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: E. Gnacadja (Eustache.Gnacadja@ulb.ac.be)
  – 10% of final note → Participation 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)
• B.R. Judd, Operator Techniques in Atomic Spectroscopy (Princeton Landmarks in Physics, 1998)
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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 \( \alpha \) and \( \beta \) rays by Rutherford
1900: Discovery of \( \gamma \) 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: \( \alpha \) is a helium nucleus and \( \beta \) is an electron (Rutherford)
Brief history (2)

1912: X rays and $\gamma$ 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 $\beta$ 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
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 (?): 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}\text{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 \times 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 \( \lambda = \) probability of disintegration per unit time → can be 10^{-21} or 10^{19} s
Units and dimensions: Multiplication by a power of c

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

- Physical constants:
  - Planck constant: $\hbar = 1.05 \times 10^{-34}$ Js $\rightarrow \hbar c = 197.33$ MeVfm
  - Proton mass: $m_p = 1.6726 \times 10^{-27}$ kg $\rightarrow m_p = 938.27$ MeV/c²
  - Neutron mass: $m_n = 1.6749 \times 10^{-27}$ kg $\rightarrow m_n = 939.57$ MeV/c²
  - Electron mass: $m_e = 9.1094 \times 10^{-31}$ kg $\rightarrow m_e = 0.511$ MeV/c² $\approx m_p/1836$
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: $m_n - m_p = 1.293332\text{ MeV}/c^2$.
- Nucleons are fermions (spin $\frac{1}{2}$).
- 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 ($r_{\text{rms}}$) of a particle (or charge radius) is defined as the radius of the charge distribution inside the particle $\rightarrow$

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

For a proton $\rightarrow$

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

with

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

For a neutron $\rightarrow$

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

with

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

$$F(q) = \frac{1}{Z} \int e^{iqr} \rho(r) dr$$
Structure of nuclei: Magnetic moment

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

\[ M = g \frac{q}{2m} S \]

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Spin</th>
<th>Charge</th>
<th>Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>1/2</td>
<td>+2/3</td>
<td>Up</td>
</tr>
<tr>
<td>d</td>
<td>1/2</td>
<td>-1/3</td>
<td>Down</td>
</tr>
<tr>
<td>c</td>
<td>1/2</td>
<td>+2/3</td>
<td>Charm</td>
</tr>
<tr>
<td>s</td>
<td>1/2</td>
<td>-1/3</td>
<td>Strange</td>
</tr>
<tr>
<td>t</td>
<td>1/2</td>
<td>+2/3</td>
<td>Top</td>
</tr>
<tr>
<td>b</td>
<td>1/2</td>
<td>-1/3</td>
<td>Bottom</td>
</tr>
</tbody>
</table>

+ 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/c² ≈ 511 keV/c²
  – Positron: charge -e, mass ≈ 511 keV/c²
  – Muon (« heavy electron »): charge -e, m_μ ≈ 209 m_e.
  – Neutrino: charge 0, mass ≈ 0 but not 0 → m_ν < 3 eV/c², 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

<table>
<thead>
<tr>
<th>Force</th>
<th>Amplitude</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong nuclear interaction</td>
<td>$\sim 1$</td>
<td>$\sim \text{fm}$</td>
</tr>
<tr>
<td>Coulomb interaction (or electromagnetic)</td>
<td>$\sim 1/137$</td>
<td>Infinite</td>
</tr>
<tr>
<td>Weak nuclear interaction</td>
<td>$\sim 10^{-5}$</td>
<td>$\sim 10^{-3} \text{ fm}$</td>
</tr>
<tr>
<td>Gravitation interaction</td>
<td>$\sim 10^{-39}$</td>
<td>infinite</td>
</tr>
</tbody>
</table>

- 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) \( \Pi^+, \Pi^- \) and \( \Pi^0 \) (index = charge)
- Due to time-energy uncertainty relation → \( \Delta t \Delta E \approx \hbar \)
- The energy fluctuation \( \Delta E \) necessary to have a possible reaction is \( \Delta E \approx m_\Pi c^2 \)
- In the time interval \( \Delta t \) the pion car travel a distance \( \sim c \Delta t \approx \hbar / (m_\Pi c) \) with \( \hbar / mc \) the reduced Compton wavelength
- This distance gives the range of the nuclear force
  \[
  m_{\Pi^+} \approx 139.570 \text{ MeV}/c^2 \quad \Rightarrow \quad \lambda_{\Pi^+} \approx 1.414 \text{ fm}
  \]
  \[
  m_{\Pi^0} \approx 134.977 \text{ MeV}/c^2 \quad \Rightarrow \quad \lambda_{\Pi^0} \approx 1.462 \text{ fm}
  \]
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 $\Pi^0$ is necessary exchanged for nn and pp interactions and np interactions can be done with various $\Pi$ → 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 → $\beta$ disintegration
- Yukawa theory can be adapted to weak interaction → weak gauge bosons ($W^+, W^-, Z^0$) mediate the weak interactions

\[ m_W \approx 80.4 \text{ GeV}/c^2 \quad \Rightarrow \quad \lambda_W \approx 0.00246 \text{ fm} \]
\[ m_Z \approx 91.19 \text{ GeV}/c^2 \quad \Rightarrow \quad \lambda_Z \approx 0.00217 \text{ fm} \]
- Short range → weakness of the interaction
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 $\rightarrow$ conservation of the total number of nucleons (neutrons and protons) minus the total number of anti-nucleons (antiprotons and antineutrons) $\rightarrow p + d \leftrightarrow p + p + \gamma$ is not allowed (charge YES, baryon number No) $\rightarrow \gamma + d \rightarrow p + n$ is allowed

- Conservation of electronic lepton number ($L_e$) $\rightarrow$ conservation of the difference between the total number of [electrons and electron neutrinos] and the total number of [positrons and electronic antineutrinos] $\rightarrow$

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

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

- Remark 1: it exists two other types of charged leptons $\rightarrow \mu^\pm$ and $\tau^\pm$ $\rightarrow$ similar conservation laws with $L_\mu$ and $L_\tau$
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: \( p \rightarrow e^+ + \gamma \) 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 \( \approx 10^{19} \) times the age of Universe)

• Remark 4: neutron is instable \( \rightarrow n \rightarrow p + e^- + \bar{\nu}_e \) (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 → neutron and neutron → 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 ($4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + n\gamma$) + ...

• 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