COURSE GUIDE

PHY 401
ELEMENTARY PARTICLE PHYSICS

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MODULE 1

UNIT 1

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1.0 INTRODUCTION

This module is a study of elementary particles, what they are, how they are produced, how they behave and how they fall into families depending on their various properties. Each of the families has its own spin which is a major instrument in grouping the particles. The particles possess some properties which are usually referred to as quantum properties. The properties allow us to group them into the various families that exist. In this module we will see how these sub-atomic particles can be produced, observed and grouped into families.

2.0 OBJECTIVES

The objectives of this study are:

- to know what elementary particles are
- to know how they are produced
- to identify equipments to detect particles
- to know the properties of the particles and
- to be able to group particles into their various families

3.0 MAIN CONTENT

3.1 Types of Elementary Particles

Elementary particles are numerous and they belong to groups and families depending on their spin quantum numbers and other properties. Shortly, you will get to know the families, their properties and you will be able to group them. However, it is worth noting that some of these particles have integer spins; others have half- integer spins while some others possess fractional charges.

3.3 Elementary Particles

There are many elementary particles known, all of them are termed elementary because they are assumed to be the basic building blocks of matter in understanding the properties of matter. More than 200 subatomic particles have been discovered so far, all detected in sophisticated particle accelerators.

These particles are studied because their study can lead to a deeper understanding of nature.

3.2.1 Definition of Elementary Particles

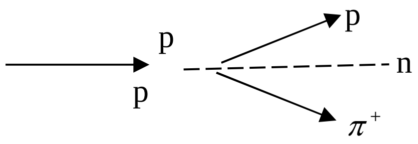
An elementary particle is one that is not known to have a substructure; that is, it is not known to be made up of smaller particles. If an elementary particle truly has no substructure, then it is one of the basic building blocks of the universe from which all other particles are made. Elementary particles therefore, are particles with no measurable internal structure; that is, they are not composed of other particles. They are the fundamental objects of quantum field theory. Many families and sub-families of elementary particles exist. Elementary particles are classified according to their spin. Fermions have half-integer spin while bosons have integer spin.

3.2.4 Origin / Production of Elementary Particles

Some of the particles were first observed in cosmic rays and this discovery opened the way to many other new particles discovery. A good example is the muon. Elementary particles are high energy particles, hence they are produced in high energy chambers like the accelerators where fast –moving particles collide to generate other lighter particles.

One good example is the collision of a proton with another proton in an accelerator. This collision will produce a neutron, a positive pion and another proton as shown below.

$$p + p \to p + n + \pi^+$$



3.2.5 Detection of Elementary Particles

These particles can be detected using any of the particle detectors in physics. The particle detectors can be the Gaseous ionization detectors like:

- Cloud chamber
- Ionization chamber
- Proportional counter
- Multi-wire Proportional Chamber
- Drift chamber
- Time projection chamber
- Geiger-Müller tube
- Spark chamber.
- Apart from these, there are also Solid-state detectors like:
- semiconductor detectors
- solid-state track detectors
- Cherenkov detector
- Scintillation counter
- Photo multiplier or Photodiode / Avalanche photodiode

3.3 Particle Families

Elementary particles are grouped into families according to their properties and behavior / interactions with other particles. They can be either fermions (with half- integral spins) or bosons (with integer spins). The families include :

i) the quarks and the leptons which are fermions
ii) the hadrons (which are the mesons and the baryons)
iii) the hyperons

The last two families here are bosons.

3.3.1 Quarks

Quarks are elementary particles with fractional charges. They also possess half- integer spins and so they are fermions. There are six quarks and six corresponding anti-quarks . There are no free quarks in nature, i.e. quarks do not exist by themselves. All quarks must be bound to another quark or anti-quark by the exchange of gluons. This is called quark confinement. Let us look at them on a table below with their properties.

Name	Symbol	Charge e	Mass (MeV/c^2)
up	u	+2⁄3	1.5 – 3.3
charm	c	+2⁄3	1,160 –1,340
top	t	+2⁄3	169,100 –173,300
down	d	−1⁄3	3.5 – 6.0
strange	s	−1⁄3	70 –130
bottom	b	−1⁄3	4,130 – 4,370

3.3.2 Leptons

There are 12 fundamental fermions, made up of six quarks and six leptons. Three of the leptons are neutrinos, and the remaining three have electric charge of −1 each. These are the electron, the muon and the tauon. The table below shows the lepton family with some properties.

Name	Symbol	Antiparticle	Charge/ e	Mass (MeV/c^2)
Electron neutrino	ν_e	ν_e	0	
Muon	μ−	μ+	−1	105.7
Muon neutrino	ν_μ	ν_μ	0	< 0.170
Tau	τ−	τ+	−1	1,777
Tau neutrino	ν_τ	ν_τ	0	< 15.5
Electron	e−	e+	−1	0.511

3.3.3 Hadrons

These are particles that interact by the strong interaction and the general classification includes mesons and baryons. The class of hadrons is further described by the two families below.

3.3.4 Mesons and Baryons

Mesons are intermediate mass particles which are made up of a quark and an anti-quark pair. On the other hand, three quark combinations give rise to baryons.

Mesons are bosons, with integral spins. They include the pi-mesons (pions), the k-mesons (or kaons) and the eta (η). The pions are positive-, negative- and neutral - pions. The neutral pion decays to an electron, positron, and gamma ray by the electromagnetic interaction on a time scale of about 10^{-16} seconds, but the positive and negative pions have longer lifetimes of about 2.6×10^{-8} s.

The baryons include the nucleons which are protons and neutrons; as well as the hyperons that are strange baryons (the lambda, the sigmas, the chis and the omega).

3.3.6 Hyperons

A hyperon is any baryon containing one or more strange quarks, but no charm quarks or bottom quarks. Being baryons, all hyperons are fermions. That is, they have half-integer spin and obey Fermi-Dirac statistics. They all interact via the strong nuclear force, making them types of hadrons. They are composed of three light quarks, at least one of which is a strange quark, which makes them strange baryons. They include three Sigma hyperons, Σ^+, Σ^0 and Σ^- . They possess rest mass of ~1,190 MeV and lifetimes of $\sim 1\times10^{-10}$ s with the exception of Σ^0 whose lifetime is shorter than 1×10^{-19} s. There is also one Lambda hyperon, $\Lambda 0$ with a rest energy of 1,115 MeV and a lifetime of 2.6×10^{-10} s. There are two Xi hyperons, also known as the cascades Ξ^0 and Ξ^{-1}.. They have rest energies of 1,315 MeV and 1,320 MeV and lifetimes of 2.9×10^{-10} s and 1.6×10^{-10} s respectively. There is one Omega hyperon, the last discovered, Ω^{-1}, with a mass of 1,670 MeV and a lifetime of 8.2×10^{-11} s.

3.3.6 Decay of Hyperons

The hyperons do participate in strong interactions and the following show their decay modes

Λ decay

$\Lambda^0 \rightarrow p+ + \pi-$
$\Lambda^0 \rightarrow n^0 + \pi^0$
Λ^0 may also decay on rare occurrences via these processes:
$\Lambda^0 \rightarrow p+ + e- + \nu e$
$\Lambda^0 \rightarrow p+ + \mu- + \nu\mu$
Σ decay
$\Sigma+ \rightarrow p+ + \pi 0$
$\Sigma+ \rightarrow n^0 + \pi+$
$\Sigma^0 \rightarrow \Lambda^0 + \gamma$
$\Sigma- \rightarrow n^0 + \pi-$
Ξ decay
$\Xi^0 \rightarrow \Lambda^0 + \pi^0$
$\Xi- \rightarrow \Lambda^0 + \pi-$
Ξ particles are also known as "cascade" hyperons, since they go through a two-step cascading decay into a nucleon by first decaying to a Λ^0 and emitting a $\pi^{\pm}$.

Ω^- decay
$\Omega- \rightarrow \Xi^0 + \pi-$
$\Xi^0 \rightarrow \Lambda^0 + \pi^0$
$\Lambda^0 \rightarrow p+ + \pi-$

4.0 CONCLUSION

Elementary particles are basic building blocks of matter. They help us to understand matter and its composition. Elementary particles come in families and they all possess spin, charge and other quantum properties. Understanding of the elementary particles and their behavior will help us to understand some basic laws and principles of physics.

5.0 SUMMARY

We have been able to see that the elementary particles are many in nature. They are observable in cosmic rays. They have many families which include: the quarks, the baryons, the mesons, the hadrons and the hyperons.

6.0 TUTOR-MARKED ASSIGNMENT

[MT 1.1] Draw a table showing the elementary particles (not anti-particles) according to their families with the following properties: symbol, charge, and spin.

[MT1.2] Differentiate between a lepton and a meson giving names of particles and some properties.

7.0 REFERENCES/FURTHER READING

An Introduction to the Physics of Nuclei and Particles by R. Dunlap. Cengage Learning; 1st edition (March 17, 2003)

https://www.youtube.com/watch?v=n-WTovOT4Lw&list=PLRN3HroZGu2lkRDsRxzqy_WU8NRk6evbD

Video link

MODULE 2

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1.0 INTRODUCTION

Elementary particles interact with each other, they can also collide one with another or even exchange some force carriers. All these can give rise to production of new particles or energies which can be linked to other smaller particles or resonances (ie intermediate particles). The interactions of the particles with one another are governed by some laws which must be obeyed before a reaction can be allowed in nature. These laws are known as conservation laws.

2.0 OBJECTIVES

The objectives of this chapter are:

- to know about the various conservation laws
- to classify the conservation laws
- to describe each law using examples
- to test whether a reaction will take place in nature or not

3.0 MAIN CONTENT

3.1 Conservation Laws

These are laws that must be obeyed before a reaction can take place in particle physics. There are many of them ranging from the law of charge conservation to the hypercharge conservation.

3.2 Classification of Laws

We are well aware of the fact that in a collision or a reaction, the total momentum is always conserved. This is a fundamental law.
Similarly, the total energy in a reaction involving these elementary particles is conserved. Elementary particles obey several such conservation laws.

3.3 Exact Conservation Laws

The exact or absolute conservation laws include those of:

i) Energy
ii) linear momentum
iii) angular momentum
iv) charge
v) baryon number
vi) lepton numbers and
vii) CPT (Change conjugation, Parity and Time reversal)

3.4 Description of Each Law

Conservation of Energy and Linear Momentum

These state that in a reaction the total energy and linear momentum are conserved.

Example: Consider a reaction where Π^- meson decays into a μ^- meson and an antineutrino $\bar{\gamma}$ i.e,

$$\Pi^- \rightarrow \bar{\mu} + \bar{\gamma}_\mu$$

$E_{\Pi^-} = E_{\mu^-} + E_{\bar{\gamma}_\mu}$ (t is conserved)

$$m_\Pi c^2 = E_\mu + E\gamma$$

$E_\mu = \left(|p_\mu|^2 c^2 + m^2{}_\mu \, c^4\right)^{1/2}$ = total energy of μ^- and that of $\bar{\gamma}_\mu$ will be

$E_\gamma = |p_2|^c$ (using $m\bar{\gamma} = 0$)

Initial momentum of the Π^- meson is zero because it is at rest and its rest mass is zero.
Hence conservation of momentum gives

$$0 = p_\mu + p_\gamma \qquad (p_\Pi = 0)$$

Or $p_\mu = -p_2$

Substitute to get energy equation as;

$$\left(|p_\mu|^2 c^2 + m^2{}_\mu \, c^4\right)^{1/2} + |p_\mu| c = m_\Pi c^2$$

or $\left(|p_\mu|^2 c^2 + m^2{}_\mu \, c^4\right)^{1/2} = m_\Pi c^2 - |p_\mu| c$

use p for the modulus $|p_\mu|$

i.e

$\cancel{p^2c^2} + m^2{}_\mu c^4 = m_\Pi^2 c^4 + \cancel{p^2c^2} - 2m_\Pi pc^3$

$$2_{m_\Pi} pc^3 = \left(m_\Pi^2 - m_\mu^2\right)C^4$$

or $p = \dfrac{\left(m_\Pi^2 - m_\mu^2\right)c}{2\, m_\Pi}$

Hence the energy of the neutrino is $E_\gamma = cp = \dfrac{\left(m_\Pi^2 + m_\mu^2\right)c^2}{2\, m_\Pi}$ and that of the μ^-- meson is $E_\mu = m_\Pi c^2 - E_\mu = \dfrac{\left(m_\Pi{}^2 - m^2{}_\mu\right)^{C^2}}{2\, m_\Pi}$

We have determine the energies of the particles μ^- and $\bar{\gamma}_\mu$ in terms of the masses of the pi-meson and muon $(m_\Pi \;\; and \;\; m_\mu)$.

This is characteristic of a two-body decay system.

In general for an n-body decay (n >2), the energies of such particles are not fixed but constrained by the two conservation laws.

In the β-decay, the energy of the electron and the antineutrino can take continuous values because it is a three body decay.

Conservation of Angular Momentum

This law states that if an isolated system is in a definite state of angular momentum the initial angular momentum is the same as the final angular momentum.

The angular momentum of a particle is the sum of its orbital angular momentum and its spin.

Example

$$K^+ \rightarrow \Pi^+ + \Pi^0$$

Decay of a $K^\pm$ meson at rest.

Total angular momentum of K^+ is zero because its orbital momentum is zero (at rest) and the spin for K^+ is zero also 0+0=0.

Therefore the total angular momentum of the system $\left(\Pi^+\Pi^o\right)$ must be zero also.

A Π-meson has a o spin, its orbital angular momentum is zero. Hence law of conservation of angular momentum is obeyed.

Conservation law of Charge

This law states that in a reaction, the total charge is conserved.
e.g $\bar{e} \rightarrow \gamma + \nu$

electron cannot decay into neutral particles such as photons and neutrons because this will violate the law of conservation of charge.

The electron is the lightest particle and a particle can decay only into particles lighter than itself so that energy can be conserved, hence the conservation law for charge makes the electron to be a stable particle. So, an isolated electron cannot decay.

We can show that the following reactions are possible because charge is conserved in each case.

$$\Pi^- \rightarrow \bar{\mu} + \bar{\gamma}_\mu$$

$$\Pi^- \rightarrow \bar{e} + \bar{\gamma}_e$$

$$\Pi^- \rightarrow \Pi^o + \bar{e} + \bar{\gamma}_e$$

and also

$$n \rightarrow p + e^{\approx} + \bar{\gamma}_e$$

Conservation of Baryon number

The electron which is the lightest charged particle is stable because of conservation of charge.

The proton is another known stable particle, but the laws of conservation of charge, energy and momentum do not explain the stability of proton.

For example

$$p \rightarrow e^+ + \Pi^o$$

$$p \rightarrow e^+ + \gamma$$

are reactions which do not take place in nature. Hence a new conservation law must be used to explain the proton stability. This is the law of conservation of baryon number B.

Each particle is assigned a baryon number B as follows:

B = 0 for photon, lepton and mesons

$$(\gamma, \nu, e, \mu, K, \eta, \pi, \tau)$$

B = + 1 for $p, n, \Lambda^o, \Sigma^{+,-,0}, \equiv^o \ \equiv^-$

B = - 1 for $\overline{p}, \overline{n}, \overline{\Lambda}^{o} \overline{\Sigma}^{+,-,0}, \equiv^{o} \ \equiv^{-}$

This baryon number is an additive number. The baryon number for a set of particles is the sum of the baryon number of each particle in the set.

This is similar to the law of conservation of charge of a system of particles.

Conservation law of baryon number states that in a reaction, the initial baryon number must be the same as the final baryon number.

Hence we can have the following reactions occurring in nature

$$p + n \rightarrow p + n + \Pi^{o}$$

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

$$p + n \rightarrow p + p + \Pi^{-}$$

But the reactions

$$p + n \rightarrow e^{+} + \partial \quad and$$

$$p + n \rightarrow \Pi^{+} + \Pi^{o}$$

are not allowed because the baryon number before (2) is not equal to the baryon number (0) after the reaction. However, the reaction. $p + \overline{n} \rightarrow \Pi^{+} + \Pi^{o}$ is allowed. Hence we can conclude that the neutron and the antineutron are very different even though they both possess same mass and charge (charge =o).

The system (pn) cannot form two pi-mesons but the system ($p\overline{n}$) can. This shows that n and $\overline{n}$ interact with proton very differently.

The proton is the lightest baryon and hence it is stable.

A decay such as $p \rightarrow e^{+} + \gamma$ is not possible, because baryon number is 1 initially and zero at the end of the reaction.

Conservation of Lepton Number

The interaction of leptons is different completely from that of baryon. Hence as we have baryon number conservation law we also have lepton number conservation law.

There is an associated lepton number for each kind of lepton and also a conservation law corresponding to the lepton number.

So, we have the conservation laws for the electron lepton number (Le) and the muon leptop number ($L\mu$).

These are:

Le = for electron e- and electron neutino
= 1 for position e^+ electro-anti $\bar{\gamma}_e$
= o for all other particles

Lμ = 1 for muon (μ^-) and muon neutrino
= -1 for antimuon ($\bar{\mu}+$) and muon antinutrino $\bar{\gamma}1$
= o for all other particles.
Lτ = 1 for tauon and its neutrino ν_τ
= -1 for anti tauon and tauon anti –neutrino ν_τ
= o for all other particles.

The lepton number is also additive like baryon numbers. If we have two-electron system then the electron lepton number is 2.

Conservation laws of electron-, muon- and tauon-lepton numbers state that in a reaction, the initial and the final electron-, muon- and tauon-lepton numbers must be the same.

Hence

$\mu^- \rightarrow \bar{e} + \gamma_\mu + \bar{\gamma}_e$

$\Pi^+ \rightarrow \mu^+ + \gamma_\mu$

$\Pi^+ \rightarrow e^+ + \gamma_e$ are possible and allowed.
But
$\mu^- \rightarrow e^- + \gamma$
$\mu^- \rightarrow e^+ + e^- + e^-$ are forbidden since final electron lepton number is one and initial electron lepton number is zero.

Origin of Exact Conservation Laws

The conservation laws are ultimately connected with some symmetries in nature; they result from some symmetry the system possesses.
For example, a particle in a spherically symmetric potential will have angular momentum that is conserved because the potential has a rotational symmetry.

In general it can be shown that the total angular momentum of an isolated system is conserved if the system has a rotational symmetry. That is, the physical properties of the systems remains the same.

The law of conservation of momentum results when a system has a translation symmetry, that is, the physical properties of the system are unchanged when it is translated by an arbitrary displacement.

3.5 Approximate Conservation Laws

The approximate conservation laws are not obeyed by all the interactions but are useful in cases where the contribution of one or the other interaction is negligible.

Some of such laws are the laws of conservation of

i) Isospin (strong)
ii) Strangeness (strong & electromag)
iii) Parity (strong & electromag)
iv) Charge conjugation (strong & electron)
v) Time reversal (strong & electromag) and
vi) Hypercharge

The law of conservation of isospin is valued only for the strong interaction.

Isospin: I-spin

The concept of isospin was used in grouping the pions together. It applies only to strongly interacting particles like mesons and baryons.
The assumption made is that if only the strong interaction were present, the pions world be completely alike. If however the electromagnetic interaction is turned on, there will be mass difference between the neutral and charged pions of about 2MeV, as well as differences in their lifetimes and magnetic moments. Application of the magnetic field cause a splitting of the level. This is similar to seaman splitting of a level in atomic spectral or better still, the fine structure in atomic spectra where one cannot control experimentally the splitting of the levels.
Isospin is designated T with its projection onto a special axis as T_3. These quantum numbers are analogous to the angular momentum J and its projection m_j respectively.

Each set of particles (or multiplet) of I-spin T possesses ($2T_{+1}$) charged states. Hence the nucleon is an I-spin doublet with $T = ½$. The proton has $T_3 = ½$ the neutron has $T_3 = - ½$.

See the table for the I-spin assignments for out already listed particles.

Strangeness

Strangeness was introduced to account for inconsistency in behavior of some particles - Λ, Σ_3 $and\,K$. They are called strange b/c they are produced at a fast rate in high Energy collision but decay at a slow rate.
It has been discovered that a large number of reactions involving the hadrons can be understood systematically only when a new quantum number is assigned to each such particles. This is known as the strangeness quantum number S.

The strangeness quantum number assigned to each hadrons is as follows:

Hadron	**Strangeness S**
$K^+, \; K^o \; \overline{\Lambda}^o \; \overline{\Sigma}^+ \; \overline{\Sigma}^o \; \overline{\Sigma}^-$	1
Anti-particles of $\Xi^o \quad \Xi^-$	2
$K^- \; \overline{K}^o \; \Lambda^o \; \Sigma^+ \; \Sigma^o \; \Sigma^-$	-1
$\Xi^o \quad \Xi^-$	-2
Other hadrons on our table	0

Observe that this strangeness quantum number is the only quantum number that is negative for the particles and positive for their antiparticles.

The strangeness number is an additive quantum number.
In a reaction, if the strangeness is conserved, the reaction has a large cross-section.

<u>Consider the reactions</u>

1 Consider the collision of a negative pion and a proton

$$\pi^- + P \rightarrow \Sigma^1 \; + \; K^+$$

and

$$\pi^- + P \rightarrow \; \Sigma^+ \; + \; K^-$$

Here the total strangeness of each $(\pi^- p)$and $(\Sigma^- k^+)$ is zero whereas that of $(\Sigma^+ + k^-)$ is – 2. thus, by the conservation of strangeness, reaction $(\pi^- p) \rightarrow (\Sigma^- K^t)$ is possible (or allowed) but $(\pi^- p) \rightarrow (\Sigma^+ K^-)$ is forbidden. Experimentally, it has been observed that reaction $(\pi^- p) \rightarrow (\Sigma^- K^+)$ has a large cross section.

2. Consider the decay of Λ^o into two particles.

Λ^o is the lightest baryon with a nonzero strangeness quantum number. The laws of conservation of baryon number and energy demand that the final products must contain a baryon lighter than Λ^o. This means that a proton or a neutron must be produced by that decay.

i.e
$$\begin{aligned} \Lambda^o &\rightarrow P + K^- \\ &\rightarrow n + K^o \end{aligned}$$

In each of these reactions, the energy is not conserved since the sum of the rest masses of the products is larger that the rest mass of Λ^o. Therefore the only way the decay can occur is through the violation of the law of conservation of strangeness. In other words the decay of Λ^o into two particles can take place only through the weak interaction. The possible reactions then are

$$\begin{aligned} \Lambda^o &\rightarrow P + \pi^- \\ &\rightarrow n \ + \ \pi^o \end{aligned}$$

Parity

In a parity transformation, the coordinates (x,yz) of a particle become $(-x, y, -z)$.

In particular if r refers to a point P in a coordinate frame, then after parity transformation, it becomes –r. This type of transformation is related to the transformation brought about by a reflection in a mirror. Mirror reflection about x-y plane followed by rotation about z-axis through 180^0.

Imagine that a mirror is kept coordinate system. Then the mirror image of r is r^1 where

$$r = \hat{i} + y\hat{j} + z\hat{k},$$
$$r^1 = x\hat{i} + y\hat{j} - z\hat{k}$$

Now rotate r^1 about z-axis through 180^0, then it will be transformed into –r, because the x- and y- component will change sign; and the z-component remains unchanged. Hence we can think of parity operation as a product of reflection about the x-y plane followed by a rotation about the z-axis.

If a law governing a physical phenomenon is found to be invariant under the transformation r → - r, the phenomenon is said to obey the law of conservation of parity. The mirror symmetry and parity are equivalent because an isolated system has a rotation symmetry.

Case 1

Consider force of gravity on a mass m$_1$, located at r$_1$ due to a mass m$_2$ located at r$_2$. Newton's law states

$$F = \frac{cm_1 m_2}{|r_1 - r_2|^3}\ (r_1 - r_2)$$

The motion of m$_1$ is given by

$$m_1 \frac{d^2r}{dt^2} = -\frac{cm_1 m_2}{|r_1 - r_2|^3}(r_1 - r_2)$$

Under parity transformation, we have, $r_1 \to -r_1$ and $r_2 \to -r_2$

Hence equation of motion becomes

$$m_1 \frac{d^2r}{dt^2} = -\frac{c\ m_1\ m_2}{|r_1 - r_2|^3}(r_1 - r_2)$$

Which is same as $m_1 \frac{d^2r}{dt^2} = -\frac{c\ m_1\ m_2}{|r_1 - r_2|^3}(r_1 - r_2)$

Thus the law of gravitation is invariant under parity

Case 2

Consider a particle with charge e moving in a uniform electric field E. The force on the particle is eE. If r is the position of the particle then the motion of particle is

$$m\frac{d^2r}{dt^2} = eE$$

To transform this equation of motion under parity we must know the transformation of E under parity. The electric field due to a charge e at a point r is given by

$$E = \frac{e}{4\Pi \in_0 |r|} r_3$$

Now transform $r \to -r$ means $E \to -E$ and equation of motion goes to

$$-m\frac{d^2r}{dt^2} = -eE$$

Which is same as the original equation, hence Electrostatic force law is invariant under parity.

Case 3a

Consider a particle moving in a uniform magnetic field B. the magnetic force is

$e\left[\frac{dr}{dt}xB\right]$ and the equation of motion then is $m\frac{d^2r}{dt^2} = e\left(\frac{dr}{dt}xB\right)$

To transform under parity we must know the transformation of B under parity.

Recall that the magnetic field produced by a current is given according to the law of Biot and Savart as

$$dB = \frac{\mu_0}{4\Pi}\frac{d\ell\ x\ r}{|r|^3}$$

Under parity therefore, $r \to^{-} r$ and $dl \to dl$ hence $dB \to dB$ or $B \to B$

A magnetic field produced by a current does not changed under parity transformation (opposite of case with electric field).

Using this result in equation of motion for the particle we get

$$-m\frac{d^2r}{dt^2} = e\left(-\frac{dr}{dt^2}x\ \ B\right)$$

$$-m\frac{d^2r}{dt^2} = -e\left(-\frac{dr}{dt}x\ \ B\right)$$

Hence we see that the magnetic force law is invariant under the parity transformation

Case 3b

In the presence of a free magnetic charge 9_m usually referred to as a magnetic monopole, how is the law affected.

Magnetic field is given as

$$B \propto \frac{9_m r}{|r|^3}$$

Sunder parity transformation B would transform as the electric field E.,

$$B \to -B$$

Motion equation becomes

$$-m\frac{d^2r}{dt^2} = e\left\{-\frac{dr}{dt}x(-B)\right\}$$

$$-m\frac{d^2r}{dt^2} = e\left\{\frac{dr}{dt}xB\right\}$$

This is not the same as before, hence, in the presence of a free magnetic monopole, the force law is not invariant under parity transformation.

It is very transformation parity is a multiplicative quantum number, the net parity of a system of particles is the product of all the orbital and intrinsic parities.

The dichotomy of orbital and intrinsic party is analogous to that of orbital and intrinsic angular momenta.

The proton has intrinsic parity + 1, the pion -1, the kaon -1, the lambda -1 and so on.

The net parity of a system of particles is the product of all the orbital and intrinsic parties.

The strong and electromagnetic interactions conserve parity but the weak interaction does not. Since the reactions that create leptons are weak, the leptons do not have intrinsic parities. Hence the electron in the hydrogen atom has a well-defined orbital parity but no intrinsic parity.
Recall that a wave function is either odd or even under the operation of changing the sing of all its coordinates.
Define P as the parity operator in the form
$p\psi(x, y, z) = \psi(-x, -y, -z)$
Two cases arise

$p\psi = +\psi$ (even parity)

$p\psi = -\psi$ (odd parity)

For instance, the wave functions for the electron in a hydrogen atom have parity $P = (-1)^{\ell}$

In fact any orbital angular momentum ℓ will contribute a factor of $(-1)^{\ell}$.

C Parity and G Parity

These are two conserved quantities that are multiplicative like the ordinary spatial parity. Both are applicable only to mesons.

C parity refers to behavior under the transformation of particles into antiparticles while G parity refers to the behaviour under this same transformation compounded with a rotation by 180^0 in isospin space.

Strong interaction conserve C and G. The electromagnetic interaction conserves C but not G. the weak interaction does not conserve their C nor G.

C is known as charge conjugation.

When failure of parity conservation was discovered it was at first thought that the product CP would be conserved by the weak interaction. The fact that the weak interaction does not conserve CP was established by experiments on K^0 mesons decay into two pions.

The violation is also rare. Violation of CP conservation carries a consequences for time-revered invariance of reactions.

Time-reversal invariance means that reactions are equally capable of proceeding forward and backward.

Time reversal transformation requires replacing t by –t.
A physical law that is invariant under time reversal.

It has been found that electromagnetic and strong interactions are invariant under time reversal.

If a physical law for a set of particle also holds for the antiparticles corresponding to the particles then the law is invariant under charge conjugations.

A general theorem known as the CPT theorem of quantum field theory asserts that any violation of CP conservation must be compensated by a violation of time reversal invariance. Thus the experiment evidence for the violation of CP conservation in the decay of K_l^o meson implies that nature is not / time symmetric.

It is believed that all interactions in nature are invariant under CPT transformation. It is exact (or absolute) conservation law. (CPT is exact). The conservation laws are associated laws are associated with symmetry operations, i.e.

Parity P $\rightarrow$ reflection symmetry in ordinary space
Isospin $\rightarrow$ rotation symmetry in Isospin space
C, G $\rightarrow$ with different kinds of particle – antiparticle exchange symmetries.

Hypercharge

In modern terminology the strangeness quantum number S has been largely superseded by the hypercharge number.

The hypercharge number equals the sum of strangeness and baryon number i.e: $Y = S + B$

Conservation of hypercharge is equivalent to the conservation of strangeness.

3.6 Uses of Conservation Laws

Conservation laws are used to ascertain which reactions will occur in nature and which ones will not occur. Some of the exact or absolute conservation laws are used to test for the reactions since they must be obeyed. These are majorly the conservation laws of charge (Q), baryon number (B), Lepton numbers (L e, Lu and L). Four of these must be tested to see the validity of the laws. Violation of any of the four laws reveal that the reaction cannot occur in nature.

3.7 Testing Reaction Equations

We want to test for certain equations to see which ones are allowed and which ones will not take place in nature.

The test will usually begin with the reaction or interaction equation
Then use the four different laws one after the other, check for the one that will be obeyed . If all four laws used are obeyed then the reaction will occur in nature.

CASE I

$\mathbf{p + n \rightarrow p + p + \pi^-}$

Charge Q: +1 + 0 = +1 +1 -1 = +1 (Q is conserved)
Baryon B: +1 +1 = +1 +1 + 0 = 2 (B is conserved)
e-lepton number L_e : 0 + 0 = 0 + 0+ 0 = 0 (Le is conserved)
μ-lepton number Lμ: 0 + 0 = + 0 + 0 +0 = 0 (Lμ is conserved)

The test shows that all the conservation laws are obeyed, hence the reaction can occur in nature. The proton can collide with a neutron to give two protons and a negative pion.

CASE II

$\mathbf{p + n \rightarrow \pi^+ + \pi^0}$

Charge Q: +1 + 0 = +1 +0 = +1 (Q is conserved)
Baryon B: +1 +1 = 0 +0 (B is <u>not</u> conserved)
e-lepton number L_e : 0 + 0 = 0 + 0 = 0 (Le is conserved)
μ-lepton number Lμ: 0 + 0 = 0 + 0 = 0 (Lμ is conserved)

In this case, the conservation law of baryon number is violated, hence the reaction cannot occur in nature. The meaning is that a proton will not collide with a neutron to produce positive and neutral pions.

4.0 CONCLUSION

It is obvious that there are two classes of conservation laws in particle Physics; namely: absolute and approximate conservation laws. The absolute (or exact) conservation laws only can be used to test the validity of a reaction taking place in nature.

5.0 SUMMARY

The exact conservation laws include the laws of conservation of Charge, Energy, linear momentum, angular momentum, Baryon number, lepton numbers of the electron, muon and tauon as well as the CPT conservation laws. The approximate conservation laws include those of Isospin, Strangeness, C- Parity, G-parity, Charge conjugation, time reversal T and hypercharge Y.

6.0 TUTOR-MARKED ASSIGNMENT

[TM 2.1] Test the following reactions and state which ones will occur in nature, also identify the laws violated by any reaction that will not occur in nature.

(a) $\mu^- \rightarrow e^- + \gamma$ (b)
$\mu^- \rightarrow e^+ + e^- + e^-$

(c) $\mu^- \rightarrow \bar{e} + \gamma_\mu + \bar{\gamma}_e$ (d) $\Pi^+ \rightarrow \mu^+ + \gamma_\mu$

(e) $p \rightarrow e^+ + \gamma$

[TM 2.2] List all the conservation laws known to you and classify them into two major groups.

[TM2.3] Write short notes on any two conservation laws from each group.

7.0 REFERENCES/FURTHER READING

Particle Physics by B. R. Martin, G. Shaw (2nd edition).

Particle Physics by B. R. Martin, G. Shaw John Wiley & Sons; 3rd edition (December 3, 2008)

Video link

https://www.youtube.com/watch?v=d1zaw-KZX1o&list=PL93B3DDC89C085C1C

MODULE 3

CONTENT

1.0 Introduction
2.0 Objectives
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    3.2 Interactions in Particle Physics
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        3.4.1 Gravitational Interactions
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1.0 INTRODUCTION

Physics is the study of all natural phenomena and it deals with all laws of nature. There are four fundamental forces that we are going to consider under this study which account for the general features of known physical processes. The weakest of the forces under consideration is also the most familiar and the first law of physics to be mathematically described. This happens to be the gravitational law discovered by Sir Isaac Newton which states that the force between any two point masses is proportional to the product of the two masses and inversely proportional to the square of their distance apart.

i.e. $F = G \ m_1 m_2 / r^2$

2.0 OBJECTIVES

The objectives of this module are

- to know which interactions exist between elementary particles
- to know the carriers of each interaction
- to know the properties of the carriers

- to know what resonances are in particle physics
- to see the symmetry models employed

3.0 MAIN CONTENT

3.1 Interactions, Resonances and Symmetry Models

Elementary particles interact with each other by the exchange of carriers of the interactions. The interactions differ as well as the carriers. Resonances are intermediate particles in a reaction. Sometimes they are transient [i.e. too short-lived to be observed].

There are also models that are used to group the particles in their various families and the grouping will enable us to identify any missing particle with its corresponding properties.

3.2 Interactions in Particle Physics

Interactions are just the forces that are responsible for reactions to take place. This reminds us of the reactions in Nuclear Physics. There are four basic interactions we shall observe here in particle physics, they are known as four forces or interactions.

3.3 Different Kinds of Interactions

The interactions in particle physics include:

(i) Gravitational interaction
(ii) Electromagnetic interaction
(iii) Weak interaction and
(iv) Strong interaction

3.3.1 The Carriers of Interactions

The fundamental forces of nature are mediated by bosons which are known as carriers. These carriers of the interactions are the bosons which must be exchanged between the particles themselves before the reaction can take place. Just as there are four interactions, we also have four carriers ; one for each interaction.
Let us look at them one after the other as listed below.

3.4 Particle Interactions and Carriers

It is believed that all interactions in particle Physics are carried out through some carriers. However, the interactions each have their own carriers. In the next sub-sections you will get to know the interactions as well as their carriers. The carriers are bosons and their properties are also stated.

3.4.1 Gravitational Interactions

The weakest of the interactions or forces under consideration is also the most familiar and the first law of physics to be mathematically described. This is the gravitational law discovered by Sir Isaac Newton. It states that the force between two point masses is directly proportional to the product of the masses and inversely proportional to the square of their distance apart.
i.e. $F = G\, m_1 m_2 / r^2$

. Because this force is always attractive and its affect on general theory of relatively cannot be tested, its effect on fundamental particles and nuclear physics is generally not considered.

CARRIER: The carriers of the gravitational interaction are known as gravitons the quanta of gravitational field. Exchange of a virtual graviton between two protons will lead to the gravitational attraction between them.

Gravitons have zero mass, spin of 2 and charge is zero.

3.4.3 Electromagnetic Interaction

Electromagnetic force is the second force to be considered.

The laws used for force relations in this case are Coulomb’s law and Biot-Savart law which are also inverse-squared laws. Light waves are examples of electromagnetic phenomenon and we have seen that electromagnetic forces govern the behavior of electrons in atoms and molecules.

Maxwell developed the theory of electromagnetism and his equations were later developed by Schrödinger, Dirac and Heisenberg. Nuclear processes can hence be thought of as electromagnetism. For example, the decay of gamma rays involve electromagnetism.

$$\gamma \rightarrow e^{+} + \overline{e}$$

CARRIER:

The carriers of electromagnetic interactions are the photons. They have mass equal to zero, spin 1 and charge zero (ie γ particles).

3.4.3 Weak Interactions

Weak interaction is also a type of nuclear force. An example of its manifestation is the beta decay of a nucleus. The Electromagnetic waves are believed to be quantized with a quantum known as a photon (γ). About 1930, this belief was developed that a force arises from exchange of photons between two charged particles. This development made Yukawa in 1935 to try it for nuclear force. He tired to exchange a massive particle so as to obtain short range of the force. i.e. Two electrons hit and came apart, there is exchange of photons, mass is equal to zero, range = ∞

For proton there must be some particle involved and this particle cannot be a photon because if range of force is infinity (∞), the uncertainty in force is also ∞ and mass must be zero to keep the law invariant.

CARRIER:

The carriers of the weak interaction are the charged W^t , W^- and the neutral Z^0 bosons.

Masses of W^t + W^- particles are 81,800 MeV/C^2 while mass of Z^0 particle = 92,600 MeV/C^2.

These enormous masses account for the extremely short range of the weak interaction (or weak force).

3.4.4 Strong Interactions

The force that holds nuclei together is strong interaction forces; which is very strong because it must overcome the Coulomb force inside the atom.

However the strong force here must be short ranged of the order of 10^{-13}cm and it is known as nuclear force because it exists inside the nucleus of the atoms. Reactions that obey this force are alpha decay, nuclear fission, nuclear fusion and scattering of nucleons by nuclei at high energy. The mathematical form of the strong force is not easily written.

CARRIER:

The carriers of the more fundamental strong interaction are the gluons. They have mass zero, spin 1 and charge zero.

They have not been detected directly but they are permanently hidden from view within the hadrons.

3.5 Resonances

Physicists prefer to call certain objects resonances rather than particles because these objects are (hypothetical) intermediate states in a reaction chain. These particles are short-lived intermediate states.

The particles include lambda with energy 1520 meV written as $\Lambda(1520)$. This is a $[K^{-}P]$ resonance; or a $[\overline{K}^{0}\Lambda]$resonance or a $[\Sigma^{+}\pi\text{-}1]$ resonance.

This $\Lambda(1520)$ was found in collisions between kaons and protons in a bubble chamber where a variety of reactions take place.
e.g

$$\begin{aligned} K^{-} + p \rightarrow \Lambda(1520) &\rightarrow K^{-} + p \\ &\rightarrow \overline{K}^{0} + p \\ &\rightarrow \Sigma^{-} + \pi^{-} \\ &\rightarrow \Sigma^{-} + \pi^{+} \\ &\rightarrow \Sigma^{0} + \pi^{0} \\ &\rightarrow \Lambda + \pi^{+} + \pi^{-} \end{aligned}$$

The reaction cross-section for each of the reactions is some function of energy. It can be plotted as a function of the centre of mass energy. The important feature of the curves is the local maximum in the cross sections at a centre of mass energy of 1520 MeV. At this energy, all the cross sections have a peak. In particle physics, a resonance is that peak located around a certain energy found in differential cross sections of scattering experiments. These peaks are associated with subatomic particles like nucleons, delta baryons, upsilon mesons) and their excitations. The width of the resonance (Γ) is related to the lifetime (τ) of the particle (or its excited state) by the relation
$\Gamma = \hbar / \tau$

where ħ is the planck constant.

3.6 Symmetry Models

The symmetry models to be studied are two types. These are Mathematical models employed in the grouping of particles to their various families. They are matrices that are unitary in nature with a determinant equals to 1. They are special unitary model with a 2x2 matrix structure [SU(2)] and special unitary model with a 3x3 matrix structure [SU(3)]. They described below.

Unitary Symmetry

I-spin was used to classify particles and resonances.

GelpMann + Ne'e man in 1961 independently extended the concept of I-spin to get a new theory for pointing out regularities among many states of the particles. Their theory is now known as the SU (3) Special Unitary Model. To understand SU (3) we must first look at SU (2).
Su (2) is a model or mathematical structure defined by the properties of 2x2 matrices which are unitary and have determinant = + 1

SU (2) is special unitary model with 2x2 matrix structure SU (3) is special unitary model with 3x3 matrix structure.

SU (2) Model

In this model, multiplets exist and can be portrayed by weight diagram. Each multiplet is characterized by a quantum number I total angular momentum. The multiplet consists of 2J+1 substates corresponding to equally spaced values of J from value + J to – J, with no state absent.
Only one number is required to specify a multiplet.

SU(3) Model

This is an extension of SU(2) to a 3x3 matrix structure, unitary with determinant = + 1.
Multiplets here are called super-multiplets because they contain SU (2) multiplets. For SU(2) we require two numbers to serve the purpose of J in SU(2) model.

Let these numbers be λ_1 and λ_2.

The number of substance is given by

$$(\lambda_1 + 1)(\lambda_2 + 1)\left(\frac{\lambda_1 + \lambda_2}{2} + 1\right)$$

Weight diagrams here are 2 dimensional with hypercharge Y on the y-axis and third component of I-spin (T_3) on x-axis.

4.0 CONCLUSION

According to the quantum theory of fields, all the interactions rely on the mechanism of exchange of quanta. Each of the force fields has its own quanta – analogous to photons – which act as carriers of the interaction.

Thus all the four forces are transmitted from one particle to another by emission, propagation and absorption of their corresponding carriers. You have also seen that resonances exist as intermediate states in a reaction.

5.0 SUMMARY

The carriers of the four interactions are bosons having integer spins. They are referred to as intermediate bosons.

These intermediate bosons and their properties are easily put on a table below

Name	**Symbol**	**Antiparticle**	**Charge (e)**	**Spin**	**Mass (GeV/c^2)**	**Interaction mediated**	**Existence**
Photon	Γ	Self	0	1	0	Electromagnetic	Confirmed
W boson	W−	W+	−1	1	80.4	Weak interaction	Confirmed
Z boson	Z	Self	0	1	91.2	Weak interaction	Confirmed
Gluon	G	Self	0	1	0	Strong interaction	Confirmed
Graviton	G	Self	0	2	0	Gravitation	Unconfirmed

6.0 TUTOR-MARKED ASSIGNMENT

[TM3.1] Why are the interaction carriers called bosons?

[TM3.2] List the interactions on a table with their corresponding carriers and their spin quantum numbers.

[TM3.3] The mass of the W^+ boson is 80.400 MeV/c^2 , Calculate the range of the weak interaction ..

7.0 REFERENECS/ FURTHER READING

Particle Physics by B. R. Martin, G. Shaw (2nd edition).

An Introduction to the Physics of Nuclei and Particles by R. Dunlap

Particle Physics by B. R. Martin, G. Shaw John Wiley & Sons; 3rd edition (December 3, 2008)

Video link

https://www.youtube.com/shorts/UmLXLWBJAdg