Announcement

- Homework (15%) + Class participation (5%)
- Midterm 1 (20%) + Midterm 2 (20%)
- Final (40%) on 3/19, Wed, 8-11 am
  - Bring calculator, open-book and open-notes
  - 30% Nuclear
  - 25% Elementary
  - 45% Atomic, statistical, and solid state focusing on common underlying ideas:
    - Energy, Hamiltonian, conservation, system, symmetry, etc.

Lecture 18

- Nuclear decay
  - Alpha decay
  - Beta decay
  - Gamma decay
- Nuclear reactions
  - Fission
  - Fusion

Radioactive decay

- An unstable nucleus (parent nucleus) can spontaneously emit small particles or energies to become a nucleus (daughter nucleus) in a more stable state.
  - Alpha decay (α = He nucleus)
  - Beta decay: β^+ decay, β^- decay, electron capture
  - Gamma decay (γ = photons)

Alpha decay

- Emits an alpha particle
- Alpha particle is He nucleus=2 protons +2 neutrons

$$^{A}_{Z}X(parent) \rightarrow ^{A-4}_{Z-2}Y(daughter) + ^{4}_{2}He$$

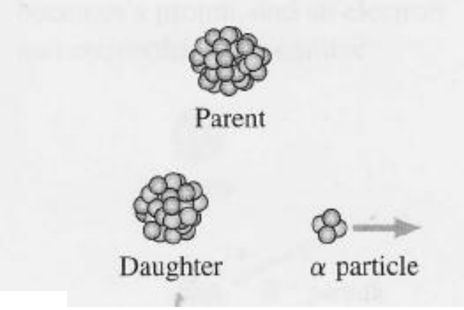
- ○ $Z_{daughter} =$
- ○ $N_{daughter} =$
- ○ $A_{daughter} =$

Released kinetic energy (Q)

$$Q =$$

$$^{238}_{92}U \rightarrow$$

Figure 11.18 Alpha decay.

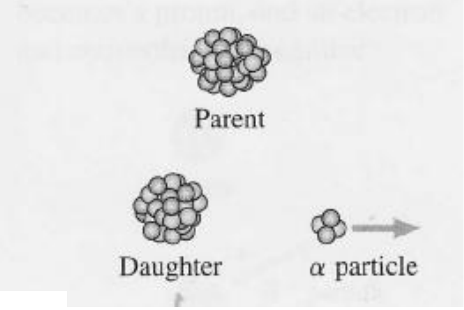


m: atomic mass

Alpha decay

- Emits an alpha particle
- Alpha particle is He nucleus=2 protons +2 neutrons

Figure 11.18 Alpha decay.



$${}^{A}_{Z}X(parent) \rightarrow {}^{A-4}_{Z-2}Y(daughter) + {}^{4}_{2}He$$

- ○ $Z_{daughter} = Z_{parent} - 2$
- ○ $N_{daughter} = N_{parent} - 2$
- ○ $A_{daughter} = A_{parent} - 4$

Released kinetic energy (Q)

$$Q = (m_{parent} - m_{daughter} - m_{{}^{4}_{2}He})\, c^2$$

m: atomic mass

${}^{238}_{92}U \rightarrow$

Alpha decay

- Emits an alpha particle
- Alpha particle is He nucleus=2 protons +2 neutrons

$$^{A}_{Z}X(parent) \rightarrow {}^{A-4}_{Z-2}Y(daughter) + {}^{4}_{2}He$$

- ○ $Z_{daughter} = Z_{parent} - 2$
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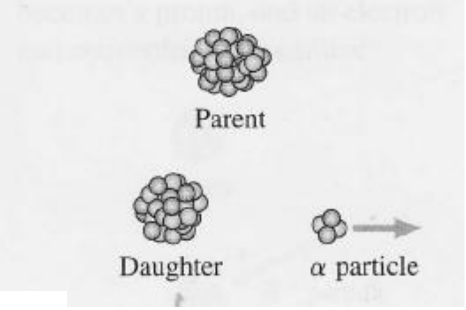
Figure 11.18 Alpha decay.



Released kinetic energy (Q)

$$Q = (m_{parent} - m_{daughter} - m_{^{4}_{2}He})\, c^2$$

m: atomic mass

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

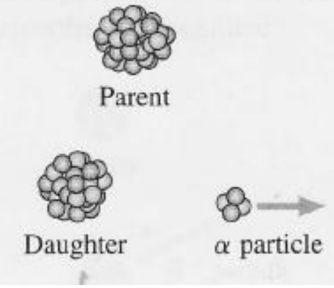
$^{238}_{92}U$	234.050784 u
$^{234}_{90}Th$	234.043593 u
$^{4}_{2}He$	4.002603 u

Uc^2 =931.5 MeV

Alpha decay

- Emits an alpha particle
- Alpha particle is He nucleus=2 protons +2 neutrons

Figure 11.18 Alpha decay.



$$ {}^{A}_{Z}X(parent) \rightarrow {}^{A-4}_{Z-2}Y(daughter) + {}^{4}_{2}He $$

- ○ $Z_{daughter} = Z_{parent} - 2$
- ○ $N_{daughter} = N_{parent} - 2$
- ○ $A_{daughter} = A_{parent} - 4$

Released kinetic energy (Q)

$$ Q = (m_{parent} - m_{daughter} - m_{{}^{4}_{2}He})\, c^2 $$

$$ {}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He $$

$$ \begin{aligned} Q &= (m_{parent} - m_{daughter} - m_{{}^{4}_{2}He})\, c^2 \\ &= (238.050784 - 234.043593 - 4.002603)uc^2 \\ &= 0.004588 \text{ x } 931.5\, MeV = 4.27\, MeV \end{aligned} $$

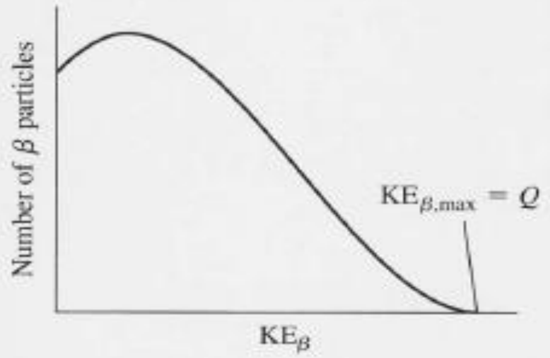
${}^{238}_{92}U$	234.050784 u
${}^{234}_{90}Th$	234.043593 u
${}^{4}_{2}He$	4.002603 u

Uc^2 =931.5 MeV

Beta decay

- Emits β^+, β^- particles (= positron, electron)
- Another particle is involved!
- To satisfy:
  - Energy conservation
    - Beta particles carry kinetic energies from 0 to maximum allowed
  - Charge conservation
    - β^+, β^- carries +1 and -1
  - Angular momentum conservation
    - β^+, β^- : spin ½

Figure 11.19 The mysterious variation in β particle energies.



$$^{A}_{Z}X(parent) \rightarrow {}_{Z+1}^{\;\;A}Y(daughter) + {}_{-1}^{\;0}\beta^-$$

???

Beta decay

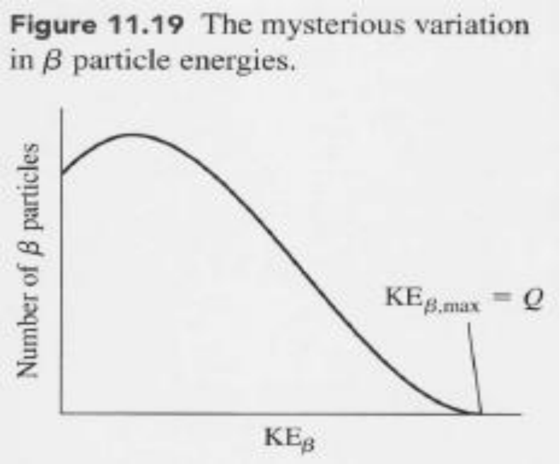
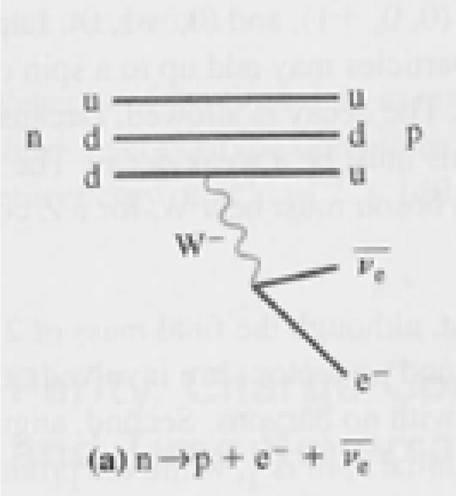


Figure 11.19 The mysterious variation in β particle energies.

- Emits β^+, β^- particles (= positron,
- Neutrino (ν) is involved!
- To satisfy:
  - Energy conservation
    - Beta particles carry kinetic energies from 0 to maximum allowed Neutrino: mass negligible
  - Charge conservation
    - β^+, β^- carries +1 and -1 Neutrino: neutral
  - Angular momentum conservation
    - β^+, β^- : spin ½ Neutrino spin=1/2

Decay Possible?

Mass=940
Charge = 0
Spin=1/2
Strangeness=0
Baryon number=1
Lepton number (e)=0



(a) $n \rightarrow p + e^- + \bar{\nu}_e$

Mass=938
Spin=1/2
Charge = +1
Strangeness=0
Baryon number=1
Lepton number=0

Mass=0
Spin=1/2
Charge = -1
Strangeness=0
Baryon number=0
Lepton number=-1

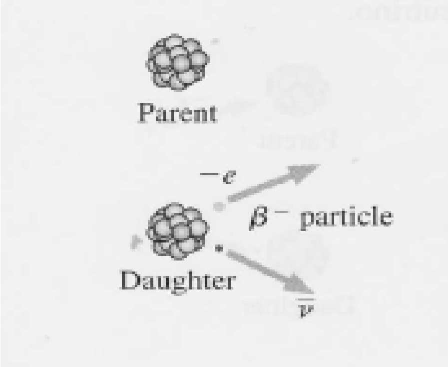
Mass=0.51
Spin=1/2
Charge = 0
Strangeness=0
Baryon number=0
Lepton number=1

Strangeness not conserved in weak decay
Some flexibility in angular momentum

β^- decay

- Emits an electron and an anti-neutrino.
- Changes a neutron inside the nucleus into a proton.

$$ {}^{A}_{Z}X(parent) \rightarrow {}^{A}_{Z+1}Y(daughter) + {}^{0}_{-1}\beta^- + \bar{\nu} $$



  - $Z_{daughter} = Z_{parent} + 1$
  - $N_{daughter} = N_{parent} - 1$
  - $A_{daughter} = A_{parent}$

Released kinetic energy

$$ Q = (m_{parent} - m_{daughter})\, c^2 $$

Example:

$$ {}^{12}_{5}B \rightarrow $$

$$ Q = $$

β^- decay

- Emits an electron and an anti-neutrino.
- Changes a neutron inside the nucleus into a proton.

$${}^{A}_{Z}X(parent) \rightarrow {}_{Z+1}^{A}Y(daughter) + {}_{-1}^{0}\beta^- + \bar{\nu}$$

- ○ $Z_{daughter} = Z_{parent} + 1$
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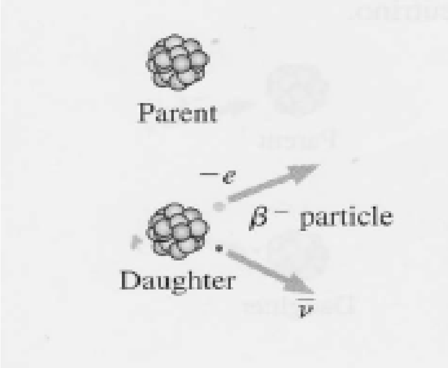


Released kinetic energy

$$Q = (m_{parent} - m_{daughter})\, c^2$$

Example:

$${}^{12}_{5}B \rightarrow {}^{12}_{6}C + {}_{-1}^{0}\beta^- + \bar{\nu}$$

$Q =$

${}^{12}_{5}B$ =12.014532 u

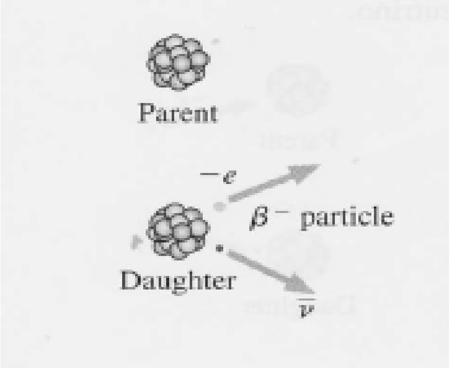
${}^{12}_{6}C$ =12 u

uc^2= 931.5 MeV

β^- decay

- Emits an electron and an anti-neutrino.
- Changes a neutron inside the nucleus into a proton.

$$ {}^{A}_{Z}X(parent) \rightarrow {}^{\;\;A}_{Z+1}Y(daughter) + {}^{\;\,0}_{-1}\beta^- + \bar{\nu} $$



- $Z_{daughter} = Z_{parent} + 1$
- $N_{daughter} = N_{parent} - 1$
- $A_{daughter} = A_{parent}$

Released kinetic energy

$$ Q = (m_{parent} - m_{daughter})\,c^2 $$

Example:

$$ {}^{12}_{5}B \rightarrow {}^{12}_{6}C + {}^{\;\,0}_{-1}\beta^- + \bar{\nu} $$

$$ Q = (12.014352 - 12)uc^2 = 13.4\ MeV $$

${}^{12}_{5}B$ =12.014532 u

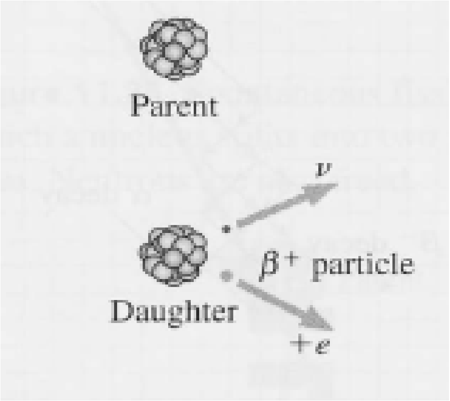
${}^{12}_{6}C$ =12 u

uc^2= 931.5 MeV

β^+ decay

- Emits a positron and a neutrino
- Changes a proton inside the nucleus into a neutron.

$${}^{A}_{Z}X(parent) \rightarrow {}_{Z-1}^{\;\;A}Y(daughter) + {}^{\;0}_{+1}\beta^+ + \nu$$



- ○ $Z_{daughter} = Z_{parent} - 1$
- ○ $N_{daughter} = N_{parent} + 1$
- ○ $A_{daughter} = A_{parent}$

Released kinetic energy

$$Q = (m_{parent} - m_{daughter} - 2m_{electron})\,c^2$$

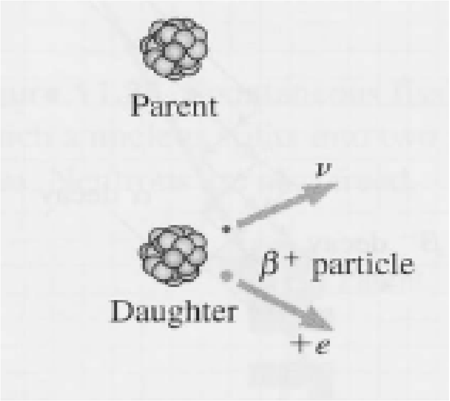
Example $\quad {}^{12}_{7}N \rightarrow$

$$Q =$$

β^+ decay

- Emits a positron and a neutrino
- Changes a proton inside the nucleus into a neutron.

$${}^{A}_{Z}X(parent) \rightarrow {}_{Z-1}^{\;\;\,A}Y(daughter) + {}^{\;\,0}_{+1}\beta^+ + \nu$$



- ○ $Z_{daughter} = Z_{parent} - 1$
- ○ $N_{daughter} = N_{parent} + 1$
- ○ $A_{daughter} = A_{parent}$

Released kinetic energy

$$Q = (m_{parent} - m_{daughter} - 2m_{electron})\,c^2$$

Example $\quad {}^{12}_{7}N \rightarrow {}^{12}_{6}C + {}^{\;\,0}_{+1}\beta^+ + \nu$

$Q =$

${}^{12}_{7}N$ = 12.018613

${}^{12}_{6}C$ =12

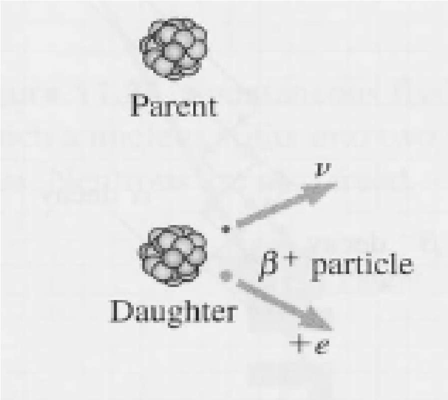
uc^2=931.5 MeV

β^+ decay

- Emits a positron and a neutrino
- Changes a proton inside the nucleus into a neutron.

$$^{A}_{Z}X(parent) \rightarrow {}_{Z-1}^{\;\;A}Y(daughter) + {}^{0}_{+1}\beta^{+} + \nu$$

- ○ $Z_{daughter} = Z_{parent} - 1$
- ○ $N_{daughter} = N_{parent} + 1$
- ○ $A_{daughter} = A_{parent}$



Released kinetic energy

$$Q = (m_{parent} - m_{daughter} - 2m_{electron})\,c^2$$

Example

$$^{12}_{7}N \rightarrow {}^{12}_{6}C + {}^{0}_{+1}\beta^{+} + \nu$$

$$Q = (12.018613 - 12 - 2 \text{ x } 0.0005486)uc^2$$
$$= 16.3\ MeV$$

$^{12}_{7}N$ = 12.018613

$^{12}_{6}C$ =12

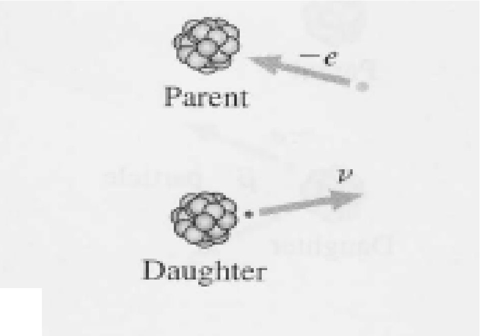
uc^2=931.5 MeV

Electron capture

- A nucleus with too many protons can change a proton into a neutron by capturing an electron.
- Electron capture is easier than decay when an electron is already exists for a nucleus to capture.

$$ {}^{A}_{Z}X(parent) + {}^{0}_{-1}\beta^{-} \rightarrow {}_{Z-1}{}^{A}Y(daughter) + \nu $$

- ○ $Z_{daughter} = Z_{parent} - 1$
- ○ $N_{daughter} = N_{parent} + 1$
- ○ $A_{daughter} = A_{parent}$



Released kinetic energy

$$ Q = (m_{parent} - m_{daughter})\, c^{2} $$

$$ {}^{11}_{6}C + {}^{0}_{-1}\beta^{-} \rightarrow $$

$$ Q = $$

Electron capture

- A nucleus with too many protons can change a proton into a neutron by capturing an electron.
- Electron capture is easier than decay since an electron is already exists for a nucleus to capture.

$$^{A}_{Z}X(parent) + {}^{0}_{-1}\beta^{-} \rightarrow {}_{Z-1}^{A}Y(daughter) + \nu$$

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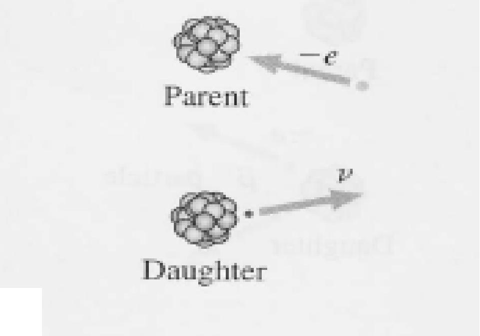

Released kinetic energy

$$Q = (m_{parent} - m_{daughter})\, c^2$$

$^{11}_{6}C$ =11.01143 u

$^{11}_{5}B$ =11.009305 u

$$^{11}_{6}C + {}^{0}_{-1}\beta^{-} \rightarrow {}^{11}_{5}B + \nu$$

$Q =$

Electron capture

- A nucleus with too many protons can change a proton into a neutron by capturing an electron.
- Electron capture is easier than decay since an electron is already exists for a nucleus to capture.

$$ {}^{A}_{Z}X(parent) + {}^{0}_{-1}\beta^- \rightarrow {}_{Z-1}^{\;\;A}Y(daughter) + \nu $$

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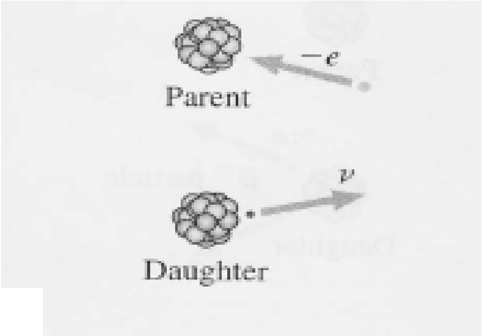
- $A_{daughter} = A_{parent}$



Released kinetic energy

$$ Q = (m_{parent} - m_{daughter})\, c^2 $$

${}^{11}_{6}C$ =11.01143 u
${}^{11}_{5}B$ =11.009305 u

$$ {}^{11}_{6}C + {}^{0}_{-1}\beta^- \rightarrow {}^{11}_{5}B + \nu $$

$$ Q = (11.01143 - 11.009305)uc^2 = 1.97\ MeV $$

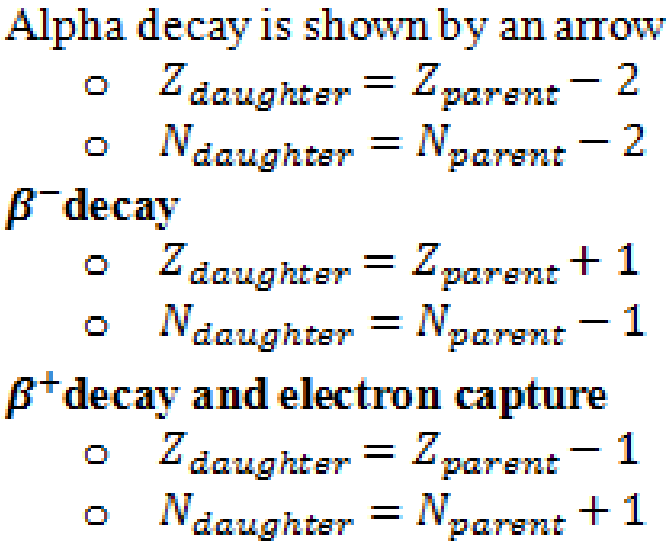
Gamma decay

- A nucleus in an excited state emits photons (gamma particles, to go into a lower energy state.
- Gamma decay does not alter N or Z.
- Gamma energies are characteristic of a given isotope, and are thus used to identify the isotope.

Figure 11.24 Gamma decay.

Radioactive decay series

- An unstable nucleus can be involved in a series of decays until it finds a stable state.
- We can plot this process on a graph that represents N and Z numbers of each nucleus in the series.



Alpha decay is shown by an arrow

- $Z_{daughter} = Z_{parent} - 2$
- $N_{daughter} = N_{parent} - 2$

β^-decay

- $Z_{daughter} = Z_{parent} + 1$
- $N_{daughter} = N_{parent} - 1$

β^+decay and electron capture

- $Z_{daughter} = Z_{parent} - 1$
- $N_{daughter} = N_{parent} + 1$

Radioactive decay series

- An unstable nucleus can
  decays until it finds a stab
- We can plot this process
  N and Z numbers of each

Alpha decay is shown by an arrow

- $Z_{daughter} = Z_{parent} - 2$
- $N_{daughter} = N_{parent} - 2$

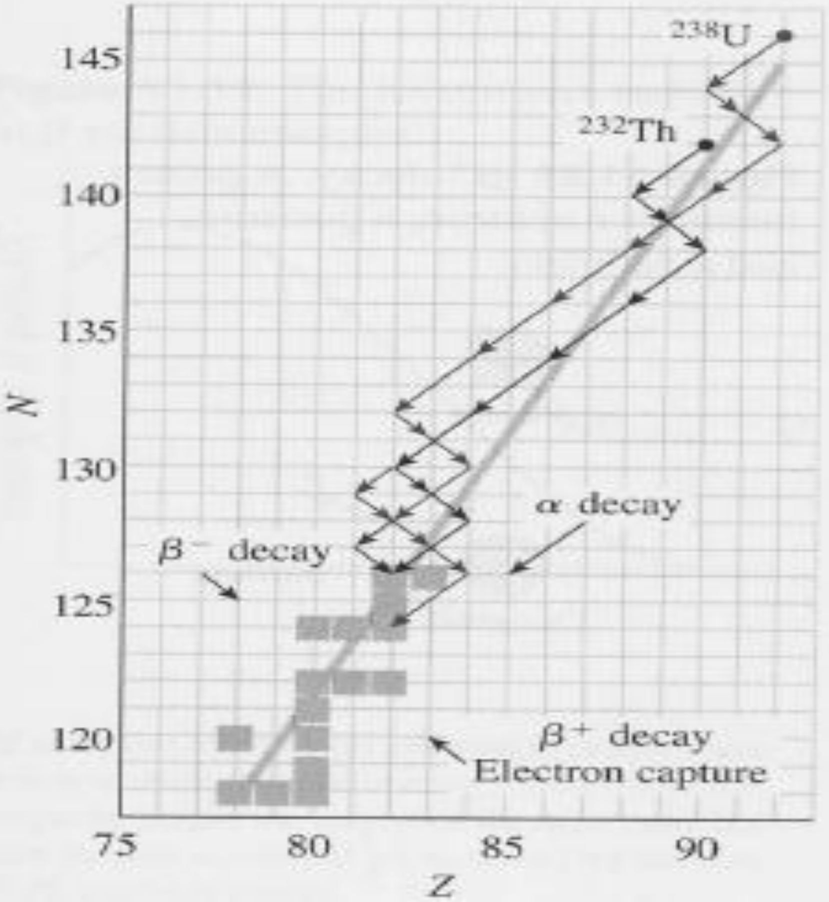
β^-decay

- $Z_{daughter} = Z_{parent} + 1$
- $N_{daughter} = N_{parent} - 1$

β^+decay and electron capture

- $Z_{daughter} = Z_{parent} - 1$
- $N_{daughter} = N_{parent} + 1$

Figure 11.23 The "directions" of α and β decays, and the decay series of uranium-238 and thorium-232.



Radioactive decay series

- An unstable nucleus can b
  decays until it finds a stab
- We can plot this process
  N and Z numbers of each

Alpha decay is shown by an arrow
  - ○ $Z_{daughter} = Z_{parent} - 2$
  - ○ $N_{daughter} = N_{parent} - 2$

β^{-}decay
  - ○ $Z_{daughter} = Z_{parent} + 1$
  - ○ $N_{daughter} = N_{parent} - 1$

β^{+}decay and electron capture
  - ○ $Z_{daughter} = Z_{parent} - 1$
  - ○ $N_{daughter} = N_{parent} + 1$

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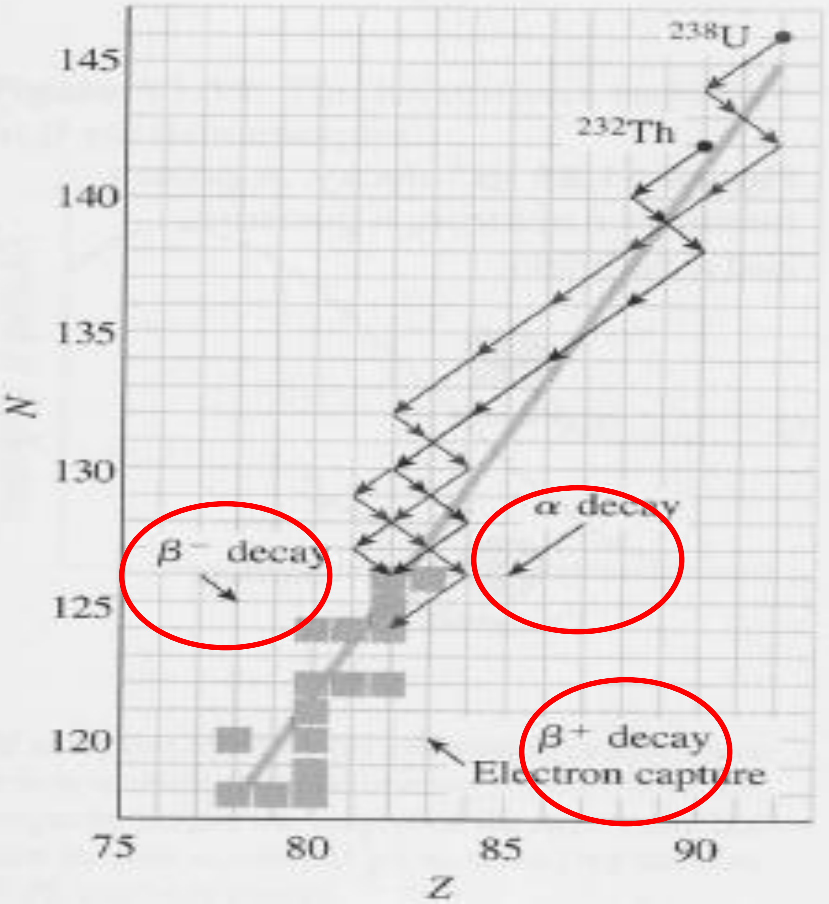

Radioactive decay series

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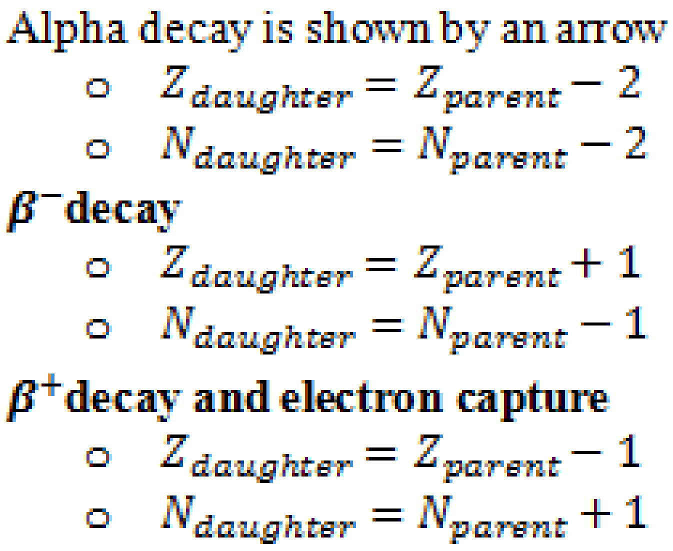


Alpha decay is shown by an arrow

- $Z_{daughter} = Z_{parent} - 2$
- $N_{daughter} = N_{parent} - 2$

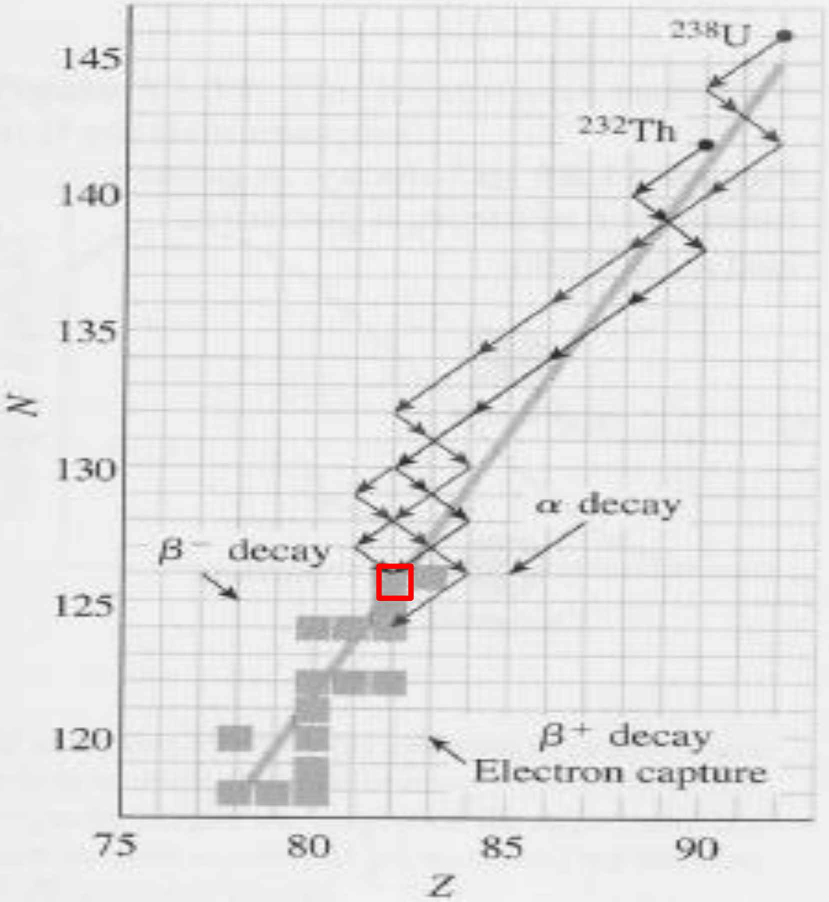
β^- decay

- $Z_{daughter} = Z_{parent} + 1$
- $N_{daughter} = N_{parent} - 1$

β^+ decay and electron capture

- $Z_{daughter} = Z_{parent} - 1$
- $N_{daughter} = N_{parent} + 1$

Figure 11.23 The "directions" of α and β decays, and the decay series of uranium-238 and thorium-232.



Pb=82 protons +126 neutrons

Radioactive decay law

- For all decays, the rate of decay over time will be proportional to the sample size:

$$\frac{dN}{dt} \propto N \qquad \frac{dN}{dt} = -\lambda N$$ where N=Number of nuclei; λ=decay constant

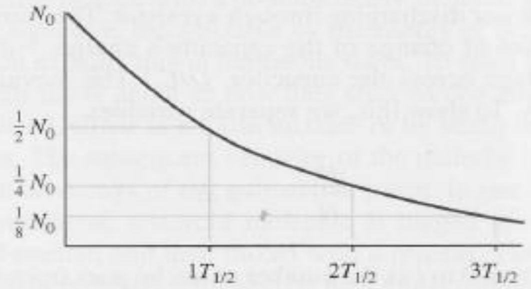


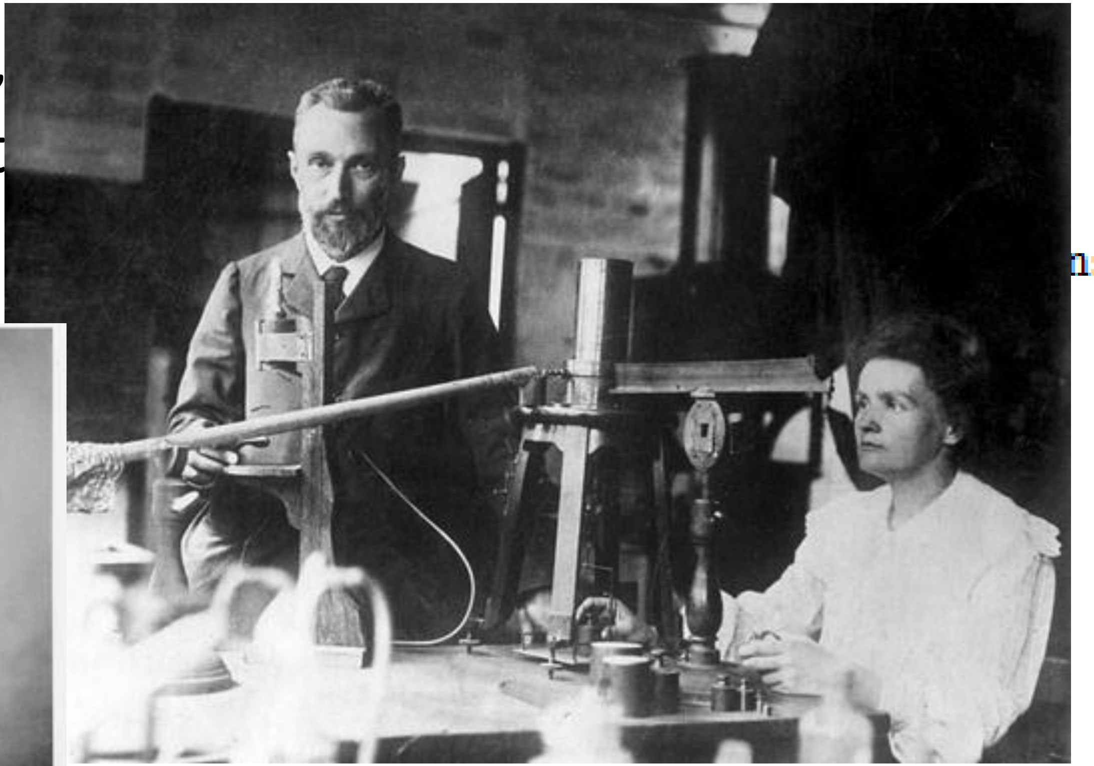
Figure 11.26 Exponential decay.

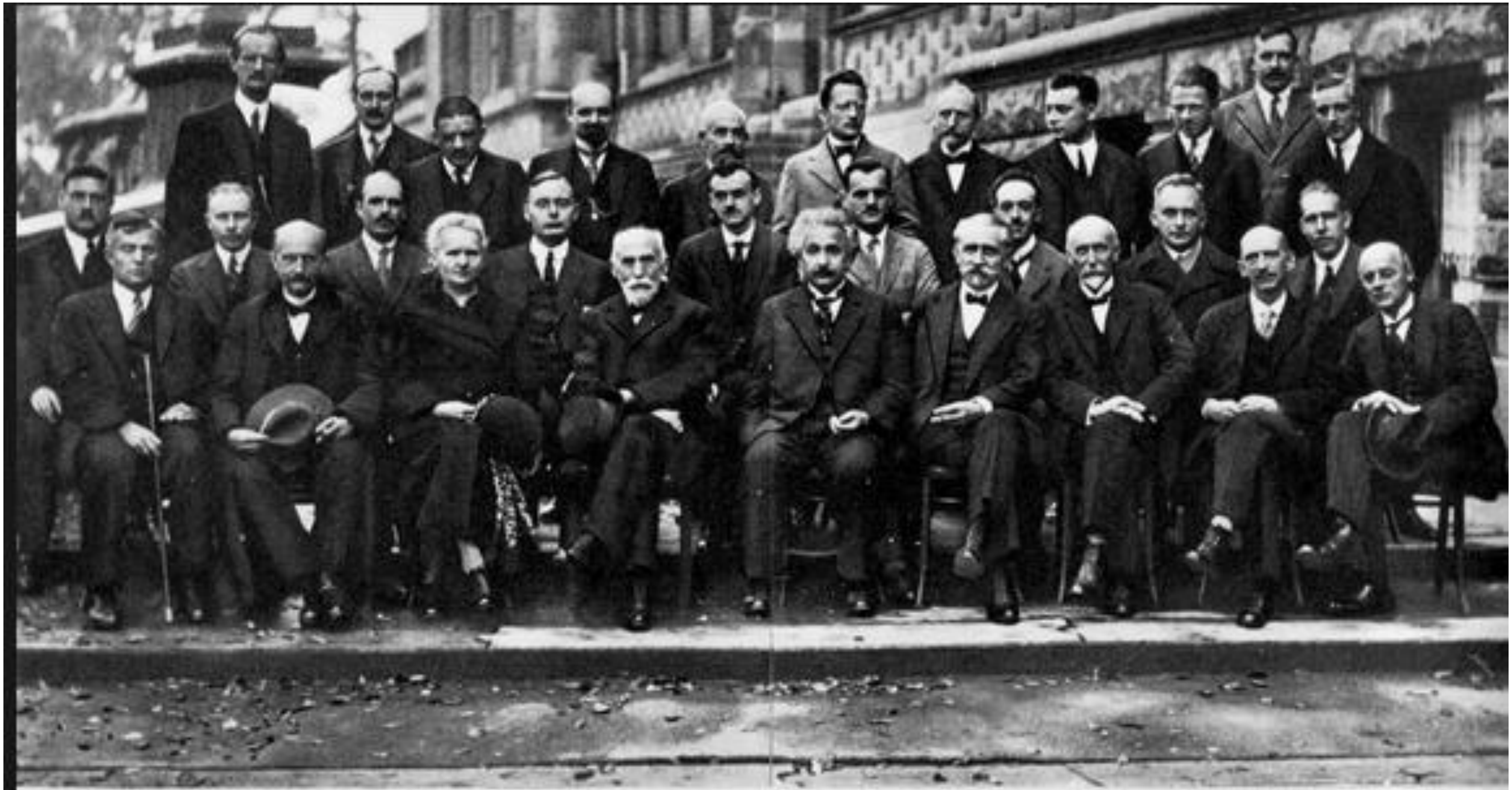
Radioactive decay law

- For all decays,
  proportional t

$$\frac{dN}{dt} \propto N$$

nstant





Photographie Benjamin Couprie

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O.W. RICHARDSON

Radioactive decay law

- For all decays, the rate of decay over time will be proportional to the sample size:

$$\frac{dN}{dt} \propto N \qquad \frac{dN}{dt} = -\lambda N$$ where N=Number of nuclei; λ=decay constant

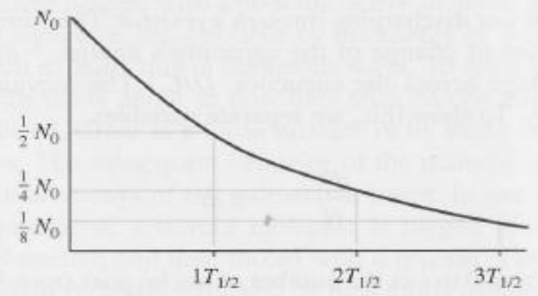
$$\frac{dN}{N} = -\lambda\, dt$$

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt$$

$$ln \frac{N}{N_0} = -\lambda t$$

$$N = N_0 e^{-\lambda t}$$

Figure 11.26 Exponential decay.



Decay rate R = λN (decays per second)

Radioactive decay law

- For all decays, the rate of decay over time will be proportional to the sample size:

$$\frac{dN}{dt} \propto N \qquad \frac{dN}{dt} = -\lambda N$$

where N=Number of nuclei; λ=decay constant

$$\frac{dN}{N} = -\lambda\, dt$$

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt$$

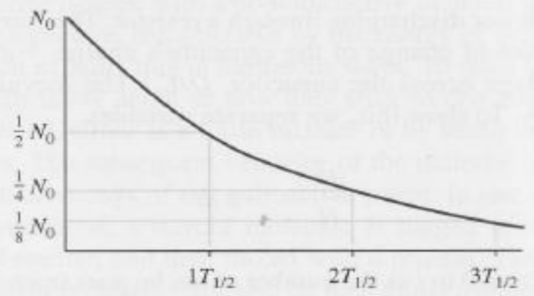
$$ln\frac{N}{N_0} = -\lambda t$$

$$N = N_0 e^{-\lambda t}$$

$$\frac{1}{2}N_0 = N_0 e^{-\lambda T_{1/2}}$$

$$\lambda = \frac{ln2}{T_{1/2}}$$

Figure 11.26 Exponential decay.



Decay rate R = λN (decays per second)

Half-life ($T_{1/2}$)

Half-life

$$\lambda = \frac{ln2}{T_{1/2}} \qquad N = N_0 e^{-\lambda t}$$

Decay rate R = λN (decays per second)

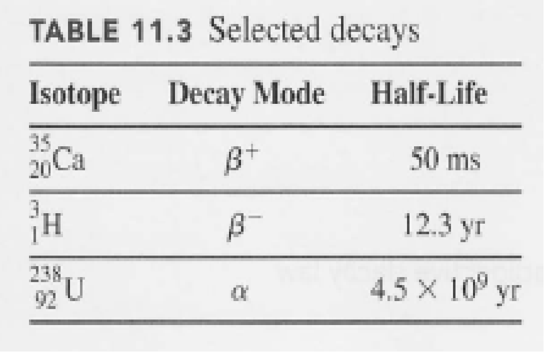


TABLE 11.3 Selected decays

Isotope	Decay Mode	Half-Life
$^{35}_{20}\mathrm{Ca}$	β^+	50 ms
$^{3}_{1}\mathrm{H}$	β^-	12.3 yr
$^{238}_{92}\mathrm{U}$	α	4.5×10^9 yr

A vessel holds 2 μg of tritium.

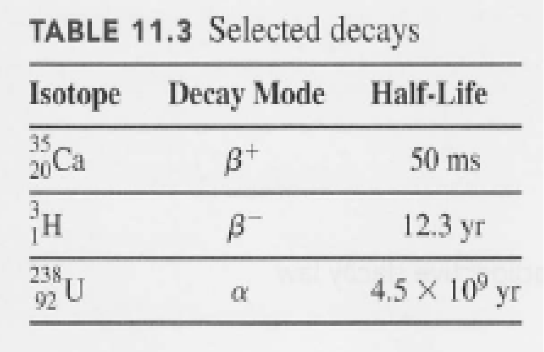
(a) Initial decay rate?

Tritium's atomic mass = 3.02 u and 1 u=1.66 x $10^{-27}\,kg$

N= $\dfrac{sample\ mass}{atomic\ mass\ of\ Tritium}$ $\quad \lambda = \dfrac{ln2}{T_{1/2}}$

$T_{1/2} = 12.3\ yr = 12.3 \times 3.16 \times 10^7 sec$

Half-life



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$$R = \lambda N = \frac{\ln 2}{T_{1/2}} \cdot \frac{sample\,mass}{atomic\,mass\,of\,Tritium} \qquad R = 7.1 \text{ x } 10^8\ decays/sec$$

(a) Time elapse before the decay rate falls to 1% of its initial value?

$$N = N_0 e^{-\lambda t}$$

$$\frac{1}{100} N_0 = N_0 e^{-\lambda t}$$

Half-life

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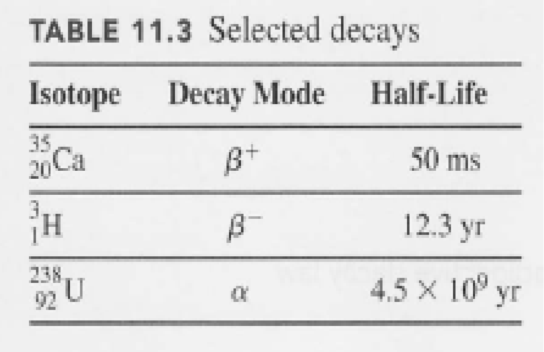

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$$N = N_0 e^{-\lambda t}$$

$$\frac{1}{100} N_0 = N_0 e^{-\lambda t}$$

$$t = \frac{-\ln\left(\frac{1}{100}\right)}{\lambda} = 2.6\ x\ 10^9 \text{ sec} = 81.7\ years$$

Carbon 14 Dating

- Carbon-14’s decay has a half-life of 5730 years.
- Carbon-14 dating only works for formerly living organisms.
- Carbon-14’s amount is constantly maintained for living organisms since living organisms exchange Carbon with the environment. Ratio of naturally produced C14/C12=1.3 x 10^{-12}
- When, a living organism dies, it stops the exchange process, thus C-14 in the dead organism decays exponentially.

Fossil age

Sample: 6 g of carbon and a decay rate (R) of 30 /min

- Since C14/C12 = 1.3×10^{-12} when the sample was alive
- Decay constant (λ)
- Current decay rate (R)=30 /min=30/60 seconds= .5 /sec
- Elapsed time $N = N_0 e^{-\lambda t}$

1 year = 3.16×10^{7} seconds

Fossil age

Sample: 6 g of carbon and a decay rate (R) of 30 /min

- Since C14/C12 = 1.3 x 10^{-12} when the sample was alive

$$N_0(C_{14}) = (1.3x\ 10^{-12}) \cdot \left(\frac{6\ g}{12\ g}\right) \cdot (6.02 \text{ x } 10^{23}) = 3.9 \text{ x } 10^{11}$$

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- Current decay rate (R)=30 /min=30/60 seconds= .5 /sec

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- Decay constant (λ)

$$\lambda = \frac{\ln 2}{T_{1/2}} =$$

- Current decay rate (R)=30 /min=30/60 seconds= .5 /sec

$$R = N \cdot \lambda =$$

- Elapsed time $N = N_0 e^{-\lambda t}$

1 year = 3.16 x 10^7 seconds

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- Decay constant (λ)

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{\ln 2}{5730\ years\ \cdot 3.16\,x10^{7} sec/year} = 3.83 \text{ x } 10^{-12} \quad /sec$$

- Current decay rate (R)=30 /min=30/60 seconds= .5 /sec

$$R = N \cdot\ \lambda = N \cdot 3.83 \text{ x } 10^{-12} \quad /sec = 0.5\ /sec$$

$$N = 1.31 \text{ x } 10^{11}$$

- Elapsed time $N = N_0 e^{-\lambda t}$

1 year = 3.16 x 10^7 seconds

$$t = -\frac{1}{\lambda}\ln\frac{N}{N_0} = -\frac{1}{3.83 \text{ x } 10^{-12} \quad /sec}\ln\frac{1.31 \text{ x } 10^{11}}{3.9 \text{ x } 10^{11}} = 2.86 \text{ x } 10^{11}\ sec \sim 9000\ years$$

Nuclear Reactions

- Chemical reactions

$$2H_2 + O_2 \rightarrow 2H_2O$$

- Nuclear reactions

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$

Nuclear Reactions

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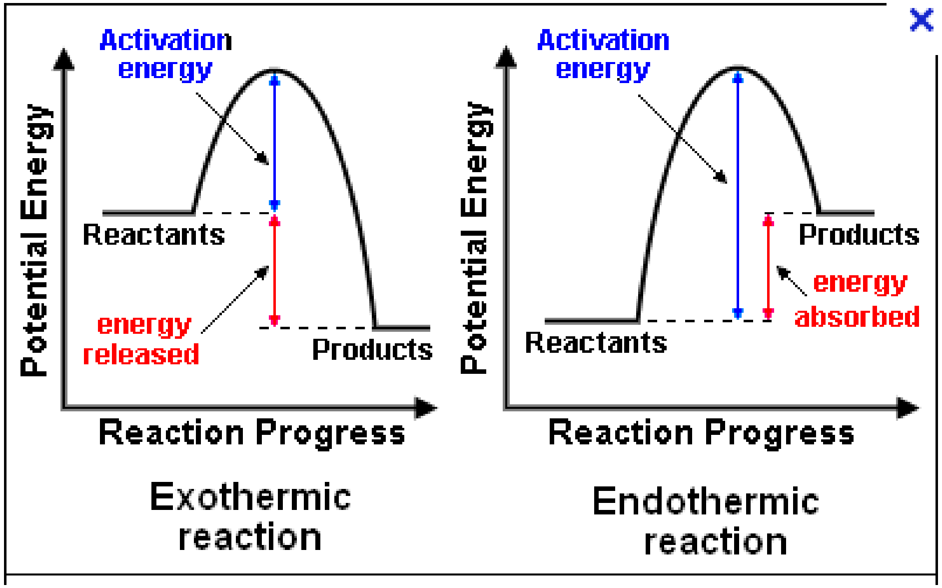
- 

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- Nuclear reactions

Exothermic $$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$

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Released kinetic energy (Q)

Nuclear Reactions

- Chemical reactions

$$2H_2 + O_2 \rightarrow 2H_2O$$

- Nuclear reactions

Exothermic $${}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He$$

Q $$= (10.012937 + 1.008665 - 7.016003 - 4.002603)\ uc^2 = 2.79\ MeV$$

Endothermic $${}^{7}_{3}Li + {}^{1}_{1}H \rightarrow {}^{7}_{4}Be + {}^{1}_{0}n$$

Q $$= (7.016003 + 1.007825 - 7.016928 - 1.008665)uc^2 = -1.64\ MeV$$

Binding energy/nucleon vs. A

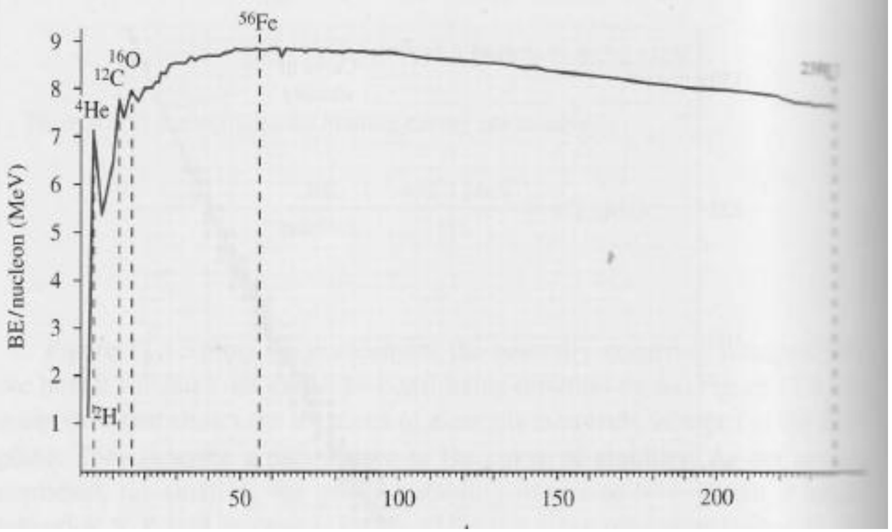

Figure 11.14 Binding energy per nucleon versus *A*.

Binding energy/nucleon vs. A

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