Lec #23: Nuclear Power. II.

LAST TIME: Begin Nuclear Power (Chaps 13-15)

TODAY: Fundamentals of Nuclear Physics

NEXT: Reactors and Environmental Impact

Fundamentals of Nuclear Physics

A. NUCLEAR STRUCTURE

1. Atoms
   - nucleus positively charged, massive, compact
   - electrons small, negatively charged, occupy "large" volume
   - chemical properties determined by electron # & excitation
   - neutral atom if # electrons = # protons
   - 92 natural "stable" elements

2. Common energy units: eV (electron-Volt) or MeV (10^6 eV)

Chemical reactions in atoms = few eV

Nuclear reactions = few to hundreds of MeV

1 eV = (1.6E-19 C) times (1 J/C)

= 1.6E-19 Joules

Metals | Metalloids | Nonmetals

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.008																1 H 1.008	2 He 4.003
3 Li 6.941	4 Be 9.012	← Transition Metals →										5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.30											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (97.91)	44 Ru 101.1	45 Rh U 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	71 Lu 175.0	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209.0)	85 At (210.0)	86 Rn (222.0)
87 Fr (223.0)	88 Ra (226.0)	103 Lr (262.1)	104 Rf (261.1)	105 Db (262.1)	106 Sg (263.1)	107 Bh (262.1)	108 Hs (265.1)	109 Mt (266.1)	110 Ds (271)	111 Rg (272)	112 ( )	113	114 ( )	115 ( )	116 ( )		

Lanthanides

57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (144.9)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.2	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0

Actinides

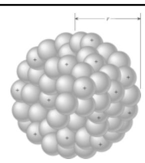
89 Ac (227.0)	90 Th 232.0	91 Pa 231.0	92 238.0	93 Np (237.0)	94 Pu (244.1)	95 Am (243.1)	96 Cm (247.1)	97 Bk (247.1)	98 Cf (251.1)	99 Es (252.1)	100 Fm (257.1)	101 Md (258.1)	102 No (259.1)

Fundamentals of Nuclear Physics (cont.)

3. Mass of free particles ($E=mc^2$)
   - proton = 1.6726E-27 kg = 938.3 MeV/c^2
   - neutron = 1.6749E-27 kg = 939.6 MeV/c^2
   - electron = 9.1094E-31 kg = 0.511 MeV/c^2
4. Binding Energy and Mass of atom < $m_p n_p + m_n n_n + m_e n_e$
   - Δmc^2 = binding energy
   - most of this (MeV's) is in nucleus
5. Nuclear Structure (protons + neutrons)
   - EM repulsion of protons; neutron immune to EM force
   - must be a force stronger than EM operating over tiny distances
   - more protons -> more EM; more neutrons -> some dilution
   - Atomic Number: Z = # of protons; N = # of neutrons
   - Nucleon Number: A = # of nucleons (A = Z + N)
   - ${}^{A}_{Z}\mathrm{X}$; X is chemical symbol e.g. ${}^{238}_{92}\mathrm{U}$ (or just ^{238}U)

Nuclear Structure

The atomic nucleus consists of positively charged protons and neutral neutrons.



$r \approx \left(1.2\times10^{-15}\,\mathrm{m}\right)A^{1/3}$

Strong Nuclear Force

Mass number : *Number of nucleons in the nucleus, A=Z+N* → A

Atomic number: *Number of protons in the nucleus* → Z

X ← **Chemical Symbol**

neutron number (N): the number of neutrons in the nucleus

Unified Mass Unit (u)

1 u = 1.6605 x 10^{-27} kg or 1 u = 931. 5 MeV

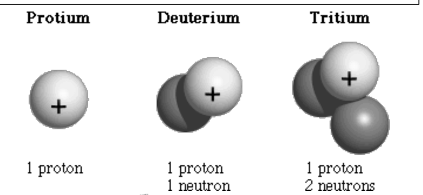
Fundamentals of Nuclear Physics (cont.)

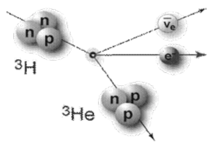
B. ISOTOPES

- same Z, therefore same chemical properties
- different N (and A), therefore
  - different mass
  - different nuclear binding energy
  - different stability
  - different behavior in nuclear reactions
- elements usually form with a mix of isotopes
- over time, this mix changes, as "unstable" isotopes "decay"
  - e.g. ^{1}H = hydrogen 99.985% stable
  - . ^{2}H = deuterium 0.015% stable
  - . ^{3}H = tritium ~0.000% half-life = 12.3 years
  - e.g. ^{238}U 99.3% half-life = 4.47 billion years
  - . ^{235}U 0.7% half-life = 0.70 billion years

Isotopes of Hydrogen

ISOTOPES: Nuclei that contain the same number of protons but a different number of neutrons.





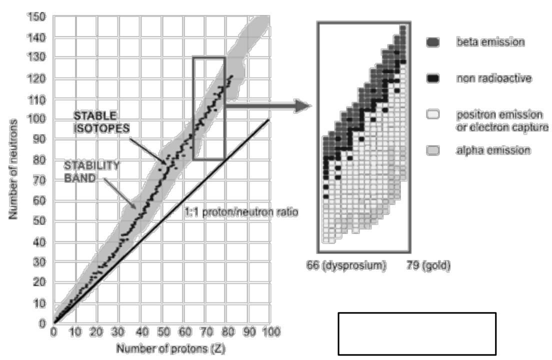
Deuterium is a stable isotope of hydrogen. Symbol: ^2H or D

Tritium is radioactive. Symbol: ^3H. It decays into a proton plus electron and anti-neutrino.

Fundamentals of Nuclear Physics (cont.)

C. STABILITY OF ISOTOPES

- certain combinations of neutron # and proton # hold together for a long time
- others transmute themselves to a different element by radioactive decay (alpha, beta, gamma, fission, …)
- adding neutrons to a stable nucleus generally makes it unstable
- ~400 stable nuclei known; all have $Z \le 83$ (Bismuth)
- generally stable if Z a/or N = 2, 8, 20, 28, 50, 82, 126
  - nuclear "shell" structure analogous to atomic shells
  - ^4He, ^{16}O, ^{40}Ca, etc. are like noble gases – very stable (tightly bound)



Nuclear Reactions

A. Radioactivity

Spontaneous "decay" to a different nuclear state, or even a different type of atom, through the emission or absorption of particles or electromagnetic energy, releasing energy

1. Alpha Decay: Emission of a helium nucleus (2P, 2N)

$${}_Z^AX \to {}_{Z-2}^{A-4}Y + {}_2^4He$$

$$\textit{Heat} = (M_x - M_Y - M_\alpha)c^2 \to \textit{K.E.} \text{ of X, Y, } \alpha$$

2. Beta Decay: Emission or absorption of electron or positron

$${}_Z^AX \to {}_{Z+1}^{A}Y + \beta^- + \underline{\nu}$$

$${}_Z^AX \to {}_{Z-1}^{A}Y + \beta^+ + \nu$$

$${}_Z^AX + \beta^- \to {}_{Z-1}^{A}X + \nu$$

3. Gamma Decay: Emission of a photon (de-excitation)

$${}_Z^AX^* \to {}_Z^AX + \gamma$$

Decay Processes

Alpha decay

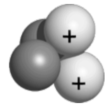
- **The α decay is a nuclear transmutation: nuclei of one element change into nuclei of a lighter element.**

Parent nucleus — **Daughter nucleus** — **α particle (helium nucleus)**

$${}_{92}^{238}U \to {}_{90}^{234}Th + {}_2^4He$$

Uranium — **Thorium**

He Nucleus charge of +2



Beta Decay

- **During beta decay, the daughter nucleus has the same number of nucleons as the parent, but the atomic number is changed by one.**

$${}_0^1n \to {}_1^1p + {}_{-1}^{0}e$$

144 N, 90 P — **143 N, 91 P** — **β-particle**

$${}_{90}^{234}Th \to {}_{91}^{234}Pa + {}_{-1}^{0}e$$

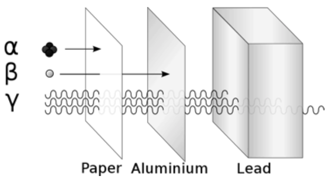
Thorium (parent nucleus) — **Protactinium (daughter nucleus)**

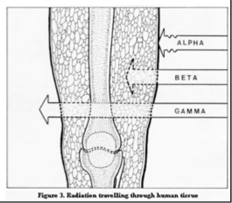
Gamma Decay

- Gamma rays are given off when an excited nucleus "falls" to a lower energy state
- The de-excitation of nuclear states results from "jumps" made by a proton or neutron
- The excited nuclear states may be the result of violent collision or more likely of an alpha or beta emission

$$^{12}_{6}C^{*}$$

$$\rightarrow {}^{12}_{6}C + \gamma_{ray}$$





Nuclear Reactions (cont.)

Table 13.1 PROPERTIES OF NUCLEAR RADIATIONS

Type of Radiation	Range
α particles	a sheet of paper, a few centimeters of air, or thousandths of a centimeter of biological tissue
β particles	a thin aluminum plate or tenths of a centimeter of biological tissue
γ rays	several centimeters of lead or meters of concrete

B. Spontaneous Decay - Exponential (Half Life)

$N = N_o e^{-\lambda t}$

Rate = λ N

1 Curie = 3.7 E 10 sec^{-1} (1 g of radium)

- Half life = ln(2)/ λ (remember the rule of 70?)
- Nuclei can also be rendered unstable in nuclear reactions

Nuclear Reactions (cont.)

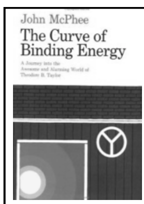
C. Neutrons

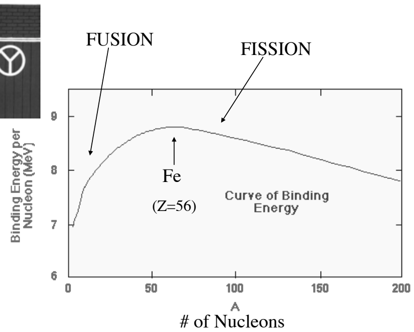
- accelerators yield charged particles with energy up to 1 TeV
- use electric currents to generate electric and magnetic fields; only accelerate *charged* particles
- neutrons can not be accelerated, focused, etc.
- free neutrons decay (~10 min) to proton + electron
- neutrons easily pass by electron cloud and are not repelled by positively charged nucleus
- if they are traveling slowly enough, they stick; if they travel faster, they scatter
  – e.g. thermal neutrons (300 K) travel ~ 2.8 km/s
- if they are captured, they can produce an unstable isotope, which can then either DECAY or FISSION

Nuclear Fission

A. Fission and Fusion

- Fission - break up into 2 or more smaller pieces
- Fusion - combine 2 or more pieces into a bigger piece
- both involve transmutation of elements
- both can be exothermic: energy released = Δmc^2
  – if $M_{big} < \Sigma M_{small}$, fusion is exothermic
  – if $M_{big} > \Sigma M_{small}$, fission is exothermic
- both processes occur in nature
  – fusion inside stars
  – fission e.g. OKLO
- fission of U discovered in late '30s
  – 1st controlled chain reaction in 1942
  – 1st uncontrolled chain reaction 1945





Nuclear Fission (cont.)

B. Fission Example

n + ^{235}U --> ^{236}U

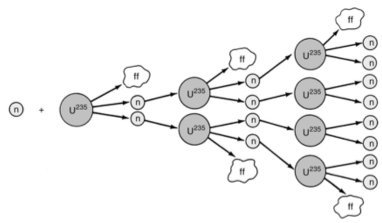
^{236}U --> A* + B* + 3n

A* and B* have too many neutrons to be stable; long series of beta decays to eventually become stable

- energy released as *kinetic energy* of products
- neutron initiates reaction, and reaction produces neutrons
- for Uranium, only slow neutrons will cause fission, but neutrons produced by fission move very fast
- need "moderator" to slow them down
- if 1 or more of these neutrons stimulates another fission, a chain reaction can result

Nuclear Fission (cont.)

- K = average # of fission inducing neutrons per fission
  - water is a moderator: it slows down neutrons
  - depends on material, moderators, shape and size of "pile", temperature, etc.
    - if K<1 reaction dies out
    - if K=1 continuous power production
    - if K>1 possibly destructive chain reaction



Nuclear Fission (cont.)

C. Enrichment of Fissile Material

- Natural isotope ratio: $^{238}U/^{235}U \sim 142$
  - 99.3% ^{238}U [changes very slowly
  - 0.7% ^{235}U over time]
- with water as moderator, need 3 or 4% ^{235}U
- with heavy water, we can use natural mix
- for bombs, need 90% or more ^{235}U (or Plutonium)
- how do we change the isotope ratio?
  - Diffusion (ORNL)
  - Centrifuge (LBL)
  - Laser (LANL)
  - Breeder reactor (Hanford, SRS)
  - Fuel reprocessing

^{238}U --> ^{235}U Enrichment in reactor

$$^{238}U + n \rightarrow {}^{239}U + \gamma$$

$$^{239}U \rightarrow {}^{239}Np + \beta^- + \bar{\upsilon} \qquad (T_{1/2} = 23.5 \text{ min.})$$

$$^{239}Np \rightarrow {}^{239}Pu + \beta^- + \bar{\upsilon} \qquad (T_{1/2} = 2.35 \text{ days})$$

$$^{239}Pu \rightarrow {}^{235}U + \alpha \qquad (T_{1/2} = 2.44 \times 10^4 \text{ years})$$

NUCLEAR POWER UNITS BY REACTOR TYPE, WORLDWIDE

Reactor Type	Units	Net MWe (in operation)	Under Construction
Pressurized light-water reactors (PWR)	243	214,234	43
Boiling light-water reactors (BWR)	91	74,941	8
Gas-cooled reactors, all types	36	12,239	0
Heavy-water reactors, all types	33	18,645	16
Graphite-moderated light-water reactors (LGR)	15	14,785	1
Liquid-metal-cooled fast breeder reactors (LMFBR)	3	928	4