Chemistry 988 – Part 1 –

MICHIGAN STATE UNIVERSITY

Radiation Detection & Measurement

Dept. of Chemistry --- Michigan State Univ.
National Superconducting Cyclotron Lab

DJMorrissey
Spring/2oo9

Course information can be found on the website:

http://www.chemistry.msu.edu/courses/cem988Nuclear/index.html

Chap. 1 Radiation Sources .. What?

Ionizing Radiation: a typical Ionization Potential for a molecule (or work function for a metal) is a few eV .. Thus, we will be concerned with “sources” that produce radiations with significantly more energy than this (later we will see that the important parameter for detectors is an effective ionization potential somewhat larger than the minimum).

Radiation types: sort by mass & charge

Gamma rays	Neutrons
Electrons +/-	Nuclear Charged Particles

Required Information: nuclide (λ, radiations), amount (N_0)

$$A \quad \frac{dN}{dt} \quad N$$

$$dN \quad Ndt \quad N \quad N_0 e^{\quad t}$$

$$\frac{N}{N_0} \quad \frac{1}{e} \quad t \quad 1/ \quad , \text{mean life}$$

$$\frac{N}{N_0} \quad \frac{1}{2} \quad t \quad \ln 2/ \quad T_{1/2}, \text{half life}$$

Auxiliary information: purity

$$\text{Specific Activity} \quad \frac{A}{mass} \quad (A \quad N)$$

$$mass \quad N\frac{MM}{N_A} \quad (if \ pure)$$

$$\text{Specific Activity} \quad \frac{N_A}{MM} \quad (if \ pure)$$

Radiation Sources .. Growth

MICHIGAN STATE UNIVERSITY

Sources: with a very few exceptions the radioactive sources that we use have to be "produced" in nuclear reactions. The production can be direct such as in a neutron capture process (n,γ) or indirectly by the decay of another nuclide.

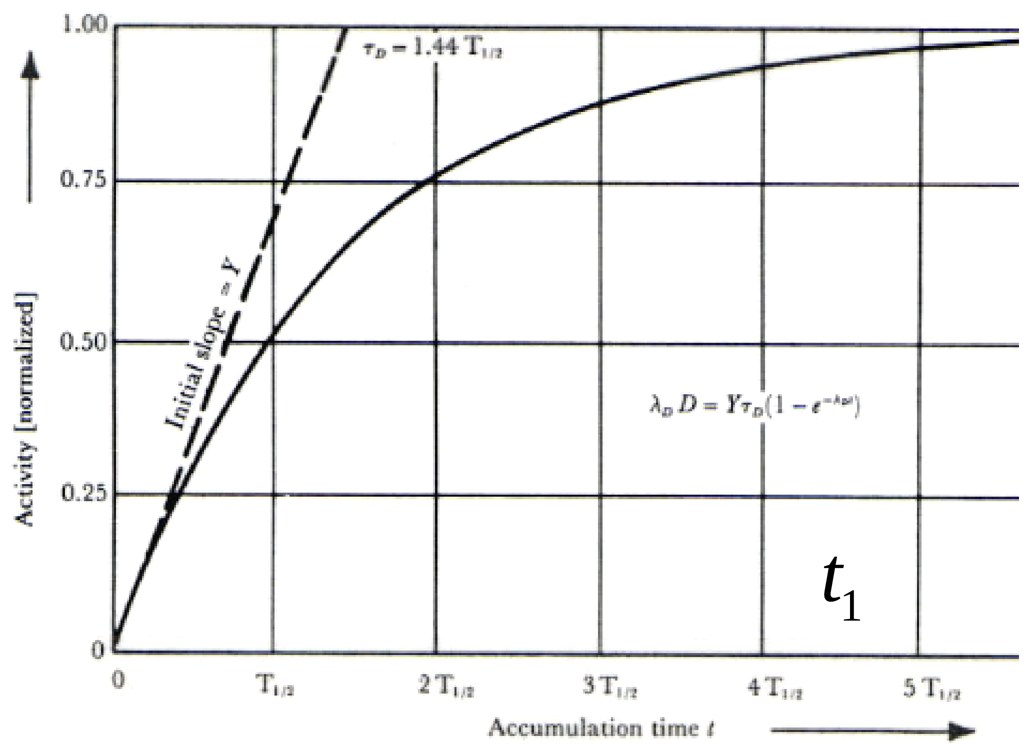
Growth: a nuclear reaction of the sort x + A → B, where "B" will be our source material

$$\left(\frac{dN_B}{dt}\right) = (\text{ProductionRate}) - (\text{DecayRate})$$

$$\left(\frac{dN_B}{dt}\right) = N_0^A \sigma_{xA} \Phi_x - \lambda_B N_B$$

$$\lambda_B N_B = \left(N_0^A \sigma_{xA} \Phi_x\right)\left(1 - e^{-\lambda_B t_1}\right) e^{-\lambda_B t_2}$$

Production up to t_1, subsequent decay t_2



Radiation Sources .. Growth & Decay

MICHIGAN STATE UNIVERSITY

Growth & Decay: often a source may consist of a decay chain: $A \xrightarrow[\tau_A]{\lambda_A} B \xrightarrow[\tau_B]{\lambda_B} C$

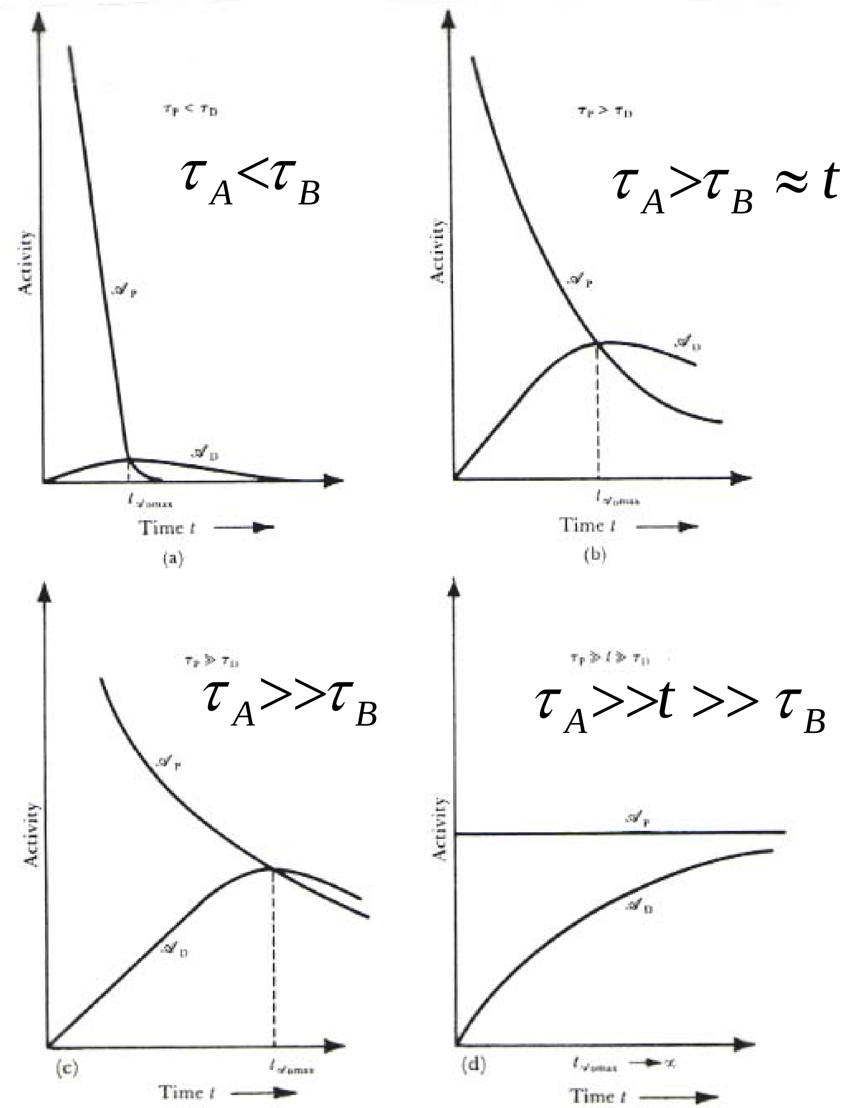
$$\left(\frac{dN_B}{dt}\right) = (\text{Production Rate}) - (\text{Decay Rate})$$

$$\left(\frac{dN_B}{dt}\right) = \lambda_A N_A(t) - \lambda_B N_B(t)$$

$$but\ N_A(t) = N_0^A e^{-\lambda_A t}$$

…

$$N_B(t) = \frac{\lambda_A}{\lambda_B - \lambda_A} N_0^A \left(e^{-\lambda_A t} - e^{-\lambda_B t}\right) + N_0^B e^{-\lambda_B t}$$



Some examples for various cases of τ_A viz. τ_B
N.B. the curves are the activities.

Radiation Sources .. Electrons –1–

MICHIGAN STATE UNIVERSITY

Beta Decay: $n \rightarrow p^{+} + e^{-} + \underline{\nu} + Q$ e.g., $^{14}C \rightarrow {}^{14}N^{+} + e^{-} + \underline{\nu} + Q$

$Q = M(^{14}N^{0}) - M(^{14}C)$

and $(p^{+} \rightarrow n + e^{+} + \nu + Q')_{A}$ e.g., $^{13}N \rightarrow {}^{13}C^{-} + e^{+} + \nu + Q'$

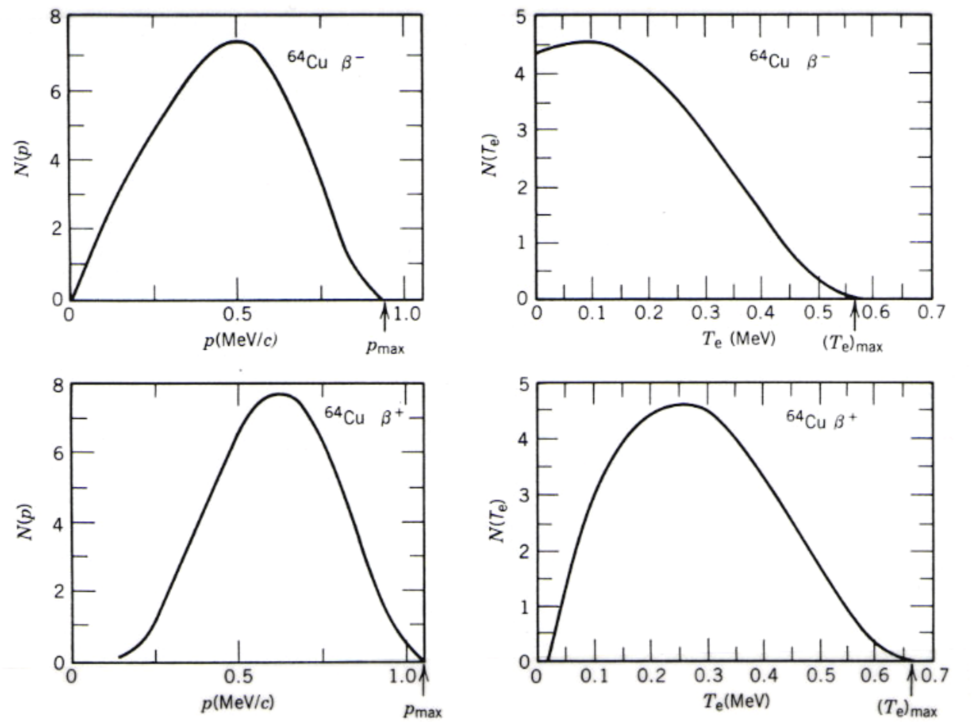
$^{13}N \rightarrow {}^{13}C^{0} + e^{-} + e^{+} + \nu + Q'$

Three-bodies in final state gives continuous energy distribution but there are thousands of radioactivities to choose from.
Note limits: 0 < Kinetic Energy < Q

$Q' = M(^{13}C^{0}) + 2\, m_{o}c^{2} - M(^{14}C)$

Phase space or Fermi Functions have Coulomb shifts …

$^{64}Cu \rightarrow {}^{64}Ni^{-} + e^{+} + \nu + Q_{\beta+} = 0.6529$ MeV
$^{64}Cu \rightarrow {}^{64}Zn^{+} + e^{-} + \underline{\nu} + Q_{\beta-} = 0.5782$ MeV



Also electron capture:
$^{64}Cu \rightarrow {}^{64}Ni + \nu + Q_{\beta+} = 1.675$ MeV

Typical energy scale …

Radiation Sources .. Electrons –2–

Internal conversion: ${}^{A}Z^{*} \rightarrow {}^{A}Z^{+} + e^{-}$, where the electron was a bound atomic electron.

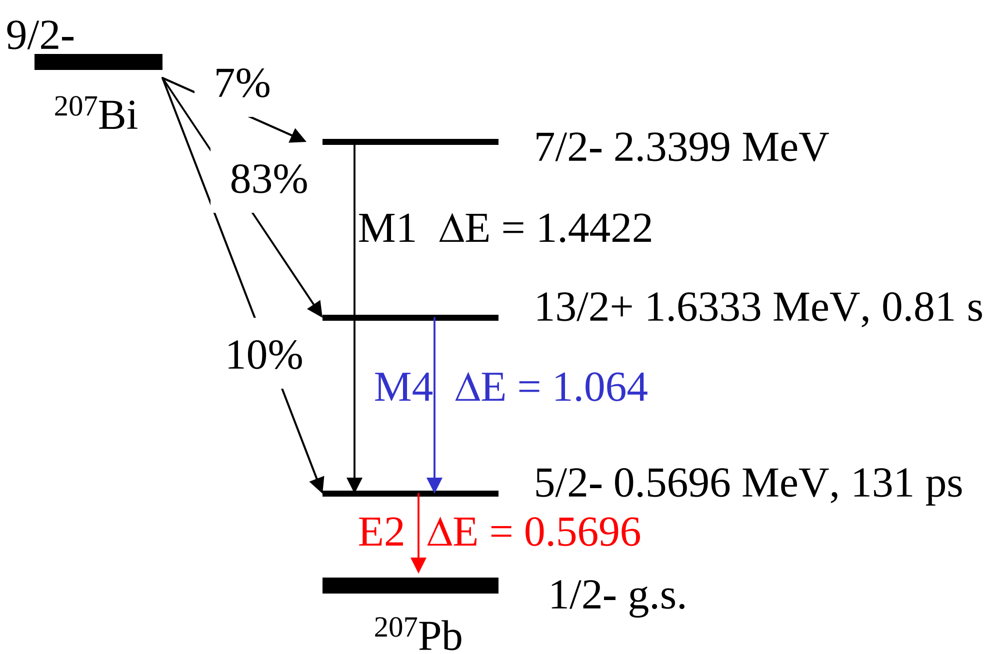
$${}^{207}Bi\ (38\ yr) \rightarrow {}^{207}Pb^{*} + \nu + Q'_{ec}$$

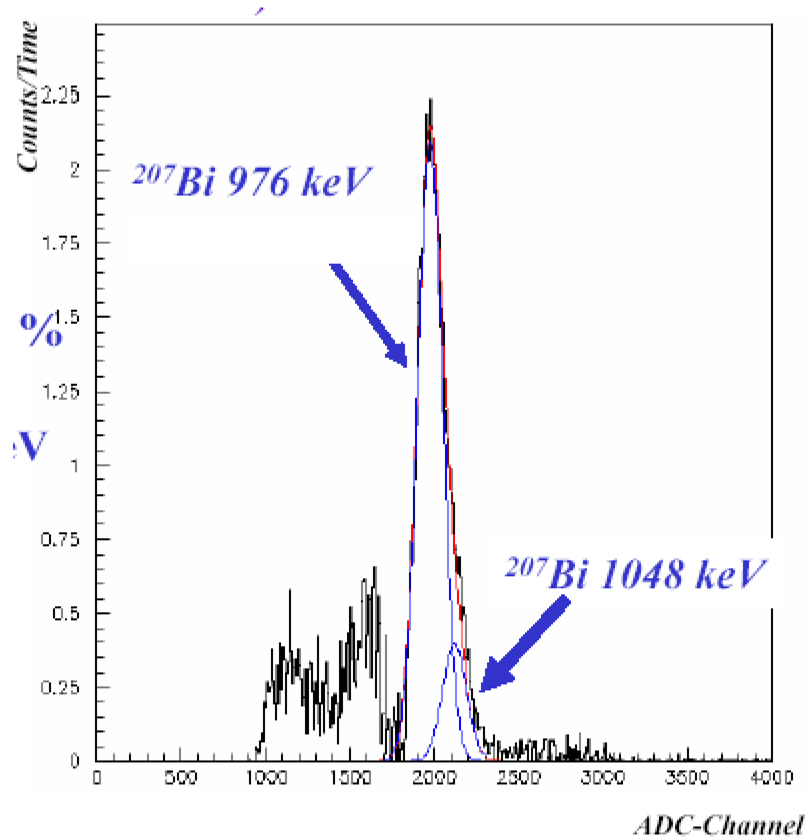
$$\rightarrow {}^{207}Pb^{+} + e^{-}\ \ (KE = \Delta E - \text{atomic B.E.})$$

K: 88 keV, L: 16 keV
(n=1, 1s) (n=2, 2s,2p)

Two-bodies in final state gives a discrete energy distribution of electrons but there are relatively few examples of sources (compared to beta-decay).

Typical energy scale …





Radiation Sources .. Charged Particles –1–

MICHIGAN STATE UNIVERSITY

Alpha Decay: $^{A}Z \rightarrow {}^{A-4}(Z\text{-}2)^{2-} + {}^{4}He^{2+} + Q_\alpha$ e.g., $^{238}U \rightarrow {}^{234}Th^{2-} + {}^{4}He^{2+} + Q_\alpha$

$$Q_\alpha = M[{}^{A-4}(Z\text{-}2)^0] + M[{}^{4}He^0] - M[{}^{A}Z]$$

Nuclei heavier than A ~ 150 are thermodynamically unstable against alpha decay but because the energy of decay is much lower than the Coulomb barrier it is a quantum mechanical tunneling process that is extremely sensitive to the Q-value of the process.
Thus, alpha decay is only important for the heaviest nuclei and it rarely feeds excited states.

The particles are quite energetic 4 - 9 MeV but interact very efficiently with electrons in materials and stop within ~100 microns in solids.

Two-body final state gives a discrete energy distribution – must account for recoil energy.

E.g., the "A=4n" natural decay chain:

$$^{232}Th \xrightarrow[\alpha, 10^{10}\,yr]{} {}^{228}Ra \xrightarrow[\beta]{} {}^{228}Ac \xrightarrow[\beta]{} {}^{228}Th$$

$$^{228}Th \xrightarrow[\alpha, 1.9\,yr]{} {}^{224}Ra \xrightarrow[\alpha, 4d]{} {}^{220}Rn \xrightarrow[\alpha, 56s]{} {}^{216}Po \xrightarrow[\alpha, 0.2s]{} \boxed{^{212}Pb}$$

$$\boxed{^{212}Pb} \xrightarrow[\beta, 11hr]{} {}^{212}Bi \xrightarrow[\beta, 61m]{} {}^{212}Po \xrightarrow[\alpha, 0.3\mu s]{} {}^{208}Pb \qquad E_\alpha = 8.78 \text{ MeV}$$

$$^{212}Bi \xrightarrow[\alpha]{} {}^{208}Tl \xrightarrow[\beta, 3m]{} {}^{208}Pb^{*} \qquad E_\gamma = 2.61 \text{ MeV}$$

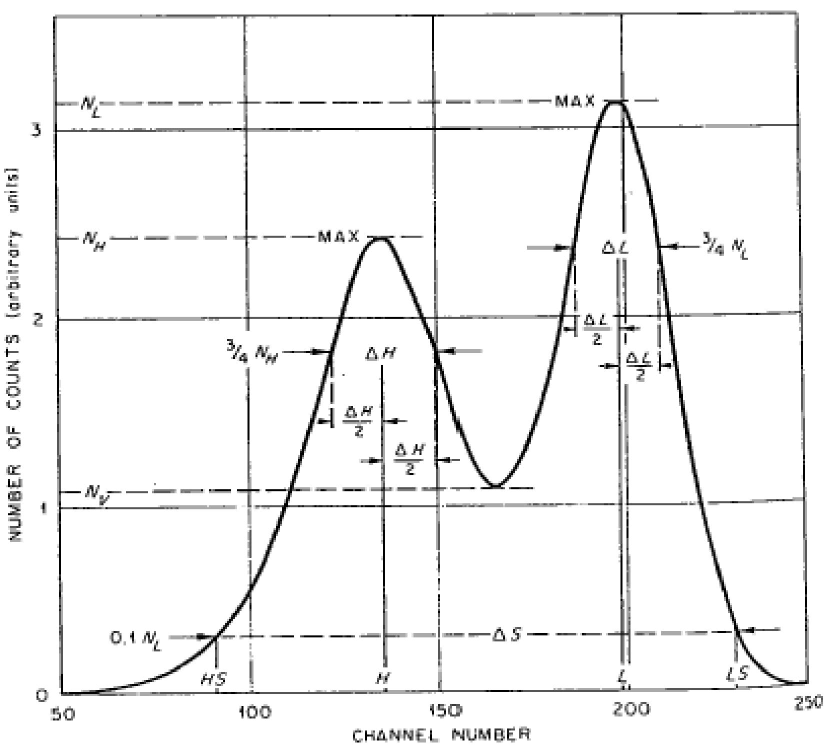
E_α=6.05, 6.09 MeV

Radiation Sources .. Charged Particles –2–

Spontaneous Fission: $^{A}Z \rightarrow {}^{A-x}(Z-y)^{*} + {}^{x}y^{*} + Q_f$ e.g., ^{252}Cf (~3% SF) TKE ~ 185 MeV

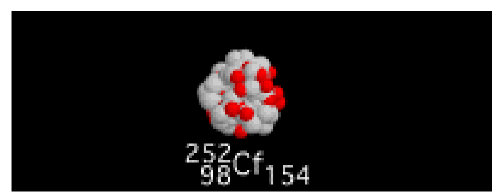
Spontaneous fission is another quantum mechanical tunneling process similar to alpha-decay that is rare in the light actinide nuclei and increases in importance with Z and limits the stability of nuclei with Z>98.

All fission processes produce a statistical distribution of radioactive products, fast neutrons and γ's.



From: Schmitt & Pleasonton, NIM 40 (1966) 204

Two-body final state gives a discrete energy distribution for each fission event but there are many mass-splits and neutron evaporation from the excited fragments. These fragments go on to β- decay eventually reaching stability.

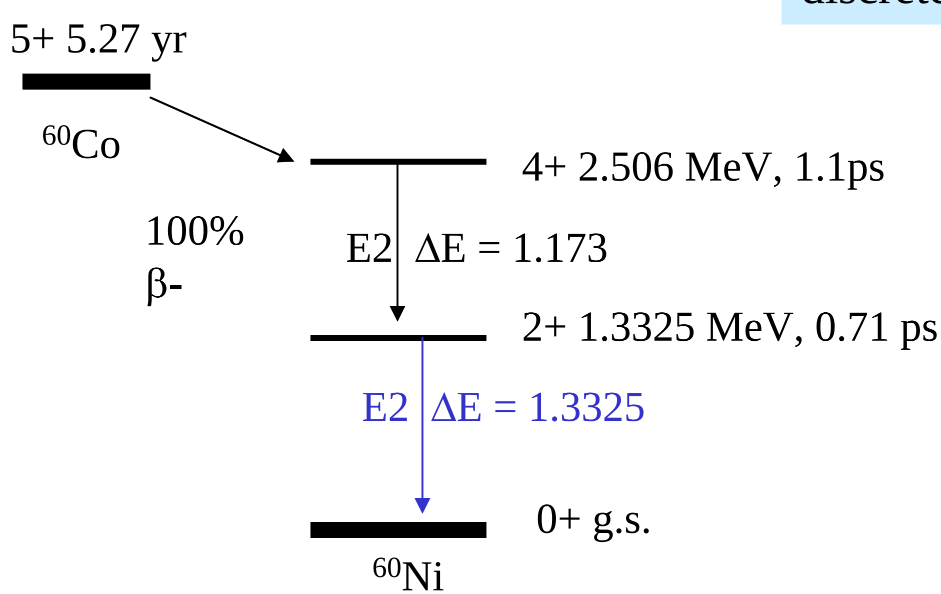


Radiation Sources .. γ rays

Gamma rays are emitted by nuclear excited states, their lifetimes are generally too short to provide useful sources (except for some special cases called “isomeric” states).

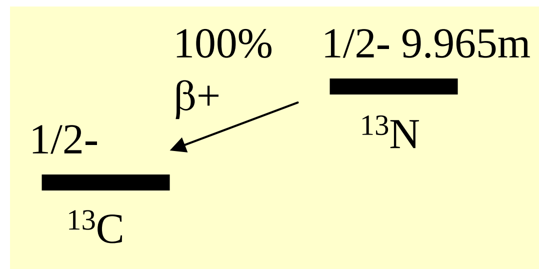
Beta-delayed: $^{A}(Z+/-1) \rightarrow {}^{A}Z^{*} \rightarrow {}^{A}Z + \gamma$ the gamma decay is for many purposes prompt, but often the lifetimes of the excited states are significant and their exponential decay can be measured.

Two-bodies in final state gives a discrete energy distribution …



There will be an angular correlation among the beta and two gammas ..

Annihilation:



Bremsstrahlung: from electron beams, continuous energy spectrum primarily used for irradiations

Radiation Sources .. neutrons

Neutrons have to be produced in nuclear reactions, the energy spectrum will depend on the reaction..

Spontaneous Fission:

^{252}Cf the neutrons are primarily emitted with a thermal energy spectrum in the rest frame of the moving fragments (KE ~ 1 MeV/u). $I \propto E^{1/2} e^{-E/T}$

PuBe & AmBe:

intimately mixed metals

$$^{238}Pu \rightarrow {}^{234}U^{2-} + {}^{4}He^{2+} + Q_{\alpha} = 5.7012 \text{ MeV}, \ KE_{\alpha} < 5.14 \text{ MeV}$$

$$^{4}He^{2+} + {}^{9}Be \rightarrow {}^{13}C^{2+*} \rightarrow {}^{12}C^{2+} + n + Q_{gg} = \ldots \text{ MeV}$$

$$\rightarrow {}^{12}C^{2+*} + n' + Q'$$

Photonuclear Reactions:

$$\gamma + {}^{9}Be \rightarrow {}^{8}Be + n + Q_{gg} = -1.666 \text{ MeV}$$

$$^{124}Sb \rightarrow {}^{124}Te^{*} \text{ (first excited state)} \rightarrow {}^{124}Te + \gamma = 1.691 \text{ MeV}, \ \text{net } Q_n = 0.025 \text{ MeV}$$

Accelerator Reactions:

$$p + {}^{7}Li \rightarrow {}^{7}Be + n + Q_{gg} = -1.64 \text{ MeV}$$

$$d + {}^{9}Be \rightarrow {}^{10}B + n + Q_{gg} = +4.36 \text{ MeV} \ \text{[MedCyc]}$$

$$d + d \rightarrow n + {}^{3}He + Q_{gg} = +3.26 \text{ MeV}$$

$$d + t \rightarrow n + {}^{4}He + Q_{gg} = +17.6 \text{ MeV} \ \text{[fusion reaction]}$$