History

- **1896**: Becquerel discovers strong ionising radiation from uranium salts. The radiation is present regardless of the chemical state or pre-treatment of the uranium
- **1898** Polonium and radium, Marie & Pierre Curie
- **1899** Observation of “radium-emanation” (radon), Rutherford
- **1902-03** Radioactivity is a sign of transmutation of one type of element to another, Rutherford, Soddy, Crookes
- **1903** β-particles = electrons, γ =electromagnetic (Becquerel), α-particles = ionised He-atoms (Rutherford)

History

- **1907** Radiation therapy of skin cancer with Ra rays (Stenbeck)
- **1911** Small atomic nucleus, α on gold foil (Rutheford, Geiger, Marsden)
- **1912** Radioactivity used as tracer in chemistry (Hevesy)
- **1913** Cosmic radiation (Heβ); Isotope concept (Fajans,Soddy); Atomic model (Bohr)
- **1919** First nuclear reaction $^{14}N(\alpha,p)^{17}O$ (Rutherford)
- **1920** Neutron prediction (Rutherford)

History

- **1921** Nuclear isomers (Hahn)
- **1924** Radioactivity in biology (Lacassagne & Lattes)
- **1928** Linear accelerator (Widerøe)
- **1930** Positron prediction (Dirac)
- **1932** Neutrino prediction (Pauli); Discovery of neutron (Chadwick); Discovery of positron (Anderson); Cyclotron (Lawrence)
- **1934** Artificial radioactivity (I.Curie, F.Joliot)
- **1935** Meson prediction (Yukawa); Liquid drop model (Bethe, von Weiszäcker)
- **1936** Neutron activation analysis (Hevesy & Levy);
- **1938** Fission (Hahn, Straβmann, Meitner), discussed separately; Electron capture (Alvarez)

History

- **1940** Neptunium and plutonium (Seaborg, McMillan, Wahl, Abelson)
- **1946** ^{14}C dating method (Libby)
- **1948** π mesons (Powell); Hyperfine anomalies indicate non-spherical nuclei (Kopfermann, Brix)
- **1949** Nuclear Shell-model (Mayer,Jensen)
- **1952** Collective model (Bohr,Mottelson)
- **1956** neutrino discovery (Cowan, Reines)
- **1940 - ?** New elements
  - Berkeley (Am-Sg) (Seaborg, Ghiorso)
  - Darmstadt (Db-112) (Münzenberg, Hofmann)
  - Dubna (114,116) (Oganessian)
- **1950 -** Development of nuclear pharmacy and radio-biochemistry
- **1980** Ground-state protons (Hofmann); prediction of ^{14}C decay (Ivascu,Poenaru)
- **1984** Discovery of ^{14}C decay (Rose,Jones)
- **1987** Discovery of double β (Elliot,Moe)
- **1993** Indication for “superheavy region” (Lazarev)
- **1991** - Radiotargeted therapy

Naturally occuring radionuclides

- Two types of natural radioactivity
- Primordial nuclides (i.e. nuclides left after the element synthesis 5 billion years ago
  - ^{40}K
  - ^{87}Rb
  - ^{238}U (with daughters)
  - ^{235}U (with daughters)
  - ^{232}Th (with daughters)
  - Etc.....
- Cosmogeneous nuclides (i.e. nuclides continuously formed through cosmological nuclear processes in the atmosphere
  - ^{14}C
  - ^{3}H
  - ^{36}Cl
  - ^{39}Ar
  - Etc......

Radioactive series in nature

- Series of radionuclides following a long-lived naturally occuring nuclide:
- Starts with:
  - ^{232}Th
  - ^{238}U
  - ^{235}U
- Ends with:
  - ^{208}Pb
  - ^{206}Pb
  - ^{207}Pb

Naturally occuring radionuclides

Naturlige isotoper			Kunstige isotoper	
Isotop	Aktivitet Bq/l	I % av tot. aktivitet	Isotop	Aktivitet Bq/l
K–40	$1{,}2\cdot10$	96	H–3	$10^{-2} - 2{,}7$
Rb–87	$1{,}1\cdot10^{-1}$	0,9	C–14	$0 - 1{,}5\cdot10^{-3}$
U–234	$4{,}7\cdot10^{-2}$	0,4	Cs–137	$7\cdot10^{-4} - 2\cdot10^{-1}$
U–238	$4{,}1\cdot10^{-2}$	0,3	Sr–90	$4\cdot10^{-4} - 1\cdot10^{-1}$
Pb–210	$5{,}0\cdot10^{-3}$	0,04	Pu–239	$7\cdot10^{-6} - 3\cdot10^{-4}$
Po–210	$3{,}7\cdot10^{-3}$	0,03		
Ra–226	$3{,}6\cdot10^{-3}$	0,03		
U–235	$1{,}9\cdot10^{-3}$	0,02		

T.Henriksen, biofysikk, UiO

α-disintegrasjon

- Three conditions determine which half-life one gets for α-decay:
- 1. Two protons and two neutrons "meet" in the surface of the nucleus and form for a short while an "α-particle" there.
- 2. This "α-particle" penetrates through the coulomb-barrier by quantum-mechanical tunneling
- 3. Theses processes proceed most easily between "equal" levels in the start- and stop-nuclides

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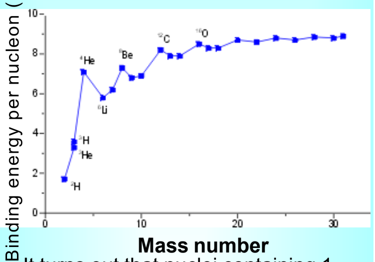
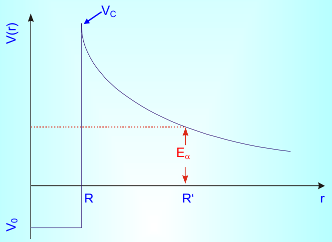
α - stable structure



It turns out that nuclei containing 1, 2, 3 or 4 α-particles (^{4}He), ^{8}Be, ^{12}C and ^{16}O have particularly high binding energy.
^{8}Be is unbound, because 2 α-particles are more energetically favourable.

α-disintegration

Large variation in half-lives from some nano-seconds to10^{15} years.
Litttle variation in energy (2,5 - 9 MeV)



Barrier penetration. The α-particle has negative biding energy, but must penetrate the coulomb-barrier on the way out (Gamow)

α-disintegration

Energy balance:
Process: (Z,N) ➜ (Z-2,N-2) + α

Energy conservation gives::

$$M(Z,N) = \underbrace{M(Z\text{-}2,N\text{-}2) + M(^4He)}_{\text{Rest mass}} + \underbrace{E_\alpha + E_r}_{\text{Kinetic energy}}$$

$$\mathbf{Q_\alpha \equiv M(Z,N) - M(Z\text{-}2,N\text{-}2) - M(^4He)}$$

(Neutral atoms)

Futhermore: $E_\alpha + E_r = Q_\alpha$
and: $m_\alpha v_\alpha = m_r v_r$, consequently:
$m_\alpha^2 v_\alpha^2 = m_r^2 v_r^2$; $m_\alpha E_\alpha = m_r E_r$ gives:
$E_\alpha + E_\alpha(m_\alpha/m_r) = E_\alpha(1+m_\alpha/m_r) = Q_\alpha$
$E_\alpha = Q_\alpha(m_r/(m_r + m_\alpha)) \approx \mathbf{Q_\alpha(1\text{-}4/A)}$
where A er the mass number of the disintegrating atom.

α-disintegration

Chemically important consequence:
The energy deposited in the recoil atom is

$$\mathbf{E_r = Q_\alpha(4/A)}$$

This is a smalll part of the decay energy, but sufficient to break any thinkable chemical binding.

Another consequence is that the recoil atom is emitted oppositely to the α-particle with a substantial kitetic energy. If the daughter nuclide(s) are radioactive, this can give very unpleasant surprices if disregarded.

β^--disintegrasjon

Pauli's neutrino postulate (1932)

In early investigations of the shape of β-spectra, a fundamental problem was discovered. The spectra were continiuous. It the process was two-particle, it should have resulted in line spectra, to conserve energy and impulse. **Solution proposed by Wolfgang Pauli: Simultaneously with the electron, the nucleus emits a massless particle, the neutrino**. The particle must have spin ½ in order to conserve angular momentum for the process.

β^--disintegration

Nobel prize 1945

Wolfgang Pauli
1900-1958

Nobel prize 1938

Enrico Fermi
1901-1954

Fermi's β-theory gives the shape of the β-spectrum:

$\mathbf{P(p_e)dp_e = c\,F(Z,E_e)(E_o-E_e)p_e^2dp_e}$

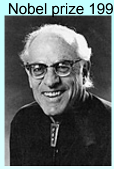
where p_e og E_e are impulse and energy for the emitted electron, and E_o er maximuml desintegration energy (often called $E_{\beta,max}$).

$F(Z,E_e)$ is the coulomb correction.

Note that the endpoint $E = E_{\beta,max}$

β^--disintegration

Nobel prize 1995



Frederick Reines
1918 - 1998

The neutrino was discovered by the socalled "reverse β-decay" by Cowan and Reines in 1956:

one has $p \rightarrow n + \nu + e^+$ and thereby:

$p + \overline{\nu} \rightarrow n + e^+$ (reverse β).

Processes giving a neutron and a positron simultaneously are so rare that they will be a unique confirmation of the antineutrino's existence.

β^--disintegration

Energy relations

β^-: $(Z,N) \Rightarrow (Z+1,N-1) + e^- + \overline{\nu}$

$M_{nucl}(Z,N) = M_{nucl}(Z+1,N-1) + E_{\beta,max} + M_e$
$(+E_r \approx 0)$

$E_{\beta,max} = M_{nucl}(Z,N) - M_{nucl}(Z+1,N-1) - M_e$

$M_{nucl}(Z,N) \approx M(Z,N) - zM_e$
$M_{nucl}(Z+1,N-1) \approx M(Z+1,N-1) - (z+1)M_e$

$E_{\beta,max} = M(Z,N) - zM_e - (M(Z+1,N-1) - (z+1)M_e) - M_e$

$\mathbf{E_{\beta,max} = M(Z,N) - M(Z+1,N-1) = Q_{\beta^-}}$

β^+-disintegration

Energy relations

β^+: $(Z,N) \Rightarrow (Z-1,N+1) + e- + \nu$

$M_{nucl}(Z,N) = M_{nucl}(Z-1,N+1) + E_{\beta,max} + M_e$
$(+E_r \approx 0)$

$E_{\beta,max} = M_{nucl}(Z,N) - M_{nucl}(Z-1,N+1) - M_e$

$M_{nucl}(Z,N) \approx M(Z,N) - zM_e$
$M_{nucl}(Z-1,N+1) \approx M(Z-1,N+1) - (z-1)M_e$

$E_{\beta,max} = M(Z,N) - zM_e - (M(Z-1,N+1) - (z-1)M_e) - M_e$

$\mathbf{E_{\beta,max} = M(Z,N) - M(Z-1,N+1) - 2M_e = Q_{\beta+} - 2M_e}$

At $Q_{\beta+} < 2M_e$ only electron capture is possible

Exotic decays

- Ground-state protons (Hofmann 1979)
- Emission of unbound protons, delayed by the coulomb barrier.
- Double β (with and without neutrino (Elliot and Moe 1987)
- Very unlikely process, but allowed, only way to bypass an odd-odd-nucleus.Very long half-lives(10^{20}y)
- ^{14}C-emission (Rose and Jones 1984)
- Exotic and particular form of decay arising because the coulomb barrier is sufficiently low for light, neutronrich fragments.

Exotic decays

- Delayed neutrons
- β^--disintegration with so high energy that it superceeds the neutron binding energy.
  - There is also 2 -and 3- neutron emission
- Delayed protons
- β^+-disintegration with so high energy that it superceeds the proton binding energy.
- Delayed α
- Delayed tritium and ^{3}He
- Delayed fisssion