Lecture 03:
Alpha, Beta, and Gamma
Radiation: Radiation and
Radioactive Material
TWO DEMOS: slide 8
slide 32 (2-3 min)

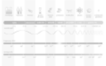
Did you know?

- Highly radioactive material decays quickly?
- The term "radiation" may sound scary, but it refers to anything emitted (that is, radiated)
  - We really only worry about radiation that breaks chemical bonds (**ionizing radiation**)

- Radiation (in broader sense) includes
  - Sound waves
  - Gravitational waves
  - Fast-moving subatomic particles from
    - Nuclear decay (alpha & beta particles, gamma rays)

- Cosmic rays (mostly muons, heavy cousins of the electron)
- Accelerators

–Other electromagnetic waves (lower energy than gamma)



- Electromagnetic waves (only wavelength varies)
  - Travel like waves
  - Interact like discrete particles
- Quantized, photon energy $E = hc/\lambda$
  - Radio & TV (0.1-10^2 m)
  - Microwave (~1 cm)
    - Heats water by resonant absorption

- Infrared (10^{-4} – 10^{-6} m); Visual (400 – 800 nm)
- UV (10-400 nm)
  - Typical chemical bond energy ~ eV
  - UV photon energy > 3 eV
  - Photons energetic enough to break chemical bonds (sun burn)

- X-rays (0.01-10 nm) 1 – 300 keV photons
  - –Named because they were new and unknown
  - –Interaction probability decreases with energy
    - Energy more mismatched with atomic energies
    - less likely to interact
  - –Higher energy x-rays are more penetrating

–Gamma rays (< 0.01 nm) 300+ keV photons

- Named as the 3rd type of radiation given off by radioactive decay

- We worry about **ionizing** radiation
  - –All radiation interacts in matter
  - –Ionizing radiation deposits enough energy to break chemical bonds
    - Weakens materials
    - Damages DNA
  - –X-rays, gamma rays (even UV), fast moving subatomic particles

Animation: particle scattering from DNA, breaking bonds

- **Radioactive** materials emit (nuclear) **radiation** via nuclear decay
  - –**Radioactivity** measured in disintegrations per time
    - 1 Becquerel = 1 disintegration / second (SI)
    - 1 curie = 3.7e10 Becquerels

- So how big is a Curie?
  - –I use microCi sources in the lab, minimal precautions
  - –Be careful with mCi
  - –AVOID Ci

Radioactive materials emit radiation via nuclear decay

- Radiation measured in particle flux
  - –#/time or #/area-time
  - –Geiger counter: cpm → dpm
  - –Let’s look at a Geiger counter!
  - –[*long* ***pause → demo***]

- [*long* ***pause***]
- DEMO: Geiger counter here
  - –Audible clicks
  - –Measure count rate on dial

- Radiation also measured in
  - –absorbed dose in exposed material
    - 100 rad = 1 Gray = 1 J/kg deposited energy
      - –Enough energy to lift 1 kg by 10 cm (4 in)
      - –Very little heat (< milli K)
      - –can break a LOT of chemical bonds

7 min

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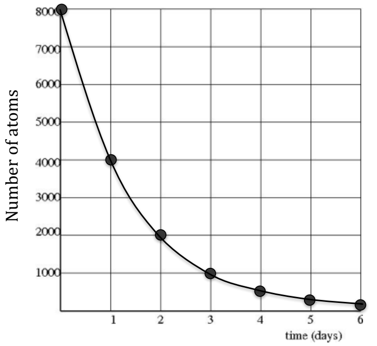
biological effects

- 100 Rem = 1 Sievert
  - –Background radiation ~ 0.6 Rem/yr
- Correct grays and rads for bio effects of different radiation in different tissues
  - –**β**,**γ** = 1, **α**=20, n,p in between
- Banana equiv dose (informal)
  - –0.1 **µ**Sv = 10 **µ**Rem

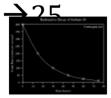
- Half Life – for POST – do not show



Show Phet animation

Half Life

- ½ nuclei in a sample decay in one **τ**
- Impossible to predict which specific nuclei
- Coin toss analogy
- 800 →400→200→100→50→25
- Short **τ**→very radioactive
  - –But not for long
- Long **τ**→not very radioactive



- Different isotopes have different half-lives
  - –Too many p or n → away from the valley of stability
  - –16O VERY stable, now add p
    - 17F τ =64 s,
    - 18Ne τ = 1.7 s,
    - 19Na τ < 40 ns

- How big is 1 Curie (4e10 disint / sec)?
- That depends on the half life
  - –238U, τ = 5e9 yr
    - Now we need to convert years to seconds
      - –π x 10^7 s story

- [...] τ = (5e9 yr)(3e7 s/yr) = 1.5e17 s
- [...] 4e10 dis/s * 1.5e17 s = 6e27 atoms
- [...](6e27 at)/(6e23 at/mo)= 10^4 mole
- [...] Weighs 10^4 * 238 g ~ 2 tons
- A couple of cubic feet

- 1 Curie (4e10 disint / sec)
  - –131I, **τ**= 8 d ~ 7e5 s
  - –[...] 4e10 dis/s * 7e5 s = 3e16 atoms
  - –[...](3e16 at)/(6e23 at/mo)= 5e-8 mole
  - –[...] Weighs (5e-8)(131 g) = 6 μg

- –So how much is left after one year?
  - 1 g of U238 is still 1 g and about 1 μCi
  - 1 g of 131I: 45τ → 2^{-45} ~ 3e-14
  - Only 6 nCi remains, the rest has decayed to 131Xe

- So how did we discover this?
  - –Crookes's tubes make cathode rays, visible on fluorescent screens
  - –Roentgen noticed fluorescent screens elsewhere in the lab glowing faintly despite shielding→ x-rays!

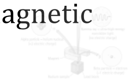
- –Crookes didn't have fluorescent screens. He kept returning fogged film to be replaced, instead of investigating why it kept fogging.
- –Limited instrumentation (film and fluor screens)

- Becquerel looked to see if fluorescent materials (which emit light) also emit x-rays.
  - –Place material on sealed film in sun.
  - –Only Uranium-sulfite worked
  - –But it worked without sunlight too
  - –then checked regular U
  - –It worked too!

- Curie's found uranium ore even more effective at fogging film than uranium itself
  - –Isolated radium and polonium

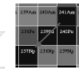
13 min

- Three main types of nuclear decay ($\alpha\beta\gamma$)
  - –All emitted by radium and its decay products
  - –Behave differently in a magnetic field
    - α deflected one way
    - β deflected the other way
    - γ undeflected

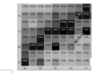


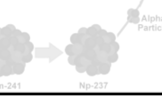
- –α and β have opposite charges
- –γ uncharged
- Fission is completely different (and much rarer)

- α particle = 4He (2p + 2n) very tightly bound
- Daughter nucleus has A-4, Z-2, N-2
  - –2p and 2n carried away by α
  - –Moves 2 down and 2 left on chart of nuclides
  - –241/95Am → 237/93Np + α
  - –238/92U → 234/90Th + α



Graphics for post
Show Phet alpha decay
without commentary





Why alpha decay and not proton emission?

- Heavy nuclei are bound by about 8 MeV per nucleon
  - –Need to find 8 MeV to emit a proton
  - –The alpha particle is already bound by 7 MeV per nucleon so it is much easier to find the energy to emit an alpha particle

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α decay due to Electric repulsion stronger than the strong force attraction

- Conserves charge, #n, and #p (expla)
- Conserves energy: Difference in BE → KE of fragments
  - –Q = (m_A – m_B – m_α)c^2
    - •Bigger Q → shorter τ
      - –4 -- 10 MeV → 10 Gyr to 100 ns

–Conserves momentum:

- •2-body decay → Equal and opposite momenta
  - –α carries most KE
  - –monoenergetic
- •Used to measure nuclear mass differences

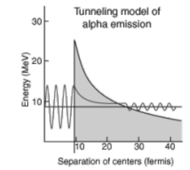
- Decay due to tunneling
  - –Classically forbidden
  - –α energy = Q > 0
  - –Describe shape of potential
    - •Potential well at r < a
    - •V ~ 1/r barrier for a < r < b
      - –V(r) = Q at r = b

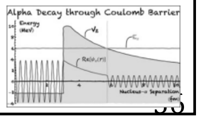
–α in well hits barrier a LOT (10^{21} Hz) til it tunnels out

- Inverse process:
  - –α's aimed at nuclei must tunnel in

Figures and graphics for post

Show Phet alpha decay
Single nucleus
Bottom half





- Tunneling details
  - –Wave function decreases exponentially in forbidden region
    - Probability decreases by 2 every 0.5 fm
  - –Barrier width ~ 30 fm

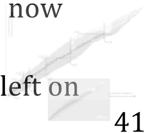
- –Prob(tunnel) ~ 2^(-60) ~ 10^-18.
  - One billion-billionth
  - Tiny!
- –Double energy
  - ~ halve barrier width
  - Probability increases to 2^(-30) ~ 10^-9.
  - τ increases by a factor of a billion!

- α Examples
  - –232/90Th, Q=4 MeV, tau = 15 Gyr
    - Age of universe
  - –226/90Th, Q = 6 MeV, tau = 30 min
  - –220/90Th, Q = 9 MeV, tau = 10^{-5} s

20 min

- Chart of the nuclides
- Proton number vs neutron number
- Stable isotopes in black
- Yellow = alpha decay (heavier, more p rich)

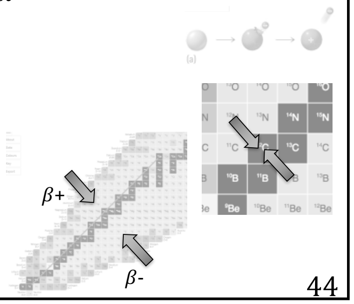
- Beta radiation and the weak nuclear force
- Two kinds of beta decay:
- RIGHT or BELOW the valley of stability (pink)
  - –Too many n: n → p + e- + anti-ν
  - –First kind of "beta decay", now beta- decay
  - –Moves diagonally up and left on the chart of nuclides



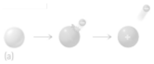
- LEFT or ABOVE the valley of stability (blue)
  - –Too many p: p → n + e+ + ν
    - beta+ decay
    - aka "positron emission"
    - Moves diagonally down and right on the chart of nuclides

- Another way to change p → n:
  - **electron conversion**
  - p + e- → n + ν
- Move one box diagonally down
- Keep total number p+n unchanged

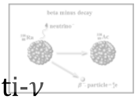
Images for post



- Weak force
  - Conserves E, p, charge, total #(n+p) (expand)
  - Conserves # electrons (e+ anti of e-
    - #e- + #ν - #e+ - #anti-nu unchanged
  - Changes p ←→n
- Atomic weight unchanged



- ν (m~0,q=0) existence inferred from continuous decay e energy spectrum
- Max e energy used to measure nuclear ΔM
- Described by Fermi theory
  - No tunneling barrier, just weak
  - Prob ~ overlap of init and final states
  - Also depends on angular momentum

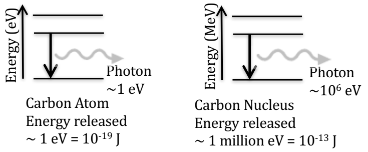


- Examples:
  - 14/6C → 14/7N + e- + anti-ν
  - 239/93Np → 239/94Pu + e- + anti-ν
  - 26/13Al → 26/12Mg + e+ + ν
- τ varies from 10^{-3} to 10^{23} s (10^{15} yr >> age of universe)

- γ rays (photons) and the EM force
  - No change in A, Z, or N
  - Most α and β decays leave excited daughter
  - De-excites via γ emission
    - Eγ ~ 0.1 to 10 MeV
    - λ ~ 10^4 to 10^2 fm

- Discrete energies characteristic of
  - Specific nuclei
  - Differences in nuclear states
- Atom →e changes orbit→emits photon
- Nucleus→n,p change orbit→emits photon

Graphic for previous slide



- Done as DEMO, 2-3 minutes?
- $\alpha\beta\gamma$ interact differently with matter
  - $\alpha\beta$ charged, interact with atomic e-, xfer E
  - α MUCH heavier and slower, interacts more
    - Slowed and stopped by a sheet of paper
  - β slowed and stopped by a few mm plastic
  - γ does not slow: either interacts & stops … OR keeps moving
    - Stopped by a few mm lead (energy dependent)

Geiger counter demo with stopping power

- You have 3 encapsulated sources $\alpha\beta\gamma$ and must swallow one, put the other in your pocket and the 3rd in your backpack. What do you do?
  - α shielded by pants cloth → pocket
  - β shielded by backpack material
  - γ not shielded by either. Swallow it.

- Blocking α and β radiation from entering your body is not hard and makes a big difference.

- Gamma radiation is always much harder to shield against. Either you have a barrier like lead, or the gamma's gonna getcha.