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 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

• 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

• **Radioactive** materials emit (nuclear) radiation via nuclear decay
  - Radioactivity measured in disintegrations per time
    - 1 Becquerel = 1 disintegration / second (SI)
    - 1 curie = $3.7 \times 10^8$ 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
• 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

• 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
    – $\beta, \gamma = 1$, $\alpha = 20$, n, p in between
  • Banana equiv dose (informal)
    – 0.1 $\mu$Sv = 10 $\mu$Rem

• Half Life
  • $1/2$ nuclei in a sample decay in one $\tau$
  • Impossible to predict which specific nuclei
  • Coin toss analogy
    • 800 $\rightarrow$ 400 $\rightarrow$ 200 $\rightarrow$ 100 $\rightarrow$ 50 $\rightarrow$ 25
  • Short $\tau$ $\rightarrow$ very radioactive
    – But not for long
  • Long $\tau$ $\rightarrow$ not very radioactive

• Different isotopes have different half-lives
  – Too many p or n $\rightarrow$ away from the valley of stability
  – $^{16}$O VERY stable, now add p
    • $^{17}$F $\tau$ = 64 s,
    • $^{18}$Ne $\tau$ = 1.7 s,
    • $^{19}$Na $\tau$ < 40 ns
• How big is 1 Curie (4e10 disint / sec)?
• That depends on the half life
  –238U, $\tau = 5e9$ yr
  • Now we need to convert years to seconds
    –$\pi \times 10^7$ s story

• $\tau = (5e9$ yr$)(3e7$ s/yr$) = 1.5e17$ s
• $4e10$ dis/s $\times 1.5e17$ s $= 6e27$ atoms
• $(6e27$ at$)/(6e23$ at/mo$) = 10^4$ mole
• $1$ Curie (4e10 disint / sec)

• $\tau$ = 8 d $\sim 7e5$ s
• $4e10$ dis/s $\times 7e5$ s $= 3e16$ atoms
• $(3e16$ at$)/(6e23$ at/mo$) = 5e-8$ mole

• 1 Curie (4e10 disint / sec)
• 1 g of U238 is still 1 g and about 1 µCi
• 1 g of 131I: $45 \tau \rightarrow 2^{-45} \sim 3e-14$
• 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 $\rightarrow$ 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 (αβγ)
  –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

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
  – $Q = (m_A - m_B - m_\alpha)c^2$
    • Bigger $Q \rightarrow$ shorter $\tau$
      – 4 -- 10 MeV → 10 Gyr to 100 ns

– Conserves momentum:
  • 2-body decay → Equal and opposite momenta
    – $\alpha$ carries most KE
    – monoenergetic
  • Used to measure nuclear mass differences

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

– $\alpha$ in well hits barrier a LOT ($10^{21}$ Hz) til it tunnels out
• Inverse process:
  – $\alpha$’s aimed at nuclei must tunnel in

Figures and graphics for post
• Tunneling details
  – Wave function decreases exponentially in forbidden region
  • Probability decreases by 2 every 0.5 fm
  – Barrier width ~ 30 fm

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

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

• 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 p: $p \rightarrow n + e^- + \bar{\nu}$
    – 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: $p \rightarrow n + e^+ + \nu$
  • beta+ decay
  • aka “positron emission”
  • Moves diagonally down and right on the chart of nuclides
Another way to change $p \rightarrow n$:

- **electron conversion**
  
  - $p + e^- \rightarrow n + \nu$
  - Move one box diagonally down
  - Keep total number $p+n$ unchanged

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

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

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- **Weak force**
  
  - Conserves E, p, charge, total $(n+p)$ (expand)
  - Conserves # electrons (e+ anti of e-)
  - $#e^- + #\nu - #e^+ - #\text{anti-nu}$ unchanged
  - Changes $p \leftrightarrow n$
  - Atomic weight unchanged

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- **$\gamma$ rays (photons) and the EM force**
  
  - No change in A, Z, or N
  - Most $\alpha$ and $\beta$ decays leave excited daughter
  - De-excites via $\gamma$ emission
  - $E_\gamma \sim 0.1$ to $10$ MeV
  - $\lambda \sim 10^4$ 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

1. 49

Graphic for previous slide

2. 50

• Done as DEMO, 2-3 minutes?
• α β γ interact differently with matter
  – α β 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

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• You have 3 encapsulated sources α β γ 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.

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

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