MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Physics Department

Physics 8.286: The Early Universe December 1, 2009
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Lecture Notes 11

INTRODUCTION TO PARTICLE PHYSICS

STATUS FOR 2009: This set of lecture notes is being skipped this year, but I am making it available for completeness. It has not been updated since 2005. The suggested reading mentioned below is certainly worthwhile, but it will not be part of the course this year.

SUGGESTED READING: "Quarks with Color and Flavor", Sheldon Lee Glashow, *Scientific American*, October 1975. This is a very good article, but there is too little time left in the term for me to assign it. I will distribute copies of the article, so that you can read it over the summer if you are interested.

SUGGESTED READING: "A Unified Theory of Elementary Particles and Forces", by Howard Georgi, *Scientific American*, April 1981. Reprinted in *Particle Physics in the Cosmos*, edited by Richard A. Carrigan, Jr. and W. Peter Trower. This article is not required, but may help you to understand the material discussed in lecture and in these notes.

INTRODUCTION:

With this lecture we will begin a survey of modern particle physics. We will begin by talking about particle physics, and then we will spend the last few lectures discussing the impact that particle physics has recently had on the study of cosmology.

These lecture notes consist of three tables, and no text. The tables contain a lot of information, but it would be dishonest if I pretended that they are self-explanatory. To understand what the tables are about, you should listen and take notes in lecture.

Note, by the way, that a much more complete list of elementary particle properties can be found in "Review of Particle Physics," S. Eidelman et al. (Particle Data Group), *Physics Letters* **B592,** 1 (2004). In addition, you can obtain (for free!) a very useful summary called the "Particle Properties Data Booklet", by signing up at the web page http://pdg.lbl.gov/pdgmail/.

The same information can be accessed through the web at http://pdg.lbl.gov/.

TABLE 1: CLASSIFICATION OF ELEMENTARY PARTICLES

LEPTONS:

Particle	Symbol	Energy	Charge	Spin	
Electron	e	0.5109989 MeV	-1	$\frac{1}{2}$	First generation
Electron neutrino	ν_e	0 - 3 eV	0	$\frac{1}{2}$	First generation
Muon	μ	105.65836 MeV	-1	$\frac{1}{2}$	Second generation
Muon neutrino	ν_μ	0 - 0.19 MeV	0	$\frac{1}{2}$	Second generation
Tau	τ	$1776.99^{+0.29}_{-0.26}$ MeV	-1	$\frac{1}{2}$	Third generation
Tau neutrino	ν_τ	0 - 18.2 MeV	0	$\frac{1}{2}$	Third generation

Each particle listed above has a corresponding antiparticle.

The neutrinos are all "left-handed", meaning that their angular momentum always points opposite their direction of motion. The antineutrinos are "right-handed".

VECTOR BOSONS:

Particle	Symbol	Energy	Charge	Spin	Comment
Photon	γ	0	0	1	Carrier of electro- magnetic interactions
Intermediate Vector Bosons	W^+, W^-	80.423 ± 0.039 GeV	± 1	1	Carrier of the weak interactions
Neutral Intermediate Vector Boson	Z^0	91.1876 ± 0.0021 GeV	0	1	Carrier of the neutral weak interactions
Gluons	g	Confined	0	1	There are 8 gluons, carriers of the strong interactions

The photon and the Z^0 are their own antiparticles, and the W^+ and W^- are antiparticles of each other. The set of eight gluons includes the antiparticles.

BARYONS:

Particle	**Symbol**	**Energy**	**Charge**	**Spin**	**Lifetime**
Proton	p	938 MeV	+1	$\frac{1}{2}$	$> 10^{32}$ years
Neutron	n	940 MeV	0	$\frac{1}{2}$	15 min ($n \to p + e + \bar{\nu}_e$)
Lambda	Λ	1116 MeV	0	$\frac{1}{2}$	10^{-10} sec ($p\pi^-, n\pi^0$)
Sigma Plus	Σ^+	1189 MeV	+1	$\frac{1}{2}$	10^{-10} sec ($p\pi^0, n\pi^+$)
Sigma Zero	Σ^0	1193 MeV	0	$\frac{1}{2}$	10^{-19} sec ($\Lambda\gamma$)
Sigma Minus	Σ^-	1197 MeV	-1	$\frac{1}{2}$	10^{-10} sec ($n\pi^-$)
Xi Zero	Ξ^0	1315 MeV	0	$\frac{1}{2}$	10^{-10} sec ($\Lambda\pi$)
Xi Minus	Ξ^-	1321 MeV	-1	$\frac{1}{2}$	10^{-10} sec ($\Lambda\pi^-$)
Delta	Δ^{++}, Δ^+ Δ^0, Δ^-	1230 to 1234 MeV	-1 to +2	$\frac{3}{2}$	10^{-23} sec ($n\pi, p\pi$)
Sigma Star	Σ^{*+}, Σ^{*0} Σ^{*-}	1382 to 1387 MeV	-1 to +1	$\frac{3}{2}$	10^{-23} sec ($\Lambda\pi, \Sigma\pi$)
Xi Star	Ξ^{*-}, Ξ^{*0}	1532 to 1535 MeV	0,-1	$\frac{3}{2}$	10^{-22} sec ($\Xi\pi$)
Omega Minus	Ω^-	1672 MeV	-1	$\frac{3}{2}$	10^{-10} sec (ΛK^-)

$\vdots$

Each particle listed above has a corresponding antiparticle.

Each particle listed above has baryon number +1, while the antiparticles have baryon number -1.

MESONS:

Particle	**Symbol**	**Energy**	**Charge**	**Spin**	**Lifetime**
Pion	π^+, π^-	139.570 MeV	±1	0	10^{-8} sec ($\mu^+\nu_\mu$)
Pion	π^0	134.977 MeV	0	0	10^{-16} sec ($\gamma\gamma$)
Kaon	$K^\pm$	494 MeV	±1	0	10^{-8} sec ($\mu^+\nu_\mu, \pi^+\pi^0$)
K Zero Short	K^0_S	498 MeV	0	0	10^{-10} sec ($\pi^+\pi^-, \pi^0\pi^0$)
K Zero Long	K^0_L	498 MeV	0	0	10^{-7} sec ($3\pi, 2\pi, \pi\mu\nu,$ $\pi e\nu$)
Eta	η	547 MeV	0	0	10^{-18} sec ($\gamma\gamma, 3\pi$)
D Plus (Minus)	D^+, D^-	1869 MeV	±1	0	10^{-12} sec (many modes— $\bar{K}^0\pi^+\pi^0$ most likely)

Particle	**Symbol**	**Energy**	**Charge**	**Spin**	**Lifetime**	
D Zero (Bar)	$D^0, \bar{D}^0$	1865 MeV	0	0	10^{-12} sec	(many modes— $K^-\pi^+\pi^0\pi^0$ most likely)
D_S Plus (Minus) was $F^{\pm}$	D_S^+, D_S^-	1968 MeV	± 1	0	10^{-12} sec	($\phi\pi^+$ has been seen)
B Plus (Minus)	B^+, B^-	5279 MeV	± 1	0	10^{-12} sec	(many modes, including $\bar{D}^0\pi^+$)
B Zero	B^0	5279 MeV	0	0	10^{-12} sec	(many modes, including $\bar{D}^-\pi^+$)
$\vdots$						
Rho	$\rho^{\pm}, \rho^0$	768 MeV	$\pm 1, 0$	1	10^{-23} sec	$(\pi\pi)$
Omega	ω	782 MeV	0	1	10^{-22} sec	(3π)
Phi	ϕ	1019 MeV	0	1	10^{-22} sec	$(3\pi, 2K)$
J/Psi	J/ψ	3097 MeV	0	1	10^{-20} sec	(many modes— $e^+e^-, \mu^+\mu^-$ most likely)
$\vdots$						
Upsilon	Υ	9460 MeV	0	1	10^{-20} sec	(many modes— $e^+e^-, \mu^+\mu^-$ $\tau^+\tau^-$ most likely)
$\vdots$						

The list above includes both particles and their antiparticles.

TABLE 2: QUARK MODEL OF BARYONS AND MESONS

QUARKS:

Name of Quark ("Flavor")	**Symbol**	**Energy**	**Charge**	**Spin**	
Up	u	∼300 MeV	$\frac{2}{3}$	$\frac{1}{2}$	First generation
Down	d	∼300 MeV	$-\frac{1}{3}$	$\frac{1}{2}$	
Charmed	c	∼1500 MeV	$\frac{2}{3}$	$\frac{1}{2}$	Second Generation
Strange	s	∼500 MeV	$-\frac{1}{3}$	$\frac{1}{2}$	
Top (Truth)	t	100 GeV ?	$\frac{2}{3}$	$\frac{1}{2}$	Third generation
Bottom (Beauty)	b	∼5 GeV	$-\frac{1}{3}$	$\frac{1}{2}$	

Each quark comes in 3 "colors". The energy, charge, spin, etc., are independent of the color. For every quark listed above there is a corresponding antiparticle. The top quark has not yet been found.

QUARK CONTENT OF MESONS:

π^+	$u\bar{d}$
π^0	$u\bar{u} - d\bar{d}$ (The minus sign has meaning in quantum theory!)
K^+	$u\bar{s}$
K_S^0	$d\bar{s} + s\bar{d}$
K_L^0	$d\bar{s} - s\bar{d}$
η	$u\bar{u} + d\bar{d}$
D^+	$c\bar{d}$
D^0	$c\bar{u}$
$\bar{D}^0$	$u\bar{c}$
F^+	$c\bar{s}$
B^+	$u\bar{b}$
ρ^+	$u\bar{d}$
ρ^0	$u\bar{u} - d\bar{d}$
ω	$u\bar{u} + d\bar{d}$
ϕ	$s\bar{s}$
J/ψ	$c\bar{c}$
Υ	$b\bar{b}$

The color content is not shown above, but the rule is that all physical particles must be "colorless". For example, the π^+ is shown as $u\bar{d}$, but if one includes the color label it must be written as:

$$\pi^+ = u_{\text{red}}\bar{d}_{\text{red}} + u_{\text{blue}}\bar{d}_{\text{blue}} + u_{\text{yellow}}\bar{d}_{\text{yellow}} \ .$$

QUARK CONTENT OF BARYONS:

p	uud
n	udd
Λ	uds
Σ^+	uus
Σ^0	uds
Σ^-	dds
Δ^{++}	uuu
Δ^+	uud
Δ^0	udd
Δ^-	ddd
Σ^{*+}	uus
Σ^{*0}	uds
Σ^{*-}	dds
Ξ^0	uss
Ξ^-	dss
Ω^-	sss

TABLE 3: FUNDAMENTAL INTERACTIONS OF NATURE

<table>
<tr><th>INTERACTION:</th><th>GRAVITATION</th><th>WEAK INTERACTIONS
$n \to p + e + \bar{\nu}$
$\pi^+ \to \mu^+ \nu$</th><th>ELECTROMAGNETISM</th><th>STRONG INTERACTIONS
($n - p$ forces in nucleus, and force which holds quarks together)</th></tr>
<tr><td>DIMENSIONLESS COUPLING (PROTON ENERGY)</td><td>$\frac{Gm_p^2}{\hbar c} = 5.9 \times 10^{-39}$</td><td>$G_F m_p^2 \approx 10^{-5}$</td><td>$\frac{e^2}{\hbar c} = \frac{1}{137}$</td><td>$1 - 10$</td></tr>
<tr><td>TYPICAL DECAY TIME</td><td>——</td><td>$\pi^\pm, K^\pm$ 10^{-8} sec
$\Lambda, \Sigma^+, \Xi, \Omega^-$ $10^{-10} s$
n 15 mins</td><td>$\pi^0 \to \gamma\gamma$ 10^{-16} s
$\Sigma^0 \to \Lambda\gamma$ 10^{-19} s</td><td>ρ, ω, ϕ
Δ 10^{-23} sec</td></tr>
<tr><td>CLASSICAL THEORY</td><td>Isaac Newton
(1687, age 44)</td><td>——</td><td>James Clerk Maxwell
(1864, age 33)
First example of a gauge theory</td><td>——</td></tr>
<tr><td>CLASSICAL RELATIVISTIC THEORY</td><td>Einstein: General Relativity
(1916, age 37)</td><td>——</td><td>James Clerk Maxwell
(1864, age 33)</td><td>——</td></tr>
<tr><td>RELATIVISTIC QUANTUM THEORY</td><td>——</td><td>V-A Theory
Feynman & Gell-Mann (1958)
Marshak & Sudarshan (1958)
FLAWED THEORY</td><td>Quantum Electrodynamics
Feynman, Schwinger, Tomanaga, Dyson (1949)</td><td>Quantum Chromodynamics, 1970's
Gauge Theory
Quarks bound by stringlike forces, about 20 tons</td></tr>
<tr><td>EXCHANGED PARTICLE</td><td>Graviton
$M = 0$, Spin$= 2$</td><td>$W^\pm$
$M \approx 81$ GeV, Spin$= 1$
Discovered in Jan '83
135 physicists saw 6 W's</td><td>Photon γ
$M = 0$, Spin$= 1$</td><td>Gluons (8 of them)
$M = 0$, Spin$= 1$</td></tr>
<tr><td>UNIFIED THEORY</td><td></td><td colspan="2">Unified Electroweak Theory
Glashow 1970 Age 37 — Weinberg 1967 Age 34 — Salam 1968 Age 42
Theory adds Z^0, with $M \approx 91$ GeV, Spin 1
Gauge Theory
Theory adds "charmed" quark.
Crucial contributions by 't Hooft, '71</td><td></td></tr>
<tr><td>GRAND UNIFIED THEORIES</td><td></td><td colspan="3">Grand Unified Theories
Georgi and Glashow, 1974
Georgi, Quinn, and Weinberg, 1974
Gauge theories
Theories add X and Y, particles with $M \approx 10^{14}$ GeV, and spin 1
Speculative</td></tr>
<tr><td>SUPER-UNIFIED THEORIES</td><td colspan="4">Supergravity?
Ferrara, Freedman, & van Nieuwenhuizen, 1976
Superstrings?
Green and Schwarz, 1981-85</td></tr>
</table>