# RADIOACTIVITY as RADIATION SOURCES

Radioactive nuclei are unstable and decay to other species with the emission of particles ($e^-$, $e^+$, $\alpha$ ) often followed by the emission of a photon ($\gamma$-ray).

- Heavy nuclei (e.g., $^{235}U$) are often naturally radioactive
- Light nuclei: can be prepared by neutron bombardment, proton collision, etc

As noted in the first lecture radiation is of particular interest in this course because of its use in many realms of experimental physics, industry and medicine. This table lists some properties of nuclear and atomic particles and radiations of use in analysis and instrumentation.

| Name | Symbol | Charge (q) | Rest Mass ($M_p$) | Energy | Source | Applications |
|---|---|---|---|---|---|---|
| Proton | p | +1 | 1 | 0-4 MeV | Accelerators | PIXE |
| Neutron | n | nonc | 1.006 | Slow <10 kcV<br>Fast ➜ MeV | Rcactor<br>Reactor<br>Reactions | Activation<br>Analysis<br>Crystallography<br>Power generation |
| Electron | $e^-$ | -1 | 1/1840 | 0 - 300 keV<br>➜ 50 MeV | Heated wires E<br>Fields<br>Accelerators | Electronics<br>Microscopy<br>X-ray generation |
| $\beta^-$-particle | $\beta^-(e^-)$ | -1 | 1/1840 | 0.01-5 MeV | Nuclear decay | Thickness monitor |
| $\beta^+$-particle | $\beta^+(e^-)$ | +1 | 1/1840 | 0.01-5 MeV | Nuclear decay | Positron imaging<br>Interacts with $e^-$ to create two $\gamma$-rays of energy 512 keV |
| $\alpha$ - particle | $\alpha$ ($^4_2He$) | +2 | 4 | 4.5 - 8 MeV | Nuclear decay | Nuclear reactions |
| Deuteron | d ($^2H$) | +1 | 2 | 0 - 10 MeV | Accelerators | Nuclear reactions |
| $\gamma$ - ray | $\gamma$ | None | None | 20 kcV - MeV | Nuclear decay | Thickness monitor |
| X - ray | X | None | None | 1 - 10 s<br>keV MeV | Electron impact<br>Excited atoms | Crystallography<br>Radiation damage |
| Fission Fragments | nucleus name | Several | >100 | 50-100 MeV | Nuclear fission | |
| Heavy ions | ion | 1 | ion | 0-2 MV | Accelerators | Ion implantation |
| Neutrino<br>Antineutrino | ν<br>ν | None | None | 0.01 - 5 MeV | $\beta$ decay | Nuclear decay |

- The nuclei of isotopes of elements can be designated

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

with: $A$ ≡ the atomic mass = # nucleons = #p + # n

$Z$ ≡ the atomic number = # protons = # e- in neutral atom

Note that it is Z which designates an element (why?) whereas A designates different isotopes of the same element.

- When an nucleus undergoes radioactive transition (also commonly called disintegration, decay, or transformation) it goes to a more stable state.

$$^{A}_{Z}X \longrightarrow {}^{A-B}_{Z-\Delta}Y + {}^{B}_{\Delta}W$$

masses

$$m(X) > m(Y) + m(W)$$

- The atomic masses for a given isotope:

$$\text{Atomic mass} = \text{Nuclear mass} + Z(m_e) - \text{atomic binding energy (BE)}$$

This table lists some radiation sources used in laboratory work, industry and medicine to provide photon and particle radiations.

| Radiation | Source | Type of Decay | Half-life | Particle Energy Emission MeV | Particle Prob. % | Photon Energy Emission MeV | Photon Prob. % | Purpose |
|---|---|---|---|---|---|---|---|---|
| alpha α | $^{241}_{95}Am$ | α | 432.7y | 5.443<br>5.486 | 13<br>85 | 0.060<br>Np L X-ray | 36<br>38 | Range expt. |
| | $^{244}_{96}Cm$ | α | 18.11y | 5.763 | 24 | Pu L X-ray | 9 | |
| α + fission | $^{252}_{98}Cf$ | α<br>Fission | 2.645y | 6.076<br>6.118<br>20γ/f<br>4n/f | 15<br>82 | 80 < 1 MeV<br>$E_n = 2.14$ MeV | | |
| beta⁻ $\beta^-$ | $^{90}_{38}Sr$ | $\beta^-$ | 28.5y | 0.546 | 100 | | | Attenuation |
| | $^{90}_{39}Y$ | $\beta^-$ | | 2.283 | 100 | | | |
| | $^{137}_{55}Cs$ | $\beta^-$ | 30.2y | 0.514<br>1.176 | 94<br>6 | 0.662 | 85 | |
| beta⁺ $\beta^+$ | $^{22}_{11}Na$ | $\beta^+$, EC | 2.603y | 0.545 | 90 | 0.511<br>1.275 | Annih γ<br>90 | |
| gamma γ# | $^{60}Co$ | $\beta^-$ | 5.271y | 0.316 | 100 | 1.173<br>1.333 | 100<br>100 | Attenuation |
| γ# | $^{137}_{55}Cs$ | $\beta^-$ | 30.2y | 0.514<br>1.176 | 94<br>6 | 0.662 | 85 | |
| X-ray | $^{55}_{26}Fe$ | EC | 2.73y | | | Mn K X-ray<br>0.00589<br>0.00649 | <br>25<br>3.4 | Mossbauer |
| | $^{125}_{53}I$ | EC | 60d | | | Te K X-ray<br>0.00274 | <br>100 | X-ray Fluorescence |

These sources are convenient for laboratory experimentation. The γ-sources labeled # have the particle which is emitted removed by the encapsulation. Ref: Phys. Rev. D 54,154 (1996)

- Atomic masses (con't)
  - The atomic mass unit (amu) is based on mass of Carbon 12
  - Mass of $^{12}C$ = 12.0000 amu
  - Mass energy equivalent for 1 amu $\equiv m_{amu}c^2$ =931.481 MeV
  - Similarly the rest mass energies of the proton, neutron and electron are

$$m_pc^2 = 938.272 \text{ MeV},$$

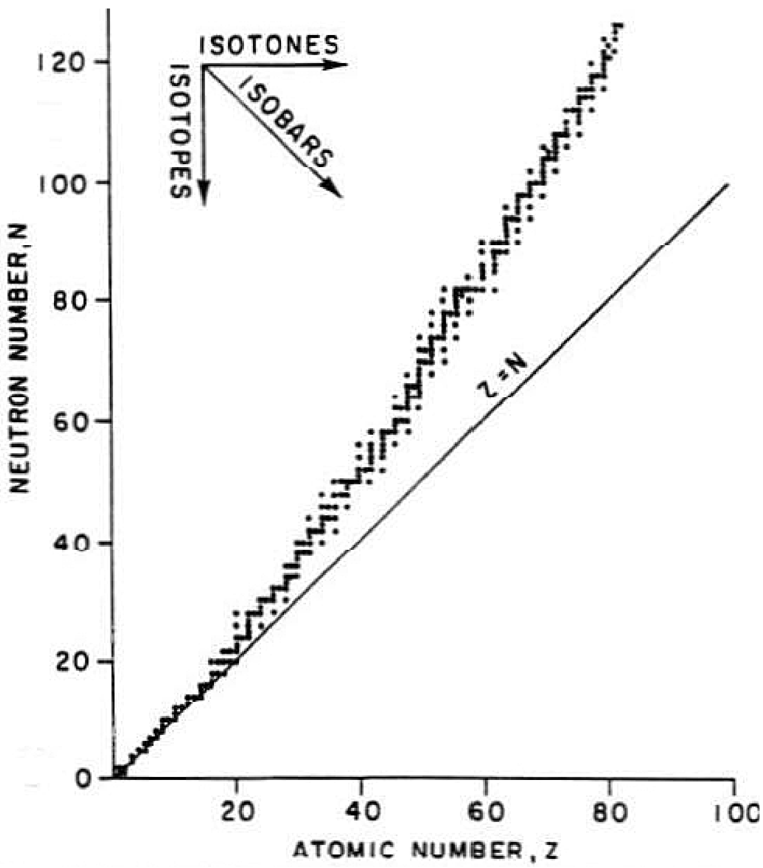
$$m_nc^2 = 939.565 \text{ MeV},$$

$$m_ec^2 = 0.511 \text{ MeV}$$

  - In loose jargon we often say the mass of an electron is 0.511 MeV, but this is understood to include a factor of $c^2$ and to be talking of the rest mass energy.

Stable Nuclei: The atomic number Z versus neutron number N for the stable nuclides. They are clustered around an imaginary line of stability. N ≈ Z for light elements; N ≈ 1.5 Z for heavy elements.

| | |
|---|---|
| ISOTOPES: | same Z, different N |
| ISOBARS: | same mass number |
| ISOTONES: | same N, different Z |



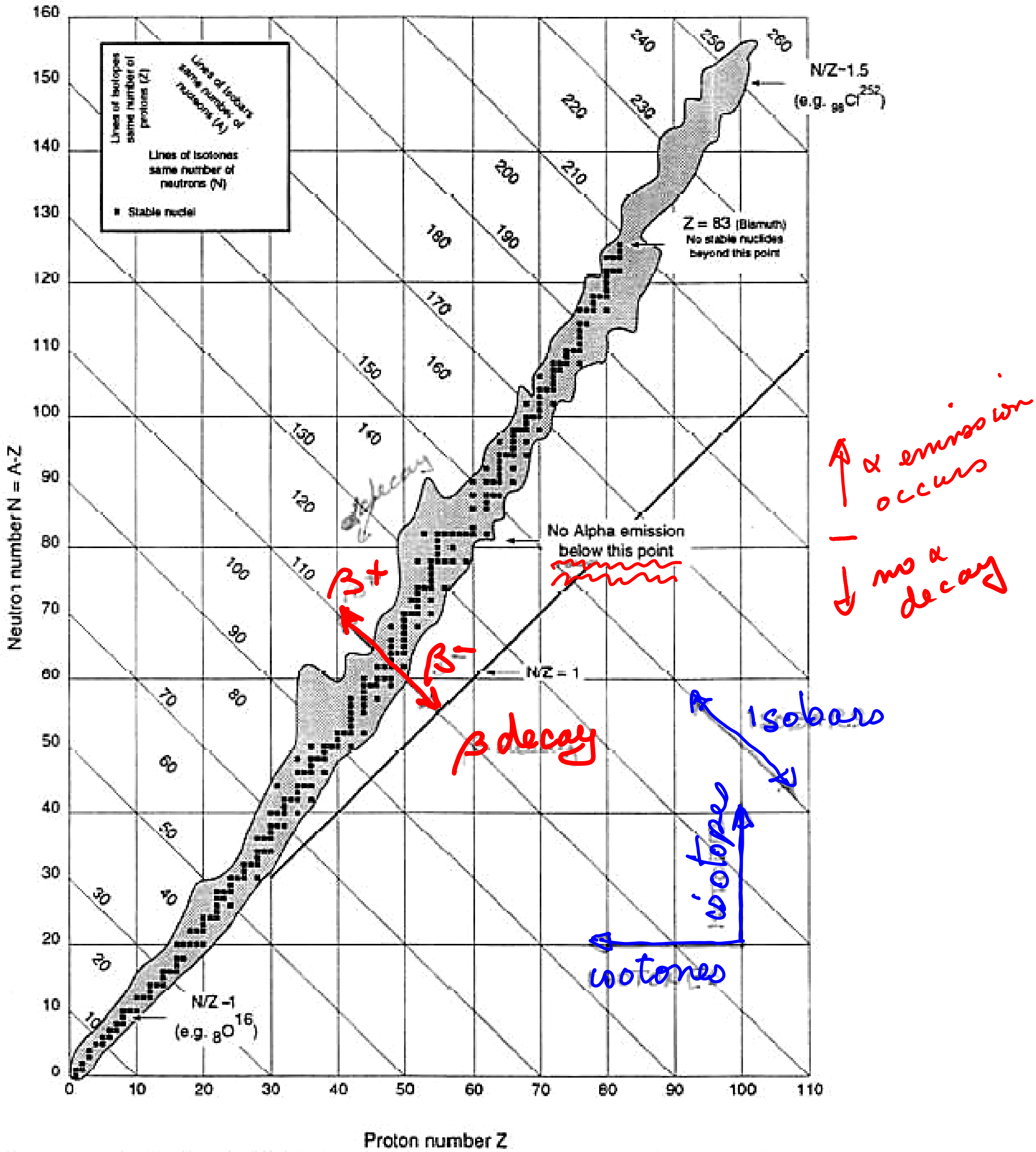
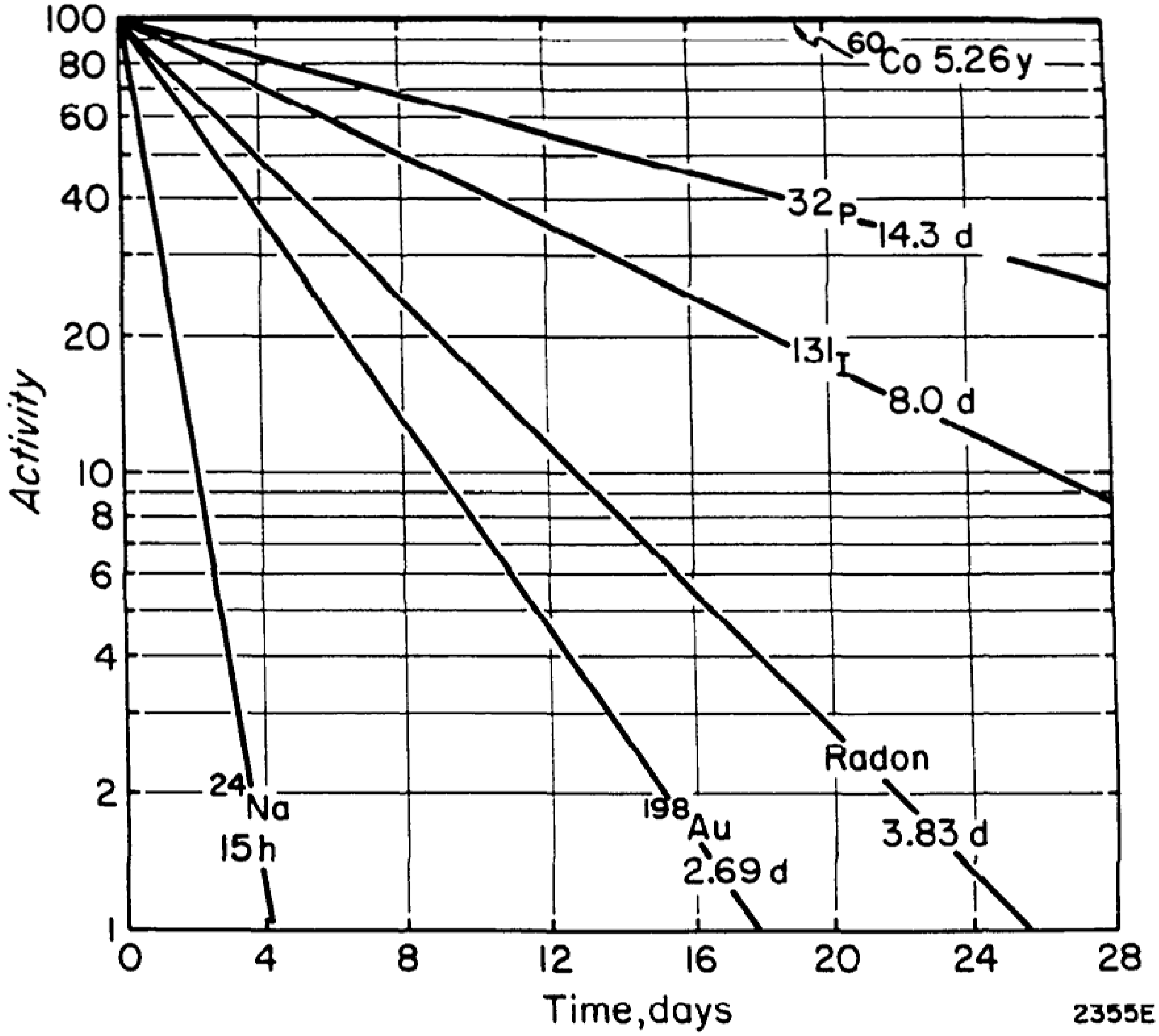



**Figure** Nuclide line of stability. The shaded area represents the range of known nuclides. The stable nuclides are indicated by small black squares, whereas all other locations in the *shaded area* represent radioactive (i.e., unstable) nuclides. Note that all nuclides with $Z > 83$ are radioactive.

- *The list of known nuclides contains ~275 stable nuclides and over 1500 radiactive nuclides.*

# Activity and Radioactive Decay

- The ejection of a nuclear particle from a particular nucleus during the decay of a mass of radioisotope is determined by random chance. There is no way to determine when a specific nucleus will disintegrate.
- However for many nuclei the decay is well defined




- From the plot it is clear that a certain fixed fraction of will decay with time.

- That is, the decay rate *dN/dt* is proportional to the number of nuclei *N*:

$$\frac{dN}{dt} = -\lambda N(t) = -\frac{1}{\tau} N(t)$$

$\lambda$ → decay constant

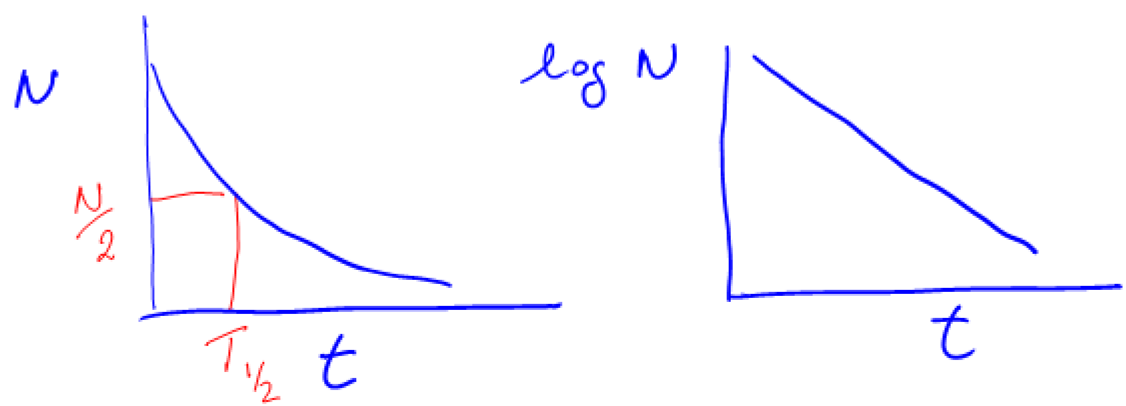
$\tau = \frac{1}{\lambda}$ → lifetime of nucleus

We all recognize this as

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

$N(t)$ → $t = t$

$N_0$ → # of nuclei at $t = 0$




- where $T_{1/2}$ is defined as the nuclei's half life: the time required for half of the nuclei in the collection to decay.
  It is easy to show that $T_{1/2} = 0.693 / \lambda$

- The strength of a radioactive source is usually defined by the ACTIVITY, A:

$$A = -\frac{\Delta N}{\Delta t} = -\frac{dN}{dt}$$

Note: that Sayer and Mansighn use the highly unusual symbol of c(t) for Activity

$$A(t) = -\frac{dN}{dt} = \lambda N = \lambda N_0 e^{-\lambda t}$$

$$\therefore \quad A(t) = A_0 e^{-\lambda t}$$

- The SI unit of activity is:
  - Disintegtrations /second, that is $s^{-1}$
  - Becquerel (Bq) *(to distinguish the context of radioactivity)*
  - after Antoine Henri Becquerel who with Marie Curie was a early investigator/discoverer of radioactivity and radium.

- The old unit is the Curie (Ci) (defined by the number of disintegrations per second from 1 gm of radium-226)
  - *1 Ci = 3.7 x $10^{11}$ Bq*

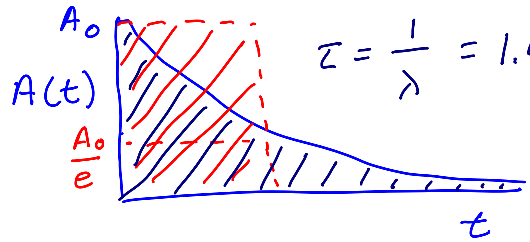
- **Specific activity, *a***
  - Defined as the activity *A* per unit mass *M* : $a \equiv A/M$
  - From the defn:

    $a = A/M = \lambda N/M = \lambda N_A/A$ where $N_A$ is Avogadro's number

  - That is the specific activity *a* of a radioisotope depends on the decay constant $\lambda$ and on the atomic mass number *A*. The units of specific activity are Bq $kg^{-1}$ or Ci $g^{-1}$ (old units).

- Mean life or Lifetime: $\tau$
  - This is the amount of time a hypothetical source with a constant activity equal to the initial activity of the actual source would have to remain active to produce the same number of disintegrations as the real decaying source

$$\tau = \frac{\int_0^\infty t\, N(t)\, dt}{\int_0^\infty N(t)\, dt}$$




$$\tau = \frac{1}{\lambda} = 1.44\, T_{1/2}$$

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## WHAT ARE THE FORMS OF RADIACTIVE TRANSITIONS:

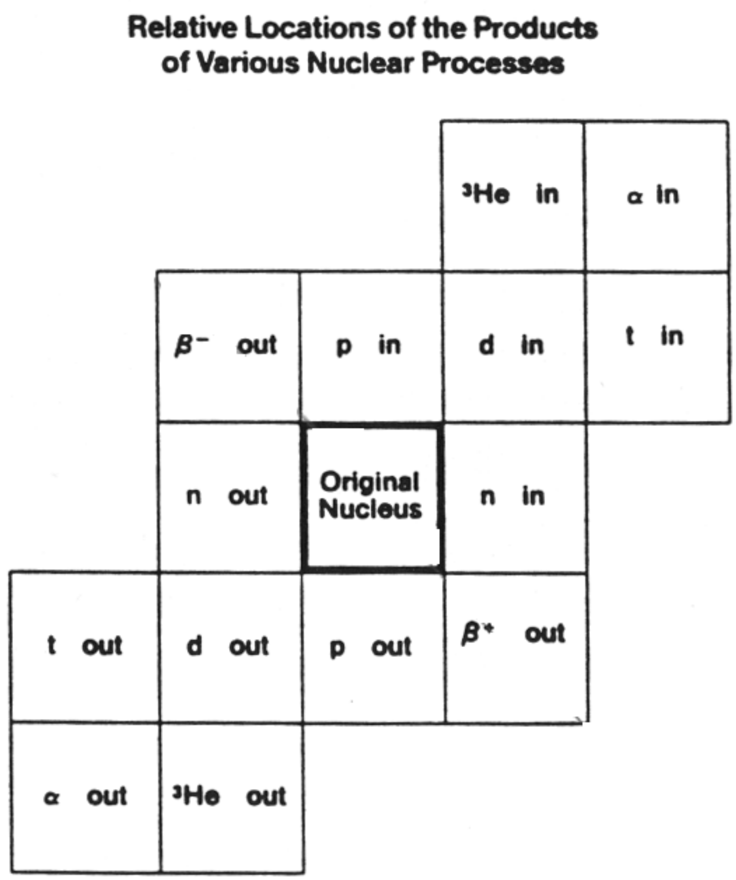
- radioactive nuclides (either natural or artificially produced) are unstable and strive to reach more stable nuclear states through various processes of decay. These can be broken down as in the following table:

| 4 Main Categories | Sub processes | Particles released |
|---|---|---|
| $\alpha$ *decay* | | $\alpha$ *particles* |
| $\beta$ *decay* | $\beta^-$ *decay* | *electrons and antineutrinos* |
| | $\beta^+$ *decay* | *positrons and neutrinos, annihilation* $\gamma$ |
| | Electron capture | |
| $\gamma$ *decay** | $\gamma$ *decay* | $\gamma$ *rays* |
| | Internal conversion | ejected orbital electrons |
| Spontaneous fission | | Neutrons, alpha particles, heavier atoms |

* also called radiative nuclear multipole transition

- Note that in each nuclear transformation the following physical properties must be conserved (among others):
  - Total energy
  - Momentum
  - Charge and atomic number
  - Atomic mass number

Relative location of the products of various nuclear processes wrt original.



## ALPHA DECAY:

- Was the first mode of radioactive decay detected in 1890's.

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + \underbrace{{}^{4}_{2}He}_{\alpha \text{ particle}}$$

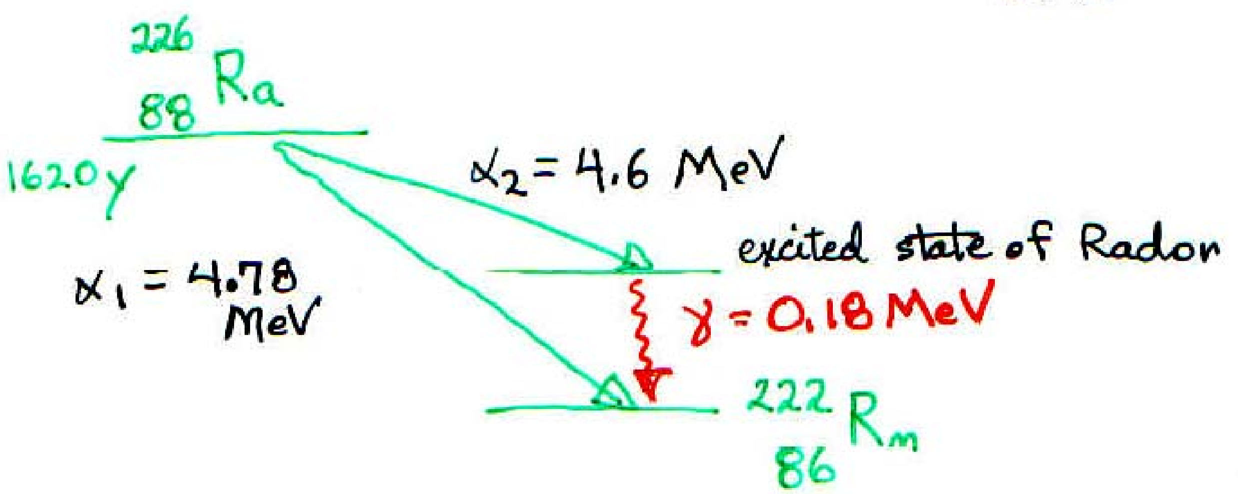
– mainly in heavy nuclei

Radium → Radon

eg

$$^{226}_{88}Ra \xrightarrow[1620\ yr]{} {}^{222}_{86}Rn + {}^{4}_{2}He$$

4.78 MeV (94.5%)
4.60 MeV + 0.18 MeV $\gamma$ (5.5%)



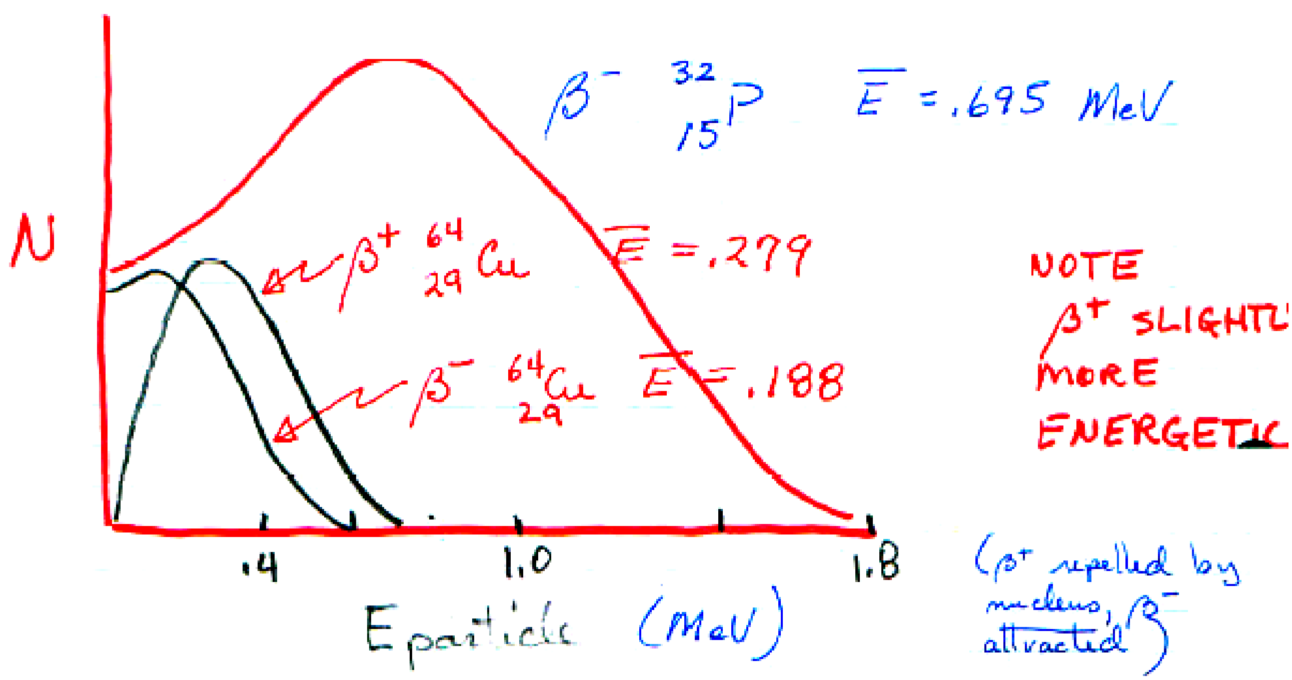

- The emitted $\alpha$ particle slows down as it moves through the medium and captures two electrons to become neutral helium. Typical $\alpha$ particle kinetic energies are between 4 and 9 MeV, corresponding in a range in air of about 1 to 10 cm, respectively, and in tissue of between $10^{-3}$ to $10^{-2}$ cm, respectively.

# BETA DISINTEGRATION (in general):

- radioactive decay scheme moderated by the Weak Interaction, one of the fundamental interactions (weak, strong, E&M and gravity).
- in this decay process the transformation is accompanied by the ejection of a positive or negative electron from the nucleus
- within the nucleus the transition is manifest as a change of nucleons

| | | |
|---|---|---|
| β- decay | $n \rightarrow p + \beta^- + \bar{\nu}$ | $\Delta Z = 1$ |
| β+ decay | $p \rightarrow n + \beta^+ + \nu$ | $\Delta Z = -1$ |

- in fact free neutrons decay by β- decay with a half life of 615 s !!
- neutrino's are required for momentum/energy conservation, as well known at Queen's these are hard to detect
- because the energy of the transformation is shared by three products, one gets a range of β particle energies is distributed. Recall $m_{neutrino}$ is zero.



## $\beta^+$ decay

emission of anti-electron

$$^{A}_{Z}X \longrightarrow \, ^{A}_{Z-1}Y + e^{+} + \nu$$

eg $\quad ^{13}_{7}N \rightarrow \, ^{13}_{6}C + \beta^{+} + \nu$

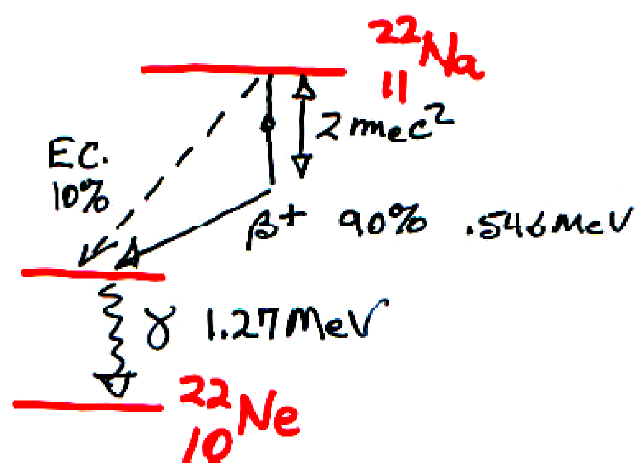
| | | |
|---|---|---|
| mass N-13 | | $13.0057388 - 7 m_e$ |
| mass C-13 | $13.0033551 - 6 m_e$ | |
| mass $\beta^+$ | $1 m_e$ | |
| mass neutrino | $\phi$ | |
| Total | $13.0033551 - 5 m_e$ | $13.0057388 - 7 m_e$ |

$\Delta M = 0.0023837$ amu $- 2 m_e$ (THRESHOLD E)

$\Delta E = 1.198$ MeV

EXAMPLE:

$$^{22}_{11}Na \rightarrow \, ^{22}_{10}Ne + e^{+} + \nu$$



# $\beta^-$-decay

emission of $\beta^-$ ($e^-$)

$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu} $$

for odd A
only 1 stable nucleus

eg $$ {}^{32}_{15}P \xrightarrow{14.3\ \text{days}} {}^{32}_{16}S + \beta^- + \nu $$

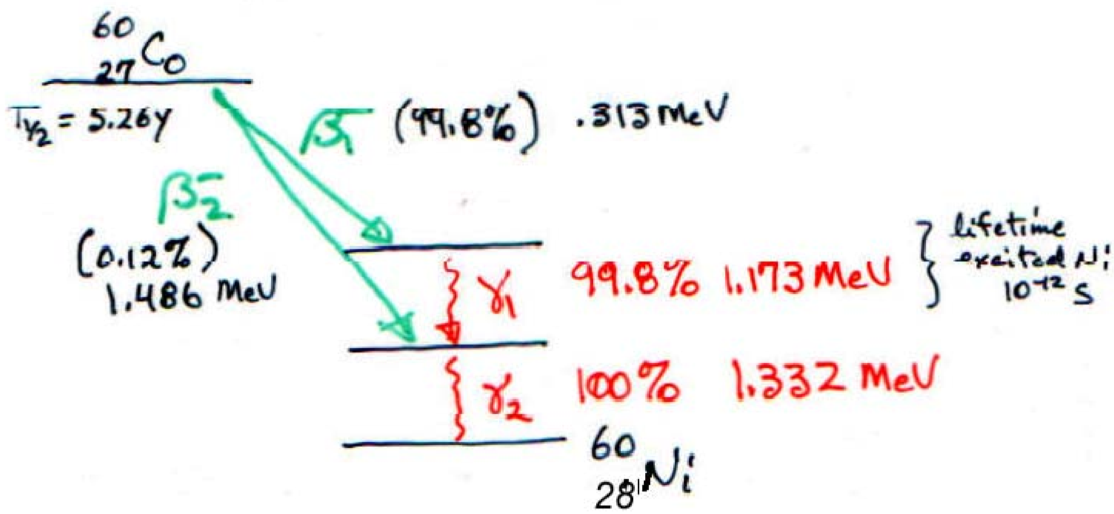
energy release

| | | |
|---|---|---|
| mass P-32 nucleus | | 31.973909 - 15 |
| mass S-32 nucleus | 31.972073 - 16 me | |
| mass $\beta^-$ | 1 me | |
| mass $\bar{\nu}$ | $\phi$ | |
| TOTAL | 31.927073 - 15 Me | |
| | | 31.973909 - 15m |

$\Delta$ = .001836 amu

$\Delta E$ = 1.71 MeV

Example: $$ {}^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + e^- + \bar{\nu} $$



## more on BETA DECAY:

- There are about 200 radionuclides used in industry and medicine, most do not occur naturally, they must be produced by **activation**.

- Beta minus emitters are activated in nuclear reactors by neutron bombardment/neutron activation

  - Adds n to the nucleus (so that reactor produced isotopes show, in general, $\beta^-$ decay)

  - e.g. $^{59}Co + n \rightarrow {}^{60}Co + \gamma$ also written as $^{59}Co(n, \gamma)^{60}Co$

    for external beam radiotherapy a typical initial $^{60}Co$ source activity is of the order of 370 TBq ($10^4$ Ci)

  - other medically interesting radioisotopes undergo $\beta^-$ decay

    e.g. Cs-137, Ir-192, Mo-99

    for sealed sources used in brachytherapy typical initial $^{192}Ir$ activity is 0.37 TBq (10 Ci).

    Molybdenum-99 is generated for use in nuclear medicine where it becomes the source for Technetium-99m ($^{99m}Tc$) used in many scans

- Beta plus emitters are proton rich radionuclides; they are usually activated by proton bombardment of a suitable target in a cyclotron. The accelerator is required to impart a sufficient kinetic energy (10-20 MeV) to enable the positive proton to penetrate the strong Coulombic repulsion from the target nucleus.

  - Adds p to the nucleus (so that cyclotron produced isotopes show, in general, $\beta^+$ decay) *(with removal of n or $\alpha$-particle)*

  - e.g. Fluorine-18 $^{18}_{8}O + p \rightarrow {}^{18}_{9}F + n$

- other medically interesting radioisotopes undergo $\beta^+$ decay

  e.g. carbon-11, nitrogen-13 and oxygen-15

- Since the proton fluence in cyclotron is much less than neutron fluence in a reactor, and since the proton capture cross-section is magnitudes of orders less than in the neutron capture cross-sections, medical $\beta^+$ sources are created with much smaller activities than $\beta^-$ made in reactors.

- $\beta^+$ sources also typically have very short half lives (order minutes to ~100 minutes)

TABLE MAIN CHARACTERISTICS OF FOUR POSITRON EMITTERS PRODUCED IN CYCLOTRONS FOR USE IN MEDICINE

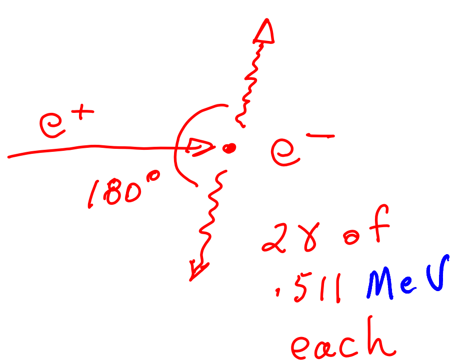
| *Radionuclide* | *Specific activity* | *Target* | *Production reaction* | *Q value* (MeV) | *Half-life* (minutes) |
|---|---|---|---|---|---|
| Carbon-11 | $8.4\times10^8$ | Nitrogen-14 | ${}^{14}_{7}N + p \rightarrow {}^{11}_{6}C + \alpha$ | -2.92 | 20.4 |
| Nitrogen-13 | $1.4\times10^9$ | Oxygen-16 | ${}^{16}_{8}O + p \rightarrow {}^{13}_{7}N + \alpha$ | -5.22 | 10 |
| Oxygen-15 | $6.0\times10^9$ | Nitrogen-15 | ${}^{15}_{7}N + p \rightarrow {}^{15}_{8}O + n$ | -3.54 | 2.1 |
| Fluorine-18 | $9.5\times10^7$ | Oxygen-18 | ${}^{18}_{8}O + p \rightarrow {}^{18}_{9}F + n$ | -2.44 | 110 |

Specific activity in Bq/kg; Q is energy required for reaction to proceed.

- At end of $\beta^+$ decay get annihilation of $\beta^+ e^-$ pair in medium

- Principle for PET imaging

  - (inject biologically labeled $\beta$+ emitter and detect the two $\gamma$'s emitted at 180° to each other to see where label has accumulated)



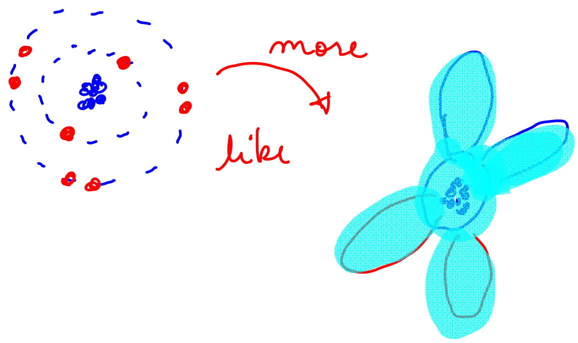
# ELECTRON CAPTURE:

$$^{A}_{Z}X + e^{-} \longrightarrow {}^{A}_{Z-1}Y + \nu$$

- There is a threshold for $\beta^{+}$ decay; need $\Delta E$ (Q) ≥ 1.022 MeV.

$$\Delta E \equiv Q = M(X) - m(Y) \geq 1.022\ \text{MeV}$$

- Electron capture provides a mechanism for unstable nucleus to decay when Q < 1.022 MeV




e- not in Kepler type Bohr orbit, rather in probabilistic cloud with a finite prob. of being somewhere in the shell volume

can be captured by nucleus

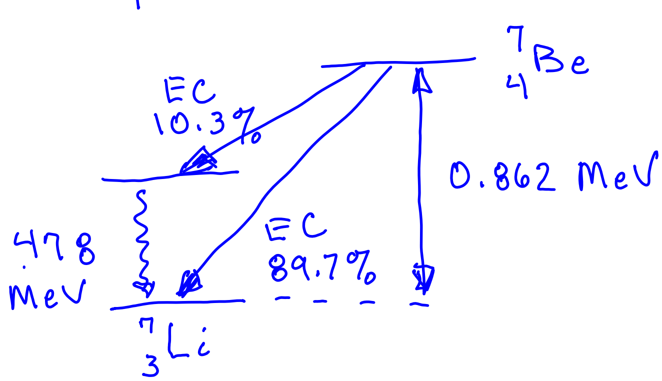
- Electron Capture $p + e^{-} \rightarrow n + \nu$
- Example 1: Previous example $^{22}_{11}Na + e^{-} \longrightarrow {}^{22}_{10}Ne + \nu$

  Branching ratio { 9.5 % EC; 90.5% $\beta^{+}$ decay

  for every 100 decays
  get 100 1.27 MeV γ's
  ~ 9-10 .87 keV x-rays
  ~ 180 .511 keV γ's

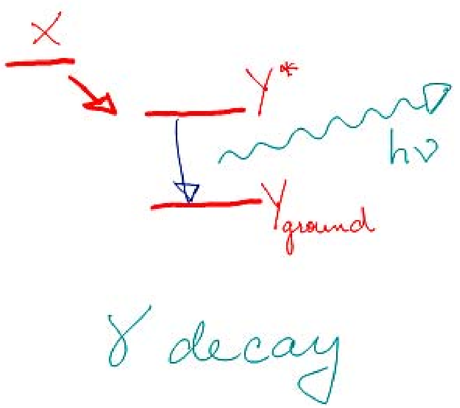
Example 2:

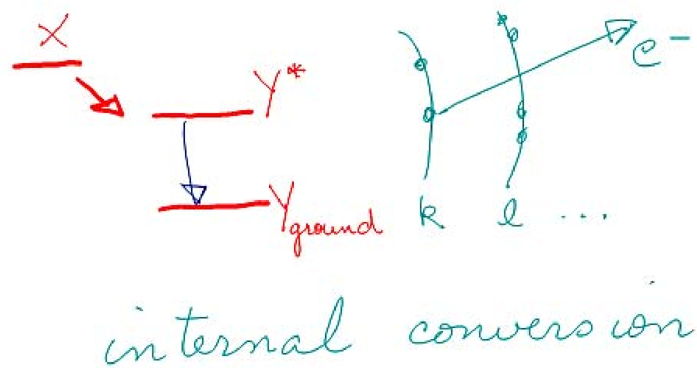
$$^{7}_{4}Be + e^{-} \longrightarrow {}^{7}_{3}Li + \nu$$



# GAMMA DECAY AND INTERNAL CONVERSION:

- We have noted that the daughter products in both the $\alpha$ decay and $\beta$ decay are often in an excited state (not their ground state energies)
- The daughters spontaneously (see below) go into the ground state either by:
  - $\gamma$ decay: with the emission of a photon (as shown a number of times above)
  - internal conversion: with the ejection of an electron from an orbital close to the nucleus (an analogue to Auger effect)



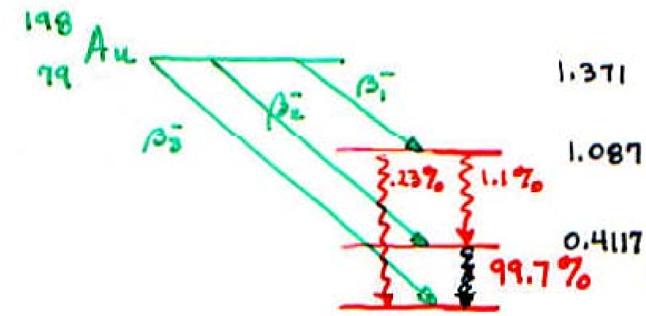

- Aside Characteristic radiation
  - Note that after electron capture or internal conversion the electron orbitals around the nucleus will have a vacancy. This can be followed by the emission of a characteristic photon as we noted in the early notes on x-ray production.
- Aside metastable states
  - If the excited daughter nuclei DO NOT decay to the ground state immediately they are said to be in metastable states and the decay to the ground state is termed isometric transitions.
  - The metastable states can be characterized with their own half life $t_{1/2}$. e.g technicium-99m ($^{99m}_{43}Tc$) has half life of 6 hrs.

# INTERNAL CONVERSION

$$^{A}_{Z}Y^{*} \longrightarrow {}^{A}_{Z}Y + e^{-}$$

- energy of an excited nucleus transferred to an atomic $e^-$
- $^{A}_{Z}Y^{*}$ often an excited daughter from previous decay

eg




→ NOT ALL γ's

γ of energy 0.412 MeV

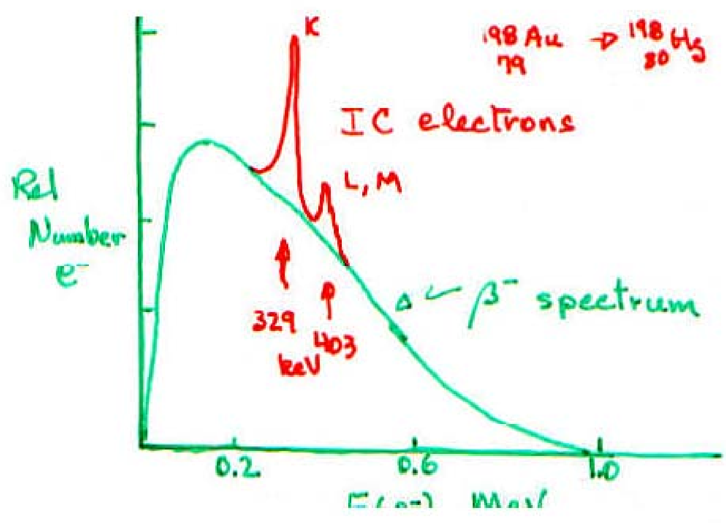
OR

~ 4.2% $e^-$ of energy keV − BE($e^-$)

K shell Hg 83 keV

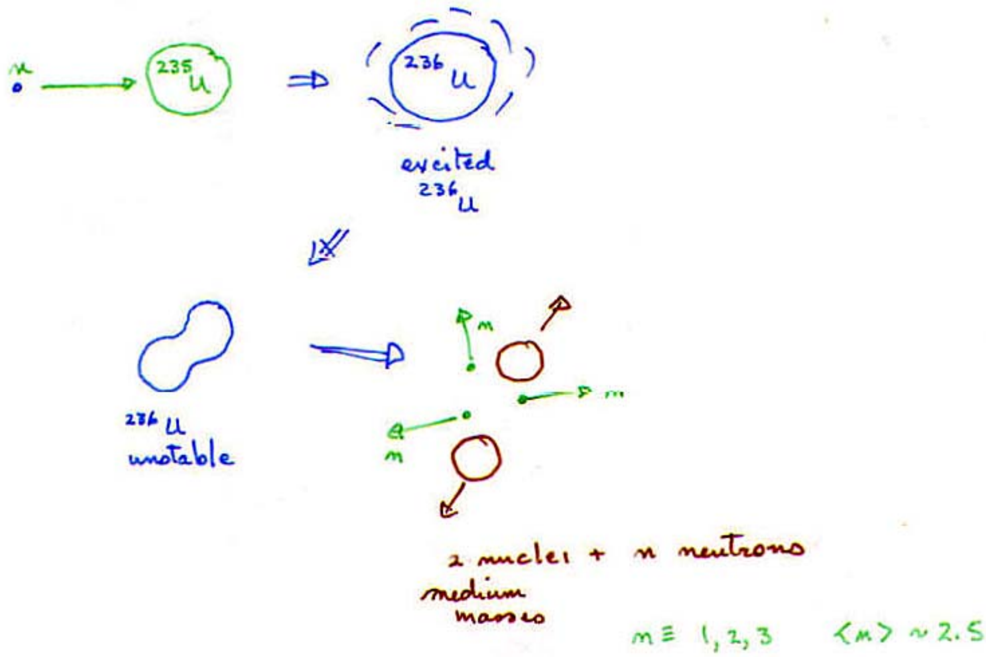
2.9% $e^-$ E = 329 keV

L/M shell 1.2%



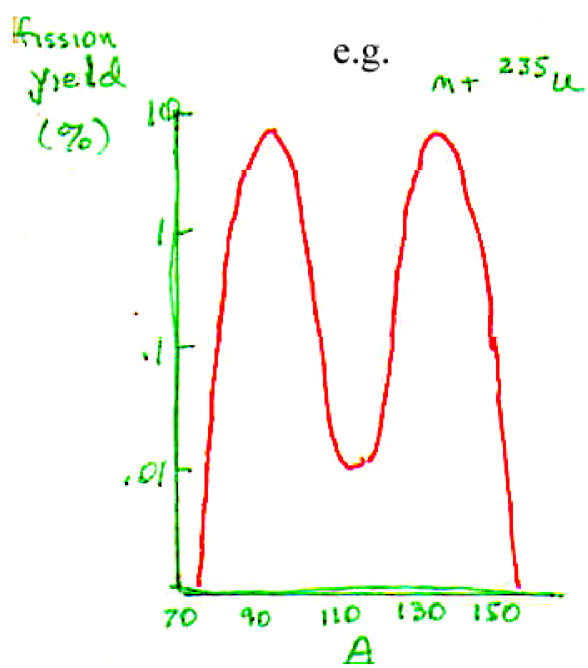
# FISSION

- Heavy nuclei with Z>92 n in an excited state (not their ground state energies)
- some heavy nuclei can be induced to fission by the capture of a neutrons (used in nuclear reactors)



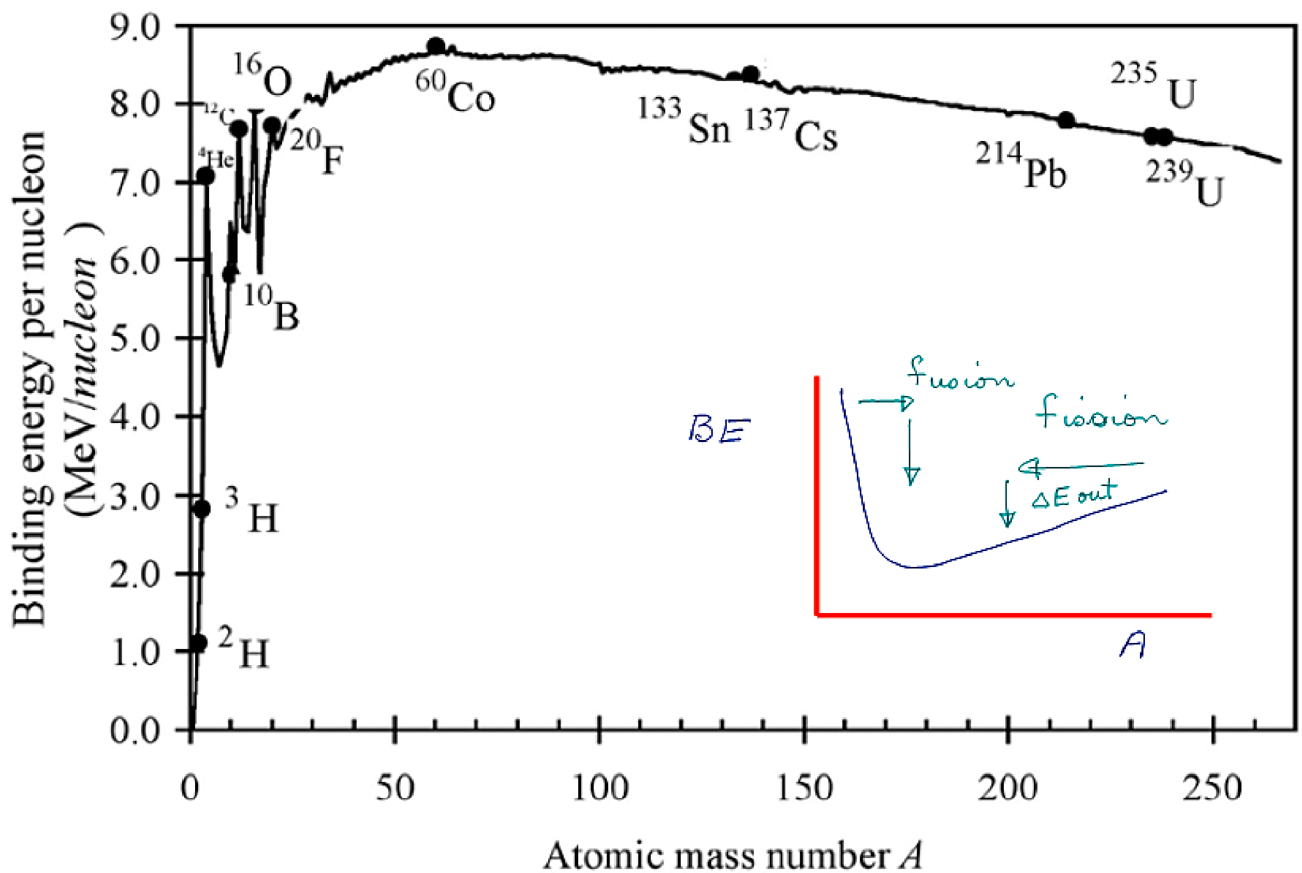

- after the decay there is a distribution of fission fragments

e.g. for n + $^{235}$U



# Fission (con't)

- the energy benefit from fission is apparent when one looks at the plot of the binding energy per nucleon (i.e., energy per neutron plus proton). (the insert is added to sketch the binding energy in the sense used up to now in the notes, more stable configurations with deeper energy level.)




- (aside) the energy gain from fusion (moving to higher A in low A regime) is also apparent from this graph.

- Fissioning nuclei also typically undergo $\alpha$ decay, then there are two possible mechanisms for transformation, each with its own half life. The effective half life is a combination as illustrated below:

eg $^{252}Cf$ undergoes fission $\bar{c}$ $T_{1/2} = 85y$
$\alpha$ - decay $\bar{c}$ $T_{1/2} = 2.65y$

what is actual $T_{1/2}$ for $^{252}Cf$?

$T_{1/2} \Rightarrow$ do not add, but rates $\lambda$ do:

$$\lambda_f = \frac{\ln 2}{T_{1/2\,f}} \qquad \lambda_\alpha = \frac{\ln 2}{2.65y}$$

$$\lambda_{TOT} = \frac{\ln 2}{85} + \frac{\ln 2}{2.65} = 0.270\,y^{-1}$$

$$T_{1/2\,tot} = 2.57\,y$$

One can also calculate the fraction of nuclei undergoing each transition

recall also

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

so can see fraction decaying by fission

$$f_{fission} = \lambda_f / \lambda_{total}$$

and so $f_\alpha = \lambda_\alpha / \lambda_{total}$