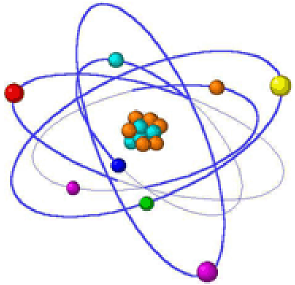
Radioisotope and Radiation Applications (FS2013)



Introduction: Motivation and Physical Basics (Week 1a)

Pavel Frajtag

17.09. 2013

General Organizational Aspects

- MSc Nuclear Engineering: Elective core course track option B, Physics and Materials
- Seven Tuesdays in this fall semester 2013: 4x45' lectures, 2x45' exercises
- Oral exam in (January) 2013, for award of 4 credits
  - 30' : 2 questions on different topics discussed in the lectures
  - 30' : for preparation, with documentation
- Coordinates of the lecturer: Pavel Frajtag
  - EPFL SB IPEP LRS, PH D3 455 (Bâtiment PH), Station 3, Lausanne, CH-1015
  - Phone: +41-21-69-33378, E-Mail: pavel.frajtag@epfl.ch; pavelcz@gmail.com
- The exercises consist of:
  - numerical examples,
  - seminar on a specific topic or PSI/EPFL-facility/laboratory
- Handouts and supplementary course material will be distributed in the lecture and/or will be available at the website:
  - http://pavel-frajtag.webnode.cz/
- **I encourage you to ask questions !**

Schedule of Lectures and Exercises

- **Week 1a** (17.09.13): Introduction: Motivation and **Physical Basics**
- Week 1b (17.09.13): Radiation Sources, Detectors
- Week 1c (17.09.13): **Seminar** & **Exercises/Organisation**

- Week 2a (24.09.13): Radiation Shielding
- **Week 2b** (24.09.13): **Biological Effects** of Radiation
- Week 2c (24.09.13): **Exercises (W1a)** & **Exercises (W1b)**

- **Week 3a** (01.10.13): **Medical Diagnostics**, Radiopharmaceuticals
- Week 3b (01.10.13): Radiotherapy: Fundamentals, Methods (part 1)
- Week 3c (01.10.13): **Seminar: Health Effects of Low Dose Radiation** & **Exercises (W2a)**

- Week 4a (15.10.13): Radiotherapy: Methods (part 2)
- Week 4b (15.10.13): Treatment Planning
- Week 4c (15.10.13): **Seminar: Proton Therapy at PSI** & **Exercises (W3b)**

- **Week 5a** (05.11.13): **Industrial Applications:** Gauges and Radiotracers
- Week 5b (05.11.13): Polymerisation, Food Irradiation, Radioisotope Batteries
- Week 5c (05.11.13): **Seminar** & **Exercises (W4a)**

- Week 6a (12.11.13): Gamma and Neutron Radiography
- **Week 6b** (12.11.13): **Applications in Natural Sciences:** Neutron Activation Analysis, Nuclear Dating
- Week 6c (12.11.13): **Seminar: NEUTRA / ICON Facilities at PSI** & **Exercises (W5a)**

- **Week 7a** (19.11.13): **Radiochemistry Applications**
- Week 7b (19.11.13): Radionuclides to Protect the Environment
- Week 7c (19.11.13): **Seminar: PROTRAC Facility at PSI** & **Exercises (W6b)**

Motivation for Medical Applications: Healing and Lifesaving!

Radiology offers:

- ☐ A variety of medical imaging technologies to diagnose and treat diseases
- ☐ Imaging at the molecular level / **unique sensitivity** at the picomolar level
- ☐ **Singular ability** to investigate specific biological targets and signalling in man
- ☐ **Unique advantages** in the investigation of movement disorders
- ☐ Technologies for the noninvasive investigation of myocardial perfusion
- ☐ **Most reliable** technologies for kidney function and transplant assessment
- ☐ Used for treatment of thyroid- and other types of cancer
- ☐ At the core of endocrinological investigations, ….
- ☐ **Statistics: 1.34 X-ray examinations per person in Switzerland in 1998!**

Motivation for Industrial/Research Applications: Unique Advantages

- ☐ Applications based on Absorption and Scattering:
  - measure remotely (non-destructive), online and in hostile environments
- ☐ Radiotracer Applications: high sensitivity
  - Tritium (T) can be determined in an atomic ratio down to T:H ~ 10^{-19} !
- ☐ Polymerisation, Sterilisation, Radioisotope Batteries:
  - radiation leads to products of higher density and higher softening temperature
  - maintenance-free energy source with high output related to mass and volume
- ☐ Gamma and Neutron Radiography:
  - provide complementary information in comparison to other techniques
- ☐ Applications in Natural Sciences (Neutron Activation Analysis, Nuclear Dating), Radiochemistry Applications, Life Sciences:
  - high sensitivity, unique method

Generally many factors: uniqueness, sensitivity, time, costs, efficiency, quality...

Literature (for all lectures)

- ☐ G.C. Lowenthal, P.L. Airey, *“Practical Applications of Radioactivity and Nuclear Reactions”,* Cambridge University Press (2001)
- ☐ K.H. Lieser, *“Nuclear and Radiochemistry”*, WILEY-VCH (2nd edition, 2001)
- ☐ James E. Martin, “Physics for Radiation Protection“, Wiley-VCH (2nd edition, 2006)
- ☐ F.M. Khan, “The Physics of Radiation Therapy“, Lippincott, Williams & Wilkins, (4th edition, 2010).

- ☐ **Additional literature will be listed at the end of each lecture!**

Week 1a: Physical Basics / Contents

- ☐ Energy
- ☐ Structure and properties of (stable) atomic nuclei
  - Nucleons, strong interaction, size of nuclei
  - Binding energy, Bethe-Weizsäcker mass formula, nuclear levels, nuclear models
- ☐ Unstable nuclei and their decay
  - Q-value, radionuclides, decay law, activity
  - Major decay modes
- ☐ Basics of nuclear reactions
  - Energetics, reaction types, cross sections, yields
- ☐ Summary
- ☐ Literature/WWW-references

Energy

- ❑ Basics:
  - **Definition:** The potential (option, possibility) to perform work.
  - Basic physical (SI-)**unit** Joule (J):
    1J=1Newton·1Meter=1Nm=1kg·m^2/s^2=1Watt·1sec=1Ws
  - Historically various notations: Joule, kWh, cal, …
  - Mass and energy are equivalent: **$E = m\cdot c^2$**

Energy units and conversion factors

Joule	SI-Unit	J	1.0
erg	CGS-Unit	erg	$1.0 \cdot 10^{-7}$
Electronvolt	Physics	eV	$1.602 \cdot 10^{-19}$
Calorie	Chemistry	cal	4.186
Kilowatt hour	Tech.	kWh	$3.6 \cdot 10^{6}$
kg coal	Tech.	kgSKE	$2.93 \cdot 10^{7}$

- ❑ There are various manifestations of energy: heat, kinetic energy, potential energy, elastic energy, electric energy, …, work.
  - Energy of electromagnetic radiation/fields: $E = h\cdot\nu$
  - Chemical (binding) energy: $C + O_2 \leftrightarrow CO_2$ + **4.2 eV**
  - Nuclear binding energy: $B(Z,N) = Zm_p + Nm_n - M(Z,N)$, e.g.,
    - fusion in the sun: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ + **26.2 MeV**
    - fission in a reactor: $n + {}^{235}U \rightarrow$ fission products + (2–3) n + **~210 MeV**

Standard Model (of elementary particle physics)

- Fundamental building blocks of matter are **fermions** (half-integer spin particles):

Family	**Quarks**	**Mass**	**Charge**	**Spin**	**Leptons**	**Mass**	**Charge**	**Spin**
first	up (u)	5 MeV	+2/3 e	½	ν_e	≈0	0	½
	down (d)	10 MeV	−1/3 e	½	e^-	511 keV	−e	½
second	charm (c)	1.3 GeV	+2/3 e	½	ν_μ	≈0	0	½
	strange (s)	200 MeV	−1/3 e	½	μ^-	106 MeV	−e	½
third	top (t)	180 GeV	+2/3 e	½	ν_τ	≈0	0	½
	bottom (b)	4.3 GeV	−1/3 e	½	τ^-	1.78 GeV	−e	½

- Interactions are mediated by exchange of **vector-bosons** (integer spin particles):

Interaction	**Boson**	**Mass**	**Charge**	**Spin**
1) Gravitation	Graviton	0	0	2
2) Electromagnetic	Photon	0	0	1
3) Strong (hadronic)	Gluon	0	0	1
4) Weak	W^+, W^-, Z^0	80 GeV, 80 GeV, 91 GeV	+e, −e, 0	1

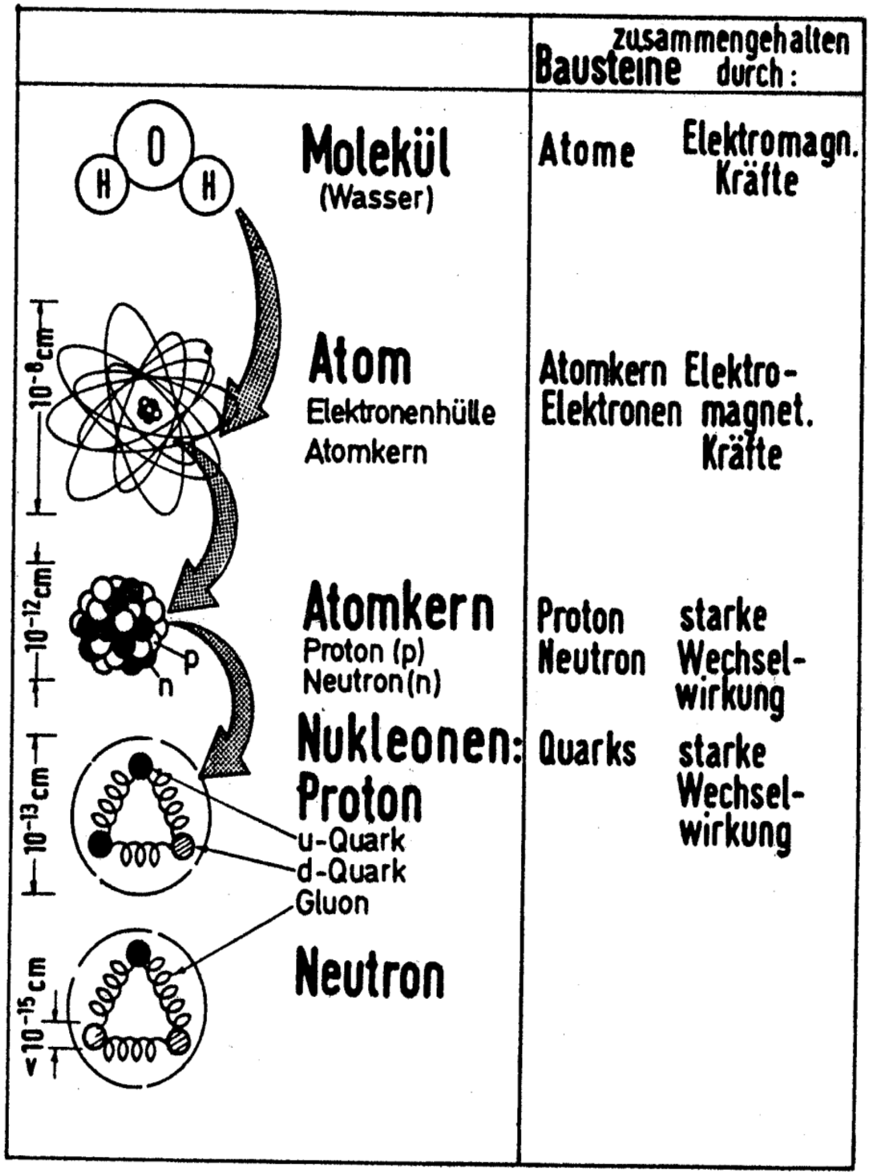
Structure and properties of stable nuclei

- Matter is structured in layers.
- Free quarks do not exist („confinement“). Hadrons (particles bound by the strong interaction) comprise Baryons (3 quark systems) and Mesons (quark-antiquark systems).
- Nuclei consist of protons (p) and neutrons (n), which are called nucleons:

Nucleon	Charge	Mass	Spin
p=(uud)	+1	938.27 MeV	½
n=(udd)	0	939.57 MeV	½

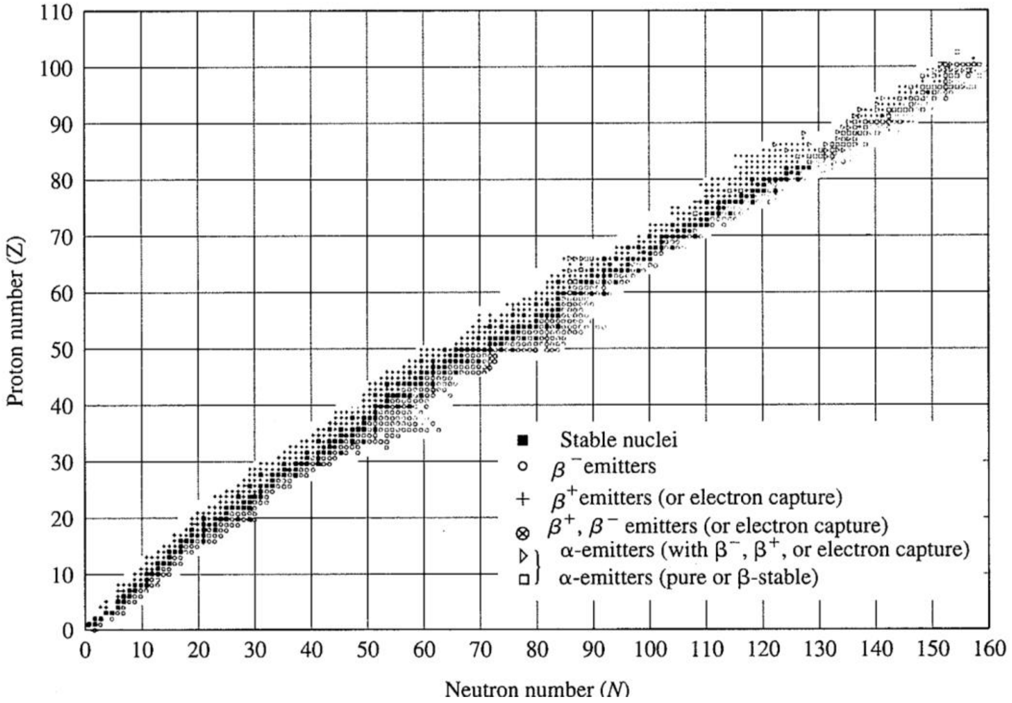
- A nucleus is characterized by its atomic number Z and its mass number A=Z+N:

${}^{A}_{Z}X_{N}$ e.g.: ${}^{14}_{6}C_{8}$

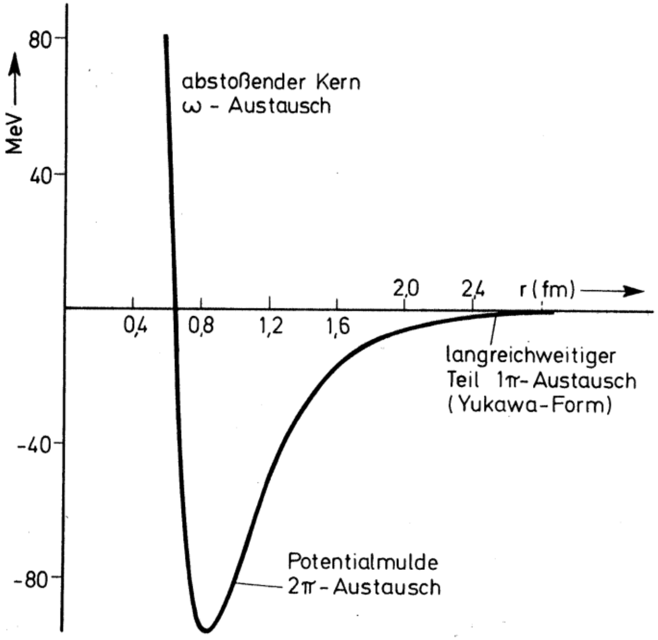


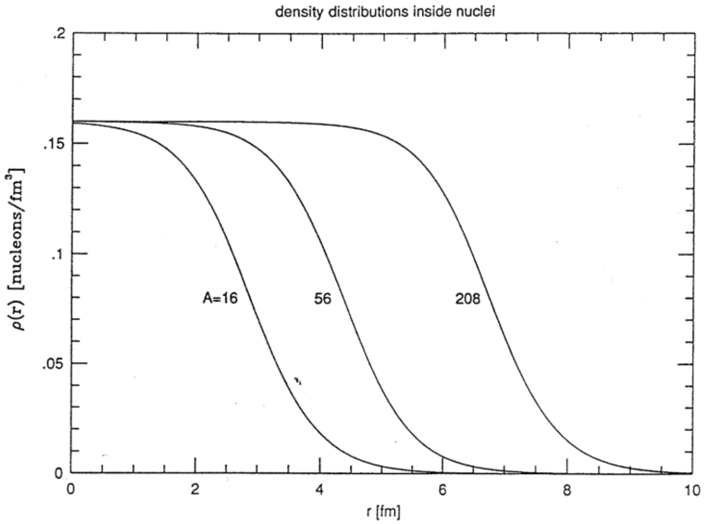
Nuclear Chart

- ☐ Plotting Z versus N gives the nuclear chart:
  - Only few combinations of Z and N lead to stable nuclei
  - For light stable atoms, N~Z
  - For Z>20 the repulsive Coulomb force between protons entails N>Z
- ☐ Nomenclature:
  - Isotopes are nuclei with equal Z, →, e.g., ${}^{1}_{1}H$, ${}^{2}_{1}H$=D, ${}^{3}_{1}H$=T
  - Isotones are nuclei with equal N, ↑, e.g., ${}^{22}Ne$, ${}^{23}Na$, ${}^{24}Mg$
  - Isobars are nuclei with equal A, \, e.g., ${}^{12}B$, ${}^{12}C$, ${}^{12}N$
- ☐ More terms: valley of stability, colour scheme in a nuclear chart, proton rich, neutron rich, proton dripline, neutron dripline



Nucleon-nucleon potential and the size of nuclei



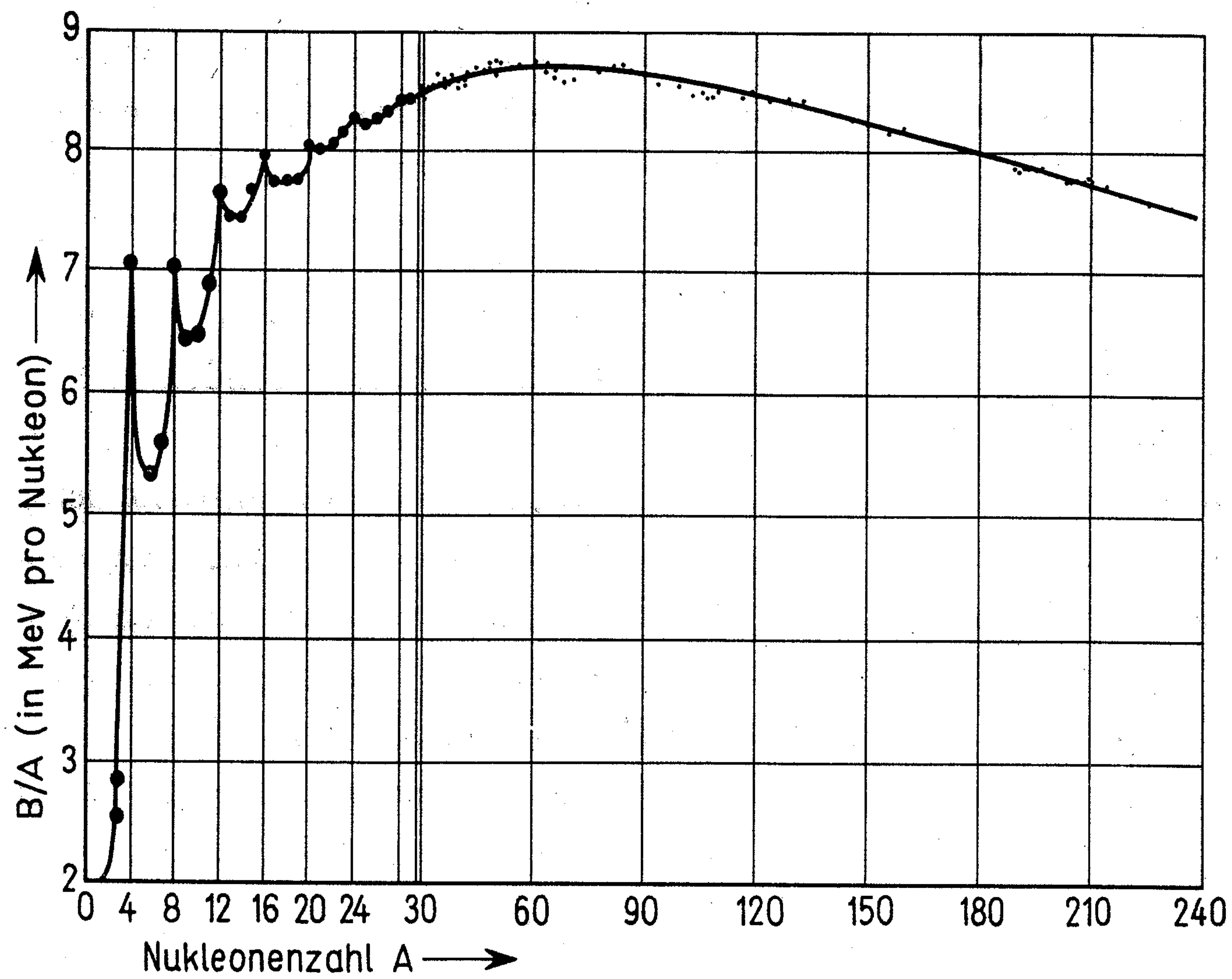


- The interaction between nucleons can be described by the exchange of mesons (qualitatively illustrated in the diagram top left) and leads to a **saturation of the nuclear forces**.
- The radii of nuclei are approximately given by: $\mathbf{R \approx r_0 \cdot A^{1/3}}$ with $r_0 = 1.2$ fm = $1.2 \cdot 10^{-13}$ cm.
- The density distribution within a nucleus can be described by a Woods-Saxon-potential and is shown in the diagram bottom left:
  - $\rho(r) = \rho_0 / (1+\exp[(r-R)/d])$, R=radius, d=diffuseness, ρ_0=central density on the order of $2.7 \cdot 10^{14}$ g/cm^3 = 270‘000 t/mm^3.
- The nucleons in a nucleus are densely packed like water molecules in a water drop (droplet model).

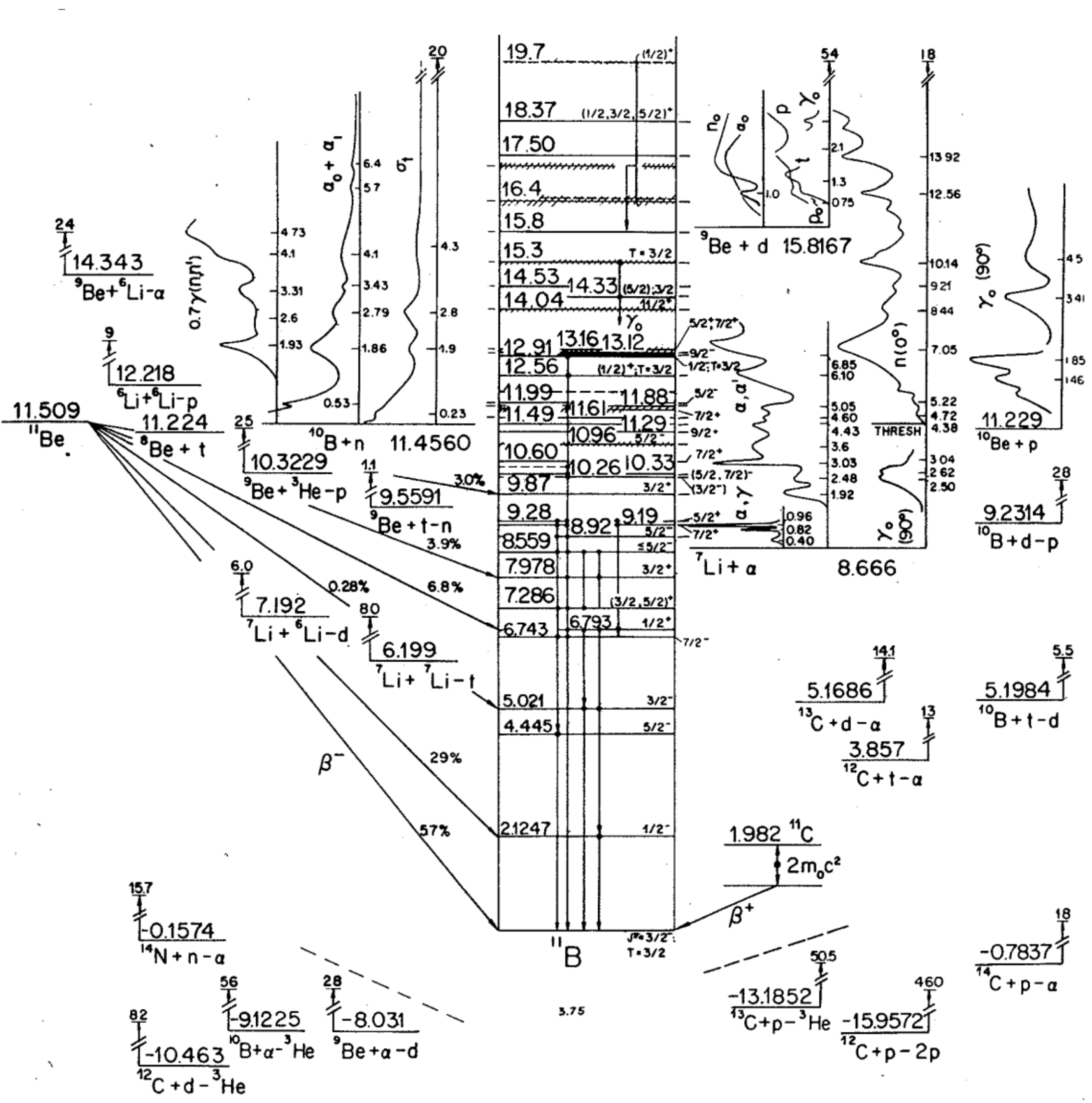
Masses and Binding Energy of Nuclei

- ☐ Masses of nuclei are expressed in terms of the atomic mass unit 1amu:
  - 1amu := 1/12 ·m(^{12}C) = 1/N_A g = $1.66057 \cdot 10^{-24}$ g with N_A=Avogadro's number
  - In these units m_p=1.0073 amu, m_n=1.0087 amu.
- ☐ The mass of a nucleus is smaller than the sum of the nucleon masses.
- ☐ The difference **$\Delta = Zm_p + (A-Z)m_n - M_{nucl}(Z,N)$** is called **mass defect** and corresponds to an energy, the **binding energy** of a nucleus **$B(Z,N) = \Delta c^2$**.
- ☐ The binding energy per nucleon f=B/A (binding fraction) is a measure of the stability of a nucleus.
- ☐ Following Bethe and Weizsäcker the binding energy can be parameterized by:
  - $B(Z,N) = a_v A - a_s A^{2/3} - a_c Z^2 A^{-1/3} - a_{sym} (N-Z)^2/A + B_{pair}(Z,N)$

Binding fraction B/A as a function of A for stable nuclei



Energy levels of nuclei and nuclear models



- Nuclei are strongly interacting many-body systems that must be described by the theory of **quantum mechanics**. (Nuclear Theory is tough!)
- **Energy levels of nuclei** have well defined energies (**discrete states**), well defined angular momentum and well defined parity **E=E(J,π)**.
- Transitions between nuclear energy levels can be triggered in various ways.
- There is a wide variety of nuclear models that are applied to describe the structure of nuclei and nuclear reactions:
  - Fermi-Gas Model
  - Droplet model
  - Shell-Model
  - Cluster Models

Unstable Nuclei and their decay

- Most combinations of Z and N lead to unstable nuclei, i.e., nuclei that disintegrate (sooner or later) spontaneously. These are called **radionuclides**.
- A necessary condition for the decay of a nucleus is that it is energetically allowed, i.e., the **Q-value** of the corresponding transition is positive: $\mathbf{Q = \Delta E = (\Sigma M_i - \Sigma M_f)\cdot c^2 > 0}$.
- Usually one distinguishes natural (occurring in nature) and artificial (man made) radionuclides.
- Radionuclides can decay in many ways:
  - Most common for light and medium weight nuclei are α, β, and γ-decays (next slide).
  - Beyond the driplines protons and neutrons may be ejected spontaneously.
  - Heavy nuclei may decay by spontaneous fission, typically into 2 or 3 fragments.
  - Heavy nuclei can also emit ^{12}C or other (closed shell) nuclei.
  - Other decay processes are electron or positron capture: $^{A}Z + e^{-} \longrightarrow {}^{A}(Z-1) + \nu_e$,
    $^{A}Z + e^{+} \longrightarrow {}^{A}(Z+1) + \nu\text{bar}_e$
  - A competing process to γ-decays is internal conversion: the de-excitation energy is transferred from the nucleus to an inner shell atomic electron.
- Radioactive mother nuclei may decay to daughter nuclei that are radioactive as well, etc., thus leading to decay chains.

Fundamental decay modes and properties of α, β, γ-radiation

❑ **α-decay**: $^{A}Z \longrightarrow {}^{A-4}(Z-2) + {}^{4}He$

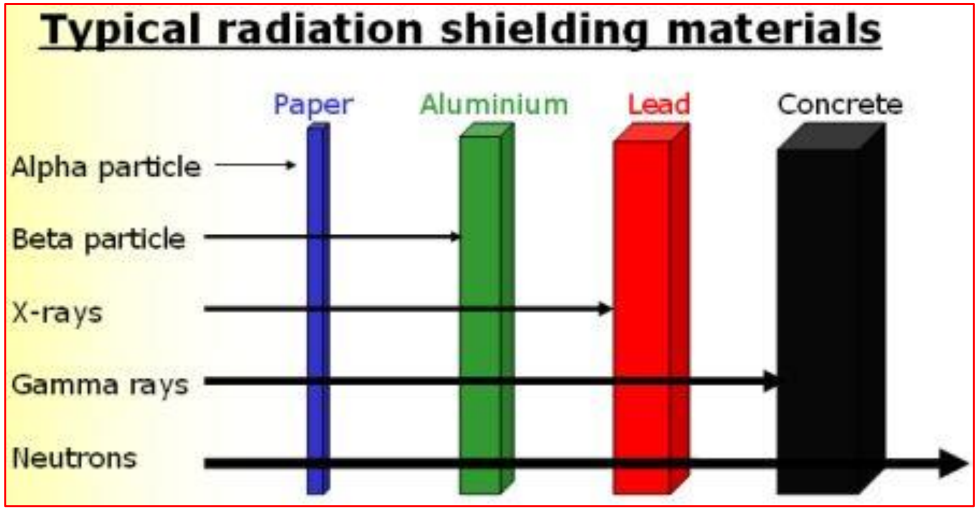
- 2-particle decay: α have discrete energies
- Theory: transmission through potential barrier (QM: tunneling)
- highly ionizing, short range

❑ **β-decay**: $^{A}Z \longrightarrow {}^{A}(Z\pm1) + e^{-/+}$ + nubar/nu

- 3-particle decay: β have energy spectrum
- Theory: Fermi's Golden Rule
- medium range, zig-zag paths
- attenuation mainly due to scattering on atomic electrons, also due to Bremsstrahlung

❑ **γ-decay**: $^{A}Z^{*} \longrightarrow {}^{A}Z + \gamma$

- 2-particle decay: γ have discrete energies
- Theory: Fermi's Golden Rule
- rather long range, attenuation due to Photoelectric and Compton effect and pair production



Attenuation law for β-, γ-rays, neutrons:

$$\boxed{I(x) = I_0\, e^{-\mu x}}$$

Decay Law and Activity

Decay Law

$$N(t) \; = \; N(t=0) \cdot e^{-\lambda t} \; = \; N_0 \cdot e^{-\frac{\ln 2}{T_{1/2}} t}$$

with

$$\lambda = \text{decay constant} \quad \left[\frac{1}{s}\right]$$

$$T_{1/2} = \frac{\ln 2}{\lambda} = \text{half-life} \quad [s]$$

$$\tau = \frac{1}{\lambda} = \text{average lifetime} \quad [s]$$

Definition: **Activity** = disintegration rate

$$A(t) \; = \; -\frac{\mathrm{dN}}{\mathrm{dt}} = \lambda \cdot N(t) \; = \; \lambda N_0 \cdot e^{-\lambda t}$$

Unit: 1 Becquerel = 1Bq = $\frac{\text{1decay}}{\text{second}} = \left[\frac{1}{s}\right]$

old unit: 1 Curie = 1Ci = $3.7 \cdot 10^{10}\ \frac{\text{decays}}{\text{second}}$

(≡ activity of one gram radium)

Derived Units for Activity

- **specific activity** = activity per gram mass $\left[\frac{Bq}{g}\right]$

  1g of nuclide ${}^{A}\mathrm{X}$ contains $\frac{6.023 \cdot 10^{23}}{A}$ atoms

  $$\Rightarrow \text{specific activity} = \lambda \cdot N(t) \;/\; 1\text{g}$$

  $$= \frac{\ln 2}{T_{1/2}} \cdot \frac{6.023 \cdot 10^{23}}{A} \;/\; 1\text{g}$$

  $$= \frac{1}{A} \cdot \frac{1}{T_{1/2}} \cdot 4.175 \cdot 10^{23} \;/\; 1\text{g}$$

- **activity concentration:** $\left[\frac{Bq}{m^3}\right], \left[\frac{Bq}{l}\right]$
- **area activity**: $\left[\frac{Bq}{m^2}\right], \left[\frac{Bq}{cm^2}\right]$
- **activity rate:** (generation, intake, release) $\left[\frac{Bq}{s}\right]$

Basics of Nuclear Reactions

- ☐ **Scattering reactions play a fundamental role in Nuclear- and Elementary particle physics!** If a beam of projectiles *x* is directed at a target consisting of nuclei ^{A}Z many processes or nuclear reactions can occur:
  - Elastic scattering: $^{A}Z + x \rightarrow {}^{A}Z + x$ [or, in abbreviated form: $^{A}Z(x,x)^{A}Z$]
  - Inelastic scattering: $^{A}Z + x \rightarrow {}^{A}Z^{*} + x'$ [or: $^{A}Z(x,x')^{A}Z^{*}$]
  - (Proper) **Nuclear reaction: $A + x \rightarrow B_k + y_k$** [or $A(x,y_k)B_k$] k=1,2,...,i.e., several product nuclides B_k and ejectiles y_k may be produced
  - Specific reactions may have specific names, e.g., radiative capture A(x,γ)B, or fission of nuclei A(n,f).
- ☐ For all nuclear reactions the following **conservation laws** are valid:
  - conservation of nucleons: $A_A + A_x = A_B + A_y$
  - conservation of charge: $Z_A + Z_x = Z_B + Z_y$
  - conservation of energy: $E_A + E_x + M_A c^2 + M_x c^2 = E_B + E_y + M_B c^2 + M_y c^2$
  - conservation of momentum: $\mathbf{p}_A + \mathbf{p}_x = \mathbf{p}_B + \mathbf{p}_y$
- ☐ The **entrance channel** and **exit channels** of a nuclear reaction may be further specified by their quantum numbers (particles, relative energy, angular momentum, spin).
- ☐ The magnitude of the **cross sections** for the various projectile induced processes depend on the energy of the projectile and on the structure of the target nucleus.

Energetics of Nuclear Reactions/Reaction Types

- ☐ The energy ΔE corresponding to the mass difference of entrance and exit channel is called **Q-value** of a nuclear reaction: $\mathbf{Q = \Delta E = (M_A+M_x - M_B - M_y)c^2}$
  - if Q>0 reactions are called exothermic: there is a net increase in the kinetic energies of the particles
  - if Q<0 reactions are called endothermic: there is a net decrease in the kinetic energies of the particles
- ☐ **For endothermic reactions** a **threshold energy** exists for the projectile x, and the reaction can only occur for E_x (kinetic energy of x) greater than the threshold energy.
- ☐ The **reaction mechanism** of a reaction depends to a large extent on the relative kinetic energy of projectile and target:
  - most **low-energy reactions proceed via formation of a compound nucleus**, i.e., via an excited intermediate state: $A + x \rightarrow \mathbf{C} \rightarrow B + y$ ($\Delta t \approx$ up to 10^{-16} sec)
  - **with increasing energy direct interactions** ($\Delta t \approx 10^{-22}$ sec) take place, in which one or several nucleons may be transferred or protons/neutrons may exchange their charge
  - at high energies nucleons may simply be knocked out of the nucleus
  - at very high energies nucleons may be knocked out and excited

Examples of Nuclear Reactions

(excluding decays and (in)elastic scattering)

- ☐ General reactions: $^{23}Na(p,\alpha)^{20}Ne$, $^{9}Be(\alpha,n)^{12}C$
- ☐ Capture reactions: $^{59}Co(n,\gamma)^{60}Co(\beta^-)$, $T_{½}=5.27a$; $^{13}C(p, \gamma)^{14}N$
- ☐ Transfer-reactions (exchange of one or several nucleons):
  - a) Stripping-reaction: $^{12}C(d,p)^{13}C$, (d,n)
  - b) Pick-up-reaction: $^{17}O(^{3}He,\alpha)^{16}O$, (t,α)
- ☐ Spontaneous fission: $^{239}Pu(f)$
- ☐ (Neutron) induced fission: $^{235}U(n,f)$

Definition of the Cross Section (XS)

Scattering reactions play a fundamental role in Nuclear- and Elementary Particle Physics !!!

Definition (microscopic) XS: $\sigma = \frac{\text{Number of reactions of given type per target } /\text{s}}{\text{flux density j of incident Particles}}$

$[\sigma] = \frac{1}{s} \cdot \frac{1}{\frac{1}{\text{cm}^2 s}} = \text{cm}^2$; "active area" ; Units: $\bar{1}$ Barn $= 1\text{b} = 10^{-24}\ \text{cm}^2$; $1\text{mb} = 10^{-27}\ \text{cm}^2$

Differential XS: $\frac{d\sigma}{d\Omega}(E,\vartheta,\varphi)$; Total XS: $\sigma_{t(otal)} = \sigma_{el} + \sigma_{in} + \sigma_\gamma + \sigma_f =: \sigma_{el} + \sigma_{a(bsorption)}$

In engineering often the macroscopic XS: $\Sigma_{r,i}(E) = N_i \cdot \sigma_{r,i}(E) \quad [\frac{1}{\text{cm}}]$

is used, e.g., for reactions of neutrons an on a nucleus (Isotope) i.

In matter consisting of a mixture of isotopes we have: $\Sigma_r(E) = \sum_i \ N_i \cdot \sigma_{r,i}(E)$

For the flux density $I(x)$ of neutrons in matter we have: $I(x + \mathrm{d}x) = I(x) - \Sigma_t\ I(x)\,\mathrm{d}x$

or $\frac{\mathrm{d}I(x)}{\mathrm{d}x} = -\Sigma_t\ I(x)$

Flux density as a function of the path a: $I(a) = I(0)\ e^{-\Sigma_t \cdot a}$

The mean free path is then given by: $\bar{\lambda} = \frac{\int_0^\infty x \cdot e^{-\Sigma_t x}\,\mathrm{d}x}{\int_0^\infty e^{-\Sigma_t x}\,\mathrm{d}x}$ with $\bar{\lambda} = \frac{1}{\Sigma_t}$

Example: Cross Section for Neutron Scattering on Carbon

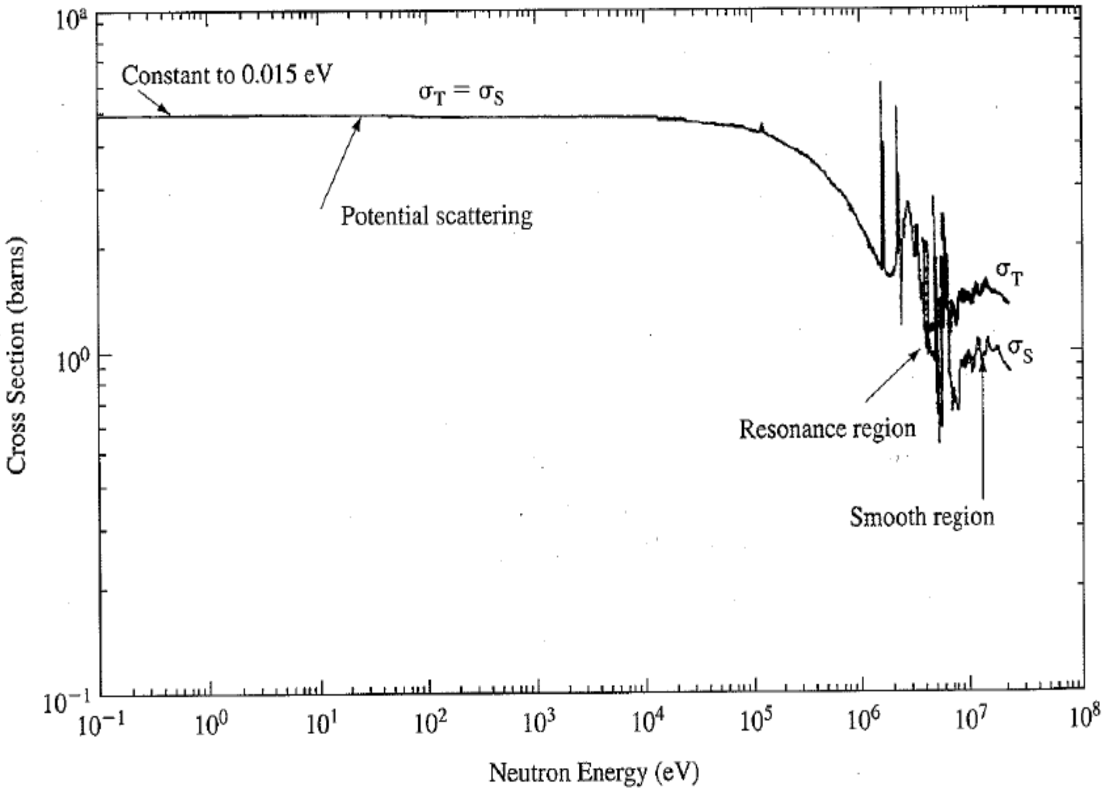


Figure 3.4 The elastic scattering and total cross-section of carbon.

- ☐ The elastic scattering cross section as a function of E_N can be divided in three regions:
  - Low energy, σ_e=const ~ $4\pi R^2$
  - Medium energy: resonances
  - High energy: smooth increase with energy
- ☐ The energy loss E–E` of the neutron in elastic scattering processes can be calculated from energy and momentum conservation:

$$E' = \frac{E}{(A+1)^2} \left[\cos\vartheta + \sqrt{A^2 - \sin^2\vartheta} \right]^2$$

$$E'_{min} = \left(\frac{A-1}{A+1}\right)^2 E$$

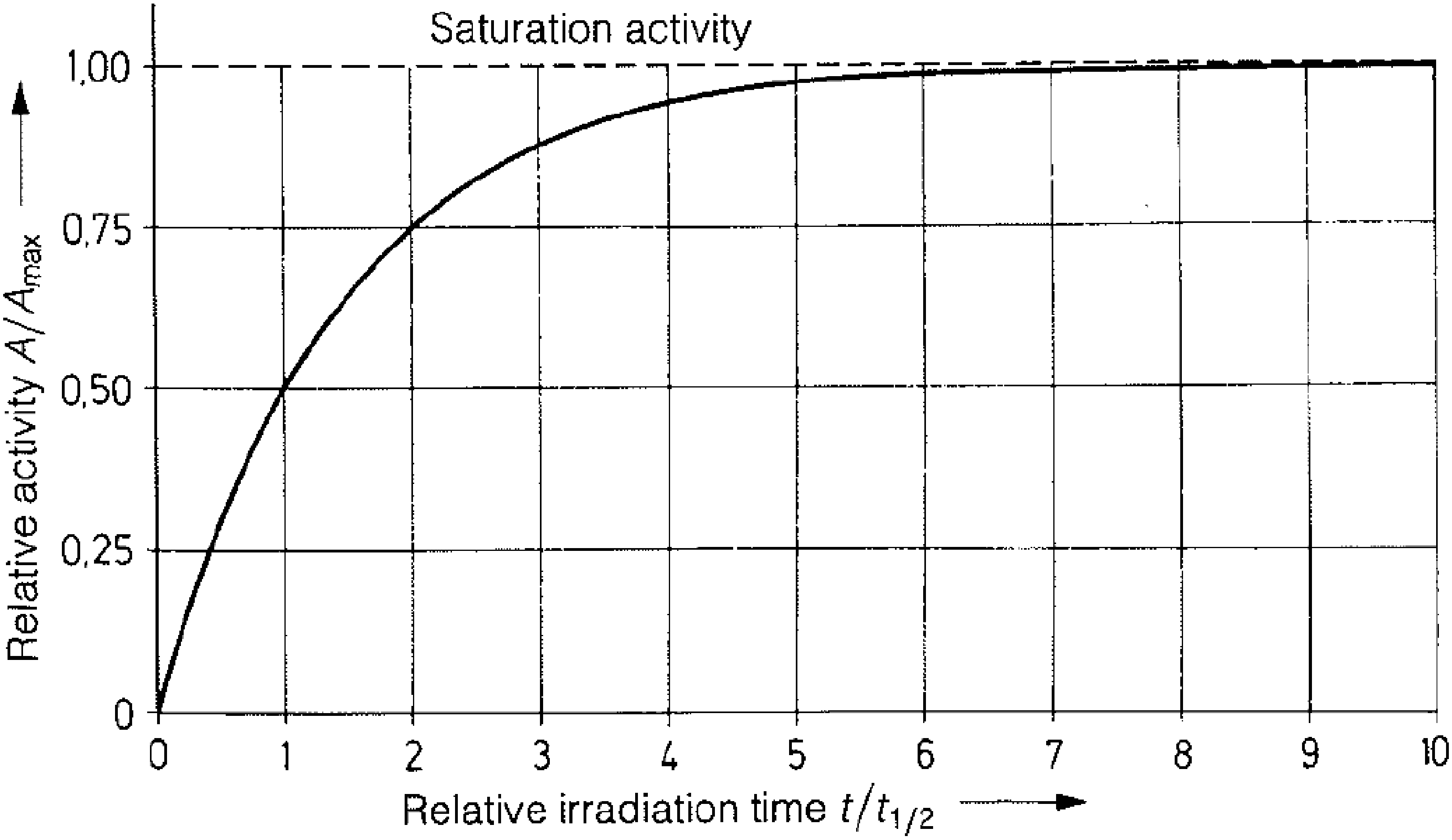
Neutron Interactions with Matter

- ☐ Neutron scattering and neutron absorption on nuclei:
  - Elastic scattering: $^{A}Z(n,n)^{A}Z$; energy loss of neutron is highest for light nuclei
  - Inelastic scattering: $^{A}Z(n,n')^{A}Z^{*}$
  - Radiative capture: $^{A}Z(n,\gamma)^{A+1}Z$
  - Nuclear reactions: $^{A}Z(n,p)$, $^{A}Z(n,\alpha)$, $^{A}Z(n,2n)$, ...
  - Fission of heavy nuclei: $^{A}Z(n,f)$
- ☐ Neutron attenuation: $I(x)=I(0)\cdot\exp(-\Sigma_t\cdot x)$, $\Sigma_t=N\cdot\sigma_t=N\cdot(\sigma_e+\sigma_i+\sigma_\gamma+\sigma_r+\ldots)$
- ☐ Again: the magnitude of the cross sections for the various neutron induced processes depends on the energy of the neutron and on the structure of the target nucleus.

Yield of Nuclear Reactions

- ☐ The **production rate** of nuclide P in the nuclear reaction T + x → P + y is given by (the activation equation): $dN_P/dt = \sigma\Phi N_T$ (σ = reaction cross section, Φ = incoming flux density of projectiles, N_T= number of target atoms).
- ☐ If P is radioactive, its **decay rate** is given by: $-dN_P/dt = \lambda N_P$.
- ☐ Thus the **net production rate** is: $dN_P/dt = \sigma\Phi N_T - \lambda N_P$.
- ☐ Integration of the last equation gives: $N_P = (\sigma\Phi N_T / \lambda)\cdot (1-\exp(-\lambda t))$ for the number of atoms of nuclide P produced after irradiation time t.
- ☐ The corresponding activity A of P is: $A = \lambda N_P = \sigma\Phi N_T\cdot (1-\exp(-\lambda t))$ [1].
- ☐ The relation between N_T and the mass m of the element containing the nuclide T is: $N_T= (N_{Av}/M) \cdot H \cdot m$ [2] (N_{Av}=Avogadro's number, M=atomic mass of the element, H=isotopic abundance of the nuclide T in the element)
- ☐ Substitution of Eq.[2] in Eq.[1] gives: $A = \sigma\Phi H\ m\ (N_{Av}/M) \cdot (1-(½)^{t/T})$ (T=half-life).

Activity as a Function of Irradiation Time



Summary (Introduction/Basics)

- ☐ Role of this lecture within MSc Nuclear Engineering: **Look beyond your nose !**
- ☐ **The application of radioisotopes and radiation offers unique advantages in many fields.**
- ☐ Protons and neutrons are the constituents of nuclei. **Nuclei must be described in the framework of Quantum Mechanics**. Energy levels of nuclei have well defined energies (discrete states), well defined angular momentum and well defined parity.
- ☐ A radioisotope corresponds to an unstable combination of neutrons and protons in the nucleus. **Radioisotopes are a part of nature!**
- ☐ **Radioisotopes are sources of radiation. They are characterized by their decay modes and the radiation emitted in the decay**.
- ☐ Their decay is described by an exponential decay law: $N(t)=N(0)\cdot\exp(-\lambda t)$ with decay constant $\lambda=\ln 2/T_{½}$ and half-life $T_{½}$.
- ☐ Decay chains can occur, in the case of both **natural and artificial radionuclides**.

Literature / WWW-references

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- National Nuclear Data Center: **http://www.nndc.bnl.gov/**
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