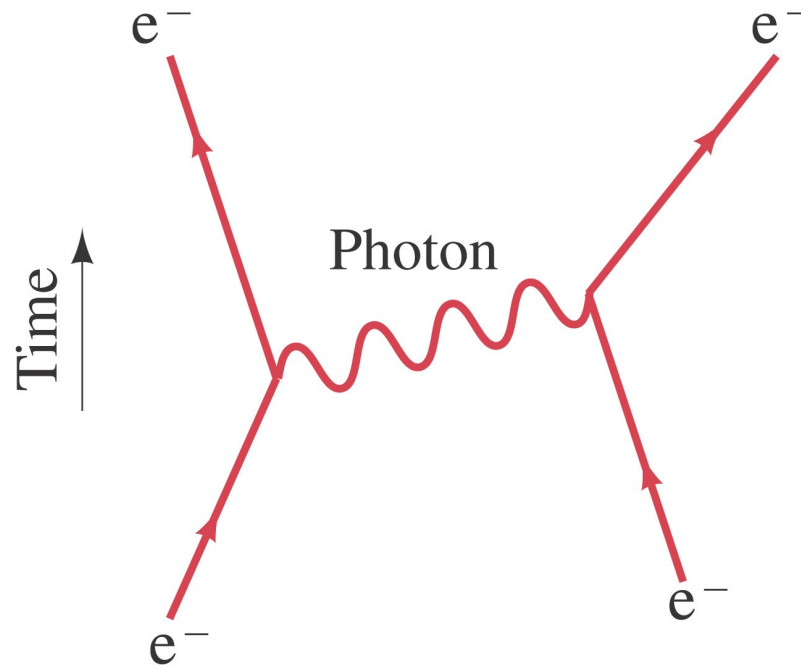


Chapter 32

Elementary Particles

A quick trip through the Particle Zoo



Basic Topics

- High-Energy Particles and Accelerators
- Forces, Interactions, and Particle Exchange
- Particles and Antiparticles
- Particle Interactions and Conservation Laws
- Particle Classification
- Particle Stability and Resonances
- Quarks
- QCD, GUTs, Strings, SUSY, and such

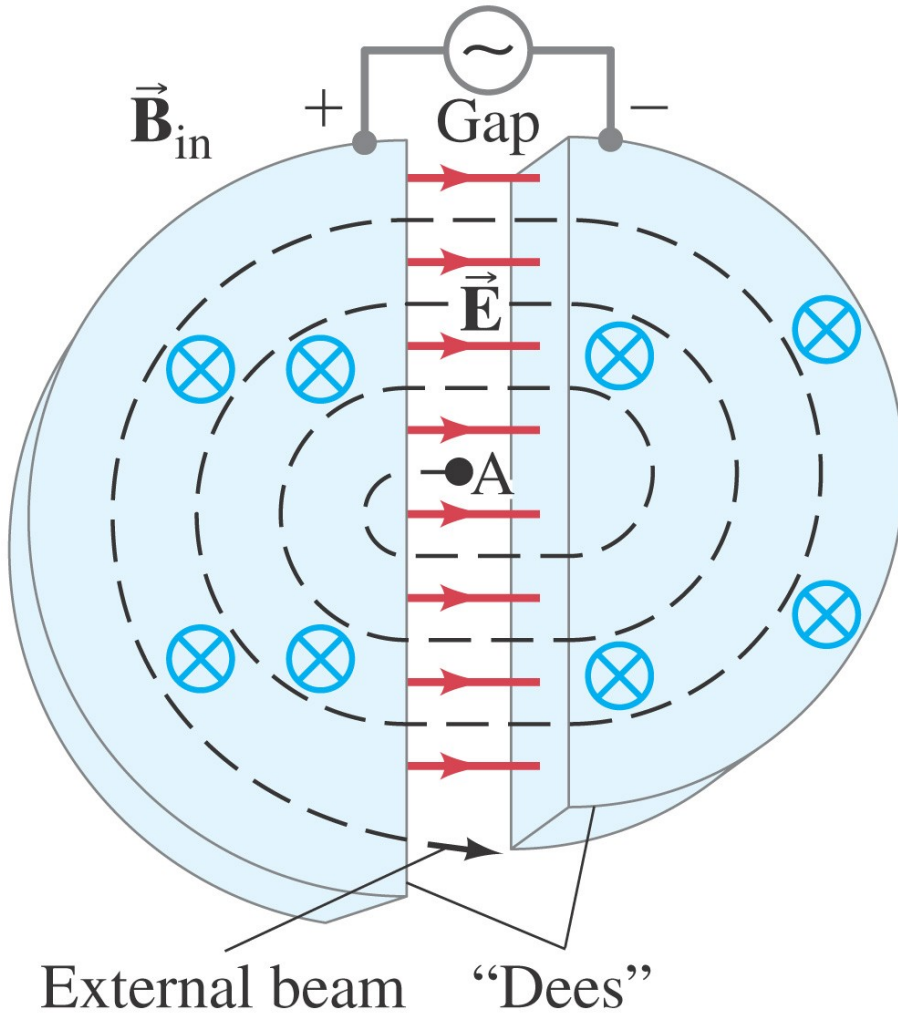
High Energy Particles and Accelerators

If an incoming particle in a nuclear reaction has sufficient energy, new particles are produced.

Also, as the energy and momentum of a particle increases, its wavelength decreases - recall $\lambda = \frac{h}{p}$, allowing it to probe details of smaller structures and to penetrate deeper into the nucleus.

At very high energies incoming particles can probe the internal structure of a proton or neutron, etc.

Early Accelerator Design: Cyclotrons



Charged particles are kept in circular paths by magnets: an electric field accelerates them. The voltage alternates to accelerate the particles each time they cross the gap.

The ac voltage is set at the “cyclotron frequency” related to the period of the orbit.

$$f = \frac{1}{T} = \frac{qB}{2\pi m}$$

Forces and Particle Exchange

The electromagnetic force acts over a distance – direct contact is not necessary. How does that work?

Because of wave-particle duality, we can think of the electromagnetic force between charged particles in two different ways. The force is mediated by either

3. an electromagnetic field, or

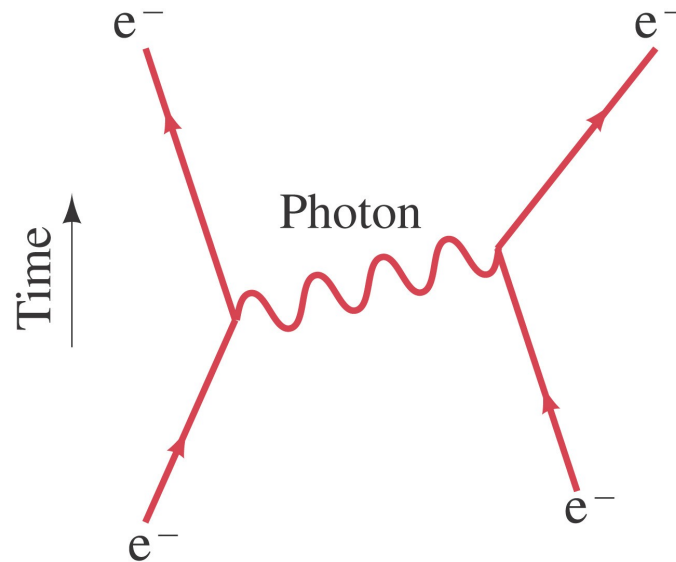
4. an exchange of (virtual) photons

depending on which ‘picture’ one wishes to use.

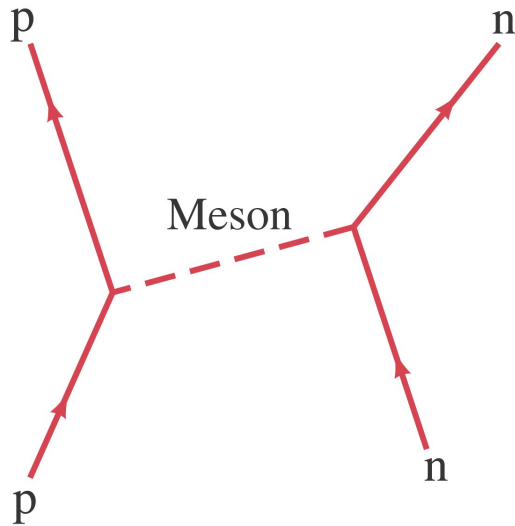
Feynman Diagrams - Particle Exchange

Physicists often visualize interactions by using Feynman diagrams, which are a kind of $x-t$ graph.

Here is a Feynman diagram for photon exchange (electromagnetic interaction) between electrons:

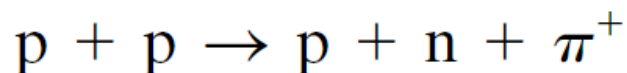
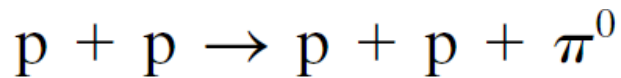


The Strong Force – Particle Exchange



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The particle related to the strong force was initially thought to be the pion (π), produced in the collision. The strong force mediator is now called a 'gluon'.



Mass of the exchanged particle can be obtained by assuming the range, d , is limited by the uncertainty principle:

$$mc^2 \approx \frac{hc}{2\pi d}$$

For $d = 1.5 \times 10^{-15}$ m, this gives 130 MeV.

Other Forces as Particle Exchange

The weak nuclear force is also carried by particles; these are called the W^+ , W^- , and Z^0 'gauge bosons'. These particles have been directly observed in various particle interactions.

A carrier for the gravitational force, called a graviton, has been proposed, but no theory yet exists that will properly accommodate it. Efforts continue to try to integrate gravity into the overall theoretical structure; 'Grand Unification Theory' includes the other three.

The Four Forces as Particle Exchange

This table lists the four known forces, their relative strength for two protons in a nucleus, and their field particle, or their force mediator.

TABLE 32–1 The Four Forces in Nature

Type	Relative Strength (approx., for 2 protons in nucleus)	Field Particle
Strong nuclear	1	Gluons [†] (mesons)
Electromagnetic	10^{-2}	Photon
Weak nuclear	10^{-6}	W^{\pm} and Z^0
Gravitational	10^{-38}	Graviton (?)

[†] Until the 1970s, thought to be mesons, but now gluons (see Section 32–10).

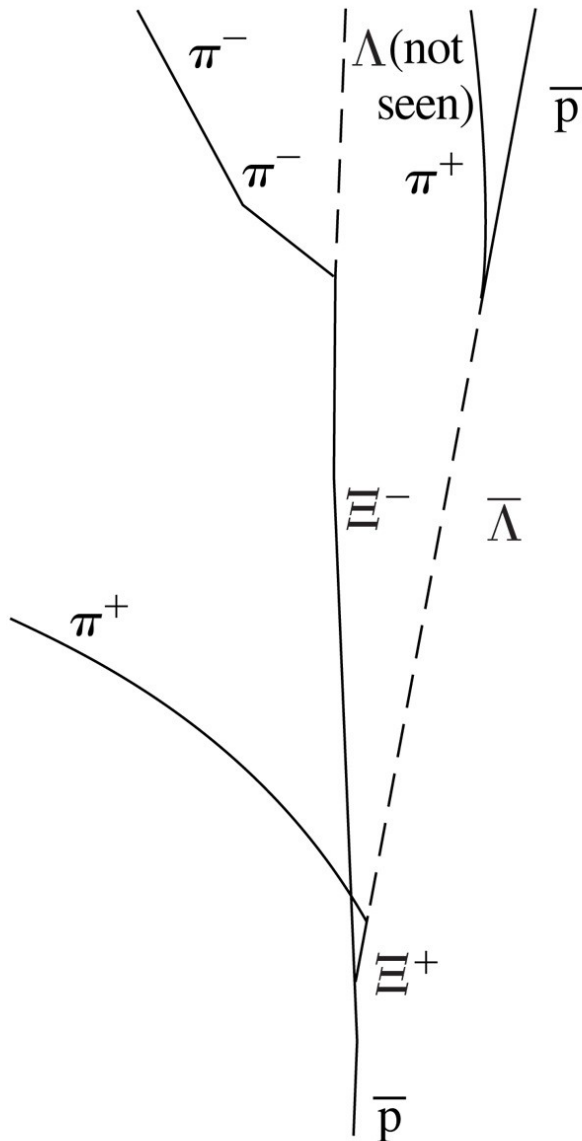
Particles and Antiparticles

The positron is the same as the electron, except for having opposite charge (and lepton number). We call the positron the antiparticle of the electron.

Every particle has an antiparticle, with the same mass but most quantum numbers being opposite.

A few particles, such as the photon and the π^0 , are their own antiparticles, as all the relevant quantum numbers are zero for them.

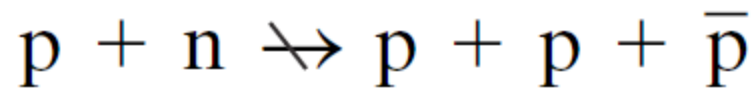
Particles and Antiparticles



This is a drawing of an interaction between an incoming antiproton and a proton (not seen) that results in the creation of several different particles and antiparticles. Most of these particles can be identified by their decay products.

Particle Interactions and Conservation Laws

In the study of particle interactions, it is found that certain interactions do not occur, even though they conserve energy and charge, such as:



New conservation laws are proposed to account for these facts, in this case the conservation of 'baryon number'. Baryon number generalizes nucleon number to include more exotic particles.

Particle Interactions and Conservation Laws

Particles such as the proton and neutron have baryon number $B = +1$; antiprotons, antineutrons, and the like have $B = -1$; all other types of particles (electrons, photons, etc.) have $B = 0$.

There are three types of **leptons** – the **electron**, the **muon** (about 200 times more massive), and the **tau** (about 3000 electron masses).

Each type of lepton is conserved separately.

Particle Interactions and Conservation Laws

The details of these laws explain various decays:

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

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

Decays that have an unequal mix of e-type and μ -type leptons are not allowed.

Neutrinos are the subject of active research.

Evidence shows that a neutrino of one type can change into a neutrino of another type; this is called 'flavor oscillation' and requires at least one type of neutrino to have mass.

Particle Classification

There are a large number of known particles. They are categorized into several groups

- **Gauge bosons** are the particles that mediate the forces
- **Leptons** interact weakly and (if charged) electromagnetically, but not strongly
- **Hadrons** interact strongly; there are two types of hadrons, baryons ($B = 1$) and mesons ($B = 0$).

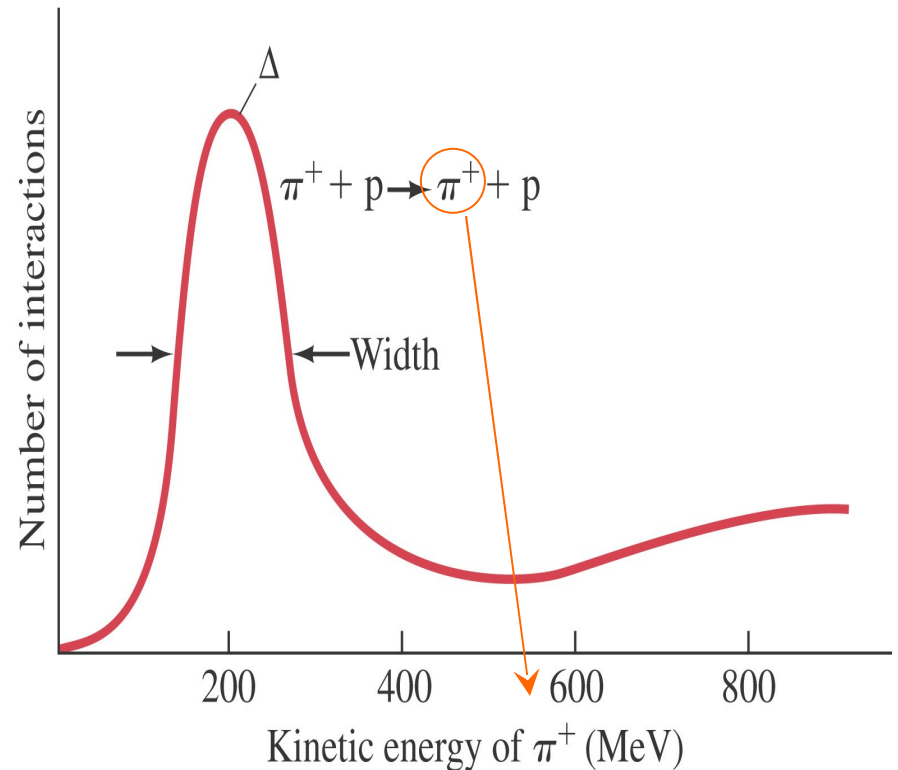
Particle Stability and Resonances

Most particles are unstable.

If they decay weakly, their lifetimes are around 10^{-13} s; if electromagnetically, $\sim 10^{-16}$ s; and if strongly, $\sim 10^{-23}$ s.

Strongly decaying particles are often not directly seen; their existence is inferred from decay products.

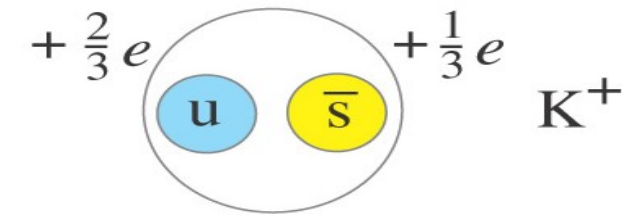
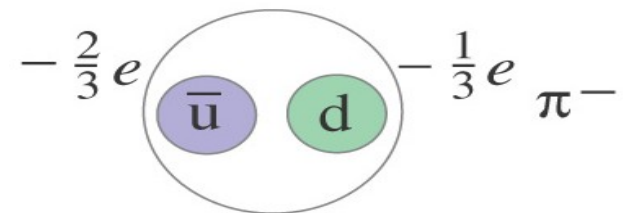
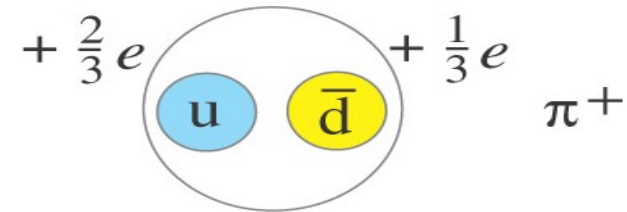
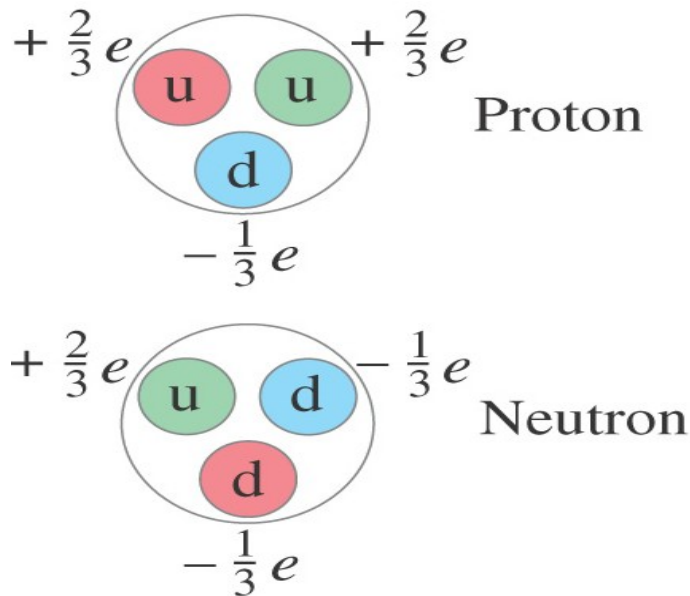
These particles are often called resonances. Their lifetime is obtained from the uncertainty principle and the variation in mass.



Quarks: the basic building blocks (?)

There are six different “flavors” of quarks; each has baryon number $B = \frac{1}{3}$; and also fractional charge.

Hadrons are made of three quarks; mesons are a quark - antiquark pair.



Quarks

This table gives properties of the six known quarks.

TABLE 32–3 Properties of Quarks (Antiquarks have opposite sign Q, B, S, c, t, b)

Quarks							
Name	Symbol	Charge Q	Baryon Number B	Strangeness S	Charm c	Bottomness b	Topness t
Up	u	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	0
Down	d	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	0	0
Strange	s	$-\frac{1}{3}e$	$\frac{1}{3}$	-1	0	0	0
Charmed	c	$+\frac{2}{3}e$	$\frac{1}{3}$	0	+1	0	0
Bottom	b	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	-1	0
Top	t	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	+1

Quarks

This is a list of some of the hadrons that have been discovered that contain c , t , or b quarks.

TABLE 32–4 Partial List of Heavy Hadrons, with Charm and Bottomness ($L_e = L_\mu = L_\tau = 0$)

Category	Particle	Anti-particle	Spin	Rest Mass (MeV/ c^2)	Baryon Number B	Strangeness S	Charm c	Bottomness b	Lifetime (s)	Principal Decay Modes
Mesons	D^+	D^-	0	1869.4	0	0	+1	0	10.6×10^{-13}	K + others, e + others
	D^0	\bar{D}^0	0	1864.6	0	0	+1	0	4.2×10^{-13}	K + others, μ or e + others
	D_S^+	D_S^-	0	1969	0	+1	+1	0	4.7×10^{-13}	K + others
	J/ψ (3097)	Self	1	3096.9	0	0	0	0	0.8×10^{-20}	Hadrons, e^+e^- , $\mu^+\mu^-$
	Υ (9460)	Self	1	9460.4	0	0	0	0	1.3×10^{-20}	Hadrons, $\mu^+\mu^-$, e^+e^- , $\tau^+\tau^-$
	B^-	B^+	0	5279	0	0	0	-1	1.5×10^{-12}	D^0 + others
	B^0	\bar{B}^0	0	5279	0	0	0	-1	1.5×10^{-12}	D^0 + others
Baryons	Λ_c^+	Λ_c^-	$\frac{1}{2}$	2285	+1	0	+1	0	2.0×10^{-13}	Hadrons (e.g., Λ + others)
	Σ_c^{++}	Σ_c^{--}	$\frac{1}{2}$	2453	+1	0	+1	0	?	$\Lambda_c^+ \pi^+$
	Σ_c^+	Σ_c^-	$\frac{1}{2}$	2454	+1	0	+1	0	?	$\Lambda_c^+ \pi^0$
	Σ_c^0	$\bar{\Sigma}_c^0$	$\frac{1}{2}$	2452	+1	0	+1	0	?	$\Lambda_c^+ \pi^-$
	Λ_b^0	$\bar{\Lambda}_b^0$	$\frac{1}{2}$	5640	+1	0	0	-1	1.1×10^{-12}	$J/\psi \Lambda^0$, $pD^0 \pi^-$, $\Lambda_c^+ \pi^+ \pi^- \pi^-$

The Elementary Particles

The particles that are now considered to be truly elementary – having no internal structure – are the quarks, the gauge bosons, and the leptons.

The quarks and leptons are arranged in three ‘generations’; or ‘families’, each has the same pattern of electric charge, but the masses increase from generation to generation.

TABLE 32–5 The Elementary Particles[†] as Seen Today

Gauge bosons	Force		First generation	Second generation	Third generation
Gluons	Strong	Quarks	u, d	s, c	b, t
W^{\pm}, Z_0	Weak	Leptons	e, ν_e	μ, ν_{μ}	τ, ν_{τ}
γ (photon)	EM				

[†] Note that the quarks and leptons are arranged into three generations each.

Summary of Chapter 32

- Particle accelerators accelerate particles to very high energy, to probe the detailed structure of matter and to produce new massive particles
- Every particle has an antiparticle, with the same mass and opposite charge (and the opposite for various other quantum numbers)
- Other quantum numbers: baryon number; lepton number; strangeness; charm; topness; bottomness
- Strong force is mediated by gluons
- Fundamental force carriers are gauge bosons

Summary of Chapter 32

- Leptons interact weakly and electromagnetically
- Hadrons are made of quarks, and interact strongly
- Most particles decay quickly, either weakly, electromagnetically, or strongly
- There are six quarks and six leptons
- Quantum ChromoDynamics is the theory of the strong interaction
- Electroweak Theory unites the electromagnetic and weak forces
- Grand Unified Theories unite all three forces