IDHAYA COLLEGE FOR WOMEN

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DEPARTMENT OF PHYSICS

SEMESTER	**:**	**IV**
CLASS	**:**	**II MSc PHYSICS**
SUBJECT- INCHARGE	**:**	**Mrs.K.KANIMOZHI**
SUBJECT NAME	**:**	**NUCLEAR AND PARTICLE PHYSICS**
SUBJECT CODE	**:**	**P16PY41**
TOPIC	**:**	**QUARK MODEL, CONSERVATION LAWS.**

SYMMETRY

- The CPT theorem appeared for the first time, implicitly, in the work of Julian Schwinger in 1951 to prove the connection between spin and statistics.
- In 1954, Gerhart Lüders and Wolfgang Pauli derived more explicit proofs, so this theorem is sometimes known as the Lüders–Pauli theorem.
- At about the same time, and independently, this theorem was also proved by John Stewart Bell. These proofs are based on the principle of Lorentz invariance and the principle of locality in the interaction of quantum fields.
- Subsequently, Res Jost gave a more general proof in the framework of axiomatic quantum field theory.
- Efforts during the late 1950s revealed the violation of P-symmetry by phenomena that involve the weak force, and there were well-known violations of C-symmetry as well.
- For a short time, the CP-symmetry was believed to be preserved by all physical phenomena, but that was later found to be false too, which implied, by **CPT invariance**, violations of T-symmetry as well.

Derivation of the CPT theorem

- Consider a Lorentz boost in a fixed direction *z*. This can be interpreted as a rotation of the time axis into the *z* axis, with an imaginary rotation parameter.
- If this rotation parameter were real, it would be possible for a 180° rotation to reverse the direction of time and of *z*. Reversing the direction of one axis is a reflection of space in any number of dimensions.
- If space has 3 dimensions, it is equivalent to reflecting all the coordinates, because an additional rotation of 180° in the *x*-*y* plane could be included.
- This defines a CPT transformation if we adopt the Feynman–Stueckelberg interpretation of antiparticles as the corresponding particles traveling backwards in time.
- This interpretation requires a slight analytic continuation, which is well-defined only under the following assumptions:

1. **The theory is Lorentz invariant;**
2. **The vacuum is Lorentz invariant;**

3. **The energy is bounded below.**

- When the above hold, quantum theory can be extended to a Euclidean theory, defined by translating all the operators to imaginary time using the Hamiltonian. The commutation relations of the Hamiltonian, and the Lorentz generators, guarantee that Lorentz invariance implies rotational invariance, so that any state can be rotated by 180 degrees.
- Since a sequence of two CPT reflections is equivalent to a 360-degree rotation, fermions change by a sign under two CPT reflections, while bosons do not. This fact can be used to prove the spin-statistics theorem.

Consequence and implications

- The implication of CPT symmetry is that a "mirror-image" of our universe — with all objects having their positions reflected through an arbitrary point (corresponding to a parity inversion), all momenta reversed (corresponding to a time inversion) and with all matter replaced by antimatter (corresponding to a charge inversion) — would evolve under exactly our physical laws. The CPT transformation turns our universe into its "mirror image" and vice versa. CPT symmetry is recognized to be a fundamental property of physical laws.
- In order to preserve this symmetry, every violation of the combined symmetry of two of its components (such as CP) must have a corresponding violation in the third component (such as T); in fact, mathematically, these are the same thing. Thus violations in T symmetry are often referred to as CP violations.
- The CPT theorem can be generalized to take into account pin groups.
- In 2002 Oscar Greenberg published an apparent proof that CPT violation implies the breaking of Lorentz symmetry. If correct, this would imply that any study of CPT violation also includes Lorentz violation. However, Chaichian *et al* later disputed the validity of Greenberg's result. Greenberg replied that the model used in their paper meant that their "proposed objection was not relevant to my result"
- The overwhelming majority of experimental searches for Lorentz violation have yielded negative results. A detailed tabulation of these results was given in 2011 by Kostelecky and Russell.

PARTICLE CLASSIFICATION

The four fundamental interactions or forces that govern the behavior of elementary particles are listed below.

- The strong force (It holds the nucleus together.)
- The electromagnetic force (It causes interactions between charges.)
- The weak force (It causes beta decay.)
- The gravitational force (It causes interaction between states with energy.)

➢ A given particle may not necessarily be subject to all four interactions. Neutrinos, for example, experience only the weak and gravitational interaction.

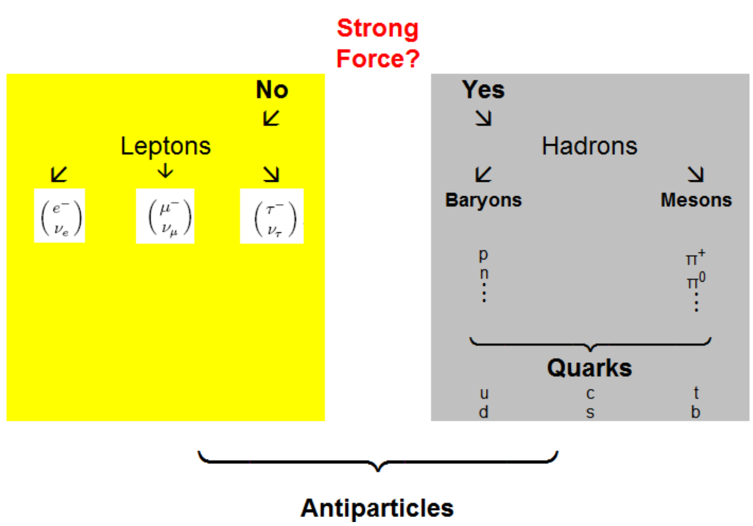
➢ The fundamental particles may be classified into groups in several ways. First, all particles are classified into **fermions**, which obey Fermi-Dirac statistics and **bosons**, which obey Bose-Einstein statistics.

➢ Fermions have half-integer spin, while bosons have integer spin. All the fundamental fermions have spin 1/2. Electrons and nucleons are fermions with spin 1/2.

➢ The fundamental bosons have mostly spin

1. This includes the photon. The pion has spin 0, while the graviton has spin
2. There are also three particles, the W^+, W^- and Z_0 bosons, which are spin
3. They are the carriers of the weak interactions.

We can also classify the particles according to their interactions.



- The electron and the neutrino are members of a family of **leptons**. Originally leptons meant "light particles", as opposed to **baryons**, or heavy particles, which referred initially to the proton and neutron.
- The pion, or pi-meson, and another particle called the muon or mu-meson, were called **mesons**, or medium-weight particles, because their masses, a few hundred times heavier than the electron but six times lighter than a proton, were in the middle.
- But that distinction turned out not to be very useful. We now recognize the muon to be almost the same as an electron, and the leptons now consist of three "generations" of pairs of particles,

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

with the heaviest of these, the tau lepton τ^-, being almost twice as massive as the proton.

- The leptons are distinguished from other particles called hadrons in that leptons do not participate in strong interactions.
- The bottom lepton in each of the three "doublets" shown above is not only neutral, but also has a very small mass. Neutrinos had been considered massless for many years, but more recent experiments have shown their mass to be non-zero.

Table of leptons

particle			**associated neutrino**		
Name	**Charge (e)**	**Mass (MeV)**	**Name**	**Charge (e)**	**Mass (MeV)**
Electron (e^-)	-1	0.511	Electron neutrino (ν_e)	0	< 0.000003
Muon (μ^-)	-1	105.6	Muon neutrino (ν_μ)	0	< 0.19
Tau (τ^-)	-1	1777	Tau neutrino (ν_τ)	0	< 18.2

Hadrons are strongly interacting particles. They are divided into **baryons** and **mesons**. The baryons are a class of fermions, including the proton and neutron, and other particles which in a decay always produce another baryon, and ultimately a proton. The mesons, are bosons. In addition to the pion, there are other spin 0 particles, four kaons and two eta mesons, and a number of spin one hadrons, including the three rho mesons, which like the pion come in charges 1 and 0. Mesons can decay without necessarily producing other hadrons.

Table of some baryons

Particle	**Symbol**	**Quark Content**	**Mass MeV/c²**	**Mean lifetime (s)**	**Decays to**
Proton	p	uud	938.3	Stable	Unobserved
Neutron	n	ddu	939.6	885.7±0.8	$p + e^- + \nu_e$
Delta	Δ^{++}	uuu	1232	6×10^{-24}	$\pi^+ + p$
Delta	Δ^+	uud	1232	6×10^{-24}	$\pi^+ + n$ or $\pi^0 + p$
Delta	Δ^0	udd	1232	6×10^{-24}	$\pi^0 + n$ or $\pi^- + p$
Delta	Δ^-	ddd	1232	6×10^{-24}	$\pi^- + n$
Lambda	Λ^0	uds	1115.7	2.60×10^{-10}	$\pi^- + p$ or $\pi^o + n$
Sigma	Σ^+	uus	1189.4	0.8×10^{-10}	$\pi^0 + p$ or $\pi^+ + n$
Sigma	Σ^0	uds	1192.5	6×10^{-20}	$\Lambda^0 + \gamma$
Sigma	Σ^-	dds	1197.4	1.5×10^{-10}	$\pi^- + n$
Xi	Ξ^0	uss	1315	2.9×10^{-10}	$\Lambda^0 + \pi^0$
Xi	Ξ^-	dss	1321	1.6×10^{-10}	$\Lambda^0 + \pi^-$
Omega	Ω^-	sss	1672	0.82×10^{-10}	$\Lambda^0 + K^-$ or $\Xi^0 + \pi^-$

Table of some mesons

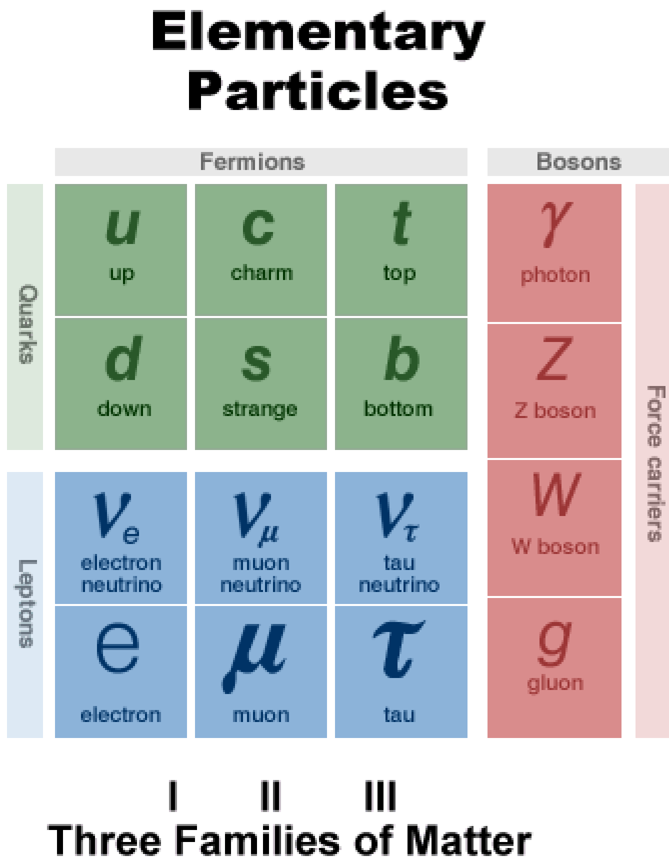
Particle	**Symbol**	**Anti-particle**	**Quark Content**	**Mass MeV/c²**	**Mean lifetime (s)**	**Principal decays**

Charged Pion	π^+	π^-	ud	139.6	2.60×10^{-8}	$\mu^+ + \nu_\mu$
Neutral Pion	π^0	Self	uu - dd	135.0	0.84×10^{-16}	2γ
Charged Kaon	K^+	K^-	$u\bar{s}$	493.7	1.24×10^{-8}	$\mu^+ + \nu_\mu$ or $\pi^+ + \pi_0$
Neutral Kaon	K^0	K^0	ds	497.7		
Eta	η	Self	uu + dd - 2ss	547.8	5×10^{-19}	
Eta Prime	η'	Self	uu + dd + ss	957.6	3×10^{-21}	

Table of Quarks

Name	**Symbol**	**Charge (e)**	**Spin**	**Mass MeV/c^2**	**Strangeness**	**Baryon number**	**Lepton number**
up	u	+2/3	1/2	1.7-3.3	0	1/3	0
down	d	-1/3	1/2	4.1-5.8	0	1/3	0
strange	s	-1/3	1/2	101	-1	1/3	0
charm	c	+2/3	1/2	1270	0	1/3	0
bottom	b	-1/3	1/2	4190-4670	0	1/3	0
top	t	+2/3	1/2	172000	0	1/3	0

In the current theory, known as the Standard Model there are 12 fundamental matter particle types and their corresponding antiparticles. In addition, there are gluons, photons, and W and Z bosons, the force carrier particles that are responsible for strong, electromagnetic, and weak interactions respectively. These force carriers are also fundamental particles.

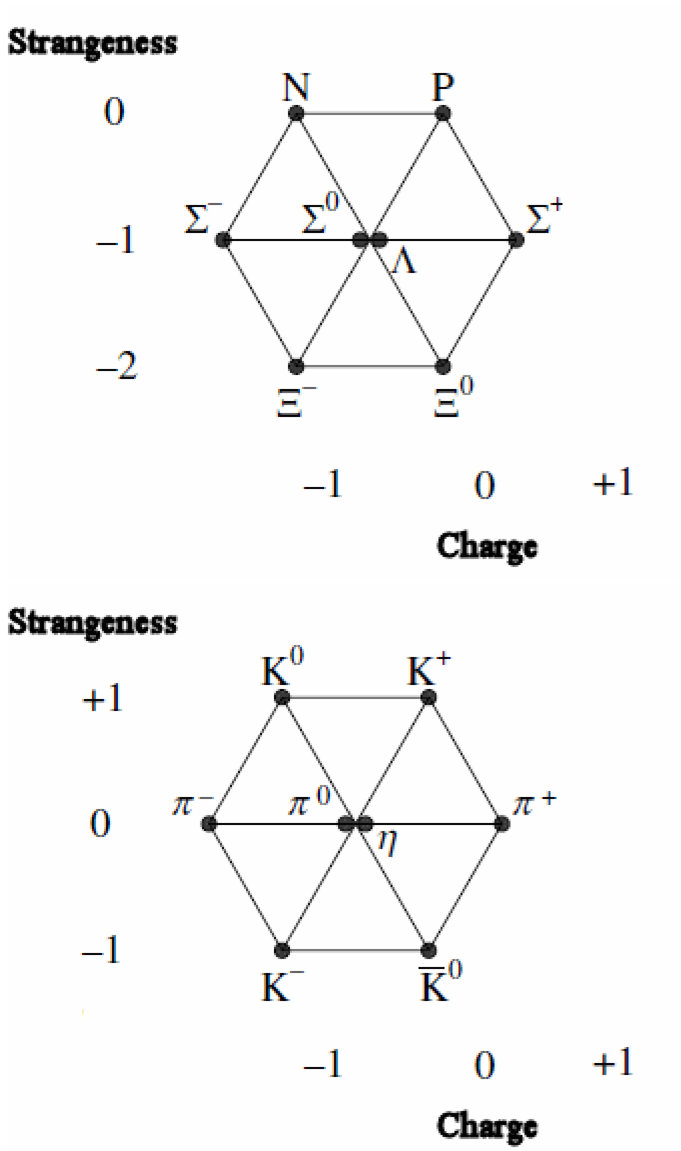


All we know is that quarks and leptons are smaller than 10^{-19} meters in radius. As far as we can tell, they have no internal structure or even any size. It is possible that future evidence will, once again, show our understanding to be incomplete and demonstrate that there is substructure within the particles that we now view as fundamental.

The Discovery of Elementary Particles

- The first subatomic particle to be discovered was the electron, identified in 1897 by J. J. Thomson. After the nucleus of the atom was discovered in 1911 by Ernest Rutherford, the nucleus of ordinary hydrogen was recognized to be a single proton. In 1932 the neutron was discovered. An atom was seen to consist of a central nucleus containing protons and neutrons, surrounded by orbiting electrons.
- However, other elementary particles not found in ordinary atoms immediately began to appear.

- In 1928 the relativistic quantum theory of P. A. M. Dirac predicted the existence of a positively charged electron, or positron, which is the antiparticle of the electron. It was first detected in 1932.
- Difficulties in explaining beta decay led to the prediction of the neutrino in 1930, and by 1934 the existence of the neutrino was firmly established in theory, although it was not actually detected until 1956.
- Another particle was also added to the list, the photon, which had been first suggested by Einstein in 1905 as part of his quantum theory of the photoelectric effect.
- The next particles discovered were related to attempts to explain the strong interactions, or strong nuclear force, binding nucleons together in an atomic nucleus. In 1935 Hideki Yukawa suggested that a meson, a charged particle with a mass intermediate between those of the electron and the proton, might be exchanged between nucleons.
- The meson emitted by one nucleon would be absorbed by another nucleon. This would produce a strong force between the nucleons, analogous to the force produced by the exchange of photons between charged particles interacting through the electromagnetic force. It is now known that the strong force is mediated by the gluon.
- The following year a particle of approximately the required mass, about 200 times that of the electron, was discovered and named the mu-meson, or muon. However, its behavior did not conform to that of the theoretical particle.
- In 1947 the particle predicted by Yukawa was finally discovered and named the pi- meson, or pion. Both the muon and the pion were first observed in cosmic rays.
- Further studies of cosmic rays turned up more particles. By the 1950s these elementary particles were also being observed in the laboratory as a result of particle collisions in particle accelerators.
- By the early 1960s over 30 "fundamental particles" had been found. A rigorous way of classifying them was needed. Were there any symmetries or patterns? Murray Gell- Mann believed that a framework for such patterns could be found in the mathematical structure of groups. A symmetry group called SU(3) offered patterns he was looking for. In 1961, after grouping the known particles, he predicted the existence of the η particle which was needed to complete a pattern. The η particle was discovered a few months later.



Example patterns for some baryons and mesons (The Eightfold Way)

- After finding the patterns an explanation was needed. In 1964 Gell-Mann published a short article showing that the patterns could be produced if the known particles were viewed as combinations of 3 fundamental subunits with fractional charge, the up, down, and strange quarks and their antiquarks.

- There were however problems with the Pauli Exclusion Principle. The quarks are spin 1/2 fermions and the Δ^{++}(uuu) and the Ω^{-}(sss) seemed to contain at least two quarks with exactly the same quantum numbers.
- The quark theory was not really accepted until deep inelastic scattering experiments revealed structure inside the protons in the later 1960s.
- The charm quark was discovered in 1974, the bottom quark in 1977, and the top quark in 1995. The tau particle was detected in a series of experiments between 1974 and 1977 and the discovery of the tau neutrino was announced in 2000. It was the last of the particles in the Standard Model of elementary particles to be detected.
- One of the current frontiers in the study of elementary particles concerns the interface between that discipline and cosmology. The known quarks and leptons, for instance, are typically grouped in three families, where each family contains two quarks and two leptons. Investigators have wondered whether additional families of elementary particles might be found.
- Recent work in cosmology pertaining to the evolution of the universe has suggested that there could be no more families than four, and the cosmological theory has been substantiated by experimental work at the Stanford Linear Accelerator and at CERN, which indicates that there are no families of elementary particles other than the three that are known today.
- For example, detailed studies of Z_0 decays at CERN revealed that there can be no more than three different kinds of neutrino. If there was a fourth, or a fifth, further decay routes would be open to the Z_0 which would affect its measured lifetime.

Conservation Laws

- Leptons carry an additive quantum number called the **lepton number L**. The leptons listed in the table above carry L = 1 and their antiparticles carry L = -1. The **electron number** carried by electrons and electron neutrinos seems to an additive quantum number which is conserved in interactions. Electrons and electron neutrinos have electron number 1 and positrons and electron anti-neutrinos carry electron number -1. Muons, or μ-mesons, behave similarly as electrons. They only have electromagnetic and weak interactions. Only their mass, 106 MeV/c^2, distinguishes them from electrons. Along with ν_μ theycarry an additive quantum number, the **muon number**, that which also seems to be conserved in interactions. Muons decay as

$$\mu^+ \dashrightarrow e^+ + \nu_\mu + \nu_e$$

- in about 10^{-6}s. The tau and its neutrino carry an additive quantum number as well, which seems to be conserved in interactions. We say that the **lepton family number LF** also seems to be conserved. However if neutrinos have mass and can change flavor, for example, if muon neutrinos can change into electron neutrinos and vice versa, then only **L is conserved**.
- Are there more such additive quantum numbers? Yes, there is a group of particles called baryons, and a corresponding conserved quantum number called **baryon number** B. Baryons have baryon number B = 1 and anti-baryons have baryon number B = -1. The lightest baryon is the proton, and it is the only stable baryon. Since the neutron decays by $n \dashrightarrow p + e^- + \nu_e$ and the electron and anti-neutrino are leptons, not baryons, B conservation requires that the neutron is also baryon.
- It is fairly easy to spot a baryon in a table of elementary particles. Suppose you are looking at a particle which might be a baryon. If it is not the proton and it is a baryon, it must decay. Baryon conservation then requires a baryon among the decay products, although you may not know which of the decay products is the baryon. Let all of the decay products themselves decay. The baryon's decay yields another baryon. Keep going until all the particles are stable. Among all the resulting particles there must be one net baryon. Since the proton is the only stable baryon, that baryon must be a proton. Hence, a particle is a baryon if and only if there is one net proton among its ultimate decay products.
- Baryons are made up of 3 quarks. All quarks have baryon number B = 1/3, and all anti-quarks have baryon number B = -1/3.
- Everything else in the table besides the baryons and leptons is called a meson. Mesons are made up of a quark and an anti-quark. Mesons have L = 0 and B = 0, and they have no net leptons or baryons in their ultimate decay products. The number of mesons is not conserved, so there is no "meson number."

- After the discovery of pions other particles were discovered in rapid pace. K-mesons (m = 494 MeV/c^2) are similar to π -mesons, they do not carry a nucleon number. The K-meson decays in the following way.

$$K^+ \text{-->} \pi^+ + \pi^0$$

- Hyperons are different. The lightest hyperon is the Λ^0 with m = 1116 MeV/c^2. It decays in the following way

$$\Lambda^0 \text{-->} p + \pi^-, \text{ or } n + \pi^0$$

- A hyperons is a baryon.
- As better accelerators became available the reaction below was observed

$$\pi^+ + n \text{-->} \Lambda^0 + K^+$$

- Obviously in the above process baryon number is conserved. It was remarkable that reactions like

$$\pi^+ + n \text{-->} \Lambda^0 + \pi^+$$

  were never observed. This prompted the introduction of a new quantum number, **strangeness**, by Gell-Mann and Pais. The strangeness S(Λ^0) = -1, S(K^+) = 1. Protons, neutron an pions have no strangeness. In decay processes involving the strong interaction strangeness is conserved.
- In decay processes involving the weak interaction, such as K-decay or hyperon decay, strangeness is not conserved. This was the first case that some quantum numbers were conserved in strong interactions and electromagnetic interactions, but not in weak interactions.
- Decay processes governed by the strong interaction can be distinguished easily from decay processes governed by the weak interaction. Characteristic reaction times for the former are on the order of 10^{-23} s while for the latter they are on the order of 10^{-10}s.