Introductory Nuclear, Atomic and Molecular Physics

PHYS-H-405

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Course organization

- Theory:
  - 3 ECTS
  - 1.5 ECTS for nuclear physics (45% of the final note) and 1.5 ECTS for atomic and molecular physics (45% of the final note)
  - Slides for nuclear physics part available on http://metronu.ulb.ac.be/pauly_cours.html
- Exercises:
  - 1 ECTS (0.5 ECTS for each part)
- Laboratories:
  - 1 ECTS
  - Organization: M. Ciccarelli (Maureen.Ciccarelli@ulb.be)
  - 10% of final note → Laboratory reports

References:

- K.S. Krane : Introductory Nuclear Physics (Wiley, 1988)
- K. Heyde : Basic Ideas and Concepts in Nuclear Physics (Institute of Physics, 1994)
- S.S.M. Wong : Introductory Nuclear Physics (Wiley, 1998)
- B.H. Bransden and C.J. Joachain, Physics of Atoms and Molecules (Prentice Hall, 2003)
- B.R. Judd, Operator Techniques in Atomic Spectroscopy (Princeton Landmarks in Physics, 1998)
- W.R. Johnson, Atomic Structure Theory (Lectures on Atomic Physics, Springer, 1998)
- R.D. Cowan, The Theory of Atomic Structure and Spectra (Los Alamos Series in Basic and Applied Sciences, 1981)

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Part I: Nuclear Physics

Part I:
Nuclear Physics

Chapter I:
Introduction

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Definition

- Nuclear physics = study of atomic nuclei →
  - Theoretical model of atomic nucleus
  - Interaction of particles with nucleus
  - Mechanisms of nuclear reactions
- Applications:
  - Medicine (nuclear medicine: application of radioactive substances in the diagnosis and treatment of disease)
  - Energy production (fission, fusion)
  - Military applications
  - Food-processing (sterilization of food by irradiation)
  - Astrophysics
  - …

Brief history (1)

1895: Discovery of X-rays by Röntgen

1896: Discovery of radioactivity from uranium by Becquerel

1897: Discovery of the electron by Thomson

1898: Pierre and Marie Curie → other materials are radioactive
→ discovery of Ra and Po

1899: Discovery of α and β rays by Rutherford

1900: Discovery of γ rays by Villard

1903: Discovery of the law of radioactive decay by Rutherford and Soddy

1905: $E = mc^2$ by Einstein

1908: Discovery of the nucleus by Rutherford

1909: α is a helium nucleus and β is an electron (Rutherford)

Brief history (2)

1912: X rays and γ rays are electromagnetic waves (von Laue)

1913: Discovery of the notion of isotope (Soddy and Richards)

1923: Use of radioactive tracers in biology by von Hevesy

1928: Theory of decay based on tunnel effect by Gamow

1929: Invention of the cyclotron by Lawrence and Livingston

1930: Pauli predicts the existence of the neutrino / Dirac predicts antimatter

1932: Discovery of neutron by Chadwick / Discovery of positron by Andersen

1934: Fermi theory for β decay

1936: Strong force occurs through meson exchange (Yukawa)

1936: Lawrence treats leukemia with ^{32}P

Brief history (3)

1938: Hahn, Strassman, Meitner and Frisch discover the fission

1939: Bethe discovers the nuclear fusion in stars

1942: First fission reactor (Fermi)

1945: First atomic bomb at Hiroshima

1948: Big Bang nucleosynthesis (Alpher, “Bethe”, Gamow)

1951: First nuclear reactor producing electricity (EBR-1, Idaho)

1952: First hydrogen bomb (Teller, Ulam) / Decision for creation of the CEAN (future SCK-CEN) in Belgium

1954: Protontherapy at Berkeley

1956: First reactor at critical state in Belgium (BR-1)

1961: First PET scan at Brookhaven

1964: Gell-Mann and Zweig propose the model of quarks

Brief history (4)

1964: Theory of Brout-Engler-Higgs boson

Mid-1970s: Standard model

1975: First nuclear reactor producing electricity in Belgium (Doel-1)

1979: Three Mile Island accident (INES 5)

1986: Tchernobyl accident (INES 7)

2011: Fukushima accident (INES 7)

2013: Experimental evidence of BEH boson (CERN)

2019: First protontherapy center in Belgium

2025-2030 (?): First fusion reactor ITER

20??: MIRRHA in Belgium: First accelerator-driven system

Units and dimensions: Typical values

- Size of the atom ≈ 10^{-10} m
- Size of the nucleus ≈ 10^{-15} m = 1 femtometer (fm) = fermi → all nuclei have radius = 2-8 fm
- Typical β or γ decay energy in the range of 1 MeV (megaelectron-volt) = 10^6 eV = $1.6021765 \times 10^{-13}$ J (1 eV = energy gained by a single unit of charge when accelerated through a potential difference of 1 V)
- Unit of mass → 1 unified atomic mass unit (u) = $1.6605390 \times 10^{-27}$ kg → 1/12 of the mass of an unbound neutral atom of ^{12}C (in ground state and at rest)
- Practically → use of mass energy rather than mass → multiplication by c^2 (c = 299 792 485 ms^{-1} ≈ 3×10^8 ms^{-1}) → 1 u = 931.502 MeV
- Unit of charge → elementary charge (e) = 1.6021766209 C (proton: e, electron: -e)
- Mean lifetime $\tau = 1/\lambda$ with λ = probability of disintegration per unit time → can be 10^{-21} or 10^{19} s

Units and dimensions: Multiplication by a power of c

- Mass m → mc^2 (energy)
- Momentum p → pc (energy)
- Time t → tc (length)

- Physical constants:
  - Planck constant: $\hbar = 1.05 \times 10^{-34}$ Js → $\hbar c = 197.33$ MeVfm
  - Proton mass: $m_p = 1.6726 \times 10^{-27}$ kg → $m_p = 938.27$ MeV/c^2
  - Neutron mass: $m_n = 1.6749 \times 10^{-27}$ kg → $m_n = 939.57$ MeV/c^2
  - Electron mass: $m_e = 9.1094 \times 10^{-31}$ kg → $m_e = 0.511$ MeV/$c^2 \approx m_p/1836$

Structure of nuclei: Nucleons

- Atomic nuclei are quantum bound states of particles called *nucleons*
- Two types of nucleons → positively charged proton and uncharged neutron
- The mass difference between proton and neutron is known with a huge precision: $m_n - m_p = 1.293\,332$ MeV/c^2
- Nucleons are fermions (spin ½)
- Nucleon is not an elementary particle → an elementary particle has its root mean square (rms) radius = 0

Root mean square radius of proton and neutron (1)

- The rms radius (r_{rms}) of a particle (or charge radius) is defined as the radius of the charge distribution inside the particle →

$$\langle r^2 \rangle_{ch}^{1/2} = \sqrt{\int r^2 \rho_{ch}(\boldsymbol{r}) d\boldsymbol{r}}$$

For a proton →

$$\langle r^2 \rangle_{ch,p}^{1/2} \approx 0.87 \text{ fm}$$

with

$$\int \rho_{ch,p}(\boldsymbol{r}) d\boldsymbol{r} = 1$$

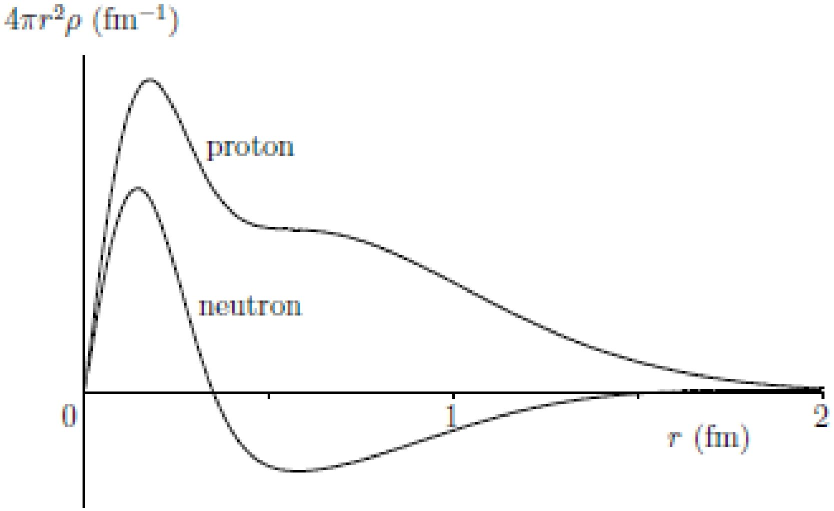
For a neutron →

$$\langle r^2 \rangle_{ch,n} \approx -0.12 \text{ fm}^2$$

with

$$\int \rho_{ch,n}(\boldsymbol{r}) d\boldsymbol{r} = 0$$

Root mean square radius of proton and neutron (2)



- The charge density of a nucleon is measured from the analysis of high energy electrons scattered from it
- Practically → measurement of charge density is made through their Fourier transform *F(**q**)* such as

$$F(\boldsymbol{q}) = \frac{1}{Z}\int e^{i\boldsymbol{q}\boldsymbol{r}}\rho(\boldsymbol{r})d\boldsymbol{r}$$

Structure of nuclei: Magnetic moment

- The spin magnetic moment is the magnetic moment induced by the spin of elementary particles:

$$\boldsymbol{M} = g\frac{q}{2m}\boldsymbol{S}$$

with ***S***: the spin, *q*: the charge, *m*: the mass, *g*: the gyromagnetic ratio

- From Dirac theory → for charged fermion: $g = 2$, for neutral fermion: $g = 0$ (small corrections from quantum electrodynamics - QED)
- Nucleon is not an elementary particle → $g_p = 5.5856947$ and $g_n = -3.826085$

Structure of nuclei: Quarks (1)

- Nucleons are composed of 3 elementary particles: the quarks

Symbol	Spin	Charge	Flavor
u	1/2	+2/3	Up
d	1/2	-1/3	Down
c	1/2	+2/3	Charm
s	1/2	-1/3	Strange
t	1/2	+2/3	Top
b	1/2	-1/3	Bottom

+ anti-quarks

- Quarks have supplementary quantum number: color charge (red, blue, green)
- Anti-quarks have anticolor (antired, antiblue, antigreen)
- Due to the phenomenon of *color confinement* → quarks are never directly observed or found in isolation
- Quarks combine to form hadrons

Structure of nuclei: Quarks (2)

- Theory to be applied to systems of quarks → quantum chromodynamics (QCD)
- Combination of 2 quarks (quark + anti-quark) → meson (pion, kaon,…)
- Combination of 3 quarks with different colors → baryon (proton, neutron, hyperon,…)
- Formation of tetraquarks and pentaquarks seems possible (seems to be observed at the CERN)
- Proton → p = u + u + d
- Neutron → n = u + d + d
- Spin of the nucleon (1/2) results from the coupling of 3 spins 1/2

Lepton

- Lepton is an elementary particle

- Spin = 1/2

- Examples:
  - Electron: charge -e, mass ≈ 0.5109989 MeV/c^2 ≈ 511 keV/c^2
  - Positron: charge +e, mass ≈ 511 keV/c^2
  - Muon (« heavy electron »): charge –e, $m_\mu \approx 209\ m_{e-}$)
  - Neutrino: charge 0, mass ≈ 0 but not 0 → $m_\nu < 3$ eV/c^2, 3 flavors (electron, muon, tau), negative helicity (projection of spin onto the direction of momentum)
  - Antineutrino: same charge and mass than neutrino → really different? → not clear but all experiments have shown positive helicity

Types of forces

Force	Amplitude	Range
Strong nuclear interaction	$\sim$ 1	$\sim$ fm
Coulomb interaction (or electromagnetic)	$\sim$ 1/137	Infinite
Weak nuclear interaction	$\sim 10^{-5}$	$\sim 10^{-3}$ fm
Gravitation interaction	$\sim 10^{-39}$	infinite

- Gravitational interaction is negligible compared to the other ones → but for systems with a huge number of particles → becomes dominating because of the weak total charge of macroscopic systems
- In nuclei → Coulomb interaction is not negligible → becomes very important when the number of protons ↗

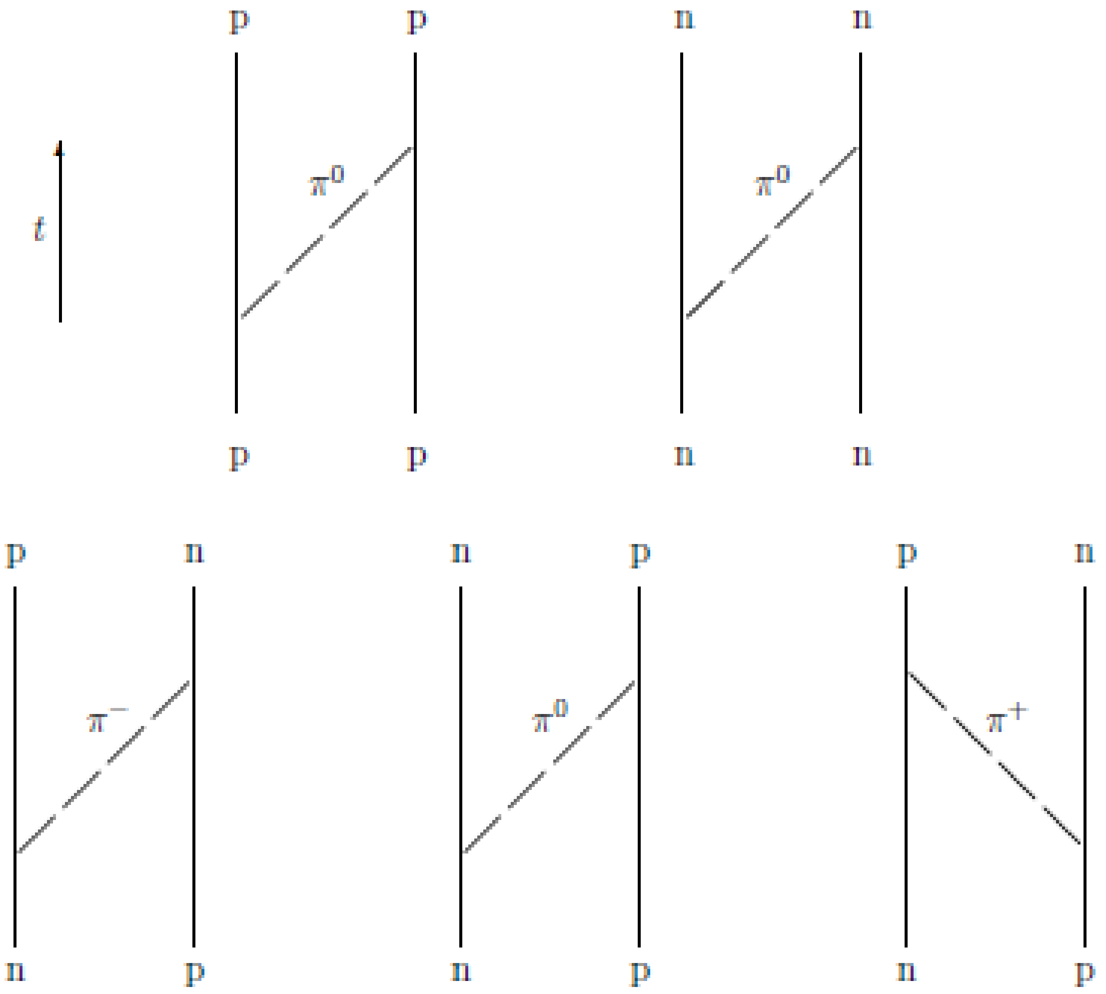
Strong nuclear interaction (1)

- During interactions → exchange of virtual particles between particles (Coulomb interaction → exchange of photons)
- For strong nuclear interaction between nucleons → exchange of mass virtual particles (Yukawa theory) → pions (or pi mesons) Π^+, Π^- and Π^0 (index = charge)
- Due to time-energy uncertainty relation → $\Delta t \Delta E \simeq \hbar$
- The energy fluctuation ΔE necessary to have a possible reaction is $\Delta E \sim m_\Pi c^2$
- In the time interval Δt the pion car travel a distance $\sim c\Delta t \sim \hbar/(m_\Pi c)$ with $\hbar$/mc the reduced Compton wavelength
- This distance gives the range of the nuclear force

$$m_{\Pi^+} \simeq 139.570 \text{ MeV/c}^2 \quad \Rightarrow \quad \lambda_{\Pi^+} \simeq 1.414 \text{ fm}$$

$$m_{\Pi^0} \simeq 134.977 \text{ MeV/c}^2 \quad \Rightarrow \quad \lambda_{\Pi^0} \simeq 1.462 \text{ fm}$$

Strong nuclear interaction (2)



Feynmann diagrams for n/p interactions

Strong nuclear interaction (3)

- Same physical mechanism for interaction between 2 protons, 2 neutrons and 1 proton/1 neutron → exchange of same type particle → very similar interactions → property of *charge independence*
- The strength of the strong interaction between any pair of nucleons is the same independently of the nucleon type (protons or neutrons)
- Charge independence is not perfect because Π^0 is necessary exchanged for nn and pp interactions and np interactions can be done with various Π → as potentials are not exactly the same → not perfect charge independence

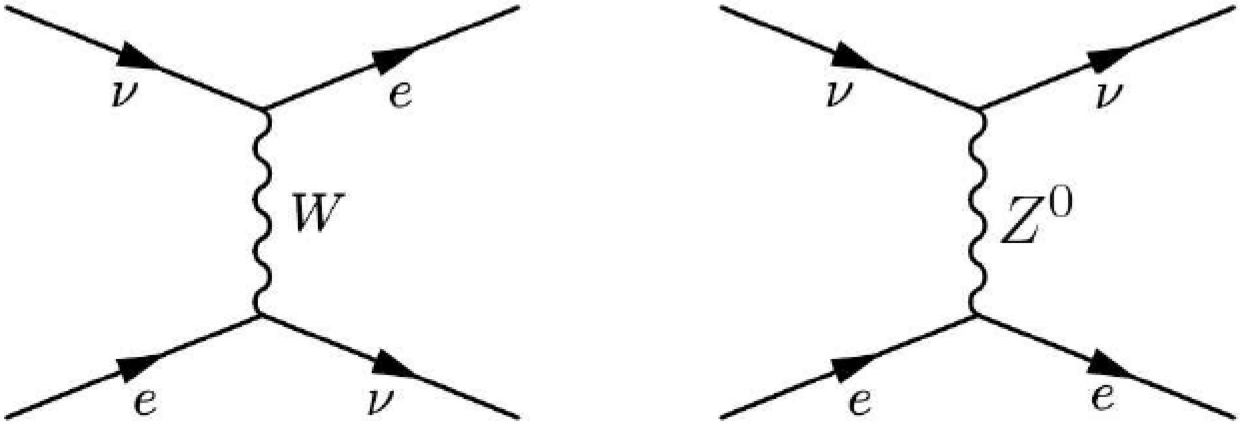
Weak nuclear interaction (1)

- Weak nuclear interaction always neglected in all calculations of nuclear structure
- This effect only appears in processes forbidden to strong nuclear interactions → β disintegration
- Yukawa theory can be adapted to weak interaction → weak gauge bosons (W^+, W^-, Z^0) mediate the weak interactions

$$m_W \simeq 80.4\ \mathrm{GeV/c^2} \quad \Rightarrow \quad \lambda_W \simeq 0.00246\ \mathrm{fm}$$
$$m_Z \simeq 91.19\ \mathrm{GeV/c^2} \quad \Rightarrow \quad \lambda_Z \simeq 0.00217\ \mathrm{fm}$$

- Short range → weakness of the interaction

Weak nuclear interaction (2)



- The electroweak theory unifies weak interaction and electromagnetic interaction
- This theory shows that at high energy ($E > m_Z c^2$) → the 2 interactions have the same order of magnitude

Conservation laws (1)

- A *conservation law* states that a particular physical quantity does not changed (is conserved) during a physical process
- A conservation law is *exact* if it was never contradicted
- A conservation law *is approximated* if the considered quantity is conserved in certain classes of physics processes but not in all (e.g. conservation of parity)
- Principals conservation laws are:
  - conservation of energy and momentum (exact)
  - conservation of angular momentum (exact)
  - conservation of electric charge (exact)
  - conservation of baryon number (approximated)
  - conservation of lepton number (approximated)
  - …

Conservation laws (2)

- Conservation of baryon number → conservation of the total number of nucleons (neutrons and protons) minus the total number of anti-nucleons (antiprotons and antineutrons) → p + d $\nrightarrow$ p + p + γ is not allowed (charge YES, baryon number No) → γ + d $\rightarrow$ p + n is allowed
- Conservation of electronic lepton number (L_e) → conservation of the difference between the total number of [electrons and electron neutrinos] and the total number of [positrons and electronic antineutrinos] →

$$L_e \equiv N(e^-) + N(\nu_e) - N(e^+) - N(\bar{\nu}_e)$$

→ $\bar{\nu}_e$ + n $\nrightarrow$ e^- + p is NOT allowed but → $\bar{\nu}_e$ + n $\rightarrow$ e^+ + n YES

- Remark 1: it exists two other types of charged leptons → $\mu^\pm$ and $\tau^\pm$ → similar conservation laws with L_μ and L_τ

Conservation laws (3)

- Remark 2: some recent experiments on neutrino oscillations shows that the only truly conserved number is the sum of the 3 lepton numbers: L = $L_e + L_\mu + L_\tau$

- Remark 3: p $\nrightarrow$ $e^+ + \gamma$ is not possible (conservation of baryon and lepton number) but a « possible » theory predicts the disintegration of proton (with a characteristic lifetime $\tau_p \approx 10^{29}$ years ≈ 10^{19} times the age of Universe)

- Remark 4: neutron is instable → n $\rightarrow$ p + e^- + $\overline{\nu}_e$ (with $Q = (m_n - m_p - m_e)^2 \approx 0.782$ MeV and $\tau_n \approx 885.7$ s)

Conservation laws: Stability of nuclei

- Conservation of energy → 1 particle of mass *m* and charge *q* can spontaneously decay into *i* particles only if (with *Q* the liberated energy):

$$m > \sum_i m_i \text{ or equivalently} \rightarrow Q = mc^2 - \sum_i m_i c^2 > 0$$

- Conservation of charge → $q = \sum_i q_i$

- These laws implies that electron and positron are stable (no particle of same charge but of smaller mass)

Origin of nuclei

- Nuclei in nature were built by nuclear reactions since the « Big Bang »
- Begin not well known → system at very high T → free quarks and gluons (bosons mediating between quarks) = quark-gluon plasma
- Time t ↗ → T ↘ → quarks and gluons combine to form hadrons and nucleons → proton $\rightarrow$ neutron and neutron $\rightarrow$ proton → but as $m_p < m_n$ → system with smallest mass is favored
- t ↗ more → T ↘ → collisions → apparition of bounded systems (with $A \leq 7$) → fixed situation = 87% of protons and 13% neutrons
- Abundance: 74% H + 23-25% He ($4p \rightarrow {}^4He + 2e^+ + 2\nu_e + n\gamma$) + …
- Other nuclei are formed during star explosion: supernova → a lot of nuclei are unstable and decay into other nuclei → process of formation + decay is called *nucleosynthesis*