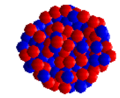

Byron Nuclear Power Plant

Nuclear Fission

What's it all about?



What's in a Nucleus

- The nucleus of an atom is made up of protons and neutrons
  - each is about 2000 times the mass of the electron, and thus constitutes the vast majority of the mass of a neutral atom (equal number of protons and electrons)
  - proton has positive charge; mass = 1.007276 a.m.u.
  - neutron has no charge; mass = 1.008665 a.m.u.
  - proton by itself (hydrogen nucleus) will last forever
  - neutron by itself will "decay" with a half-life of 10.4 min
  - size of nucleus is about 0.00001 times size of atom
    - atom is then mostly empty space

Puzzle: Carbon-based a.m.u.

- The atomic mass unit (a.m.u.) is based on ^{12}C
  - 6 protons, 6 neutrons, 6 electrons
  - defined to be 12.0000000000 a.m.u.
- Adding up the constituent masses:
  - protons: 6×1.00727647 = 6.04365876
  - neutrons: 6×1.008664923 = 6.051989538
  - electrons: 6×0.000548579909 = 0.0032914
  - all together: 12.09894
- But this isn't 12.000000
  - differs by 0.82%
- What could possibly *lower* the mass?

What holds it together?

- If like charges repel, and the nucleus is full of protons (positive charges), why doesn't it fly apart?
  - repulsion is from electromagnetic force
  - at close scales, another force takes over: the *strong nuclear force*
- The *strong force* operates between quarks: the building blocks of both protons and neutrons
  - it's a short-range force only: confined to nuclear sizes
  - this binding overpowers the charge repulsion
  - and the *binding energy* **reduces** the mass of the composite
    - separating tightly bound particles requires energy input
    - so much energy, that it registers mass equivalent via $E = mc^2$
    - mass left after separating must account for energy to split

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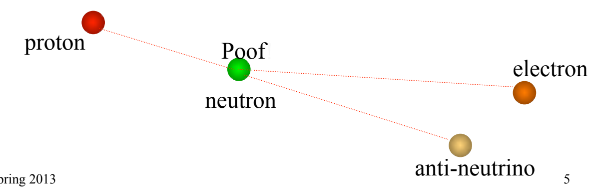
What's the deal with neutrons decaying?!

- A neutron, which is heavier than a proton, can (and will!) decide to switch to the lower-energy state of the proton
- Charge is conserved, so produces an electron too
  - and an anti-neutrino, a chargeless, nearly massless cousin to the electron



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Insight from the decaying neutron

- Another force, called the weak nuclear force, mediates these "flavor" changes
- Does this mean the neutron is *made* from an electron and proton?
  - No. But it will do you little harm to think of it this way
- Mass-energy conservation:
  - Mass of neutron is 1.008665 a.m.u.
  - Mass of proton plus electron is 1.007276 + 0.000548 = 1.007824
  - difference is 0.000841 a.m.u. (more than the electron mass)
  - in kg: 1.4×10^{-30} kg = 1.26×10^{-13} J = 0.783 MeV via $E = mc^2$
    - 1 a.m.u. = 1.6605×10^{-27} kg
    - 1 eV = 1.602×10^{-19} J
  - excess energy goes into *kinetic* energy of particles

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Counting particles

- A nucleus has a definite number of protons (*Z*), a definite number of neutrons (*N*), and a definite total number of *nucleons*: $A = Z + N$
  - example, the most common *isotope* of carbon has 6 protons and 6 neutrons (denoted ^{12}C; 98.9% abundance)
    - $Z = 6$; $N = 6$; $A = 12$
  - another stable *isotope* of carbon has 6 protons and 7 neutrons (denoted ^{13}C; 1.1% abundance)
    - $Z = 6$; $N = 7$; $A = 13$
  - an *unstable* isotope of carbon has 6 protons and 8 neutrons (denoted ^{14}C; half-life is 5730 years)
    - decays via beta decay to ^{14}N
- Isotopes of an element have same *Z*, differing *N*

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Full notation

- A fully annotated nucleon symbol has the total nucleon number, *A*, the proton number, *Z*, and the neutron number, *N* positioned around the symbol

$$^{A}_{Z}X_{N}$$

  - redundancy in that $A = Z + N$
- Examples:
  - carbon-12: $^{12}_{6}C_{6}$
  - carbon-14: $^{14}_{6}C_{8}$
  - uranium-235: $^{235}_{92}U_{143}$
  - uranium-238: $^{238}_{92}U_{146}$
  - plutonium-239: $^{239}_{94}Pu_{145}$

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Radioactivity

- Any time a nucleus spontaneously emits a particle…
  - electron through beta (β^-) decay
    - increase Z by 1; decrease N by 1; A remains the same
  - positron (anti-electron) through beta (β^+) decay
    - decrease Z by 1; increase N by 1; A remains the same
  - alpha (α) particle (^{4}He nucleus)
    - decrease Z by 2; decrease N by 2; decrease A by 4
  - gamma (γ) ray (high-energy photon of light)
    - Z, N, A unchanged (stays the same nucleus, just loses energy)
- …we say it underwent a *radioactive* transformation
- Certain isotopes of nuclei are radioactively unstable
  - they will eventually change flavor by a radioactive particle emission
  - α, β, γ emission constitutes a minor change to the nucleus
    - not as dramatic as splitting the entire nucleus in two large parts

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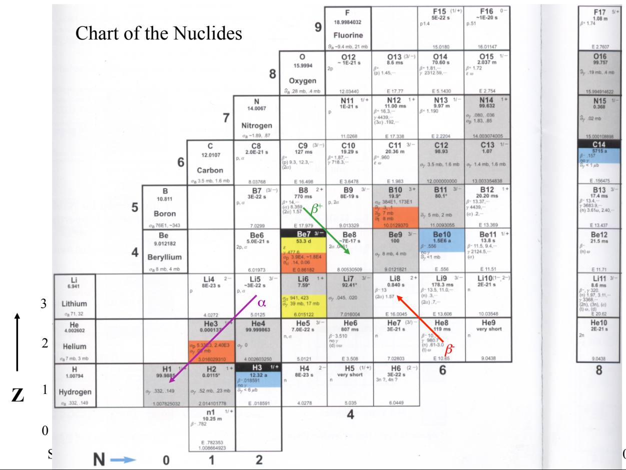
The Physicist's Periodic Table



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Radioactivity Demonstration

- Have a Geiger counter that clicks whenever it detects a gamma ray, beta decay particle, or alpha particle.
  - not 100% efficient at detection, but representative of rate
- Have three sources:
  - ^{14}C (carbon-14) with half life of 5730 years (to ^{14}N)
    - about 4200 β^- decays per second in this sample
    - corresponds to 25 ng, or 10^{15} particles
  - ^{90}Sr (strontium-90) with half-life of 28.9 years
    - about 180 β^- decays per second in this sample (actually double this)
    - contains about 40 pg (240 billion nuclei; was 450 billion in 1987)
    - produced in nuclear reactor
  - ^{40}K (potassium-14) with half-life of 1.27 Gyr (to ^{40}Ca)
    - 0.0117% of natural potassium
    - 4 cm^3 of KCl has ~4×10^{18} ^{40}K particles; 70 β^- decays/sec

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Natural radioactive dose in mrem/year

Source	**Sea Level**	**Denver**
cosmic rays	28	55
terrestrial (rock)	46	90
food and water	40	
air (mostly radon)	200	
air travel	1 per 1,000 miles traveled	
house	7 if made of stone/brick/concrete	
medical X-ray	40 each (airport X-ray negligible)	
nuclear med. treatment	14 each	
within 50 miles of nuclear plant	0.009	
within 50 miles of coal plant	0.03	
total for no travel/medical	**316**	**387**

source: http://www.epa.gov/radiation/understand/calculate.html

1 mrem carries 0.000055% chance of developing cancer: 350 mrem/yr → expect cancer in 5000 years

Fission of Uranium

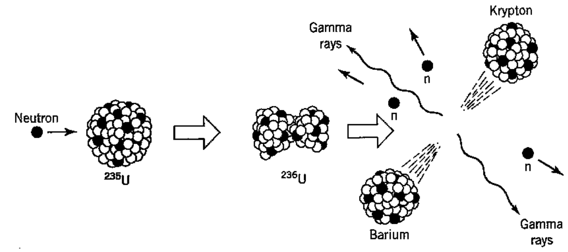

Figure 6.1 Three steps in the neutron-induced fission of ^{235}U. The combination of a neutron and ^{235}U forms ^{236}U in a highly excited state, that promptly fissions into two lighter nuclei, emitting neutrons and gamma rays in the process.

Barium and Krypton represent just one of many potential outcomes

Fission

- There are only three known *nuclides* (arrangements of protons and neutrons) that undergo fission when introduced to a slow (thermal) neutron:
  - ^{233}U: hardly used (hard to get/make)
  - ^{235}U: primary fuel for reactors
  - ^{239}Pu: popular in bombs
- Others may split if smacked hard enough by a neutron (or other energetic particle)

How much more *fissile* is ^{235}U than ^{238}U?

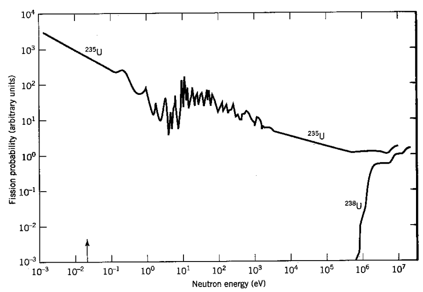

Figure 6.2 The fission probability for ^{235}U and ^{238}U as a function of neutron energy. The arrow at 0.025 eV indicates the energy of thermalized neutrons. For ^{238}U the fission probability becomes appreciable only above about 1 MeV neutron energy.

Bottom line: at thermal energies (arrow), ^{235}U is 1000 times more likely to undergo fission than ^{238}U even when smacked hard

Uranium isotopes and others of interest

Isotope	Abundance (%)	half-life	decays by:
^{233}U	0	159 kyr	α
^{234}U	0.0055	246 kyr	α
^{235}U	0.720	704 Myr	α
^{236}U	0	23 Myr	α
^{237}U	0	6.8 days	β^-
^{238}U	99.2745	4.47 Gyr	α
^{239}Pu	no natural Pu	24 kyr	α
^{232}Th	100	14 Gyr	α

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The Uranium Story

- *No* isotope of uranium is perfectly stable:
  - ^{235}U has a half-life of 704 million years
  - ^{238}U has a half-life of 4.5 billion years (age of earth)
- No heavy elements were made in the Big Bang (just H, He, Li, and a tiny bit of Be)
- Stars only make elements as heavy as iron (Fe) through natural thermonuclear fusion
- Heavier elements made in catastrophic supernovae
  - massive stars that explode after they're spent on fusion
- ^{235}U and ^{238}U initially had similar abundance

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Uranium decay

- The natural abundance of uranium today suggests that it was created about 6 billion years ago
  - assumes ^{235}U and ^{238}U originally equally abundant
  - Now have 39.8% of original ^{238}U and 0.29% of original ^{235}U
  - works out to 0.72% ^{235}U abundance today
- Plutonium-239 half-life is too short (24,000 yr) to have any naturally available
- Thorium-232 is *very* long-lived, and is a major contributor to geothermal heat
  - though ^{238}U, ^{235}U, and ^{40}K contribute as well

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Why uranium?

- Why mess with "rare-earth" materials? Why not force lighter, more abundant nuclei to split?
  - though only three "slow-neutron" fissile nuclei are known, what about this "smacking" business?
- Turns out, you would actually *loose* energy in splitting lighter nuclei
- Iron is about the most tightly bound of the nuclides
  - and it's the release of binding energy that we harvest
  - so we want to drive toward iron to get the most out

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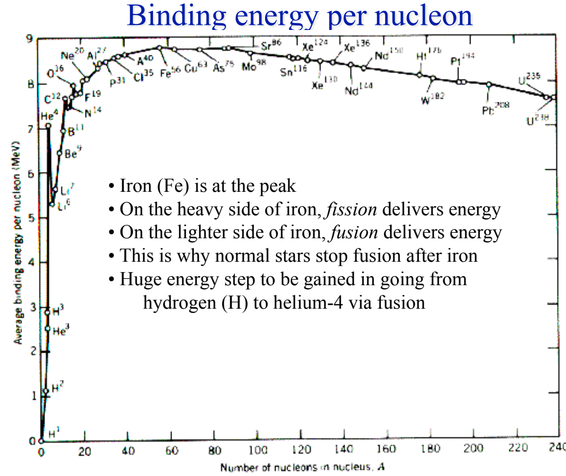
Binding energy per nucleon



- Iron (Fe) is at the peak
- On the heavy side of iron, *fission* delivers energy
- On the lighter side of iron, *fusion* delivers energy
- This is why normal stars stop fusion after iron
- Huge energy step to be gained in going from hydrogen (H) to helium-4 via fusion

What does uranium break into? (fish 'n chips)

- Uranium doesn't break into two equal pieces
  - usually one with mass around 95 a.m.u. and one with mass around 140 a.m.u.
- The fragments are very neutron-rich, and some drip off immediately
  - these can spur additional fission events…
- Even after the neutron-drip, the fragments rapidly undergo radioactive transformations until they hit stable configurations

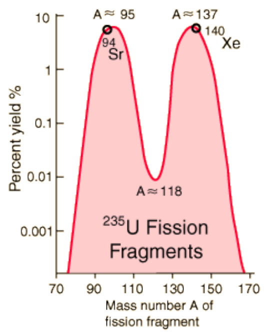
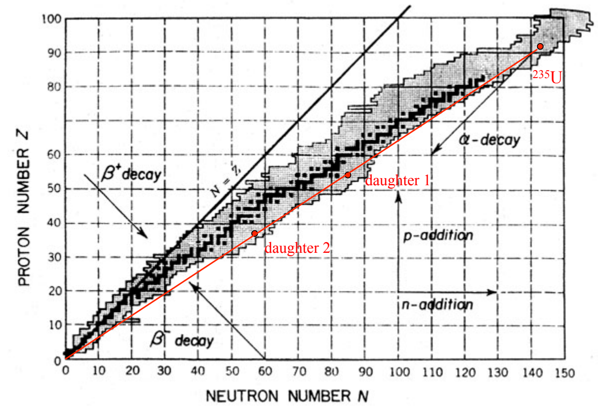


Chart of the nuclides

daughter nuclei from fission are neutron-rich, and β^- decay toward black (stable) nuclei
some can fall outside of neutron "drip line" in white region (don't have to be right on red line)



■ stable nuclide
■ radioactive (unstable) nuclide

Messy details summarized

- ^{235}U will undergo spontaneous fission if a neutron happens by, resulting in:
  - two sizable nuclear fragments flying out
  - a few extra neutrons
  - gamma rays from excited states of daughter nuclei
  - energetic electrons from beta-decay of daughters
- The net result: lots of banging around
  - generates heat locally (kinetic energy of tiny particles)
  - for every gram of ^{235}U, get 65 trillion Joules, or about 16 million Calories
  - compare to gasoline at roughly 10 Calories per gram
    - a tank of gas could be replaced by a 1-mm pellet of ^{235}U!!

Aside on nuclear bombs

- Since neutrons initiate fission, and each fission creates more neutrons, there is potential for a chain reaction
- Have to have enough fissile material around to intercept liberated neutrons
- Critical mass for ^{235}U is about 15 kg, for ^{239}Pu it's about 5 kg
- Bomb is dirt-simple: separate two sub-critical masses and just put them next to each other (quickly) when you want them to explode!
  - difficulty is in *enriching* natural uranium to mostly ^{235}U

Assignments

- Continue to read chapter 6
- Optional Do the Math reading:
  - 29. Nuclear Options
- Power Plant tour sign up sheets up front
  - Tuesday 2:00 to 2:50 PM
  - Wednesday 2:00 to 2:50 PM
  - must wear long pants and closed-toed shoes