Focus 10
Nuclear Chemistry

Nuclear decay occurs whenever a nucleus containing a certain # nucleons (nucleons ≡ a proton or neutron) is put in an energy state that is not the lowest possible one for a system with that number of nucleons

- nucleus put into the unstable state as a consequence of a nuclear reaction
  - home made particle accelerator
  - natural events that happened 10^{10} years ago when our part of the universe was formed
  - occurs now during certain types of stellar death processes

$Z+N=A$ ${}^{A}_{Z}X$

or

${}^{Z}X^{A}$

$Z \equiv$ protons
$N \equiv$ neutrons
$A \equiv Z+N$

Unstable nuclei that originate from natural events are often called "radioactive"; the process that occurs in their decay is often called radioactive decay or radioactivity

- important process: provides clues about the origin of the universe

Nuclear decay divides intself into 3 categories:

① α-decay: spontaneous emission of an α-particle from a nucleus of large atomic #
- sets upper limit on the atomic numbers of the chemical elements occurring in nature

② β-decay: spontaneous emission or absorption of an electron or positron by a nucleus

③ γ-decay: spontaneous emission of high energy photons when a nucleus makes a transition from an excited state to its ground state.

1896 Henri Becquerel: phosphorescent materials (external light (energy) source)
=> knew of studies investigating cathode ray tubes + X-rays

used U salts in his studies
+ showed similar but different
than x-rays => more complex
=> didn't need external energy
as signal came from U itself
(radioactive decay)

Followed up by his graduate student, Marie
Curie + her numerous discoveries
both died from their work, Becquerel
from handling radioactive materials
and Curie from aplastic anemia
(not radium toxicity) but unshielded
x-ray tubes.

α-decay: common in nuclei with atomic
number > Z = 82 (Pb). Involves
decay of an unstable "parent" nucleus
to its "daughter" nucleus by the
emission of an α-particle, the nucleus
^4_2He (or $_2He^4$)

spontaneous because it is energetically
favored

mass of parent nucleus > mass of daughter
nucleus plus mass of α-particle

reduction in nuclear mass in decay is primarily due to a reduction in the Coulomb energy of the nucleus when its charge $Z\bar{e}$ is reduced by the charge $2\bar{e}$ carried away by the α-particle.

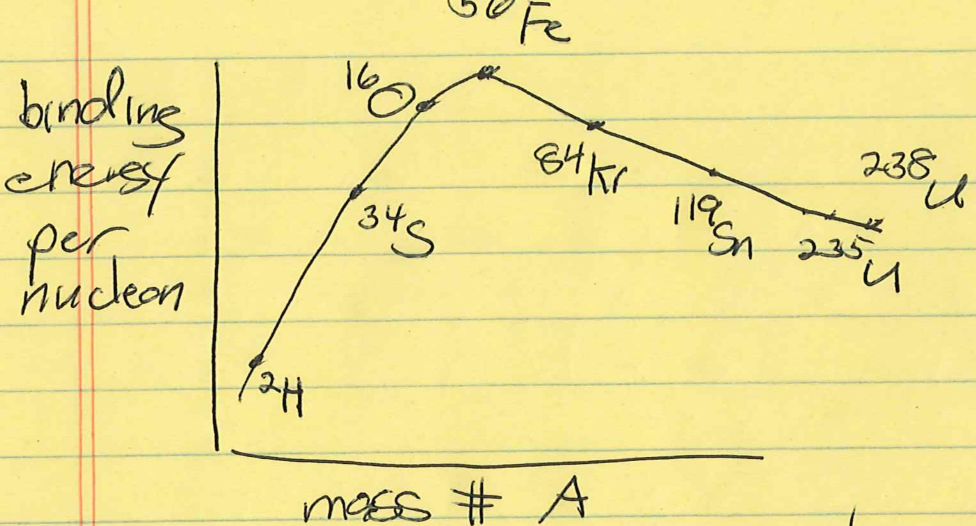
The energy made available in the decay is the energy equivalent of the mass difference. Decay energy is carried away by the α-particle as kinetic energy.

α-decay energy: $E = mc^2$

$$E = [\underbrace{M_{Z,A}}_{\text{parent}} - (\underbrace{M_{Z-2,A-4}}_{\text{daughter}} + \underbrace{M_{2,4}}_{\alpha\text{-particle}})]c^2 > 0$$

if $E > 0$ then decay occurs. If $E \leq 0$ then stable.

Note: Z decreases by 2
A decreases by 4



A $\simeq$ 60 is where average binding energy per nucleon $\Delta E / A$ is maximum.

Fig 10C.1

element ~ Fe, most stable nucleus

Marie Curie discovered Po 1898 named after her birthplace of Poland

O
S
Se
Te
Po

In news: in 1998, Alexander Litvinenko publically accused superiors of ordering the assination of tycoon Boris Berezersky

Litvinenko was an officer in Russian State Security Service (military counter intelligence), who later became a dissident + writer

- he was put on trial, released + went to England (political asylum)

wrote a book about Putin regime, Nov 2006 was killed in England

$^{210}_{84}Po$ α decay

- more isotopes than any other element (12)

- 2.5×10^{11} times (w/w) as toxic as HCN

- found as contaminant in tobacco

$^{209}_{83}Bi + ^{1}_{0}n \rightarrow ^{210}_{84}Po + e^{-} \longrightarrow ^{206}_{82}Pb + ^{4}_{2}He$

$t_{1/2} \sim 138$ days + energy

rate of energy use: power Watt = $\frac{\text{joule}}{\text{sec}}$

work joule = 1 Newton · meter

$1\,J = \frac{kg\,m^2}{sec^2}$ $E = \frac{1}{2}mv^2$ 2 kg mass at velocity of 1 m/sec

~4.4 lbs

~2.25 mph

α-particle => thermal energy

decay of $^{210}_{84}Po$ $141\,\frac{W}{g}$ ≈ 317 mph

used as a heat source in space satellites

½ g capsule reaches temperatures of >500°C

emits α-particle => excite surrounding gas -> blue glow

$^{210}_{84}Po$ low melting (254°C) fairly volatile metal

50% is vaporized in air in 45 hrs at 55°C (130°F)

lethal in μg amounts due to complete absorption of the energy of the α-particle into tissue

lethal dose: 0.03 μcuries $\sim 6.8 \times 10^{-12}$ g

β-decay; involves a nucleus Z, A emitting a negatively charged electron and being transformed into a nucleus Z+1, A (∃ 2 other types of β decay)

Z increases by 1 A remains fixed

N decreases by 1

Nuclei whose Z values are not the most stable wrt A values can change Z to attain stability by 3 different β-decay processes:

1) electron emission: occurs in radioactive series

e^- leaves; Z ↑ by 1, A fixed
N ↓ by 1

2) electron capture: nucleus captures negatively charged atomic electron

3) positron emission: nucleus emits a positively charged positron

for 2 + 3 $Z \downarrow 1$ A remains fixed
$N \uparrow 1$

Electron emission takes place if the mass $m_{Z,A}$ of the initial nucleus exceeds the mass $m_{Z+1,A}$ of the final nucleus plus one electron rest mass, m.

decay energy $E = [m_{Z,A} - (m_{Z+1,A} + m)]c^2 > 0$

initial mass, final mass, 1 e⁻ rest mass

must be positive for decay to occur

In terms of atomic masses by adding + subtracting Z electron rest masses

$$E = [m_{Z,A} + \underbrace{Zm}_{Ze^- \text{ rest masses}} - (m_{Z+1,A} + Zm + m)]c^2 > 0$$

Decay energy in electron emission:

$E = [M_{Z,A} - M_{Z+1,A}]c^2 > 0$ atomic masses

e^- emission occurs when initial atomic mass > final atomic mass because mass of e^- added to the atom is compensated for by the mass of the electron emitted by the nucleus

Electron capture: occurs if mass $m_{Z,A}$ of initial nucleus plus $1e^-$ rest mass exceeds mass $m_{Z-1,A}$ of final nucleus

energy of decay:

$$E = [(m_{Z,A} + m) - (m_{Z-1,A})]c^2$$

$$E = [m_{Z,A} - (m_{Z-1,A} - m)]c^2$$

or

$$E = [m_{Z,A} + Zm - (m_{Z-1,A} + Zm - m)]c^2$$

in terms of atomic masses, decay energy in electron capture is

$$E = [M_{Z,A} - M_{Z-1,A}]c^2 > 0$$

when energy is positive, e^- capture occurs mass of e^- taken from the atom in the capture is compensated for by the mass of the e^- captured by the nucleus

Positron emission requires the mass $m_{Z,A}$ of initial nucleus to exceed the mass $m_{Z-1,A}$ of the final nucleus plus one positron rest mass, which also equals m

Energy of decay $E = [m_{Z,A} - (m_{Z-1,A} + m)]c^2$
or

$$E = [m_{Z,A} + Zm - (m_{Z-1,A} + Zm - m) - 2m]c^2$$

or in atomic masses

$$E = [M_{Z,A} - M_{Z-1,A} - 2m]c^2 > 0$$

atom must emit $1e^-$ since nucleus emits 1 positron & has 1 less positive charge. Cannot be compensated of e^- masses found in other β-decay processes.

Thus, in order to have the decay energy in positron emission positive (>0 required) the initial atomic mass must exceed final atomic mass by more than $2e^-$ rest masses

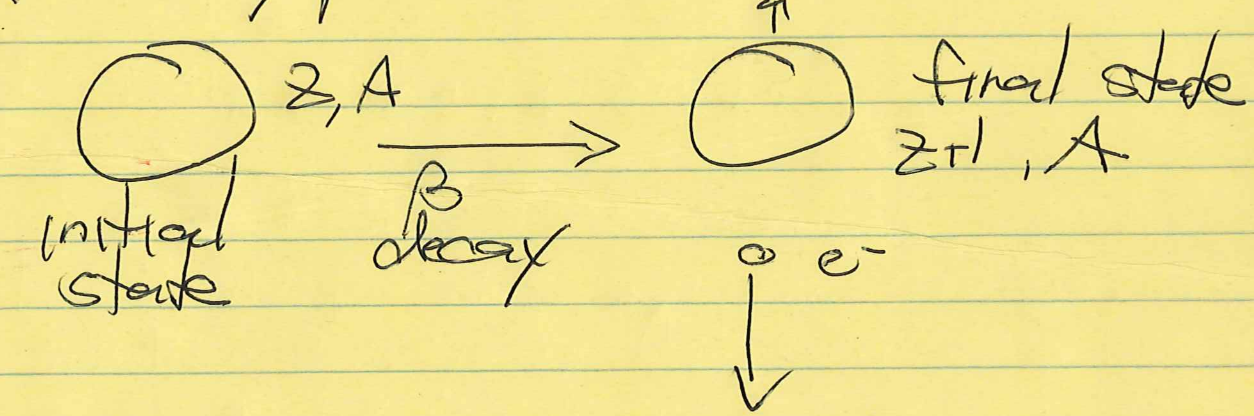
$M_{Z,A} > M_{Z+1,A}$ e^- emission can occur

$M_{Z,A} > M_{Z-1,A}$ e^- capture can occur

not common | Positron emission can only occur if $M_{Z,A} > M_{Z-1,A} + 2m$

positron capture can also occur but even more rare.

β-decay process: common e^- emission

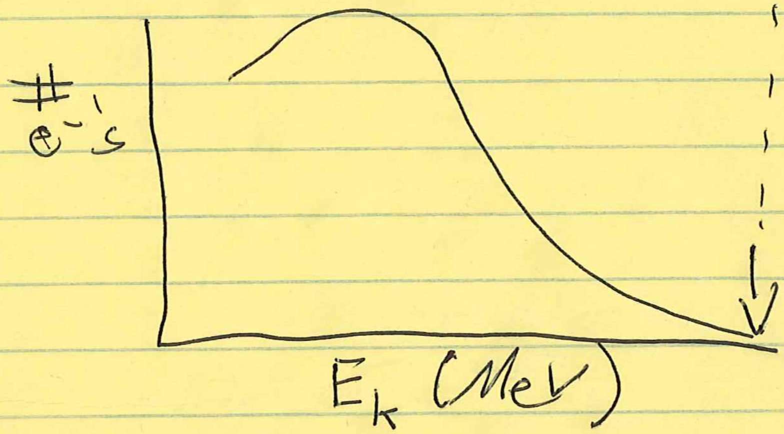


recoils only linear momentum conserving way in which the available energy (decay energy) can be shared.

nuclei so massive: recoil velocities very low & they carry no kinetic energy

e^- should carry away almost all of the decay energy/E in the form of KE or E_{KE}

Problem: e^- emitted with a spectrum of energies



Endpoint KE^-_{max}

e^- carry less energy than released energy

1931 Wolfgang Pauli postulated that a particle, now called the antineutrino $\bar{\nu}$ also emitted

=> not detected (normally) as its interactions with matter are extremely weak

also postulated 1) zero charge conserv. of charge

2) intrinsic spin $s = \frac{1}{2}$ angular momentum

$\bar{e}$ ½
nucleus integer value

3) zero rest mass ?

Assume Z, A ; $Z+1$ A => even
i = integer form i + f states

other issues:

isolated neutrons $^{0}n^{1} \rightarrow {}_{1}^{1}H + e + \bar{\nu}$ (proton, electron, antineutrino)
$({}_{0}^{1}n)$

$[M_{0,1} - M_{1,1}]c^2 = +0.78\ MeV$
$t_{1/2} \sim 1000$ sec
$\sim 16\frac{2}{3}$ minutes

but ${}_{0}^{1}n$ in nucleus does not decay
nuclear interaction stronger than β decay

[now proton decay theory $10^{31} - 10^{36}$ years
Japan 6.6×10^{36} yrs
Canada $> 2.1 \times 10^{29}$ yrs]

We'll talk about Rutherford in 1911
scattering of nucleus by α-particles
nucleus: protons + neutrons
[β-decay in nucleus would be a
problem - but not]

1938 Otto Hahn, Lise Meitner, Fritz Strassmann
nuclear fission (1944 Nobel prize)

1935 Chadwick mass of n determined
1934 Fermi β-decay $^{0}n^{1} \rightarrow {}_{1}^{1}H + e + \bar{\nu}$
1938 Nobel prize
slow neutron irradiation -> new
elements (not fusion but
fission - missed)

1953 Reines & Cowan

$$\bar{\nu} + {}_1H^1 \rightarrow {}_0n^1 + \bar{e}$$
positron

alternative form of neutron decay
equivalence of destruction of antiparticle positron & creation of associated particle electron

$$ {}_0n^1 + \bar{e} \rightarrow {}_1H^1 + \bar{\nu}$$
$$ {}_0n^1 \rightarrow {}_1H^1 + \bar{\nu} + e^-$$

[Note energy scale:

$$1\,eV = 96.48\ kJ/mol = 23.06\ \frac{kcal}{mol}$$

$$MeV \sim 9.7 \times 10^7\ kJ/mol \simeq 2.3 \times 10^7\ \frac{kcal}{mol}]$$

3) Gamma decay
γ-rays emitted from many nuclei of the radioactive series
photons of electromagnetic radiation that carry away excess energy when nuclei make γ-decay transitions from excited states to lower energy states
γ-rays energies $> 10^{-3}$ MeV
β-decay leaves daughter nucleus in excited states