Chemistry 985 – Part 1 –

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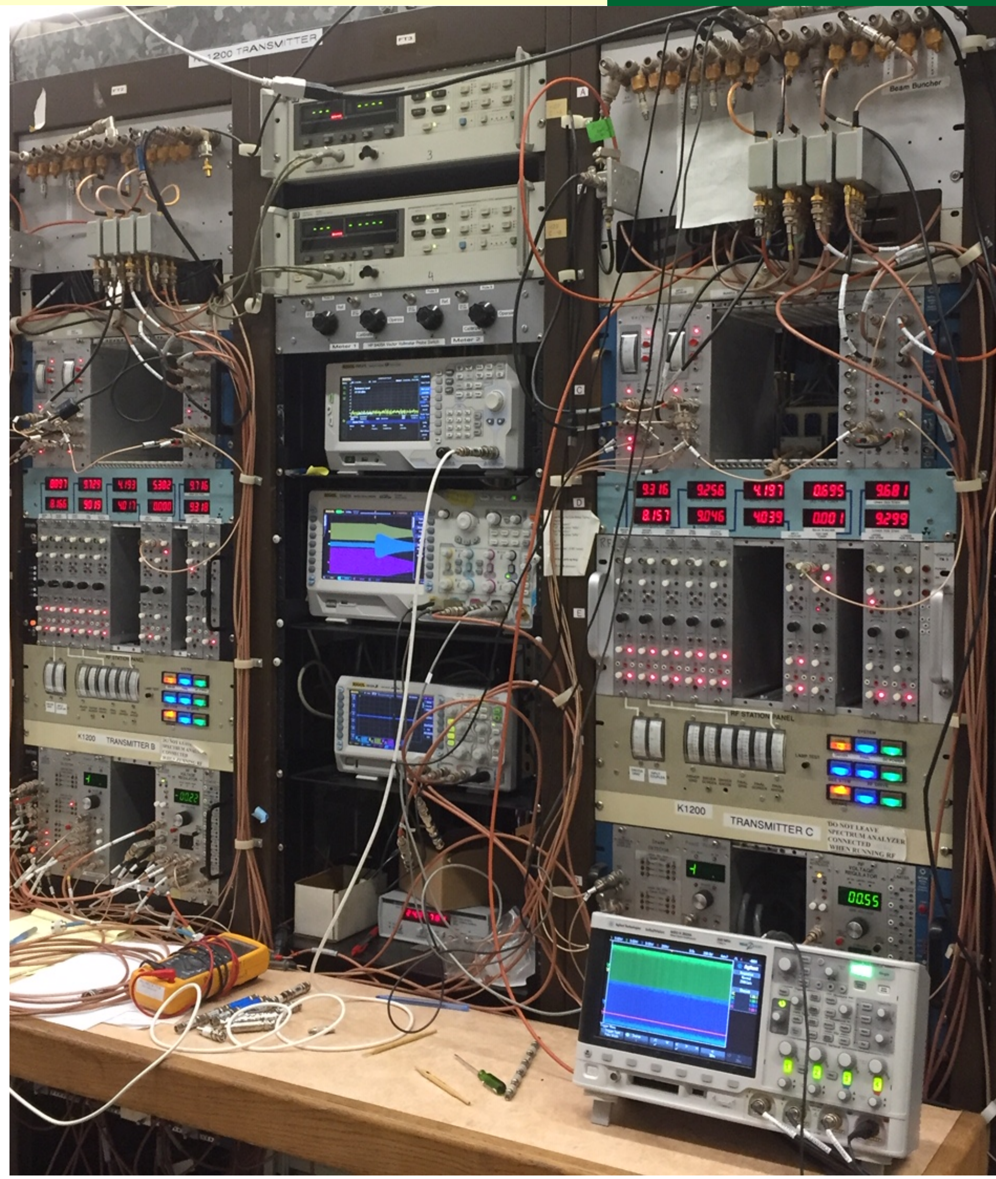
Radiation Detection
& Measurement

Dept. of Chemistry
&
National Superconducting
Cyclotron Lab

Michigan State Univ.



DJMorrissey
Fall/2o19

Course information can be found at:
http://www.chemistry.msu.edu/courses/cem985/index.html

Week 1: Chap. 1 Sources of Radiation

Introduction

-- Roll back the fog

-- General Nomenclature

-- Decay Equations

-- Laboratory Sources

--- Electrons

--- Charged Particles

--- Gamma Rays

--- Neutrons

Interaction of Radiation with Matter

Vacuum Technology

Robert W. Cameron,
Aerial photographer

Chap. 1 Radiation Sources .. What?

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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 and devices that can detect 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, sorted by:

Mass →

Charge ↓

Gamma Rays		Neutrons	(Atoms)
	Electrons +/-	Protons +	Heavy ions (1+)
			Nuclear Ions (q+)

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

$$A = \left(\frac{-dN}{dt}\right) = \lambda N$$

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

$$if\ \ t = 1/\lambda = \tau, \text{ meanlife} \rightarrow \frac{N}{N_0} = \frac{1}{e}$$

$$if\ \ t = \ln 2/\lambda = T_{1/2}, \text{ half-life} \rightarrow \frac{N}{N_0} = \frac{1}{2}$$

Auxiliary information: purity

$$\text{SpecificActivity} = \frac{A}{mass} \quad (A = \lambda N)$$

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

$$\text{SpecificActivity} \leq \frac{\lambda N_A}{MM} (= if\ pure)$$

Radiation Sources .. Growth

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

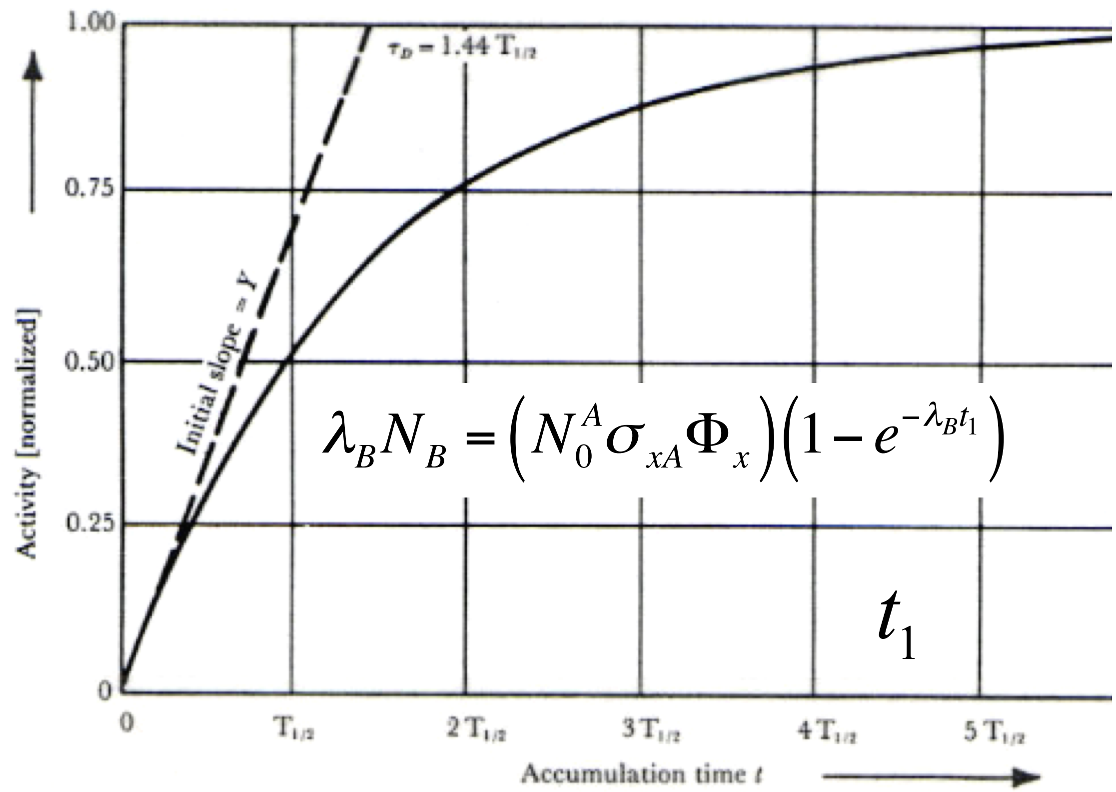
Growth: a nuclear reaction of the sort x + A → B, where "B" will be our source material

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

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

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

Production up to t_1, note "saturation"
subsequent decay t_2



Radiation Sources .. Growth & Decay

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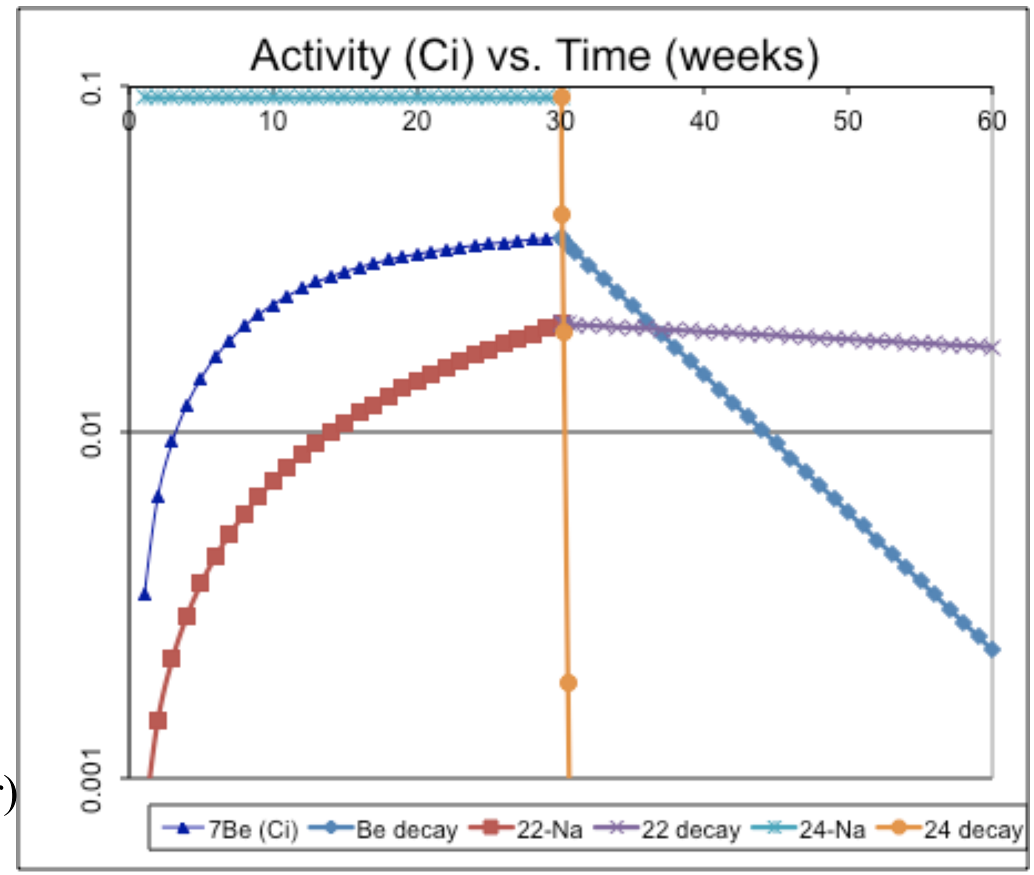

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Production up to t_1, note “saturation”
subsequent decay t_2

For example, important activities produced in ^{27}Al targets are: 7-Be (53 d), 22-Na (2.6yr), 24-Na (15 hr)

Radiation Sources .. Decay & Growth

Decay & Growth: often a source may consist of a decay chain: $A \underset{\tau_A}{\overset{\lambda_A}{\rightarrow}} B \underset{\tau_B}{\overset{\lambda_B}{\rightarrow}} C$

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

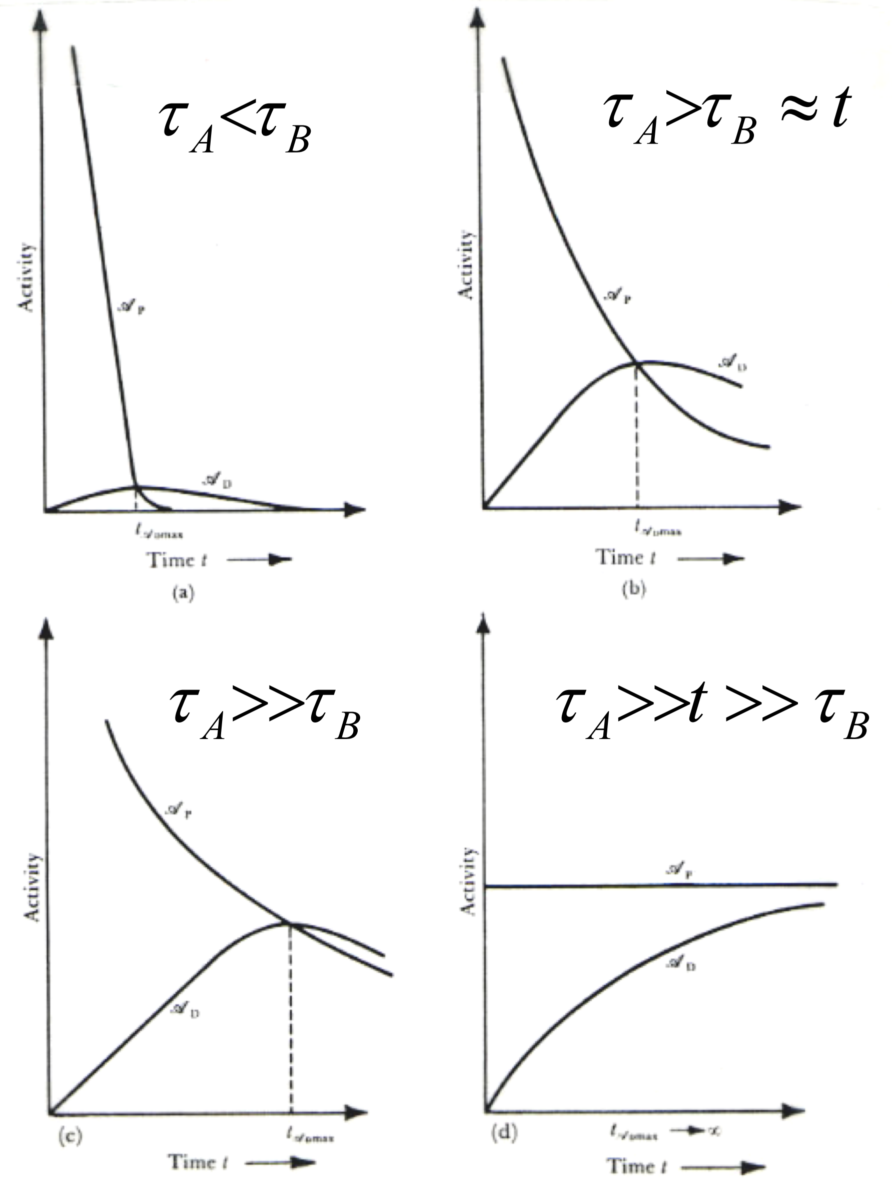
$$\left(\frac{dN_B}{dt}\right) = \lambda_A N_A(t) - \lambda_B N_B(t)$$

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

...

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

$$for\ \lambda_B \neq \lambda_A$$



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

Special case (d) of "Secular Equilibrium"

Radiation Sources .. Electrons –1–

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Beta Decay: $n \rightarrow p^+ + e^- + \underline{\nu} + Q$ e.g., $^{14}C_8 \rightarrow {}^{14}N_7^+ + e^- + \underline{\nu} + Q$

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

and $(p^+ \rightarrow n + e^+ + \nu + Q')_A$ e.g., $^{13}N_6 \rightarrow {}^{13}C_7^- + e^+ + \nu + Q'$

$$^{13}N_6 \rightarrow {}^{13}C^0 + e^- + e^+ + \nu + Q'$$

$$Q' = M(^{13}C^0) + 2\, m_o c^2 - M(^{13}N^0)$$

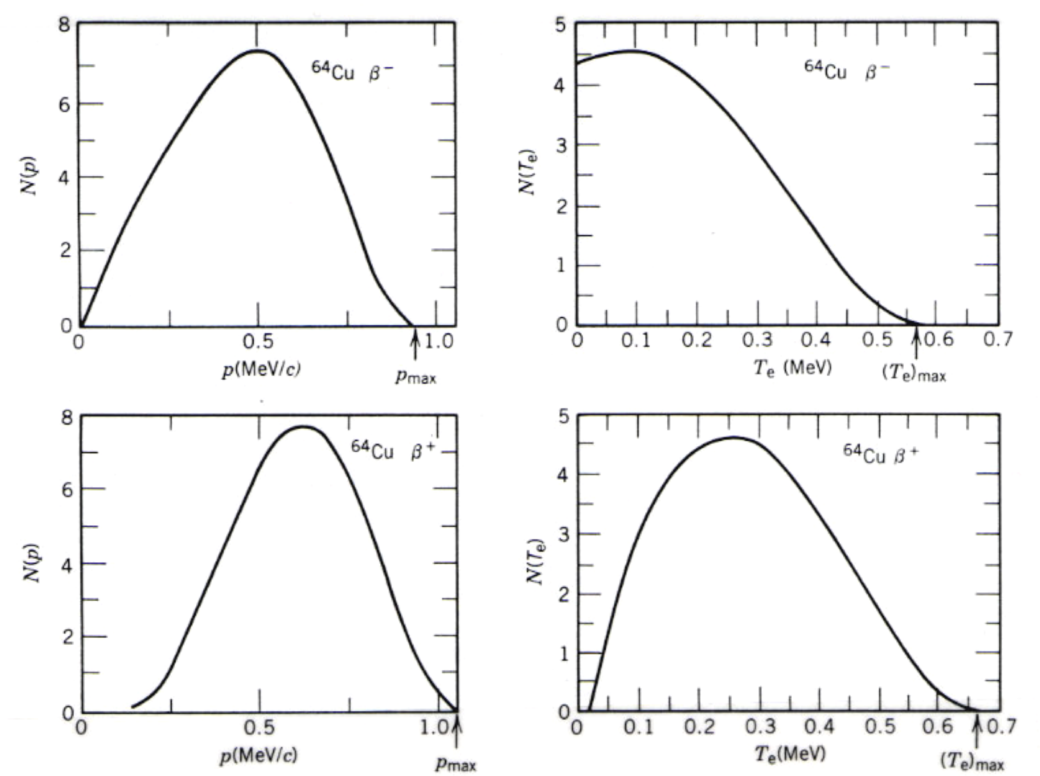
Three-bodies in final state gives continuous energy distribution but, in principle, there are thousands of radioactivities to choose from.
Note limits: 0 < electron Kinetic Energy < Q

Phase space or Fermi Functions favor largest energy differences, have Coulomb shifts …

$^{64}Cu_{35} \rightarrow {}^{64}Ni^- + e^+ + \nu + Q_{\beta+} = 0.6529$ MeV
$^{64}Cu_{35} \rightarrow {}^{64}Zn^+ + e^- + \underline{\nu} + Q_{\beta-} = 0.5782$ MeV

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

Typical energy scale …



Radiation Sources .. Electrons –2–

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

$^{207}Bi_{124}$ (38 yr) $\rightarrow$ $^{207}Pb^{*}$ + ν + Q'_{ec}

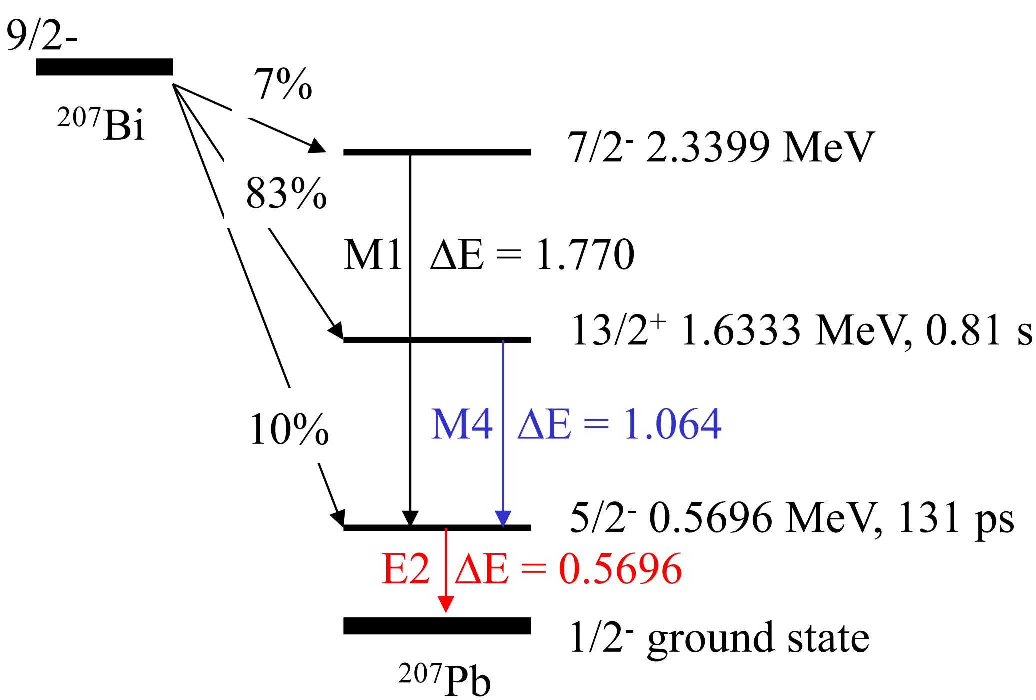
$\hookrightarrow$ $^{207}Pb^{+}$ + e^{-} (KE=ΔE – atomic B.E.)

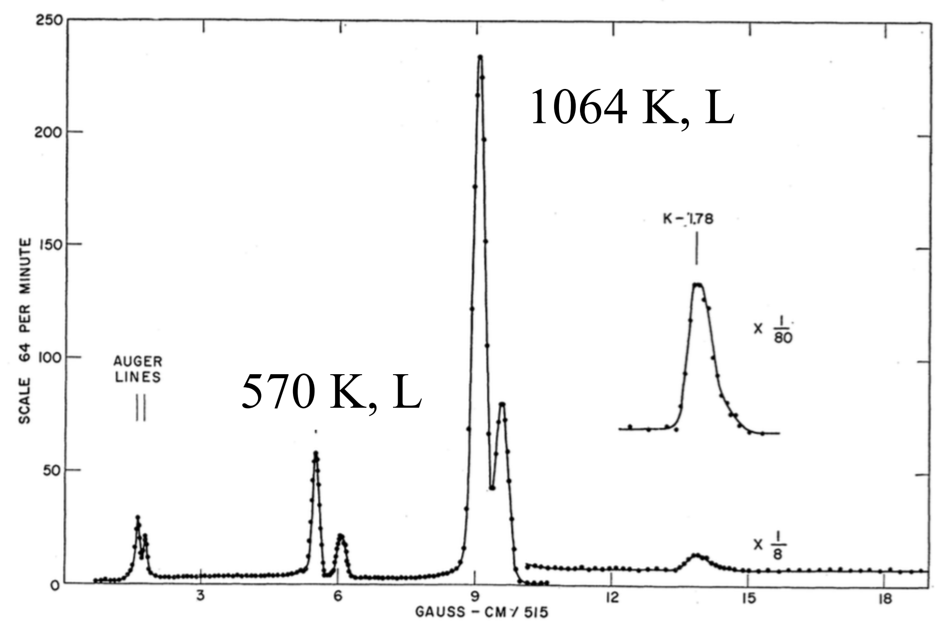
K: 88 keV, L: 16 keV

(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 such sources (compared to beta-decay).

Typical energy scale …





PR99 (1955) 695

Radiation Sources .. Charged Particles –1–

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

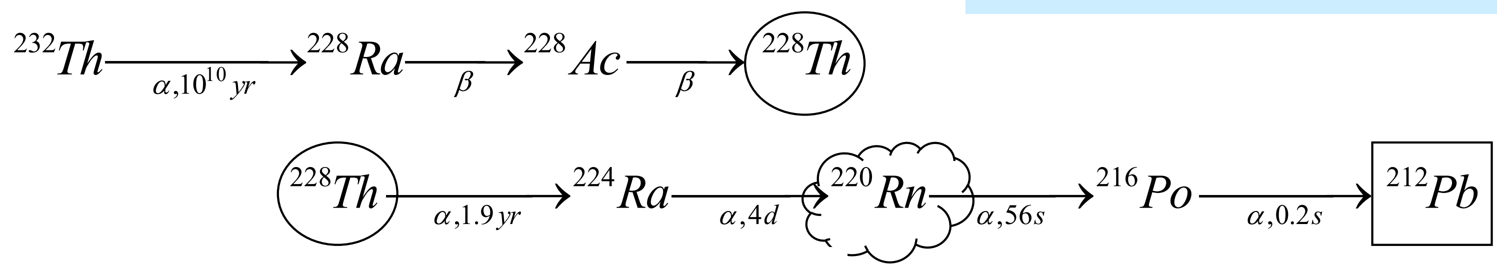
$$Q_\alpha = M[{}^{A-4}(Z-2)^0] + M[{}^{4}He^0] - M[{}^{A}Z]$$

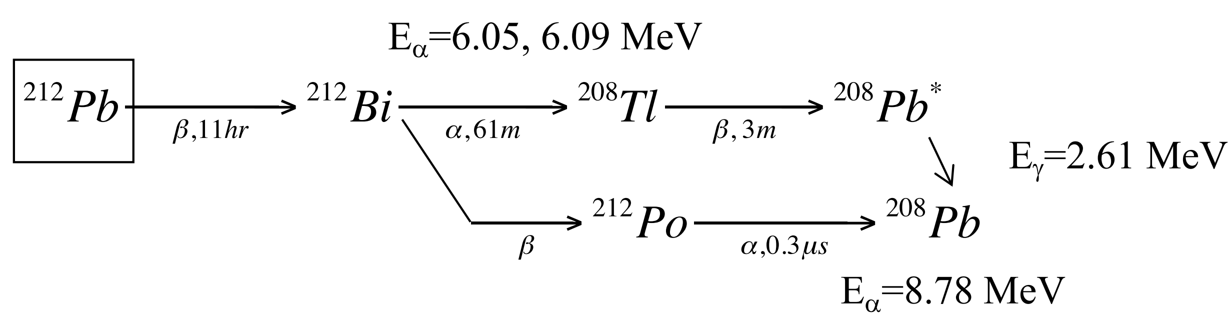
Nuclei heavier than A ~ 150 are thermodynamically unstable against alpha decay BUT the energy of decay is much lower than the Coulomb barrier forcing the process to go via a quantum mechanical tunneling process that is extremely sensitive to the Q-value of the process.
Thus, alpha decay is only important for the heaviest nuclei AND it tends not to feed excited states.

The particles are quite energetic 4 to 9 MeV but interact very efficiently with electrons in materials and so the alphas "stop" after moving <100 microns in solids.

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

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





Radiation Sources .. Charged Particles –2–

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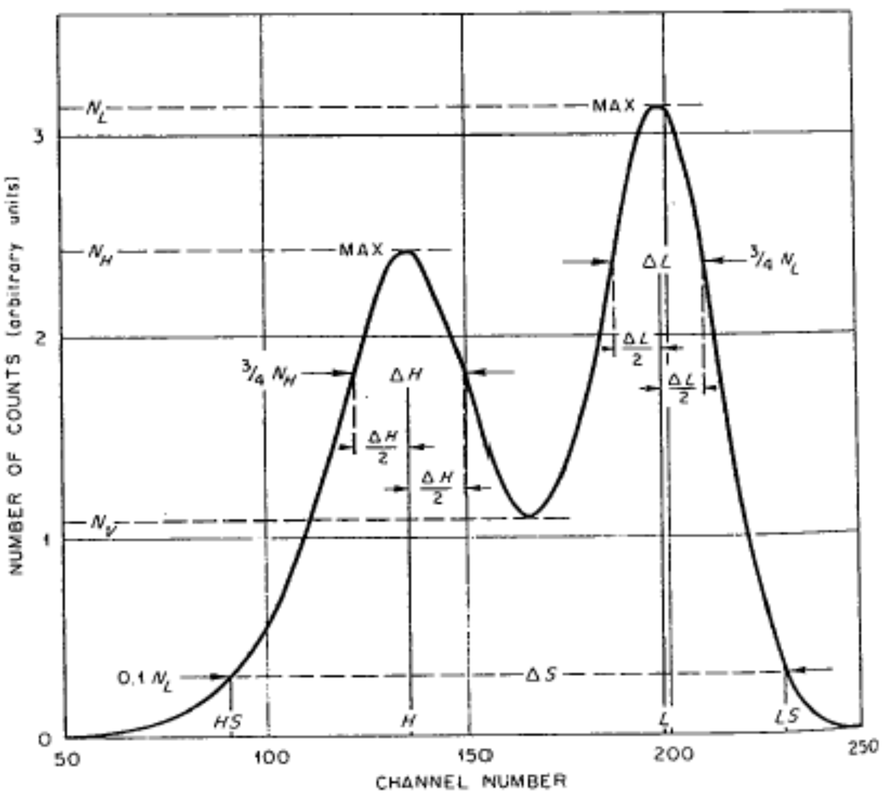
Spontaneous Fission: $^{A}Z \rightarrow {}^{A-x}(Z-y)^* + {}^{x}y^* + Q_f$ e.g., ^{252}Cf (~3% SF) TKE ~ 185 MeV

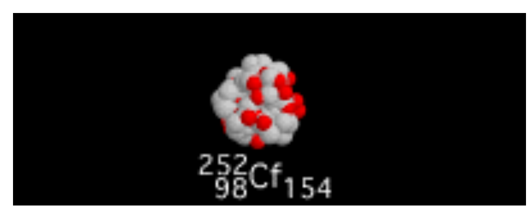
Spontaneous fission is another quantum mechanical tunneling process similar to alpha-decay that is rare in the light actinide nuclei and increases in importance with Z and generally limits the stability of nuclei with Z>98.

All fission processes produce a statistical distribution of radioactive (n-rich) 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

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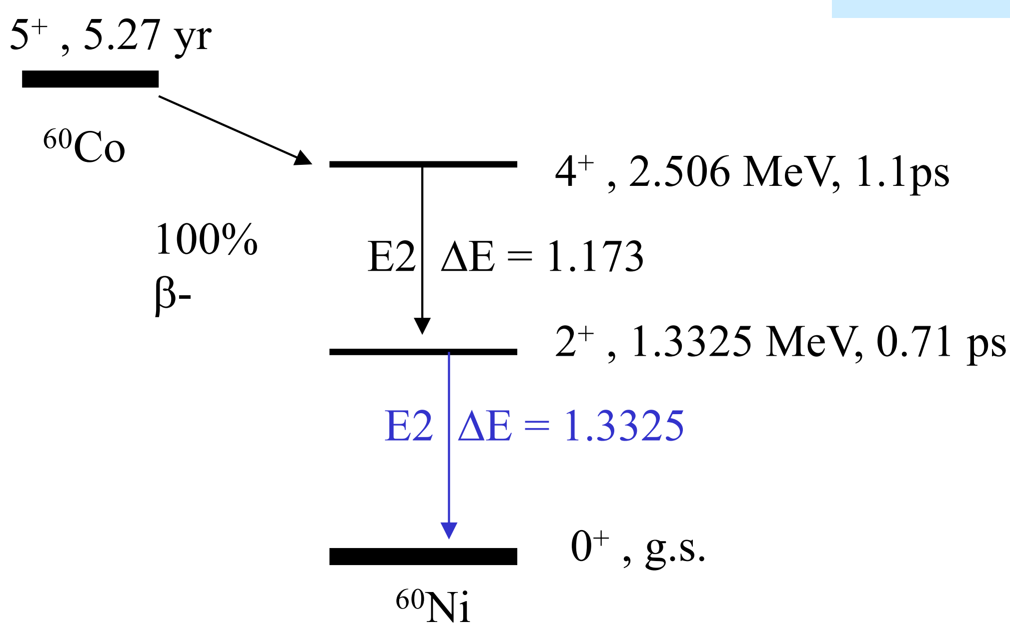
Gamma rays are emitted by nuclear excited states, their lifetimes are generally too short to provide useful sources (except for some special cases called "isomeric" states).

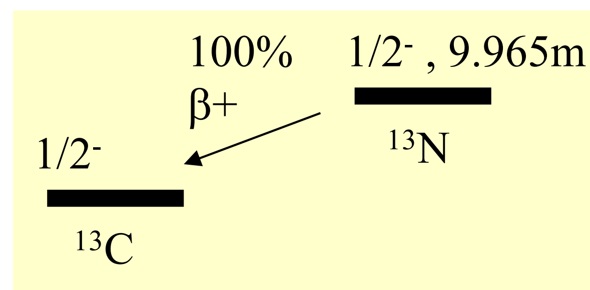
Beta-delayed: $^{A}(Z+/-1) \rightarrow {}^{A}Z^{*} \rightarrow {}^{A}Z + \gamma$ the gamma decay is for many purposes prompt, but often the lifetimes of the excited states are significant and their exponential decay can often be measured.

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

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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, i.e. an alloy

$$^{238}Pu \rightarrow {}^{234}U^{2-} + {}^{4}He^{2+} + Q_{\alpha} = 5.593\ \text{MeV},\ \ KE_{\alpha} = 5.499\ \text{MeV (max …)}$$

$$^{4}He^{2+} + {}^{9}Be \rightarrow {}^{13}C^{2+*} \rightarrow {}^{12}C^{2+} + n + Q_{gg} = 5.702\ \text{MeV}$$

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

$$\searrow {}^{12}C^{2+} + \gamma$$

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:

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

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

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

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