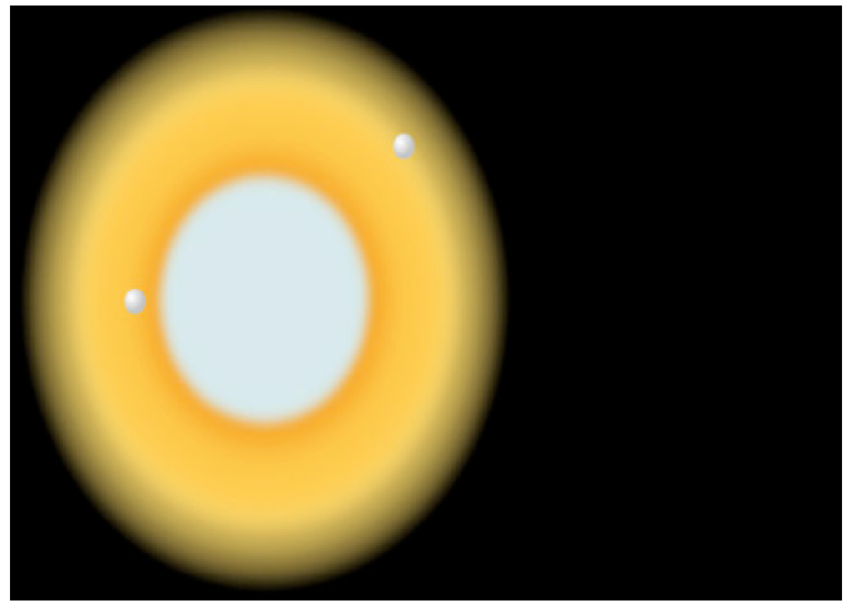
The nucleus of the atom

- In 1919, Rutherford starts to collect the first data indicating that there is another structure within the nucleus- the proton.
- Two years later, James Chadwick and E.S. Bieler conclude that some strong force holds the nucleus together.
  - Why? If protons in nucleus (and not electrons) then what keeps the repulsive force from driving the nucleus apart?
  - Nucleus confined to a very small volume ($<10^{-14}$ m in diameter), 0.01% of diameter of atom
    - density is 10^{17} kg/m^3



So here we are in 1930

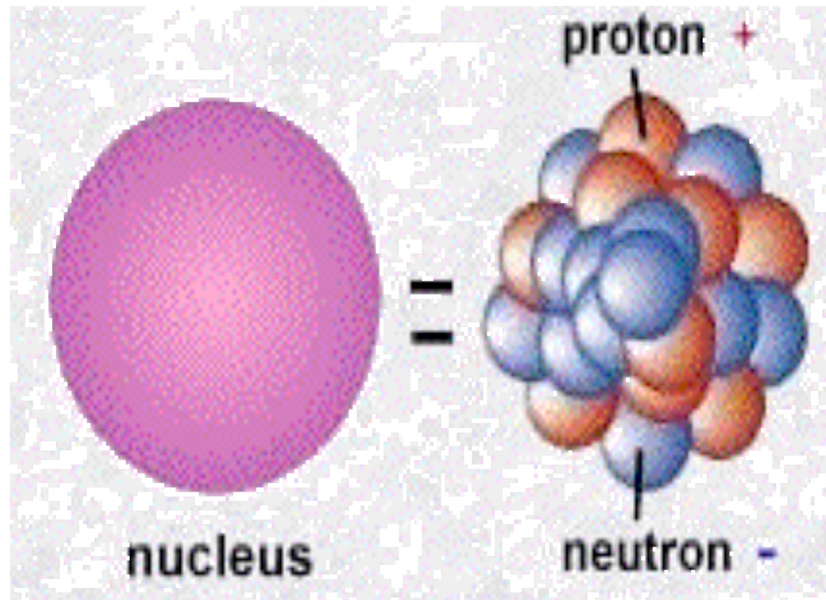
- There were three fundamental particles- electron, proton, and photon.
- There were three fundamental forces- gravity, electromagnetic, and the strong nuclear force.
- Gravity we know is much weaker than the other forces
  - strong force is about 100X stronger than EM force
    - naturally occuring elements only have up to 100 protons
    - strong force between protons *saturates* but EM repulsive force doesn't
    - for more than 100 protons repulsive force wins
- There were still some "details" to work out but many felt like Max Born, who said, "Physics as we know it will be over in six months."

  - Who is Max Borns granddaughter ?

- Olivia Newton-John
  - as far as I know, John Travolta is not related to any famous physicist

The nucleus

- The nucleus had ceased to be fundamental. It was composed of positively charged protons and neutrally charged neutrons (not actually discovered until 1931 by Chadwick).



Characterizing atoms

- Nuclei of atoms consist of protons and neutrons
- Surrounding the nucleus are the electrons
- Characterize nuclei by following characteristics
  - Atomic number Z: # of protons in nucleus (also equal to # electrons for normal atom)
  - Neutron number N: # of neutrons in nucleus
  - Mass number A: # of nucleons (protons + neutrons) in nucleus
- ${}^{A}_{Z}X$: X is symbol for element, A is atomic mass and Z is atomic number
- Isotopes of an element have the same atomic number but different atomic weight
  - same number of protons and electrons
    - same chemical properties
  - different number of neutrons
    - different nuclear properties

Masses

$E_R = mc^2$

TABLE 29.1 Mass of the Proton, Neutron, and Electron in Various Units

Particle	Mass kg	u	MeV/c^2
Proton	$1.672\,6 \times 10^{-27}$	1.007 276	938.28
Neutron	$1.675\,0 \times 10^{-27}$	1.008 665	939.57
Electron	9.109×10^{-31}	5.486×10^{-4}	0.511

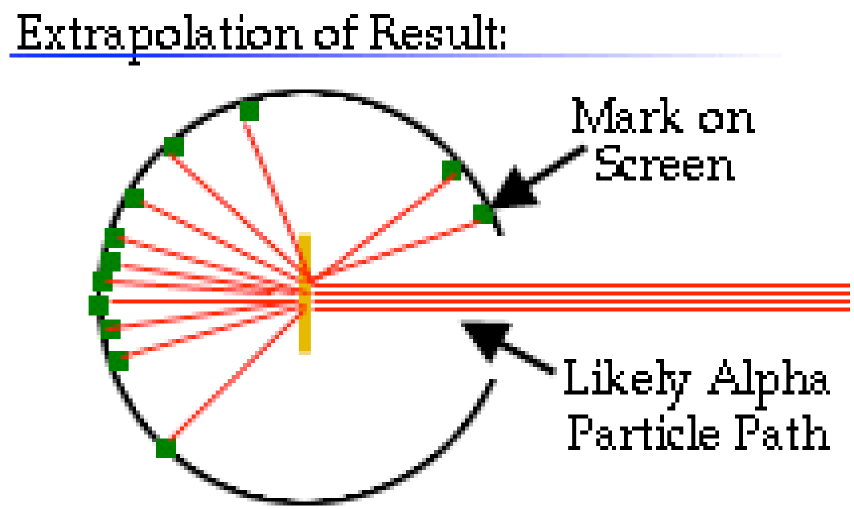
note the factor of 2000 difference

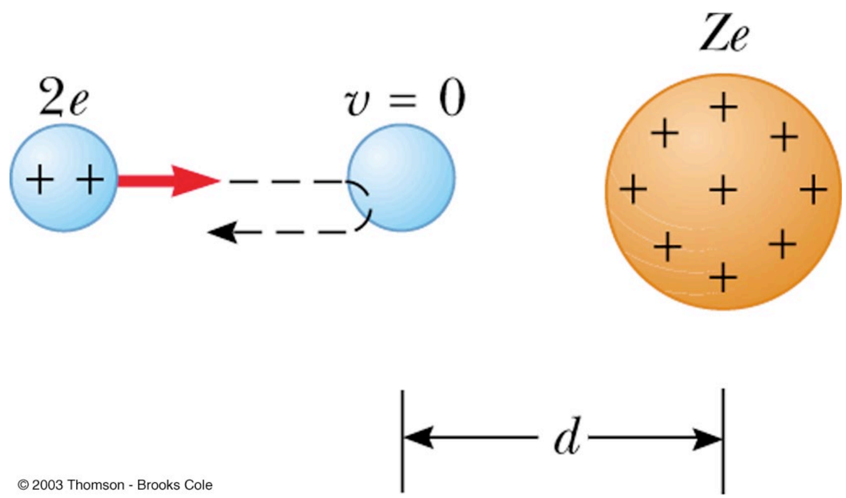
unified mass unit: 12C has a mass of 12 amu

1 u = 1.660559 X 10-27 kg

Radius of nucleus

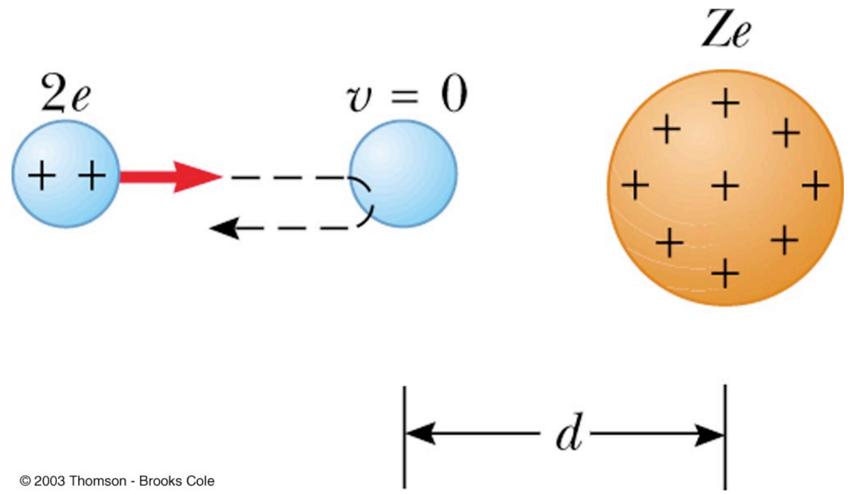
- Rutherford found an expression for how close an alpha particle can come to a nucleus
- For a head-on collision all of kinetic energy is changed to potential energy
  - $\frac{1}{2}mv^2 = k\frac{(2e)(Ze)}{d}$
  - d is the distance of closest approach

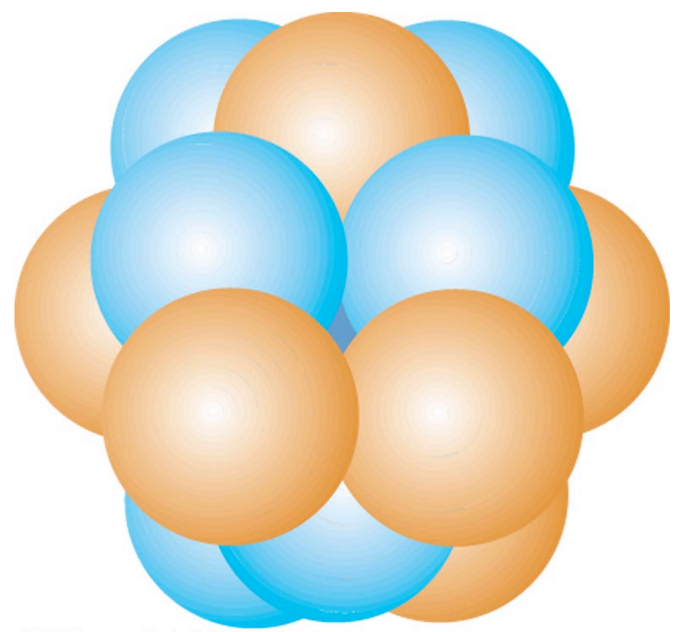




Solve for d

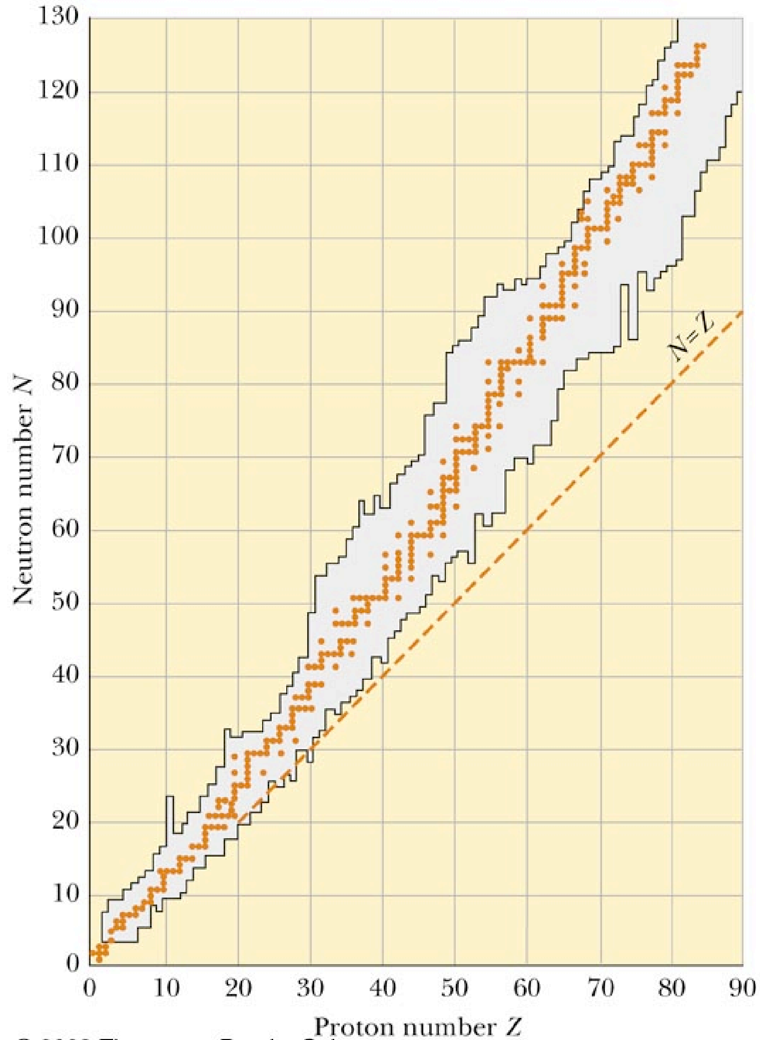
- $$d = \frac{4kZe^2}{mv^2}$$
- …or a distance of about 3.2 X 10^{-14} m for alpha particles on a gold nucleus
- From these results, Rutherford concluded that the positive charge in a nucleus is concentrated in a sphere whose radius is no greater than ~10^{-14} m or about 10 fermis (1 fermi = 1 X 10^{-15} m)
- Nuclear radii go as:
  - $r=r_oA^{1/3}$
  - A is the # of nucleons and $r_o=1.2X10^{-15}$ m
  - all nuclei have roughly the same density





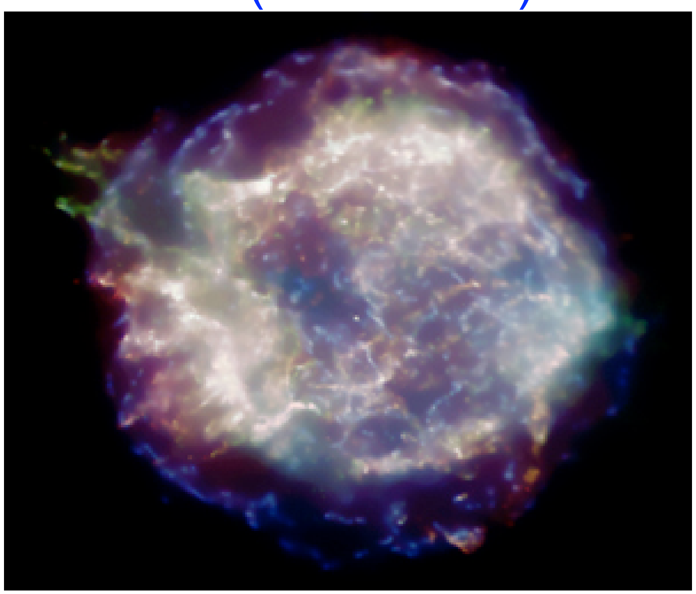
Stable nuclei

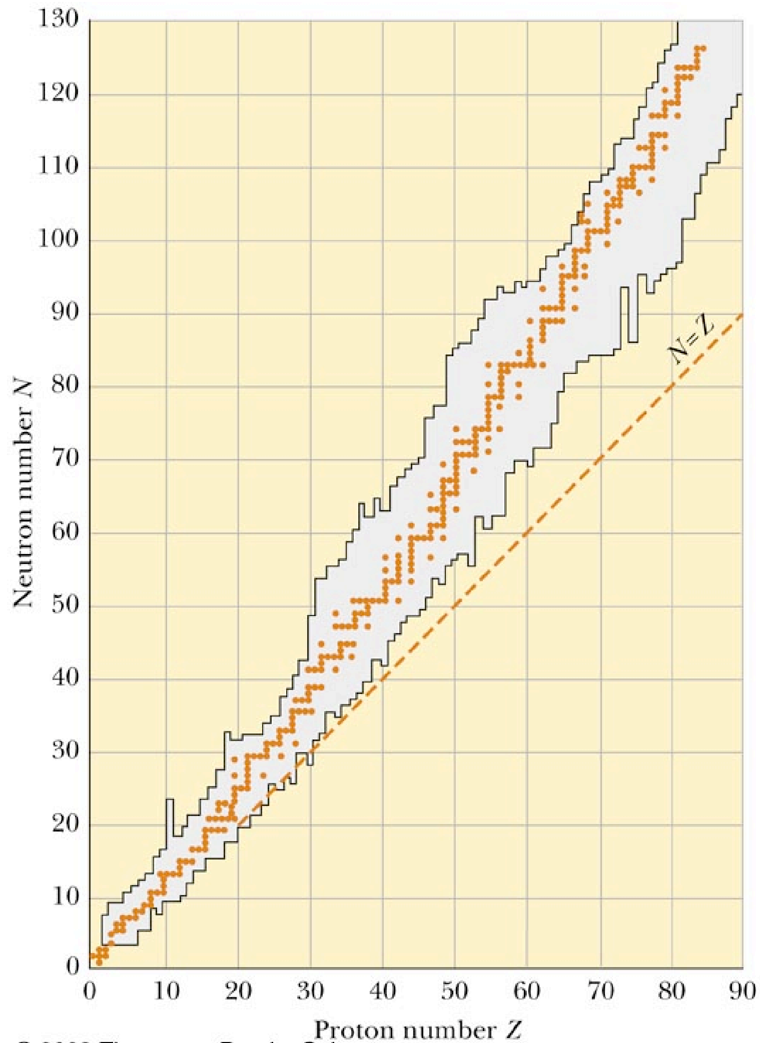
- The nucleus can exist only because the strong nuclear force between nucleons in a nucleus is stronger than the electrostatic repulsive force between the protons
- Light elements have roughly the same number of protons and neutrons
- Heavier elements have more neutrons than protons (neutrons contribute to the strong binding force inside the nucleus but not to the repulsive EM force)
- Isotopes within the shaded region are stable



Unstable nuclei

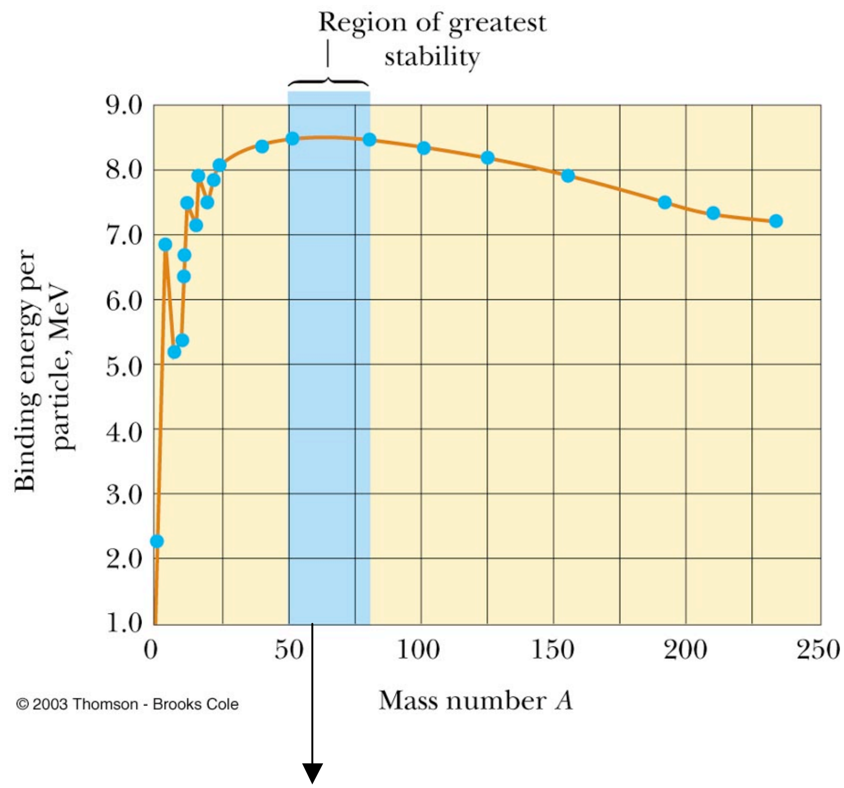
- The heavier elements in the universe were all made in supernova explosions
- Unstable isotopes are produced (too many neutrons) which then decay to the stable isotopes
- One of areas of concentration of NSCL (and of RIA)





Binding Energy

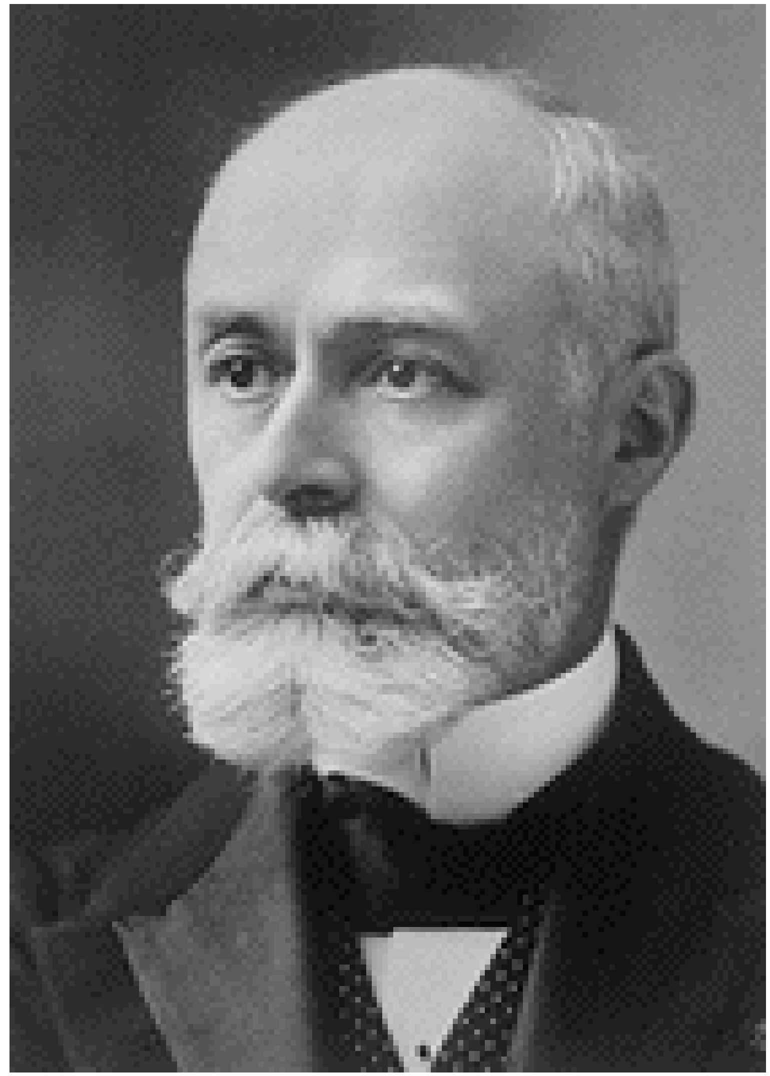
- The total mass of a nucleus is less than the sum of the masses of the protons and neutrons that comprise it
- This difference is called the binding energy of the nucleus and can be thought of as the energy that must be added to a nucleus to break it apart



iron has the highest binding energy

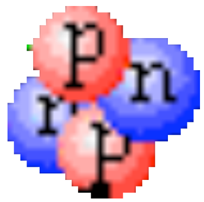
Radioactivity

- In 1896, Henri Becquerel, while investigating fluoresence in uranium salts, accidentally discovered radioactivity
- Work by Curies and others showed that radioactivity was the result of the decay or disintegration of unstable nuclei
- Up til that point, atoms were believed to be indestructible and forever
- Cleared up a major question as to why the interior of the Earth was still molten
- Shared the 1903 Nobel prize with the Curies
- Work by Curies and others showed that radioactivity was the result of the decay or disintegration of unstable nuclei



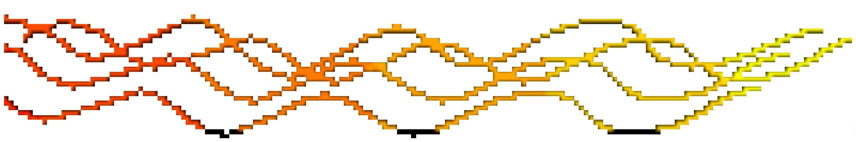
Radiation

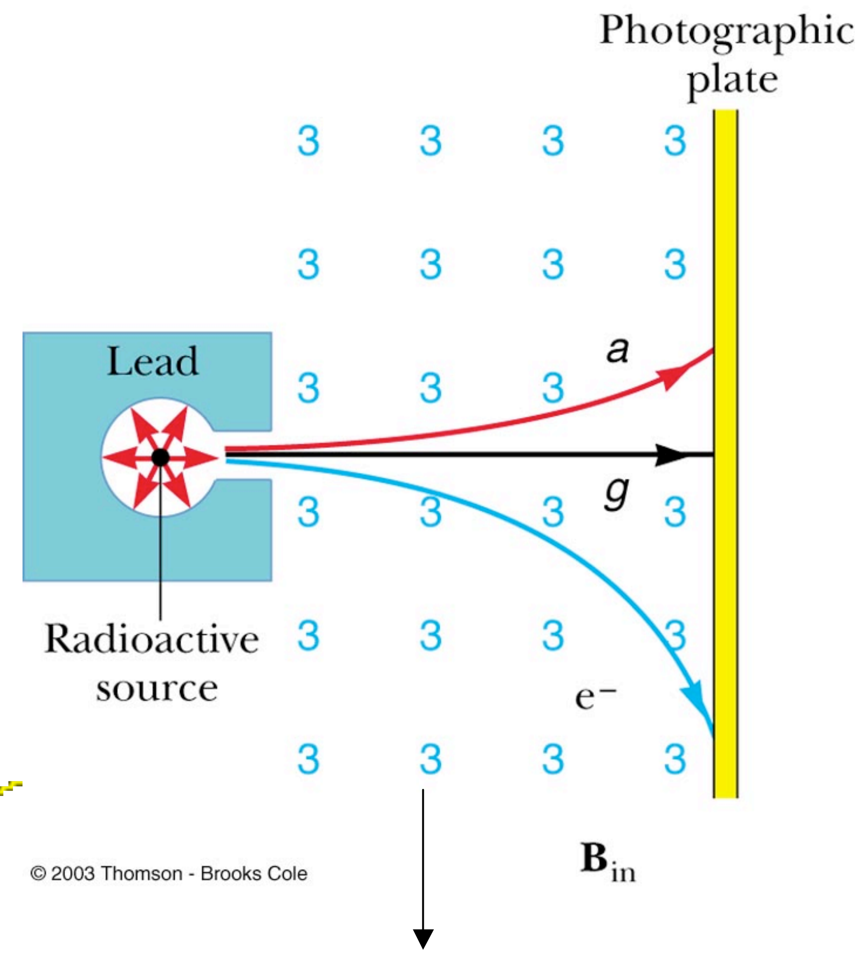
- Alpha particles are helium nuclei (2 p, 2 n):



- Beta particles are speedy electrons:

- Gamma radiation is a stream of photons:

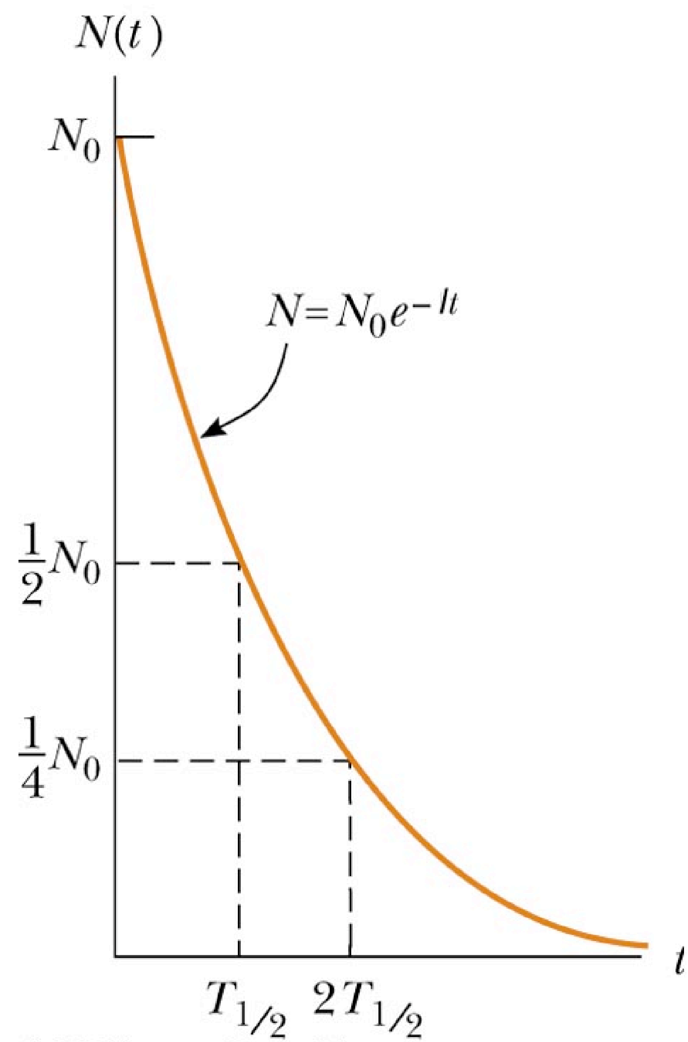




these are supposed to be x's

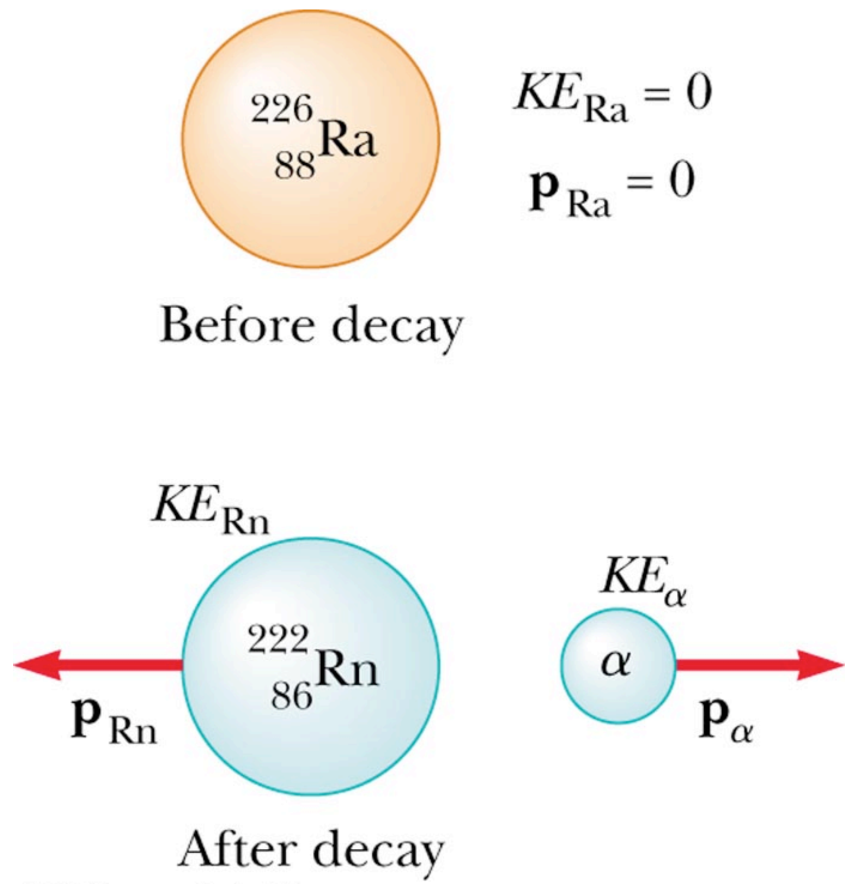
Half-life

- If a radioactive sample contains N radioactive nuclei at some instant, the number of nuclei that decay in a time Δt is proportional to N
  - $\Delta N/\Delta t \propto N$
  - $\Delta N = -\lambda N \Delta t$
  - where λ is a decay constant
- $R = |\Delta N/\Delta t| = \lambda N$
  - rate of which atoms decay
- $N=N_o e^{-\lambda t}$
- $T_{1/2}$ (half-life) is time it takes for half of sample to decay
- Decay constants vary greatly for different radioactive decays and thus so do half-lives



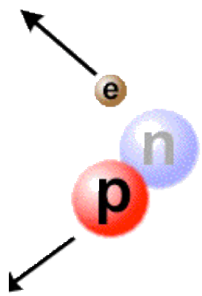
Alpha decay

- ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$
- X is called the parent nucleus and Y the daughter nucleus
- Example is Radium, decaying into Radon and an alpha particle
- In order for alpha emission to occur, mass of the parent must be greater than combined mass of daughter and alpha particle
  - excess mass converted into kinetic energy, most of which is carried by the alpha particle

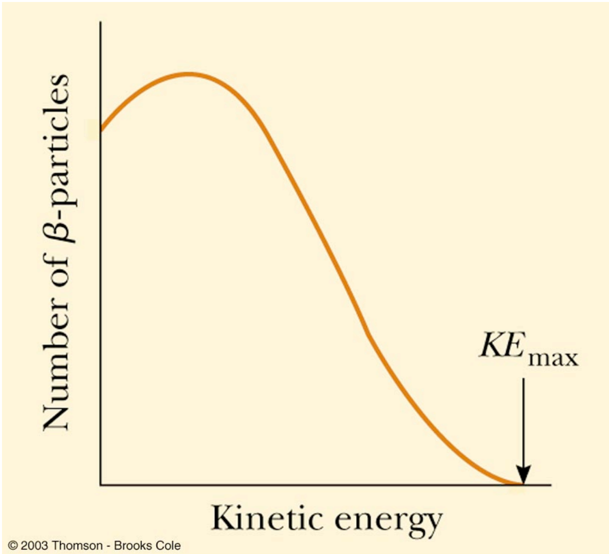


Beta decay

- When a radioactive nucleus undergoes beta decay, the daughter nucleus has the same number of nucleons as the parent nucleus but he atomic number is changed by 1
  - ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X + e^-$
- A neutron turns into a proton emitting an electron
  - ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + e^-$



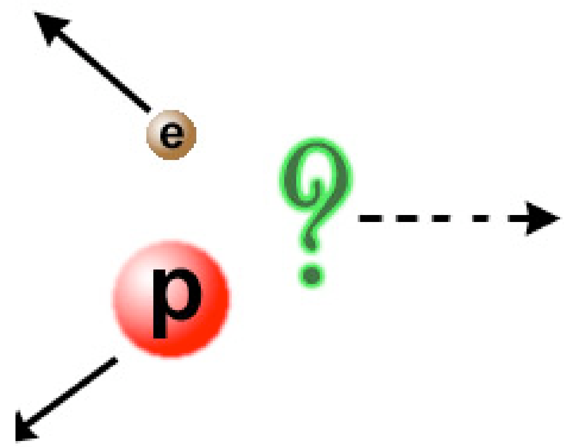
One problem: expect the electron to carry away almost all of the kinetic energy but it doesn't



It has a range of energies.

Problemo, big problemo

- Is Momentum Conserved?
- How can we account for the discrepancies?
- Wolfgang Pauli suggested a bizarre idea, another particle, one not yet seen, was carrying the missing energy and could be used to solve the momentum issue.
- For Conservation of Charge, the new particle would have to be neutral.
- According to other experiments, the particle would have to be incredibly light, perhaps even be massless!

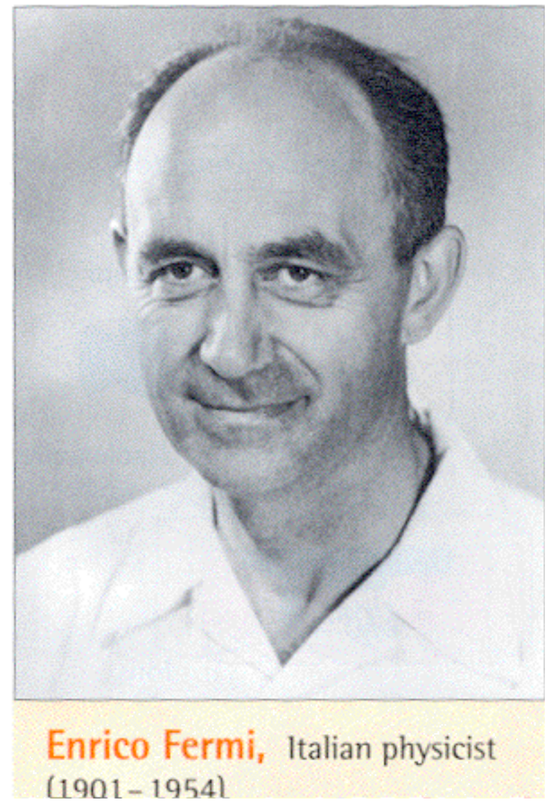


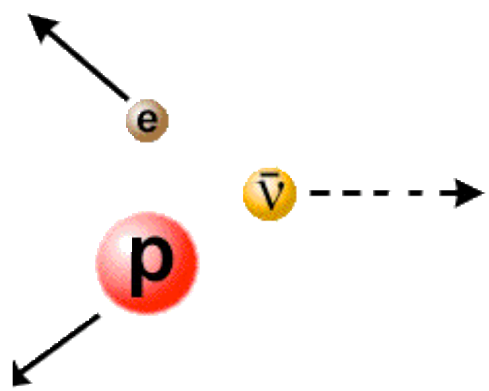
A joke name but it stuck

- Due to those characteristics, the Italian physicist Enrico Fermi suggested calling it

  Neutrino

  Italian for “little neutral one.”





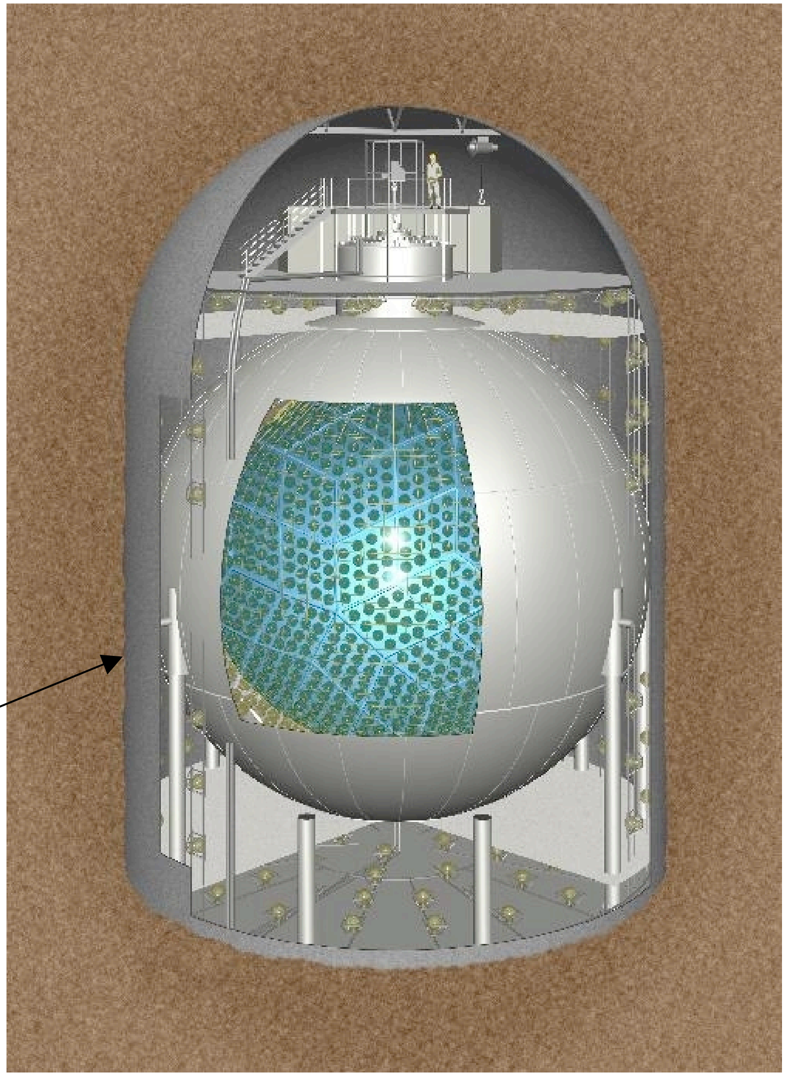
-zero electric charge
-very small mass (if any)
-a spin of 1/2
-very weak interaction with matter, making it difficult to detect

New interaction force

- Since the beta decay happened to free neutrons outside the nucleus, the Strong Nuclear Force could not be responsible.
- Thus physicists were led to consider another fundamental force- the Weak Nuclear Force.
- At this point, there were
  - Five Fundamental Particles: electron, proton, neutron, electron, photon, and neutrino.
  - and Four Fundamental Forces (or Interactions): Gravity, Electromagnetic, Strong Nuclear Force, and Weak Nuclear Force.
- The Weak Force is weaker than Electromagnetic or Strong, but is stronger than Gravity.

Mass of neutrinos

- Not until 1956 was there convincing experimental evidence that neutrinos really existed. An experiment at a nuclear reactor conducted by Fred Reines was able to measure interactions resulting from neutrinos. Why was this so difficult? Because the neutrinos only interacted via the weak force. The incredibly vast majority of them passed through the detector without leaving any trace.
- Currently there's an experiment in Japan called Kamland which is designed to detect neutrinos from Japan's working nuclear power plants



Solar neutrinos

- The nuclear reactions in the Sun produce neutrinos. Trillions of them are passing through your body every second. Why don't you feel them? Because their probability of interacting is so small.
- An experiment set up by Ray Davis to look for neutrinos from the Sun (in the Homestake Mine in South Dakota) found only ~1/2 of the number expected (running from 1970 through the present)
- Have nuclear reactions in the Sun stopped?
- Within the last 2 years, it has been understood that there are 3 types of neutrinos and that the neutrinos produced in the Sun metamorphize into another type (that can't be detected) before they reach the Earth.

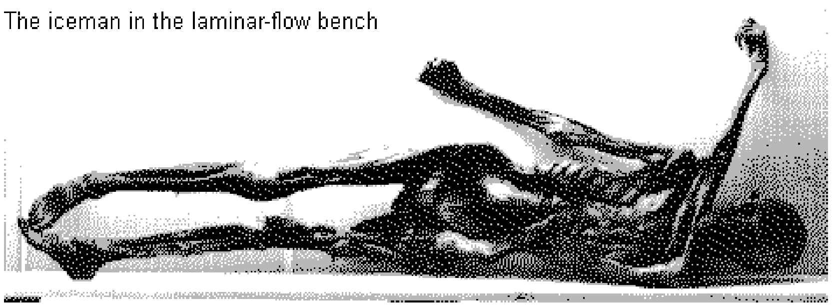
Whew!

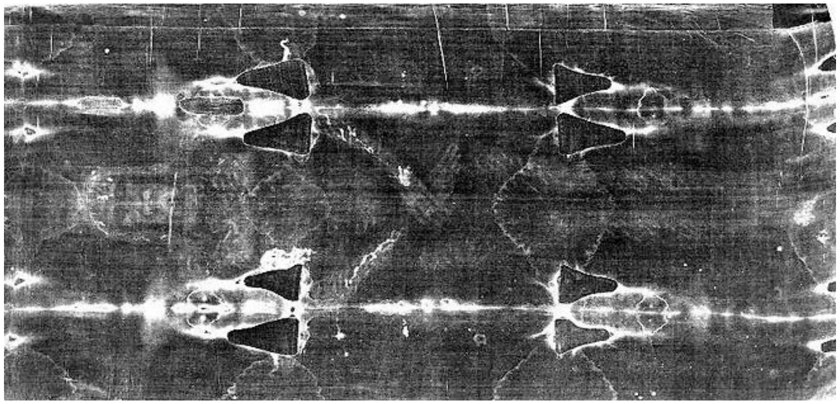
Radioactive Dating

- We can often use radioactivity to measure the age of an object (artifact, fossil, etc)
- Consider ^{14}C dating
  - cosmic ray interactions in the upper atmosphere cause nuclear interactions that produce ^{14}C from ^{14}N
  - living organisms breathe in carbon dioxide that has both ^{12}C and the radioactive ^{14}C
  - so all living creatures have the same ratio of ^{14}C to ^{12}C ($\sim 1.3\mathrm{X}10^{-12}$)
  - when the organism dies, however, it no longer absorbs carbon dioxide from the air, and so the ratio of ^{14}C to ^{12}C decreases
- Can measure the rate for the reaction below per unit mass, and from it calculate how long something has been dead
  - $${}^{14}_{12}C \rightarrow {}^{14}_{7}N + e- + \nu$$
  - the greater the rate the more recently it has died

Carbon dating

- Works on samples from about 1 to 25,000 years ago
  - why not longer?
  - half-life of ^{14}C is 5730 years, so longer than 5 half-lives too small a fraction of ^{14}C is left ($2^5=32$ so <1/32nd left)
- Examples:
  - Dead Sea Scrolls date to 1950 years ago
  - Iceman dates to 5300 years ago
  - Shroud of Turin to 700 years ago





Radioactivity

- Radioactivity can be classified into 2 groups
  - unstable nuclei found in nature (natural radioactivity)
  - nuclei produced in the lab through nuclear reactions (artificial radioactivity)

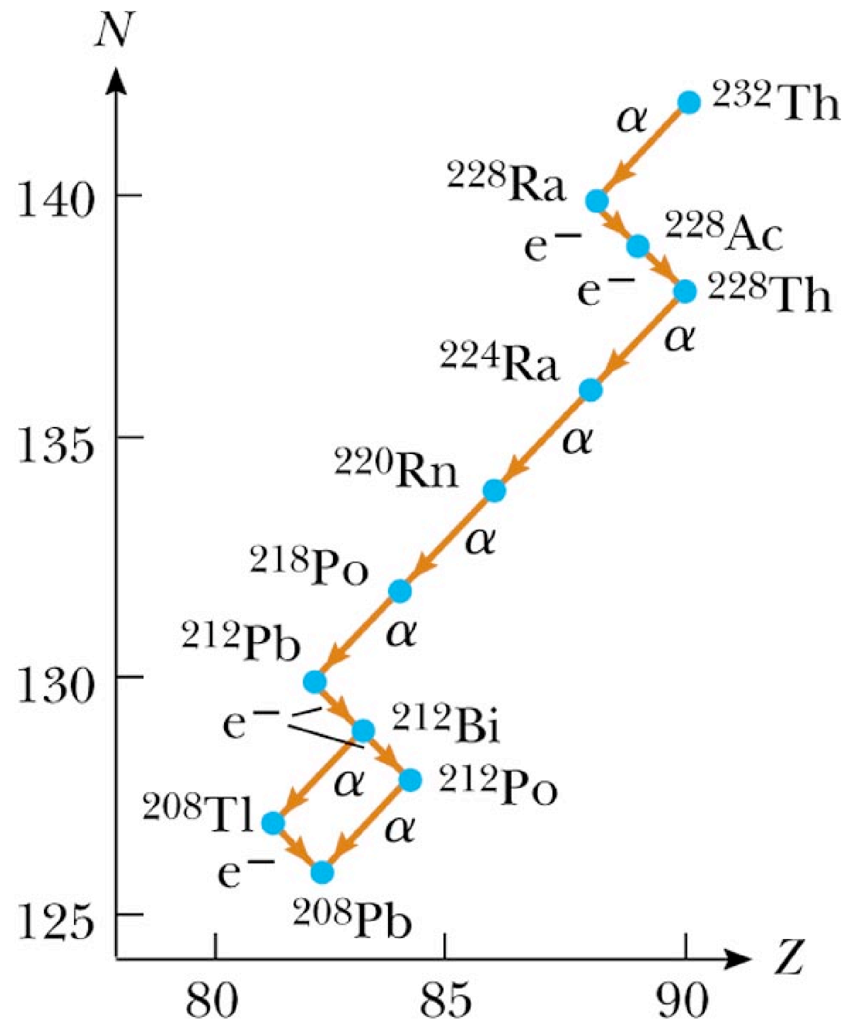
Four radioactive series shown below. Uranium, Actinium and Thorium are all found in nature. Neptunium is trans-uranic.

TABLE 29.2 The Four Radioactive Series

Series	Starting Isotope	Half-life (yr)	Stable End Product
Uranium	$^{238}_{92}U$	4.47×10^{9}	$^{206}_{82}Pb$
Actinium	$^{235}_{92}U$	7.04×10^{8}	$^{207}_{82}Pb$
Thorium	$^{232}_{90}Th$	1.41×10^{10}	$^{208}_{82}Pb$
Neptunium	$^{237}_{93}Np$	2.14×10^{6}	$^{209}_{83}Bi$

Decay chain for Thorium

- Start with ^{232}Th
  - half-life for first decay is ~14 billions years
- End with ^{208}Pb



Radiation damage

- Radiation damage in biological organisms is primarily due to ionization effects in cells
  - normal function of a cell can be disrupted when highly reactive ions or radicals are formed as a result of ionizing radiation
  - damage to a great number of cells can lead to death
  - cells which do survive the radiation may become defective and cancerous
- Can divide radiation damage into 2 types
  - somatic (to non-reproductive cells)
  - genetic (to reproductive cells)
- Units of radiation damage
  - rad: that amount of radiation that deposits .01 J into 1 kg of absorbing material
  - rem is defined as the product of dose in rads and RBE (relative biological effectiveness) factor

TABLE 29.3 RBE Factors for Several Types of Radiation

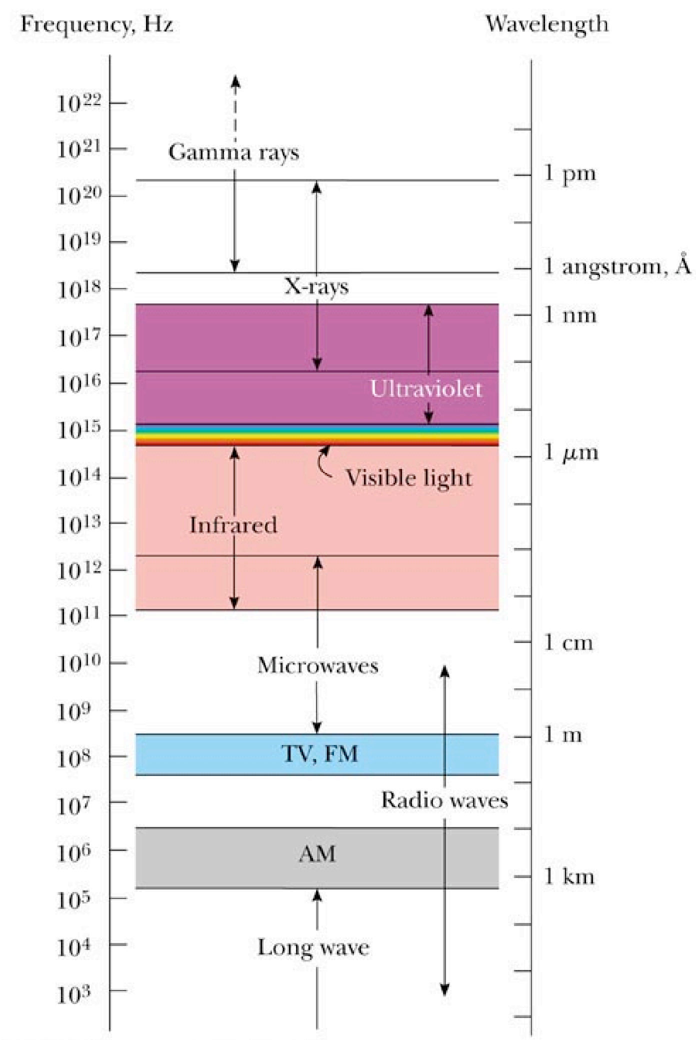
Radiation	RBE Factor
x-Rays and gamma rays	1.0
Beta particles	1.0–1.7
Alpha particles	10–20
Slow neutrons	4–5
Fast neutrons and protons	10
Heavy ions	20

Radiation exposures

- Low level radiation from cosmic rays, radioactive rocks, soil, air deliver a dose of about 0.13 rem/year
- Upper limit recommended by government is 0.5 rem/year
- Acute whole-body dose of 500 rem results in a mortality rate of ~50%
- Natural sources of exposure
  - cosmic rays: 14%
  - radon: 58%
  - food: 12%
  - ground: 16%
- Equivalent exposure from medical X-rays
  - chest/teeth/arms and legs: a few days
    - also equivalent to the radiation exposure from a 4-hour plane flight
  - breast, spine, abdomen: a few months
  - barium enema: a few years

What about exposure from microwave ovens?

- $E=hc/\lambda$

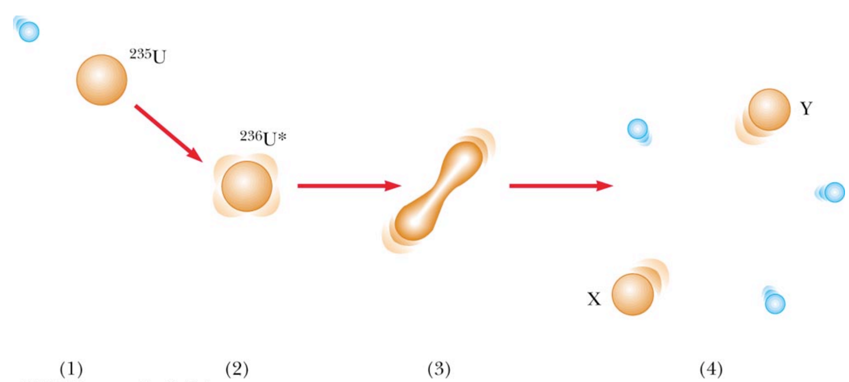


Nuclear fission

- Nuclear fission occurs when a heavy nucleus such as ^{235}U splits or fissions into 2 smaller nuclei
- In such a reaction the total mass of the products is less than the original mass of the heavy nucleus
  - where does the extra mass go?
  - into kinetic energy of decay products, about 200 MeV (not just of academic interest)
- Consider a slow neutron interacting with a ^{235}U nucleus (one possible reaction)

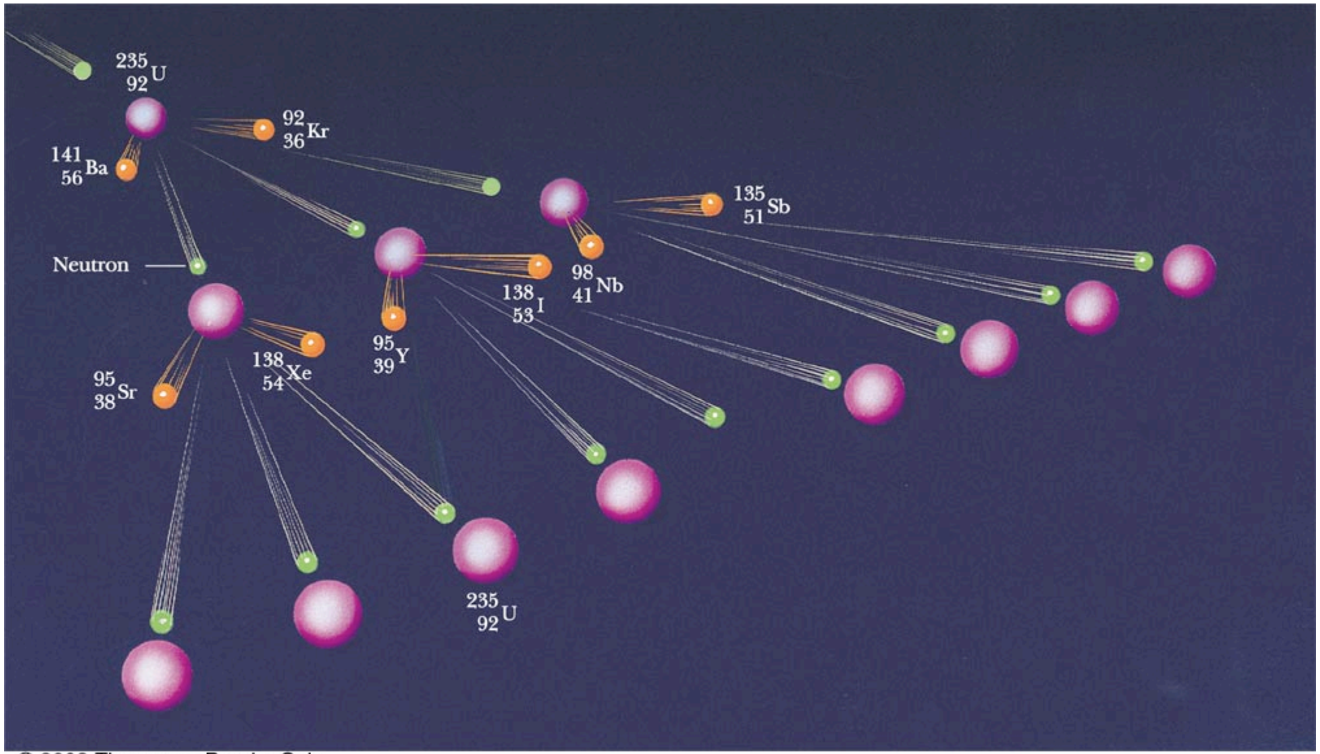
$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n $$

- ^{235}U captures slow-moving neutron
- Capture results in formation of $^{236}U^*$; excess energy of this nucleus causes it to undergo violent oscillations
- ^{236}U nucleus becomes elongated
- Nucleus splits into 2 fragments, emitting several neutrons in the process



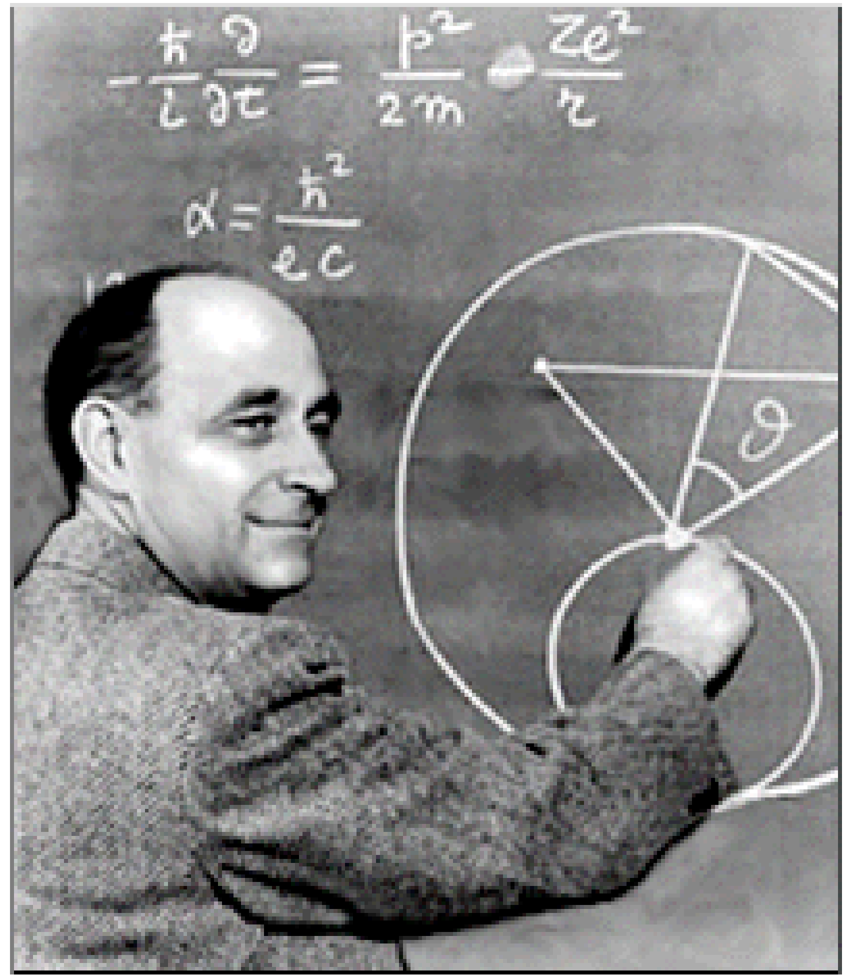
Chain reaction

Average number of neutrons emitted is ~2.5; when chain reaction occurs fast, it's a bomb; when reaction occurs slowly and controlled it's a nuclear reactor



First chain reaction

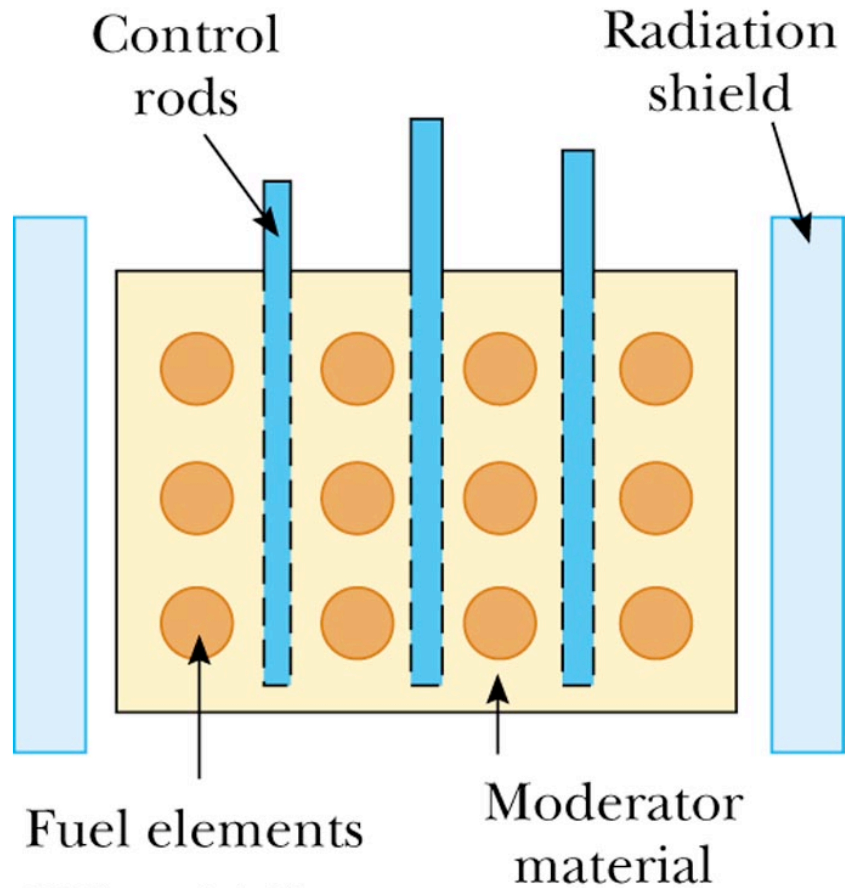
- In 1942, Enrico Fermi and collaborators built a nuclear pile underneath the football stadium and obtained the first controlled nuclear chain reaction
- Their measurements confirmed that the construction of an atomic bomb was a possibility



Enrico Fermi Physicist 1901 - 1954

Nuclear Reactor

- in a reactor have control rods which can absorb neutrons to slow the reaction down



Operating principles