1.4 The Tools of the Trade!

Two things are required for material analysis:

- excitation mechanism for originating characteristic signature (radiation)
- radiation detection and identification system (spectroscopy)

For dating techniques you need either:

- measurement of activity $A(t)$
- counting of radioactive atoms $N(t)$
Accelerators for Excitation Processes

Required energy transfer for atomic processes:  \( E \approx 1 \text{ keV} - 5 \text{ MeV} \)

Required energy transfer for nuclear processes:  \( E \approx 1 \text{ MeV} - 15 \text{ MeV} \)

Two kind of accelerators are in use:

- cyclotron
- Van de Graaff
**Technical Principle of the cyclotron**

Period $T$ for particle with mass $m$ and charge $q$ in magnetic field $B$:

$$T = \frac{2 \cdot \pi \cdot m}{q \cdot B}$$

Energy of particle in cyclotron of radius $R$:

$$E = \frac{1}{2} m \cdot v^2 = \frac{q^2 \cdot B^2 \cdot R^2}{2 \cdot m}$$

E < 20 MeV (relativistic effects) sufficient for material analysis.

Acceleration across Voltage gap $\Delta V$ between the Dees: $\Delta E = q \cdot \Delta V$
Technical Principle of the Van de Graaff

potential: $U = \frac{Q}{C}$ with $Q =$ charge and $C =$ capacity

Energy: $E = \frac{1}{2} m \cdot v^2 = q \cdot U$;

with $U$ up to 10000000 $V$: $E \leq q \cdot 10^7 eV = 10 \cdot q$ MeV

Sufficient energy for necessary excitation mechanisms!
The single-ended Van de Graaff

1. charging system
2. Belt
3. Terminal charge pick-up
4. High pressure N₂/CO₂ gas vessel
5. Ion source

6. Acceleration tube
7. Vacuum tube
8. Generating voltmeter
9. Analyzing magnet
10. Target system
The Tandem Accelerator

Advantage of ion-source at ground

Total energy: \( E = (1+q)V_{term} \)
The smallest and the largest

Zürich tandem for $^{14}\text{C}$ analysis

Holifield tandem (ORNL) for $^{36}\text{Cl}$ analysis
Typical Accelerator Laboratory for Material Analysis and Dating

beam-production

Mass analysis or dating

Material analysis
Electron Beam Production

Electron beam electron source

Release of electrons by filament heating, light-bulb extraction and acceleration through electric fields

$$E_e = \frac{1}{2} m_e v_e^2 = e \cdot U$$
Ion Beam Production by Sputter Source

Sputtering & charge exchange

SNICS II Schematic Diagram

Extraction and focusing

$E_{\text{ion}} \approx 100 \text{ keV}$
Signatures through reaction processes

- $A(a,a)A$
- $A(a,a')A^*$
- $A(a,b)B$
- $A(a,\gamma)C$

*(in-) elastic scattering

⇒ characteristic particle energy
⇒ characteristic X-ray radiation
⇒ characteristic $\gamma$-ray radiation

Nuclear reaction processes

⇒ characteristic $\gamma$-radiation
⇒ characteristic particle break-up
Some background

The probability for a reaction to occur is the cross-section $\sigma$!

$$\sigma \approx \pi R^2$$

Typical radius of nucleus $\approx 10^{-12}$ m

cross section $\approx$ area, unit barn:

$1$ barn $= 1 \cdot 10^{-24}$ cm$^2$
Total probability for reaction \( \approx \) Yield

If target has thickness \( d \), and target material has

\# nuclei/volume: \( n_0 \) [part./cm\(^3\)]

\[ Y = \sigma \cdot n_0 \cdot d \]

The yield gives the intensity of the characteristic signal from the reaction process per incoming particle with the cross section \( \sigma \)! It also gives the number of reaction products per incoming particle!
Example:

Cosmic ray bombardment of air produces the radioisotope $^{14}$C by the $^{14}$N(n,p)$^{14}$C reaction. Calculate the number of produced $^{14}$C assuming an average $^{14}$N density of $5 \cdot 10^{19}$ part/cm$^3$ along the cosmic ray path length of 1.0 km, a reaction cross section of $\sigma = 0.1$ barn and a cosmic ray induced neutron flux of $2.15 \cdot 10^3$/cm$^2$s.

$Y^{(14}C) = \sigma \cdot n^{(14}N) \cdot d = 0.1 [\text{barn}] \cdot 5 \cdot 10^{19} [\text{part / cm}^3] \cdot 1 [\text{km}]$

$Y^{(14}C) = 1 \cdot 10^{-25} [\text{cm}^2] \cdot 5 \cdot 10^{19} [\text{part / cm}^3] \cdot 10^5 [\text{cm}] = 0.5 / \text{neutron}$

a cosmic ray flux of $2.15 \cdot 10^3 [\text{neutrons / cm}^2 \text{s}]$

yields a total production rate of: $1.08 \cdot 10^3 [^{14}C / \text{cm}^2 \text{s}]$

for entire surface area of earth: $S = 1.3 \cdot 10^{12} [\text{cm}^2]$

$^{14}$C production of: $1.4 \cdot 10^{15} [^{14}C / \text{s}] = 4.4 \cdot 10^{22} [^{14}C / \text{y}] = 1.02 [\text{g / y}]$
Another Example

Estimate the number of $^{14}\text{C}$ atoms produced in the mummy of Ramses II by 3290 years of cosmic ray bombardment!

Cosmic ray flux at ground level of $\sim 1 \cdot 10^4$ particles/m$^2$ s.

Adopt a cross section of $\sigma = 0.1$ barn for $^{14}\text{N}(n,p)^{14}\text{C}$.

The mummy contains $2 \cdot 10^{25}$ $^{14}\text{N}$ particles & $1.6 \cdot 10^{15}$ $^{14}\text{C}$ particles.
**Estimate of $^{14}$C production & $^{14}$C content**

**Production: use standard production equation!**

\[ Y^{(^{14}C)} = \sigma [\text{barn}] \cdot N^{(^{14}N)} \cdot I_{\text{cosmic}} [\text{particles/m}^2 \text{ s}] \cdot t \]
\[ Y^{(^{14}C)} = 0.1 \cdot 10^{-24} \ [\text{cm}^2] \cdot 2 \cdot 10^{25} \cdot 10^4 [\text{particles/m}^2 \text{ s}] \cdot 3290 [y] \]
\[ Y^{(^{14}C)} = 0.1 \cdot 10^{-24} \ [\text{cm}^2] \cdot 2 \cdot 10^{25} \cdot 1 [\text{particles/cm}^2 \text{ s}] \cdot 3290 \cdot 3.15 \cdot 10^7 [s] \]
\[ Y^{(^{14}C)} = 2.07 \cdot 10^{11} \text{ particles are produced in the mummy.} \]

**Content: use standard decay equation!**

\[ N (t) = N_0 \cdot e^{-\lambda \cdot t} \]
\[ N (3290 \ y) = 1.6 \cdot 10^{15} \cdot e^{-\frac{\ln 2}{5730} \cdot 3290 \ y} \]
\[ N (3290 \ y) = 1.075 \cdot 10^{15} \quad ^{14}C \text{ particles are contained in the mummy!} \]
Absorption and Transmission

Absorption and transmission of the initial beam with intensity $I_0$ depends on the target thickness $d$ and total interaction cross section $\sigma_{tot} = \sigma_i$ for all possible reactions between projectiles and target material of cross section $\sigma_i$:

$$I(d) = I_0 \cdot e^{-\mu \cdot d}$$

$$\mu = n_0 \cdot \sum_i \sigma_i$$
Cosmic Ray Absorption in Atmosphere

\[ I(d) = I_0 \cdot e^{-\mu d}; \quad \mu = n_0 \cdot \sum_i \sigma_i \]

How many of the \(2.15 \cdot 10^3/cm^2\) neutrons produced at 12 km height will reach the surface of the earth assuming an average nitrogen density of \(5 \cdot 10^{19}\) part/cm\(^3\) and an interaction cross section of 0.1 barn?

\[ I_n(12km) = 2.15 \cdot 10^3 \text{ [n/cm}^2\text{s]} \cdot e^{-5 \cdot 10^{19}[\text{N/cm}^3] \cdot 0.1 \cdot 10^{-24}[\text{cm}^2] \cdot 1.2 \cdot 10^6[\text{cm}]} \]

\[ I_n(12km) = 5.3 \text{ [n/cm}^2\text{s]} \]
Interaction processes between projectile and target material

• atomic excitation processes \( \Rightarrow X\text{-ray-visible light} \)
  (Coulomb Interaction between projectile and atomic electrons): \( \sigma_i \approx [\text{kbarn}] \)

• elastic scattering processes \( \Rightarrow \) char. particle energies
  (mechanical momentum without energy transfer): \( \sigma_i \approx [\text{barn}] \)

• inelastic scattering processes \( \Rightarrow \) char. \( \gamma \)-radiation
  (mechanical momentum and energy transfer): \( \sigma_i \approx [\text{barn}] \)

• radiative capture reactions \( \Rightarrow \) char. \( \gamma \)-radiation
  (Coulomb Interaction between projectile and atomic nucleus): \( \sigma_i \approx [\mu\text{barn}] \)

• nuclear reaction processes \( \Rightarrow \) char. particle radiation
  (Strong Interaction between projectile and atomic nucleus): \( \sigma_i \approx [\text{mbarn}] \)
Radiation Detectors

Radiation detectors are based on material which shows a high probability (cross section) for interacting with a particular kind of radiation (in a particular energy range)! The interaction process initiates an excitation or ionisation event in the material (e.g. atomic excitation, or solid state excitation) which results in light or particle emission which in turn can be used for generating an electrical pulse for analyzing and interpreting the event in the data acquisition electronics. There are three kind of detector materials:

- Scintillator
- Solid State Detector
- Ionisation Chamber

- X-ray, $\gamma$-ray, and neutron radiation
- Particle- and $\gamma$-ray radiation
- Particle radiation
Example: NaI scintillator

- Photons in the visible light range are created by excitation of NaI material with radiation
- photons are absorbed on photo cathode and generate free electrons by photo-effect
- electrons are multiplied in photo multiplier and converted to an electrical signal
Ionization chamber and semiconductor detectors

Detectors are based on the principle of ionization along the track of energetic charged particle, production of ion-electron pairs, which are accelerated by attached electrical fields to anode or cathode pole of detector, charge pulse is converted in electrical pulse, pulse height corresponds to energy loss of initial energetic particle.
Summary

• Tools are needed to instigate the characteristic excitation processes by energy transfer

• Tools are needed to analyze the characteristic light or radiation signatures