INTRODUCTION TO PARTICLE PHYSICS

PHYS 5380

Recommended reading:
Elementary level

Medium Level
David Griffith, *Introduction to Elementary Particles*

Advanced
F. Halzen and A. Martin, *Quarks and Leptons*
Gordon Kane, *Modern Elementary Particle Physics, updated edition*

Experimental techniques
Konrad Kleinknecht, *Detectors for Particle Radiation*

R. Stroynowski, Fall 2016
Textbooks

* first choice

Elementary level (general)

*Donald Perkins, Introduction to High Energy Physics
Cindy Schwartz, The subatomic ZOO
R.M. Barnett, H. Muhry and H. Quinn, The Charm of Strange Quarks

Medium Level (theory)

L. Okun, Leptons and Quarks
C. D. Coughlan and J. E. Dodd, The ideas of particle physics
*David Griffith, Introduction to Elementary Particles
Martinus Veltman, Facts and Mysteries in Elementary Particle Physics

Advanced (theory)

Abraham Seiden, Particle Physics, a comprehensive introduction
F. Halzen and A. Martin, Quarks and Leptons
K. Gottfried and V. Weiskopf, Concepts of Particle Physics
*Gordon L. Kane: “Modern Elementary Particle Physics: Updated Edition”
Chris Quigg, Gauge Theories of Strong, Weak and Electromagnetic Interactions
Bjorken and Drell, Quantum Field Theory
Kerson Huang, Quarks, Leptons and Gauge Fields
B.R. Martin and G. Shaw, Particle Physics
W.N. Cottingham and D.A. Greenwood, An Introduction to the Standard Model of Particle Physics
Byron P. Roe, Particle Physics at the New Millenium

Experimental techniques

* Richard Fernow, Introduction to experimental particle physics
Bruno Rossi, High Energy Physics
Konrad Kleinknecht, Detectors for Particle Radiation
Klaus Grupen and Boris Shwartz: “Particle Detectors”
Syllabus

Aug 22 (Mon)  Introduction, historical perspective, discovery of the electron, nucleus and neutron
Aug 24(Wed)  “
Aug 26(Fri)  Quantum mechanics and relativity, particle –wave duality
Aug 29(Mon)  Neutrino  “
Aug 31(Wed)  Forces and interactions
Sep  2(Fri)  LABOR DAY – no class
Sep  7(Wed)  Particle ZOO: Leptons (electrons, muons, neutrinos), quarks (pions, kaons, resonances), bosons - carrier of the force
Sep  9(Fri)  “
Sep 12(Mon)  Symmetries, conservation laws and quantum numbers: E-p, charge, angular momentum, parity, isospin, G-parity, lepton number, baryon number, flavor, charge conjugation
Sep 14(Wed)  “
Sep 16(Fri)  “
Sep 19(Mon)  Static quark model, relativistic kinematics, lab-vs-cm
Sep 21(Wed)  Dynamics, DIS, parton model
Sep 23(Fri)  CP violation, CKM matrix
Sep 26(Fri)  Weak interactions, the Standard Model, neutrino mixing
Sep 28(Wed)  Higgs
Sep 30(Fri)  Astrophysics connection (composition of the universe, dark matter, dark energy)
Oct  3(Mon)  FALl BREAK – no class
Oct  5(Wed)  Astrophysics questions
Oct  7(Fri)  Feynman diagrams
*Oct 10(Mon)  “
Oct 12(Wed)  Particle detectors: charged particles: ionization (emulsion, cloud and bubble chambers, wire chambers - spark, proportional, drift chambers), limitations on momentum measurements: Energy loss: Bethe-Bloch, dE/dx, radiation length, bremsstrahlung, Coulomb scattering, position in space
Oct 14(Fri)  Photon detection
Oct 17(Mon)  Calorimetry
Oct 19(Wed)  Particle detectors: neutrals: decays of pi0, Ks, Lambda, photon conversions, neutron interactions
Oct 21(Fri)  Scintillators, fibers
Oct 24(Mon)  Particle identification: TOF, Cerenkov light, dE/dx, muons
Oct 26(Wed)  Readout electronics, trigger, solid state trackers, radiation damage
Oct 28(Fri)  Particle detectors – neutrinos
Oct 31(Mon)  Detector systems, ATLAS
Nov  2(Wed)  Particle acceleration techniques: electrostatic, RF; cyclotron, synchrotron, linacs, storage rings
Nov  4(Fri)  “
Nov  7(Mon)  “
Nov  9(Wed)  “
Nov 11(Fri)  Student Presentation
Nov 14(Mon)  Student Presentation
Nov 16(Wed)  Student Presentation
Nov 18(Fri)  Student Presentation
Nov 21(Mon)  Student Presentation
*Nov 23(Wed)  Thanksgiving – no class
*Nov 25(Fri)  Thanksgiving – no class
Nov 28(Mon)  Student Presentation
Nov 30(Wed)  Student Presentation
Dec 2(Fri)  Student Presentation
Dec 5(Mon)  Open questions, Grand Unification, Supersymmetry, superstrings

**Tentative subjects for seminar presentations**

- Dark matter
- Magnetic monopole
- Neutrino Oscillations/Dune
- Gravitational waves/LIGO
- CP violations
- Higgs boson
- Supersymmetry
- Antimatter
- Dark energy

**Grading**

Homework 40%, Presentation – 40%, class participation – 20%
“Now the smallest Particles of Matter may cohere by the strongest Attractions and compose bigger Particles of weaker Virtue. There are therefore Agents of Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out.”
History of Elementary Particles

Chemical Elements

Subatomic Particles

Different Kinds of Basic Matter

Earth

Fire

Air

Water

Electron

Proton

Quarks

Leptons

B.C.

A.D.
The “elementary particles” at the end of the 19th century:

The Atoms of the 92 Elements

1. Hydrogen
2. Helium
3. Lithium

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92. Uranium

Mass $M_H \approx 1.7 \times 10^{-24}$ g

increasing mass

Mass $\approx 238 M_H$

Estimate of a typical atomic radius

Number of atoms /cm$^3$: $n = \frac{N_A}{\rho}$

Atomic volume: $V = \frac{4}{3} \pi R^3$

Packing fraction: $f \approx 0.52 - 0.74$

Example: Iron ($A = 55.8$ g; $\rho = 7.87$ g cm$^{-3}$)

$R = (1.1 \div 1.3) \times 10^{-8}$ cm
1894 – 1897: **Discovery of the electron**

Study of “cathode rays”: electric current in tubes at very low gas pressure (“glow discharge”) \( \rightarrow \) Current carried by particles

Measurement of the electron mass: \( m_e \approx M_H/1836 \)

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?” (J.J. Thomson)

“What good is it for?” (Queen Victoria)

**ATOMS ARE NOT ELEMENTARY**

Thomson’s atomic model (plum pudding):
- Sphere with uniform positive charge distribution
- Radius \(~ 10^{-10}\) m
- Electrons with negative electric charge embedded in the sphere
1896: **Discovery of natural radioactivity**  
(Henri Becquerel, Maria Skłodowska-Curie)  
\(\alpha\) – heavy, charged, \(\beta\) – light, charged, \(\gamma\) - neutral

1909–13: **Rutherford’s scattering experiments**  
Discovery of the atomic nucleus

α–particles: nuclei of Helium atoms spontaneously emitted by heavy radioactive isotopes  
Typical α – particle velocity \(\approx 0.05 \, c\)  \((c : \text{speed of light})\)
Expectations for $\alpha$ – atom scattering

$\alpha$ – atom scattering at low energies is dominated by Coulomb interaction

$\alpha$ – particles with impact parameter $= b$ “see” only electric charge within sphere of radius $= b$ (Gauss theorem for forces proportional to $r^{-2}$)

For Thomson’s atomic model the electric charge “seen” by the $\alpha$ – particle is zero, independent of impact parameter

$\Rightarrow$ no significant scattering at large angles is expected
Rutherford’s observation:
significant scattering of $\alpha$ – particles at large angles, consistent with scattering expected for a sphere of radius $\approx$ few $\times$ $10^{-15}$ m and electric charge $= Z e$, with $Z = 79$ (atomic number of gold) and $e = |\text{charge of the electron}|$

an atom consists of
a positively charged nucleus
surrounded by a cloud of electrons

Nuclear radius $\approx 10^{-15}$ m $\approx 10^{-5} \times$ atomic radius
Mass of the nucleus $\approx$ mass of the atom
(to a fraction of 1‰)
First (wrong) ideas about nuclear structure (before 1932)

**Observations**
- Mass values of light nuclei $\approx$ multiples of proton mass (to few %)
  (proton $\cong$ nucleus of the hydrogen atom)
- $\beta$ decay: spontaneous emission of electrons by some radioactive nuclei

**Hypothesis:** the atomic nucleus is a system of protons and electrons strongly bound together

Nucleus of the atom with atomic number $Z$ and mass number $A$:

- a bound system of $A$ protons and $(A - Z)$ electrons
- Total electric charge of the nucleus $= [A - (A - Z)]e = Z\,e$

**Problem with this model:**
- Too many protons in the nucleus (need electrons in the nucleus to balance the charge) e.g., $M(\text{He}) \sim 4 \times M(\text{H})$ but there are only 2 orbital electrons
- Chemical isotopes have different masses
- Quantum mechanics – hyperfine splitting of Nitrogen spectral lines indicates angular momentum (spin) of N nucleus $= 1$
  - Electron, proton spin $= \frac{1}{2}\hbar$ (measured)
  - $N(A = 14, Z = 7)$: 14 protons + 7 electrons $= 21$ spin $\frac{1}{2}$ particles
**DISCOVERY OF THE NEUTRON** (Chadwick, 1932)

**Neutron**: a particle with mass $\approx$ proton mass but with zero electric charge

**Solution to the nuclear structure problem:**

Nucleus with atomic number $Z$ and mass number $A$:

a bound system of $Z$ protons and $(A - Z)$ neutrons

Nitrogen anomaly: no problem if neutron spin $= \frac{1}{2}\hbar$

Nitrogen nucleus ($A = 14, \ Z = 7$): 7 protons, 7 neutrons $= 14$ spin $\frac{1}{2}$ particles

$\Rightarrow$ total spin has integer value

Should observe new type of radiation (neutrons) resulting from the bombarding of Be with $\alpha$ particles

Neutron source in Chadwick’s experiments: a $^{210}\text{Po}$ radioactive source ($5 \text{ MeV } \alpha$ – particles) mixed with Beryllium powder $\Rightarrow$ emission of electrically neutral radiation capable of traversing several centimeters of Pb:

$$^4\text{He}_2 + ^9\text{Be}_4 \rightarrow ^{12}\text{C}_6 + \text{ neutron}$$

$\alpha$ - particle
How do we detect neutral particles?

• Passage of charged particles through matter

Interaction with atomic electrons

- **ionization**
  (neutral atom $\rightarrow$ ion$^+$ + free electron)

- **excitation of atomic energy levels**
  (de-excitation $\rightarrow$ photon emission)

Interaction with atomic nucleus

- **inelastic collisions**
  (many secondary particles)

- **elastic collisions**
  (recoil nucleus)

Probability of interaction with nucleus is much smaller than probability of interaction with atomic electron.

• Size of the electron shell/size of the nucleus $\sim 10^5$
• Range of electromagnetic force/range of strong force $\sim \infty$
Energy loss

Ionization + excitation of atomic energy levels → energy loss

Mean energy loss rate – \( \frac{dE}{dx} \)

- proportional to \((\text{electric charge})^2\)
  of incident particle

- for a given material, function only
  of incident particle velocity

- typical value at minimum:
  \(-\frac{dE}{dx} = 1 – 2 \text{ MeV }/(\text{g cm}^{-2})\)

**NOTE:** traversed thickness \((dx)\) is given in \(\text{g}/\text{cm}^2\) to be independent of material density (for variable density materials, such as gases)
→ multiply \(dE/dx\) by density \((\text{g}/\text{cm}^3)\) to obtain \(dE/dx\) in MeV/cm
Passage of neutral particles through matter

Residual range of a charged particle with initial energy $E_0$ that is losing energy only by ionization and atomic excitation:

$$R = \int_0^R dx = \int_{E_0} \frac{1}{dE / dx} dE = MF(v)$$

$$E_0 = Mc^2 / \sqrt{1 - (v/c)^2}$$

=>$>$ the measurement of $R$ for a particle of known rest mass $M$ is a measurement of the initial velocity

Passage of neutral particles through matter: no interaction with atomic electrons

=>$>$ detection possible only in case of collisions producing charged particles

Neutron discovery:

observation and measurement of nuclear recoils in an “expansion chamber” filled with Nitrogen at atmospheric pressure

An old gaseous detector based on an expanding vapour; ionization acts as seed for the formation of liquid drops. Tracks can be photographed as strings of droplets
Assume that incident neutral radiation consists of particles of mass $m$ moving with velocities $v < V_{\text{max}}$

Determine max. velocity of recoil protons ($U_p$) and Nitrogen nuclei ($U_N$) from max. observed range

$$U_p = \frac{2m}{m + m_p} V_{\text{max}}$$

$$U_N = \frac{2m}{m + m_N} V_{\text{max}}$$

From non-relativistic energy-momentum conservation

$m_p$: proton mass; $m_N$: Nitrogen nucleus mass

$$\frac{U_p}{U_N} = \frac{m + m_N}{m + m_p}$$

From measured ratio $U_p / U_N$ and known values of $m_p, m_N$

determine neutron mass: $m = m_n \approx m_p$

Present mass values: $m_p = 938.272 \text{ MeV}/c^2 \quad m_n = 939.565 \text{ MeV}/c^2$