Detection of Ionizing radiation

Introduction

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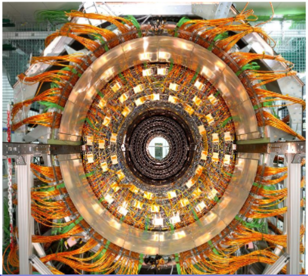



Outline

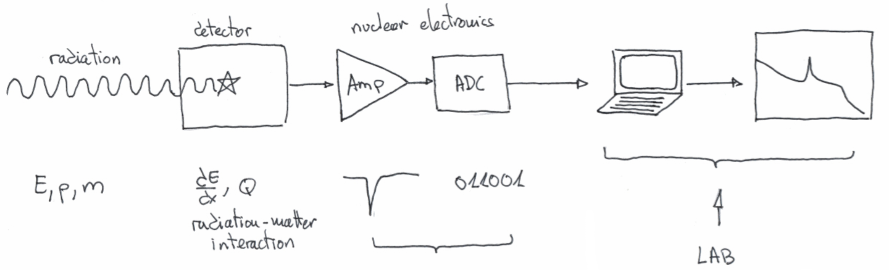
Section 1

Introduction

1. Introduction

Objectives

❒ Study of ionizing radiations and their detection

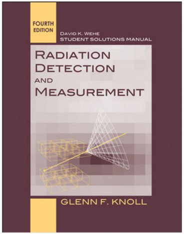


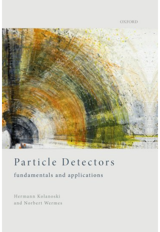
Scope of the course

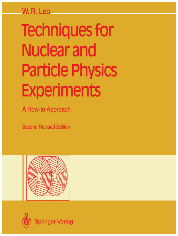
- Interaction of ionizing radiation with matter:
  - mechanisms, characteristics, applications
  - heavy & light charged particles, neutrons, γ-rays
  - basic dosimetry
- Detection of ionizing radiation:
  - main principles, some examples, applications)
  - Gaseous detectors
  - Semiconducting detectors
  - Scintillators
- Electronics in nuclear physics experiments
- Accelerators
- Production of radioisotopes

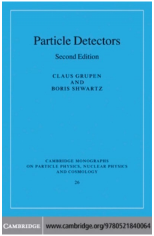
Bibliography

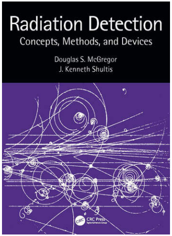
- Main references:
  - G.F. Knoll, Radiation Detection and Measurement
  - H. Kolanoski, N. Wermes, Particle Detectors (fundamentals and applications)
- Recommended references:
  - W.R. Leo Techniques for Nuclear and Particle Physics Experiments
  - C. Grupen, B. Schwartz Particle Detectors (2nd edition)
- To go in depth:
  - D. McGregor, J. Kenneth Shultis, Radiation Detection: Concepts,Methods and Devices.











Course activities

- Course activities spans over the two semesters.

- Theory
  - Lectures: Ionizing radiation and its detection
    Accelerators and Artificial radioactivity
  - Exercices Bulletin available after each chapter
  - Project on an advanced topic

- Laboratory:
  - 1st semester: Discovery of basic techniques and concepts
  - 2nd semester: Project.
    - Physics measurement: Several topics available
    - Two oral presentations: March and June

Planning: Theory Lectures

- All lectures at 08h30-10h30 except the first one (14h00-16h00)
  - E. Cortina lectures will take place at LLN.
    Bat. Marc de Hemptinne room E.161
  - N. Severijns lectures will be at Heverlee
    Ahrenberg III campus room 200E 01.212
  - Th. Cocolios lectures will be at
    13/12 at 200E 01.212 (Heverlee)
    20/12 ar E.161 (LLN)

- Online room always available:
  https://eu.bbcollab.com/guest/8fdb41d7b1124cbd83cc34ae780faaee
- Lectures will be broadcasted but not recorded.

- Advanced topics: Topics available on Toledo/Moodle
  Choice by the end of October
  Oral presentation in February 2024

Planning: Theory Lectures

Date	Lecturer	Contents
Mon. 02/10/23	E. Cortina	Introduction + Radiation sources
Wed. 04/10/23	E. Cortina	Interaction of Radiation with matter (I)
Wed. 11/10/23	E. Cortina	Interaction of Radiation with matter (II)
Wed. 18/10/23	N. Severijns	General Properties of Detectors
Wed. 25/10/23	E. Cortina	Gas Detectors
Wed. 08/11/23	N. Severijns	Scintillation Detectors
Wed. 15/11/23	E. Cortina	Semiconductor Detectors
Wed. 22/11/23	N. Severijns	Light Detectors
Wed. 29/11/23	N. Severijns	Electronics
Wed. 06/12/23	N. Severijns	Electronics
Wed. 13/12/23	Th. Cocolios	Accelerators
Wed. 20/12/23	Th. Cocolios	Production of radioisotopes

Planning: Laboratory

- Laboratories are "freely" accessible. You only come when you wish/can.
  - Heverlee: rooms 00.89-90 and 01.84b
  - LLN: Bat. Marc de Hemptinne room E.064
- Assistants will be available:
  - Sem.1: Mondays 13h00-16h00 (from Oct 24, 2023)
  - Sem.2: Thursdays 13h00-16h00

- Introductory session: Heverlee: 24/10 18h00-19h00 at 200D-05.34
  LLN: 24/10 18h30-19h30 at E.161
  - Safety rules reminder
  - Radiation protection formalities: dosimeter
  - Logbook usage introduction
  - Presentations of projects and lab activities
  - Laboratory visit

Practical Informations

- When?
  - Theory: Wednesdays 8h30-10h30 (except 1st lecture)
  - Exercices: 15h-16h on selected Mondays (classroom+broadcasted)
  - Labs: Sem.1: Mondays 13h00-16h00 (from Oct 30, 2023)
    Sem.2: Thursdays 13h00-16h00

- Where?
  - Bat. Marc de Hemptinne room E.161
  - Ahrenberg III campus room 200E 01.212
  - Broadcasted on
    https://eu.bbcollab.com/guest/8fdb41d7b1124cbd83cc34ae780faaee
  - Labs: Nuclear instrumentation labs at KU Leuven and UCLouvain

- Slides, announcements, infos, ...
  Toledo: toledo.kuleuven.be
  Moodle: moodle.uclouvain.be/course/view.php?id=3817

Evaluation

- Written exam (in June): (45%)
  5-6 questions over the topics treated during the theory and the exercices lectures.
  - One question about nuclear electronics
  - One question about Artificial Radioactivity and Accelerators

- Individual project over an advanced topic. (10%)
  List of topics quite soon on Moodle/Toledo
  - Oral presentation in February/March 2024.

- Laboratory project: (45%)
  - Two presentations in 2nd semester
    - Presentation about exp. measurements in Sem 1.
    - Final presentation of the project

- At least 7/20 in each of the above activities. Overall mark >10/20
  - Written exam: overall mark AND Accel. and Art. Radiac. question

Section 2

Prerequisites

Prerequisites

1. Basics on Atomic Physics and Solid State
   - Bohr Model
   - Quantum numbers
   - Energy bands
   - Ionization potential
   - Chapter 2: Turner. Atoms, Radiation and Radiation Protection
2. Basics on Nuclear Structure
   - Binding Energies
   - Nuclear level diagrams
   - Nuclear reactions
   - Nuclear stability
   - Chapter 3: Turner. Atoms, Radiation and Radiation Protection
3. Basics on relativistic kinematics → Exercices
4. Counting Statistics → Self-learning module in Toledo/Moodle

Relativistic kinematics

- Radiation study needs relativistic treatment.
- Relativity → c=light speed is a constant in any reference frame
- The momentum $\vec{p}$ of a particle of (rest) mass m_0 is

$$\vec{p} = m_0 \vec{v} = m_0 \vec{\beta} c \qquad \vec{\beta} = \frac{\vec{v}}{c}$$

- A quantity related to β is the so called Lorentz factor γ:

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

- Relativistic Energy: $E^2 = m_0^2 c^4 + p^2 c^2$
  - If $p = 0$ then $E = m_0 c^2$
  - m_0 = rest mass

Relativistic kinematics

- Lorentz transformation: Relation between E and $\vec{p}$ in frames moving with velocity $\vec{\beta}$ wrt each other

$$\begin{pmatrix} E^* \\ p_\parallel^* \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\beta \\ -\gamma\beta & \gamma \end{pmatrix} \begin{pmatrix} E \\ p_\parallel \end{pmatrix}$$

- Useful relations:

$$\vec{\beta} = \frac{\vec{p}}{E} \qquad \gamma\beta = \frac{p}{m_0} \qquad E = \gamma m_0$$

Relativistic kinematics

- Relativistic Kinetic Energy

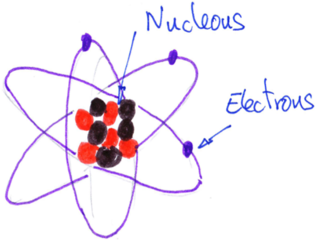
$$E_k = E - m_0 = m_0(\gamma - 1)$$

- Useful relations:

$$p = \sqrt{E_k(E_k + 2m_0)}$$

$$\varepsilon = \frac{E_k}{m_0} \quad \rightarrow \quad \begin{aligned} \gamma &= \varepsilon + 1 \\ \beta &= \frac{\sqrt{\varepsilon(\varepsilon+2)}}{\varepsilon+1} \\ \gamma\beta &= \sqrt{\varepsilon(\varepsilon+2)} \end{aligned}$$

Atomic and Nuclear Structure

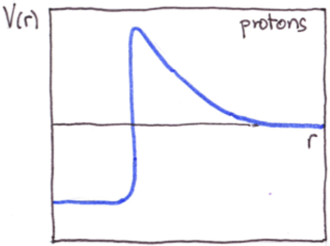


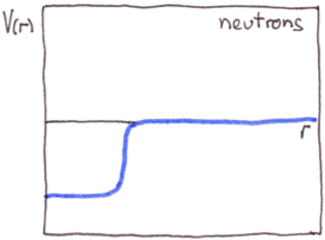
electron	Point-like	
proton-neutron	1 fm	10^{-15} m
nucleus	10 fm	10^{-14} m
atom	1 Å	10^{-10} m

- Nucleus of an atom is identified by two numbers:
  - Z : number of protons
  - A : number of nucleons=protons+neutrons
- Nucleus size: $R(fm) = 1.3\,A^{\frac{1}{3}}$
- Each species of an atom is called nuclide
- Nuclide representation : ${}^{A}_{Z}X$ X=Chemical Symbol
  - Same Z and different A → ISOTOPES
  - Same N and different Z → ISOTONES

Forces in the nucleus

- There are two forces acting in the nucleus:
  - Strong force (range ~1 fm). Attractive
  - EM force. Repulsive. Only protons
  - Nucleus is a potential well
    - Energy levels (QM)
- Protons approaching to nucleus ${}^{A}_{Z}X$:
  - R> 1 fm
    - Repulsive EM potential (Z protons)
  - R≤ 1 fm (Energetic protons)
    - Potential drops abruptly
    - Protons "feels" strong force and "falls" in the potential well
    - Proton is part nucleus → nuclear transf.
- Neutrons
  - No repulsive potential
  - Neutrons of any energy can approach to nucleus and make a nuclear reaction





Example

Estimate the minimum energy that a proton would have to have in order to react with the nucleus of a stationary Cl atom.

Solution :

proton	$A = 1$ $Z = 1$	$r_p = 1.3 \times 1^{1/3} = 1.3$ fm
Cl	$A = 35$ $Z = 17$	$r_{Cl} = 1.3 \times 35^{1/3} = 4.4$ fm

Proton should have enough energy to overcome the coulomb barrier.

$$V(r) = k_0 \frac{q_1 q_2}{r}$$

$q_p = 1e$

$q_{Cl} = 17e$

$e = 1.609 \times 10^{-19}\, C$

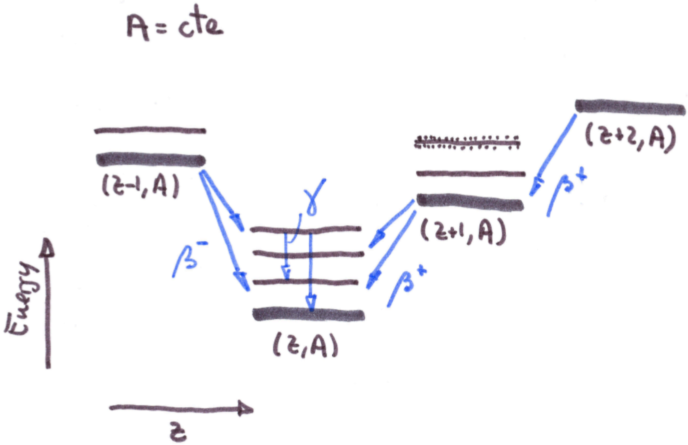
$k_0 = \frac{1}{4\pi\varepsilon_0} = 8.98755 \times 10^9\, Nm^2 c^{-2}$

$$V(r) = 7.0 \times 10^{-13}\, J$$
$$= 4.4 MeV$$

Nuclear levels

- Nucleus is a quantum mechanical system
  - Quantized levels
  - ΔE between levels ~ MeV
- Strong force is more complicated than other forces (i.e. electromagnetic)
  - Nuclear levels cannot be computed precisely
  - Measured experimentally
- Finite number of energy levels:
  - Ground state (lower energy)
  - Excited states: represented as ${}^{Am}_{Z}\mathrm{X}$
- Some nucleus have no excited state: ${}^{2}_{1}\mathrm{H}$=deuteron, ${}^{4}_{2}\mathrm{He}$=alpha
- Energy levels diagrams=Useful graphical representation of nuclear level structure

Nuclear levels



http://nucleardata.nuclear.lu.se/toi/sumframe.htm
http://www.lnhb.fr/nuclear-data/module-lara/
https://www-nds.iaea.org/relnsd/NdsEnsdf/masschain.html

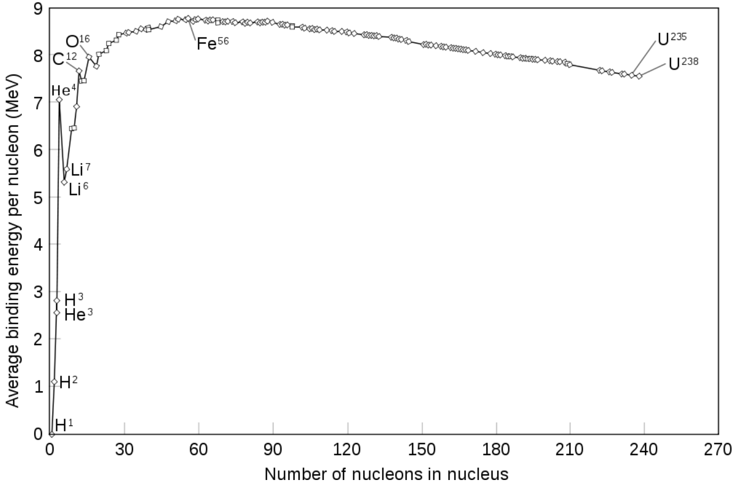
Nuclear Binding Energies

- Nuclear binding energy (B) is the minimum energy required to separate a nucleus into its components. (Z protons, N neutrons)
- Its mass equivalent relates the nuclear mass (m_N) to the mass of protons (m_p) and neutrons (m_n)

$$m_N = Nm_n + Zm_p - \frac{B}{c^2}$$

  - By definition B is positive for a bound system
  - B decreases nucleus mass
  - Nuclear stability increases as B increase
- Nuclear binding energy is approximately linear wrt A
  - Each nucleon is bound to nucleus with the same energy: $B/A \sim$7-8 MeV
  - in the plot B/A vs A shows interesting features explained by semi-empirical mass formula (liquid drop model)

Nuclear Binding Energies



Nuclear Binding Energies

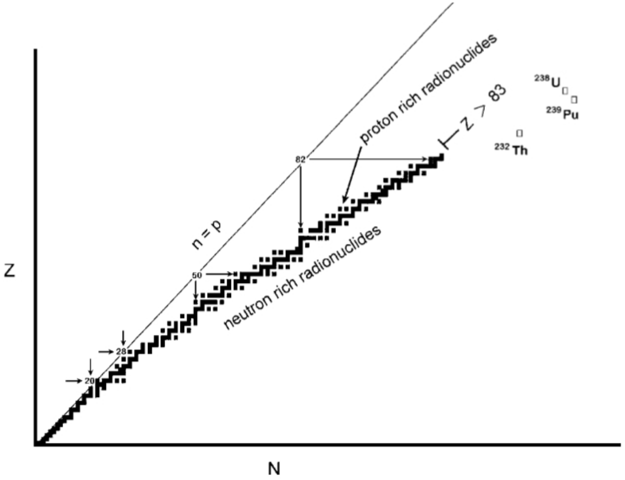
- In general what is tabulated are atomic masses (m).

$$m = Nm_n + Z(m_p + m_e) - \frac{B}{c^2} - \frac{b}{c^2}$$

- $b(eV) \simeq 20.8 \times Z^{7/3}$ is the binding energy of the electrons
- the effect of electronic binding energies is quite limited
  - 3 orders of magnitude less than B
  - Cancels out when using mass differences (usual case)
- Atomics mass usually given in atomic mass units
- Sometimes atomic mass are given as mass excess Δ(in MeV)

$$\Delta = (m - Au)c^2$$

Nuclear stability



http://www.nndc.bnl.gov
https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Units: Distance, Area, Time

- Units used are those commonly used in nuclear and particle physics
- Most of times derived from SI, but some are specific of these fields.

- Distance:
  Nuclear dimensions are of the order of 10^{-15} m = 1 fm = 1 fermi
- Area:
  Mostly encountered when discussing cross-sections. 1 barn = 100 fm^2
- Time:
  Used SI units: seconds (s) Time scale for nuclear processes is quite short (10^{-19}-10^{-11} s)
  Lifetimes can cover a large range (10^{-25}-10^{39} s)
  Long periods may be expressed in hours, days, weeks, years, ...

Units: Energy

- Traditional unit for measurement of radiation energy is the electron-volt (eV).
  1 eV = Kinetic energy gained by an electron through a potential difference of 1 V.

$$1eV = 1.6 \times 10^{-19}\, J$$

- Usually used multiples of this quantity

1 keV	=	10^3 eV	X-Rays
1 MeV	=	10^6 eV	KE in cyclotron
1 GeV	=	10^9 eV	m_p
1 TeV	=	10^{12} eV	LHC

$$C_{water} = 4.18 J/kgK$$
$$Q = mC\Delta T = 1\, eV$$
$$\Delta T = \frac{Q}{mC} = 3.82 \times 10^{-20}\, K$$

$$m_{bee} = 1\, gr \quad v_{bee} = 1\, m/s$$
$$m_{bee}c^2 = 9 \times 10^3\, J$$
$$= 5.8 \times 10^{32}\, eV/c^2$$
$$KE_{bee} = \frac{1}{2} m_{bee} v_{bee}^2$$
$$\sim= 10^{-3}\, J$$
$$= 6.25 \times 10^{16}\, eV$$

$$T_{LHC} = 14 \times 10^{12}\, eV$$
$$10^{14}\ \text{protons}$$
$$E_T = 10^{14} \cdot 14 \times 10^{12}\, eV$$
$$= 10^8\, J$$
$$10^8\, J \rightarrow m = 100\,\text{tons}$$
$$v = 100\, km/h$$

Units: Mass

- Atomic and Nuclear masses are given in atomic mass units (u)
- It is defined as one twelfth of the rest mass of an unbound atom of carbon-12 in its nuclear and electronic ground state.

$$1u = 1.660\ 539\ 066\ 60(50) \times 10^{-27}\, kg$$

- When dealing with particles we use the rest mass (m_0) expressed in MeV/c^2 or GeV/c^2
- These mass units come from Einstein relation $E = mc^2$

$$1u = 931.494\,102\,42(28)\ \text{MeV/c}^2$$

$$m_p = 938.272\ 088\ 16(29)\ \text{MeV/c}^2$$
$$m_n = 939.565\ 420\ 52(54)\ \text{MeV/c}^2$$
$$m_e = 0.510\ 998\ 950\ 00(15)\ \text{MeV/c}^2\ (\sim 511\ \text{keV/c}^2)$$

Nuclear masses data sources

- The reference of all data is:
  The AME2020 atomic mass evaluation (II). Tables, graphs, and references.
  M.Wang et al. Chinese Phys. C 45 030003 (2021).
  https://iopscience.iop.org/article/10.1088/1674-1137/abddaf

- Nuclear data charts:
  - https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html
  - https://www.nndc.bnl.gov/

- On paper. Quite outdated. (available on Toledo/Moodle)
  - Turner. Appendix D.
  - Martin. Appendix B

Section 3

Ionizing radiation and its sources

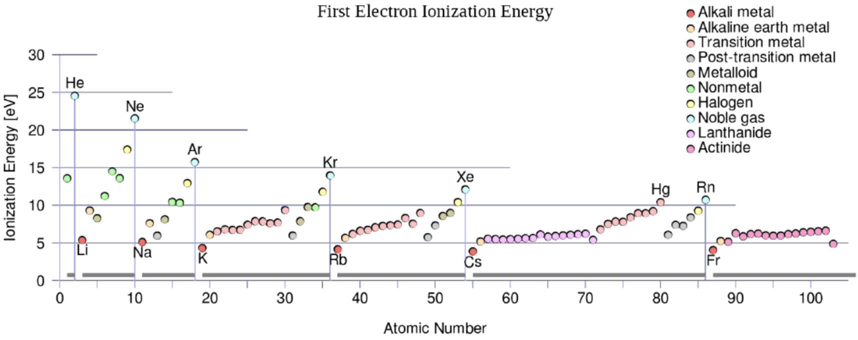
Ionizing and non-ionizing radiation

- Non-Ionizing radiation refers to any type of radiation that does not carry enough energy per quantum to ionize atoms or molecules
  - Electromagnetic radiation with $\lambda > 300$ nm
  - Very low energy neutrons
  - Some charged particles interactions

- Usually non-ionizing radiation is harmless, but it can produce effects
  - It can excite the atoms
  - Intense infrared laser can be dangerous to retina
  - Microwaves can heat food
  - ...

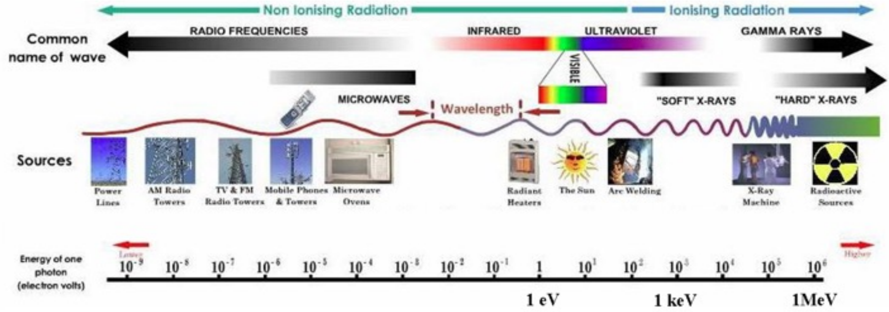
- Ionizing radiation is then any kind of radiation that can ionize atoms and molecules.

Ionization Energies of Atoms



- Average excitation potential
  - Gas ~30 eV
  - Semiconductor ~3 eV
  - Scintillator ~100 eV

Example: Ionizing vs. non-ionizing EM radiation



Sources of ionizing radiation

- Radiation has two main kind of sources: Natural sources and Artificial sources
  - Artificial sources
    - Radioactive decays and nuclear reactions
    - Accelerators → Lectures in Dec
    - Nuclear reactors
    - X-ray machines
  - Natural sources:
    - Cosmic radiation
    - Terrestrial radiation
    - Radioisotopes from biosphere

Discover by yourself the natural sources

Key questions

- What's the cosmic radiation? what's its origin? composition?
- Do you know ^{14}C? How it's produced?
- Where are the places in which you can find natural radiation?
- Do you know if a banane or the human body is radioactive?

Ionizing radiation

- During this lectures we are going to divide ionizing radiations in four categories

	Charged Particles	Neutral Particles
Light Particles	e^+ e^-	X-rays γ-rays
Heavy Particles	p,d,α μ,π,K heavy nuclei	neutrons

- The main reason of this classification is their interaction with matter
  - Charged and neutral particles do not interact with matter in the same way
  - For charged particles: $m_\mu \sim 200 m_e$, $m_p \sim 2000 m_e$: Radiative phenomena should be taken into consideration for electrons

Nuclear reactions

- Interaction between a nucleus A and an incident particle a
- Nuclear reaction produces another particle b and a resulting nucleus B

$$a + A \rightarrow b + B \qquad \equiv \qquad A(a, b)B$$

- Nuclear reactions can be divided into two categories:
  - Scattering: $a = b$
  - Reactions: $a \neq b$

- An special type of nuclear reactions are nuclear decays

$$A \rightarrow B + b$$

Nuclear reactions

- Scattering processes can be
  - Elastic: Conserve Kinetic Energy. (i.e. Coulomb scattering)
  - Inelastic: Kinetic energy is not conserved (i.e. nucleus is left in an excited state)
- Reactions can be classified into three categories
  - Direct reactions: incident particle interacts with a limited number of nucleons (high energy)
  - Compound nuclear reactions: incident particle becomes bound to the nucleus before the reaction continues. The final state depends on the compound nucleus
  - Resonance reactions: Intermediate state between previous cases. The incident particle becomes quasi-bound to the nucleus before the reaction continues

Nuclear reactions

- Several conservation laws must be considered in nuclear reactions
  - Mass/energy, momentum and charge must be ALWAYS be conserved
  - Kinetic energy cannot be conserved
- At low energies the number and identity of particles do not change.
  - Number of neutrons and protons will not change
  - Exception: Processes with weak interactions (i.e β decays)
- Low energy processes generally involves
  - p, n
  - Bound systems with A low (i.e d, α)
- At high energies ($E_a > 280 MeV$) new particles can be created

Nuclear reactions: Energetics

- Energetics of nuclear reactions can be established with atomic masses
  - It's important to look for the number of electrons before and after
- In a reaction $a + A \rightarrow B + b$ the Q-value is defined as:

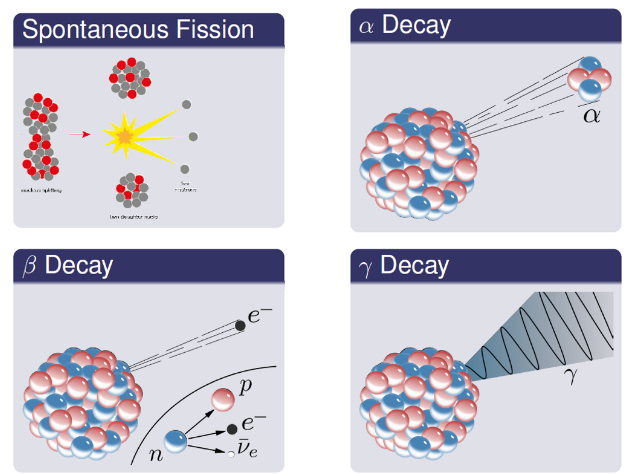
$$Q = m_N(A) + m_N(a) - m_N(B) - m_N(b)$$

- Reactions with $Q > 0$ are called exothermic reactions
  - Reaction products have a mass smaller than the initial nuclides
  - All decay processes are exothermic
- Reactions with $Q < 0$ are called endothermic reactions
  - Initial nuclides have a mass smaller than the reaction products
  - This reactions can always occur if additional kinetic energy is supplied to incident particle.
  - Energetic balance should be done always in the center-of-mass frame

$$E_{cm} = \frac{E_{lab}}{1 + \frac{m_a}{m_A}} > Q$$

Radioactive decay

- Radioactive Decay: is the process by which a nucleus of an unstable atom decreases its total energy by spontaneously emitting radiation/



Radioactive decay

- Radiactivity is a spontaneous transformation
  - Important source of information in Nuclear and Atomic Physics
  - Spontaneus processes → Q of the reaction is positive
- Origin: rearrangement of the nucleus constituents because they are not arranged in the lowest energy state
- Radioactive transformation involves emission of particles:
  - Emission of α particles → α-decay.
  - Emission of $e^{\pm}$ → $\beta^{\pm}$-decay, Internal Conversion, Auger electrons
  - Emission of photons→ γ-decay, $X-rays$
  - Emission of neutrons (evaporation), protons, fission fragments
- The rate of decay or transformations is described by its activity:
  - Number of atoms that decay per unit time
  - Unit: Becquerel = 1 disintegration per second → 1 Bq = 1 s^{-1}
  - Curie (Ci): Activity of 1 gr of ^{226}Ra → 1 Ci = 3.7 × 10^{10} Bq.
  - Activity decays exponentially with time

Exponential Decay

- $N(t)$: Number of atoms of a radionuclide at time t
- λ: Probability that the radionuclide decays in a dt (constant)
- $dN(t)$: Number of disintegration can be expressed as:

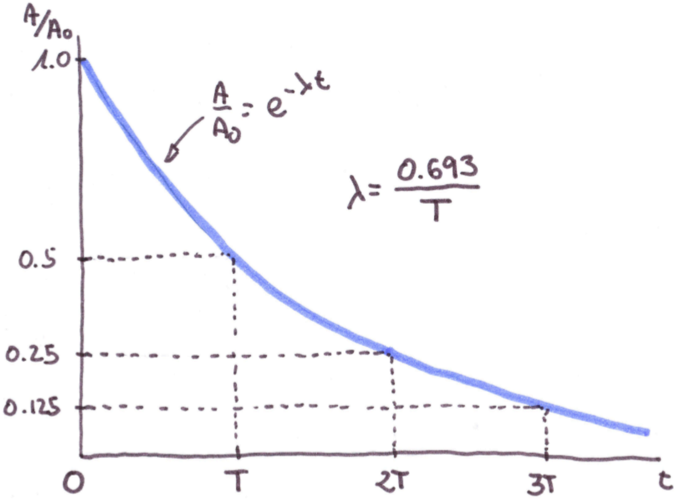
$$\begin{aligned} dN(t) &= -\lambda N(t)dt \\ A = -\frac{dN(t)}{dt} &= \lambda N(t) \end{aligned} \quad \rightarrow \quad \begin{cases} \ln N = -\lambda t + C \rightarrow C = \ln N_0 \\ \ln \frac{N}{N_0} = -\lambda t \\ N(t) = N_0 e^{-\lambda t} \end{cases}$$

- The activity $A(t)$ is proportional to $N(t)$

$$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t} = A_0 e^{-\lambda t}$$

where $A_0 = \lambda N_0$ is the initial activity

Exponential Decay



Lifetime

- What's the probability that a nucleus will not decay in a time t?

$$\frac{\text{Atoms not decaying in } t}{\text{Atoms at t=0}} = \frac{N_0 e^{-\lambda t}}{N_0} = e^{-\lambda t}$$

- What's the probability to decay in $t + dt$?

$$\begin{array}{rcccccc} p(t)dt & = & \text{Proba. to survive} & \times & \text{Proba. to decay in dt} & \times & dt \\ & = & e^{-\lambda t} & \times & \lambda & \times & dt \end{array}$$

- Average lifetime τ:

$$\tau = \frac{\int_0^\infty t\,p(t)dt}{\int_0^\infty p(t)dt} = \frac{\int_0^\infty t\lambda e^{-\lambda t}dt}{\int_0^\infty \lambda e^{-\lambda t}dt} = \frac{1}{\lambda}$$

- Half-life (T or $T_{1/2}$): Time it takes to reduce the activity or a nucleus a factor $\frac{1}{2}$

$$\frac{N(T)}{N_0} = \frac{1}{2} = e^{-\lambda t} \rightarrow T = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

Effective lifetime

- Besides nuclear decay other processes can reduce the activity of a source
- One example is a sample of radioactive material located in a physiological system
  - The atoms can follow a nuclear disintegration (λ_r)
  - The radioisotopes can also be removed by biological processes (λ_b)
- We need to take into account all removal processes

$$\lambda_{eff} = \lambda_r + \lambda_b + \text{ other removal processes}$$

- Analogously we can define an effective half-life time as

$$\frac{\ln 2}{T_{eff}} = \frac{\ln 2}{T_r} + \frac{\ln 2}{T_b} + \cdots$$

$$\frac{1}{T_{eff}} = \frac{1}{T_r} + \frac{1}{T_b} + \cdots$$

Activity-mass relationship

- The activity of a radiosotope is related to the number of atoms

$$A = \lambda N$$

- The number of atoms (N) is also related to the mass m

$$1\,\text{mol} = N_A\,\text{atoms}$$

$$m(t) \propto N(t)$$

- Then the mass of the radioisotope will follow an exponential decay

$$m(t) = m_0 e^{-\lambda t}$$

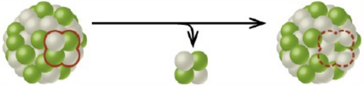
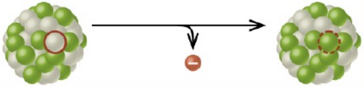
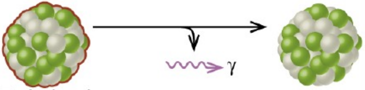
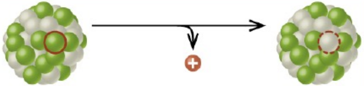
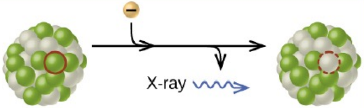
Specific activity

- The specific activity (SA) of a sample is defined as its activity per units mass
- Units or SA are: Bq g^{-1} or Ci g^{-1}
- In case of a pure radionuclide, SA is determined by λ and its atomic weight M.
  - Number of atoms per gram of nuclide $N = \frac{N_A}{M} = \frac{6.02\times10^{23}}{M}$

$$SA = \lambda N = \frac{6.02 \times 10^{23}\,\lambda}{M} = \frac{4.17 \times 10^{23}}{MT}$$

- If T is in seconds then SA is in Bq g^{-1}

Radioactive Decay Modes

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}^{A}_{Z}X \quad {}^{4}_{2}He + {}^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	${}^{A}_{Z}X \quad {}^{0}_{-1}e + {}^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	${}^{A}_{Z}X \quad {}^{0}_{0}\gamma + {}^{A}_{Z}Y$	 Excited nuclear state	A: unchanged Z: unchanged
Positron emission	${}^{A}_{Z}X \quad {}^{0}_{+1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	${}^{A}_{Z}X \quad {}^{0}_{-1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

Light Charged particles sources

- Light Charged particles = electrons and positrons.

- Main sources of electrons and positrons are:
  - β decay
  - Internal Conversion electrons
  - Auger Electrons
  - Accelerators and the technology associated
  - Photon pair-conversion
  - Cosmic Radiation

Discussion

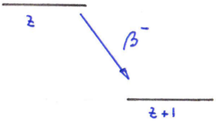
- Do you have electron/positron sources at home?
- If yes, what's the energy of the electrons/positrons?

Beta Decay

- β decay represent two types of conversions in nucleus: β^- and β^+
- $\beta^- =$ electron, $\beta^+ =$ positron

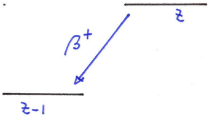
- β^- decay: conversion of a neutron to a proton:

$$ {}^{A}_{Z}\mathrm{M} \rightarrow {}^{\;\;A}_{Z+1}\mathrm{D} + e^- + \overline{\nu}_e $$



- β^+ decay: conversion of a proton to a neutron:

$$ {}^{A}_{Z}\mathrm{M} \rightarrow {}^{\;\;A}_{Z-1}\mathrm{D} + e^+ + \nu_e $$



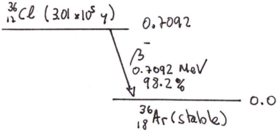
- A process competitive with β^+ decay is electron capture. A proton in the nucleus interacts with an atomic electron giving:

$$ {}^{A}_{Z}\mathrm{M} + e^- \rightarrow {}^{\;\;A}_{Z-1}\mathrm{D} + \nu_e $$

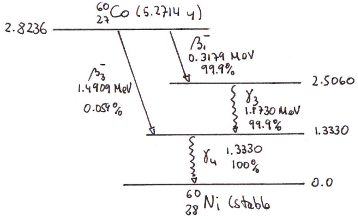
Beta Decay

- Few isotopes decay only through β decays

Nuclide	Half-Life	Endpoint (MeV)
^{3}H	12.26 y	0.0186
^{14}C	5730 y	0.156
^{32}P	14.28 d	1.710
^{33}P	24.4 d	0.248
^{35}S	87.9 d	0.167
^{36}Cl	3.08×10^{5} y	0.714
^{45}Ca	165 d	0.252
^{63}Ni	92 y	0.067
^{90}Sr^{90}Y	27.7y/64h	0.546/2.27
^{99}Tc	2.2×10^{5}y	0.292
^{147}Pm	2.62 y	0.224
^{204}Tl	3.81 y	0.766

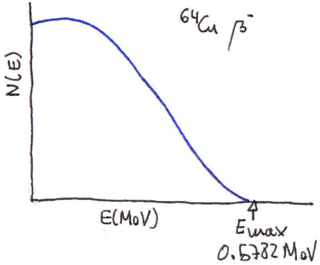


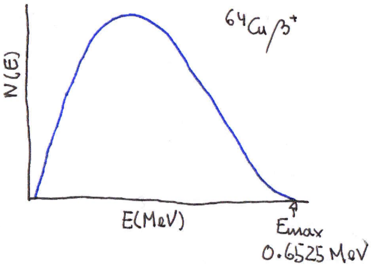
- Most of β decays populate an excited state.
- De-excitation can be done by
  - γ emission
  - Internal conversion electron



Energetics of Beta Decay

- ν and $\overline{\nu}$ interacts too weakly with matter
  - Needed to explain the fundamental interaction ...
  - ... but not detected
- It's a 3-body decay → $\beta^{\pm}$ has continuous spectra
- Q of the reaction gives the end-point of the spectra
- β^{+} spectrum skewed to higher energies:
  - Coulomb repulsion kicks energy





Energetics of Beta Decay

- "Fundamental" interactions do not allow β^+ decays:

$$n \rightarrow p + \beta^- + \overline{\nu} \quad \rightarrow \quad m_n > m_p + m_{e^-} + m_{\overline{\nu}} \quad \rightarrow \quad Q > 0$$
$$p \rightarrow n + \beta^+ + \nu \quad \rightarrow \quad m_p < m_n + m_{e^+} + m_{\nu} \quad \rightarrow \quad Q < 0$$

- We have to look at the whole picture
  - Neutrons and protons are embedded in nucleus
  - What matters is nuclide mass (m_N), not m_p or m_n
  - Nuclear binding energies play a role
- Neutron decay.

$$T_{1/2}(n) \simeq 15\,\text{min}$$

- Proton decay. Still not detected

$$T_{1/2} > 1.01 \times 10^{34}\,\text{years} \quad \text{(SuperK exp)}$$

Energetics of Beta Decay

- β^- : "fundamental" decay allowed

$$Q_{\beta^-} = m_N({}^{A}_{Z}\mathrm{M}) - m_N({}_{Z+1}^{\;\;A}\mathrm{D}) - m_e$$

$$\Big\downarrow \; m({}^{A}_{Z}\mathrm{M}) = m_N({}^{A}_{Z}\mathrm{M}) + Zm_e - b_Z$$

$$= m({}^{A}_{Z}\mathrm{M}) - m({}_{Z+1}^{\;\;A}\mathrm{D})$$

  - b_Z is not considered. What matters is the difference $b_Z - b_{Z+1}$ that is negligibly small

- β^+ : "fundamental" decay forbidden

$$Q_{\beta^+} = m_N({}^{A}_{Z}\mathrm{M}) - m_N({}_{Z-1}^{\;\;A}\mathrm{D}) - m_e$$
$$= m({}^{A}_{Z}\mathrm{M}) - m({}_{Z-1}^{\;\;A}\mathrm{D}) - 2m_e$$

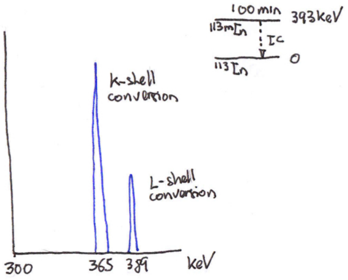
  - β^+ decay occurs only if $m({}^{A}_{Z}\mathrm{M}) - m({}_{Z-1}^{\;\;A}\mathrm{D}) > 2m_e$

Internal Conversion (IC) electrons

- Most of the times the de-excitation of an excited nuclear state is done through a γ-decay.
- Sometimes γ-decay is inhibited (i.e angular momentum, etc...)
- An alternative process is to transfer the energy directly to an orbital electron

$$E_{e^-} = E_{ex} - E_b$$

- The electron can be in any of the atomic shells
  - One peak for every shell
  - Sometimes convoluted with other spectra (i.e. β decay)
- Practical source for monoenergetic electrons in the lab (100's keV - MeV)

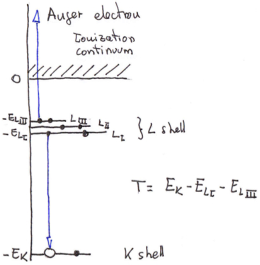


Auger electrons

- Analogue of internal conversion electrons but for atomic excitations

- A vacancy in the electronic levels may appear
  - As result of an electron capture process
  - Because of ionization process
- Most often vacancy is filled by another electron from outer shells
  - Emission of a characteristic X-ray photon
- Alternatively the energy can be transferred to an orbital electron

$$E_{e^-} = E_{vac} - E_{shell} - E_b$$



- Discrete spectrum
- E_{e^-} lower than those of β or IC electrons
  - Process favored for low-Z atoms.
  - High self absorption.

Heavy charged particles sources

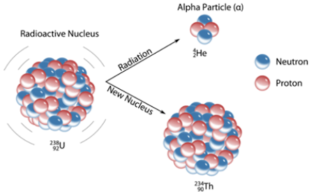
- Heavy charged particles = Any charged particle except e^- and e^+
  - Includes any charged particle in the particle zoo as well as nuclei
  - Only 4 out ~250 "survives" to be effectively detected: $\mu^\pm, \pi^\pm, K^\pm, p^\pm$,

- The main sources of heave charged particles are:
  - α decay: natural (cosmogenic) and artificial
  - Fission products (induced or spontaneous)
  - Accelerators and interactions therein
  - Cosmic Radiation

Alpha decay

- Disintegration of a parent nucleus through the emission of an α-particle $= {}^4_2\text{He}$

$$^{A}_{Z}\text{M} \rightarrow ^{A-4}_{Z-2} D + ^4_2 He + Q_\alpha$$



- It is governed by the combination of the strong nuclear force and the electromagnetic force in an analogous way to spontaneous fission.
  - Energetically interesting because of the high binding energy for α

- It typically occurs in heavy nuclei ($A > 150$), with the lightest observed systems to α decay being $^{108-110}$Te.

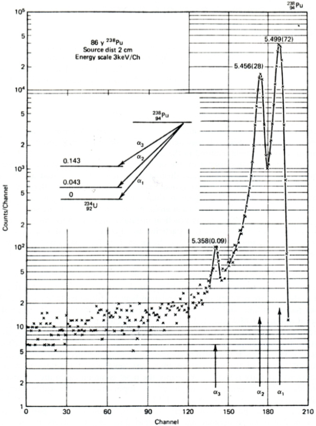
Energetics of Alpha decay

- α-decays occurs between nuclear states: Monoenergetic spectra
- In case daughter nucleus has several excited states it can appear one energy line per excited state.

$$
\begin{aligned}
Q = m_N(M) - M_N(D) - m_N(\alpha) \\
= \quad T_D \quad + \quad T_\alpha \\
= \frac{p^2}{2m_N(D)} + \frac{p^2}{2m_N(\alpha)} \\
= \frac{p^2}{2m_N(\alpha)}\left(1 + \frac{m_N(\alpha)}{m_N(D)}\right)
\end{aligned}
$$

$$\frac{m_N(\alpha)}{m_N(D)} \simeq \frac{4}{A-4}$$

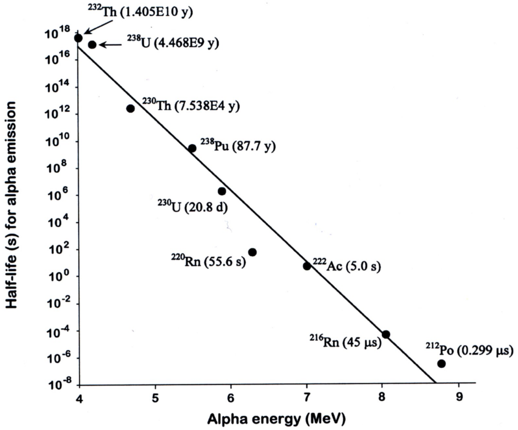
$$Q = E_\alpha\left(1 + \frac{4}{A-4}\right) \quad \rightarrow \quad \boxed{E_\alpha = \frac{A-4}{A}Q}$$



- α-decay Q values are roughly 4-7 MeV with very little variation

Alpha decay: Geiger-Nuttall relationship

- There is a strong correlation between $T_{1/2}(\alpha)$ and E_α.
  - The higher the energy, the lower the lifetime → Geiger-Nuttall Relationship



Martin: Fig 3.16

Naturally Radioactive Series

Uranium	^{238}U	$\alpha\beta\beta\alpha\alpha\alpha\alpha\alpha\beta\beta\alpha\beta\beta\alpha$	^{206}Pb	$\Delta Z = 10, \Delta A = 32$
Thorium	^{212}Th	$\alpha\beta\beta\alpha\alpha\alpha\alpha\beta\beta\alpha$	^{208}Pb	$\Delta Z = 8, \Delta A = 24$
Actinium	^{235}U	$\alpha\beta\alpha\beta\alpha\alpha\alpha\alpha\beta\alpha\beta$	^{207}Pb	$\Delta Z = 10, \Delta A = 28$
Neptunium	^{237}Np	$\alpha\beta\alpha\alpha\beta\alpha\alpha\alpha\beta\alpha\beta$	^{209}Bi	$\Delta Z = 10, \Delta A = 28$

- Naturally ^{237}Np no longer exists: $T_{1/2}$ is only 2.6 × 10^6 y.
- Precursors of ^{237}Np are ^{241}Am or ^{241}Pu, produced in reactors
- An important series is that of ^{238}U and its subseries:

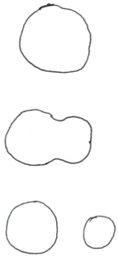
$$^{238}_{92}\mathrm{U} \xrightarrow[4.5\times10^9\,y]{\alpha} {}^{234}_{90}\mathrm{Th} \xrightarrow[24.1\,d]{\beta^-} {}^{234}_{91}\mathrm{Pa} \xrightarrow[6.8\,h]{\beta^-} {}^{234}_{92}\mathrm{U} \xrightarrow[2.5\times10^5\,y]{\alpha} {}^{230}_{90}\mathrm{Th} \xrightarrow[7.5\times10^4\,y]{\alpha}$$

$$^{226}_{88}\mathrm{Ra} \xrightarrow[1600\,y]{\alpha} {}^{222}_{86}\mathrm{Rn} \xrightarrow[3.8\,d]{\alpha} {}^{218}_{84}\mathrm{Po} \xrightarrow[3.1\,m]{\alpha} {}^{214}_{82}\mathrm{Pb} \xrightarrow[26.8\,m]{\beta^-} {}^{214}_{83}\mathrm{Bi} \xrightarrow[19.9\,m]{\beta^-} {}^{214}_{84}\mathrm{Po}$$

$$\xrightarrow[164.3\,\mu s]{\alpha} {}^{210}_{82}\mathrm{Pb} \xrightarrow[22.3\,y]{\beta^-} {}^{214}_{83}\mathrm{Bi} \xrightarrow[5.01\,d]{\beta^-} {}^{210}_{84}\mathrm{Po} \xrightarrow[138.4\,d]{\alpha} {}^{206}_{82}\mathrm{Pb}$$

Fission products

- Fission: split of nucleus in two or more smaller fragments
- Most of the time fission is inhibited by the large nuclear potential barrier
- The origin of fission is a distortion of the spherical nuclear shape
  - Induced fission. (i.e. n+^{235}U in nuclear reactors).
  - Spontaneous fission. Only for (Z>83).
- In each fission, two fragments are generated back to back.
  - Heavy (A~143) → small KE
  - Light (A~108) → higher KE
- Spontaneous fission is the only spontaneous source of energetic heavy particles
  - Relevant case: ^{252}Cf



$$T_{1/2}^{\text{sp. fission}} = 85\,\text{years}$$

$$T_{1/2} = 2.65\,\text{years} \quad \rightarrow \quad 1\,\mu g\,^{252}\text{Cf} = \begin{cases} 1.92\times10^{7}\,\alpha/s \\ 6.16\times10^{6}\,\text{SF}/s \\ 2.30\times10^{6}\,\text{n}/s \end{cases}$$

Also α and n emission

Fission products

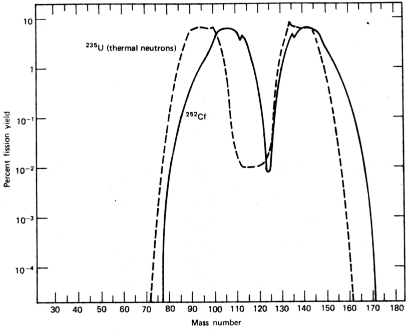


Figure 1-4 (a) The mass distribution of ^{252}Cf spontaneous fission fragments. Also shown is the corresponding distribution from fission of ^{235}U induced by thermal neutrons. (From Nervik.[4])

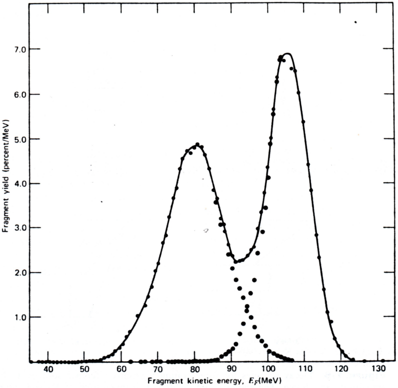


Figure 1-4 (b) The distribution in kinetic energy of the ^{252}Cf spontaneous fission fragments. The peak on the left corresponds to the heavy fragments, and that on the right to the light fragments. (From Whetstone.[5])

Knoll: Fig 1-4

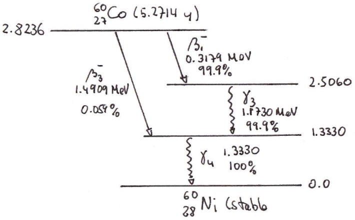
Light neutral particles sources

- Light Neutral particle = photon

- Main sources of photons:
  - Gamma decays after α or β decay
  - Gamma decays Nuclear reactions
  - Annihilation radiation ($e^+ + e^- \rightarrow \gamma\gamma$)
  - Bremsstrahlung: Continuous X-rays
    Synchrotron radiation
  - Characteristic X-rays: Electron capture
    Internal conversion, Auger electrons
    Atomic excitations

Gamma decay

- γ radiation emitted by excited nuclei in their transition to lower energy levels.
- Similar to atomic transitions.
- As it's a transition between nuclear levels γ rays are monoenergetic



- Excited nuclei can be obtained:
  - As a result of a α or β decay
  - As a result of a nuclear reaction
- γ de-excitation is a fast process (~ps)
- $E_{max} = 2.754$ MeV (^{24}Na)

Energetics of γ Decay

- The energetics of γ-decay can be described in terms of the initial and final state masses:

$$E_\gamma = (M_i - M_f)c^2 - E_R$$

where E_γ is the emitted γ-ray energy and E_R the nucleus recoil energy

- Momentum conservation requires

$$p_R = \frac{E_\gamma}{c} \quad \rightarrow \quad E_R = \frac{E_\gamma^2}{2M_f c^2}$$

This derivation is non-relativistic, but it's justified because $E_\gamma = 1$ MeV, A=100 then $E_R = 5$ eV.

- Thus in general we can ignore E_R then

$$E_\gamma = (M_i - M_f)c^2$$

Electron capture (EC)

- Competitive process of β^+
- Proton in the nucleus interacts with an inner orbital electron

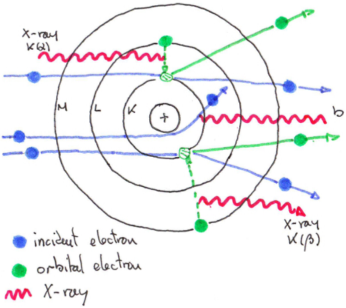
$$ {}^{A}_{Z}\mathrm{M} + e^- \rightarrow {}_{Z-1}^{\ \ A}\mathrm{D} + \nu_e \qquad Q_{EC} = m_N({}^{A}_{Z}\mathrm{M}) + m_e - m_N({}_{Z-1}^{\ \ A}\mathrm{D}) = m({}^{A}_{Z}\mathrm{M}) - m({}_{Z-1}^{\ \ A}\mathrm{D}) - b_e $$

  - Energetically EC is only possible in proton-rich nucleus
  - 90% K-shell e^-, $< 10\%$ L-shell e^-, $< 1\%$ M-shell e^-
- Binding energy of the electron captured should be considered:
  - e^- captured inner sell $\rightarrow$ b_e= many tens of keV
- Sometimes EC is favored wrt β^+ because of the $2m_e^-$ threshold
- EC involves the disappearance of an e^- that is immediately filled
  - Emission of characteristic X-Rays or Auger electrons
  - This emission is the only energy emission produced

X-rays

- X-rays: Electromagnetic radiation with $E_\gamma = 1$ keV - few 100's keV
- Discovered by Roetgen in 1895
- Used extensively in medicine, industry and security.
- Two origins: Characteristic X-rays and bremsstrahlung

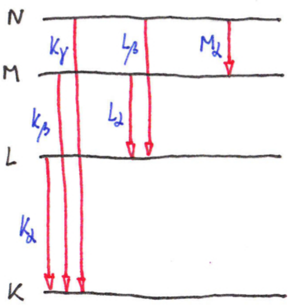
- Characteristic X-rays
  - Atomic transitions.
  - Discrete spectrum
- Bremsstrahlung
  - Braking radiation by electromagnetic interactions with nucleus
  - Mainly by electrons.
  - Same underlying physics as synchrotron radiation



Characteristic X-rays

- Orbital electrons can be disrupted from their configuration:
  - Originated by some excitation process (decay, reaction)
  - Electrons rearrange themselves emitting electromagnetic radiation
- Energy of the photons is determined by atomic levels
  - X-rays are characteristic of each atom
  - Series of monoenergetic peaks
    - K_α, K_β, K_γ: vacancy created in K-shell
    - L_α, L_β: vacancy created in L-shell
- Photon energy increases with Z

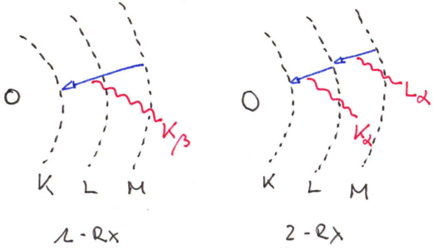
Z=1	H	13.6 eV
11	Na	~1 keV
31	Ga	~10 keV
88	Ra	~100 keV



http://www.nist.gov/pml/data/xraytrans/index.cfm

Characteristic X-rays

- Auger electron emission is a competitive process to X-ray emission
- Several X-ray emission can be present in the rearrangement



- Emission of X-rays is called X-ray fluorescence

$$Y = \text{Fluorescence Yield} = \frac{\#\text{ of X-ray}}{\#\text{ vacancies}} \rightarrow Y = \begin{cases} 0 & Z \text{ low} \\ 1 & Z \text{ high} \end{cases}$$

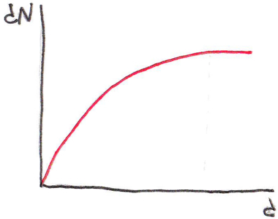
Sources of characteristic X-Ray

X-ray emission after Radioactive Decay

- Electron capture
  - Process competitive with β^+:
  - One orbital electron is captured creating a vacant usually in the K-shell

$$^{A}_{Z}\mathrm{X} + e^- \rightarrow {}^{A}_{Z\text{-}1}\mathrm{Y} + \nu + \text{X-ray}$$

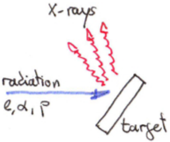
- Internal conversion
  - Nuclear de-excitation does not emit electromagnetic radiation.
  - Ejection of an orbital electron → X-ray emission
- X-rays suffers a lot of self-absorption
  - Increase radioisotope deposit → reach limiting value
  - Only surface atoms contribute

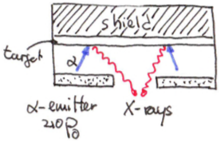


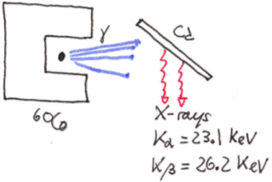
Sources of characteristic X-Ray

Excitation by external bombardment

- Also called PIXE: Particle induced X-ray Emission
- External radiation impinging in a target can ionize the atom
- In case of electrons characteristic X-rays will superimpose bremsstrahlung spectra
- Needed an accelerator or a radioactive source

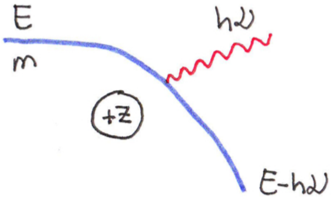






Bremsstrahlung

- If fast electrons hits a material, it can loose energy through electromagnetic interaction

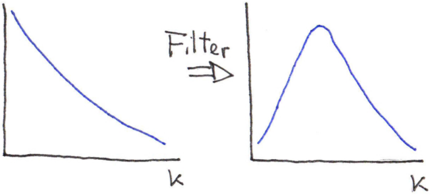


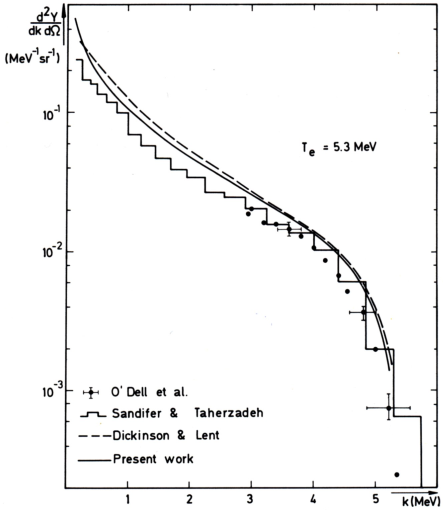
$$\frac{d\sigma}{dk} \propto Z^2 \frac{1}{m^2} \frac{1}{k}$$

- Typical values $E_e \simeq$ few MeV
  $E_\gamma <$ few MeV
- Continuous spectrum
- Peaked at low k
- More important for materials with high Z
- Only important for low mass particles (electrons and HE muons)

Bremsstrahlung

- Continuous spectrum.
- It always appears when electrons interacts with matter.
- Using filters spectrum can be modified
  - Elimination of low energy part
  - Far to be monoenergetic

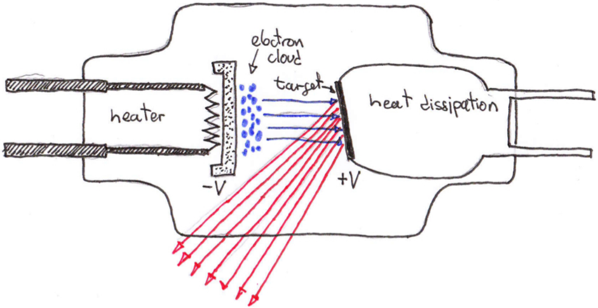




Knoll: Fig 1-6

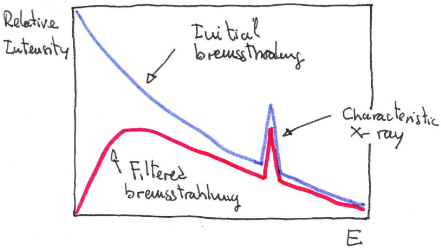
X-ray machines

- All system in high vacuum
- Heat filament (usually in W)
  - It "boils" electrons
  - Electrons are focused into a point in the target
  - Electrons accelerated by a HV 30-70 kV.
- Target made of W or Mo (high Z)
  - Electrons stopped abruptly in target
  - X-ray production by
    - Bremsstrahlung (mainly)
    - Target characteristic X-rays
- Only 1% of electron energy converted into X-rays
- 99% electron energy used to "heat" the target
- Cooling systems needed
  - Water or oil cooling
  - Rotating targets



- Maximum RX energy: all electron energy transferred to one RX.

$$E_e = eU = h\nu_{max} = h\frac{c}{\lambda_{min}} \quad \rightarrow \quad E_{max} = Uev, \quad \nu_{max} = \frac{eU}{h}, \quad \lambda_{min} = \frac{hc}{eU} = \frac{1240}{U}\, nm$$



Heavy neutral particle

- Heavy neutral particle: mainly neutrons (also K^0's in HE interactions)
- The main sources of neutrons
  - Spontaneous fission: $^{252}\mathrm{Cf} \rightarrow$ 2 fission fragments + neutrons
  - Nuclear reactions:
    - Interaction of α with matter $^4_2\alpha + ^9_4\mathrm{Be} \rightarrow ^{12}_8\mathrm{C} + ^1_0\mathrm{n} + 5.71$ MeV
    - Nuclear reactors:
  - Photo-neutrons: $^9_4\mathrm{Be} + h\nu \rightarrow ^8_4\mathrm{Be} + ^1_0\mathrm{n} - 1.67$ MeV
    $^2_1\mathrm{H} + h\nu \rightarrow ^1_1\mathrm{H} + ^1_0\mathrm{n} - 2.23$ MeV
  - Nuclear reactions (mono-energetic and continuous spectra)
    - Mono-energetic: $D + D \rightarrow n +^3 He$ Q=3.27 MeV E_n=2.45 MeV
      $D + T \rightarrow n + \alpha$ Q=17.56 MeV E_n=14.05 MeV
    - Continuous: $D + Be \rightarrow n + X$
      Cyclotron LLN: $E_D = 50\,MeV \rightarrow E_n \in [0,50]\,MeV\ \overline{E}_n = 20\,MeV$
- In general, if there are neutrons there are also photons