Announcements

1. Remember to bring your evaluation pin #'s and Thinkpad's to lab this week.
2. Makeup exam ≤ Wed. 4/20/05 at 10 AM (do not miss class!)
3. Extra credit possibilities – send me email about this if you are interested
4. Nuclear physics (Chapters 43 & 44) – next two lectures

   Description of nuclei – mass deficit

   Nuclear decay processes – half life – α,β,γ particles

   – units Ci, rad, rem

   Nuclear reactions – fission and fusion

Motivation

- General education
- Opportunities and dangers
- Nuclear power possibilities
- Astrophysics connections

THREE MILE ISLAND: 1979 In 1979 a cooling malfunction caused part of the core to melt a 2 reactor at Three Mile Island near Harrisburg PA. The reactor was destroyed. Some radioactive gas was released a couple of days after the accident, but not enough to cause any dose above background levels to local residents. There were no injuries or adverse health effects from the accident.

THE CHERNOBYL DISASTER: On April 26, 1986 at 1:23 am technicians at the Chernobyl Power Plant in the Ukraine (former Soviet Union) allowed the power in the fourth reactor to fall to low levels as part of a controlled experiment which went wrong. The reactor overheated causing a meltdown of the core. The people of Chernobyl were exposed to radioactivity 100 times greater than the Hiroshima bomb. It is estimated that over 15 million people have been victimized by the disaster in some way and that it will cost over 60 Billion dollars to make these people healthy.

Z

Period	1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	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 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	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 (98)	44 Ru 101.1	45 Rh 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
6	55 Cs 132.9	56 Ba 137.3	57 La* 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 190.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac~ (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 --- ()	111 --- ()	112 --- ()		114 --- ()		116 --- ()		118 --- ()

Ingredients of nucleus:

Z protons (each with mass m_p = 1.007276 u)

N neutrons (each with mass m_n = 1.008665 u)

$A \equiv Z + N$

u ≡ (1/12) x mass of C for A=12 (1.66053886 x 10^{-27} kg, 931.494043 MeV/c^2)

Note: in these units, m_e = 0.00054857990945 u

Notation: $^{A}_{Z}N$ examples: $^{12}_{6}C$, $^{238}_{92}U$

Ref: http://physics.nist.gov/cuu/Constants/Table/allascii.txt

Atomic Weights and Isotopic Compositions for All El

Z	Isotope	A	Relative Atomic Mass	Isotopic Composition	Standard Atomic Weight
1	H	1	1.007 825 032 1(4)	99.9885(70) %	1.007 94(7)
	D	2	2.014 101 778 0(4)	0.0115(70)	
	T	3	3.016 049 2675(11)		
2	He	3	3.016 029 309 7(9)	0.000 137(3)	4.002 602(2)
		4	4.002 603 2497(10)	99.999 863(3)	
3	Li	6	6.015 122 3(5)	7.59(4)	6.941(2)
		7	7.016 004 0(5)	92.41(4)	
26	Fe	54	53.939 6148(14)	5.845(35)	55.845(2)
		56	55.934 9421(15)	91.754(36)	
		57	56.935 3987(15)	2.119(10)	
		58	57.933 2805(15)	0.282(4)	
27	Co	59	58.933 2002(15)	100	58.933 200(9)

Ref: http://www.physics.nist.gov/PhysRefData/Compositions/index.html

mass of neutral atom
➔ includes Z electrons

Z		A			
27	Co	59	58.933 2002(15)	100	58.933 200(9)

Mass of nucleus:

$$M_{sum} = Zm_p + (A-Z)m_n + Zm_e = 59.474281 \text{ u}$$

$$\Delta M = 0.5410806 \text{ u}$$

What should we do with this mass deficit?

(A) Chalk it up to inaccuracy of my calculator.

(B) Figure that NIST made a mistake.

(C) Give up on physics as a quantitative science.

(D) Find some meaning associated with ΔM.

mass of neutral atom
➔ includes Z electrons

Z		A			
27	Co	59	58.933 2002(15)	100	58.933 200(9)

Mass of nucleus:

$$M_{sum} = Zm_p + (A\text{-}Z)m_n + Zm_e = 59.474281 \text{ u}$$

$$\Delta M = 0.5410806 \text{ u} = 504.0135 \text{ MeV }/c^2$$

$$\Delta M/A = 8.5426 \text{ MeV }/c^2 \text{ /nucleon}$$

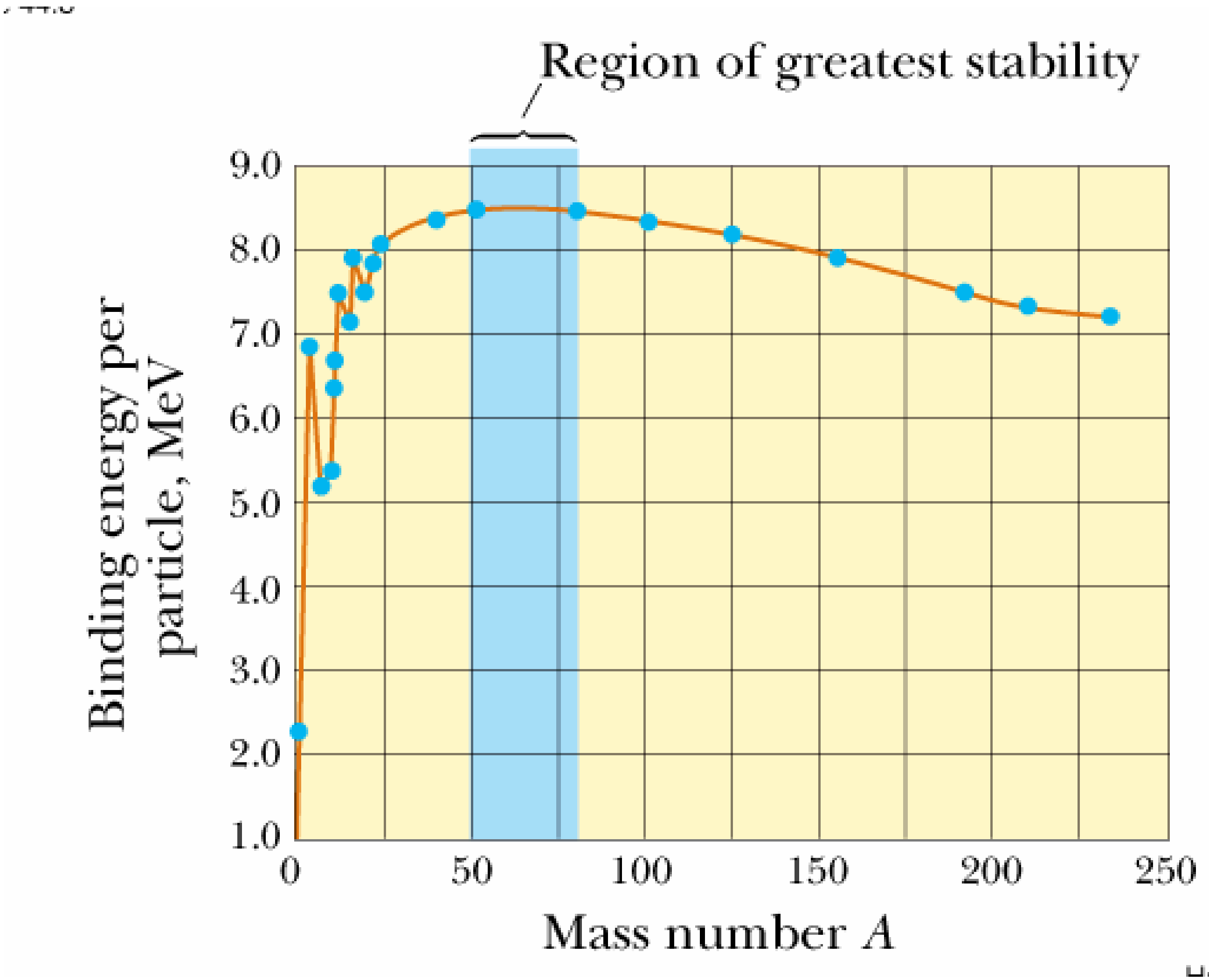
➔ energy associated with nuclear "binding"

Another example:

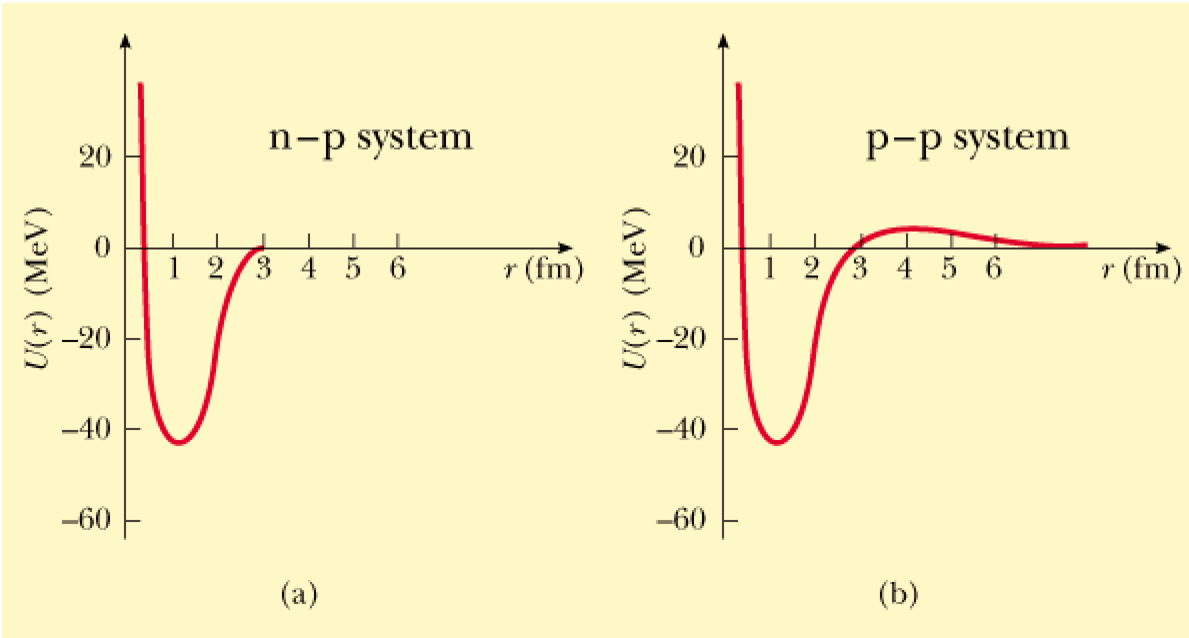
2	He	3	3.016 029 309 7(9)	0.000 137(3)	4.002 602(2)
		4	4.002 603 2497(10)	99.999 863(3)	

$$\Delta M/A({}^4_2He) = 7.1 \text{ MeV}/c^2/\text{nucleon}$$

$$\Delta M/A({}^3_2He) = 2.6 \text{ MeV}/c^2/\text{nucleon}$$


Region of greatest stability
Binding energy per particle, MeV
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
50
100
150
200
250
Mass number A

➔There must be a strong attraction between nuclear particles



1. HRW6 43.P.020. [53069] You are asked to pick apart an alpha particle (^4He) by removing, in sequence, a proton, a neutron, and a proton. Calculate

(a) the work required for each step,

[ ] MeV (energy to remove a proton)

[ ] MeV (energy to remove a neutron)

[ ] MeV (energy to remove another proton)

(b) the total binding energy of the alpha particle, and

[ ] MeV

(c) the binding energy per nucleon.

[ ] MeV (energy per nucleon)

Some needed atomic masses are

^4He	4.00260 u	^2H	2.01410 u
^3H	3.01605 u	^1H	1.00783 u
n	1.00867	-	-

1. $${}^4_2He + Q \rightarrow {}^3_1H + {}^1_1H$$

2. $${}^3_1H + Q \rightarrow {}^2_1H + n$$

3. $${}^2_1H + Q \rightarrow {}^1_1H + n$$

Note: electron contribution to mass is not neglibible.

Not all nuclei are stable:

Some types of nuclear decay

$\alpha \equiv {}^{4}_{2}He^{++}$ Ex: ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + \alpha$

$\beta \equiv e^{-}$ or e^{+} Ex: ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-}$

$\gamma \equiv$ (photon) Ex: ${}^{12}_{5}B \rightarrow {}^{12}_{6}C^{*} + e^{-} + \bar{\nu}$

Measure of radioactive decays:

Decay rate: $$\frac{dN}{dt} = -\lambda N$$

Solution: $$N(t) = N_0 e^{-\lambda t}$$

$$\left| \frac{dN}{dt}(t) \right| = N_0 \lambda e^{-\lambda t}$$

Half-life:

When N(t) = ½ N_0:

$$N(T_{1/2}) = N_0 e^{-\lambda T_{1/2}} \equiv \tfrac{1}{2} N_0$$

$$\Rightarrow T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.6931472}{\lambda}$$

$$\text{Note that: } N(t) = N_0 \left(\frac{1}{2}\right)^{\left(t/T_{1/2}\right)}$$

Some units of nuclear decay:

1 Ci (Curie) ≡ 3.7 x 10^{10} decays/s

1 Bq (Becquerel) ≡ 1 decay/s

Example:

Suppose that you have a sample of 10^{23} ${}^{14}_{6}C$ nuclei

each of which has a half-life of 5730 years. How many Curies of radiation is this?

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.6931472}{\lambda}$$

$$\lambda = \frac{0.6931472}{T_{1/2}} = 3.8\times10^{-12}\,\text{decays/s}$$

$$\left|\frac{dN}{dt}\right| = \lambda N = 3.8\times10^{-12}\times10^{23}\,\text{decays/s} = 10.4\,\text{Ci}$$

Online Quiz for Lecture 29
Nuclear Physics -- Apr. 18,2005

Suppose you have a sample of 6.02×10^{23} atoms of ^{97}Tc which has a half-life of 2.6×10^{6} years.

1. How many Curies does this sample have?
   (a) 0.001
   (b) 0.1
   (c) 10
   (d) 1000
   (e) None of these
2. How long will it take before the sample has only 3.01×10^{23} ^{97}Tc atoms left?
   (a) 1.3×10^{6} years
   (b) 2.6×10^{6} years
   (c) 5.2×10^{6} years
   (d) 26×10^{6} years
   (e) None of these.

$$\frac{dN}{dt} = \frac{\ln 2}{T_{1/2}} N_0 \left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}} = \frac{\ln 2}{T_{1/2}} N$$

$$= \frac{\ln 2 \cdot 6.02 \times 10^{23}}{2.6 \times 10^{6} \times 3.16 \times 10^{7} s} \frac{1 Ci}{3.7 \times 10^{10} / s}$$

$$= 0.137 Ci$$

Effects of radiation in matter

Release of energetic particles –

α, n, p → move atoms in materials

e^-, e^+, γ → remove or excite electrons

→ cause chemical reactions

Quantitative measures of radiation dose

rad ("radiation absorbed dose"): amount of radiation that increases the energy of 1kg of absorbed materials by 0.01 J.

gray (Gy): 1 Gy = 100 rad

RBE ("relative biological effectiveness" factor): ratio of biological damage of radiation type to that of γ rays

rem ("radiation equivalent in man"): rad x RBE

sievert (Sv): 1 Sv = 100 rem

Some RBE factors

Radiation type	RBE
γ rays	1
β particles	1-1.7
n (slow)	4-5
n & p (fast)	10
α particles	10-20
heavy ions	20

Some typical values of dose

Source	Dose
Background radiation	0.13 rem/year
Recommended limit	0.5 rem/year
Diagnostic chest X-ray	0.01 rem
Mammogram	0.1 rem
Fatal dose	400-500 rem

Summary of radiation units:

Radiation dose: Amount of radiation absorbed/unit mass

1 Gy = 1 J/kg of absorbed radiation = 100 rad

1 Sv = RBE x (dose in Gy units) = 100 rem

RBE: relative biological effectiveness

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5. HRW6 43.P.069. [53088] A typical chest x-ray radiation dose is 248 μSv, delivered by x rays with an RBE factor of 0.85. Assuming that the mass of the exposed tissue is one-half the patient's mass of 90 kg, calculate the energy absorbed in joules.

_____ mJ

Example:

A sealed capsule containing the radiopharmaceutical $^{32}_{15}P$ with an initial radioactivity of 5.22×10^6 Bq, is implanted into a 0.1 kg tumor. Each decay produces e^- particles at an energy of 7×10^5 eV. Determine the absorbed dose in a 10 day period. $T_{1/2}$ =14.26 days. Assume all emitted particles are absorbed.

dose = RBE x (number of decays) x (energy released)/mass

RBE → 1

number of decays → $N_0\left(1-\left(\frac{1}{2}\right)^{10/14.26}\right)$

energy released → $7 \times 10^5 \times 1.6 \times 10^{-19}$ J

mass → 0.1 kg

$$N_0 = \left|\frac{dN}{dt}\right|_0 \Big/ \frac{\ln 2}{T_{1/2}} = 5.22 \times 10^6 \Big/ \frac{\ln 2}{14.26 \times 86400} = 9.2785 \times 10^{12}$$

dose = 4 J/kg = 400 rem = 4 Sv