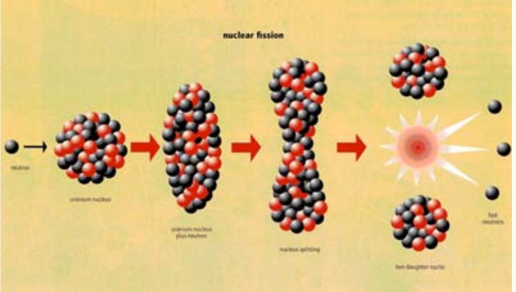
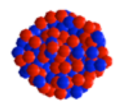


Nuclear Energy

Fission, Fusion, the Sun's Energy



What's in a Nucleus

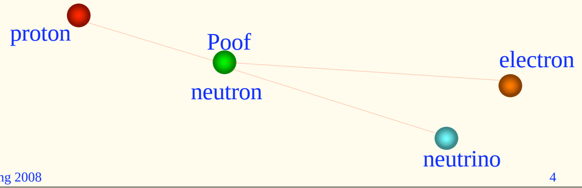
- The nucleus of an atom is made up of protons and neutrons
  - each is about 2000 times the mass of the electron, and thus constitutes the vast majority of the mass of a neutral atom (equal number of protons and electrons)
  - proton has positive charge; mass = 1.007276 a.m.u.
  - neutron has no charge; 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

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

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



Insight from the decaying neutron

- Another force, called the weak nuclear force, mediates these “flavor” changes
  - referred to as beta decay
- 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.
  - 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

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

Fission of Uranium

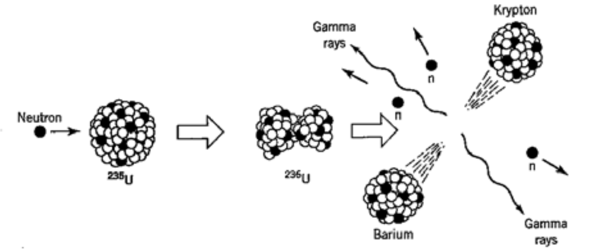


Figure 6.1 Three steps in the neutron-induced fission of ^{235}U. The combination of a neutron and ^{235}U forms ^{236}U in a highly excited state, that promptly fissions into two lighter nuclei, emitting neutrons and gamma rays in the process.

Barium and Krypton represent just one of many potential outcomes

Resulting mass products add up to 99.9% of the mass that went in

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?

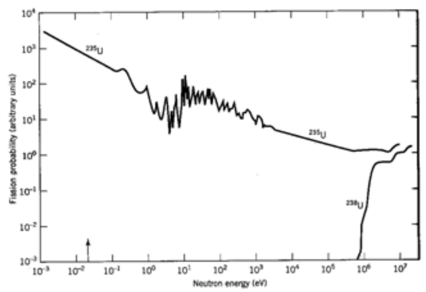


Figure 6.2 The fission probability for ^{235}U and ^{238}U as a function of neutron energy. The arrow at 0.025 eV indicates the energy of thermalized neutrons. For ^{238}U the fission probability becomes appreciable only above about 1 MeV neutron energy.

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

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

Uranium decay

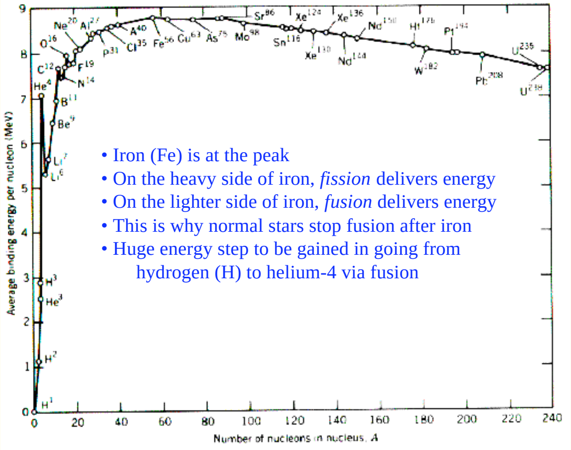
- The natural abundance of uranium today suggests that it was created about 6 billion years ago
  - assumes ^{235}U and ^{238}U originally equally abundant
  - Now have 39.8% of original ^{238}U and 0.29% of original ^{235}U
  - works out to 0.72% ^{235}U abundance today
- Plutonium-239 half-life is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

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

2×Q

Binding energy per nucleon

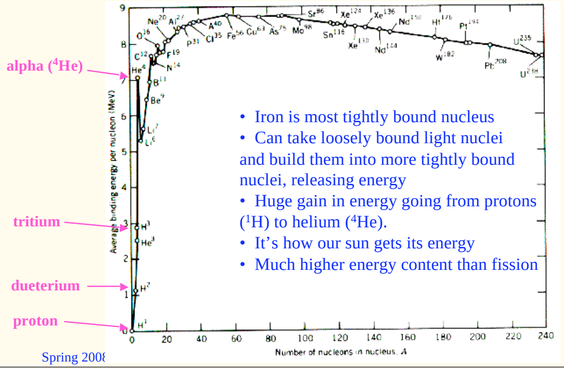


- Iron (Fe) is at the peak
- On the heavy side of iron, *fission* delivers energy
- On the lighter side of iron, *fusion* delivers energy
- This is why normal stars stop fusion after iron
- Huge energy step to be gained in going from hydrogen (H) to helium-4 via fusion

---

Fusion: The big nuclear hope

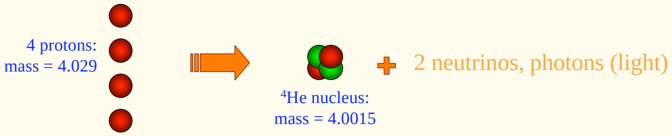
- Rather than rip nuclei apart, how about putting them together?



- Iron is most tightly bound nucleus
- Can take loosely bound light nuclei and build them into more tightly bound nuclei, releasing energy
- Huge gain in energy going from protons (^{1}H) to helium (^{4}He).
- It’s how our sun gets its energy
- Much higher energy content than fission

Thermonuclear fusion in the sun

- Sun is 16 million degrees Celsius in center
- Enough energy to ram protons together (despite mutual repulsion) and make deuterium, then helium
- Reaction per mole ~20 million times more energetic than chemical reactions, in general


4 protons:
mass = 4.029

^{4}He nucleus:
mass = 4.0015

+ 2 neutrinos, photons (light)

$E=mc^2$ balance sheets

- Helium nucleus is *lighter* than the four protons!
- Mass difference is 4.029 – 4.0015 = 0.0276 a.m.u.
    - 0.7% of mass disappears, transforming to energy
    - 1 a.m.u. (atomic mass unit) is 1.6605×10^{-27} kg
    - difference of 4.58×10^{-29} kg
    - multiply by c^2 to get 4.12×10^{-12} J
    - 1 mole (6.022×10^{23} particles) of protons → 2.5×10^{12} J
    - typical chemical reactions are 100–200 kJ/mole
    - nuclear fusion is ~20 million times more potent stuff!
    - works out to 150 million Calories per gram
        - compare to 16 million Cal/g uranium, 10 Cal/g gasoline

---

Artificial fusion

- 16 million degrees in sun's center is *just* enough to keep the process going
    - but sun is *huge*, so it seems prodigious
- In laboratory, need higher temperatures still to get worthwhile rate of fusion events
    - like 100 million degrees
- Bottleneck in process is the reaction:

  $^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{H} + e^+ + \nu$ (or proton-proton → deuteron)
- Better off starting with deuterium plus tritium
    - ^{2}H and ^{3}H, sometimes called ^{2}D and ^{3}T
- Then:

  $^2\text{H} + {}^3\text{H} \rightarrow {}^4\text{He} + \text{n} + 17.6$ MeV (leads to 81 MCal/g)

Deuterium everywhere

- Natural hydrogen is 0.0115% deuterium
    - Lots of hydrogen in sea water (H_2O)
- Total U.S. energy budget (100 QBtu = 10^{20} J per year) covered by sea water contained in cubic volume 170 meters on a side
    - corresponds to 0.15 cubic meters per second
    - about 1,000 showers at two gallons per minute each
    - about one-millionth of rainfall amount on U.S.
    - 4 gallons per person per year!!!

Tritium nowhere

- Tritium is unstable, with half-life of 12.32 years
    - thus none naturally available
- Can make it by bombarding ^{6}Li with neutrons
    - extra n in D-T reaction can be used for this, if reaction core is surrounded by "lithium blanket"
- Lithium on land in U.S. would limit D-T to a hundred years or so
    - maybe a few thousand if we get lithium from ocean
- D-D reaction requires higher temperature, but could be sustained for *many* millennia

Nasty by-products?

- Practically none: not like radioactive fission products
- Building stable nuclei (like ^{4}He)
  - maybe our voices would be higher…
- Tritium is the only radioactive substance
  - energy is low, half-life short: not much worry here
- Extra neutrons can tag onto local metal nuclei (in surrounding structure) and become radioactive
  - but this is a small effect, especially compared to fission

Why don't we embrace fusion, then?

- Believe me, we *would* if we *could*
- It's a huge technological challenge, always 50 years from fruition
  - must confine plasma at 50 million degrees!!!
  - all the while providing fuel flow, heat extraction, tritium supply, etc.
  - hurdles in plasma dynamics: turbulence, etc.
- Still pursued, but with decreased enthusiasm, increased skepticism
  - but man, the payoff is huge: clean, unlimited energy

Fusion Successes?

- Fusion *has* been accomplished in labs, in big plasma machines called *Tokamaks*
  - got ~6 MW out of Princeton Tokamak in 1993
  - but put ~12 MW *in* to sustain reaction
- Hydrogen bomb also employs fusion
  - fission bomb (e.g., ^{239}Pu) used to generate extreme temperatures and pressures necessary for fusion
  - LiD (lithium-deuteride) placed in bomb
  - fission neutrons convert lithium to tritium
  - tritium fuses with deuterium

References and Assignments

- References:
  - Physics 12, offered spring quarter
  - Energy: A Guidebook, by Janet Ramage
- Final Exam Review Sessions
  - Wed 6/11 8–10 PM Solis 104 (Murphy-led)
  - Thu 6/12 8–10 PM Solis 104 (Wilson-led)
- Assignments:
  - Read Chap. 34 pp. 671–674; skim rest as needed/interested
  - HW8, due 6/06: 30.E.42, 27.E.10, 27.E.11, 27.E.15, 27.E.20, 27.E.29, 28.E.31, 28.E.33, plus four more required problems posted on website
  - Last Q/O due Friday 6/06 by midnight