

## 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.who.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, Oct 18, 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

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- **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

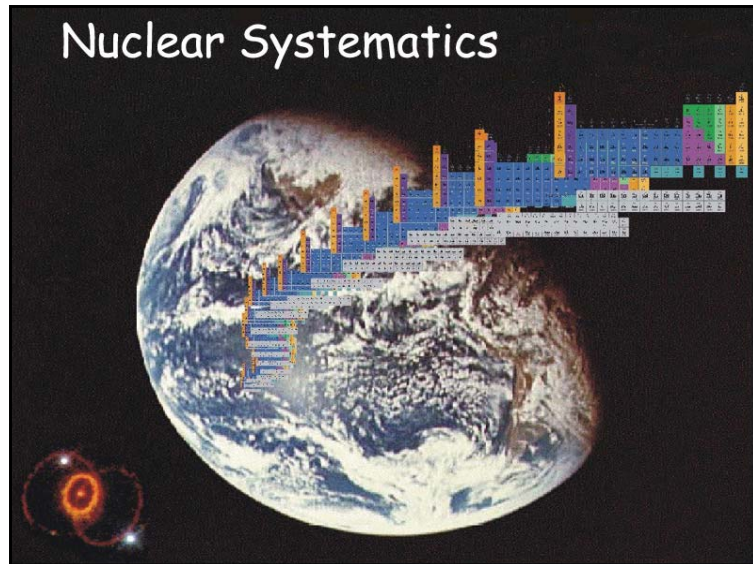
21 Lectures & 4 Problem Sessions\*

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

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- 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,  $10^{-15}\text{m}$ )
  - **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,  $10^{-18}\text{m}$ )
  - **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
- $1 \text{ g matter} \rightarrow 10^{14} \text{ J} \sim 2 \times 10^{13} \text{ cal}$

**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\*\*

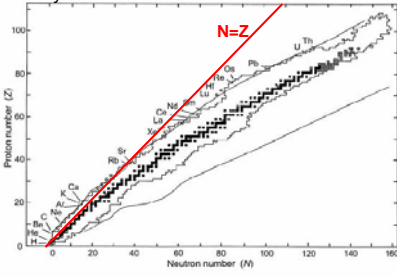
\*Largely baryonic (n & p)  
\*\*Dark energy is part of space-time fabric: space-time fabric is an unfurled 4-D part of an 11-D manifold (M-brane theory)

Familiar "matter" is Fermionic: protons, neutrons, electrons all have  $\frac{1}{2}$  integer spin  
Fermions cannot occupy the same space/wave function state

• Atoms consist of: **What are Isotopes?**

- Electrons ( $e^-$ ) in orbit
  - # $e^-$  define chemical state (ionization, bonding)
  - Number/distribution defined by nuclear charge & shell structure
  - Size  $\sim 1-3 \times 10^{-10}$  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  $\sim 1-3 \times 10^{-15}$  m\*
- Not all combinations of  $n$  and  $p$  are stable
  - # $n = N \sim \#p = Z$
  - $A = N + Z$
- Mass  $n \sim p, \sim 2000 \times e^-$

\*1 tsp nuclear matter weighs  $5 \times 10^9$  tons



The graph shows the relationship between the number of protons (Z) on the y-axis and the number of neutrons (N) on the x-axis, both ranging from 0 to 180. A red diagonal line represents the condition N=Z. Data points for various elements are plotted, showing a general trend where the number of neutrons increases with the number of protons. Elements labeled include H, He, Li, Be, B, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn, Fr, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr.

## Isotopes $\begin{matrix} A \\ Z \\ X \end{matrix}$

Most\* elements have a number of stable isotopes:

- Hydrogen has 2
  - $^1\text{H}$  has 1 proton, 0 neutrons (most abundant)
  - $^2\text{H}$  (deuterium) has 1 proton, 1 neutron  $^2_1\text{H}$
- Oxygen has 3
  - $^{16}\text{O}$  has 8 protons, 8 neutrons (most abundant)
  - $^{17}\text{O}$  has 8 protons, 9 neutrons (most rare)
  - $^{18}\text{O}$  has 8 protons, 10 neutrons (2<sup>nd</sup> most abundant)
- Fluorine has only 1
  - $^{19}\text{F}$  (9 protons, 10 neutrons)  $^{19}_9\text{F}$
- Tin has 10 (all with 50 protons, 71-82 neutrons)  $^{82}_{50}\text{Sn}$

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

\*Technetium & Promethium have no stable isotopes, e.g.  $^{98}\text{Tc} \sim 4.2$  Ma

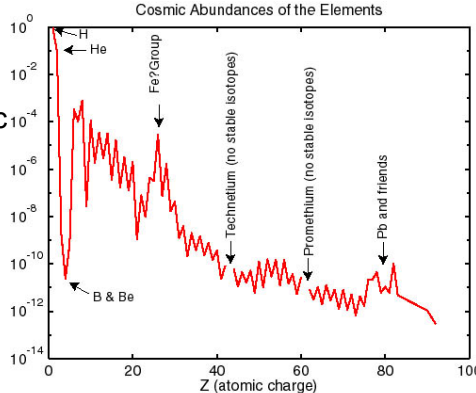
## Lecture 1

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

## Cosmic abundance of the elements

Obtained from:

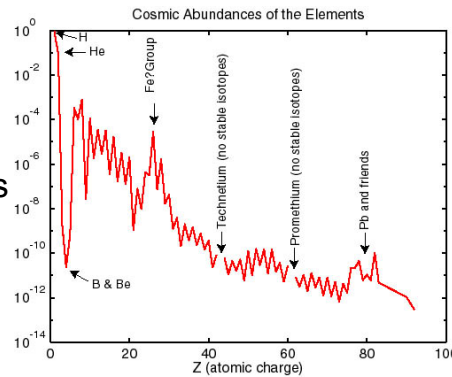
- solar spectra
- stellar/galactic spectra
- meteorite samples
- cosmic dust
- cometary samples



The graph shows the cosmic abundance of elements as a function of their atomic number (Z). The y-axis is logarithmic, representing relative abundance from  $10^0$  down to  $10^{-14}$ . The x-axis is linear, representing Z from 0 to 100. The curve shows a general downward trend with oscillations. Key features are labeled: H and He at Z=1 and 2; B & Be at Z=5 and 6; Fe? Group at Z=26; Technetium (no stable isotopes) at Z=43; Promethium (no stable isotopes) at Z=61; and Pb and friends at Z=82.

## Cosmic abundance of the elements

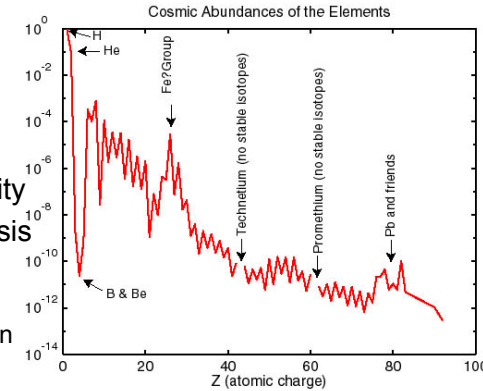
- Note Log Scale and Range
- General decrease with increasing mass
- Bulge at Fe
- Dip at B, Be
- ZigZag Pattern
- Bulge at Pb



## Cosmic abundance of the elements

Why???

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

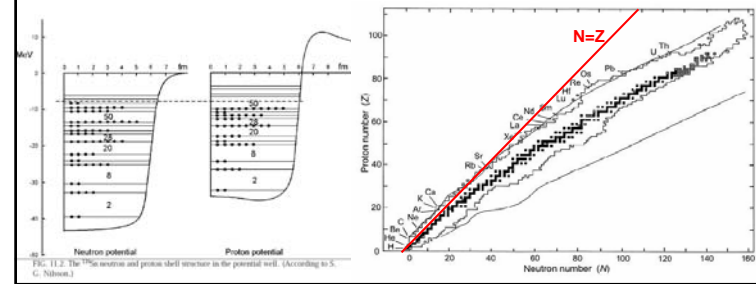


## Lecture 1

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

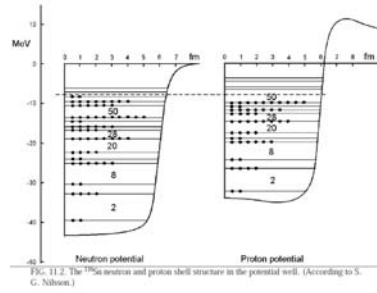


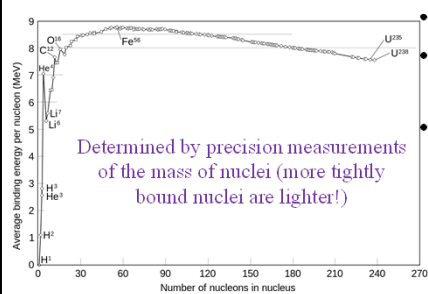
FIG. 11.2. The  $^{190}\text{Se}$  neutron and proton shell structure in the potential well. (According to S. G. Nilsson.)

\* 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

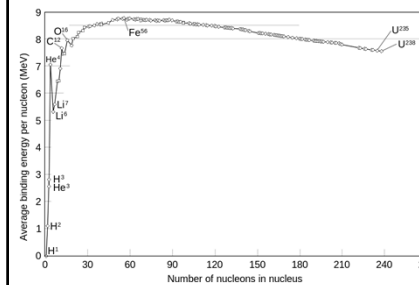


- Mass = energy
- Number nucleons
  - the more the merrier
- spin pairing (fermions)
  - favours even #s
  - also the abundance of stable isotopes

# 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!

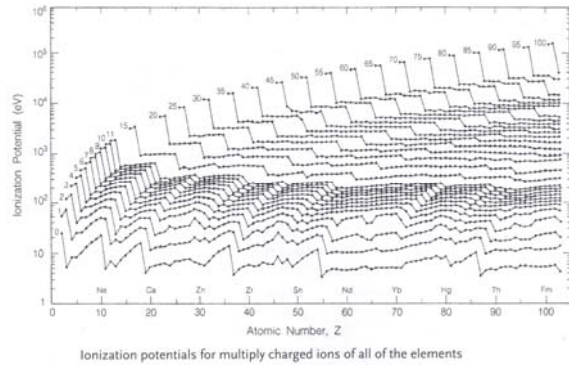
## Controlling factors on nuclear stability



- 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,...
  - $^{208}\text{Pb}$  is “doubly magic”: Pb @ end of decay chains

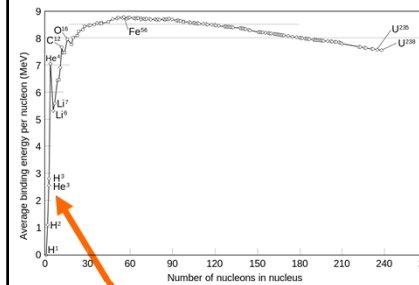
Elements with magic “Z” generally have many more isotopes than neighbors

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



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

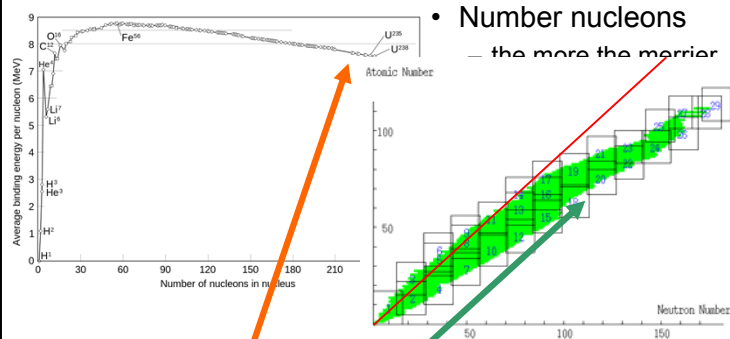
## Controlling factors on nuclear stability



- 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



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

- Number nucleons
  - the more the merrier
- coulomb repulsion
  - limits ultimate size

## Lecture 1

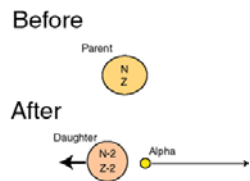
1. Underlying Principles
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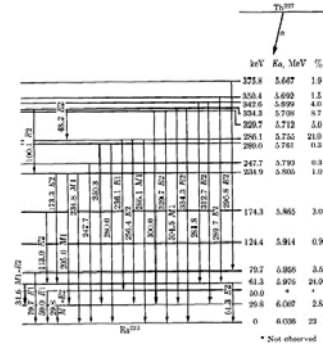
## Modes of Radioactive Decay

- Alpha

- done by heavy nuclei (e.g.,  $^{232}\text{Th}$ ,  $^{238}\text{U}$ ,  $^{235}\text{U}$ )
- involves strong nuclear force
- emission of  $^4\text{He}$  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  $\sim 10\text{s}$  of microns
  - (charged particle)



## Alpha Decay



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

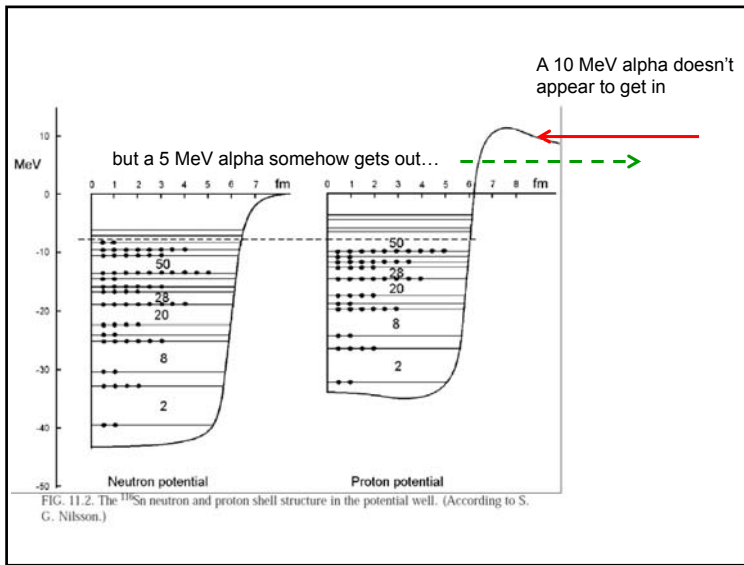
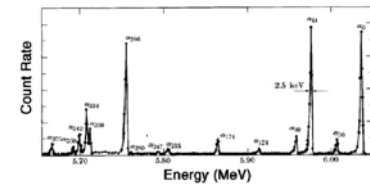
Before



After

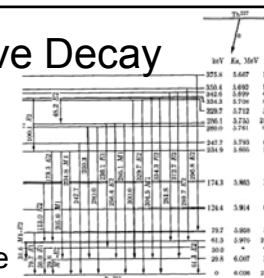


- Quantized transitions lead to mono-energetic radiation
  - Only one unique way to share energy & momentum
- Gamma decay from excited states



## 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)



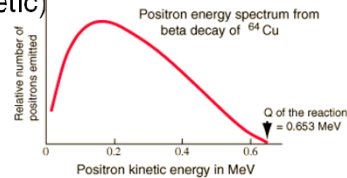


## Modes of Radioactive Decay

- Alpha
- Gamma
- Beta
  - emission of electron, positron, or by electron capture (inner orbital  $e^-$ )
  - involves weak nuclear force
  - energy spectrum in emitted  $\beta^+$  or  $\beta^-$  (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

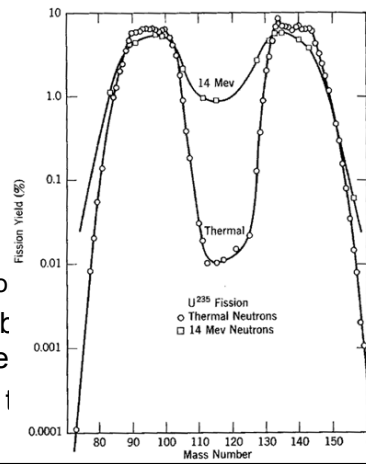
- Alpha
- Gamma
- Beta
  - emission of electron, positron, electron capture
  - involves weak nuclear force
  - energy spectrum (QM  $\rightarrow$  3 body problem\*)
  - emission of neutrino  $\nu_e$  (next best thing to nothing), a V.I.P.\*\* in particle physics, cosmology, and stellar evolution
  -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

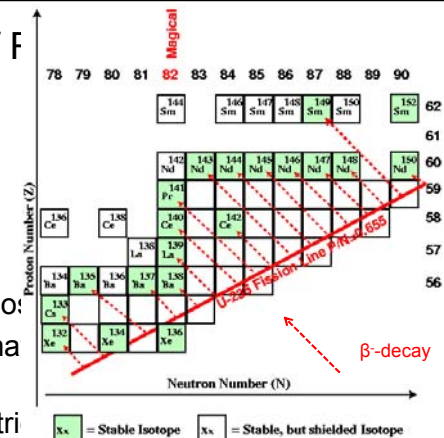
## Modes of Radioactive Decay

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



## Modes of F

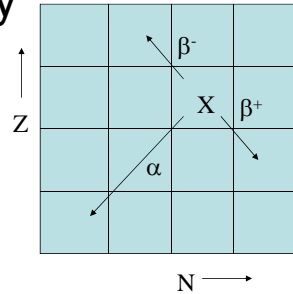
- Alpha
- Beta
- Gamma
- Fission
  - caused by squoo:
  - wobbly nuclei ma if kicked
  - split is asymmetri
  - characteristic isotopic signatures



Important evidence for past events

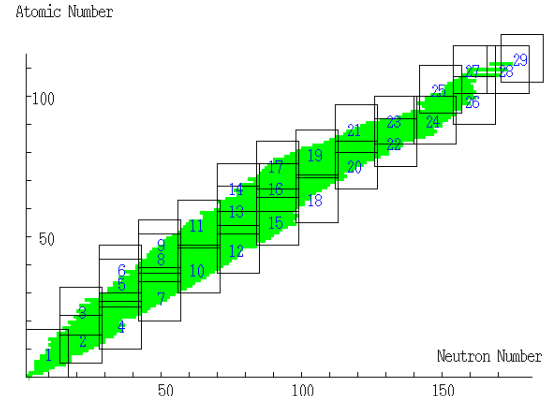
# Radioactive decay

- Occurs by 4 mechanisms:
  - $\alpha$ ,  $\beta^-$ ,  $\gamma$ , & fission
- $\alpha$  decay results in loss of 2 protons and 2 neutrons
- $\beta^+$  decay results from an p to n transition
- $\beta^-$  decay results from a n to p transition
- Fission splits down "mixing line"
- All of these transitions can lead to  $\gamma$  decay (no change in N or Z)



$\alpha$  decay can lead to yet another  $\alpha$  decay or  $\beta^-$  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

41	<b>&gt;500 Ma or "stable"</b>																Nb 78	Nb 79	Nb 80	Nb 81													
40	<b>&gt;1 Month</b>																Zr 74	Zr 75	Zr 76	Zr 77	Zr 78	Zr 79	Zr 80	Zr 81	Zr 82								
38	<b>&gt;10 Minutes</b>																Sr 68	Sr 69	Sr 70	Sr 71	Sr 72	Sr 73	Sr 74	Sr 75	Sr 76	Sr 77							
36	<b>&gt;0.1 Sec</b>																Kr 66	Kr 67	Kr 68	Kr 69	Kr 70	Kr 71	Kr 72	Kr 73	Kr 74	Kr 75	Kr 76						
34																	Se 62	Se 63	Se 64	Se 65	Se 66	Se 67	Se 68	Se 69	Se 70	Se 71	Se 72	Se 73	Se 74				
32																	Ge 58	Ge 59	Ge 60	Ge 61	Ge 62	Ge 63	Ge 64	Ge 65	Ge 66	Ge 67	Ge 68	Ge 69	Ge 70	Ge 71	Ge 72		
30																	Zn 56	Zn 57	Zn 58	Zn 59	Zn 60	Zn 61	Zn 62	Zn 63	Zn 64	Zn 65	Zn 66	Zn 67	Zn 68	Zn 69	Zn 70		
28																	Ni 54	Ni 55	Ni 56	Ni 57	Ni 58	Ni 59	Ni 60	Ni 61	Ni 62	Ni 63	Ni 64	Ni 65	Ni 66	Ni 67	Ni 68		
26																	Fe 52	Fe 53	Fe 54	Fe 55	Fe 56	Fe 57	Fe 58	Fe 59	Fe 60	Fe 61	Fe 62	Fe 63	Fe 64	Fe 65	Fe 66		
24																	Cu 46	Cu 47	Cu 48	Cu 49	Cu 50	Cu 51	Cu 52	Cu 53	Cu 54	Cu 55	Cu 56	Cu 57	Cu 58	Cu 59	Cu 60		
22																	Ti 42	Ti 43	Ti 44	Ti 45	Ti 46	Ti 47	Ti 48	Ti 49	Ti 50	Ti 51	Ti 52	Ti 53	Ti 54	Ti 55	Ti 56		
20																	Ca 38	Ca 39	Ca 40	Ca 41	Ca 42	Ca 43	Ca 44	Ca 45	Ca 46	Ca 47	Ca 48	Ca 49	Ca 50	Ca 51	Ca 52		
18																	Ar 34	Ar 35	Ar 36	Ar 37	Ar 38	Ar 39	Ar 40	Ar 41	Ar 42	Ar 43	Ar 44	Ar 45	Ar 46	Ar 47	Ar 48		
16																	S 30	S 31	S 32	S 33	S 34	S 35	S 36	S 37	S 38	S 39	S 40	S 41	S 42	S 43	S 44		
14																	Si 26	Si 27	Si 28	Si 29	Si 30	Si 31	Si 32	Si 33	Si 34	Si 35	Si 36	Si 37	Si 38	Si 39	Si 40	Si 41	
12																	Mg 22	Mg 23	Mg 24	Mg 25	Mg 26	Mg 27	Mg 28	Mg 29	Mg 30	Mg 31	Mg 32	Mg 33	Mg 34	Mg 35	Mg 36	Mg 37	
10																	Ne 18	Ne 19	Ne 20	Ne 21	Ne 22	Ne 23	Ne 24	Ne 25	Ne 26	Ne 27	Ne 28	Ne 29	Ne 30	Ne 31	Ne 32	Ne 33	
8																	O 14	O 15	O 16	O 17	O 18	O 19	O 20	O 21	O 22	O 23	O 24	O 25	O 26	O 27	O 28	O 29	O 30
6																	C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	C 18	C 19	C 20	C 21	C 22	C 23	C 24	C 25	C 26
4																	Be 6	Be 7	Be 8	Be 9	Be 10	Be 11	Be 12	Be 13	Be 14	Be 15	Be 16	Be 17	Be 18	Be 19	Be 20	Be 21	Be 22
2																	He 2	He 3	He 4	He 5	He 6	He 7	He 8	He 9	He 10	He 11	He 12	He 13	He 14	He 15	He 16	He 17	He 18

At the top end, we run out of stability

98	Ba237	Ba238	Ba239	Ba240	Ba241	Ba242	Ba243	Ba244	Ba245	Ba246	Ba247	Ba248	Ba249	Ba250	Ba251
98	Cf236	Cf237	Cf238	Cf239	Cf240	Cf241	Cf242	Cf243	Cf244	Cf245	Cf246	Cf247	Cf248	Cf249	Cf250
97	Bk235	Bk236	Bk237	Bk238	Bk239	Bk240	Bk241	Bk242	Bk243	Bk244	Bk245	Bk246	Bk247	Bk248	Bk249
96	Am234	Am235	Am236	Am237	Am238	Am239	Am240	Am241	Am242	Am243	Am244	Am245	Am246	Am247	Am248
96	Am233	Am234	Am235	Am236	Am237	Am238	Am239	Am240	Am241	Am242	Am243	Am244	Am245	Am246	Am247
94	Pu232	Pu233	Pu234	Pu235	Pu236	Pu237	Pu238	Pu239	Pu240	Pu241	Pu242	Pu243	Pu244	Pu245	Pu246
93	Np231	Np232	Np233	Np234	Np235	Np236	Np237	Np238	Np239	Np240	Np241	Np242	Np243	Np244	Np245
92	U 230	U 231	U 232	U 233	U 234	U 235	U 236	U 237	U 238	U 239	U 240	U 241	U 242	U 243	U 244
91	Pa229	Pa230	Pa231	Pa232	Pa233	Pa234	Pa235	Pa236	Pa237	Pa238	Pa239	Pa240	Pa241	Pa242	Pa243
90	Th228	Th229	Th230	Th231	Th232	Th233	Th234	Th235	Th236	Th237	Th238	Th239	Th240	Th241	Th242
89	Ac227	Ac228	Ac229	Ac230	Ac231	Ac232	Ac233	Ac234	Ac235	Ac236	Ac237	Ac238	Ac239	Ac240	Ac241
88	Ra226	Ra227	Ra228	Ra229	Ra230	Ra231	Ra232	Ra233	Ra234	Ra235	Ra236	Ra237	Ra238	Ra239	Ra240
87	Fr225	Fr226	Fr227	Fr228	Fr229	Fr230	Fr231	Fr232	Fr233	Fr234	Fr235	Fr236	Fr237	Fr238	Fr239
86	Rn224	Rn225	Rn226	Rn227	Rn228	Rn229	Rn230	Rn231	Rn232	Rn233	Rn234	Rn235	Rn236	Rn237	Rn238
86	At223	At224	At225	At226	At227	At228	At229	At230	At231	At232	At233	At234	At235	At236	At237
84	Po222	Po223	Po224	Po225	Po226	Po227	Po228	Po229	Po230	Po231	Po232	Po233	Po234	Po235	Po236
83	Bi221	Bi222	Bi223	Bi224	Bi225	Bi226	Bi227	Bi228	Bi229	Bi230	Bi231	Bi232	Bi233	Bi234	Bi235

Consider downloading [Isotope Explorer](http://isotopes.lbl.gov/toi.html) from <http://isotopes.lbl.gov/toi.html>

## Final Notes

Although not really a mode of decay

- If a suitably energetic photon enters a nuclear field it can create a pair (e.g.,  $e^+$  and  $e^-$ )

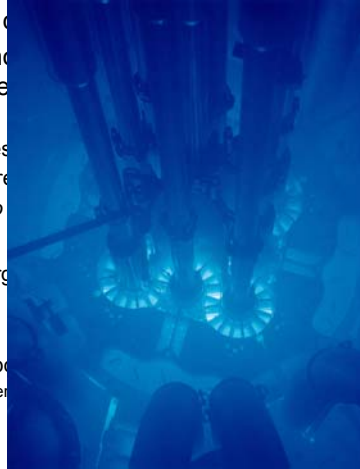
- Sum of rest mass energies
- They move in opposite directions
- This can happen *in vacuo*

Also there is Bremsstrahlung

- Photons emitted when a charged particle is bent in a magnetic field)

• And Cherenkov radiation

- A photonic boom (like sonic boom)
  - When charged particles go faster than the speed of light in a medium (traveling)



## Lecture 1

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