosons
- ↙ Gauge bosons: gluon, W and Z bosons, photon
- ↘ Higgs boson ⟶ undiscovered – Large Hadron Collider (LHC) – CERN 2009
  ↓
  (mass arises from interaction with Higgs boson)
- graviton ⟶ not discovered

Interaction	current theory	mediators	strength	range (m)
strong	quantum chromodyn. QCD	gluons	10^{38}	10^{-15}
electromagnetic	quantum electrodyn. QED	photons	10^{36}	∞
weak	electroweak theory	W and Z bosons	10^{25}	10^{-18}
gravitation	general relativity	gravitons (not discovered)	1	∞

→ Electromagnetic interaction

↳ due to electric charge

Every charge is continually emitting and absorbing VIRTUAL photons
(↓ not directly observed)

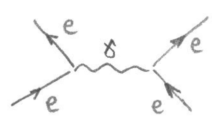
Charge can emit a virtual photon of energy $h\nu$
without violating cons. of energy or momentum
provided it exists for no longer than $\Delta t = \hbar / \Delta E$
Virtual photon can travel

$$R = c\Delta t = c\hbar / \Delta E = c\hbar / h\nu = \frac{c h \lambda}{2\pi h c} = \frac{\lambda}{2\pi}$$

and be absorbed by 2nd charge
which can emit virtual photon which is absorbed by 1st charge, ...

→ this exchange of virtual photons is the origin of the Coulomb force between the two charges

Feynman diagram



{ Coulomb repulsion between two e^-

→ Strong interaction → all hadrons interact via strong interaction

↳ due to color charge (leptons don't have color charge)

↳ mediators: gluons

→ Weak interaction → leptons and quarks participate

↳ mediators: W^+, W^-, Z^0 bosons $(s=1)$

interactions mediated by $W^{\pm}$ change quark flavor

Flavor – is a **quantum number**

→ conserved number associated with conserved quantity

Ex: energy conservation → principal quantum number (n)

there are quantum numbers associated with { angular momentum, spin }

↓

- leptons : lepton number (L=1)
- quarks : baryon number (B=1/3)
- electric charge

} **always** conserved

↓ example

can know and explain which particles may or not be created from collisions and in decays

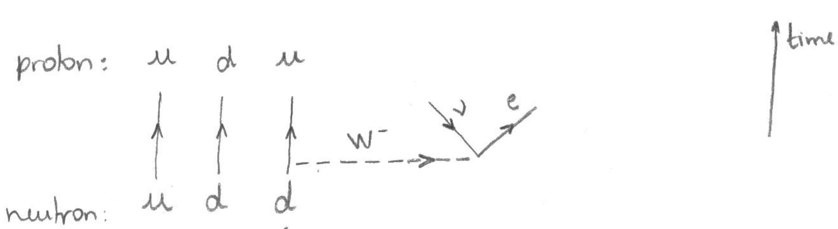
other quark flavors → conserved by strong interaction
→ violated by weak interaction

↓

strangeness, charm, bottom, etc

Free nucleon decay → occurs via **weak** interaction because { strong force and electromagnetism cannot change flavor }

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



↳ emits a W^- and changes to u quark and W^- decays to e^- and $\bar{\nu}_e$

What conservation laws (if any) are violated by the following reactions?

a) $n \longrightarrow p\,\pi^-$

✓ no leptons – no prob. with cons. of lepton number
✓ net charge is zero before and after – charge is conserved
✓ baryon number is conserved, $B=+1$ before and after

✗ **BUT** energy is NOT conserved

rest energy of proton (938.3 MeV) + pion (139.6 MeV) > neutron (939.6 MeV)

b) $\Lambda^0 \longrightarrow \bar{p}\,\pi^+$

✓ no leptons
✓ charge is zero
✗ does NOT conserve baryon number

$B(\Lambda^0) = +1 \qquad B(\bar{p}) = -1 \qquad B(\pi^+) = 0$

c) $\pi^- \longrightarrow \mu^-\,\bar{\nu}_\mu$

✓ no baryons
✓ charge (−1)
✓ rest energy of π^- (139.6 MeV) > μ^- (105.7 MeV) + $\bar{\nu}_\mu$

OK → difference appears as kinetic energy of the muon and neutrino

✓ lepton number

$L(\pi^-) = 0 \qquad L(\mu^-) = 1 \qquad L(\bar{\mu}_\nu) = -1$

↑ not lepton

OK

- Main name behind conservation laws and symmetries

(!) **Emmy Noether**

↓

theorem 1918: every conservation law is a consequence of a symmetry

(!) **Chien-Shiung Wu**

↳ violation of parity

Chen Nin Yang and Tsung-Dao Lee } → Nobel in Physics 1957

Check also:
- Sophie Germain (1776 - 1831)
- Émilie du Châtelet (1706 - 1749)
- Hypatia (370? - 415)

www.agnesscott.edu/Lriddle/women/women.htm