Welcome to 12.744 Lecture 1

- **Logistics and organizational**
- Course Objectives and Layout
  - What you can expect, and what is expected of you
  - Resources
- Introduction to isotopes, nuclear structure, stability, and radioactivity

Welcome to 12.744 Logistics

- Tuesdays & Thursdays in Clark 331* video-linked to MIT 9-151
  - 13:00-14:30
- Recitation with Kyrstin?

* Will change to Clark 271 once A/V problems solved (but will remain in MIT 9-151)

Welcome to 12.744 Resources

- Material:
  - Reading lists (journal articles & texts)
  - Verbal Lectures
  - Slides presented (on web)*
  - Additional resources/links (on web)*

  You are responsible for all material

* http://www.whoi.edu/sites/12744

All in PDF format (slides in 2 X 2 for annotation)

Welcome to 12.744: Grading

- 40% for 4 Assessed Exercises
  - Handed out on Sep 25, Oct18, Nov 6 & 27
  - Late policy: 25% of grade deducted per day late (unless documented legitimate reason)
- 20% for class participation
  - Lecture recitation*
  - During lectures and problem sessions
- 40% for final exam
  - Tuesday, December 18, closed book

*One student (chosen at random) will present a 5 minute summary of previous lecture

Welcome to 12.744
Lecture 1

- Logistics and organizational
- **Course Objectives and Layout**
  - **What you can expect, and what is expected of you**
  - **Resources**
- Introduction to isotopes, nuclear stability, and radioactivity.

Welcome to 12.744
Objectives

To build a strong, intuitive, and quantitative understanding of isotopes as tools for understanding earth and ocean processes

- You'll learn
  - The underlying physical-chemical principles
  - Stable, radioactive, and radiogenic isotopes
  - Devise, construct, and solve geochemical mass balances
  - Understand and use isotope systems as tools

Course Structure

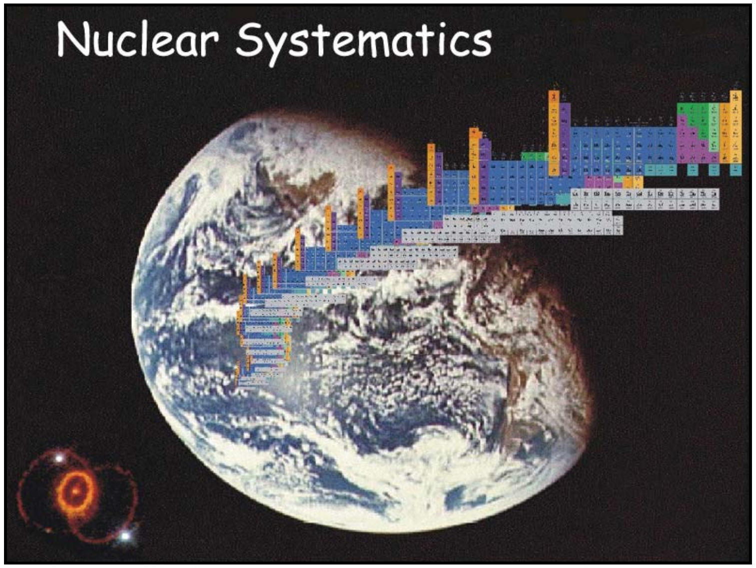
21 Lectures & 4 Problem Sessions*

1. Nuclear Systematics
   – Nucleosynthesis, radioactive decay, dating
2. Earth Formation and Evolution
   – Planetary, atmosphere/ocean formation & cosmogenic isotopes
3. Stable Isotopes
   – Measurement, fractionation, MIF, clumped
4. Applications
   – Water column, earth system exchange processes

*Each problem session introduces a problem set

Welcome to 12.744
Lecture 1

- Logistics and organisational
- Course Objectives and Layout
  - What you can expect, and what is expected of you
  - Resources
- **Introduction to isotopes, nuclear stability, and radioactivity**



Lecture 1

1. Underlying Principles
2. Cosmic abundance of the elements and isotopes
3. Isotope Stability
4. Radioactive Decay

First, May the Force(s) be with you

Four fundamental forces of nature

1. Strong nuclear (short range, 10^{-15}m)
   - **Strength = 1**
   - Between consenting nucleons (n & p)
2. Electromagnetic (infinite, but shielded)
   - **Strength = 10^{-2}**
   - Between charged particles (p & e)
3. Weak nuclear force (short range, 10^{-18}m)
   - **Strength = 10^{-13}**
   - Beta decay
4. Gravity (infinite range, cannot be shielded)
   - **Strength = 10^{-39}**
   - Related to mass, space-time

Key Underlying Concepts

Newtonian Physics

– Conservation of energy and momentum

Relativity $E = mc^2$ For every particle there is an anti-particle (annihilation on contact)

- Matter = energy = gravity
- 1 g matter → 10^{14} J ~ 2 x 10^{13} cal

Quantum mechanics

- Wave/particle duality
  - Tunneling, E.M. field *v.s.* photons
- Uncertainty principle
  - Virtual particles
- Quantization and spin
  - Mono-energetic transitions
  - Fermions and Bosons: fundamental statistical differences (half *vs* integer spin)

The universe consists of
- 0.5% visible matter (stars, etc.)*
- 3.5% dust, gas*
- 23% Dark Matter
- 73% Dark Energy**

*Largely baryonic (n & p)

**Dark energy is part of space-time fabric: space-time fabric is an unfurled 4-D part of an 11-D manifold (M-brane theory)

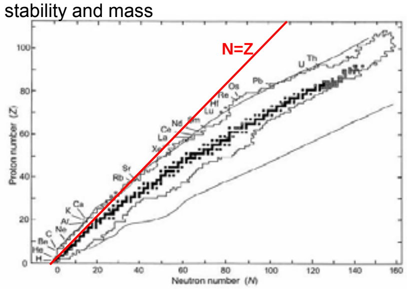
Familiar "matter" is Fermionic: protons, neutrons, electrons all have ½ integer spin

Fermions cannot occupy the same space/wave function state

What are Isotopes?

- Atoms consist of:
  - Electrons (e^-) in orbit
    - $\#e^-$ define chemical state (ionization, bonding)
    - Number/distribution defined by nuclear charge & shell structure
    - Size ~1-3 x 10^{-10} m
  - and a nucleus, with
    - Protons (charged) that define the element (chemistry)
      - $\#p = \#e^-$ for neutral atom
    - Neutrons (neutral) that add stability and mass
    - Size ~1-3 x 10^{-15} m*
  - Not all combinations of n and p are stable
    - $\#n = N \sim \#p = Z$
    - $A = N + Z$
  - Mass n ~ p, ~ 2000 x e^-

*1 tsp nuclear matter weighs 5×10^9 tons



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

Most* elements have a number of stable isotopes:

- Hydrogen has 2
  - ^{1}H has 1 proton, 0 neutrons (most abundant)
  - ^{2}H (deuterium) has 1 proton, 1 neutron $^{2}_{1}H$
- Oxygen has 3
  - ^{16}O has 8 protons, 8 neutrons (most abundant) $^{16}_{8}O$
  - ^{17}O has 8 protons, 9 neutrons (most rare)
  - ^{18}O has 8 protons, 10 neutrons (2nd most abundant)
- Fluorine has only 1
  - ^{19}F (9 protons, 10 neutrons) $^{19}_{9}F$
- Tin has 10 (all with 50 protons, 71-82 neutrons) $^{82}_{50}Sn$

Sometimes Z is dropped because element name is enough, e.g., ^{238}U

*Technetium & Promethium have no stable isotopes, e.g. ^{98}Tc ~ 4.2 Ma

Lecture 1

1. Underlying Principles
2. **Cosmic abundance of the elements and isotopes**
3. Isotope Stability
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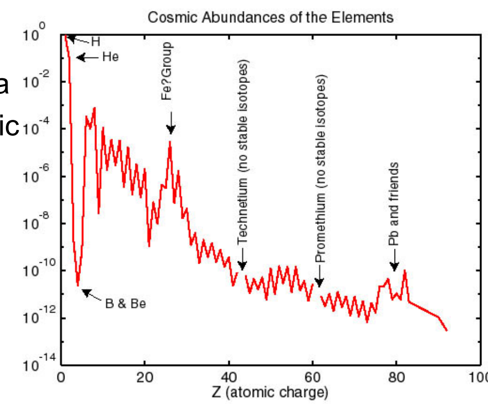
Cosmic abundance of the elements

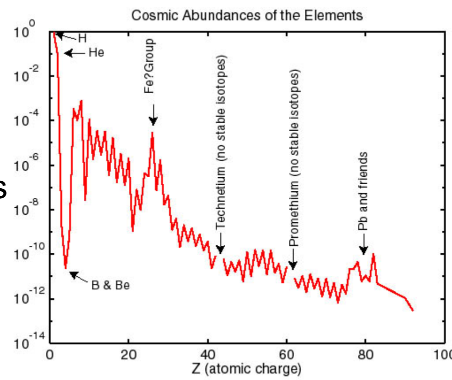
Obtained from:

- solar spectra
- stellar/galactic spectra
- meteorite samples
- cosmic dust
- cometary samples



Cosmic abundance of the elements

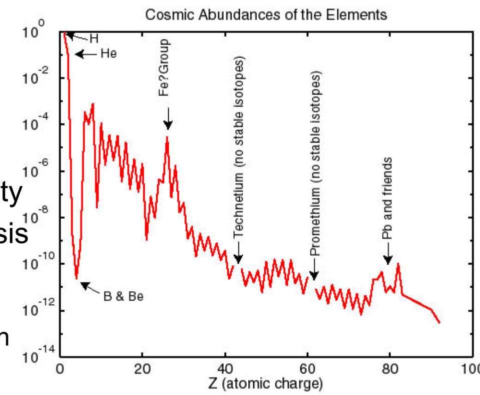
- Note Log Scale and Range
- General decrease with increasing mass
- Bulge at Fe
- Dip at B, Be
- ZigZag Pattern
- Bulge at Pb



Cosmic abundance of the elements

Why???

- Two answers:
  1. nuclear stability
  2. nucleosynthesis
     - big bang
     - galactic and stellar evolution

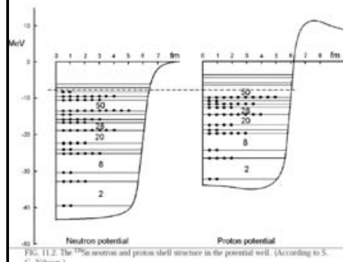


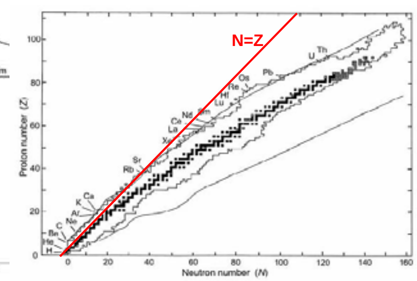
Lecture 1

1. Underlying Principles
2. Cosmic abundance of the elements and isotopes
3. **Isotope Stability**
4. Radioactive Decay

Isotopes

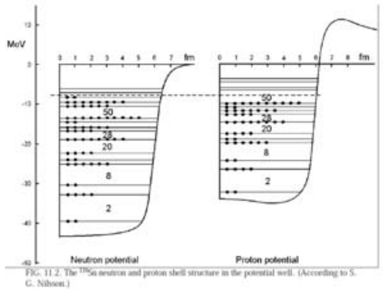
- Not all combinations of N and Z are "legal" (i.e., stable)
- Nuclear "stability" governed by
  - Quantum mechanical rules, nuclear forces, & electrostatic charge
  - Neutrons and protons fit into nuclear potential well, with Q-M energy levels and spin-pairing (they're fermions!)





Nuclear potential wells

- Vertical distance is energy level*
  - Lower means more stable
  - Negative means bound, 0 means free, positive means a barrier
- Horizontal distance from left is from center of nucleus
  - 1 fm = 10^{-15} m
- Think of "filling a cup"
- Note the following:
  - Quantized shell levels
    - Like electron orbitals
  - Protons see coulomb repulsion (charged)
    - Shape inside nucleus: balance between coulomb and strong nuclear forces
    - Coulomb barrier outside of nucleus
  - Neutrons more bound than protons
    - No barrier outside of nucleus
    - Filling both cups level means N > Z
- A more stable nucleus is lighter
  - Negative energy = mass deficit

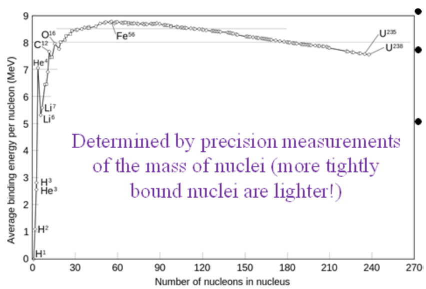


* 1 MeV = 10^6 electron volts (energy of a singly charged particle accelerated through a million volts)
Since $E=mc^2$ you have:
mass of proton ~ 1000 MeV
mass of electron ~ 0.5 MeV

Isotopes

- Nuclear "stability" governed by
  - Quantum mechanical rules
  - Nuclear forces
  - Electrostatic charge
- Different elements have varying numbers of stable isotopes
- When a nucleus is "unstable" it decays
  - The more unstable, the quicker it decays
    - Rates vary from <10^{-10} seconds to >10^{12} years

Controlling factors on nuclear stability

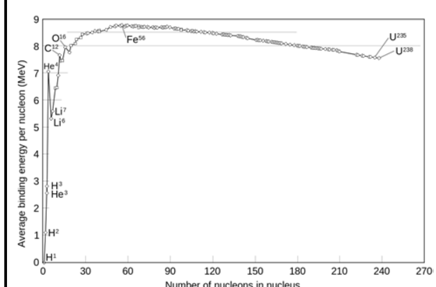


- Mass = energy
- Number nucleons
  - the more the merrier
- spin pairing (fermions)
  - favours even #s
  - also the abundance of stable isotopes

# p	# n	# n+p	#stable
Even	Even	Even	157
Even	Odd	Odd	53
Odd	Even	Odd	50
Odd	Odd	Even	4

Also means spin pairing distinguishes between n & p!

Controlling factors on nuclear stability

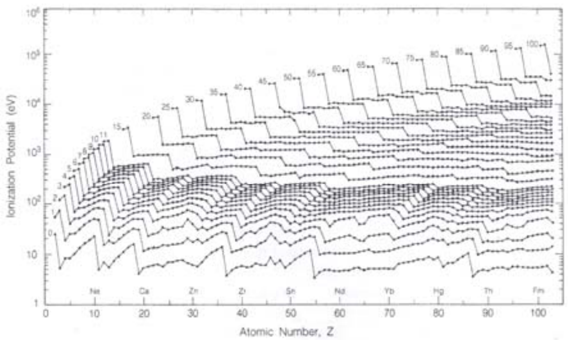


- Number nucleons
  - the more the merrier
- spin pairing
  - favours even #s
- shell structure
  - "magic numbers"
  - like atomic shells
  - popular #s of n or p

  2, 8, 14, 20, 28,…
  - ^{208}Pb is "doubly magic": Pb @ end of decay chains

Elements with magic "Z" generally have many more isotopes than neighbors

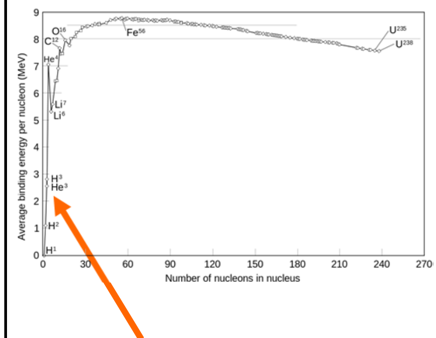
Quantum shells affect nuclear stability just like electron shells affect ionization potentials:



Ionization potentials for multiply charged ions of all of the elements

But the nuclear effect is not as pronounced as atomic shell structures (more forces & issues at work here…)

Controlling factors on nuclear stability

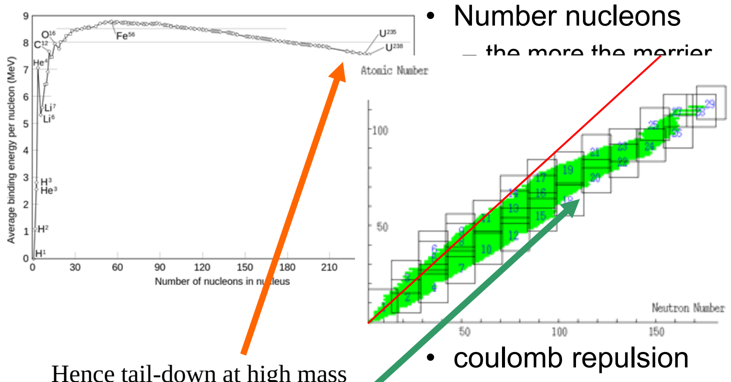


- Number nucleons
  - the more the merrier
- spin pairing
  - favours even #s
- shell structure
  - “magic numbers”
- surface tension
  - like liquid drop
  - (unrequited bonds)

Hence tail-down at low mass
(high surface area to volume ratio)

Controlling factors on nuclear stability

- Number nucleons
  - the more the merrier



- coulomb repulsion
  - limits ultimate size

Hence tail-down at high mass
… and drift to high-n nuclei

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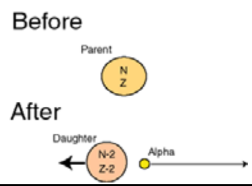
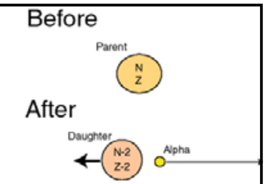
4. **Radioactive Decay**

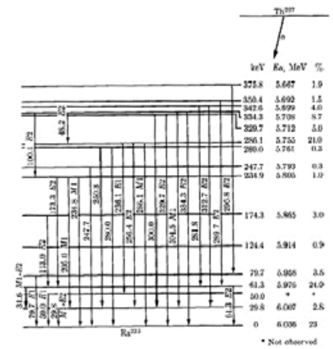
Modes of Radioactive Decay

- Alpha
  - done by heavy nuclei (e.g., ^{232}Th, ^{238}U, ^{235}U)
  - involves strong nuclear force
  - emission of ^4He nucleus (a doubly magic nucleus)
    - $\Delta A = 4$, $\Delta N = 2$, $\Delta Z = 2$
  - half-life inversely related to energy:
    - 10^{24} change in T for 3-fold change in energy
    - quantum-mechanical tunnelling
  - mono-energetic transitions (QM)
    - To a variety of nuclear (excited) states
      - Branching ratios
  - range ~ 10s of microns
    - (charged particle)



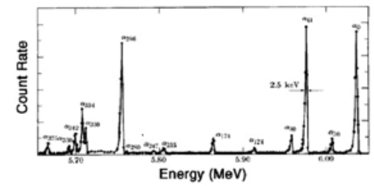
Alpha Decay





- Quantized transitions lead to mono-energetic radiation
  - Only one unique way to share energy & momentum
- Gamma decay from excited states

Bouncing > 6 MeV alpha particles off the daughter nucleus *doesn't* induce the reverse reaction! Why???



A 10 MeV alpha doesn't appear to get in

but a 5 MeV alpha somehow gets out…

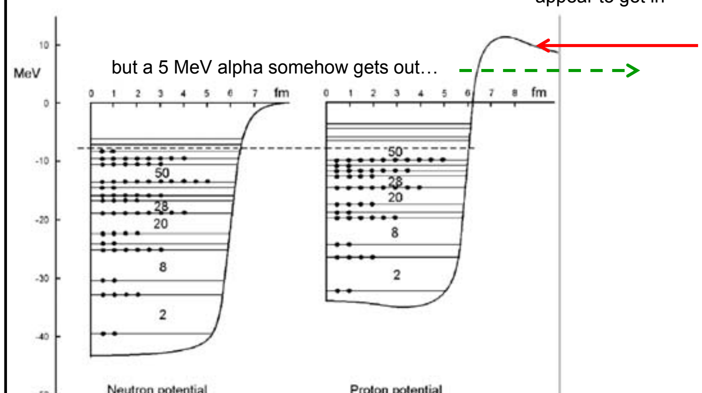
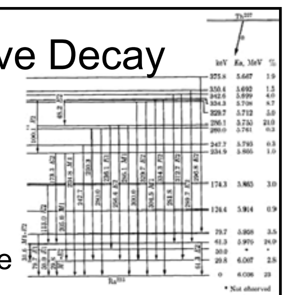


FIG. 11.2. The ^{116}Sn neutron and proton shell structure in the potential well. (According to S. G. Nilsson.)

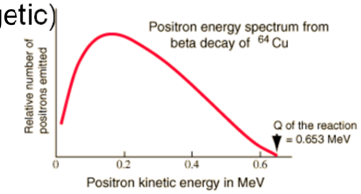
Modes of Radioactive Decay



- Alpha
- Gamma
  - emission of photon
  - involves electromagnetic force
  - results from alpha or beta decay
  - mono-energetic (QM), shell transitions, obeys spin rules
  - doesn't change chemistry (Z) or mass number (A = Z + N)
  - a shell transition in nucleus (just like electronic de-excitation)

Modes of Radioactive Decay

- Alpha
- Gamma
- Beta
  - emission of electron, positron, or by electron capture (inner orbital e^-)
  - involves weak nuclear force
  - energy spectrum in emitted β^+ or β^- (they are NOT monoenergetic)



*with 2 particles, only one unique way of sharing energy and momentum: 2 equations with 2 unknowns…

Must be a 3 body decay!

Modes of Radioactive Decay

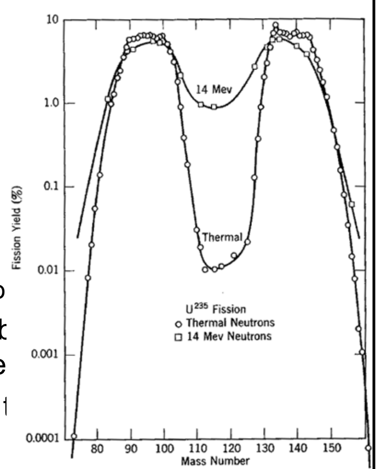
- Alpha
- Gamma
- Beta
  - emission of electron, positron, electron capture
  - involves weak nuclear force
  - energy spectrum (QM ➔ 3 body problem*)
  - emission of neutrino ν_e (next best thing to nothing), a V.I.P.** in particle physics, cosmology, and stellar evolution
  - Range (e ~ microns, neutrino ~ infinite)

*with 2 particles, only one unique way of sharing energy and momentum: 2 equations with 2 unknowns…

** Very Interesting Particle… also takes away 1/3 of the energy

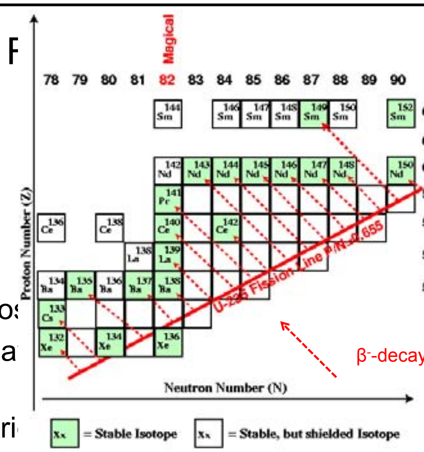
Modes of Radioactive Decay

- Alpha
- Beta
- Gamma
- Fission
  - caused by squishy, rules apply
    - e.g. ^{235}U more fissio
  - wobbly nuclei may b if kicked (by particle
  - Different sensitivity t
  - split is asymmetric



Modes of F

- Alpha
- Beta
- Gamma
- Fission
  - caused by squoos
  - wobbly nuclei ma if kicked
  - split is asymmetri
  - characteristic isotopic signatures



Important evidence for past events

Radioactive decay

Occurs by 4 mechanisms:
- α, β, γ, & fission

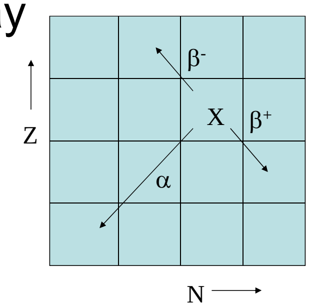
α decay results in loss of 2 protons and 2 neutrons

β^+ decay results from an p to n transition

β^- decay results from a n to p transition

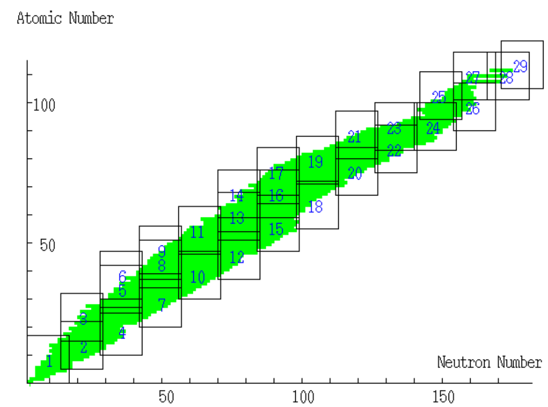
Fission splits down "mixing line"

All of these transitions can lead to γ decay (no change in N or Z)



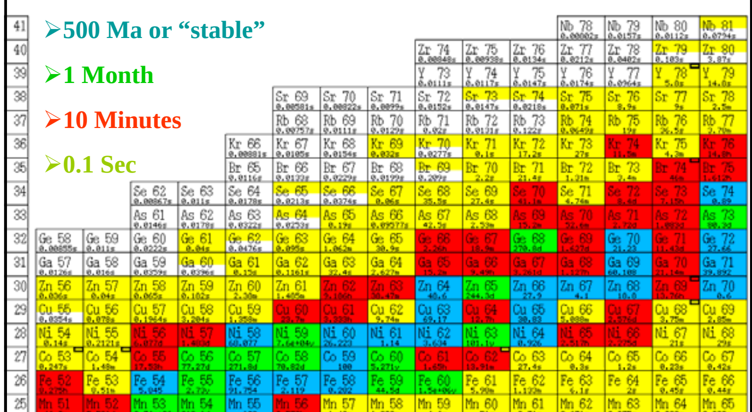
α decay can lead to yet another α decay or β^- decay (decay chains)

Chart of the nuclides



http://wwwndc.tokai.jaeri.go.jp/CN/

The further away an isotope is from the "valley of stability", the faster it decays



At the top end, we run out of stability

Consider downloading Isotope Explorer from http://isotopes.lbl.gov/toi.html

Final Notes

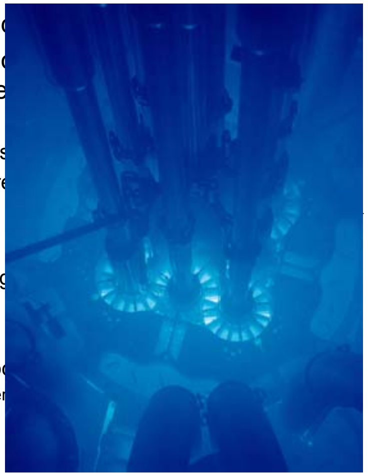
Although not really a mode of

- If a suitably energetic ph nuclear field it can create (e.g., e^+ and e^-)
  - Sum of rest mass energies
  - They move in opposite dir
  - This can happen *in vacuo*

Also there is Bremsstrahlung

- Photons emitted when a charg is bent in a magnetic field)

- And Cherenkov radiation
  - A photonic boom (like sonic b
    - When charged particles go faster traveling)



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