ENGY.3310 Fundamentals of Nuclear Science and Engineering
Exam #2 Spring 2016

Problem 1. Nuclear Stability (15 points)

Within the context of nuclear stability, answer the following questions:

a. The magic numbers are 2, 8, 20, 28, 50, 82, and 126. Explain this statement. Also, what does it mean if an isotope is doubly magic?

b. The binding energy per nucleon (BE/A) for ${}^{26}_{13}\mathrm{Al}$, ${}^{27}_{13}\mathrm{Al}$, and ${}^{28}_{14}\mathrm{Si}$ are listed here in order from the highest to lowest value: 8.45 MeV, 8.33 MeV, and 8.15 MeV. Identify which BE/A corresponds to each isotope and clearly explain the rationale for your selection.

c. In the semi-empirical mass formula there is an asymmetric correction term given by

$$BE_{asym} = -\zeta(A-2Z)^2/A$$

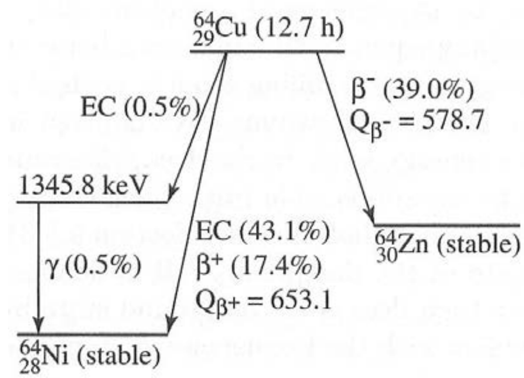
Explain what this means and, based on your discussion, clearly justify the form of this correction term to the total binding energy.

Problem 2. Radioactive Decay -- Basic Concepts and Decay Diagrams (20 points)

Given the decay diagram for Cu-64, answer the following questions:

a. What is the activity in Ci associated with a 0.01 g sample of Cu-64?

b. What is the gamma power in Watts associated with the same Cu-64 sample?



Problem 3. Radioactive Decay Calculations -- Betavoltaics (30 points)

Betavoltaics is related to the direct conversion of beta radiation into small amounts of useable electrical current/power (for example, one possible use is as a small battery for a pacemaker). In particular, a certain heart pacemaker that uses a ${}^{147}\mathrm{Pm}$ source requires a minimum of 200 μW of power from its betavoltaic battery to function properly. Note, however, that the device only operates with an efficiency of 0.95% (the conversion efficiency of these type of devices is always quite low). This problem asks you to explain the decay reaction and to determine the initial loading of ${}^{147}\mathrm{Pm}$ needed for operation of a particular device, as follows:

a. ${}^{147}\mathrm{Pm}$ decays via β^- decay with a half-life of 2.623 years. Identify the daughter product, D, and determine the Q-value for this decay reaction, where the reaction can be written as ${}^{147}_{61}\mathrm{Pm} \rightarrow \mathrm{D} + \mathrm{e}^- + \bar{\nu}$ (note that the anti-neutrino is assumed to have negligible rest mass).

b. Determine the specific activity of ${}^{147}\mathrm{Pm}$ in Ci/g and its maximum specific power in W/g.

c. Since the emitted electrons have a range of energies, the average specific power is only about 27.7% of the maximum value computed in Part b. In addition, as noted above, the power conversion efficiency of the betavoltaic device is only 0.95%. With this information, what activity is needed to meet the minimum 200 μW power requirement of the pacemaker?

d. If the betavoltaic battery is to have a minimum design lifetime of 5 years, what initial loading of ^{147}Pm is required?

Note #1: You may use the attached atomic mass data, as needed...

Note #2: If you don't get reasonable results for the initial parts of this problem, use the following intermediate results for subsequent parts. Note that these values are **not correct** and should be used only if absolutely necessary:

$Q = 0.25$ MeV/decay $\alpha = 900$ Ci/g $P_{max} = 1.33$ W/g

Problem 4. Particle Attenuation in Thick Targets (20 points)

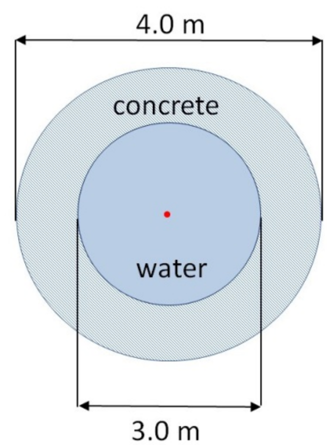
Consider a 40 mil thick (0.040 inches = 0.1016 cm) sheet of borated aluminum. The B-Al sheet has fully enriched B-10 with a resultant loading of 0.025 g of B-10 per gram of B-Al material and the overall material density is about 2.71 g/cm^3.

A reasonable average total cross section for thermal neutrons in B-10 is 3400 b and for Al-27 $\sigma_t = 1.55$ b.

From the above information, estimate the total macroscopic cross section of the B-Al alloy, the mean free path for thermal neutrons in the sheet, and the probability that a thermal neutron can pass through the 40 mil sheet without a collision.

Problem 5. Radiation Protection -- Distance and Shielding (15 points)

A small Am-Be isotropic neutron source that emits 1.3×10^7 neutrons/second is usually stored in a tall cylindrical concrete tank filled with water. The top view of the usual storage geometry is shown in the sketch (not to scale). The neutrons are emitted at high energy and suitable average macroscopic cross sections for water and concrete at high energy are 0.56 cm^{-1} and 0.12 cm^{-1}, respectively. Note also that, at high energies, air can be considered as essentially a vacuum for neutron transport over distances of a few meters.



For this system, estimate the uncollided flux (neutrons/cm^2-s) at a distance of 2 m from the source under the following scenarios:

a. The source is placed vertically above of the water and tank region so that it is only surrounded by air.

b. The source is in the center of the tank region (both radially and vertically), but the water has been drained from the tank. What is the uncollided flux on the outside surface of the tank (i.e. 2 m from the source)?

c. What is the uncollided flux on the outside surface of the tank if the source is in the same location as in Part b, but now the tank is full of water?

Some Useful Information for Use on (closed-book) Exams

Constant	Symbol	Value (with alternate units in some cases)	
Speed of light (in vacuum)	c	$2.997\ 924\ 58 \times 10^{8}$ ms^{-1}	
Electron charge	e	$1.602\ 176\ 53 \times 10^{-19}$ C	
Atomic mass unit	u	$1.660\ 538\ 9 \times 10^{-27}$ kg	931.494 043 MeV/c^2
Electron rest mass	m_e	$9.109\ 382\ 6 \times 10^{-31}$ kg	0.510 998 92 MeV/c^2 $5.485\ 799\ 09 \times 10^{-4}$ u
Proton rest mass	m_p	$1.672\ 621\ 7 \times 10^{-27}$ kg	938.272 03 MeV/c^2 1.007 276 466 9 u
Neutron rest mass	m_n	$1.674\ 927\ 3 \times 10^{-27}$ kg	939.565 36 MeV/c^2 1.008 664 915 6 u
Hydrogen atom rest mass	$M({}^1_1H)$	$1.673\ 532\ 6 \times 10^{-27}$ kg	1.007 825 032 2 u
Planck's constant	h	$6.626\ 069\ 3 \times 10^{-34}$ J s	$4.135\ 6674 \times 10^{-15}$ eV s
Avogadro's constant	N_A	$6.022\ 141\ 5 \times 10^{23}$ mol^{-1}	
Boltzmann constant	k	$1.380\ 650\ 5 \times 10^{-23}$ J K^{-1}	8.617343×10^{-5} eV K^{-1}
Ideal gas constant (STP)	R	8.314 472 J mol K^{-1}	
Electric constant	ε_o	$8.854\ 187\ 817 \times 10^{-12}$ F m^{-1}	

Conversion Factors

1 MeV = 1.602×10^{-13} J 1 Ci = $3.7\text{x}10^{10}$ decays/sec

κ = average recoverable energy per fission = 200 MeV/fission

Table B.1. Atomic mass tables *(cont.)*

N	Z	A	El	Atomic Mass (μu)	N	Z	A	El	Atomic Mass (μu)	N	Z	A	El	Atomic Mass (μu)
86	56		Ba	141 916448	92	54	146	Xe	145 947300	84	65		Tb	148 923242
85	57		La	141 914074	91	55		Cs	145 940160	83	66		Dy	148 927334
84	58		Ce	141 909240	90	56		Ba	145 930110	82	67		Ho	148 933790
83	59		Pr	141 910040	89	57		La	145 925700	81	68		Er	148 942170
82	60		Nd	141 907719	88	58		Ce	145 918690	80	69		Tm	148 952650
81	61		Pm	141 912950	87	59		Pr	145 917590	79	70		Yb	148 963480
80	62		Sm	141 915193	86	60		Nd	145 913112	95	55	150	Cs	149 957970
79	63		Eu	141 923400	85	61		Pm	145 914692	94	56		Ba	149 945620
78	64		Gd	141 928230	84	62		Sm	145 913037	93	57		La	149 938570
77	65		Tb	141 938860	83	63		Eu	145 917200	92	58		Ce	149 930230
76	66		Dy	141 946270	82	64		Gd	145 918305	91	59		Pr	149 927000
75	67		Ho	141 959860	81	65		Tb	145 927180	90	60		Nd	149 920887
90	53	143	I	142 944070	80	66		Dy	145 932720	89	61		Pm	149 920979
89	54		Xe	142 934890	79	67		Ho	145 944100	88	62		Sm	149 917271
88	55		Cs	142 927330	78	68		Er	145 952120	87	63		Eu	149 919698
87	56		Ba	142 920617	77	69		Tm	145 966500	86	64		Gd	149 918655
86	57		La	142 916059	93	54	147	Xe	146 953010	85	65		Tb	149 923654
85	58		Ce	142 912381	92	55		Cs	146 943860	84	66		Dy	149 925580
84	59		Pr	142 910812	91	56		Ba	146 933990	83	67		Ho	149 933350
83	60		Nd	142 909810	90	57		La	146 927820	82	68		Er	149 937760
82	61		Pm	142 910928	89	58		Ce	146 922510	81	69		Tm	149 949670
81	62		Sm	142 914624	88	59		Pr	146 918980	80	70		Yb	149 957990
80	63		Eu	142 920287	87	60		Nd	146 916096	79	71		Lu	149 972670
79	64		Gd	142 926740	86	61		Pm	146 915134	96	55	151	Cs	150 962000
78	65		Tb	142 934750	85	62		Sm	146 914893	95	56		Ba	150 950700
77	66		Dy	142 943830	84	63		Eu	146 916741	94	57		La	150 941560
76	67		Ho	142 954690	83	64		Gd	146 919089	93	58		Ce	150 934040
91	53	144	I	143 949610	82	65		Tb	146 924037	92	59		Pr	150 928230
90	54		Xe	143 938230	81	66		Dy	146 930880	91	60		Nd	150 923825
89	55		Cs	143 932030	80	67		Ho	146 939840	90	61		Pm	150 921203
88	56		Ba	143 922940	79	68		Er	146 949310	89	62		Sm	150 919928
87	57		La	143 919590	78	69		Tm	146 961080	88	63		Eu	150 919846
86	58		Ce	143 913643	93	55	148	Cs	147 948900	87	64		Gd	150 920344
85	59		Pr	143 913301	92	56		Ba	147 937680	86	65		Tb	150 923098
84	60		Nd	143 910083	91	57		La	147 932190	85	66		Dy	150 926180
83	61		Pm	143 912586	90	58		Ce	147 924390	84	67		Ho	150 931681
82	62		Sm	143 911995	89	59		Pr	147 922180	83	68		Er	150 937460
81	63		Eu	143 918774	88	60		Nd	147 916889	82	69		Tm	150 945430
80	64		Gd	143 922790	87	61		Pm	147 917468	81	70		Yb	150 955250
79	65		Tb	143 932530	86	62		Sm	147 914818	80	71		Lu	150 967150
78	66		Dy	143 939070	85	63		Eu	147 918154	96	56	152	Ba	151 954160
77	67		Ho	143 951640	84	64		Gd	147 918110	95	57		La	151 946110
76	68		Er	143 960590	83	65		Tb	147 924300	94	58		Ce	151 936380
91	54	145	Xe	144 943670	82	66		Dy	147 927180	93	59		Pr	151 931600
90	55		Cs	144 935390	81	67		Ho	147 937270	92	60		Nd	151 924680
89	56		Ba	144 926920	80	68		Er	147 944440	91	61		Pm	151 923490
88	57		La	144 921640	79	69		Tm	147 957550	90	62		Sm	151 919728
87	58		Ce	144 917230	78	70		Yb	147 966760	89	63		Eu	151 921740
86	59		Pr	144 914507	94	55	149	Cs	148 952720	88	64		Gd	151 919788
85	60		Nd	144 912569	93	56		Ba	148 942460	87	65		Tb	151 924070
84	61		Pm	144 912744	92	57		La	148 934370	86	66		Dy	151 924714
83	62		Sm	144 913406	91	58		Ce	148 928290	85	67		Ho	151 931740
82	63		Eu	144 916261	90	59		Pr	148 923791	84	68		Er	151 935080
81	64		Gd	144 921690	89	60		Nd	148 920144	83	69		Tm	151 944300
80	65		Tb	144 928880	88	61		Pm	148 918329	82	70		Yb	151 950170
79	66		Dy	144 936950	87	62		Sm	148 917180	81	71		Lu	151 963610
78	67		Ho	144 946880	86	63		Eu	148 917926	97	56	153	Ba	152 959610
77	68		Er	144 957460	85	64		Gd	148 919336	96	57		La	152 949450