SS2011: 
Introduction to Nuclear and Particle Physics
Part 2

Lectures: Elena Bratkovskaya

Wednesday, 14:00-16:30
Room: Phys _ _. 101

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WS2010/2011: Introduction to Nuclear and Particle Physics, Part 1

- Nuclear structure
- Nuclear models
- Dirac equation
- Klein-Gordon equation
- Field theory of nucleons and mesons
- Nuclear forces
- SU (N) symmetry
- Chiral symmetry
- Physics of the Nucleon
- Parton model
- Quark-gluon plasma

Script of lectures for Part 1 (WS10/11)
http://th.physik.uni-frankfurt.de/~brat/index.html
SS2011: 
‘Introduction to Nuclear and Particle Physics, Part 2’

- Nuclear reactions
- Scattering theory
- Feynman diagrams
- One-boson-exchange model
- Thermodynamic model
- Non-equilibrium models for strongly interacting systems
- Transport approaches to relativistic heavy-ion collisions

Script of lectures + tasks for homework:
http://th.physik.uni-frankfurt.de/~brat/index.html
Tutorial:

Thursday, 12:00-14:00
Room: Phys 02.116

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Thomas Lang
Christoph Herold
Lecture 1

Properties of nuclei, nuclear reactions

SS2011: 'Introduction to Nuclear and Particle Physics, Part 2'
Scales in the Universe

- Matter: $10^{-1}$ m
- Crystal: $10^{-9}$ m
- Atom: $10^{-10}$ m
- Nucleus: $10^{-14}$ m
- Nucleon: $10^{-15}$ m

- Quark-Gluon Plasma
- Hadron Structure and Hadronic Matter Research
- Quark Matter Research
- Dense Plasma Research
- Nuclear Structure and Astrophysics
- Interdisciplinary Research with Ions Beams
Global Properties of Nuclei

A - mass number gives the number of nucleons in the nucleus
Z - number of protons in the nucleus (atomic number)
N – number of neutrons in the nucleus

\[ A = Z + N \]

In nuclear physics, nucleus is denoted as \( ^A_ZX \), where X is the chemical symbol of the element, e.g. \( ^1_1H – hydrogen, \) \( ^{12}_6C – carbon, \) \( ^{197}_79Au – gold \)

Different combinations of Z and N (or Z and A) are called nuclides

- nuclides with the same mass number \( A \) are called isobars
- \( ^{17}_7N, \) \( ^{17}_8O, \) \( ^{17}_9F \)
- nuclides with the same atomic number \( Z \) are called isotopes
- \( ^{12}_6C, \) \( ^{13}_6C \)
- nuclides with the same neutron number \( N \) are called isotones
- \( ^{13}_6C, \) \( ^{14}_7N \)
- nuclides with neutron and proton number exchanged are called mirror nuclei
- \( ^3_1H, \) \( ^3_2He \)
- nuclides with equal proton number and equal mass number, but different states of excitation (long-lived or stable) are called nuclear isomers
- \( ^{180}_73Ta, \) \( ^{180m}_73Ta \)

E.g.: The most long-lived non-ground state nuclear isomer is tantalum-180m, which has a half-life in excess of 1,000 trillion years
Stability of nuclei

- **Stable nuclei**
- **Unstable nuclei**

**Decay schemes**:

- **α-decay** – emission of α-particle (\(^4\)He): \( ^{238}\text{U} \rightarrow ^{234}\text{Th} + \alpha \)
- **β-decay** - emission of electron (\(\beta^-\)) or positron (\(\beta^+\)) by the weak interaction

  - **\(\beta^-\) decay**: the weak interaction converts a neutron (n) into a proton (p) while emitting an electron (e\(^-\)) and an electron antineutrino (\(\nu_e\)): \( n \rightarrow p + e^- + \bar{\nu}_e \)

  - **\(\beta^+\) decay**: the weak interaction converts a proton (p) into a neutron (n) while emitting a positron (e\(^+\)) and an electron neutrino (\(\nu_e\)): \( p \rightarrow n + e^+ + \nu_e \)
- **Fission** - spontaneous decay into two or more lighter nuclei
- **Proton or neutron emission**
Stability of nuclei

Stable nuclei only occur in a very narrow band in the Z – N plane. All other nuclei are unstable and decay spontaneously in various ways.

In the case of a **surplus of protons**, the inverse reaction may occur: i.e., the conversion of a proton into a neutron via $\beta^+$-decays.

Isobars with a large surplus of neutrons gain energy by converting a neutron into a proton via $\beta^-$-decays.

Fe- and Ni-isotopes possess the maximum binding energy per nucleon and they are therefore the most stable nuclides.

In heavier nuclei the binding energy is smaller because of the larger Coulomb repulsion. For still heavier masses, nuclei become unstable due to **fission** and decay spontaneously into two or more lighter nuclei → the mass of the original atom should be larger than the sum of the masses of the daughter atoms.
Unstable nuclides are radioactive and are called radionuclides. Their decay products ('daughter' products) are called radiogenic nuclides.

About 256 stable and about 83 unstable (radioactive) nuclides exist naturally on Earth.

The probability per unit time for a radioactive nucleus to decay is expressed by the decay constant $\lambda$. It is related to the lifetime $\tau$ and the half life $t_{1/2}$ by:

$$\tau = \frac{1}{\lambda} \quad \text{and} \quad t_{1/2} = \ln \frac{2}{\lambda}$$

The measurement of the decay constants of radioactive nuclei is based upon finding the activity (the number of decays per unit time):

$$A = -\frac{dN}{dt} = \lambda N$$

where $N$ is the number of radioactive nuclei in the sample.

The unit of activity is defined 1 Bq [Becquerel] = 1 decay/s.
The mass of the nucleus: \[ M(Z, N) = m_N \cdot N + m_P \cdot Z - E_B \]

\( E_B \) is the binding energy per nucleon or mass defect (the strength of the nucleon binding). The mass defect reflects the fact that the total mass of the nucleus is less than the sum of the masses of the individual neutrons and protons that formed it. The difference in mass is equivalent to the energy released in forming the nucleus.

- The general decrease in binding energy beyond iron (\(^{58}\)Fe) is due to the fact that, as nuclei get more massive, the ability of the strong force to counteract the electrostatic repulsion between protons becomes weaker.
- The most tightly bound isotopes are \(^{62}\)Ni, \(^{58}\)Fe, and \(^{56}\)Fe, which have binding energies of 8.8 MeV per nucleon.
- Elements heavier than these isotopes can liberate energy by nuclear fission; lighter isotopes can yield energy by fusion.

**Fusion** - two atomic nuclei fuse together to form a heavier nucleus

**Fission** - the breaking of a heavy nucleus into two (or more rarely three) lighter nuclei
Nuclear reactions
Nuclear reactions

The proton size: $\Delta L \sim 1 \text{ fm} = 10^{-15} \text{ m} = 10^{-13} \text{ cm}$

In order to study experimentally such small objects, one needs a probe of the same or smaller size!

Quantum mechanics $\Rightarrow$ wave-corpuscular duality:

the particle exhibits both wave and particle properties

- de-Broglie wave-length $\lambda$ or reduced wave-length $\lambda = \frac{\lambda}{2\pi}$

\[
\lambda = \frac{\hbar}{p} = \frac{\hbar c}{\sqrt{2mc^2E_{\text{kin}}} + E_{\text{kin}}^2} \approx \begin{cases} 
\frac{\hbar}{\sqrt{2mE_{\text{kin}}}} & \text{for } E_{\text{kin}} \ll mc^2 \\
\frac{\hbar c}{E_{\text{kin}}} \approx \frac{\hbar c}{E} & \text{for } E_{\text{kin}} \gg mc^2.
\end{cases}
\]

with the kinetic energy $E_{\text{kin}} = E - mc^2$, the total energy $E^2 = mc^2 + p^2c^2$

$\Rightarrow$ in order to localize the particle to small size, one needs to accelerate it to high energy, i.e. to resolve small structures, large beam energies are required.

The largest wavelength that can resolve structures of linear extension $\Delta x$, is of the same order: $\lambda \lesssim \Delta x$
Nuclear reactions

From the Heisenberg’s uncertainty principle the corresponding particle momentum is:

\[ p \gtrsim \frac{\hbar}{\Delta x}, \quad pc \gtrsim \frac{\hbar c}{\Delta x} \approx \frac{200 \text{ MeV fm}}{\Delta x}. \]

The connection between kinetic energy, momentum and reduced wave-length of photons (\(\gamma\)), electrons (e), muons (\(\mu\)), protons (p), and \(^4\text{He}\) nuclei (\(\alpha\)).

Atomic diameters are typically a few °A (10\(^{-10}\) m), nuclear diameters a few fm (10\(^{-15}\) m):

- Thus to study nuclei, whose radii are of a few fm, beam momenta of the order of 10-100 MeV/c are necessary.
- Individual nucleons have radii of about 0.8 fm and may be resolved if the momenta are above \(\approx 100 \text{ MeV/c}\).
- To resolve the constituents of a nucleon, the quarks, one has to penetrate deeply into the interior of the nucleon. For this purpose, beam momenta of many GeV/c are necessary.
A nuclear reaction is a process in which two nuclei collide to produce products different from the initial particles.

\[ a_1 + a_2 \rightarrow b_1 + b_2 + \ldots, \]

initial particles \hspace{1cm} final particles

Types nuclear reactions:

- elastic reactions:
  the initial channel = the final channel

- inelastic reactions:
  the final channel differs from the initial channel

Example:

- \( p + ^{14}\text{N} \rightarrow ^{14}\text{N} + p \)
- \( p + ^{14}\text{N} \rightarrow ^{14}\text{N}^* + p \)
- \( p + ^{14}\text{N} \rightarrow ^{15}\text{O} + \gamma \)
- \( p + ^{14}\text{N} \rightarrow ^{14}\text{O} + n \)
- \( p + ^{14}\text{N} \rightarrow ^{13}\text{N} + p + n \)
- \( p + ^{14}\text{N} \rightarrow 8p + 7n \)
Elastic reactions

In an elastic process

\[ a + b \rightarrow a' + b' \]

the same particles are present both before and after the scattering, i.e. the initial and in the final state are identical (including quantum numbers) up to momenta and energy.

The target \( b \) remains in its ground state, absorbing merely the recoil momentum and hence changing its kinetic energy.

The scattering angle and the energy of the projectile particle \( a \) and the production angle and energy of target \( b \) are unambiguously correlated.

momentum transfer \( Q: \)

\[ Q = P_{a'} - P_a \]
i) In inelastic reactions

\[ a + b \rightarrow a' + b^* \rightarrow c + d \]

A part of the kinetic energy transferred from \( a \) to the target \( b \) excites it into a **higher energy state** \( b^* \). The excited state will afterwards return to the ground state by emitting a light particle (e.

g. a photon or a \( \pi \)-meson) or it may decay into two or more different particles.

ii) In inelastic reactions

\[ a+b \rightarrow c+d+e \]

The beam particle may completely disappear in the reaction. Its total energy then goes into the **production of new particles.**

- A measurement of a reaction in which only the scattered particle \( a \) is observed (and the other reaction products are not), is called an **inclusive measurement.**

- If all reaction products are detected, one speaks of an **exclusive measurement.**
Conservation laws of nuclear reactions

- Electric charge conservation law
- Baryon number conservation law
- Energy conservation law
- Momentum conservation law
- Angular momentum conservation law
- Parity conservation law
- Isospin and its projection conservation law

Example: Consequences of the electric charge and baryon number conservation law:

One can find a missing product X of the reaction (e.g.): $p + ^7\text{Li} \rightarrow ^4\text{He} + X$

$Z_{\text{initial}} = Z(p) + Z(^7\text{Li}) = 1 + 3 = 4 = Z_{\text{final}} = Z(^4\text{He}) + Z(x) = 2 + Z(x) \Rightarrow Z(x) = 2$

$A_{\text{initial}} = A(p) + A(^7\text{Li}) = 1 + 7 = 8 = A_{\text{final}} = A(^4\text{He}) + A(x) = 4 + A(x) \Rightarrow A(x) = 4$

$X = \alpha$-particle
Energy-momentum conservation

**Energy and momentum conservation**: 
\[ \text{a+b} \rightarrow \text{c+d} + \ldots \]  

\[ N_{\text{final}} - \text{number of the particles in the final state}; N_{\text{initial}}=2 \text{ for (1)} \]

\[ E_a + E_b = E_c + E_d + \ldots \Leftrightarrow \sum_{i=1}^{N_{\text{initial}}} E_i = \sum_{i=1}^{N_{\text{final}}} E_i \]

\[ \vec{p}_a + \vec{p}_b = \vec{p}_c + \vec{p}_d + \ldots \Leftrightarrow \sum_{i=1}^{N_{\text{initial}}} \vec{p}_i = \sum_{i=1}^{N_{\text{final}}} \vec{p}_i \]

where \[ E_i^2 = c^2 p_i^2 + c^4 m_i^2 \]

**Kinetic energy**: \[ T_i = E_i - c^2 m_i \]

\[ T_a + m_a c^2 + T_b + m_b c^2 = \sum_{i=1}^{N_{\text{final}}} (T_i + m_i c^2) \]  

\[ T_a + T_b = \sum_{i=1}^{N_{\text{final}}} T_i - Q \]

Energy transfer of the reaction: \[ Q = \sum_{i=1}^{N_{\text{initial}}} m_i c^2 - \sum_{i=1}^{N_{\text{final}}} m_i c^2 \]

**Exothermic reaction**: \[ Q>0 \] : reaction in which energy is released by the system into the surrounding environment.

**Endothermic reaction**: \[ Q<0 \] : reaction in which energy is absorbed by the system from the surrounding environment.
Let's find the threshold energy for the reaction – the minimal kinetic energy when the reaction is possible

Consider laboratory frame: \( \vec{p}_b = 0, \ E_b = m_b \)

4-momenta
\[
p_a = (E_a, \vec{p}_a), \quad p_b = (m_b, 0)
\]

Energy and momentum conservation laws \( \Rightarrow \) the invariant energy \( s \) is conserved

\[
s = (p_a + p_b)^2 = \left( \sum_{i=1}^{N_{\text{final}}} p_i \right)^2
\] (5)

In the laboratory frame:

\[
s = (p_a + p_b)^2 = (E_a + E_b)^2 - (\vec{p}_a + \vec{p}_b)^2 = E_a^2 + 2E_a m_b c^2 + m_b^2 c^4 - \vec{p}_a^2
\] (6)

\[
= (m_a^2 c^4 + m_b^2 c^4 + 2(T_{\text{kin}} + m_a c^2) m_b c^4) = 2T_{\text{kin}} m_b c^2 + (m_a + m_b)^2 c^4
\]

The threshold (=minimal kinetic) energy of incoming particle \( a \) \( \Rightarrow \) all goes to the mass production of the final particles which are at rest (i.e. \( T_{i\ \text{kin}} = 0 \) for \( i=1,...N_{\text{final}} \))

\( \Rightarrow \) The threshold (minimal) invariant energy:

\[
s_{\text{th}} = 2T_{\text{th}} m_b c^2 + (m_a + m_b)^2 c^4 = \left( \sum_{i=1}^{N_{\text{final}}} m_i \right)^2 c^4
\] (7)
Energy-momentum conservation

Threshold energy:

(in the laboratory frame) \[ T_{th} = \frac{1}{2m_b} \left( \left( \sum_{i=1}^{N_{\text{final}}} m_i \right)^2 - (m_a + m_b)^2 \right) c^2 \] (8)

\[ T_{th} = \frac{1}{2m_b} \left( \sum_{i=1}^{N_{\text{final}}} m_i - m_a - m_b \right) \left( \sum_{i=1}^{N_{\text{final}}} m_i + m_a + m_b \right) c^2 \] (9)

\[ T_{th} = |Q| \left( 1 + \frac{m_a}{m_b} + \frac{|Q|}{2m_b c^2} \right) \] (10)

where \( Q \) is the energy of the reaction – eq.(4)

- In the nonrelativistic limit where \( Q << 2m_b c^2 \)

(in the laboratory frame) \[ T_{th} = |Q| \left( 1 + \frac{m_a}{m_b} \right) \] (11)
The cross section gives the probability of a reaction between the two colliding particles.

Consider an idealised experiment:

- we bombard the target with a monoenergetic beam of point-like particles \(a\) with velocity \(v_a\).
- a thin target of thickness \(d\) and total area \(A\) with \(N_b\) scattering centres \(b\) and with a particle density \(n_b\).
- each target particle has a cross-sectional area \(\sigma_b\), which we have to find by experiment!

⇒ Some beam particles are scattered by the scattering centres of the target, i. e. they are deflected from their original trajectory. The frequency of this process is a measure of the cross-section area of the scattering particles \(\sigma_b\).
The total reaction rate (i.e. the total number of reactions per unit time):

\[ \dot{N} \equiv \frac{dN}{dt} = \Phi_a N_b \sigma_b \]  \hspace{1cm} (12)

\( \Phi_a \) is the flux - the number of projectiles hitting the target per unit area \( A \) and per unit time \( dt \) and has dimensions [(area\( \times \)time\(^{-1}\)]:

\[ \Phi_a = \frac{\dot{N}_a}{A} = n_a v_a \]  \hspace{1cm} (13)

The total number of target particles within the beam area is

\[ N_b = n_b A \ d \]  \hspace{1cm} (14)

from (12) \( \Rightarrow \) \( \sigma_b \) reaction cross-section:

\[ \sigma_b = \frac{\dot{N}}{\Phi_a N_b} \]  \hspace{1cm} (15)

\[ \sigma_b = \frac{\text{number of reactions per unit time}}{\text{beam particles per unit time} \times \text{scattering centres per unit area}} \]
Cross section of the nuclear reaction

Physical interpretation of $\sigma_b$:

1) Geometric reaction cross-section
the area presented by a single scattering centre to the incoming projectile $a$

2) Total reaction (or scattering) cross-section

This naive description of the geometric reaction cross section as the effective cross sectional area of the target particles is in many cases a good approximation to the true reaction cross-section (e.g.: as for pp-scattering at high energy)

The reaction probability for two particles, however, generally may be very different from these geometric considerations.

Furthermore, a strong energy dependence is also observed (e.g.: the reaction rate for the capture of thermal neutrons by uranium, for example, varies by several orders of magnitude within a small energy range) – resonant scattering.

$\Rightarrow$ In experiment one measures the reaction cross section which generally is not equal to the geometrical reaction cross section determined by the size of the interacting particles. The reaction cross section depends on the strength of the interaction and the presence of intermediate resonant states.
Cross section of the nuclear reaction

Total reaction (or scattering) cross-section

In analogy to the total cross-section, cross-sections for elastic reactions $\sigma_{el}$ and for inelastic reactions $\sigma_{inel}$ may also be defined. The inelastic part can be further divided into different reaction channels.

The total cross-section is the sum of these parts:

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$  \hspace{1cm} (16)

The cross-section is a physical quantity with dimension of [area], and is independent of the specific experimental design.

A commonly used unit is the barn, which is defined as:

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

1 millibarn = $1 \text{ mb} = 10^{-31}$ m$^2$

Typical total cross-sections at a beam energy of 10 GeV, for example, are

$\sigma_{pp}(10 \text{ GeV}) \approx 40 \text{ mb}$ for proton-proton scattering;

$\sigma_{vp}(10 \text{ GeV}) \approx 7 \cdot 10^{-14} \text{ b} = 70 \text{ fb}$ for neutrino-proton scattering.
Luminosity of the nuclear reaction

The quantity

\[ \mathcal{L} = \Phi_a \cdot N_b \]  \hspace{1cm} (18)

is called the \textit{luminosity}.

Like the flux, it has the dimension of \[[\text{area} \times \text{time}]^{-1}]\.

From (12): \[ \dot{N} = \frac{dN}{dt} = \Phi_a N_b \sigma_b \] and (14): \[ N_b = n_b \cdot d \cdot A \]

\[ \mathcal{L} = \Phi_a \cdot N_b = \dot{N}_a \cdot n_b \cdot d = n_a \cdot v_a \cdot N_b \] \hspace{1cm} (19)

⇒ the luminosity is the product of

• the number of incoming beam particles per unit time \( \dot{N}_a \)

• the target particle density in the scattering material \( n_b \)

• and the target’s thickness \( d \)

Or

• the beam particle density \( n_a \)

• their velocity \( v_a \)

• and the number of target particles \( N_b \) exposed to the beam
In practice, only a fraction of all the reactions are measured. A detector of area $A_D$ is placed at a distance $r$ and at an angle $\theta$ with respect to the beam direction, covering a solid angle $\Delta \Omega = A_D/r^2$.

The rate of reactions seen by this detector is then proportional to the differential cross-section $d\sigma(E, \theta)/d\Omega$:

$$\dot{N}(E, \theta, \Delta \Omega) = \mathcal{L} \cdot \frac{d\sigma(E, \theta)}{d\Omega} \Delta \Omega$$  \hspace{1cm} (20)$$

If the detector can determine the energy $E$ of the scattered particles then one can measure the doubly differential cross-section $d^2\sigma(E,E', \theta)/d\Omega\ dE'$.

The total cross-section $\sigma$ is then the integral over the total solid angle and over all scattering energies:

$$\sigma_{\text{tot}}(E') = \int_0^{E'_{\text{max}}} \int_{4\pi} d\Omega \ dE' \frac{d^2\sigma(E,E',\theta)}{d\Omega\ dE'}$$ \hspace{1cm} (21)$$
The “Golden Rule”

The cross-section can be experimentally determined from the reaction rate \( \frac{dN}{dt} \).

Now we outline how it may be calculated in theory.

The reaction rate is dependent on the properties of the interaction potential described by the Hamilton operator \( H_{\text{int}} \). In a reaction, this potential transforms the initial-state wave function \( \psi_i \) into the final-state wave function \( \psi_f \).

The transition matrix element or the probability amplitude for the transition, is given by:

\[
\mathcal{M}_{fi} = \langle \psi_f | H_{\text{int}} | \psi_i \rangle = \int \psi_f^* \ H_{\text{int}} \ \psi_i \ dV \tag{22}
\]

According to the uncertainty principle, each particle occupies a volume \( h^3 = (2\pi\hbar)^3 \) in phase space, the six-dimensional space of momentum and position.

Consider a particle scattered into a volume \( V \) and into a momentum interval between \( p' \) and \( p' + dp' \). In momentum space, the interval corresponds to a spherical shell with inner radius \( p' \) and thickness \( dp' \) which has a volume \( 4\pi p'^2 dp' \)

\( \Rightarrow \) the number of final states available is:

\[
dn(p') = \frac{V \cdot 4\pi p'^2}{(2\pi\hbar)^3} \ dp'
\]  \tag{23}
The “Golden Rule”

Energy and momentum of a particle are connected by:

\[ dE' = v' dp' \]

\[ \Rightarrow \text{the density of final states in the energy interval } dE' \text{ is given by:} \]

\[ \varrho(E') = \frac{d n(E')}{dE'} = \frac{V \cdot 4 \pi p'^2}{v' \cdot (2\pi \hbar)^3} \]  \hspace{1cm} (24)

The connection between the reaction rate, the transition matrix element and the density of final states is expressed by Fermi’s golden rule.

It expresses the reaction rate \( W \) per target particle and per beam particle in the form:

\[ W = \frac{2\pi}{\hbar} |M_{fi}|^2 \cdot \varrho(E') \]  \hspace{1cm} (25)

From (12), (14) we know

\[ W = \frac{\dot{N}(E)}{N_b \cdot N_a} = \frac{\sigma \cdot v_a}{V} \]  \hspace{1cm} (26)

where \( V = N_a/n_a \) is the spatial volume occupied by the beam particles.

\[ \Rightarrow \text{the cross-section is:} \]

\[ \sigma = \frac{2\pi}{\hbar \cdot v_a} |M_{fi}|^2 \cdot \varrho(E') \cdot V \]  \hspace{1cm} (27)
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