Atomic nuclei and radioactivity

Stability and disintegration

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Concepts and definitions

- Atomic number - number of protons in the nucleus (Z)
- Isotopes - atoms with same Z but different number of neutrons (N)
- Mass number: A = Z+N
- Isobars: Atoms with same A, but different Z (and N)
  - e.g. ^{81}Zn,^{81}Ga,^{81}Ge
- (Isotones - atoms with same N but different Z)
- Nuclide: atom type characterized by a specific N and Z
- Nucleon, proton or neutron
- Isomer, atoms a specifiv nuclide, in a particularly long-lived excited state, different from the ground state

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Isotopes

	^{17}F	^{18}F	^{19}F	^{20}F	^{21}F	^{22}F	^{23}F	^{24}F
	64.5s	1.82h	stabil	11.0s	4.4 s	4.2 s	2.3 s	0.3 s
	β^+	β^+	100%	β^-	β^-	β^-	β^-	β^-

- Fluorine isotopes exist on the following masses; 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, in total 12.
  - ^{19}F is the only stable F isotope
  - ^{18}Fand ^{17}Fare β^+-active
  - All the remaining are β^--active
- ^{16}F is **unbound**, i.e. it does not exist. It is not possible. This position is called the “proton drip-line”. All lighter F-isotopes are also unbound
- ^{28}F is unbound, so is ^{30}F and all heavier F-isotopes. ^{28}F and ^{30}F are just above the “neutron drip-line”

Notation

$$^{A}_{Z}\mathbf{X}_{N}$$

- A - mass number
- Z - proton number
- N - neutron number
- X - chemical element signature

Example: Or just:

$$^{36}_{17}\mathbf{Cl}_{19} \qquad ^{36}\mathbf{Cl}$$

Do not use: ~~Cl-36~~ or ~~$\mathbf{Cl}^{36}$~~

Energies and units

- 1 eV (electron-volt) = 1.6•10^{-19} J
- 1 keV = 10^{3} eV
- 1 MeV = 10^{6} eV
- 1 GeV = 10^{9} eV
- 1 TeV = 10^{12} eV
- ~eV - chemical binding
- ~keV - binding energies for inner shell electrons in heavy elements
- 511 keV electron rest mass
- ~MeV - energies in simple nuclear processes
- ~200 MeV - fission energies
- 0.94 GeV - nucleon rest mass (proton or neutron)

Disintegration and time

- **Assumptions:**
- 1. We have a number N radioactive atoms of the same nuclide
- 2. Their probability of decay is independent of their past history
- 3. They decay without interactions with the surroundings
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- What is the disintegration rate as a function of time ?

The decay law

Consider a time-interval Δt. During this time a number of atoms $-\Delta N$ (positive number) will disintegrate. We consider Δt so small that the condition $-\Delta N << N$ is fulfilled. Then we have:

$-\Delta N \propto \Delta t$ and
$-\Delta N \propto N$ (assumption 3)
Hence: $-\Delta N = \lambda N \Delta t$
or: $-dN = \lambda N dt$ i.e. $-dN/N = \lambda dt$
Integration:

assumption 2

$$\int_{No}^{N} -dN/N = \int_{t=0}^{t} \lambda dt = \lambda \int_{t=0}^{t} dt$$

gives $-\ln (N/N_o) = \lambda t$ or

$$\mathbf{N=N_o e^{-\lambda t}}$$

Like a 1st order chemical reaction

Disintegration and number of atoms

The constant λ is the decay constant, characteristic of each nuclide, and expresses the probability per unit time that one atom will decay. Hence the product

$$\mathbf{\lambda N \equiv D}$$

expresses the number of disintegrations per unit time, or the disintegration-rate of that particular nuclide. As for a 1st order chemical reaction, we have:

$$\mathbf{\lambda = \ln(2)/T_{½}}$$

It is also easily seen that for a single decay, one has:

$$\mathbf{D = D_o e^{-\lambda t}}$$

where D_o is the disintegration rate at t=0

Unit

- Unit for disintegration-rate (decay-rate): 1 becquerel = 1 Bq
- 1 Bq = 1 disintegration per second
- 1 kBq = 10^3 Bq
- 1 MBq = 10^6 Bq
- 1 GBq = 10^9 Bq
- 1 TBq = 10^{12} Bq
- 1 PBq = 10^{15} Bq
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- Disintegration rate should be specified to a particular nuclide, or to total disintegration rate

Disintegration rate and mass

The total amount of Pu in the world was in 1992 approximately 1100 tons. Calculate the disintegration rate, assuming that all Pu is ^{239}Pu, with half-life of 24 000 years.

1) Find the number of moles:
$n= 1.1 \bullet 10^9/239 = 4.6 \bullet 10^6$
2) Number of atoms:
$N = N_A \bullet n = 6.022 \bullet 10^{23} \bullet 4.6 \bullet 10^6$
$= 2.8 \bullet 10^{30}$
3) $D = \lambda N = N(\ln 2)/T_{½} =$
$2.8 \bullet 10^{30} \bullet (\ln 2)/(24000 \text{ (y)} \bullet 3.16 \bullet 10^7 \text{ (s/y)}) =$

$$\mathbf{2.5 \bullet 10^{18} \text{ Bq}}$$

Environmental aspects

The Kara Sea is about 2000 km long, 500 km wide and 200 m deep.

Total volume: V = 200•500 000•2000 000 = $2 \bullet 10^{14}$ m^3.

Assume: Someone gets holds on all the wolrd's Pu, dissolves it in nitric acid and pours it into the Kara Sea, where it is not sedimented.
Specific activity; $2.5 \bullet 10^{18}$ Bq/$2 \bullet 10^{14}$ m^3
= 12500 Bq/m^3 = **12.5 Bq/l**

Decay law, example

- A source of ^{99m}Tc (6.0 h) has a disintegration rate of $1.0 \bullet 10^7$ Bq. What is the disintegration rate after 3.0 hours ?
- $\lambda = (\ln 2)/T_{½} = (\ln 2)/6.0(h) = 0.116(h^{-1})$
- $D = D_o e^{-\lambda t} = 1.0 \bullet 10^7 e^{-0.116 \bullet 3.0} =$ **$7.1 \bullet 10^6$ Bq**
- How many atoms ^{99m}Tc are present now ?
- $N = D/\lambda = DT_{½}/(\ln 2) =$
  $7.1 \bullet 10^6 \bullet (6.0 \bullet 3600)/(\ln 2) =$ **$2.2 \bullet 10^{11}$**
- What's the number of moles ?
- $2.2 \bullet 10^{11}/6.022 \bullet 10^{23} =$ **$3.7 \bullet 10^{-13}$**