# Chapter 16

## Elementary Particle Physics

### 1. Introduction

Elementary particle

- Elementary particle
  ↓
  constituents of matter at the most fundamental level

Definition

(i) Same type of particles (for example, two electrons) have identical properties (except for their position and conditions of motion) are indistinguishable.

(ii) There is no compelling theoretical and experimental reason to believe that they are made of more fundamental constituents

Clearly, this is a time-dependent statement.

For example, Before 1970's proton and neutron were considered as elementary particles

Now, they are considered as "composite" made of quarks.

In Appendice A and B, we present the list of "elementary particles" in 1970 and 2000 respectively.

# Elementary Particle Physics
## (General Remarks)

Study the properties of elementary particles and interactions between elementary particles.

Elementary particle physics ⟷ High Energy Physics.

— Why high energies?

(1) Resolution

$$\Delta x \sim \frac{\lambda}{\sin\phi} \gtrsim \lambda$$

↓

See (2-26) of Gasiorowicz and Fig. 2-2

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

$$\Delta x = \frac{h}{p\sin\phi} = \frac{h}{q}$$

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

↓

relativistic energy-momentum relationship.

To probe small distance ⇒ high energies.

分類：
編號：
總號：

Transform back to the laboratory system

$p^\mu = (\frac{E}{c}, p_x, p_y, p_z)$ is a four-vector

$p$ $\quad p^2 = \frac{E^2}{c^2} - \vec{p}^{\,2} = \frac{1}{c^2}(E^2 - \vec{p}^{\,2}c^2) = m^2c^2$

$p_1 + p_2$ is also a four-vector

$(p_1+p_2)^2 = p_1^2 + p_2^2 + 2p_1 \cdot p_2$

$= \frac{1}{c^2}(E_1+E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$ is a Lorentz scalar (invariant)

Evulate $(p_1+p_2)^2$ in the laboratory system

$\Rightarrow \quad 2M_p^2c^2 + 2\frac{E_1}{c} \cdot M_pc$

Evulate $(p_1+p_2)^2$ in the center of mass system.

$\Rightarrow \quad (E_1^* + E_2^*)^2/c^2$

$2M_p^2c^2 + 2E_{th}M_p = (E_1^*+E_2^*)^2_{min} = (4.976\ GeV^2)/c^2$

$2E_{th}M_pc^2 = (4.976^2 - 1.757688)\ GeV^2$

$\Rightarrow E_{th} \sim 12.26\ GeV$

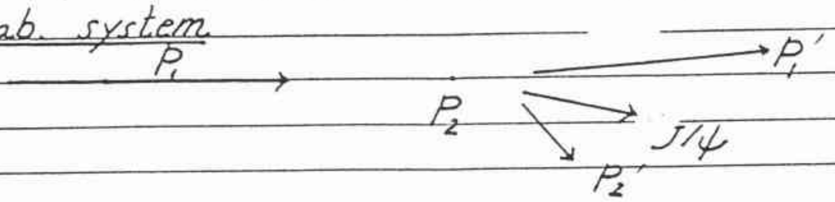
Note: the use of invariant scalar is of great importance

(This has been discussed in Chapter 3)

Relativistic kinematics are used. A (useful) convenient units for high energy physics (known as natural units) is given in Appendix C.
Furthermore, the understanding of physics in this domain necessitates a fusion of quantum mechanics and special relativity.

(b) $p + p \longrightarrow p + p + J/\psi$

Lab. system




Fixed target machine

$P_2$ is at rest, stationary
↓
lab. system

$E_{th}$ : threshood energy
→ minimum laboratory energy of the incident protron for above process to occur

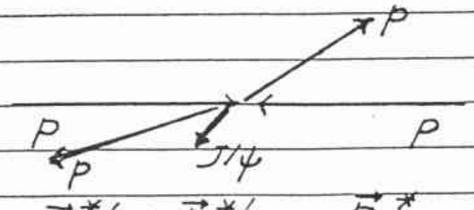
$$\vec{P}_1 = \vec{P}_1' + \vec{P}_2' + \vec{P}_{J/\psi} \qquad \text{momentum conservation.}$$

$$\sqrt{\vec{P}_1^{\,2} c^2 + M_p^2 c^4} + M_p c^2 = \sqrt{\vec{P}_1'^{\,2} c^2 + M_p^2 c^4} + \sqrt{\vec{P}_2^{\,2\prime} c^2 + M_p^2 c^2} + \sqrt{\vec{P}_{J/\psi}^{\,2} c^2 + m_{J/\psi}^2 c}$$

energy conservation.

It is difficult to solve for the minimum $|\vec{P}_1|$ that can simultaneously satisfy the energy-momentum conservati equations

Center of mass system




$$\vec{0} = \vec{P}_1^{*\prime} + \vec{P}_2^{*\prime} + \vec{P}_{J/\psi}^{*} \qquad \text{momentum conservation}$$

$$E_1^* + E_2^* = \sqrt{\vec{P}_1^{*2\prime} c^2 + M_p^2 c^4} + \sqrt{\vec{P}^{*2\prime} c^2 + M_p^2 c^4} + \sqrt{\vec{P}_{J/\psi}^{*2} c^2 + m_{J/\psi}^2 c^4}$$

energy conservation.

$(E_1^* + E_2^*)_{min}$ clearly is given by $2 M_p c^2 + m_{J/\psi} c^2 \simeq 4.976$ GeV

since $\vec{P}_1^{*\prime} = \vec{P}_2^{*\prime} = \vec{P}_{J/\psi}^{*} = 0$ trivially satisfy the momentun conservation equation.

(2) Some of the fundamental constituents have high masses and finite lifetime

$\Rightarrow$ requires high energies for their production.

Example.

$J/\psi$ : rest energy $\sim 3100$ MeV $= 3.1$ GeV

width $\Gamma \sim 0.063$ MeV

$$\tau \sim \frac{\hbar}{\Gamma} \sim 10^{-20} \text{ sec.}$$

(a) $e^+ + e^- \longrightarrow J/\psi \longrightarrow \mu^+\mu^-$, hadrons, $\cdots$

$\overrightarrow{\quad e^+ \quad}\ \overleftarrow{\quad e^- \quad}$ $e^+$-$e^-$ collider

In the center of mass system

$E^*_{e^+} = E^*_{e^-} = 1.55$ GeV  Richter et al.

## 2. Historical Development

(i) 1897 J. J. Thomson discovered electron

The birth of elementary particle physics

$e/m_e = 1.759 \cdot 10^8$ Coulomb/gm
↓
adjusted crossed electric and magnetic field

negatively charged.

1906 Millikan's oil drop experiment
↓
measurement of e
↓
$e = 1.6 \cdot 10^{-19}$ Coulomb

Use e as a unit of charge. $Q(e^-) \equiv -1$

Rest energy of electron $= m_e c^2 = 0.511$ MeV.

References.

"The Discovery of Subatomic Particles" by Steven Weinberg

"Elementary Particles, A Short History of Some Discoveries in Atomic Physics" by C. N. Yang

"From X-Rays to Quarks: Modern Physicists and Their Discoveries" by E. Segre

(ii) 1905 Einstein proposed that for some purposes light can be made of particles, later called photons.

photon ⟷ electromagnetic field

particle field

| | |
|---|---|
| 分類： | |
| 編號： | |
| 總號 | |

Reference "Subtle is the Lord, the Science and Life of Albert Einstein" by A. Pais.

Photoelectric effect $E = \hbar\omega$ Millikan 1914-1916

Compton scattering $\vec{p} = \hbar\vec{k}$ Compton 1922-1923

$\omega = |\vec{k}|c \Rightarrow E = |\vec{p}|c \Rightarrow m_\gamma = 0$

Photons have zero (rest) mass and zero charge.

Photons always travels at the speed of light, so they cannot contained within atoms.

(iii) 1911 Rutherford scattering $\Rightarrow$ discovered the nucleus of the atom.

Atomic size $\sim 10^{-8}$ cm

Nuclear size $\sim 10^{-12}$ cm

(iv) 1913 Bohr's model of hydrogen atom

Hydrogen nucleus $\longleftrightarrow$ proton $p$

1919

Discovery of the proton, evidence for the proton as a constituent of the nucleus.

Rutherford: He + N (atom) $\longrightarrow p + X$

$Q(p) = +1$

$M_p c^2 = 938.26$ MeV

In 1913, there were three "elementary particles"

$e^-, \gamma, p$

(v) From 1913-1930 $\Rightarrow$ development of quantum mechanics

study of atomic structure.

We shall mention the following important developments because they are immediately related to our discussion in this section.

1925 Pauli's exclusion principle

1925 Goudsmit and Uhlenbeck
↓ from the study of atomic spectra
spin of electron

Electron has spin $\frac{1}{2}$

$S_z = \pm \frac{1}{2}\hbar$

Proton has spin $\frac{1}{2}$

$\hbar = \frac{h}{2\pi}$ , $h$ = Planck constant

Photon has spin 1 (but only two spin states)

(vi) 1932 Chadwick discovered the neutron $n$ in the following reaction

$${}^{4}_{2}\alpha + {}^{9}_{4}Be \longrightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

[ super-script → A , subscript → Z ]

Before the neutron is discovered, it was thought that for a nucleus with charge $Ze$ and mass number $A$ is made of $A$ protons and $(A-Z)$ electrons

Difficulty with this picture
${}^{14}_{7}N$

In this picture, should be made of 14 protons and 7 electr
⇒ nuclear spin must be half-integer

Experimentally, it was found that the nuclear spin of ${}^{14}_{7}N$ is 1

1932 Heisenberg ( Ivanenko, Majorana) ⇒ protons and neutrons are the nuclear constituents

$Q(n) = 0$

$M_n c^2 = 939.55$ MeV ( neutron is slightly heavier than proton)

Neutron also has spin $\frac{1}{2}$

Neutron has magnetic moment ⇒ it has electromagnetic interaction.

(vii) 1930 Pauli's suggestion of the existence of neutrino

β - decays have been studied since the work of radioactivity by Becqueral (1896) and Curie (1898)

It was assumed to be two - body decay, for example,

$$^{228}_{88}Ra \longrightarrow ^{228}_{89}Ac + \underset{e^-}{\beta}$$

Difficulty. Two-body decay ⇒ unique electron energy in the rest system of the decaying nucleus

$$M \longrightarrow m_1 + m_2$$

In the rest system of M, relativistic kinematics gives

$$Mc^2 = \sqrt{\vec{p}^{*2}c^2 + m_1^2 c^4} + \sqrt{\vec{p}^{*2}c^2 + m_2^2 c^4}$$

M, $m_1$, $m_2$ are fixed ⇒ $|\vec{p}^*|$ and energies of $m_1$, $m_2$ are fixed

Applied to above reaction, one expects the energy of the outgoing $e^-$ to be unique

However, experimentally, the energy spectrum of the electron is continuous

Pauli suggested that there is an undetected particle "neutrino" produced together with $^{228}_{89}Ac + e^-$, the reaction is actually

$$^{228}_{88}Ra \longrightarrow ^{228}_{89}Ac + e^- + \text{"}\nu\text{"}$$

| |
|---|
| 分類: |
| 編號: |
| 總號: |

The existence of neutrino ⇒ make continous spectrum and energy-momentum conservation compatible.

1933 Fermi used Pauli's idea to construct a β-decay theory that gives an electron energy spectrum that is consistent with experimental data.

The basic reaction is $n \rightarrow p + e^- + \nu$

⇒ neutrino spin is required to be half-integer in order to satisfy the angular momentum conservation.

Spin is taken to be $\frac{1}{2}$

$Q(\nu) = 0$

$m_\nu = 0$ (from the end point of electron energy spectrum)

recently, the are indication that $m_\nu \neq 0$

↓

will be discussed in Chapter 10

After Fermi's work, most phyicists accepted the existence of the neutrino

Experimentally, neutrino was first "observed" by Reines and Cowan in 1953-1959

Most of the material has been discussed in earlier Chapters

| | |
|---|---|
| 分類： | |
| 編號： | |
| 總號： | |

(viii) 1932 Anderson, 1933 Blackett and Occhialini discovered positron $e^+$ in the cosmic radiation
[ Reference: "Nuclear and Particle Physics" by H. Frauenfelder and E. M. Henley ]

Importance of the discovery of $e^+$.

(a) It is the starting point of a series of discoveries of new particles from cosmic radiation

(b) It provides the first important confirmation of prediction from relativistic quantum theory
↳ anti-particle

1928 Dirac theory of electron

Dirac equation spin $\frac{1}{2}$ relativistic wave equation

Free particle equation

分類：
編號：
總號

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

$$[\, E = \pm \sqrt{p^2 + m^2} \,]$$

$T + V = E$ $\qquad \vec{p} \to -i\hbar\nabla, \quad E \to i\hbar\frac{\partial}{\partial t}$

$$\Rightarrow \left(\frac{-\hbar^2}{2m}\nabla^2 + V\right)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

↑

Schrodinger equation

Second order derivative with respect to space
first order derivative with respect to time
⇒ impatible with special relativity

Klein - Gordon equation

$$-\frac{\partial^2}{\partial t^2}\psi = -\nabla^2\psi + m^2\psi = 0$$

↕

$$\frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = \nabla^2\psi - \frac{m^2c^2}{\hbar^2}\psi$$

It does not give the hydrogen spectrum when
Coulomb potential is introduced

↓

it does not describe the electron
it is suitable in describing
spinless particle.
(since no spin variable has
been introduced)

Dirac equation (relativistic spin $\frac{1}{2}$ wave equation)

$$i\beta\frac{\partial\psi}{\partial t} = -i\beta\vec{\alpha}\cdot\nabla\psi + m\psi$$

Dirac equation is first order in time and space
derivatives

Now $\vec{\alpha}$, $\beta$ are $4\times4$ matrices

$\psi$ is a column matrix with 4 - components

For a fixed momentum $\vec{p}$, there are 4 plane wave solutions

Two solutions with $E = \sqrt{\vec{p}^2 + m^2}$
Obviously representing the two spin states

Two more solutions with $E = -\sqrt{\vec{p}^2 + m^2}$
↓
negative energy state.

Advantages of the Dirac equation.

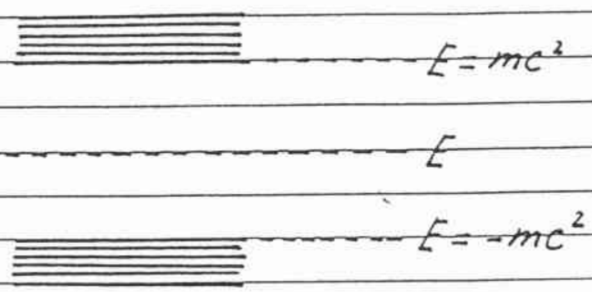
(i) It is a relativistic wave equation
(ii) Spin comes out naturally
(iii) It gives the correct hydrogen atom spectrum
(iv) It gives $g = 2$
↓
gyromagnetic ratio

$$\mu = g \mu_B S$$

$$\mu_B = \frac{e\hbar}{2mc} = \text{Bohr magneton}$$

Difficulties in excluding the negative energy states

(i) There is no a-prior reason in quantum mechanics to exclude transition to negative energy states
(ii) The positive energy eigenstates alone do not form a complete set




Transition of a Dirac particle can occur with emissions of photons
1930 Oppenheimer and Tamm
lifetime of electrons against such transition.

分類：
編號：
總號：

⇒ some mechanism must exist that forbids rapid transition to negative energy states

Dirac's assumption (1930) about the vacuum:
(a) All negative energy states are filled with particles. no particle in the positive energy state
(b) The Dirac vacuum does not produce an external field and do not contribute to the charge, energy, momentum and the spin of the system

One particle (electron) state: one particle in the positive energy state, all negative energy states are filled

$$Q(\text{one electron state}) = -1$$

One "hole" state: no particle in the positive energy state, one particle is missing from the negative energy state ⇒ the "hole" has positive energy and positive charge

$$Q(\text{one "hole" state}) = +1$$

At the time Dirac postulated the hole theory, only the electron and the proton were known

Dirac identified
particle ⟷ electron
hole ⟷ proton

1930 Oppenheimer pointed out that if proton were identifi with electron hole, then the $e^- p$ system (i.e., the hydrogen atom) would be annihilated within $\sim 10^{-10}$ sec.
⇒ electron "hole"

1931 Weyl showed that holes must have the same mass as the removed electron → hole should be identified with the positive electron

↓

Dirac accepted the interpretation of Weyl
⇒ predicted the existence of $e^+$

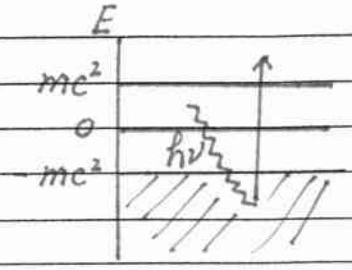
1932-33 Anderson observed the track of cosmic ray in a Wilson chamber with magnetic field → discovered tracks had a curvature → positive particles of about the electron mass.

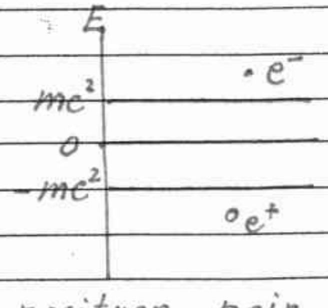
Direction of motion was determined by the insertion of a lead plate into the chamber

Particle, in traversing the lead plate, lost energy and its radius of curvature became smaller than before they entered the lead plate $\Rightarrow$ discovery of $e^+$

Pair creation by radiation $\longleftrightarrow$ the incoming photon lifts an electron from a negative energy state to a positive energy state $\Rightarrow$ a positron (hole) and an electron.
[ Note: from energy-momentum conservation consideration pair creation (production) by a single photon is not possible without an agent, such as a nucleus, to take up some momentum ]

Pair annihilation $\longrightarrow$ positive energy electron falling into the hole with energy carried away by photons.




Electron-positron pair production.

(a) A photon of energy $h\nu$ (>1.02 MeV) is absorbed by a negative-energy electron, which give the electron a positive energy.

(b) The resulting hole in the negative energy electron sea behaves like an electron of positive charge.

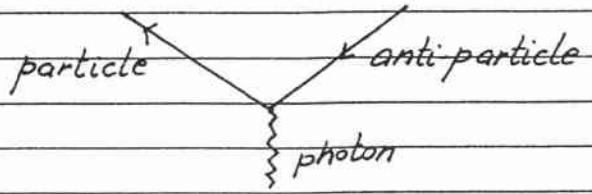
anti-particle $\leftrightarrow$ particle moving backward in time

$\downarrow$

mass (particle) = m (antiparticle)
J (particle) = J (anti-particle)
N (particle) = − N (anti-particle

$\downarrow$

any additive quantum number whose value for the photon is zero




| particle | anti-particle | |
|---|---|---|
| $e^-$ | $e^+$ | positron (1932) |
| $p$ | $\bar{p}$ | anti-proton (1935) |
| $n$ | $\bar{n}$ | anti-neutron |
| $\mu^-$ | $\mu^+$ | |
| $\pi^0$ | $\pi^0$ | |
| $\gamma$ | $\gamma$ | |
| ⋮ | ⋮ | |

In 1933, elementary particles were
$e^-$, $\gamma$, $p$, $n$, "$\nu$" and $e^+$

Reference on anti-particle.

Feynman "The Reason for Anti-Particles" in "Elementary Particles and the Laws of Physics − The 1986 Dirac Memorial lectures", Cambridge University Press 1987.

(ix) 1935 Yukawa's prediction of the existence of meson

Nucleus is made of p and n.

$\downarrow$

existence of nuclear force

Nuclear force is strong at short distance

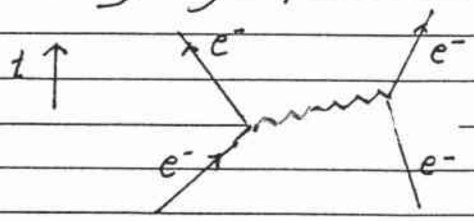
$\downarrow$ binding the nucleus — $\downarrow$ ~ nuclear size

In the late 1920's and early 1930's

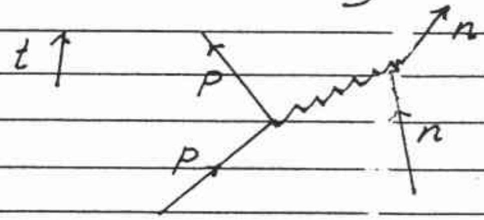
↓

the development of the quantum theory of the radiatio
field
by
Dirac, Jordan, Pauli, and Heisenberg

Electromagnetic interaction is described through the exchange of photon




Yukawa suggested that the strong interaction should be described through the exchange of meson




Analogy between the two is extensively used.

Review of the electromagnetic interaction

Working in the Lorentz gauge, $\nabla \cdot \vec{A} + \frac{1}{c}\frac{\partial \phi}{\partial t} = 0$

( $\vec{A}$ = vector potential, $\phi$ = scalar potential), the

Maxwell equations can be written as

$$\nabla^2 \vec{A} - \frac{1}{c^2}\frac{\partial^2 \vec{A}}{\partial t^2} = -\frac{4\pi}{c}\vec{J}$$

and

$$\nabla^2 \phi - \frac{1}{c^2}\frac{\partial^2 \phi}{\partial t^2} = -4\pi\rho$$

We shall concentrate on the equation for the scalar potential

For the source free case, we have

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 0 \quad \text{free field equation}$$

The equation can be obtained from $E^2 = \vec{p}^2c^2$ (relativistic energy-momentum relati... for a massless particle, remembering $m_\gamma = 0$) by $\vec{p} \to -i\hbar\nabla$, $E \to i\hbar\frac{\partial}{\partial t}$ (the same procedure in obtaing the Schrodinger equation)

For a static source located at the origin, the equation becomes

$$\nabla^2\phi = -4\pi q\,\delta(\vec{r})$$

$$\Rightarrow \quad \phi \sim \frac{q}{r} \quad \text{Coulomb potential}$$

$\phi$ can be interpreted either as the potential or as the wave amplitude of the associated massless photon

Strong interaction

Free meson with rest mass $m$ satisfies the relativistic energy-momentum relation

$$E^2 = \vec{p}^2c^2 + m^2c^4$$

With $\vec{p} \to -i\hbar\nabla$, $E \to i\hbar\frac{\partial}{\partial t}$, one obtain

$$\nabla^2\psi - \frac{m^2c^2}{\hbar^2}\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = 0$$

↓

Klein-Gordan equation

For a static source for the meson field (such as a neutron or proton) located at the origin, one obtains

$$\nabla^2\psi - \frac{m^2c^2}{\hbar^2}\psi = -4\pi g\,\delta(\vec{r})$$

$$\Rightarrow \text{For } r \neq 0 \quad \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\psi}{\partial r}\right) = \frac{m^2c^2}{\hbar^2}\psi(r)$$

$$\psi(r) \sim \frac{g\,e^{-r/R}}{r} \quad \text{is the solution}$$

with $R = \frac{\hbar}{mc}$.

分類:
編號:
總號:

$$\frac{\partial}{\partial r}\left(g\,\frac{e^{-r/R}}{r}\right) = g\,\frac{1}{r}\left(-\frac{1}{R}\right)e^{-r/R} + g\,e^{-r/R}\left(-\frac{1}{r^2}\right)$$

$$\frac{1}{r^2}\,\frac{\partial}{\partial r}\left(r^2\frac{\partial\psi}{\partial r}\right) = \frac{1}{r^2}\,\frac{\partial}{\partial r}\left[-\frac{gr}{R}\,e^{-r/R} - g\,e^{-r/R}\right]$$

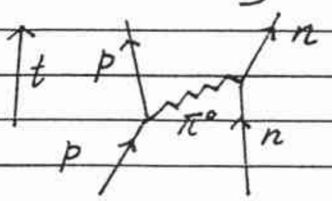
$$= \frac{1}{r^2}\left[-\frac{g}{R}\,e^{-r/R} + g\frac{r}{R^2}\,e^{-r/R} + \frac{g}{R}\,e^{-r/R}\right]$$

$$= \frac{1}{r}\,g\,\frac{1}{\frac{\hbar^2}{m^2c^2}}\,e^{-r/R} = \frac{m^2c^2}{\hbar^2}\,g\,\frac{e^{-r/R}}{r}$$

$g\,e^{-r/R}$ is known as the Yukawa potential

$R = \frac{\hbar}{mc}$ = range of the interaction is inversely proportional to the mass of the exchanged particle

Wick's argument




$\pi^0$ is emitted by the proton before it is absorbed by the neutron

We shall work in the rest system of the proton

$E_i = M_p c^2$

After $\pi^0$ is emitted $E = \sqrt{\vec{p}^2c^2 + m_\pi^2c^4} + \sqrt{\vec{p}^2c^2 + M_pc^4}$

Energy violation $\gtrsim m_\pi c^2$

$\Delta E\,\Delta t \sim \hbar$ uncertainty relation

$\Rightarrow$ In order to measure the energy to an accuracy of $\Delta E$, one needs $\Delta t > \frac{\hbar}{\Delta E}$

$\Rightarrow$ $\pi^0$ can be emitted by a proton and live for $\Delta t < \frac{\hbar}{m_\pi c^2}$ before it is absorbed by the neutron

$\Rightarrow$ range of the interaction $\lesssim \frac{\hbar}{m_\pi c}$

Yukawa's predictions.

(a) The meson should have a mass $\sim 200-300\,m_e$

Use $R = \frac{\hbar}{mc}$ and $R \sim 1\,fm = 10^{-13}\,cm$

| | |
|---|---|
| 分類: | |
| 編號: | 1-30 |
| 總號: | |

(b) The meson should be unstable with a lifetime $\tau \sim 10^{-7}$ sec

$n \rightleftharpoons p + e^- + \bar{\nu}$ ; $n \rightleftharpoons p + \pi^-$

Use micro-reversibility

$\pi^- \rightleftharpoons n + \bar{p}$

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

$\Rightarrow \quad \pi^- \rightarrow n + \bar{p} \rightarrow e^- + \bar{\nu}$

(c) The meson should interact strongly with n and p
$\Leftrightarrow$ basic idea of Yukawa, i.e., strong interaction between n and/or p is due to exchange of the meson.

Yukawa

Figure 16–7 Hideki Yukawa was the first Japanese physicist to win the Nobel prize.

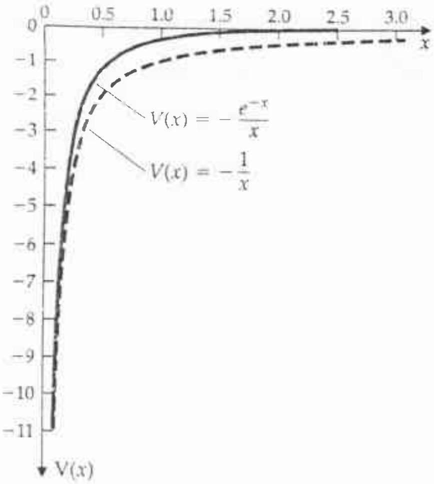



Figure 16–8 Comparison of the shapes of the Yukawa potential $e^{-x}/x$ and the coulomb potential $1/x$.

## 16–4 The Yukawa Hypothesis and Pions

In 1934, shortly after the discovery of the neutron, the Japanese physicist Hideki Yukawa (•Fig. 16–7) had the inspired idea that the nuclear forces could be described by an analogue of the electromagnetic field. This field would have quanta that are analogous to photons, and the nuclear force, with its retardation effects, could be generated by the exchange of the quanta of the field. He found that if the quantum had a mass $\mu$, then the proper analogue of the coulomb potential $e^2/(4\pi\varepsilon_0 r)$ would take the form (•Fig. 16–8)

$$V(r) = -g^2\frac{\exp(-\mu c r/\hbar)}{r}, \tag{16–7}$$

where $g$ is some coupling strength analogous to the electric charge $e$. This result reduces to the coulomb form when $\mu = 0$. The **range** $r_0$ of the potential is defined to be the distance where the exponential factor falls to $1/e$; that is,

$$r_0 = \frac{\hbar}{\mu c}. \tag{16–8}$$

We can understand the association of a mass $\mu$ with the range if we use the energy–time uncertainty relation. A virtual quantum requires the "borrowing" of an energy of at least $\mu c^2$. This can be done for a time $\Delta t \cong \hbar/\mu c^2$ during which the virtual quantum can propagate for a distance of, at most, $c\Delta t = \hbar/\mu c$. That distance matches precisely $r_0$. If $\mu = 0$, the range is infinite.

The potential in Eq. (16–7) is known as the **Yukawa potential**. Yukawa predicted the associated quanta, subsequently named pi-mesons, or **pions** (symbolized by $\pi$). He estimated their mass by its association with an experimental value for the range that came from the known properties of nuclear forces (see Chapter 15), namely

$$m_\pi = \frac{\hbar}{r_0 c} = \frac{1.05\times10^{-34}\,\text{J}\cdot\text{s}}{(1.2\times10^{-15}\,\text{m})(3.0\times10^{8}\,\text{m/s})} = 0.3\times10^{-27}\,\text{kg} \cong 320 m_e.$$

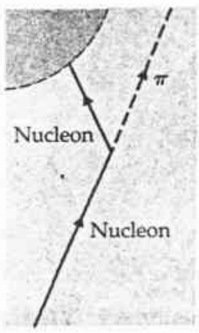



Figure 16–9 Feynman diagram containing a vertex in which a nucleon emits a pion and becomes a virtual nucleon.

In energy units, $m_\pi c^2 = 163$ MeV. Yukawa did not specify the spin of the meson, but the particle had to be a boson, since it was emitted by a nucleon, and a nucleon remains in the final state (•Fig. 16–9). Nucleons have spin 1/2, so the meson must have integer spin. Analogy with photons suggested that it would have spin 1, whereas simplicity suggested spin 0.

## (X) 1940-1947 The $\pi - \mu$ story

1940 William and Roberts observed the $\beta$-decay of a particle of mass $\simeq 250\, m_e$ in the cloud chamber.
1941 Rastetti measured its lifetime to be $\tau \sim 2\cdot 10^{-6}$ sec
All these results seem to support the identification of this particle with the meson suggested by Yukawa
The hypothesis was proved to be untenable by the experiments of Conversi, Pancini, and Piccioni in 1947
Experimental facts:
(a) Negative "mesons" coming to rest in the carbon absorbe
(b) It is observed to decay.
Implication
We shall through a rough order of magnitude estimate show that $\mu$ is not a strongly interacting particle
[ Reference: "Introduction to High Energy Physics" 1st edition.

$\mu$ captured by the carbon nucleus
↓
form $\mu$-atom in the ground state
↓
an atom with $\mu \leftrightarrow e$

$m_\mu \sim 250\, m_e \Rightarrow$ the Bohr orbit is $\ll$ that of the hydrogen atom
Use Bohr model to calculate the Bohr orbit and classic velocity of $\mu$

$$v = Zc\frac{1}{137}$$

$$r_0 = 137\frac{\hbar}{Zmc}$$

$m$ is the reduced mass

$$\frac{1}{m} = \frac{1}{m_\mu} + \frac{1}{M_C}$$

($M_C$ ↳ Carbon nucleus)

The nuclear radius $R = R_0 A^{\frac{1}{3}}$

$$R_0 \sim \frac{\hbar}{mc}$$

The fraction of time spen by the $\mu$ inside the nucleus is

$$\frac{\int_0^R \psi^*(r)\psi(r) r^2 dr}{\int_0^\infty \psi^*(r)\psi(r) r^2 dr} = \frac{\int_0^R e^{-2r/r_0} r^2 dr}{\int_0^\infty e^{-2r/r_0} r^2 dr}$$

$$\sim \frac{\frac{1}{3}R^3}{\frac{1}{4}r_0^3} \sim \left(\frac{R}{r_0}\right)^3 = \frac{AZ^3}{(137)^3}$$

[ For $R \ll r$

$$\int_0^R e^{-2r/r_0} r^2 dr = \int_0^R r^2 dr = \frac{1}{3}R^3$$

$$\int_0^\infty e^{-2r/r_0} r^2 dr = \frac{1}{4} r_0^3 \;]$$

Distance travelled inside nuclear matter during mean lifetime $\tau \sim 2 \cdot 10^{-6}$ sec

$$l = \left(\frac{R}{r_0}\right)^3 v\tau = \frac{AZ^3}{(137)^3} Zc \frac{1}{137} \tau$$

$$= \frac{1.7}{10^4} AZ^4 \text{ cm}$$

For carbon target, it is observed that $\mu$ nearly always decay $\Rightarrow$ $\mu$ will travel a mean distance $l \simeq 1$ cm ($\sim 10^{13} R_0$)

A strongly interaction particle in nuclear matter should have an interaction mean free path $\simeq R_0$

$\Rightarrow$ $\mu$ is not a strongly interction particle, it is not the Yukawa particle. 1947 Bethe and Marshak suggested that two particle might be involved [ the lighter $\mu$ being ~~the~~ decay product of heavier mesons $\leftrightarrow$ Yukawa quanta

1947 Lattes, Muirhead, Occialini and Powell observed in cosmic ray
↓
emulsion experiment

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \quad \tau \sim 10^{-8} \text{ sec}$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

1947 Perkins, Occhialini and Powell observed events $\rightarrow$ capture of $\pi^-$ when they come to rest in emulsion the mass energy released leading to distingration of the capturing nucleus
$\Rightarrow$ pions have strong interaction with nuclei and are produced copiously in high energy nuclear interaction
$\Rightarrow$ should be identified as the particle predicted by Yukawa

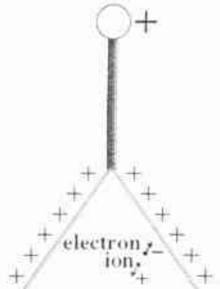
$\mu^\pm$: $m \sim 200\, m_e$ do not interact strongly → lepton

$\mu^\pm \rightarrow e^\pm + \nu + \bar{\nu}$, $\tau \sim 2 \cdot 10^{-6}$ sec

$\pi^\pm$ $m \sim 270\, m_e$, interact strongly with nuclei

$\pi^\pm \rightarrow \mu^\pm + \nu$, $\tau \sim 10^{-8}$ sec

# Cosmic Ray




Electroscope

**Victor Hess** (1883–1964, Nobel prize 1936) and **Theodor Wulf** (1868–1946). These physicists discovered cosmic rays. In 1910 Theodor Wulf, a Jesuit College teacher in Valkenburg, the Netherlands, made a sensitive electroscope (Wulf's electroscope). It was known that such an instrument, after being charged, slowly lost its charge and it was believed that this was due to radiation from the earth. It was known at the time that radio-activity would discharge such an instrument. Wulf asked the French physicist Langevin for help to do the experiment at the top of the Eiffel tower. The result, carefully analyzed, was unexpected: the electroscope discharged much faster than anticipated given the absorption of radiation by the air!

An electroscope is a very simple device of which the main part consists of two conducting leaves. When charging this setup the leaves will repel another, and they will spread out, as in the picture. If a charged particle passes by, knocking off electrons from atoms, the resulting ions or electrons drift to the leaves, thereby discharging them, and they fall back.

Hess decided to investigate the issue in a systematic manner. He started off with some experiment in a meadow in Vienna. In order to get higher up he became a balloonist, taking Wulf's electroscope to heights of up to 5 km. After some 8 flights (sometimes unmanned), a few of them at night and one during a solar eclipse (to eliminate the sun as a source) he established that at high altitudes the effect was stronger than near the ground, concluding that the effect was due to radiation from outer space. Millikan entered the field later on, and having a better sense of public relations coined the name cosmic rays (replacing the name ultra-radiation). At first, on the basis of his own experiments, Millikan doubted Hess's results, but later on he turned around, and in fact became more prominent in the public eye than Hess. The Swedes however recognized the facts and awarded half of the 1936 Nobel prize to Hess for the discovery of cosmic rays (the other half to Anderson). Perhaps they should have included Wulf.

James Chadwick (1891–1974) | Hideki Yukawa (1907–1981) | Cecil Powell (1903–1969)

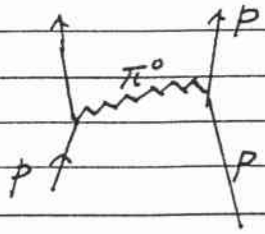
**Fig. 13.4** Chadwick discovered the neutron in 1932. Yukawa predicted the $\pi$ meson in 1934, and Powell observed it in cosmic rays in 1947.

**Fig. 13.5** "Who ordered the $\mu$-meson?" — Isidor Isaac Rabi (1898–1968).

(Xi) 1948-1951 Discovery of $\pi^0$ and determination of its mass

1936 Experiments showed that (apart from the Coulomb interaction) proton-proton and neutron proton forces are approximately equal.

1938 Kemmer showed that in order to explain this result it is necessary to assume the existence of neutral mesons as well as the charged ones




$\pi^0 \to 2\gamma$

1950 Carlson et al. in cosmic ray studies with nuclear emulsion.
Bjorklund et al. in Berkeley synchro-cyclotron.

1951 Panofsky et al measured $m_{\pi^0}$

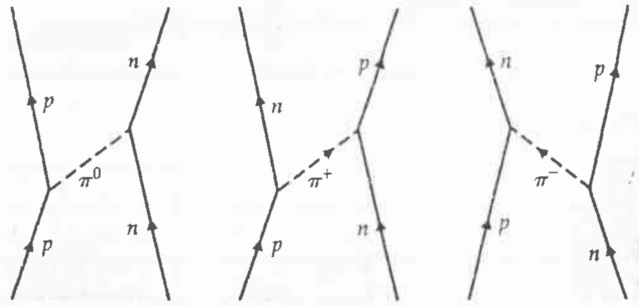
A beam of $\pi^-$ impinges on a target containing liquid hydrogen. The $\pi^-$ is captured by the protons in a very short time and moves in Bohr orbit (s-states) around the protons
[ The capture time is $\sim 10^{-12}$ sec << lifetime of $\pi^-$ ]
When the $\pi^-$ is in such state it has essentially zero kinetic energy

It can interact with the proton and produce $\gamma$ via

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

The energy spectrum for $\gamma$ is expected to have the following form.

[ Neglect the kinetic energy of $\pi^-$ in its Bohr orbit and its binding energy ]




Feynman diagrams showing how the exchange of $\pi^+$, $\pi^-$, and $\pi^0$ give rise to proton–nucleon scattering. (a) In the exchange of a $\pi^0$ the nucleons do not change charge. In (b) and (c) there is an exchange of charge among the nucleons.

Any quantum that can be exchanged could also be expected to be produced as a physical particle in a reaction with sufficient energy. This condition set the stage for experimental efforts to prove the existence of pions by their direct production. When the pion was discovered in the late 1940s, experiments showed that the spin was 0. The mass turned out to be in the vicinity of 140 MeV/$c^2$, remarkably close to the predicted value. Pions come in three charge forms, $\pi^+$, $\pi^0$, and $\pi^-$, which allows them to mediate the forces between nucleons and antinucleons (•Fig. 16–10).

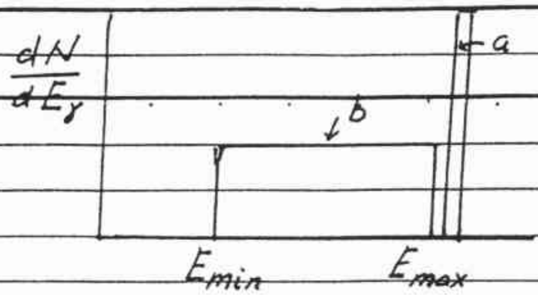
The Yukawa hypothesis has an importance that transcends its direct application to nuclear forces. Calculations in relativistic quantum mechanics—the calculations that use Feynman diagrams—show that

**(i)** any particle that is exchanged by two particles (•Fig. 16–10) gives rise to a force between the two particles and

**(ii)** the only consistent way to construct interactions between sets of particles is by postulating the exchange of *some* particle between them.

It is understood that the emission and absorption of the particle being exchanged must not violate any conservation laws. For example, $n \to p + \pi^-$ and $\pi^- + p \to n$, which occur in the interaction leading to the reaction $n + p \to p + n$ (•Fig. 16–10) are permissible, whereas $n \to p + \pi^+$ and $\pi^+ + p \to n$, each of which violates charge conservation, are not. If the latter reaction were allowed it would in turn allow the (forbidden) process $n + n \to p + p$.

There was a brief and interesting detour along the way to the discovery of pions: Particles for which $mc^2 \cong 110$ MeV were discovered in cosmic rays in 1936—after Yukawa's suggestion. Although their mass was about right for them to be pions, measurements of their absorption in matter showed that they did not interact strongly enough with nuclei to give rise to the nuclear force. They were a new and unexpected particle dubbed the **muon**, symbol $\mu$. When the physicist I. I. Rabi first heard of them he asked, "Who ordered that?" It turned out that muons were just like electrons, only heavier, and that they had very little to do with nuclear forces. We shall see later that they nevertheless play an important role in elementary particle physics.




Unstarred quantities referred to the lab. system
Starred quantities referred to the c. m. system of $\pi^0$

Case a  $\gamma$ from $\pi^- + p \to n + \gamma$

$$m_{\pi^-} + m_p = \sqrt{\vec{p}^2 + m_n^2} + |p|c$$

$$\Rightarrow \quad |\vec{p}| = \frac{1}{2}\left[m_p + m_{\pi^-} - \frac{m_n^2}{m_p + m_{\pi^-}}\right] \rightarrow \text{unique value}$$

can be use to determine $m_{\pi^-}$

Case b  $\pi^0$ will have unique energy in the lab. system
↓
$\pi^0$ will have unique $v$ (and $\gamma$) in the lab

In the rest system of the $\pi^0$

$$E_\gamma^* = \frac{m_{\pi^0}}{2}, \quad P_\gamma^* = \frac{m_{\pi^0}}{2}$$

$$E_\gamma = \gamma(E^* + vP_{\parallel}^*) = \gamma \frac{m_{\pi^0}}{2}\left(1 + \frac{v}{c}\cos\theta^*\right)$$

$$E_{max} = \frac{1}{\sqrt{1 - v^2/c^2}} \frac{m_{\pi^0}}{2}\left(1 + \frac{v}{c}\right)$$

$$E_{min} = \frac{1}{\sqrt{1 - v^2/c^2}} \frac{m_{\pi^0}}{2}\left(1 - \frac{v}{c}\right)$$

Measure $E_{max}$, $E_{min}$ $\Rightarrow$ $v$, $m_{\pi^0}$

Now we shall show the distribution between $E_{min}$ and $E_{max}$ is flat

$\pi^0$ has spin 0 $\Rightarrow$ no preferred direction

$$\Rightarrow \frac{dN}{d\Omega^*} = \text{constant} \Rightarrow \frac{dN}{d\cos\theta^*} = \text{constant}$$

$$\Rightarrow \frac{dN}{dE_\gamma} = \text{constant}$$

$\because$ $N$ is Lorentz invariant

$$E_\gamma = \gamma(E^* + v P_\parallel^*)$$

$$= \gamma \frac{m_{\pi^0}}{2}(1 + \frac{v}{c}\cos\theta^*$$

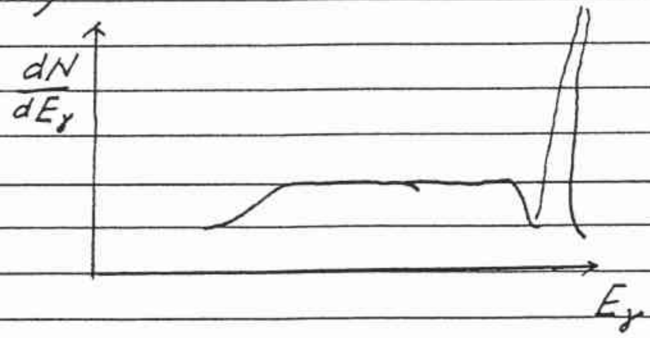
$$\Rightarrow dE_\gamma \propto d\cos\theta^*$$

[Remember $m_{\pi^0}$, $v$, $\gamma$ are all constants]

↓

expected spectrum

Experimentally




The round off at the edge is due to finite resolution of the apparatus

The presence of the $\gamma$ from $\pi^- + p \to n + \gamma$ provided a means to understand the resolution

With the resolution known $\Rightarrow E_{max}, E_{min}$ can be determined
$\Rightarrow m_{\pi^0}$ can be determined

Results:

$$m_{\pi^-}c^2 - m_{\pi^0}c^2 = 4.60 \text{ MeV}$$

$$m_{\pi^+}c^2 = 139.6 \text{ MeV.}$$

**Wolfgang (Pief) Panofsky** (1919). Pief created the Stanford Linear Accelerator Centre, and developed a linear electron (and positron) accelerator. SLAC is arguably the most successful particle physics laboratory, generating three Nobel prizes. He was SLAC director from 1961 till 1984. I was there in 1963 during SLAC's building phase, and I was deeply impressed by Pief's leadership, knowledge and intelligence.

Educated in Princeton and Caltech (PhD), he participated in the Manhattan Project (atomic bomb) and after a period in Berkeley joined the Stanford University faculty in 1951. He very much involved himself in arms control issues, and remains an important US government advisor to this day.

His achievements are immense, and he received a large number of distinctions. Ironically not the Nobel prize.

His father, Erwin Panofsky (1892–1968), was a most famous German art historian. Being Jewish, he fled Nazi Germany in 1934 and after a short while went to the Institute for Advanced studies in Princeton. He had another son, Hans Panofsky (1917–1988), also very intelligent, who advanced the understanding of clear-air turbulence and the dispersion of pollutants. When both sons studied at Princeton University their intelligence was quickly recognized; as one of them appeared slightly smarter than the other they were dubbed the smart and the dumb Panofsky.

Pief, being in Munich, was once asked if he wanted to go to some museum. He answered: my father often spent hours explaining pictures to me and at some point I decided not to see any more of them.

分類：
編號：
總號：

1928 $e^-$, $p$, $\gamma$ are the elementary particles

electromagnetic interaction (only) was well studied.

Quantum mechanics was established in describing atomic physics

$\alpha$ - decay , $\beta$ - decay , $\gamma$ - decay were known

$\alpha$ - decay ↓ is understood as quantum tunneling

$\beta$ - decay ↓ electron spectrum were began to be measured.

Klein - Gordan equation were purposed.

Dirac equation ⟶ relativistic spin $\frac{1}{2}$ wave equation

↓

describe electron

predict the existence of positron.

interpretation based on the Dirac sea of negative energy solution

relativity
quantum mechanics ⇒ anti-particle

Discovery of positron by Anderson in 1932-33

(趙忠堯)

↓

Anti - particle

Nuclear physics

1932 Discovery of neutron by Chadwick

Proton and neutrons are the nuclear constituents

$\Rightarrow$ strong interaction
↓
nuclear force

short range, "strong"

Yukawa's model

nuclear force between nucleons are transmitted by $\pi$'s

$\Rightarrow$ range, mass relation

$$R = \frac{\hbar}{m_\pi c}$$

1940 - 1947 $\pi^\pm - \mu^\pm$ discovery

1950 - 1951 Discovery of $\pi^0$, and the measurement of $\pi^0$ mass $\Rightarrow$ $\pi^0$ spin cannot be 1 (Yang, Landau)

$\pi^0 \to 2\gamma$

Study of the $\beta$ - decay

Pauli suggested the existence of the neutrino.
↓
1930

1933 Fermi's proposed the four fermion interaction.

Experimentally detected by Reines, Cowan et al.
↓
the emerging of elementary particle physics

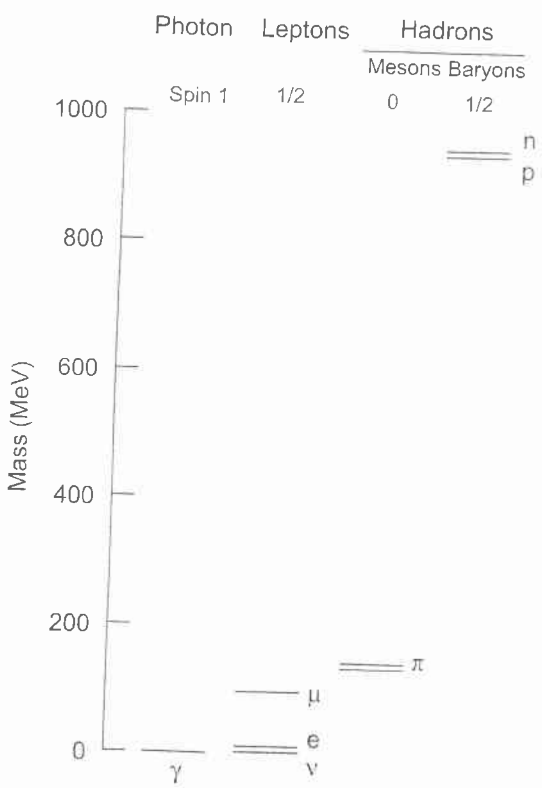



**Fig. 13.6** The elementary particle spectrum as of 1947, the triumphant year of QED.

Elementary particle physics ———— following areas

Experimental — Theoretical

Accelerator — Detector — Phenomenology — Formalism

Computational

Experimentally, interactions among elementary particles are studied (probed) through

(i) Scattering

Examples: $\pi^- + p \longrightarrow \pi^- + p$

$\bar{p} + p \longrightarrow \pi^+ + \pi^- + \pi^+ + \pi^- + \pi^0$

(ii) Decay

Example: $n \rightarrow p + e^- + \nu_e$ — $\beta$ - decay

$\pi^0 \rightarrow \gamma + \gamma$

(iii) Bound states.

Examples. Positronium $(e^+e^-)$

Charmonium $(\bar{c}\,c)$. $J/\psi$, $\psi'$, $\psi''$ ....

To tools used are

Accelerators: LINAC, Collider, ...

Detectors: Proportional ounter, Bubble Chambers
Cerenkov Counter, Calorimeter

# Elementary Particle Physics at 1947

$e^-, e^+ ; \gamma$

$p, n$

$\pi^\pm, \pi^0$

$\mu^\pm$

"$\nu$"

## Scattering

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

$e^- + e^+ \rightarrow \mu^+ + \mu^-$

$p + p \rightarrow p + p$

$\pi^\pm + p \rightarrow \pi^\pm + p$

## Decays

$e^-, e^+, \gamma, p, \nu$ stable

$n \rightarrow p + e^- + \nu$

$\pi^- \rightarrow \mu^- + \nu \; ; \; \pi^+ \rightarrow \mu^+ + \nu$

$\pi^0 \rightarrow 2\gamma$

$\mu^- \rightarrow e^- + \nu + \nu \; ; \; \mu^+ \rightarrow e^+ + \nu + \nu$

## Bound state

$e^+ e^-$ positronium $\quad$ $p e^-$ hydrogen atom.

$p n$ deuteron

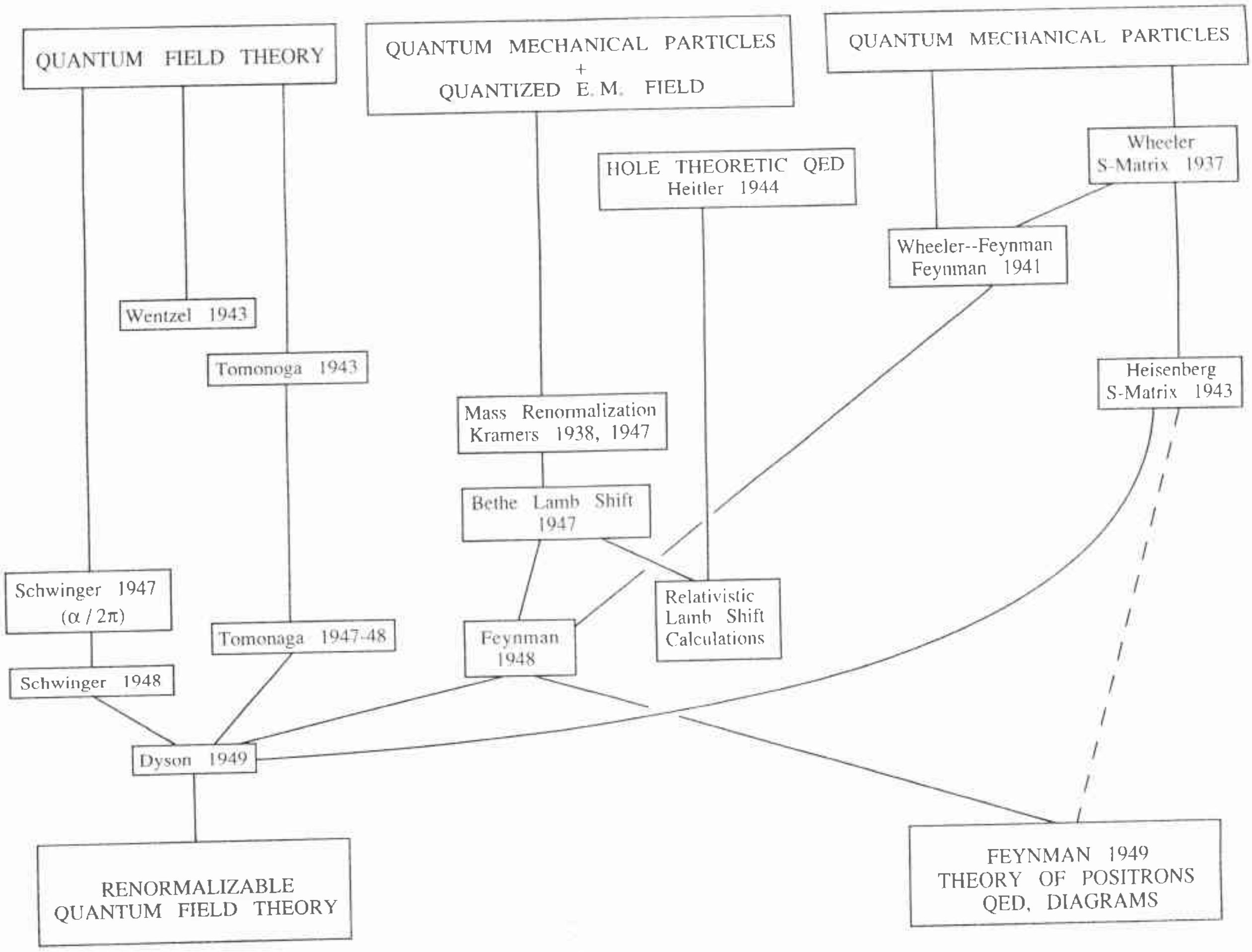

QUANTUM FIELD THEORY
QUANTUM MECHANICAL PARTICLES + QUANTIZED E.M. FIELD
QUANTUM MECHANICAL PARTICLES
HOLE THEORETIC QED Heitler 1944
Wheeler S-Matrix 1937
Wheeler--Feynman Feynman 1941
Wentzel 1943
Tomonoga 1943
Heisenberg S-Matrix 1943
Mass Renormalization Kramers 1938, 1947
Bethe Lamb Shift 1947
Schwinger 1947 (α / 2π)
Relativistic Lamb Shift Calculations
Tomonaga 1947-48
Feynman 1948
Schwinger 1948
Dyson 1949
FEYNMAN 1949 THEORY OF POSITRONS QED, DIAGRAMS
RENORMALIZABLE QUANTUM FIELD THEORY

Figure 1.2

14. Schwinger at Harvard University. (Courtesy AIP Niels Bohr Library)

23. Richard Feynman, 1959. (Courtesy AIP Niels Bohr Library, *Physics Today* Collection)

Freeman J. Dyson (1923–)

**Fig. 12.6** All divergences in QED can be absorbed into mass and charge renormalization.

| | |
|---|---|
| 分類： | |
| 編號： | |
| 總號： | |

10. Tomonaga, 1970. (Courtesy of Tomonaga Memorial, University of Tsukuba)

| |
|---|
| 分類： |
| 編號： |
| 總號： |

# Quantum Field Theory

Dirac equation's calculation of hydrogen atom

electromagnetic field $A_\mu(\vec{r},t)$ and electron are treated not at equal footing

1930's ( late 1920 and early 1930)

↓

theory of electromagnetic radiation

Dirac, Pauli, Heisenberg, Jordan, Wigner

$A_\mu(x,t)$ electromagnetic field

$\psi_e(x,t)$ electron field

$$\mathcal{L} = \mathcal{L}_{em} + \mathcal{L}_e + \mathcal{L}_{int}$$

$\mathcal{L}$ ↓ $\mathcal{L}(A_\mu, \psi_e)$

$\mathcal{L}_{em}$ ↓ function of $A_\mu$

$\mathcal{L}_e$ ↓ function of $\psi_e(x,t)$

$\mathcal{L}_{int}$ ↘ interaction Lagrangian. $ie\bar{\psi}_e\gamma_\mu\psi_e A_\mu$

Euler-Lagrange equation

$\mathcal{L}_{em}$ ⇒ Free Maxwell field.

$\mathcal{L}_e$ ⇒ Free Dirac field.

$\mathcal{L}$ ⇒ Full Maxwell equation with source term $J_\mu \propto e\,\bar{\psi}_e\gamma_\mu\psi_e$

Use canononical quantization

↓

quantum field theory for electromagnetic interaction.

No exact solution can be found

↓

perturbation method has to

be used.

photon is the quanta of the electromagnetic field.

electron is the quanta of the electron field.

The lowest order perturbation calculation (so called tree diagram) for $e^- + e^- \to e^- + e^-$ can be made.

and agree well with the experiment.

This is all very well.

- The electromagnetic field (photon) and electron field (electron) are treated with equal footing.
- The $\mathcal{L}$ (Lagrangian) density is well-grounded. it follows from action principle. It is Lorentz invariant, gauge invariant and local.

$\Rightarrow$ all the properties we want for our theory.

Yet, when we naively calculate the higher order term $\Rightarrow$ divergent results.

$\Rightarrow$ The theory is stuck for ~ 20 years.

1947 - 1949 Schwinger, Tomonaga, Feynman, Dyson found a procedure, known as renormalization that can remove all the divergence $\Rightarrow$ finite.

result for all order of perturbation for the quantum theory of electron and photon.

↓

Quantum Electrodynamics
(QED)

Schwinger, Tomonaga, and Feynman used different approaches.

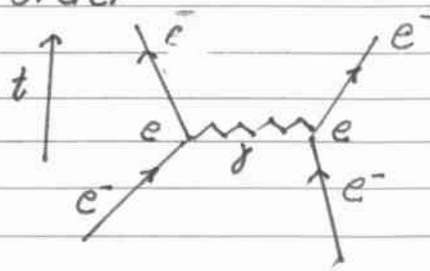
It is Dyson who showed they are all equivalent.

Feynman's approach → space-time approach.

Feynman diagram is the basic tool used by "all" elementary particle physicists

Example $e^- + e^- \to e^- + e^-$

Lowest order



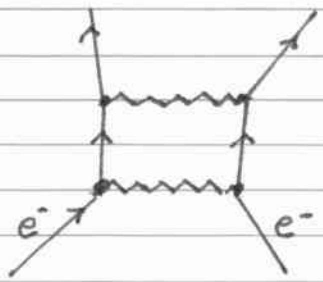

e is the coupling constant

In the appropriate unit

$$e^2 = \frac{1}{137}$$

↓

expansion parameter for perturbation expansion.




an example for higher order diagram.

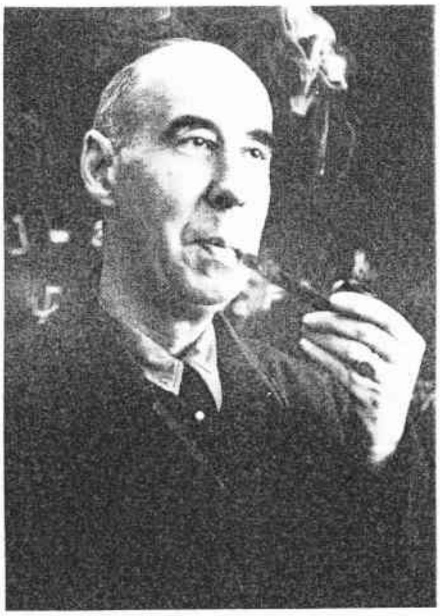
分類:
編號:
總號:

Feynman rules

specifies how the diagrams are calculated by specifi the vertex, interline and external line

Feynman rules are determined by the Lagrangian density.

Note: with Feynman rule, the calculations of the Feynman diagram are specified.



**Ernest Stückelberg von Breidenbach zu Breidenstein und Melsbach** (1905–1984). This brilliant physicist who introduced the idea of baryon number (as we call it today) did several things that were Nobel prize worthy; as he published mostly in a rather inaccessible journal (*Helvetica Physica Acta*), and moreover not in English, his work went largely unnoticed. He suggested a finite range for the nuclear forces (Nobel prize to Yukawa, 1949) and he also developed a formulation of quantum field theory as also done later by Feynman (see Chapter 9 on particle theory).

Stückelberg suffered from cyclothymie. This leads to manic depressive periods, and he had to be hospitalized periodically. In his later years he was always accompanied by a little dog that was claimed to be there to guide him home in case he lost his way. The dog was always present when his master gave a seminar, and I have actually witnessed that the dog answered to a question from the public (in fact, from T. D. Lee) with a short bark while Stückelberg just watched.

Whenever Stückelberg travelled he took along all of his books and papers that he might conceivably need. This led to a large number of heavy and big suitcases and trunks for even the smallest of trips.

In the book by R. Crease and C. Mann, *The Second Creation*, on page 140, there is a very nice interview with Baron Stückelberg. Memorable is one of his parting words in that interview: "We live too long."

**Richard Feynman** (1918–1988). The most important contribution of Feynman, in my view, is his introduction of the diagram method named after him, and the theoretical tool, path integrals, that he developed. Truly wonderful work.

Part of the formal theory associated with those diagrams was published before, in French, by Stückelberg in the somewhat inaccessible journal, *Helvetica Physica Acta*. This including the idea that a positron may be viewed as an electron going backwards in time (this is basically the idea of crossing). It is unlikely that Feynman knew of that work, yet when he learned of it he dutifully acknowledged that in his papers. There are some anecdotes associated with that, not necessarily true.

On the evening of the day (in 1965) that Feynman celebrated his Nobel prize he received a telegram during the party: "Send back my notes, please", signed Stückelberg. According to my source (unpublished biography of Stückelberg by Ruth Wenger) the originator of the joke was Gell-Mann. I asked Gell-Mann if he had sent this telegram, but he denied that, adding that it was a nice idea.

When Feynman, after receiving his prize in Stockholm, gave a lecture at CERN, Geneva, he was afterwards introduced to Stückelberg. He asked Stückelberg: "Why did you not draw diagrams?" To which Stückelberg answered: "I had no draughtsman". Stückelberg, always the perfect gentleman and very conscious of his standing as a baron, apparently felt it below his dignity to draw those simple figures himself.

Feynman was a very charming person to talk to, and he was a gifted teacher. Well-known are his textbooks on physics, and he came very much in the public eye in connection with his part in the

| | |
|---|---|
| 分類: | |
| 編號: | |
| 總號: | |

The Stueckelberg - Feynman approach.

We shall follow the pedestrian version given by Frauenfelder and Henley, "Subatomic Physics" P. 166 - 170

Consider a particle moving along positive $x$ axis with positive momentum $p$ and positive energy $E^+$

$$\psi(x,t) = e^{\frac{i}{\hbar}(px - E^+ t)}$$

↓ plane wave

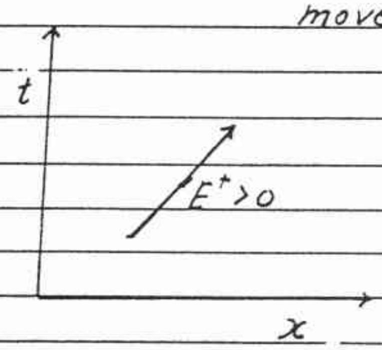
The phase of the wavefunction is constant if

$$px - E^+ t = \text{constant}$$

or if

$$x = \frac{E^+}{p} t$$

↓ move to the right

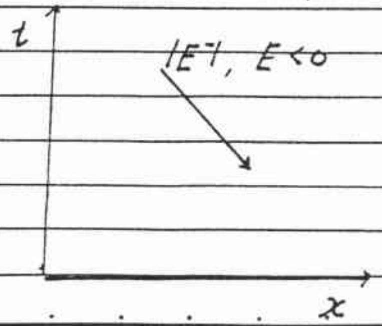



For negative energy

$$\psi(x,t) = e^{\frac{i}{\hbar}(px - E^- t)} \qquad E^- < 0$$

$$\Rightarrow \quad x = \frac{E^-}{p} t = \frac{|E^-|}{p}(-t)$$

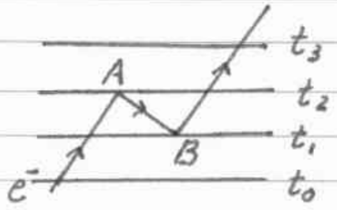
↓ can be interpreted as a particle moving backward in time but having a positive energy $|E^-|$



| | |
|---|---|
| 分類: | |
| 編號: | |
| 總號: | |

The notation that we are immersed in an infinite sea of negative energy electrons is an unsetting one

It was rendered unnecessary with the development of quantum electrodynamics by Feynman and Stuckelberg




At $t = t_1$ ⇒ 3 particles appear

two moving forward in time
one moving backward in time.

Conservation of charge
the one moving backward
⇒ particle with positive charge
⇒ positron $e^+$

At A ⇒ annihilation ($e^- - e^+$)

At B ⇒ pair production.

⇒ Feynman developed this intuitive way of understanding anti matter, revealing it to be the inevitable result of the merger between quantum mechanics and relativity.

Particles with integral spin also have anti-particle.

In general, an anti-particle has exactly the same mass as the particle, but with electric charge, baryon number, strangeness ‥, opposite in sign to that of the particle.

A few, such as $\pi^0$, $\gamma$, are their own antiparticles.

Note: $n \neq \bar{n}$ since they have opposite baryon number
↓
neutron and anti neutron are different

分類：
編號：
總號：

A particle of $-q$ in magnetic field

$$m \frac{d^2\vec{x}}{dt^2} = -q \frac{d\vec{x}}{dt} \times \vec{B}$$
$$= q \frac{d\vec{x}}{d(-t)} \times \vec{B}$$

↓

a particle with charge $q$ moving backward in time satisfies the same equation of motion as a particle with charge $-q$ moving forward in time

· negative energy solution can be looked at as a particle moving backward in time having positive energy

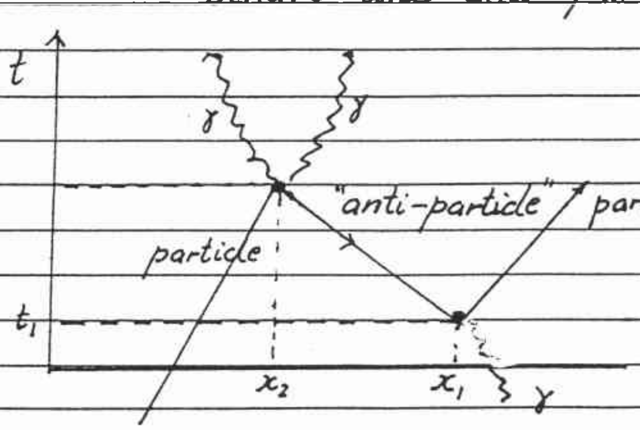
· a particle moving backward in time satisfies the same equation of motion as a particle with opposite charge moving forward in time.

a particle with charge $q$ and negative energy behaves like a particle with charge $-q$ and positive energy

the particle with charge $-q$ is the anti-particle of the one with charge $q$

↓

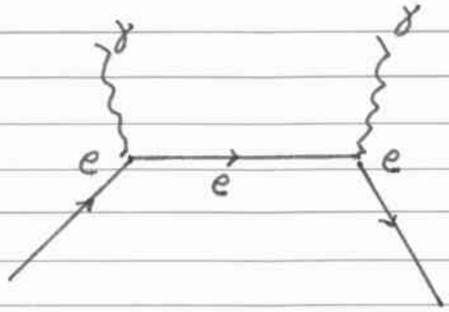
the negative energy states behave like anti-particle




negative energy states of a particle is replaced by anti-particle

anti-particle concept applies just as well to bosons as to fermions

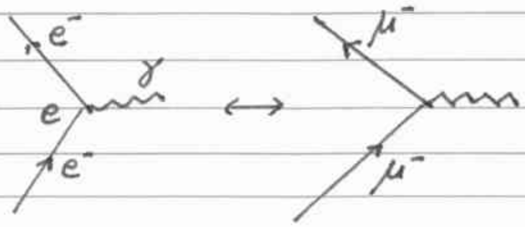
## The Stuckelberg - Feynman approach of $e^+ + e^- \to \gamma + \gamma$



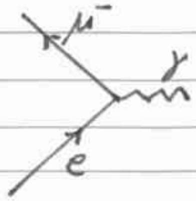

$e - \mu$ universality

↓

$e - \mu$ has the same properties except for their mass and electron number and $\mu$ - number

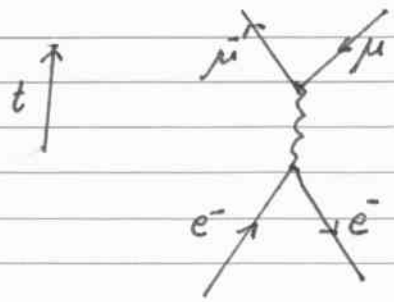


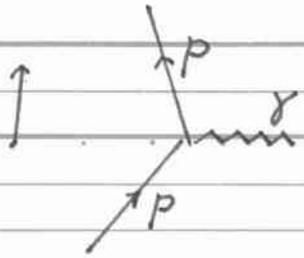

but




is forbidden (we shall discuss this point in next section)

$e^+ e^- \to \mu^+ \mu^-$

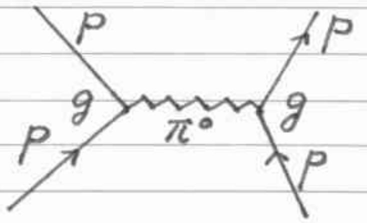





exists.

Now we go into strong interaction

$p + p \longrightarrow p + p$




$\mathcal{L}_{int} = g \bar{\psi}_p \psi_p \pi$ Yukawa

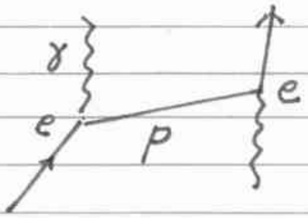
In the appropriate unit

$g \sim 1$

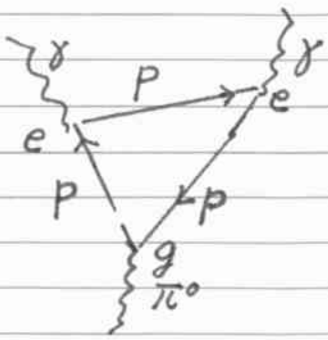
The perturbation method breaks down.

However, it can be used to make rough order of magnitude estimates.

$\gamma + p \rightarrow \gamma + p$



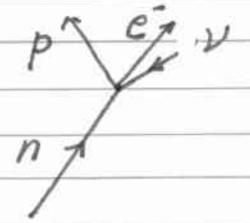

Furthermore $\pi^0 \rightarrow 2\gamma$




second order electromagnetic interaction.

Now we go to weak interaction.

$n \to p + e^- + \nu$



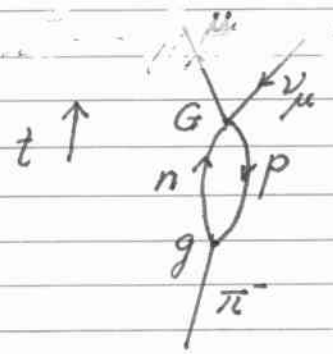

Fermi's four fermion interaction

$G\, \psi_p \gamma_\mu \psi_n\, \psi\, \gamma_\mu\, \psi$

The theory is not renormalizable

In the appropriate unit $\sim 10^{-7}$
↓ can be used for rough estimates

$\pi^- \longrightarrow \mu^- \nu$




so we expect this process to be a weak process.

At energy < 1 GeV, the processes can be roughly (~1950) divided into strong, electromagnetic, and weak interaction with distinct strength.

QED is a "complete" theory.

Strong and weak interaction theory are rather primitive.

| 分類： |
| --- |
| 編號： |
| 總號： |


**Fig. 12.9** Bethe, Schwinger, Feynman, and Weisskopf (with student J. Bruce French) calculated the Lamb shift independently during 1947–1948, using renormalization to circumvent the "ultraviolet catastrophe".

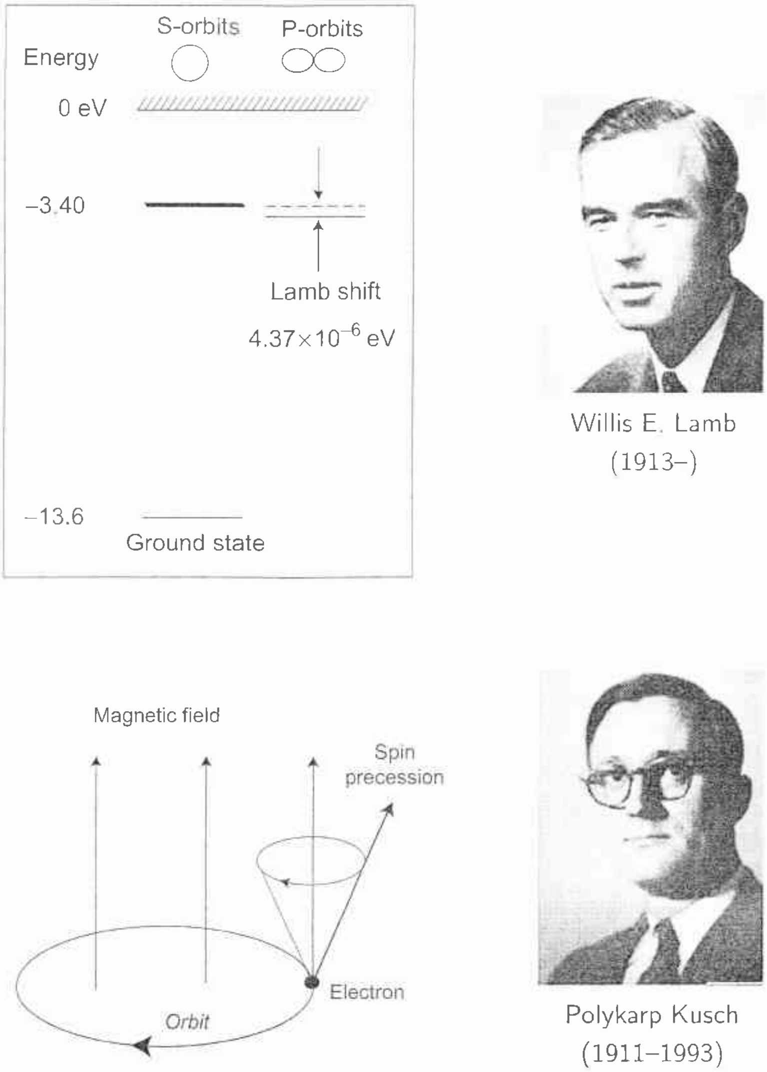



**Fig. 12.7** Lamb shift (upper panel) and anomalous magnetic moment of electron (lower panel). The Lamb shift is due mainly to the difference in self-energy of an electron in the 2S and 2P states of hydrogen, and amounts to one part in a milion. The drawing in lower panel shows an electron in a circular orbit in a uniform magnetic field, and its spin precesses about the magnetic field. According to Dirac theory, these two periodic motions should be prefectly synchronized. Due to the vertex correction however, the

$\mu^- \to e^- + \nu + \nu$ 4 fermions

↓ weak interaction

$n \to p + e^- + \nu$ note $n \not\to p + \mu^- + \nu$

↓ energy-momentum conservation consideration

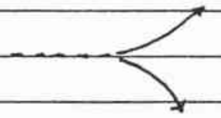
$\pi^- \to \mu^- + \nu$

These processes have similar strength.

(xii) 1947 - 53 Strange particle production, associated production and strangeness quantum number.

1947 Rochester and Butle obtained evidences for the existence of massive unstable particles in the cosmic radiation

One picture showed the decay of a neutral into two charged particles



V - event

$K^0 \to \pi^+ + \pi^-$

and the others → decay of a charged particle

$K^+ \longrightarrow \mu^+ + \nu$

$K^+ \longrightarrow \pi^+ \pi^- \pi^+$ (Bristol group)

Summary of the situation in 1953

(a) Unstable particle heavier than nucleons → hyperons

$\Lambda \to p + \pi^-$, $\Sigma^+ \to p + \pi^0$, $\Sigma^+ \to n + \pi^+$, etc

(b) Unstable particles with mass between that of the pion and the proton → kaons

$\underset{\hookrightarrow \tau}{K^+} \longrightarrow \pi^+ + \pi^- + \pi^+$, $\underset{\hookrightarrow \theta}{K^+} \to \pi^+ + \pi^0$

$K^+ \to \pi^+ + \pi^-$, $K^+ \to \mu^+ + \nu$ etc.

1951 Fowler et al., Armenteros et al. showed that the production of hyperons and kaons was probably a few per cent of that for producing pions

↓

strong interactions existed between kaon, hyperon, pion and nucleon

Lifetime for kaon and hyperon

$\tau \sim 10^{-8} - 10^{-10}$ sec

Problem. If $\pi^- + p \to \Lambda + \pi^0$ can occur via strong interaction then we would expect $\Lambda \to p + \pi^-$ to have a lifetime of $\sim 10^{-23}$ sec.

As if all this were not enough, a new class of particles, dubbed the **strange particles**, was discovered.[3] These particles were counterparts of the pions, the nucleons, and the other resonances involving pions and nucleons, but they differed in that their production patterns required the existence of a new label, or quantum number, something suggested by the American physicist M. Gell-Mann (•Fig. 16–16) and the Japanese physicist K. Nishijima. This new quantum label, the **strangeness**, was assigned so that its conservation would make the production and decay pattern consistent—in much the same way that baryon number is assigned. Particles with nonzero strangeness are termed **strange particles**. For example, a strange particle called the $\Lambda^0$ ($\Lambda$ is a capital Greek *lambda*), of mass $m_\Lambda = 1{,}115\ \text{MeV}/c^2$, decays in a pattern similar to that of the $\Delta$; that is,

$$\Lambda^0 \to p + \pi^-. \tag{16–9}$$

However, this decay is $10^{14}$ times slower than $\Delta$ decay. One assigns a nonzero strangeness to the $\Lambda^0$ and a zero strangeness to the pion and the proton and postulates that strangeness is conserved in the production reactions and *violated* in the decay reactions. This postulate allows for the systematic explanation of all the production and decay rates of strange particles.

As the number of particles, strange and nonstrange, grew, people began to look for ways of explaining their proliferation.

Argument: If $\pi^- + p \to \Lambda + \pi^0$ can occur via strong interaction, then, by the principle of microscopic reversibility

$$\Lambda \to \pi^- + p + \pi^0 \text{ can occur via strong interactio}$$

(Note: $\pi^0$ is its own anti-particle

$$p + \pi^0 \rightleftarrows p \text{ can occur via strong interaction}$$

(basic idea of Yukawa)

$$\Lambda \to \pi^- + \pi^0 + p \to \pi^- + p \text{ can occur via strong interaction.}$$

Typical time involved in strong interaction.

Range ~ 1 fm for strong interaction

Cross section ~ $10^{-26}\ cm^2$

⇒ if two strongly interacting particles are within the range of strong interaction (of each other) then there is high probability for them to interact.

⇒ the typical time for two strongly interacting particles to be within the range of strong interaction is

$$\sim 10^{-13}\ cm/c \sim 10^{-23}\ sec$$

⇒ typical reaction time for strong interaction

$$\sim 10^{-23}\ sec$$

Problem: Λ, K must be produced via strong interaction, yet $\pi^- + p \to \Lambda + \pi^0$ cannot proceed via strong interactic

1952 Pais: hypothesis of associated production

Kaons and hyperons must be created (or destroyed) in pairs for strong interaction to occur. If only one strange particle is present, then only weak interaction can occur.

For example

$\pi^- + p \to K^0 + \Lambda$

$\pi^- + p \to K^+ + \Sigma^-$

$p + p \to p + p + K^+ + K^-$

$K^- + p \to \Sigma^- + \pi^+$ etc.

can proceed via strong interaction

But

$\pi^- + p \to K^0 + n$

$\pi^- + p \to \Lambda + \pi^0$

$\Lambda \to p + \pi^-$

$K^+ \to \pi^+ + \pi^0$

cannot proceed via strong interaction.

分類：
編號：
總號：



**Abraham Pais** (1918–2000). Pais, the author of the books mentioned in the introduction, was a very accomplished physicist. Together with Gell-Mann he published a paper introducing the idea of particle mixing. This was in connection with $K^0$–$\bar{K}^0$ mixing, a very curious system indeed. When producing a $K_0$ it would after a while become an $\bar{K}^0$ and the other way around. In the end this resolved itself into a combination of two mixtures, called $K_S$ and $K_L$. They have very different properties; $K_S$ decays quite quickly, while $K_L$ lives much longer.

Pais introduced the idea of associated production, which is in fact the idea of a new quantum number now called strangeness which had to be conserved in all but weak interactions. Actually, several Japanese physicists published similar ideas at about the same time. This rule explains why certain particles were always produced in pairs (one with strangeness +1, the other −1, so that the sum was 0), given that the initial particles would have no strangeness. This was generally the case, because proton and neutron have strangeness zero, and the new particles were seen in collisions of protons with the protons or neutrons in a nucleus.

Pais, Jewish, living in the Netherlands during World War II, barely survived. He was released from jail just before the end of the war, after an appeal by a very courageous lady armed with a letter from Kramers to Heisenberg (who did not intervene). Perhaps the commanding officer saw the end coming, reason for a leniency extremely rarely seen. A friend of Pais, arrested at the same time, was shot.

Remarks

(a) $\pi^+ + n \to \Lambda + K^+$ can occur via strong interaction

$\Rightarrow \Lambda \to \pi^+ + n + K^- \to p + K^-$ should be able to proceed via strong interaction. It seems that $\Lambda \to p + K^-$ would still make $\Lambda$ to have a lifetime of $\sim 10^{-23}$ sec

This is not so because $\Lambda \to p + K^-$ is forbidden by energy momentum conservation

(Note $m_\Lambda < m_p + m_K$)

($K^-$ is the anti-particle of $K^+$)

(b) Pions are copiously produced in cosmic ray through strong interaction. It decays slowly because it is the lightest strongly interacting particle.

(c) Muons are copiously produced in cosmic ray even though muons are not strongly interacting because muons are decay products of pions which are copiously produced through strong interaction.

Gell-Mann (1953), Nishijima (1955) introduce the additive quantum number — strangeness $S$

Assign $\pi^\pm, \pi^0, n, p$ to have $S = 0$

$K^+, K^0, \bar{\Lambda}, \bar{\Sigma}$ to have $S = +1$

$K^-, \bar{K}^0, \Lambda, \Sigma$ to have $S = -1$

For a reaction to occur via strong interaction, strangeness must be conserved, i.e., $\Delta S = 0$

If $\Delta S \neq 0$, then it can at most proceed via weak interaction.

Remarks:

(a) It is more precise formulation than the hypothesis of associated production.

(b) $S$ is a new quantum number

(c) Strangeness conservation $\to$ approximate symmetry.

分類：
編號： 1-39
總號：

(xiii) Resonances

Most particles whose discoveries are described in the preceeding sections have lifetimes of $10^{-10}$ sec or more.

↓

they travel a perceptible distance before decay

The development of particle accelerators and the measurement of scattering cross sections revealed new particles in the form of resonances

↓

particles with small lifetimes as measured through

$\Delta E \, \Delta t \sim \hbar$

↕

width of the resonance
( ~ 10 to 200 MeV)

↓

$$\tau \sim \frac{\hbar}{100\,\text{MeV}} \sim 10^{-25}\ \text{sec}$$

↓

they can decay via strong interaction.

[ The first resonance Δ(1236) was discovered by Fermi et al 1952
⇒ the number of "elementary particles" grow to ~ 300 ]

It became imperative to classify these particles
[ Resonance will be studied when we review the scattering theory

· Fermions and bosons

Fermions : particles with half-integer spin.
obey Fermi-Dirac statistics
examples : $p, n, \Lambda, \Sigma, \Delta$ etc.

Bosons : particles with integer spin
obey Bose-Einstein statistics
examples : $\pi, K, \gamma, \rho$ etc.

**Luis Alvarez** (1911–1988). After Glaser came up with the idea of a bubble chamber Alvarez was quick to realize the potentialities of such an instrument. With considerable energy he put himself to the task of building bubble chambers, and to use them for physics purposes. With his group of very talented engineers and physicists (the distinction was not always clear) at Berkeley he started constructing a then relatively large hydrogen bubble chamber (10 inch = 25 cm long), with which a large amount of physics was done. They discovered many of the particles mentioned in this section. Alvarez received the 1968 physics Nobel prize.

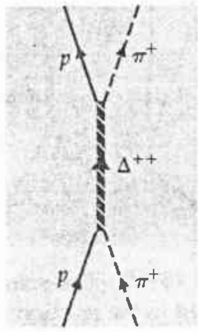
In a subsequent daring step the Berkeley group went on to construct a much larger hydrogen bubble chamber (72 × 20 × 15 inch = 183 × 51 × 84 cm) for the then large sum of $2.5 million. The problems were huge: liquid hydrogen (or deuterium) had to be kept at a temperature of −250°C, and the magnet surrounding the bubble chamber was very large (100 tons, using some 2 Megawatts to power it).

The first very significant result obtained with the 72-inch chamber was due to Pevsner and his group at Johns Hopkins University. The chamber (filled with deuterium) was exposed to a beam of pions from the Bevatron (a 6-GeV accelerator in Berkeley) and photographs were taken and sent to Johns Hopkins. The result was the discovery of the $\eta$, which particle completed the octet of mesons as described in this Chapter.

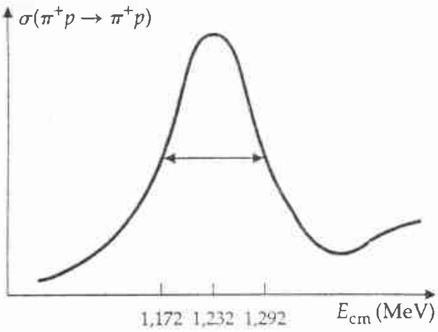
The relation of Alvarez with the then director of LBL (Lawrence Berkeley National Laboratory), Edwin MacMillan, deteriorated to the point that it interfered with the physics done. So it goes.

# Resonances

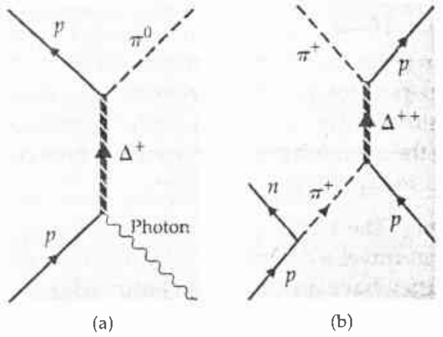
The discovery of pions in the late 1940s coincided with a return of many physicists from defense-related work in World War II, and their successes brought with them a national commitment to the growth of science, including such esoteric fields as elementary particle physics. The construction of accelerators of ever-increasing energy allowed an exploration of the interactions of pions with nucleons. Already in 1952 the elastic scattering of $\pi^+$ by protons (an analogue of Compton scattering of light by electrons) yielded an interesting phenomenon: The incoming pion and the proton formed a new "particle" of mass 1,232 MeV/$c^2$, which then decayed back into a proton (or neutron) and a single pion (•Fig. 16–12). The "particle" was not stable; indeed, its lifetime was exceedingly short. One can think about such particles by analogy to spectral lines in atoms. For example a photon impinging on one particle (the ground state of hydrogen) "produces" an excited state of hydrogen, which then decays back to the ground state. If $hf$ is the excitation energy, the light that is emitted has a frequency $f \pm \Delta f$ and an energy spread $2h\Delta f$ (the width of the spectral line). A




Feynman diagrams for the formation of a $\Delta^{++}$ particle in the collision of a $\pi^+$ and a proton. The $\Delta^{++}$ bears some resemblance to the "compound nucleus" described in Chapter 15.




The "width" of the $\Delta^{++}$ appears in the shape of the cross section for the reaction $\pi^+ + p \to \pi^+ + p$. The initial collision produces the $\Delta^{++}$ particle, which exists for a time $\Delta t$ determined by the energy uncertainty, which we call the "width" (here about 120 MeV) in this context.



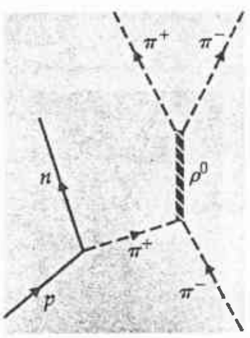

The existence of the Δ particle is independent of how it is produced, as shown by the fact that it can be produced (a) by photons impinging on a proton and (b) in nucleon–nucleon collisions.

measurement of the energy spread can be used, via the relation $\Delta t = \hbar/\Delta E$, to determine the lifetime of the excited state. For the 1,232-MeV/$c^2$ particle, subsequently named the Δ particle, a measurement of the energy of the outgoing pion showed that the width of the line was in the vicinity of 120 MeV/$c^2$ (•Fig. 16–13), so that the lifetime is

$$\tau_\Delta = \frac{\hbar}{\Delta E} = \frac{1.05 \times 10^{-34}\ \text{J}\cdot\text{s}}{(120\ \text{MeV})(1.6 \times 10^{-13}\ \text{J/MeV})} = 5 \times 10^{-24}\ \text{s}.$$

This lifetime is so short—smaller than the time it takes a photon to traverse the diameter of a proton—that one is reluctant to use the term "particle." In fact, the object is more commonly called a **resonance**. Nevertheless, the description of the $\Delta^{++}$ and its nearly-equal-mass partners $\Delta^+$, $\Delta^0$, and $\Delta^-$ as particles has much justification. For example, the Δ's have a definite spin $S = 3/2$. Moreover, they can be produced in other ways—for instance, in photoproduction and in production by virtual pions (•Fig. 16–14). The characteristics of the Δ do not depend on how it is produced.

More experiments uncovered many other unstable particles. An example is the ρ-meson (see Example 16–3), which comes in three charge states ($\rho^+$, $\rho^0$, and $\rho^-$) and has spin 1 and mass $m_\rho c^2 \cong 770$ MeV. This particle decays primarily into a pair of pions with $\Delta E \cong 150$ MeV (•Fig. 16–15).




The ρ meson is produced in the reaction $\pi$ + nucleon $\to \rho$ + nucleon. The ρ decays quickly to a pair of pions. The energy distribution of the two pions in the final state shows clearly that they are the decay products of a single particle.

Fermi - Dirac statistics

1, 2 are identical fermions such as $2e^-$, or $2p$

$$\psi(1,2) = -\psi(2,1)$$

Bose - Einstein statistics

1, 2 are identical bosons such as $2\pi^0$

$$\psi(1,2) = \psi(2,1)$$

Application of Bose - Einstein statistics
↓
Proof that $\rho^0 \not\leftrightarrow \pi^0\pi^0$
(However $\rho^0 \to \pi^+ + \pi^-$ is allowed)

Note $\rho^0$ has spin 1, $\pi^0$ has spin 0

$$\psi(\vec{r}_1, \vec{r}_2) = \tilde{\Psi}(\vec{R})\,\phi(\vec{r})$$

$\tilde{\Psi}(\vec{R})$ ↳ center of mass motion; $\phi(\vec{r})$ ↳ relative motion.

$$\vec{R} = \frac{1}{2}(\vec{r}_1 + \vec{r}_2), \quad \vec{r} = \vec{r}_1 - \vec{r}_2$$

In spherical coordinate $\phi(\vec{r})$ with a fixed angular momentum $l$ can be written as

$$\sum_{m=-l}^{l} R_{El}(r)\, Y_{lm}(\theta,\phi)$$

$Y_{lm}$ ↓ spherical harmonics

$$1 \leftrightarrow 2 \iff \vec{R} \to \vec{R}, \quad \vec{r} \to -\vec{r}$$

$$r \to r, \ \theta \to \pi - \theta, \ \phi \to \pi + \phi \leftrightarrow x = -x, \ y = -y, \ z \to -z$$

[Note: $x = r\sin\theta\cos\phi$, $y = r\sin\theta\sin\phi$, $z = \cos\theta$]

$$\psi(\vec{r}_2, \vec{r}_1) = \sum_m \tilde{\Psi}(\vec{R})\, R_{El}(r)\, Y_{lm}(\pi-\theta, \pi+\phi)$$

$$= \sum_m \tilde{\Psi}(\vec{R})\, R_{El}(r)\, (-1)^l\, Y_{lm}(\theta,\phi)$$

$$= (-1)^l\, \psi(\vec{r}_1, \vec{r}_2)$$

Bose - Einstein statistics requires $l$ to be even
If $\rho^0 \to 2\pi^0$, then angular momentum conservation would require $l = 1$.

These two requirements are incompatible

$$\Downarrow$$

$$\rho^0 \not\leftrightarrow 2\pi^0$$

· Application of Fermi-Dirac statistics

Consider the two neutron system

$$\psi_{tot} = \phi(\text{space}) \cdot \alpha(\text{spin})$$

Under $1 \leftrightarrow 2$

$$\phi( \quad \longrightarrow (-1)^{\ell}\phi(\text{space})$$

Spin $= 0$, the singlet spin wavefunction is given by

$\frac{1}{\sqrt{2}}(\alpha_1\beta_2 - \alpha_2\beta_1)$ [ $\alpha \to$ spin up, $\beta \to$ spin down ]

$\Rightarrow$ anti-symmetric under $1 \leftrightarrow 2$

Spin $= 1$, the triplet spin wavefunctions are given by

$\alpha_1\alpha_2$, $\frac{1}{\sqrt{2}}(\alpha_1\beta_2 + \alpha_2\beta_1)$, $\beta_1\beta_2$

$\Rightarrow$ symmetric under $1 \to 2$

For $S = 1$, Fermi-Dirac statics requires

$$(-1)^{\ell} = -1$$
$$\Downarrow$$
$\ell$ must be odd

For $S = 0$, Fermi-Dirac statistics requires

$$(-1)(-1)^{\ell} = -1$$
$$\Downarrow$$
$$\ell = \text{even}$$

Spectroscopic notation $\quad {}^{2S+1}L_J$

Singlet $\quad {}^1S_0$, ${}^1P_1$, ${}^1D_2$, ${}^1F_3$, ...

〰 states are ruled out by Fermi-Dirac statistics

Triplet $\quad {}^3S_1$, ${}^3P_2$, ${}^3P_1$, ${}^3P_0$, ${}^3D_3$, ${}^3D_2$, ${}^3D_1$, ${}^3F_4$, ${}^3F_3$, ${}^3F_2$, ....

〰 states are ruled out by Fermi-Dirac statistics

1932 Heisenberg $\Rightarrow$ concept of isospin.

· Proton and neutron may be treated as different isospin spin states of the same particle

$$p \to |\tfrac{1}{2}, \tfrac{1}{2}\rangle \ , \quad n \to |\tfrac{1}{2}, -\tfrac{1}{2}\rangle$$

Later, the concept wave extended that $\pi^+, \pi^0, \pi^-$ can be treated as different isospin state of the same particles

$$\pi^+ \to |1,1\rangle \ , \ \pi^0 \to |1,0\rangle \ , \ \pi^- \to |1,-1\rangle$$

Two isospin $=1$ particle can form $I = 2, 1, 0$ states

Among them only $I=1$ state is anti-symmetric under $1 \to 2$

$\pi^+\pi^-$ system

$$\psi = \phi(\text{space})\, \chi(\text{isospin})$$

$l=1$ $\phi$(space) is anti-symmetric
[Note $\vec{a}\times\vec{b}$ is anti-symmetric under $\vec{a} \leftrightarrow \vec{b}$]
Bose-Einstein statistics $\Rightarrow$ $\chi$ (isospin) must be anti-symmetric $I=1$]

If $\rho^0 \to \pi^+ + \pi^-$ and isospin invariance holds then $\rho^0$ have $I=1$
$\Rightarrow \rho^+, \rho^-$ must exist

Two identical particles in the same quantum states
$\Rightarrow \psi$ must be symmetric under $1 \leftrightarrow 2$

Fermi-Dirac statistics requires for two identical fermions $\psi$ must be anti-symmetric

$\Rightarrow$ two identical fermions cannot exist in the same quantum state

$\Rightarrow$ Pauli's exclusion principle

No restriction on bosons. They may exist in the same state.

Laser does exist ($\gamma$ has spin $1 \Rightarrow$ it is a boson)

| | |
|---|---|
| 分類： | |
| 編號： | |
| 總號： | |

Milestones in Particle Physics (with introduction) is given in Appendix D

A Chronological List of Disoveries (with introduction) is given in Appendix E

| 分類： |
| --- |
| 編號： |
| 總號： |

TABLE 1.1

| Interaction | Typical coupling constant | Typical cross sections | Typical lifetimes |
| --- | --- | --- | --- |
| Strong | $g^2/\hbar c \sim 10$ | $10^{-26}$ cm$^2$ = $10^4$ $\mu$b | $10^{-23}$ sec |
| Electromagnetic | $e^2/\hbar c = \frac{1}{137}$ | $10^{-29}$ cm$^2$ = 10 $\mu$b | $10^{-16}$ sec |
| Weak | $\sim 10^{-7}$ | $10^{-38}$ cm$^2$ = $10^{-8}$ $\mu$b | $10^{-8}$ sec |
| Gravitational | $\sim 10^{-45}$ | — | — |

A summary of the couplings in the various interactions is given in Table 1.1.

## 3. The Fundamental Forces (Interaction) in Nature

To understand the properties of elementary particles, we must be able to describe the forces between them.

Particles in nature are subject to four fundamental forces: strong, electromagnetic, weak and gravitational.

They are listed in order of decreasing strength.

[ The "strength" of a force is an intrinsically ambiguous notation — after all, it depends on the nature of the source and on how far away you are. So the numbers in the following table should not be taken too literally, and (espically in the case of weak force) you will see quite different figures quoted elsewhere ]

| Interaction (Force) | Relative Strength* | Typical Lifetimes for Decays via a Given Interaction | Rang of Force | Theory | Mediator |
|---|---|---|---|---|---|
| Strong | 1 | $\lesssim 10^{-20}$ sec | Short ($\sim 1 fm$) | Chromodaynamics | Gluon |
| Electrodynamics | $\simeq 10^{-2}$ | $\simeq 10^{-16}$ sec | Long ($\propto \frac{1}{r^2}$) | Electrodynamics | Photon |
| Weak | $\simeq 10^{-6}$ | $\gtrsim 10^{-10}$ sec | Short ($\simeq 10^{-3} fm$) | Flavordynamics | W and Z |
| Gravitational | $\simeq 10^{-43}$ | ? | Long ($\propto \frac{1}{r^2}$) | Geometrodynamics | Graviton |

[* For two u quarks at $3 \cdot 10^{-17}$ m ]

| |
|---|
| 分類: |
| 編號: |
| 總號: |

The strong force is responsible for binding quarks tightly together to form protons, neutrons, and other hadrons. It is extremely short-range and is negligible for seperation greater than approximately $10^{-15}$ m. The nuclear force that binds neutrons and protons in nuclei is currently believed to be a residual effect of the more basic strong force between quarks, much as the molecular force binding electrically neutral atoms together in molecules is a residual electrical interaction.

The electromagnetic force which binds electrons and protons within atoms and molecules to form ordinary matter. It is a long range force that decreases in strength as the inverse square of the seperation between interacting particles.

The physical theory that describes the electromagnetic force is called electrodynamics. Its classical formulation was given by Maxwell. The quantum theory of electrodynamics was perfected by Tomonaga, Feynman, and Schwinger in the 1940s.

The weak force is a short-range force that account for
beta decay
weak decays
neutrino interaction.

分類:
編號:
總號:

The classical (non-relativistic) theory of gravity is Newton's law of universal gravitation.

Its relativistic generalization is Einstein's general theory of relativity ("geometrodynamics" would be a better term).

A completely satisfactory quantum theory of gravity has yet to be worked out.

Each of these forces is mediated by the exchange of a particle.

The gravitational mediator is called the gr.viton

The electromagnetic forces are mediated by photon, strong forces by the gluon, and weak forces by the intermediate vector bosons W and Z.

The weak forces were unknown to classical physics

Their theoretical description was given a relativistic quantum formulation right from the start.

The first theory of the weak force was presented by Fermi in 1933.

It was refined by Lee and Yang, Feynman and Gell-Mann and others in the fifties and put in the present form by Glashow, Weinberg, and Salam in the sixties
↓
GWS theory

[The GWS model treats weak and electromagnetic interactions as different manifestations of a single electroweak force, and in this sense the four forces reduce to three]

[ For reasons that will appear in due course, the theory of weak interaction is sometimes called flavordynamics ]

The gravitational force is a long-range force that holds the planets, stars together

For the moment, most people assume that gravity is simply too weak to play a significant role in elementary particle physics.

# 4. Classification of Particles

Classification of particles according to their interactions

- Photon: mediator of electromagnetic interaction: $\gamma$
- Leptons: do not participate in strong interaction
  all known leptons are fermions (spin $\frac{1}{2}$)
  $e, \mu, \nu_e, \nu_\mu$
- Hadrons: strongly interacting particles
  they may also participate in electromagnetic and weak interaction

Baryons: hadrons with half-integer spin.
examples: $p, n, \Lambda, \Sigma, \Omega, \cdots$

Mesons hadrons with integer spin.
examples: $\pi, K, \rho, \omega, \phi, J/\psi, \cdots$

# Conversation Laws and Quantum Numbers

Conservation laws are important to an understanding of why certain decays and reactions occur and others do not.

In general, the laws of conservation of energy, linear momentum, and angular momentum must be followed for all processes.

For example, $A \rightarrow B + C$ occurs

$\Rightarrow \quad m_A > m_B + m_C$

[ Energy-momentum conservation (in the center of mass system of A

$$m_A c^2 = \sqrt{\vec{p}^{*2}c^2 + m_B^2 c^4} + \sqrt{\vec{p}^{*2}c^2 + m_C^2 c^4}$$ ]

The conservation laws are related to time translation, space translation and space rotation invariance respectively.

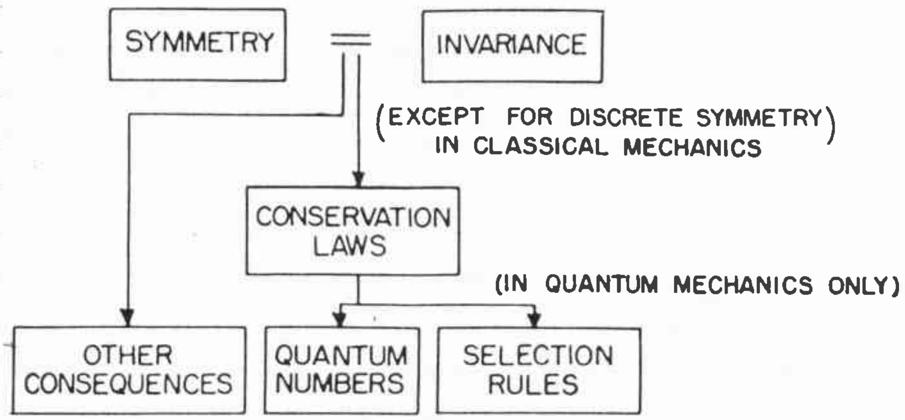


TABLE 1.2

| Conserved quantity | Interaction: Strong | Electromagnetic | Weak |
|---|---|---|---|
| $B$ (baryon no.) | Yes | Yes | Yes |
| $L$ (lepton no.) | Yes | Yes | Yes |
| $I$ (isospin) | Yes | No | No ($\Delta I = 1$ or $\frac{1}{2}$) |
| $G$ ($G$-parity) | Yes | No | No |
| $S$ (strangeness) | Yes | Yes | No ($\Delta S = 1$) |
| $P$ (parity) | Yes | Yes | No |
| $C$ (charge conjugation parity) | Yes | Yes | No |
| $CP$ | Yes | Yes | Yes (but $10^{-3}$ violation in $K^0$ decay) |
| $CPT$ | Yes | Yes | Yes |

| Transformation | Conserved quantity, or eigenvalue |
|---|---|
| Space displacement | Momentum |
| Time displacement | Energy |
| Spatial rotation | Angular momentum |
| Space inversion | Parity, ±1 |
| Rotation in isospin space | Isospin |
| Charge conjugation | *C*-parity, ±1 |
| *G*-conjugation | *G*-parity, ±1 |
| Gauge transformation | Electric charge, baryon number, lepton number |

Absolute conservation laws
↓
obeyed by all processes

- Energy-momentum conservation.
- Angular momentum conservation.
  [ Angular momentum is the vectorial sum of orbital angular momentum and spin (angular momentum) ]
- Electric charge conservation
  Assign each particle an electric charge quantum number Q

  Electric charge (quantum number) conservation
  ↓
  total charge before the process must equals the total charge after the reaction

  Energy-momentum conservation, electric charge conseration.
  electron is the lightest particle carrying charge
  ⇒ electron must be stable.
  [ Stability of the electron is an evidence for electric charge conservation ]

- Baryon number conservation.
  Assign a baryon number $B = +1$ for all baryons, $B = -1$ for anti-baryon, and $B = 0$ for all others.

  The law of conservation of baryon number ⇒ for a reaction to occur, the sum of the baryon numbers before the process must equal to the sum of baryon numbers after the process.

⇕

the net number of baryons remains constant in any process.

[ To produce anti-proton in proton-proton collision ; the process with the lowest threshold energy is
$p + p \rightarrow p + p + p + \bar{p}$ ]

[ If baryon number is absolutely conserved, the proton must be absolutely stable ]

[ If it were not for the law of conservation of baryon number, $p \rightarrow e^+ + \pi^0$ could occur.
However, such decay has never been observed
At present, we can say only that the proton has a half life of at least $10^{31}$ year. ( the estimated of the Universe is $\sim 10^{10}$ years )
In some recent version of grand unified theory, physicists predicted that proton is unstable. ]

· Lepton number conservation

There are three conservation law involving leptons $L_e, L_\mu, L_\tau$, one of each variety of lepton.

The laws of conservation of lepton
↓
the sum of $L_e$, $L_\mu$, and $L_\tau$ before a reaction or decay must equal the sum of after the reaction or decay.

Example $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Before the reaction $L_\mu = +1$ , $L_e = 0$
After the reaction $L_\mu = 0 + 0 + 1 = +1$
$L_e = 1 - 1 + 0 = 0$

Example $\pi^+ \rightarrow \mu^+ + \nu_\mu + \nu_e$
Before the reaction $L_\mu = 0$ , $L_e = 0$
After the reaction $L_\mu = 0$, $L_e = +1$

$\Rightarrow$ decay is not possible

Leptons

| Particle Name | Symbol | Rest Mass ($MeV/c^2$) | Lifetime (s) | $L_e$ | $L_\mu$ | $L_\tau$ | Anti-Particle |
|---|---|---|---|---|---|---|---|
| Electron | $e^-$ | 0.511 | stable | +1 | 0 | 0 | $e^+$ |
| Electron Neutrino | $\nu_e$ | $< 7\ eV/c^2$ | stable | +1 | 0 | 0 | $\bar{\nu}_e$ |
| Muon | $\mu^-$ | 105.7 | $2.2 \cdot 10^{-6}$ | 0 | +1 | 0 | $\mu^+$ |
| Muon Neutrino | $\nu_\mu$ | $< 0.3$ | stable | 0 | +1 | 0 | $\bar{\nu}_\mu$ |
| Tau | $\tau^-$ | 1784 | $< 4 \cdot 10^{-15}$ | 0 | 0 | +1 | $\tau^+$ |
| Tau-Neutrino | $\nu_\mu$ | $< 30$ | stable | 0 | 0 | +1 | $\bar{\nu}_\tau$ |

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

Recent experiments indicates that neutrinos may have a small but non-zero mass and there may be small violation of lepton number conservation.

$\downarrow$

have significance in cosmological models and the predictions of the future of the Universe.

| |
|---|
| 分類： |
| 編號： |
| 總號： |

Approximate Conservation Laws
↓
Valid only for strong and/or electromagnetic interactions

Isospin $I$, $I_3$

Similar to spin in mathematical structure (in particular, their addition rule)

Some particles with similar masses( $\frac{\Delta m}{m} \sim$ few %) and similar strong interaction properties

We assign these particle to the same isomultiplet)

$I$: $2I+1$ = number of particles (states) in the same iso .

$I_3$ $I_3 = I, I-1, \cdots -I+1, I$
in decreasing order of the electric charge of the particle (states) in the isomultiplet.

Example proton $p$, neutron $n$ forms an iso-doublet

$2I+1 = 2$ (there are two particles in the isomultiplet)
⇓
$I = \frac{1}{2}$

Proton has $I = \frac{1}{2}$, $I_3 = \frac{1}{2}$
Neutron has $I = \frac{1}{2}$, $I_3 = -\frac{1}{2}$

Example $\pi^+$, $\pi^0$, $\pi^-$ belong to an isomultiplet

$2I+1 = 3 \Rightarrow I = 1$

$\pi^+$: $I=1$, $I_3 = +1$
$\pi^0$: $I=1$, $I_3 = 0$
$\pi^-$: $I=1$, $I_3 = -1$

Strangness $S$

$S = 2\langle Q\rangle - B$

| |
|---|
| 分類： |
| 編號： |
| 總號： |

$\langle Q \rangle$ is the average value of the electr charge in the same isomultiplet.

$B$ is the baryon number

[ Particles in the same isomultiplet have the same strangeness ]

Example: proton (p), neutron n

$$\langle Q \rangle = \frac{1}{2}, \quad B = 1 \Rightarrow S = 0$$

Example $\Lambda^0$ belong to an iso-singlet

$$\langle Q \rangle = 0, \quad B = 1 \Rightarrow S = -1$$

Example $\{K^+, K^0\}$ form an isodoublet

$$\langle Q \rangle = \frac{1}{2}, \quad B = 0 \Rightarrow S = +1$$

All particles discovered before 1975 satisfy the Gell-Mann Nishijima relation (1955)

$$Q = I_3 + \frac{S + B}{2}$$

Example proton (p) neutron (n)

$$Q(\text{proton}) = \frac{1}{2} + \frac{0+1}{2} = 1$$

$$Q(\text{neutron}) = -\frac{1}{2} + \frac{0+1}{2} = 0$$

Example $\Lambda$

$$Q(\Lambda) = 0 + \frac{-1+1}{2} = 0$$

The hadrons can be labelled by quantum numbers $(Q, B, I, I_3, S)$

[ Anti-particle and particle have opposite quantum numbers.

Isospin conservation valid for strong interaction

[ Note: I spin is similar to spin, in particular, their addition rule ]

$I_3$ conservation: valid in strong and electromagnetic interaction

Strangeness $(S)$ conservation: valid in strong and electromagnetic

分類：
編號：
總號：

interaction.

Classification according to half-life

Stable: particles that cannot decay $\tau = \infty$

Example $\nu_e, \nu_\mu, \gamma, e^-, p$, etc

Can only decay via weak interaction $\tau > 10^{-10}$ sec

Example: $n, \pi^\pm, \Lambda, K^+$ etc

Can decay via electromagnetic interaction $\tau \sim 10^{-17} - 10^{-20}$ sec

Example: $\pi^0 \to \gamma\gamma$, $\Sigma^0 \to \Lambda^0 + \gamma$, etc

Can decay via strong interaction $\Gamma > 1$ MeV, $\tau < 10^{-23}$ sec

Example $\Delta^{++} \to p\pi^+$, $\rho^0 \to \pi^+\pi^-$, etc.

(i) $\pi^- + p \rightarrow n + K^0$

| | $\pi^-$ | $p$ | $n$ | $K^0$ |
|---|---|---|---|---|
| $Q$ | -1 | 1 | 0 | 0 |
| $I_3$ | -1 | $\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ |
| $I_3$ | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{1}{2}$ |
| $S$ | 0 | 0 | 0 | +1 |
| $B$ | 0 | 1 | 1 | 0 |

Cannot be electromagnetic or strong interaction.

(ii) $\bar{p} + p \rightarrow p + \pi^-$

| | $\bar{p}$ | $p$ | $p$ | $\pi^-$ |
|---|---|---|---|---|
| $B$ | -1 | 1 | 1 | 0 |

$\Rightarrow$ Baryon number is not conserved.

$\downarrow$

the process will not happen

(iii) $e^- + p \rightarrow \bar{\nu}_e$

| | $e^-$ | $p$ | $\bar{\nu}_e$ |
|---|---|---|---|
| $L_e$ | 1 | 0 | -1 |
| $B$ | 0 | 1 | 0 |

$\downarrow$

cannot happen

(iv) $\Delta^{++} \rightarrow \pi^+ + \pi^+ + n$

| | $\Delta^{++}$ | $\pi^+$ | $\pi^+$ | $n$ |
|---|---|---|---|---|
| | 3/2 | 0 | 0 | $\frac{1}{2}$ |
| $Q$ | 2 | 1 | 1 | 0 |
| $B$ | 1 | 0 | 0 | 1 |
| $I_3$ | $\frac{3}{2}$ | 1 | 1 | $-\frac{1}{2}$ |
| $I$ | $\frac{3}{2}$ | 1 | 1 | $\frac{1}{2}$ |
| $S$ | 0 | 0 | 0 | 0 |

conservation is possible, orbital angular momentum

conservation of isospin is possible

$1 \otimes 1$: $2, 1, 0$ ; with $\frac{1}{2}$: $\frac{5}{2}, \frac{3}{2}$ ; $\frac{3}{2}, \frac{1}{2}$ ; $\frac{1}{2}$

分類：
編號：
總號：

(v) $\Delta^{++} \rightarrow K^+ + K^+ + n$

| | $\Delta^{++}$ | $K^+$ | $K^+$ | $n$ |
|---|---|---|---|---|
| S | 0 | 1 | 1 | 0 |

$\Delta S = 2$

$\Delta S = 1$ for weak interaction

(vi) $\pi^- + p \rightarrow K^0 + \Lambda^0$

| | $\pi^-$ | $p$ | $K^0$ | $\Lambda^0$ |
|---|---|---|---|---|
| Q | -1 | 1 | 0 | 0 |
| B | 0 | 1 | 0 | 1 |
| $I_3$ | -1 | $\frac{1}{2}$ | $-\frac{1}{2}$ | 0 |
| I | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | 0 |
| | $\frac{3}{2}, \frac{1}{2}$ | | $\frac{1}{2}$ | |
| S | 0 | 0 | +1 | -1 |

Strong interaction.

**Bruno Pontecorvo** (1913–1993) and **Melvin Schwartz** (1932). Pontecorvo has had essentially all the ideas for neutrino experiments. He was the first to think of the so-called chlorine-argon method for detecting neutrinos (including neutrinos from the sun), and he also introduced neutrino mixing (in 1957). The chlorine-argon method was put into practice and further developed by Davis, who demonstrated that reactor antineutrinos were different from neutrinos, and who detected neutrinos from the sun (Nobel prize 2002).

The idea for neutrino experiments at the big machines is due to both Schwartz and Pontecorvo. Schwartz went on to do the experiment, together with Lederman, Steinberger, Goulianos, Gaillard, Mistry and Danby. Lederman, Schwartz and Steinberger received the 1988 Physics Nobel prize for this landmark experiment.

Pontecorvo, a devoted communist, already politically active in the thirties, moved to Russia in 1950 in a somewhat fugitive way. He was one of those scientists who were blamed for defecting to Russia taking along atomic bomb secrets. In his case there is not much substance to that; he was never actually involved in weapons research. He just believed in communism. I guess he paid the price.

Schwartz later suggested beam dump experiments at SLAC, and he had in fact a short run. He showed me a few pictures (dubbed Melons by some) at the time of the 1971 Amsterdam conference, and to me it was immediately clear that he had observed neutral current neutrino events. Conflicts with the SLAC directorate (Panofsky) led a somewhat embittered Schwartz to leave physics, and he started a successful electronics company called Digital Pathways. Personally I believe that he was a better physicist than businessman. He is too honest.

分類：
編號：
總號：

**Leon Lederman** (1922) and **Jack Steinberger** (1921). They shared with Schwartz the 1988 Nobel prize for the discovery of the muon-neutrino at the Brookhaven neutrino experiment.

**Tsung Dao Lee** (1926) and **Chen Ning Yang** (1922). They shared the 1959 Nobel prize for their work on parity violation. This concerns the behaviour of physics laws when considered through a mirror. Thus do two sets of experiments, and observe the results directly, but also, independently, in a mirror. The question is whether the laws deduced from such experiments will be the same. They analyzed the situation assuming that this is not so, and indeed it is not. When observing the decay of a pion at rest into a muon (and an antineutrino) the muon spins in a left-handed way along the direction of movement in ordinary space, while in the mirror one observes a muon spinning in the opposite way.

Lee and Yang collaborated till 1962, when they broke apart for reasons of their own. In my opinion the sum was better than the two individually, an example of synergy. They had just started on a systematic investigation of vector bosons (the *W* and *Z* of weak interactions), and there is no telling how far they could have gone in developing the Standard Model. Lee was very strong on Feynman diagrams, while Yang was together with Mills the originator of gauge theories (also called Yang-Mills theories) that are an essential ingredient of the Standard Model.

The idea of Schwartz for a neutrino experiment caused Lee and Yang to analyze the situation in precise detail. Their work, published in 1960, became the guiding light for both the Columbia and CERN neutrino physicists. Together with Markstein from IBM Lee and Yang did one of the first large scale computer calculations concerning the possible detection of the vector bosons in a neutrino experiment. None were actually seen, they were too heavy.

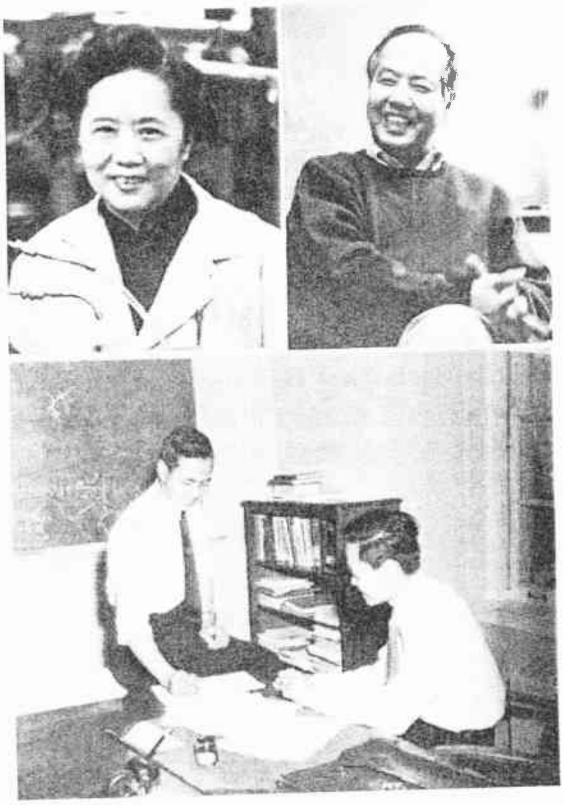


**Fig. 14.1** Upper left: Chien-Shiung Wu (1912–1997) led the experiment that discovered parity violation. Upper right: Tsung-Dao Lee (1926– ), who, together with Chen-Ning Yang, suggested the experiment, and explained it in terms of the two-component neutrino. Bottom: Lee and Yang in 1957 at the Institute for Advanced Study, Princeton, possibly discussing parity violation.

The Fall of Parity

James W. Cronin
(1931–)

Val L. Fitch
(1925–)

分類：
編號：
總號：

# Quark Model of Gell-Mann and Zweig.

## Hadrons
- there are a large number of them.
- they have size (not point-like)

Hadrons are composite

Fermi - Yang (1949)
suggested that
pions are made of
$N\bar{N}$
$N \rightarrow$ nucleons

Sakata model (1956)
All hadrons are made of $(p, n, \Lambda)$ and their anti-particles $(\bar{p}, \bar{n}, \bar{\Lambda})$
→ generalized Fermi-Yang model to include strangness

The model was successful in treating mesons, but run into difficulty in describing baryons

## Quark Model
Assume hadrons are made of quarks and their antiparticles
Mesons are made of a quark and antiqurk $(q\bar{q})$
Baryons are made of three quarks

Quarks and their quantum numbers

| | B | S | I | $I_3$ | Q |
|---|---|---|---|---|---|
| u | $\frac{1}{3}$ | 0 | $\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{2}{3}$ |
| d | $\frac{1}{3}$ | 0 | $\frac{1}{2}$ | $-\frac{1}{2}$ | $-\frac{1}{3}$ |
| s | $\frac{1}{3}$ | -1 | 0 | 0 | $-\frac{1}{3}$ |

- All quarks have spin $\frac{1}{2}$
- Baryons are made of $QQQ \Rightarrow B = \frac{1}{3}$ for all quarks
  ↓ $B=1$
- Q (electric charge) is determine through Gell-Mann Nishijima relation.

**Enrico Fermi** (1901–1954). In 1934 he published the first theory of weak interactions. He made an analogy between a proton emitting a photon (proton $\rightarrow$ proton + photon) and a neutron emitting an electron-neutrino pair (neutron $\rightarrow$ proton + electron + neutrino). Thus he treated the electron-neutrino pair analogously to a photon. This is in fact quite in line with modern ideas according to which neutron decay essentially goes in two steps: neutron $\rightarrow$ proton + $W^-$ $\rightarrow$ proton + electron + neutrino. In addition to that Fermi was one of the most successful experimental physicists of his era. He directed the construction of the first nuclear reactor and essentially started a whole new chapter of physics by studying pion-proton and pion-neutron collisions.

Fermi was of tremendous importance to US physics as an educator. In 1938 he was told by Bohr that he would get the Nobel prize; since his wife, Laura, was Jewish, they decided not to return from Stockholm to Italy but instead switch to New York, where Fermi became a professor at Columbia University. He later moved to Chicago. Among his students there were Chamberlain, T. D. Lee and Steinberger, to name a few. Thus also through his students did Fermi have a tremendous influence on physics in the US.

Chen-Ning-Yang (1922–)

**Fig. 9.1** From Maxwell to non-Abelian gauge theory.

### The Quark Model

What to do? One is confident in calling certain particles elementary only as long as there are not too many of them. The very existence of 100 chemical elements suggests that atoms have an underlying structure. The search for a pattern in the particles we have described was spearheaded by Gell-Mann. The end result was a picture in which all the hadrons—the strongly interacting states, all the states we have described thus far except the photon, the electron, and the close partners of the electron—are constructed from a set of basic building blocks: the **quarks** and their antiparticles.[4]

[3] A term such as this responds in a whimsical fashion to a necessity. Later in the book we'll meet others: color, flavor, charm, and so forth. Such terms refer, for the most part, to something that is either exactly or approximately conserved. You might say that we need a word to express a conservation law for something we had not earlier seen to be conserved; any word for the conserved quantity will serve the purpose.

[4] The word "quark" was taken by Gell-Mann from a phrase in James Joyce's novel *Finnegans Wake*.

• **Figure 16–16** Murray Gell-Mann made enormous contributions to the development of elementary particle physics. For more than two decades he blazed trails in almost every area of that field.

# Mesons

Low lying mesons $\leftrightarrow$ Ground states of $q\bar{q}$

$\Rightarrow$ the relative orbital angular momentum is $\ell = 0$

Since the spin of $q\ (\bar{q})$ is $\frac{1}{2}$ $\Rightarrow$ the low-lying mesons have spin 0 or 1, with the following quantum numbers.

| | $B$ | $S$ | $I_3$ | $Q$ |
|---|---|---|---|---|
| $u\bar{u}$ | 0 | 0 | 0 | 0 |
| $u\bar{d}$ | 0 | 0 | 1 | 1 |
| $u\bar{s}$ | 0 | 1 | $\frac{1}{2}$ | 1 |
| $d\bar{u}$ | 0 | 0 | $-1$ | $-1$ |
| $d\bar{d}$ | 0 | 0 | 0 | 0 |
| $d\bar{s}$ | 0 | 1 | $-\frac{1}{2}$ | 0 |
| $s\bar{u}$ | 0 | $-1$ | $-\frac{1}{2}$ | $-1$ |
| $s\bar{d}$ | 0 | $-1$ | $-\frac{1}{2}$ | 0 |
| $s\bar{s}$ | 0 | 0 | 0 | 0 |

Agrees with the 9 $J = 0$ low lying mesons
$\pi^+, \pi^-, \pi^{0▲}, K^+, K^-\ K^0\ \bar{K}^0, \eta^▲, \eta'^▲$
(▲s ha the same quantum numbers as $u\bar{u}, d\bar{d}, s\bar{s}$)
and the 9 $J = 1$ low lying mesons
$\rho^+, \rho^-, \rho^{0▲}, K^{*+}, K^{*-}, K^{*0}, \bar{K}^{*0}, \omega^▲, \phi^▲$

$\Rightarrow$ Quark model successfully describes the low lying meson state.

For higher mass mesons, they are described as excited $q\bar{q}$ state (the relative orbital angular momentum between $q\bar{q}$ need not be zero)

The agreement between quark model and experimental result is again satisfactory.

# Baryons

Low lying baryons $\leftrightarrow$ Ground state of $qqq$
$\Rightarrow$ the relative orbital angular momentum among the quarks should be zero

Quantum numbers made of qqq are as follows

| | Q = −1 | Q = 0 | Q = +1 | Q = +2 |
|---|---|---|---|---|
| −3 | sss | | | |
| −2 | ssd | ssu | | |
| −1 | sdd | sdu | suu | |
| 0 | ddd | ddu | duu | uuu |

Now we shall discuss the spin arrangement

- All three quarks are the same
  Example sss

| s s s | $J_3$ | Number of States |
|---|---|---|
| ↑ ↑ ↑ | $\frac{3}{2}$ | 1 |
| ↑ ↑ ↓ | $\frac{1}{2}$ | 1 |
| ↑ ↓ ↓ | $-\frac{1}{2}$ | 1 |
| ↓ ↓ ↓ | $-\frac{3}{2}$ | 1 |

There are 4 states, just what a $J=\frac{3}{2}$ particle needs.
⇒ At sss, uuu, ddd ⇒ there is a $J=\frac{3}{2}$ particles

- Two of the quarks are the same, the other quark is different
  Example ssd

| ssd | $J_3$ | Number of states | |
|---|---|---|---|
| ↑↑↑ | 3/2 | 1 | |
| ↑↑↓ | 1/2 | 2 | the quark with spin down could be d or s ⇒ two states |
| ↑↓↓ | −1/2 | 2 | the quark with spin up could be d or s ⇒ two states |
| ↓↓↓ | −3/2 | 1 | |

- All three quarks are different
  Only usd one possibility

| usd | $J_3$ | Number of states | |
|---|---|---|---|
| ↑↑↑ | 3/2 | 1 | |
| ↑↑↓ | 1/2 | 3 | The spin down quark may be u, d or s ⇒ three states |
| ↑↓↓ | −1/2 | 3 | The spin up quark may be u, d, s ⇒ three states |
| ↓↓↓ | −3/2 | 1 | |

| 分類： |
| --- |
| 編號： |
| 總號： |

There are all together 8 states

Among them, 4 are needed for $J=\frac{3}{2}$ particle.
The other two sets of $J_3=\frac{1}{2}$, $J_3=-\frac{1}{2}$ states should correspond to 2 $J=\frac{1}{2}$ particle

Quark model would predict the following structure for the low-lying baryon states

$J=\frac{3}{2}$

| S ↓ \ Q → | −1 | +0 | +1 | +2 |
| --- | --- | --- | --- | --- |
| −3 | sss | | | |
| −2 | ssd | ssu | | |
| −1 | sdd | sdu | suu | |
| 0 | | | | uuu |

$J=\frac{1}{2}$

| S ↓ \ Q → | −1 | 0 | +1 |
| --- | --- | --- | --- |
| −3 | | | |
| −2 | ssd | ssu | |
| −1 | sdd | (sdu)* | suu |
| 0 | | ddu | duu |

* doubly occupied

Experimentally

$J=\frac{3}{2}$

| S \ Q | −1 | 0 | +1 | 2 |
| --- | --- | --- | --- | --- |
| −3 | "$\Omega^-$" | | | |
| −2 | $\Xi^{*-}$ | $\Xi^{*0}$ | | |
| −1 | $Y^-$ | $Y^0$ | $Y^+$ | |
| 0 | $\Delta^-$ | $\Delta^0$ | $\Delta^+$ | $\Delta^{++}$ |

$J_3=\frac{1}{2}$

| S \ Q | −1 | 0 | +1 |
| --- | --- | --- | --- |
| −2 | $\Xi^-$ | $\Xi^0$ | |
| −1 | $\Sigma^-$ | $\Sigma^0, \Lambda$ | $\Sigma^+$ |
| 0 | | n | p |

When the quark model was proposed, $\Omega^-$ had not be found
⇒ quark model predicted its existence

The discovery of "$\Omega$" provided strong support for the quark model.

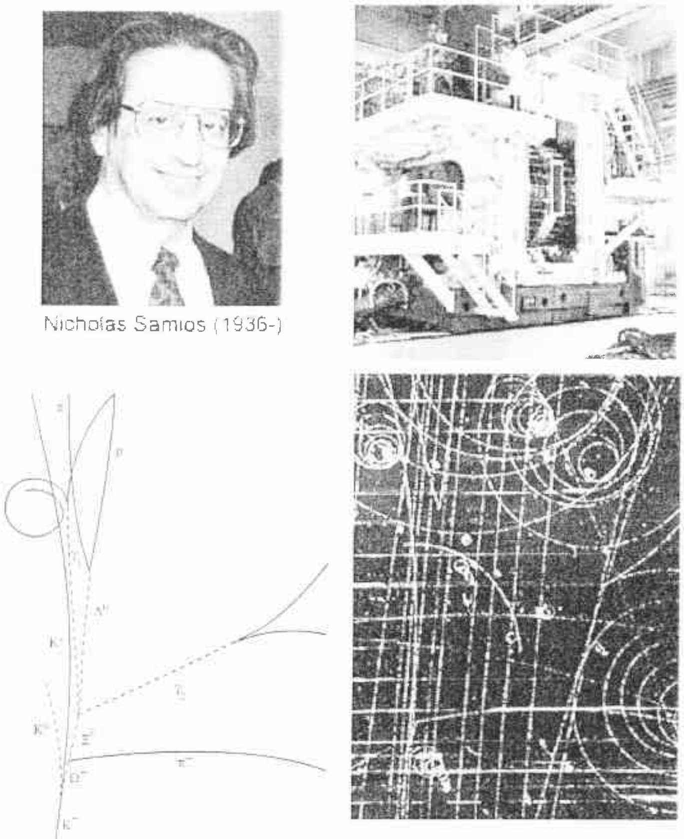
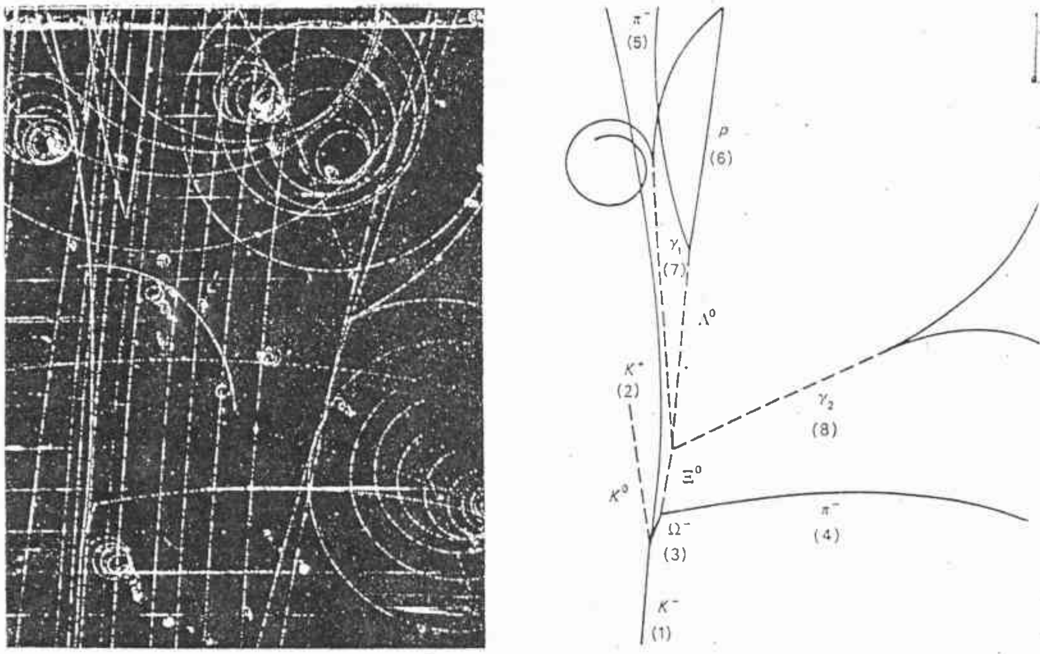



**Fig. 16.4** The last piece fell into place: in 1964, the Omega minus was discovered at the AGS (Alternating Gradient Synchrotron) at Brookhaven National Laboratory. Clockwise from left: team leader Nicholas Samios; the 60″ bubble chamber used for detection; photograph of track in the reaction recorded; diagram of tracks, in which the Omega minus is seen at lower left, just above the incident K minus.




The first Ω⁻ event (Barnes *et al.*, 1964). (Courtesy, Brookhaven National Laboratory.)

$$K^- + p \to \Omega^- + K^+ + K^0$$

$\Omega^- \to \Xi^0 + \pi^-$ ($\Delta S = 1$ weak decay)

$\Xi^0 \to \pi^0 + \Lambda$ ($\Delta S = 1$ weak decay)

$\Lambda \to \pi^- + p$ ($\Delta S = 1$ weak decay)

$\pi^0 \to \gamma + \gamma$ (E.m. decay)

$\gamma \to e^+e^-$, $\gamma \to e^+e^-$.

Baryons are constructed of three quarks, because that is the only way to make a state with $B = 1$. A look at the way three quarks can be combined to make the proper electric charges would suggest that

$$p = uud \qquad \text{and} \qquad n = udd. \tag{16–11}$$

As far as angular momentum is concerned, the three quarks are arranged in combinations with no orbital angular momentum and with one quark's spin aligned in the direction opposite to the spins of the two others. In this way the nucleons would have spin 1/2. From that point of view, the Δ-states are easy to understand: They are the same sort of combination of up and down quarks as the nucleons, but with the spins aligned, so that the Δ is a spin-3/2 particle. For example,

$$\Delta^{++} = uuu. \tag{16–12}$$

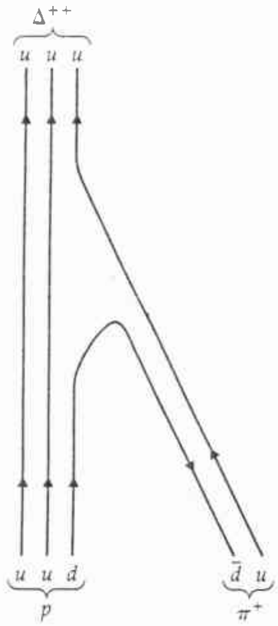
• Figure 16–17 shows how production of the $\Delta^{++}$ state appears in the quark model.

Strange baryons such as the $\Lambda^0$ would involve a single strange quark:

$$\Lambda^0 = usd. \tag{16–13}$$

The $\Lambda^0$ is also a spin-1/2 particle, so the same remarks about angular momentum that we made for the nucleons apply to it.

The quark model of the observed particles has turned out to be very useful both for classification and for making predictions. Entire series of mesons and baryons are explained by including orbital angular momentum in the wave functions. Or we can predict that any state with $B = 0$ can be made only with equal numbers of quarks and antiquarks, so that such states must have integer spin. Or we can understand the differences in mass among various particles in terms of the differences in mass among the quarks that constitute them.




Quark model depiction of the production of $\Delta^{++}$ in a $\pi^+$–$p$ collision. The annihilation of the $d$ and the $\bar{d}$ is accompanied by the production of virtual gluons, not shown here.

# The "Color" Quantum Number

In addition to the "flavor" quantum numbers discovered in above section, the quark also possess "color" qua number

Origin
$J_z = \frac{3}{2}$ $\Delta^{++} \rightarrow u\uparrow u\uparrow u\uparrow$
(the orbital angular momentum among quarks $= 0$)

u quark has spin $\frac{1}{2}$ $\Rightarrow$ should obey the Fermi-Dirac statistics

The above assignment violate the Fermi-Dirac statistics.

The resolution $\Rightarrow$ each quark possesses a new quantum number "color" (If the three u quark in $\Delta^{++}$ carrying different quark number then it will not violate Exclusion Principle)
But usually when new quantum number is introduced, the number of hadrons will also increase in disagreement with experiments.

After further study, one found that if each quark could possess three possible "color", (for convenience, we choose them to be red, blue and green) and all baryons and mesons are color singlet, then the above two problems can be readily solved simultaneously.

The color wave function for baryons has the following form

$$\frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr)$$

The color wave function for mesons has the form

$$\frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$$

The type of quarks increase by threefold, yet the number of hadrons remain unchanged.

Experimental support
The decay rate of $\pi^0 \rightarrow 2\gamma$ and $R = \frac{\sigma(e^+e^- \rightarrow all)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ will disagree with experimental result if "color" is not included and in excellent agreement if "color" is included.

# Heavy Quarks

Discovery of $J/\psi$ (1974) Ting and Richter
↓
charmed quark c

Discovery of $\Upsilon$ (1977) Ledermann
↓
bottom quark b

Discovery of top quark t (1995)
F-NAL CDF and D0 groups

$m_t \sim 175\ GeV/c^2$


**Burton Richter** (1931) and **Samuel Ting** (1936) are credited with the discovery of the charm quark in 1974. Actually, they did not discover that quark, but a bound state of a charm quark and an anticharm quark; the interpretation in terms of a new quark took a few years. Richter and Ting shared the Nobel prize in 1976.

Richter (and his group) did the experiment at SLAC (Stanford Linear Accelerator Center near San Francisco) using electron-positron collisions. Ting (and his group) studied proton collisions at BNL (Brookhaven National Laboratory, Long Island). The discovered quark bound state was called $\psi$ by Richter and $J$ by Ting; today it is known as the $J/\psi$.

The discovery of the $J/\psi$ was precisely what theory was waiting for. The charm quark was theoretically predicted, but no one had expected a charm-anticharm particle with the properties as measured. It was unstable, but it lived too long. It took some time before it was understood that this was indeed a charm-anticharm bound state, and what precisely the mechanism was. The SLAC people in their unmatched PR skill spoke of the discovery as the "November revolution that turned the wheel". Well, the wheel had already turned a few years before.

CERN failed to discover the $J/\psi$ at the intersecting storage rings where it was produced copiously, and you can understand the tumultuous discussions at CERN after the $J/\psi$ had been discovered. I tried to find out who or what was to blame, but everybody pointed to everybody. Most of the wisdom was after the fact. There was also misery at Frascati as described in Chapter 7.

**Martin Perl** (1927) (left, Nobel prize 1995) is credited with the discovery of the tau particle, in 1975. It is very much like the muon and the electron but much heavier. For example the muon decays part of the time into an electron and a pair of neutrinos, and the tau similarly goes into a muon and a pair of neutrinos. The coupling constants involved are equal within the experimental precision.

The discovery of the tau meant to me personally that there had to be a third family. In this I was way behind: Kobayashi and Maskawa had already argued in 1973 that there should be a third family. Their arguments were based on considerations of quark mixing (discussed in Chapter 3), and at the time they were really hard to swallow although strictly logical.

The Italian physicist **Antonino Zichichi** (1929) was in a sense a forerunner to Perl. He had already been searching for new types of leptons, using antiprotons colliding with protons as well as electron-positron collisions at Frascati. Perl, at Stanford, profited from the higher energy of the positron-electron machine at SLAC.

# Standard Model of Fundamental Particles and Interactions

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

| Leptons spin = 1/2 | | |
|---|---|---|
| Flavor | Mass GeV/$c^2$ | Electric charge |
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| $e$ electron | 0.000511 | −1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | −1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | −1 |

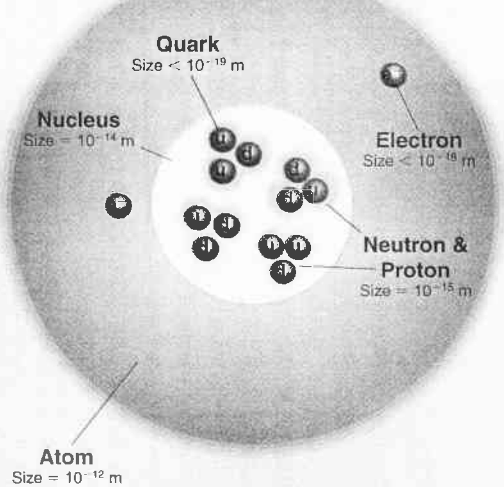
| Quarks spin = 1/2 | | |
|---|---|---|
| Flavor | Mass GeV/$c^2$ | Electric charge |
| u up | 0.003 | 2/3 |
| d down | 0.006 | −1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | −1/3 |
| t tau neutrino | 175 | 2/3 |
| b tau | 4.3 | −1/3 |

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-25}$ GeV s $= 1.05 \times 10^{-34}$ J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60 \times 10^{-19}$ coulombs.

The **energy** unit of particle physics is the electron volt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/$c^2$ (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60 \times 10^{-10}$ joule. The mass of the proton is 0.938 GeV/$c^2$ $= 1.67 \times 10^{-27}$ kg.

## Structure within the Atom




If the protons and neutrons in this picture were each 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across!

## BOSONS

force carriers
spin = 0, 1, 2, ...

| Unified Electroweak spin = 1 | | |
|---|---|---|
| Name | Mass GeV/$c^2$ | Electric charge |
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | −1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

| Strong (color) spin = 1 | | |
|---|---|---|
| Name | Mass GeV/$c^2$ | Electric charge |
| g gluon | 0 | 0 |

**Color Charge** Each quark carries one of the three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interaction and hence no color charge.

**Residual Strong Interaction** The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction which binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

**Quarks Confined in Mesons and Baryons** One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color force between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons $q\bar{q}$ and baryons $qqq$.

# Properties of the Interactions

## Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| p | proton | uud | 1 | 0.938 | 1/2 |
| $\bar{p}$ | Anti-proton | $\bar{u}\bar{u}\bar{d}$ | −1 | 0.938 | 1/2 |
| n | neutron | udd | 0 | 0.940 | 1/2 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | −1 | 1.672 | 3/2 |

**Baryons** are a type of hadron composed of three quarks (or three antiquarks).

## Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

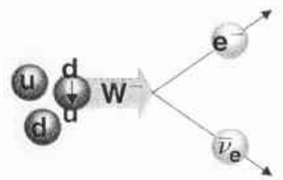
| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | −1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2.980 | 0 |

**Matter and Antimatter** For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or 0 charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., $Z^0$, gamma, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

This chart has been made possible by the generous support of:
US Department of Energy
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator
American Physical Society, Division of Particles and Fields
Burle Industries, Inc.

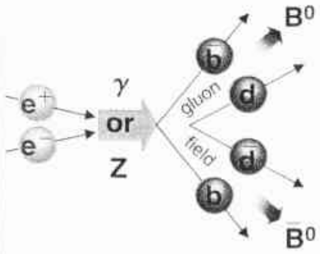
| Property \ Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual |
|---|---|---|---|---|---|
| Acts on: | Mass - Energy | Flavor | Electric charge | Color Charge | See Residual Strong interaction note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Gravitation (not yet observed) | $W^+ W^- Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at: $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| Strength relative to electromag for two u quarks at: $3 \times 10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | |
| for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

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



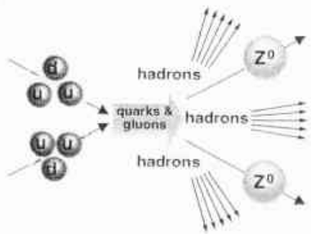

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron $\beta$ decay.

### $e^+e^- \rightarrow B^0 \bar{B}^0$




An electron and positron (antielectron) colliding at high energy can annihilate to produce $B^0$ and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

### $p p \rightarrow Z^0 Z^0$ + assorted hadrons




Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yeild vital clues to the structure of matter.

• **Figure 16–27** A summary chart for many of the phenomena and properties discussed in this chapter. (Copyright 1999 by the Contemporary Physics Education Project, Lawrence Berkeley National Laboratory, Berkeley, CA. Reprinted by permission.)

分類：
編號：
總號：

*Davis in his chemistry lab at Brookhaven, with a component of a neutrino detection system. (Image courtesy Brookhaven National Laboratory.)*

Masatoshi Koshiba
(1926–)

**Fig. 14.4** Disturbing the order: CP violation (Cronin and Fitch, 1964); neutrino mass (Koshiba, 1998).