Nuclear Energy

- **Today:**
  - Ch. 42: Review
  - Ch. 43: Fission and fusion
  - Remarks on final exam

Review: nuclear terminology

- Z = atomic number = number of protons
- N = number of neutrons
- A = mass number = Z + N = number of nucleons
- Radioactive nuclide: spontaneous *radioactive decay* with an exponential decay curve and “half-life”.
- *Alpha (α):* Emission of a helium nucleus (α particle).
- *Beta (β):* Emission of an electron (β^-) or positron (β^+).
- *Gamma (γ):* Emission of a photon (γ-ray).
- Neutrino: Like electron but zero charge and mass.
- Antiparticles: positrons and antineutrinos.

Leptons: $(e^-,\ \upsilon)$ Antileptons: $(e^+,\ \bar{\upsilon})$

Nuclear Forces

The four fundamental forces of nature:

- Gravity
- The electromagnetic interaction
- The strong nuclear interaction
- The weak nuclear interaction

Nucleons attract each other through the *strong nuclear force*.

The strong force is *very short-range,* not inverse square, so that it has no effect on atomic physics and chemistry.

But it is *very strong* so that it overcomes the Coulomb repulsion to hold the nucleons inside the nucleus.

The *weak nuclear force* is extremely weak, but is responsible for some forms of nuclear radioactivity.

Review: Nuclear masses

The mass of the nucleus is also approximately proportional to A, the number of nucleons.

But not exactly, thanks to $E = mc^2$.

The strong force pulls the nucleons together. Work would be needed to pull apart the nucleons. This amount of work is called the binding energy ΔE.

So the nucleus has *less* energy than A separate nucleons. So the nucleus has less *mass* than A separate nucleons.

$$\boxed{M c^2 = Z m_p c^2 + N m_n c^2 - \Delta E}$$

Beta decay

$$\boxed{n \rightarrow p + e^- + \bar{\upsilon}}$$

The fundamental beta-decay process changes a neutron into a proton, with the emission of an electron.

But there is also emission of an *antineutrino.*

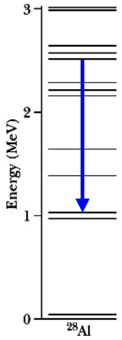
Electrons (e^-) and neutrinos (υ) are *leptons.* (L=1)

Positrons (e^+) and antineutrinos ($\bar{\upsilon}$) are *antileptons.* (L=-1)

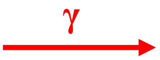
Neutrinos have zero mass, zero charge, but they have spin ½ like electrons, and are fermions.

Conservation Laws:

Charge:	(ΔZ=0)	0 = 1 - 1 + 0
Nucleons:	(ΔA=0)	1 = 1 + 0 + 0
Energy:	(ΔE=0)	$M_n c^2 = M_p c^2 + M_e c^2 + KE$
Leptons:	(ΔL=0)	0 = 0 + 1 - 1



Gamma rays

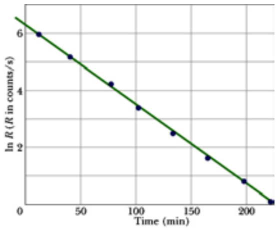


Gamma-ray emission during quantum jump between excited states of an aluminum nucleus.

$$E_\gamma = hf = \frac{hc}{\lambda} \approx 1.2\ MeV$$

$$\lambda = \frac{hc}{E} = \frac{1240\ eV \cdot nm}{1.2\ MeV} = 10^{-3}\ nm = 10^{3}\ \ fm$$

Radioactive decay



Spontaneous process.

Cannot predict when any particular nucleus will decay.

Result is just like decay of charge on a capacitor in an RC circuit. The number of nuclei remaining decreases *exponentially* with time. So the *decay rate R* (and intensity of the emitted radiation) does also.

$$\boxed{R = R_0 e^{-t/\tau}}$$

Meanlife is τ

Halflife is $T_{1/2} = (\ln 2)\tau$

Semilog plot shows straight line. $\ln R = \ln R_0 - t/\tau$

Q.42-3

$$^{64}Cu_{29} \rightarrow {}^{64}Ni_{28} + e^{+} + \upsilon$$

$$T_{1/2} = 12.7\ hrs$$

Suppose at time t=0 we have 800 atoms of the radioactive copper isotope $^{64}Cu_{29}$

At time t=12.7 hours we find that we have only 400 atoms of copper; the other 400 have changed to nickel $^{64}Ni_{28}$

At time t=25.4 hours how many atoms of copper will we have?

(1) 600 (2) 400 (3) 300 (4) 200 (5) 100 (6) 0

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Suppose at time t=0 we have 800 atoms of the radioactive copper isotope. At time t=12.7 hours we find that we have only 400 atoms of copper; the other 400 have changed to nickel.

At t=25.4 hours how many atoms of copper will we have?

We see that the half-life is 12.7 hours.

This means that half of the remaining copper atoms will decay during any period of 12.7 hours.

Thus half the remaining 400 will be gone.

(1) 600 (2) 400 (3) 300 $\boxed{\text{(4) 200}}$ (5) 100 (6) 0

Final Exam

- Counts for 20% of grade.
- Format (midterm×2): 12 MC questions + 4 problems
- Covers entire semester.
- Chapters (21-44) are not equally covered.
- Calculators are permitted.

Review basic concepts!

Chapter 43: Nuclear energy

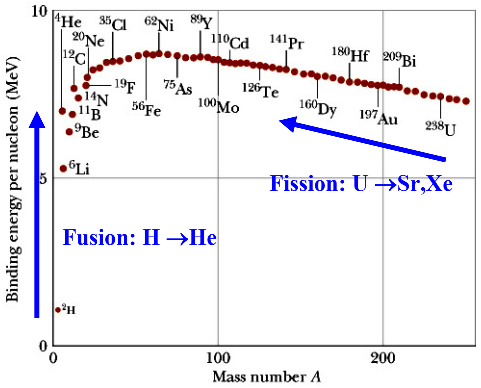
Can we get useful energy from nuclear reactions?

Two possibilities:

- **Fission:** Breakup of heavy nuclei.
- **Fusion:** Merging of light nuclei.

In both cases, the final nuclei are *more stable* (greater binding energy per nucleon) than the initial nuclei, so the total mass is less, and the excess energy is released, typically as heat.

Fission and Fusion



Fission: U →Sr,Xe

Fusion: H →He

Typical fission process

$$n + {}^{235}U_{92} \to {}^{236}U_{92} \to {}^{140}Xe_{54} + {}^{94}Sr_{38} + \underline{2n} + K$$

Conservation laws:

Charge: (ΔZ=0) 92 = 54 + 38 + 0

Nucleons: (ΔA=0) 1+235 = 140 + 94 + 1+1

Energy: (ΔE=0) $M_U c^2 + m_n c^2 = M_{Xe} c^2 + M_{Sr} c^2 + 2m_n c^2 + K$

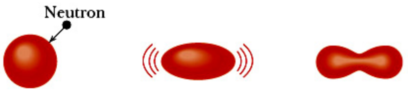
Leptons: (ΔL=0) 0 + 0 = 0 + 0 + 0

The two final neutrons lead to the famous *chain reaction!*

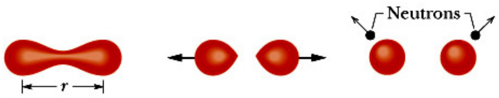
Fig. 43-1: U→X+Y where $Z_X+Z_Y=92$ and $A_X+A_Y\approx 234$

The fission reaction process

1. Thermal neutron is captured and nucleus is excited:

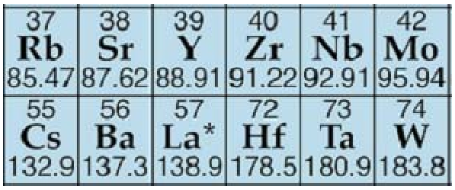


2. Excited nucleus fissions and releases neutrons:



Q.43-1 In this fission reaction, what element is “X”?

$$n + {}^{235}U_{92} \to {}^{139}Cs_{55} + {}^{95}X + 2n + K$$



37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94
55 Cs 132.9	56 Ba 137.3	57 La* 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.8

1. Rb
2. Sr
3. Y
4. Zr
5. Nb
6. Mo

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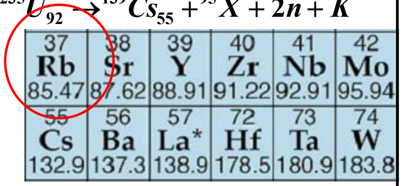

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3. Y
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To conserve charge, the atomic numbers of the fragments must add up to 92: X = 92 – 55 = 37.

From chart, Z=37 means Rubidium.

Electric power from fission

- Well-established technology.
  - Heat engine drives turbines which drive generators.
  - Fission replaces combustion as heat source.
- With proper safeguards a nuclear power plant can be safer and cleaner than a coal-burning plant.
- Environmental factors:
  - Heat is delivered at a lower temperature, so by the second law of thermodynamics there is more waste heat, more thermal pollution of air, rivers, lakes.
  - Less radioactivity dumped into atmosphere than by a coal-burning plant.
  - Used fuel rods are radioactive and must be disposed of *very carefully* – unsolved political problem.

Fusion

$$2p + 2n \to He \quad (+30\,MeV)$$

How to make this happen in practice?
Can’t get free protons and neutrons to start this reaction.

Sun uses inverse beta decay, but this is much too slow for us.

$$p + e^- \to n + \nu$$
$$4p + 2e \to He + 2\upsilon$$

Start with heavy isotopes as in the H bomb.

$${}^2H + {}^2H \to {}^4He$$
$${}^1H + {}^3H \to {}^4He$$

Use very hot gas (plasma) of heavy hydrogen (deuterium) ${}^2H_1$.

Thermonuclear Energy

- Half-century old R&D project to produce useful power from controlled fusion.
- Must have ionized gas (plasma) at very high T.
- Must a way of containing this gas.
- Magnetic confinement: ions circling in strong B.
- Inertial confinement: Zap a fuel pellet with lasers.

Chance for fusion in hot plasma

Want to fuse two deuterons to make helium.
Need to make two nuclei collide: r = 3 fm.
Coulomb potential energy for Q = +e:

$$V(r) = \frac{kQ}{r} = \frac{9\times10^{9}\times1.6\times10^{-19}}{3\times10^{-15}} = 4.8\times10^{5}\ V$$

$$U(r) = QV = 480\ keV$$

T = 400 million K has been achieved.
What fraction of protons will have this much energy?

$$kT = (8.6\times10^{-5}\ eV/K)\times(4\times10^{8}\ K) = 34\ keV$$

$$e^{-U/kT} = e^{-480/34} = e^{-14} = 9\times10^{-7} = 1/million$$

When will we have fusion power?

Potentially tremendous source.

Still not in view after 50 years of R&D.