A 300 Level Course: POST-SIWES SEMESTER

PHYS 340: NUCLEAR AND PARTICLE PHYSICS I

Credit: 2 units. Duration of Course: 8 weeks of didactic lectures

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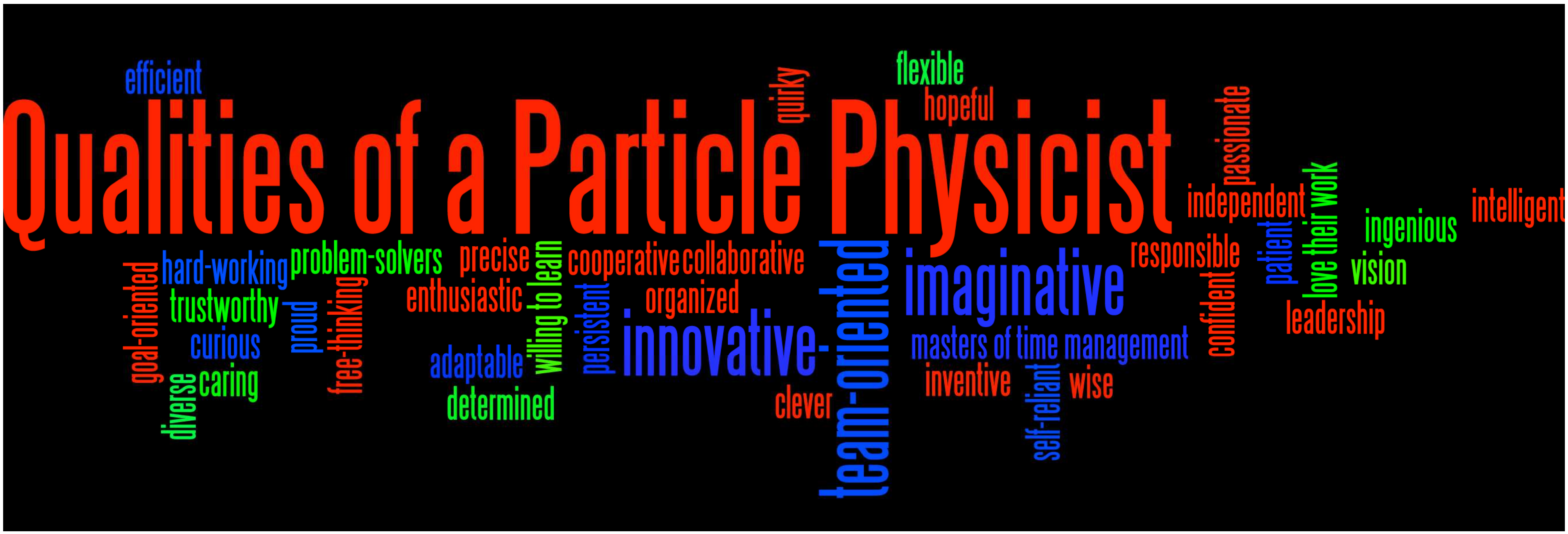
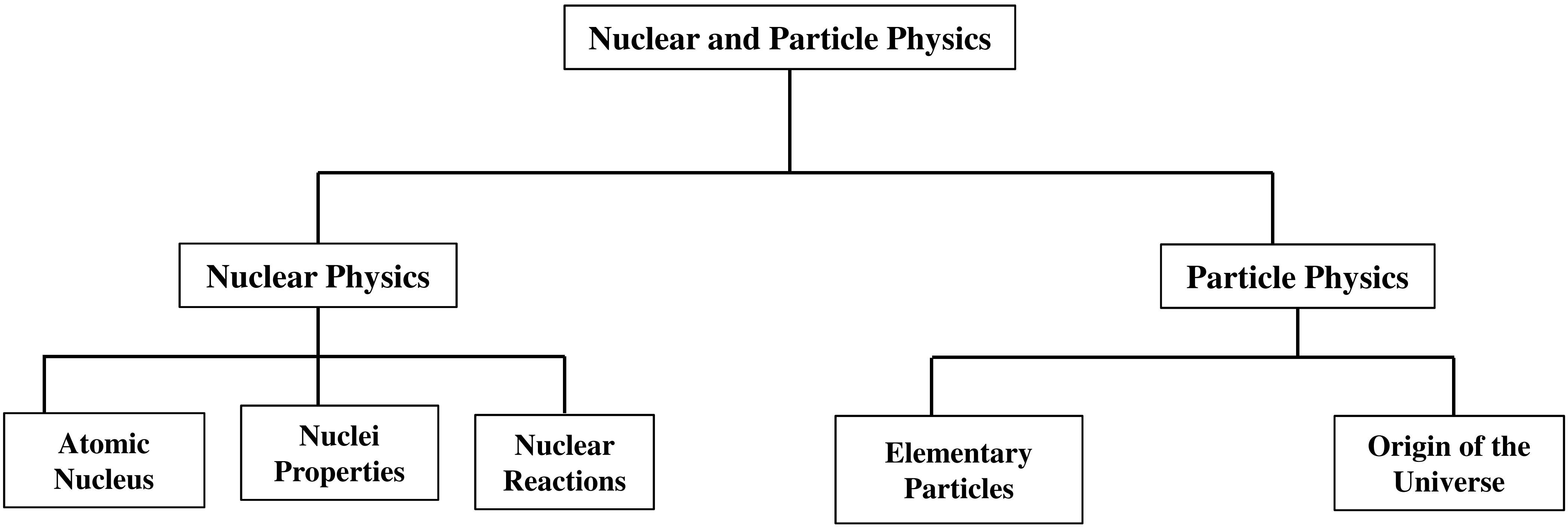
TOPIC: Elementary Particle Physics



ORGANOGRAM: INTRO. TO COURSE DESCRIPTION



Quantity	*Symbol*	*Value*
Speed of light in vacuum	c	2.998×10^8 ms^{-1}
Planck's constant	h	4.136×10^{-24} GeV s
	$\hbar \equiv h/2\pi$	6.582×10^{-25} GeV s
	$\hbar c$	1.973×10^{-16} GeV m
	$(\hbar c)^2$	3.894×10^{-31} GeV^{2}m^2
electron charge (magnitude)	e	1.602×10^{-19} C
Avogadro's number	N_A	6.022×10^{26} kg-mole^{-1}
Boltzmann's constant	k_B	8.617×10^{-11} MeV K^{-1}
electron mass	m_e	0.511 MeV/c^2
proton mass	m_p	0.9383 GeV/c^2
neutron mass	m_n	0.9396 GeV/c^2
W boson mass	M_W	80.43 GeV/c^2
Z boson mass	M_Z	91.19 GeV/c^2
atomic mass unit	$u \equiv (\frac{1}{12}\text{mass}\ {}^{12}\text{C atom})$	931.494 MeV/c^2
Bohr magneton	$\mu_B \equiv e\hbar/2m_e$	5.788×10^{-11} MeV T^{-1}
Nuclear magneton	$\mu_N \equiv e\hbar/2m_p$	3.152×10^{-14} MeV T^{-1}
gravitational constant	G_N	$6.709 \times 10^{-39}\hbar c(\text{GeV}/c^2)^{-2}$
fine structure constant	$\alpha \equiv e^2/4\pi\varepsilon_0\hbar c$	$7.297 \times 10^{-3} = 1/137.04$
Fermi coupling constant	$G_F/(\hbar c)^3$	1.166×10^{-5} GeV^{-2}
strong coupling constant	$\alpha_s(M_Z c^2)$	0.119

$$1\ eV = 1.602\ \times 10^{-19} J$$

$$1\ eV/c^2 = 1.783 \times 10^{-38} kg$$

$$1\ fermi = 1\ fm = \ 10^{-15} m$$

$$1\ barn = 1b = 10^{-28} m^2$$

$$1\ Tesla = 1T = 0.561\ \times\ 10^{30}\ MeV/c^2 C^{-1} s^{-1}$$

$$1\ year = 3.1536\ \times\ 10^7 s$$

PARTICLE	SYMBOL	ELEMENTARY CHARGE	REST MASS (amu)	ENERGY EQUIVALENT (MeV)
Alpha	α, $^4He^{2-}$	+2	4.00154	3,727
Proton	p, $^1H^+$	+1	1.007276	938
Electron	e^-	-1	0.000549	0.511
Negatron (beta minus)	β^-	-1	0.000549	0.511
Positron (beta plus)	β^+	+1	0.000549	0.511
Neutron	n^0	0	1.008665	940

amu, atomic mass unit , defined as 1/12th the mass of a carbon-12 atom. Elementary charge is a unit of electric charge where 1 is equal in magnitude to the charge of an electron.

Transition: Atomic Physics – Nuclear Physics – Particle Physics

1896: Henri Becquerel discovered radioactivity

1897: Pierre and Marie Curie and Ernest Rutherford *et al* further investigated this phenomenon.

1903: Nobel prize in Physics jointly awarded to Becquerel and Pierre and Marie Curie.

1908: Nobel prize in Chemistry awarded to Rutherford.

Around 1896: J.J Thompson established the nature of cathode rays (free electrons).

*__1894__: Stoney coined the word "electron" with symbol e^-

Around 1896: Thompson was able to measure the mass and charge of electron.

1906: Thompson was awarded the Nobel Prize in Physics and suggested the "plum pudding model"

***1905**: Philipp von Lenard had received the Physics Prize for his work on cathode rays.

Transition: Atomic Physics – Nuclear Physics – Particle Physics

1911: Rutherford *et al* and Geiger and Marsden began to work on nuclear size determination through alpha-scattering methods.

***Long ago**: Soddy coined the word *isotopism* and conceived isotopic atoms.

1932: Chadwick made a classic discovery on the explanation of isotopes.

Around 1930s: Irene curie and Federic Joloit observed that neutral radiation was emitted when alpha particles bombarded beryllium which led to the study of neutral radiation.

1913: Neils Bohr applied the newly emerging quantum theory and the result was the now well-known Bohr model of the atom.

*Refined modern versions of this model, including relativistic effects described by the **Dirac** equation.

Heisenberg later applied quantum mechanics to the nucleus, now viewed as a collection of neutrons and protons, collectively called nucleons.

Transition: Atomic Physics – Nuclear Physics – Particle Physics

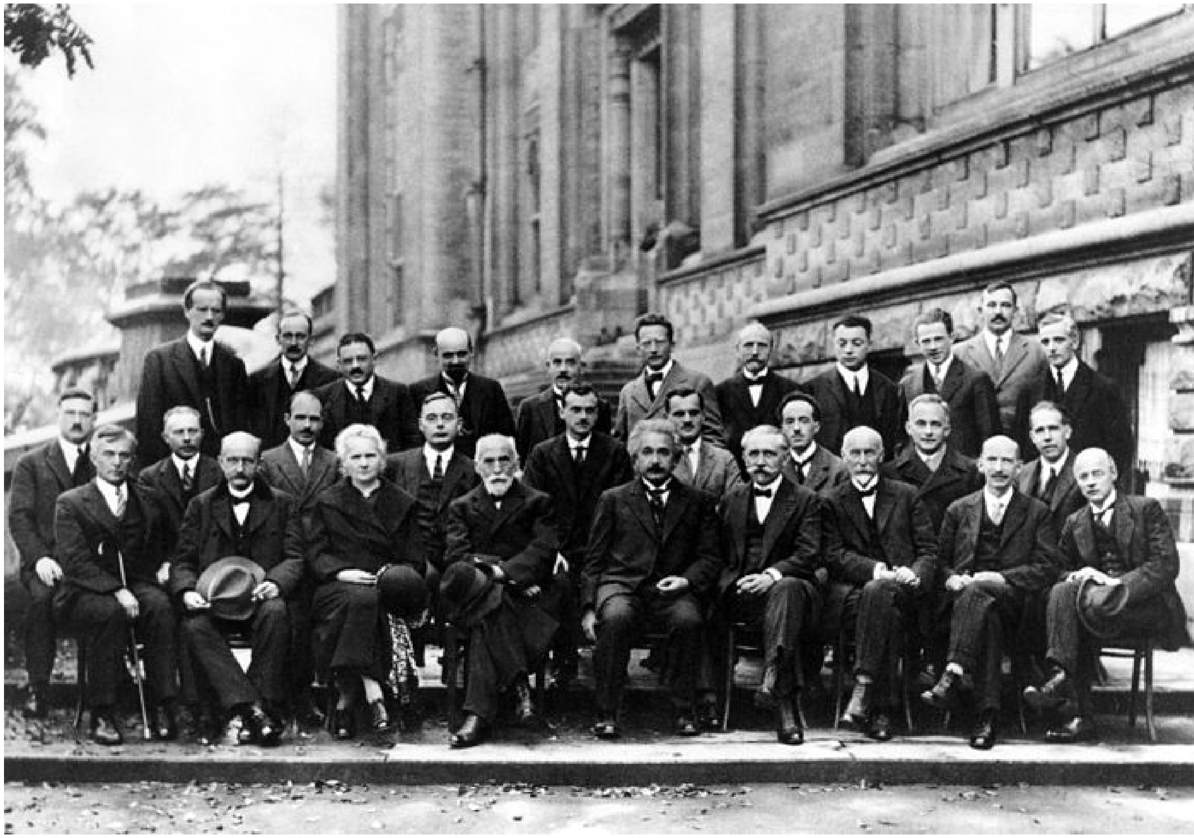
Frederick Soddy was awarded the **1921** Nobel Prize in Chemistry for his work on isotopes.

Irene Curie and Frederic Joliot received the **1935** Nobel Prize in Chemistry for synthesizing new radioactive elements.

James Chadwick received the **1935** Nobel Prize in Physics for his discovery of the neutron.

Werner Heisenberg received the **1932** Nobel Prize in Physics for his contributions to the creation of quantum mechanics and the idea of isospin symmetry.

Solvay Conference



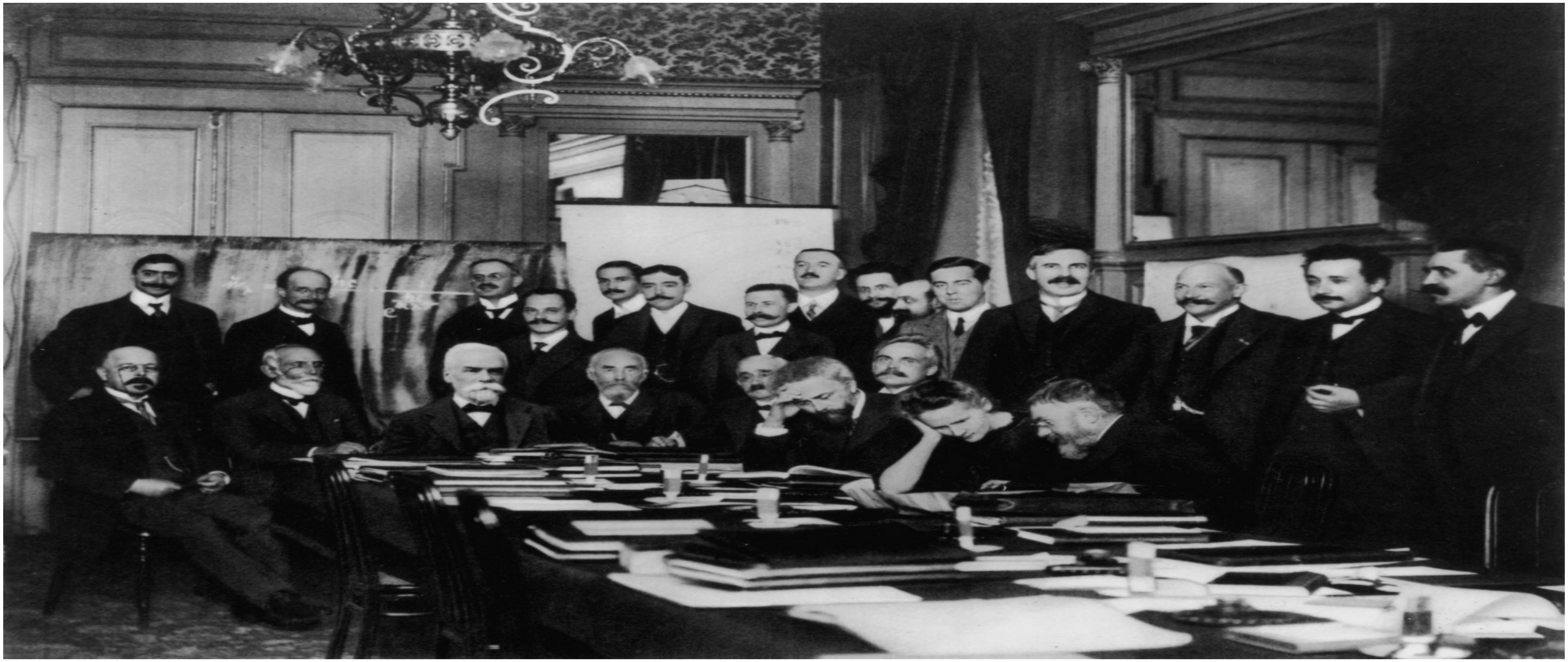
Picture order: left to right:

Back: Auguste Piccard, Émile Henriot, Paul Ehrenfest, Édouard Herzen, Théophile de Donder, Erwin Schrödinger, JE Verschaffelt, Wolfgang Pauli, Werner Heisenberg, Ralph Fowler, Léon Brillouin

Middle: Peter Debye, Martin Knudsen, William Lawrence Bragg, Hendrik Anthony Kramers, Paul Dirac, Arthur Compton, Louis de Broglie, Max Born, Niels Bohr

Front: Irving Langmuir, Max Planck, Marie Curie, Hendrik Lorentz, Albert Einstein, Paul Langevin, Charles-Eugène Guye, CTR Wilson, Owen Richardson

Solvay Conference



The Emergence of Particle Physics: the Standard Model and Hadrons.

The 19th century view of atoms as particles had been replaced and a larger group of physically smaller entities now enjoyed this status: electrons, protons and neutrons; and two electrically neutral particles: photons and neutrinos.

The neutrino was postulated by Fermi in 1930 to explain the apparent non-conservation of energy observed in the decay products of some unstable nuclei where β-rays are emitted, the so-called β-decays.

Prior to Fermi's suggestion, β-decay had been viewed as a parent nucleus decaying to a daughter nucleus and an electron.

The 1950s also saw technological developments that enabled high-energy beams of particles to be produced in laboratories.

1960s heralded the discovery of a very large number of unstable particles with very short lifetimes.

The Emergence of Particle Physics: the Standard Model and Hadrons.

The quark model was firstly suggested by Murray Gell-Mann in the 1960s and George Zweig independently and simultaneously this model which postulated that the new particles were bound states of three families of more fundamental physical particles.

Gell-Mann called these quarks (q). Because no free quarks were detected experimentally, there was initially considerable skepticism for this view.

However, evidence for the existence of quarks as real particles came in the 1960s from a series of experiments analogous to those of Rutherford et al where high-energy beams of electrons and neutrinos were scattered from nucleons.

Gell-Mann received the 1969 Nobel Prize in Physics for contributions and discoveries concerning the classification of elementary particles and their interactions

The Emergence of Particle Physics: the Standard Model and Hadrons.

The best theory of elementary particles we have at present is called, rather prosaically, the **standard model**.

This aims to explain all the phenomena of particle physics, except those due to gravity, in terms of the properties and interactions of a small number of elementary (or fundamental) particles, which are now defined as being point-like, without internal structure or excited states.

Particle physics thus differs from nuclear physics in having a single theory to interpret its data.

An elementary particle is characterized by, amongst other things, its mass, its electric charge and its spin. The spin is a permanent angular momentum possessed by all particles in quantum theory, even when they are at rest.

Elementary Particles

Elementary particle physics is also called high-energy physics.

The discovery all elementary particles have been through experiments, mathematical computations and simulations and with the use of particle accelerators.

All known elementary particles have been grouped under two main classes: Hadrons and Leptons.

Hadrons: They are particles that interact mainly by strong interaction.

Leptons: They are particles that respond to weak interaction.

In classical physics we describe the interaction of charged particles in terms of electric and magnetic forces. In quantum mechanics we can describe this interaction in terms of emission and absorption of photons.

Classification of Elementary Particles

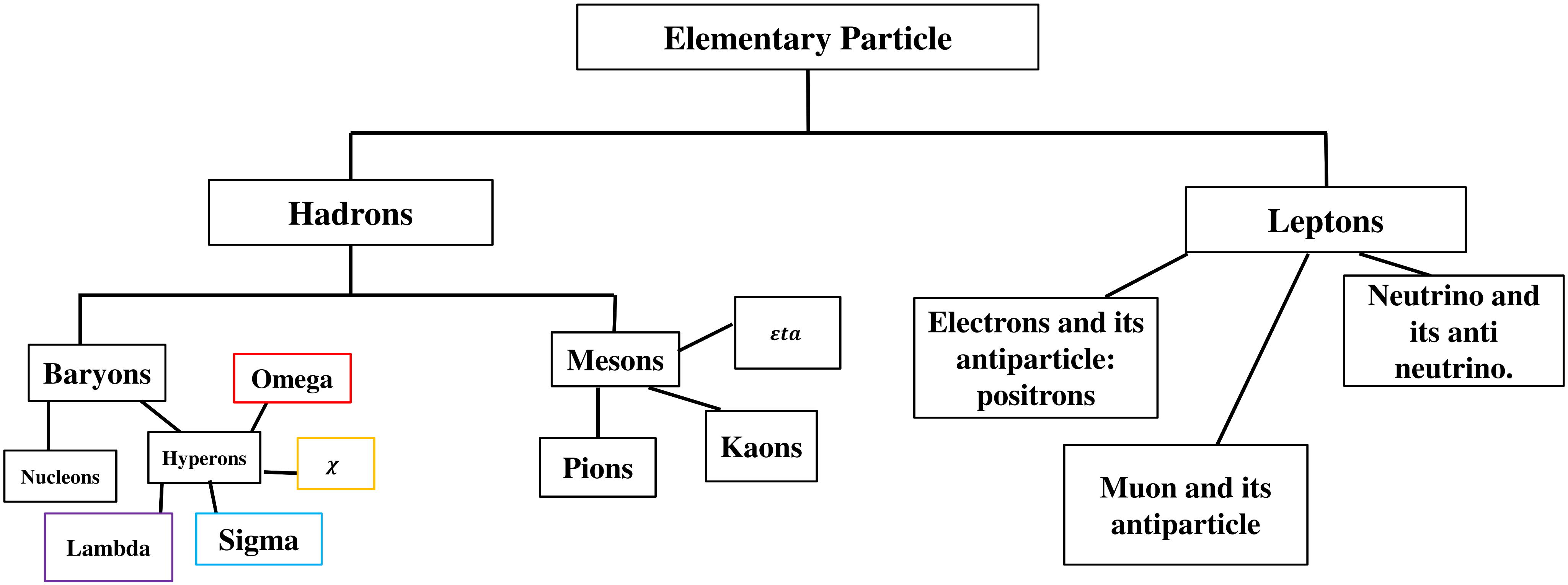


TABLE 10.1: ELEMENTARY PARTICLE CHARACTERISTICS

Class	Name	Particle	Anti particles	Rest Mass in MeV	Mean life (Sec.)	Spin ($\hbar$)	L_e	L_μ	B	S	Y	T	T_z
							(antiparticles have opposite signs)						
Mass less Boson	Photon	γ	(γ)	0	Stable	1							
	Graviton	g	g	0	Stable	2							
Lepton (Fermions)	Electron	e^-	e^+	0.51	Stable	½	+1	0	0				
	Muon	μ^-	μ^+	106	2×10^{-6}	½	0	+1	0				
	e-neutrino	ν_e	$\bar{\nu}_e$	0	Stable	½	+1	0	0				
	μ-neutrino	ν_μ	$\bar{\nu}_\mu$	0	Stable	½	0	+1	0				
Hadrons Mesons (Boson)	Pion	π^+	π^-	140	2.6×10^{-8}	0	0	0	0	0	0	1	+1
		π^0	(π^0)	135	0.8×10^{-16}	0	0	0	0	0	0	1	0
		π^-	π^+	140	2.6×10^{-8}	0	0	0	0	0	0	1	−1
	Kaon	K^+	K^-	494	1.24×10^{-8}	0	0	0	0	+1	+1	½	+½
		K^0	$\overline{K^0}$	494	1.24×10^{-8}	0	0	0	0	+1	+1	½	−½
	Eta	η^0	(η^0)	549	7×10^{-19}	0	0	0	0	0	0	0	0
Hardrons Baryons (Fermion)	Nucleon Proton	p	$\overline{p}$	938.3	Stable	½	0	0	+1	0	+1	½	+½
	Neutron	n	$\overline{n}$	938.6	930	½	0	0	+1	0	+1	½	−½
	Lambda Hyperon	Λ^0	$\overline{\Lambda^0}$	1116	26×10^{-10}	½	0	0	+1	−1	0	0	0
	Sigma hyperon	Σ^+	$\overline{\Sigma^-}$	1189	0.8×10^{-20}	½	0	0	+1	−1	0	1	+1
		Σ^0	$\overline{\Sigma^0}$	1192	5.8×10^{-20}	½	0	0	+1	−1	0	1	0
		Σ^-	$\overline{\Sigma^+}$	1197	1.5×10^{-10}	½	0	0	+1	−1	0	1	−1
	xi hyperon	Ξ^0	$\overline{\Xi^0}$	1315	3×10^{-10}	½	0	0	+1	−2	−1	½	+½
		Ξ^-	$\overline{\Xi^+}$	1321	1.7×10^{-10}	½	0	0	+1	−2	−1	½	−½
	omega hyperon	Ω^-	$\overline{\Omega^+}$	1672	1.3×10^{-10}	3/2	0	0	+1	−3	−2	0	0

Properties of Particles

<u>Type 1: Baryons</u>

Among the baryons, the proton is relatively stable. However, the current theories of elementary particles indicate that proton should be unstable, such that it decays into leptons.

Neutrons remain stable so long as they stay inside a nucleus.

The hyperons are heavier than the nucleons.

Baryons are also called fermions.

Types of hyperon: Lambda, Sigma, Ksi and Omega.

Properties of Elementary Particles

Types of Hyperons

1) Lambda hyperon

It was the first hyperon discovered in the studies of cosmic rays.

The rest mass from its probable decay is around $2183m_e$

The decay through strong interactions are:

$\lambda \rightarrow p + \pi^{-}$ (66%)

$\lambda \rightarrow n + \pi^{0}$ (34%)

The mean life of lambda-hyperon is $2.6 \times 10^{-10}s$

Properties of Elementary Particles

2) The sigma hyperon

There are three types of sigma hyperons: Σ^+, Σ^- and Σ^0.

The known decay modes (strong interaction) for the charged sigma hyperons are:

$\Sigma^+ \rightarrow p + \pi^0$ (53%) [Rest mass m(Σ^+)= 2327m_e Rest mass energy m(Σ^+)c^2= 1189MeV]

$\Sigma^+ \rightarrow n + \pi^+$ (47%) [Rest mass m(Σ^-)= 2342m_e Rest mass energy m(Σ^-)c^2= 1197MeV]

Only one decay mode is observed for Σ^-

$\Sigma^- \rightarrow n + \pi^-$ (100%) [Rest mass m(Σ^0)= 2333m_e Rest mass energy m(Σ^0)c^2= 1192MeV]

The mean life of sigma hyperons are:

$\tau(\Sigma^+) = 0.8 \times 10^{-10} sec.$

$\tau(\Sigma^-) = 1.5 \times 10^{-10} sec.$

$\tau(\Sigma^0) = 5.8 \times 10^{-20} sec.$

Properties of Elementary Particles

3) Xi (Ksi) Hyperon

There are two types of Xi hyperons. Ξ^0 and Ξ^-

These hyperons decay into cascade decay and they are know as cascade particles.

The decay modes of Xi-hyperons are given as:

$$\Xi^0 \rightarrow \lambda + \pi^0 \rightarrow p + \pi^-$$

$$\Xi^- \rightarrow \lambda + \pi^- \rightarrow p + \pi^-$$

Properties of Elementary Particles

The rest mass and rest mass energy of Xi-hyperons have been estimated as:

$m(\Xi^0) = 2573 m_e$ and $m(\Xi^0)c^2 = 1315$ MeV

$m(\Xi^-) = 2585 m_e$ and $m(\Xi^-)c^2 = 1321$ MeV

The mean life times are:

$\tau(\Xi^0) = 3 \times 10^{-10} sec.$ $\tau(\Xi^-) = 1.7 \times 10^{-10} sec.$

Properties of Elementary Particles

4) Omega hyperon (Ω^-)

It is the heaviest hyperon.

It undergoes into cascade decays through weak interactions.

The sequence of Ω^- is given below:

$$\Omega^- \to \Xi^0 + \pi^- \to \Xi^- \square + \pi^0 \to p + \pi^-$$

The rest mass and rest mass energy has been estimated to be:

$m(\Omega^-) = 3272 m_e$ $\quad$ $m(\Omega^-)c^2 = 1672$ MeV

The mean life is: $\tau(\Omega^-) = 1.3 \times 10^{-10} sec$

Properties of Elementary Particles

Type 2: Mesons

These are particles having rest mass between electron mass and proton mass. All the mesons have spin zero and as such they are bosons.

In 1935 the Japanese physicist Hideki Yukawa suggested that a hypothetical particle that he called a meson might mediate the nuclear force.

He showed that the range of the force was related to the mass of the particle.

In 1947 a family of three particles, called π mesons or pions, were discovered. Their charges are +e, -e and zero, and their masses are about 270 times the electron mass.

The pions interact strongly with nuclei, and they are the particles predicted by Yukawa.

Properties of Elementary Particles

Examples of Mesons are: Pions, Kaons and εta

1) Pions or pi mesons: production and properties

As predicted by H. Yukawa, pions are carriers of strong nuclear interaction. They were first discovered by C.F Powell in 1947 in the studies of cosmic rays.

The result of cosmic ray investigations revealed that pions are produced by nucleon-nucleon collision and also by interaction of high-energy photons with nucleons.

This led to believe that pions can be produced artificially using high energy particle accelerators.

The pions were first produced in 1948 when a strong beam of 380 MeV alpha particles obtained from the synchrocyclotron at the Berkeley laboratory were made to strike a carbon target.

Properties of Elementary Particles

Examples of Mesons are: Pions, Kaons and εta

1) Pions or pi-mesons: production and properties

The expected pions were detected in photographic emulsion.

The first pion so detected was negatively charged.

The most suitable targets for the production of pions through nucleon-nucleon collision have been hydrogen and deuterium.

The π^+ mesons are produced through the following reactions:

$p + p \ \rightarrow D + \ \pi^+$

$p + p \rightarrow p + n + \ \pi^+$

	Particle	Decay mode	Relative probability %	Half-life, s
	Photon	Stable		
	Graviton	Stable		
Leptons	Neutrino	Stable		
	Electron	Stable		
	Muon	$\mu^- \rightarrow e^- + \nu + \overline{\nu}$		1.52×10^{-6}
Mesons	Pion	$\pi^+ \rightarrow \mu^+ + \nu$	100	1.80×10^{-8}
		$\rightarrow e^+ + \nu$	$\sim 10^{-4}$	
		$\pi^0 \rightarrow \gamma + \gamma$	99	6×10^{-17}
		$\rightarrow \gamma + e^+ + e^-$	1	
	Kaon	$K^+ \rightarrow \mu^+ + \nu$	63	8.56×10^{-9}
		$\rightarrow \pi^+ + \pi^0$	21	
		$\rightarrow 2\pi^+ + \pi^-$	5.6	
		$\rightarrow \pi^0 + e^+ + \nu$	4.8	
		$\rightarrow \pi^0 + \mu^+ + \nu$	3.4	
		$\rightarrow \pi^+ + 2\pi^0$	1.7	
		$K^0 \rightarrow \pi^+ + \pi^-$	35	6.0×10^{-11}
		$\rightarrow 2\pi^0$	15	
	Eta	$\eta^0 \rightarrow \gamma + \gamma$	33	$< 10^{-16}$
		$\rightarrow \pi^0 + \gamma + \gamma$	20	
		$\rightarrow 3\pi^0$	20	
		$\rightarrow \pi^+ + \pi^- + \pi^0$	5	
		$\rightarrow \pi^+ + \pi^- + \gamma$		
Baryons	Proton	Stable		
	Neutron	$\eta^0 \rightarrow p^+ + e^- + \overline{\nu}$		$\sim 7.0 \times 10^2$
	Lambda	$\Lambda \rightarrow p^+ + \pi^-$	66	1.76×10^{-10}
		$\rightarrow n^0 + \pi^0$	34	
	Sigma	$\Sigma^+ \rightarrow p^+ + \pi^0$	53	
		$\rightarrow n^0 + \pi^+$	47	5.6×10^{-11}
		$\Sigma^0 \rightarrow \Lambda + \gamma$		$< 7 \times 10^{-15}$
		$\Sigma^- \rightarrow n^0 + \pi^-$		1.1×10^{-10}
	Xi	$\Xi^0 \rightarrow \Lambda + \pi^0$		2.0×10^{-10}
		$\Xi^0 \rightarrow \Lambda + \pi^-$		1.2×10^{-10}
	Omega	$\Omega^- \rightarrow \Lambda + K^-$	50	10^{-10}
		$\rightarrow \Sigma^0 + \pi^-$	50	

*To obtain the decay of antiparticles, change all particles into antiparticles on both sides of the equations.

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5) Nuclear Reactor Physics by Weston M. Stacey

6) University Physics with Modern Physics by Hugh D. Young and Roger A. Freedman

About Lecturer:

Opadele A.E is a physics enthusiast with special interest in Medical Physics. He loves to present the complex theories in physics in seemingly simple approach for effectual understanding.

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If you have any questions, let me know