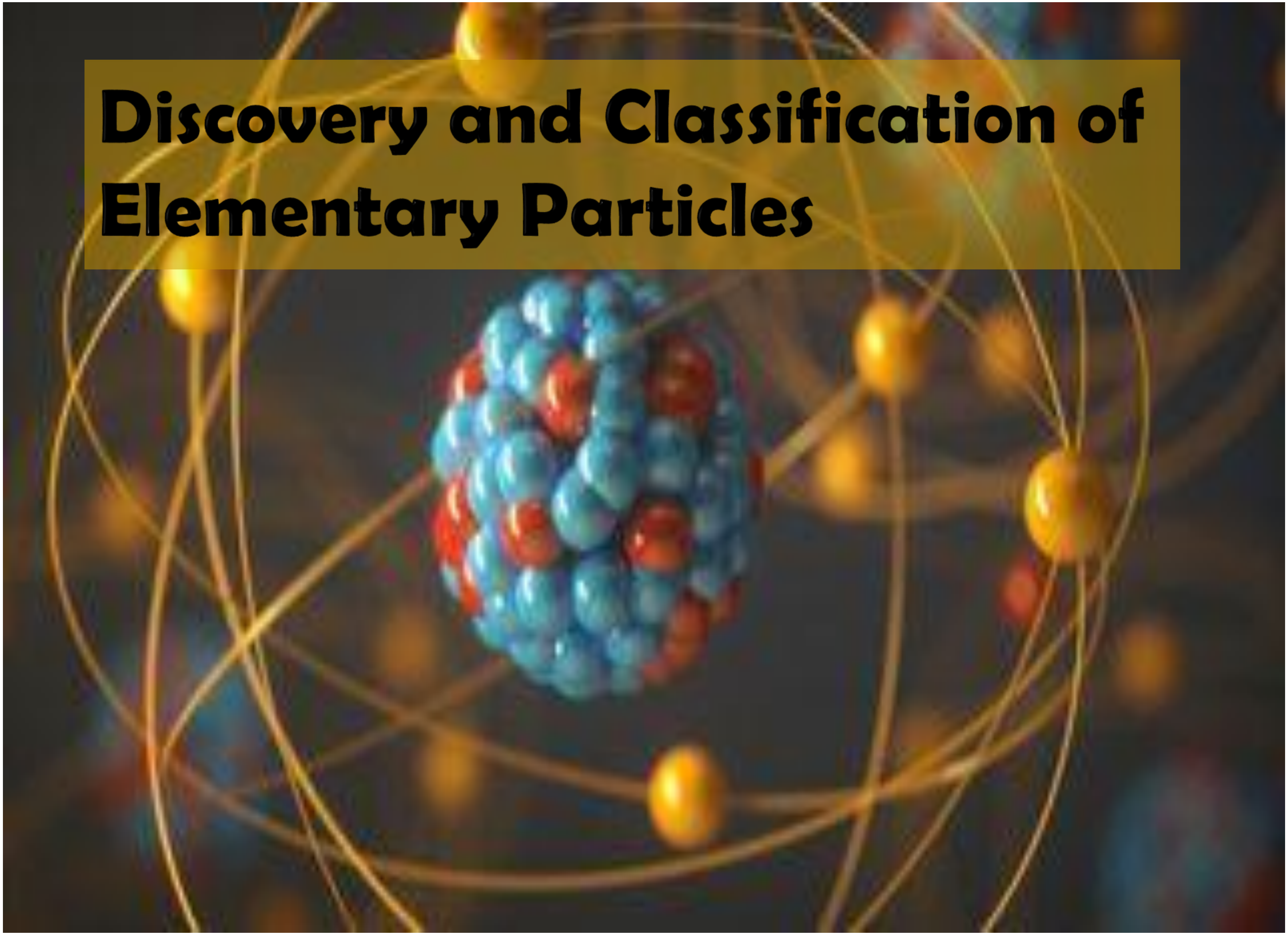
Discovery and Classification of Elementary Particles



Elementary Particles

- We began our study of subatomic physics by finding answers to some of the basic questions about nature is a foremost goal of science:

  - **What are the basic building blocks of matter?**
  - **What is inside the nucleus?**
  - **What are the forces that hold matter together?**
  - **How did the universe begin?**
  - **Will the universe end, and if so, how and when?**

The Building Blocks of Matter

- We have thought of electrons, neutrons, and protons as elementary particles, because we believe they are basic building blocks of matter.

- However, in this chapter the term **elementary particle** is used loosely to refer to hundreds of particles, most of which are unstable.

Early Discoveries

- **In 1930 the known elementary particles were the proton, the electron, and the photon.**
- Thomson identified the electron in 1897, and Einstein's work on the photoelectric effect can be said to have defined the photon (originally called a *quantum*) in 1905. The proton is the nucleus of the hydrogen atom.
- Despite the rapid progress of physics in the first couple of decades of the twentieth century, no more elementary particles were discovered until 1932, when Chadwick proved the existence of the neutron, and Carl Anderson identified the positron in cosmic rays.

The Positron

- Dirac in 1928 introduced the relativistic theory of the electron when he combined quantum mechanics with relativity.
- He found that his wave equation had negative, as well as positive, energy solutions.
- His theory can be interpreted as a vacuum being filled with an infinite sea of electrons with negative energies.
- If enough energy is transferred to the "sea", an electron can be ejected with positive energy leaving behind a hole that is the *positron*, denoted by e^+.

Antiparticles

- Dirac's theory, along with refinements made by others opened the possibility of **antiparticles** which:
  - Have the *same mass* and *lifetime* as their associated particles
  - Have the *same magnitude* but are *opposite in sign* for such physical quantities as electric charge and various quantum numbers

- All particles, even neutral ones (with some notable exceptions like the neutral pion), have antiparticles.

Cosmic Rays

- *Cosmic rays* are highly energetic particles, mostly protons, that cross interstellar space and enter the Earth's atmosphere, where their interaction with particles creates cosmic "showers" of many distinct particles.

Positron-Electron Interaction

- The ultimate fate of positrons (antielectrons) is annihilation with electrons.

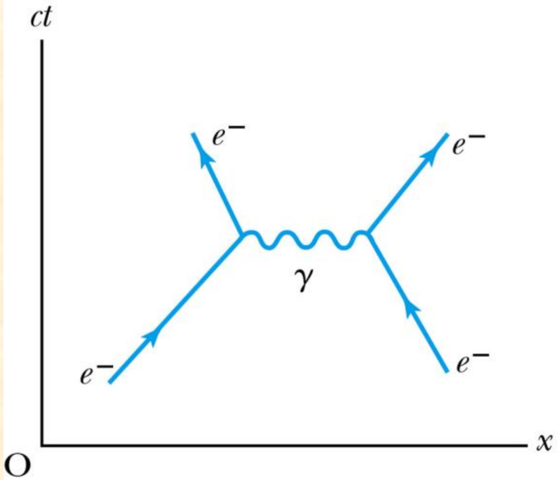
- After a positron slows down by passing through matter, it is attracted by the Coulomb force to an electron, where it annihilates through the reaction

$$e^{+} + e^{-} \rightarrow 2\gamma$$

Feynman Diagram

- Feynman presented a particularly simple graphical technique to describe interactions.
- For example, when two electrons approach each other, according to the quantum theory of fields, they exchange a series of photons called *virtual* photons, because they cannot be directly observed.
- The action of the electromagnetic field (for example, the Coulomb force) can be interpreted as the exchange of photons. In this case we say that the photons are the *carriers* or *mediators* of the electromagnetic force.

Figure: Example of a Feynman spacetime diagram. Electrons interact through mediation of a photon. The axes are normally omitted.



Yukawa's Meson

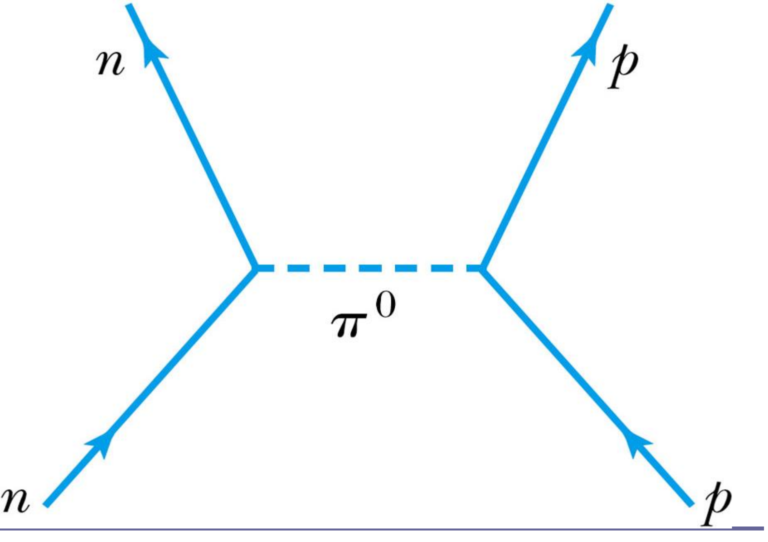
- The Japanese physicist Hideki Yukawa had the idea of developing a quantum field theory that would describe the force between nucleons analogous to the electromagnetic force.

- To do this, he had to determine the carrier or mediator of the nuclear strong force analogous to the photon in the electromagnetic force which he called a ***meson*** (derived from the Greek word *meso* meaning "middle" due to its mass being between the electron and proton masses).

Yukawa's Meson

- Yukawa's **meson**, called a **pion** (or *pi-meson* or π-meson), was identified in 1947 by C. F. Powell (1903–1969) and G. P. Occhialini (1907–1993)
- Charged pions have masses of 140 MeV/c^2, and a neutral pion π^0 was later discovered that has a mass of 135 MeV/c^2, a neutron and a proton.

Figure: A Feynman diagram indicating the exchange of a pion (Yukawa's meson) between a neutron and a proton.



The Fundamental Interactions

- The fundamental forces in nature responsible for all interactions:
  1) Gravitation
  2) Electroweak (electromagnetic and weak)
  3) Strong

- The electroweak is sometimes treated separately as the electromagnetic and the weak force thus creating *four fundamental forces*.

The Fundamental Interactions

- We have learned that the fundamental forces act through the *exchange or mediation of particles* according to the quantum theory of fields. ***The exchanged particle in the electromagnetic interaction is the photon***. All particles having either electric charge or a magnetic moment (and also the photon) interact with the electromagnetic interaction. The electromagnetic interaction has very long range.

The Fundamental Interactions

- In the 1960s Sheldon Glashow, Steven Weinberg, and Abdus Salam (Nobel Prize for Physics, 1979) predicted that particles, which they called W (for weak) and Z, should exist that are responsible for the weak interaction.

- This theory, called the *electroweak* theory, unified the electromagnetic and weak interactions much as Maxwell had unified electricity and magnetism into the electromagnetic theory a hundred years earlier.

Other Mesons

- We previously saw that Yukawa's pion is responsible for the nuclear force. Now we know there are other mesons that interact with the strong force. Later we will see that the nucleons and mesons are part of a general group of particles formed from even more fundamental particles **quarks**. The particle that mediates the strong interaction between quarks is called a **gluon** (for the "glue" that holds the quarks together); it is massless and has spin 1, just like the photon.

- Particles that interact by the strong interaction are called **hadrons**; examples include the neutron, proton, and mesons.

The Graviton

- It has been suggested that the particle responsible for the gravitational interaction be called a **graviton**.
- The graviton is the mediator of gravity in quantum field theory and has been postulated because of the success of the photon in quantum electrodynamics theory.
- It must be massless, travel at the speed of light, have spin 2, and interact with all particles that have mass-energy.
- The graviton has never been observed because of its extremely weak interaction with objects.

The Fundamental Interactions

Table 14.1 The Fundamental Interactions

Interaction	Relative Strength	Range	Mediating Particle
Strong	1	10^{-15} m	Gluons
Electroweak:			
Electromagnetic	10^{-2}	∞	Photons
Weak	10^{-6}	10^{-18} m	$W^{\pm}$, Z bosons
Gravitation	10^{-43}	∞	Graviton

The Standard Model

- The most widely accepted theory of elementary particle physics at present is the **Standard Model**.
- It is a simple, comprehensive theory that explains hundreds of particles and complex interactions with **six quarks, six leptons, and three force-mediating particles**.
- It is a combination of the electroweak theory and quantum chromodynamics (QCD), but does not include gravity.

Classification of Elementary Particles

Bosons and Fermions

- ***The integral spin particles obeying Bose-Einstein statistics are called Bosons.***
- ***Gravitons are also bosons, having spin 2.***
- ***(Photons , mesons)***
- ***The half and odd integral spin particles obeying Fermi-Dirac distribution statistics are called Fermions .***
- ***(Proton , neutron , electron)***

Bosons

Photons

- ***Photon has zero mass and a spin unity . It is as a mass less boson like Graviton.***

Mesons

- ***Mesons are bosons because of their integral spin.***

Mesons

❖ ***Mesons classified into three types :***

i. ***Pions*** *(The pion (π-meson) is a meson that can either have charge or be neutral.)* (π^+ , π^- , π^0)

ii. ***Kaons*** *(K-meson are also called strange particle)* (K^+, K^-, K^0)

iii. ***Eta*** *(It is also called charge less particle)* (η^o)

Fermions

❖ *Fermions classified into two categories:*

- *Leptons (lighter in weight)*
- *Baryons (Heavier in weight)*

Leptons

✓ ***Leptons contain electrons (e^-), muons (μ^-), neutrino(ϑ_μ, ϑ_e) and Tauon (τ^-) and their anti-particles.***

- Antiparticles :
  - Have the *same mass* and *lifetime* as their associated particles
  - Have the *same magnitude* but are *opposite in sign* for such physical quantities as electric charge and various quantum numbers
  - ***Antiparticles of Leptons:***

- ***electron - positron(e^+) , muon – anti muon(μ^+),***
- ***neutrino – anti neutrino($\bar{\vartheta}_e$, $\bar{\vartheta}_\mu$),***
- ***tauon – anti tauon(τ^+)***

Baryons

- The *neutron* and *proton* are the best-known baryons. Its called Nucleons.
- Second type Baryons are Hyperons. They are more unstable and heavier.

➢ Hyperons :

- Lambda(Λ^o)[mass about 2180Me]
- Sigma ($\Sigma^+, \Sigma^o, \Sigma^-$) [mass 2320 to 2340 Me]
- Ksi(Ξ^o, Ξ^-)
- Omega(Ω^-)

❖ *proton and neutron :*

- ***I= ½***

❖ *Lambda :*

- Lambda has $S = -1$, B = 1, I = 0

❖ *Sigma :*

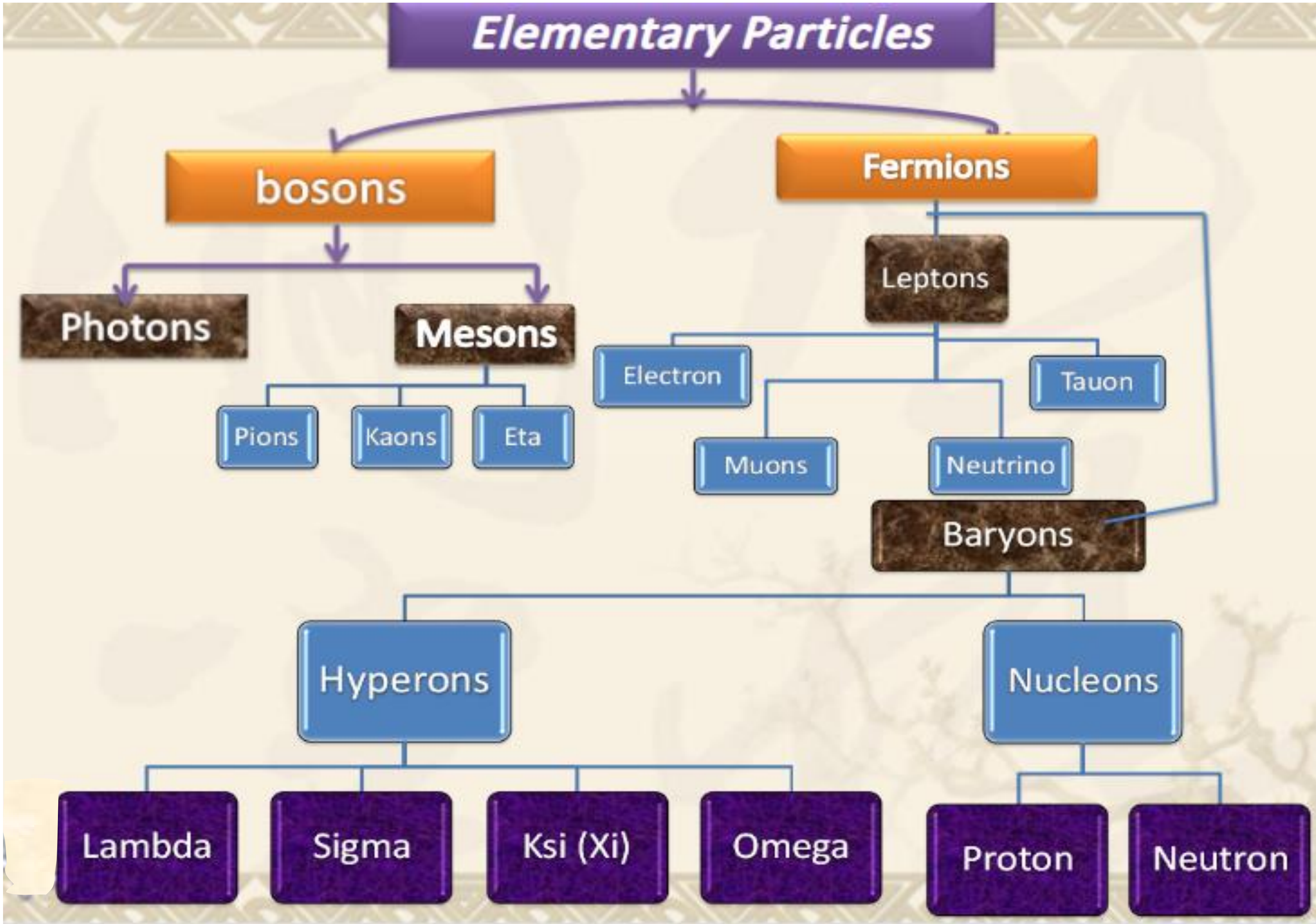
- The Sigma have $S = +1$, B = 1, I= 1

❖ *Ksi:*

- The xi has $S = -2$, B=1, I = ½

❖ *Omega :*

- the omega has $S = -3$, B=1, I= 0.


Elementary Particles
bosons
Fermions
Photons
Mesons
Pions
Kaons
Eta
Leptons
Electron
Tauon
Muons
Neutrino
Baryons
Hyperons
Nucleons
Lambda
Sigma
Ksi (Xi)
Omega
Proton
Neutron

Particles and Lifetimes

- The lifetimes of particles are also indications of their force interactions.
- Particles that decay through the strong interaction are usually the shortest-lived, normally decaying in less than 10^{-20} s.
- The decays caused by the electromagnetic interaction generally have lifetimes on the order of 10^{-16} s, and
- The weak interaction decays are even slower, longer than 10^{-10} s.