22.02 Intro to Applied Nuclear Physics

Final Exam

Monday, May 16, 2010 Solutions

Problem 1: Short Questions *30 points*

1. What characteristic of the nuclear force explains the volume term in the semi-empirical mass formula (in other words, it explains why the binding energy is almost proportional to A: $B \approx a_v A$)?

   The nuclear force is charge-independent and very short range. Thus each nucleon (irrespective of being a neutron or a proton) is interacting mostly only with a constant number of neighbors, giving $B \sim A$ and not with all other nucleons, which would give $B \sim A(A-1)$

2. What is the spin of the deuteron? What is the degeneracy of this state? What characteristic of the nuclear force determines the deuteron spin?

   Since the nuclear force has a spin-dependent part, it is more energetically favorable for the deuteron to be in a spin triplet state. This state has a trifold degeneracy

3. In the shell model, we fill up the energy levels with nucleons, based on the degeneracy of each level, to determine the occupied levels and e.g. obtain the nucleus spin/parity assignment. Why do we consider neutrons and protons separately in filling the levels?

   When predicting the nuclear structure of nuclides, each level cannot have an arbitrary large number of protons and neutrons with that particular energy, since these particles are fermions, to which the Pauli exclusion principle applies. Hence only a number equal to the degeneracy of each level can be fitted in each level. However, neutrons and protons are different particles, non-identical, so the Pauli's principle does not apply to a mixture of them.

4. We used the Fermi golden rule to obtain the decay rate for gamma and beta decay. What are the two factors in the Fermi Golden rule and what is their meaning?

   Besides numerical factors, the Fermi golden rule is given by the product of the matrix element and of the density of states. The first one gives the probability of a transition from the initial state to a final state. The second one multiplies this probability by the number of states available, to finally give the total transition rate.

5. What conservation laws determine the selection rules in gamma decay?

   Parity conservation and total angular momentum conservation.

6. Consider an experimental setup where a beam of alpha particles are fired at a thin gold foil. Alpha particles are then detected at a certain angle from the initial beam direction. What type of cross-section is an experiment like this measuring?

   Since we only measure the scattered beam at a particular angle, we are measuring the differential cross section $d\sigma/d\Omega$. In the particular case of alpha particles scattered by nuclei, this correspond to the Rutherford scattering cross section

7. If the target of the alpha particles was not a thin foil, what competing process would determine the scattering and slowing down of the alpha particles? Estimate the maximum energy loss per alpha particle for each collision in this process.

   While in the previous experiment there is a certain probability to scatter against the nuclei, in general it is more probable that scattering happens with the much more abundant electrons in the material. Then the process is measured by the Coulomb cross-section. Because the electron is much less massive than the alpha particle, in a head-on collision the electron acquired twice the initial alpha velocity : $v_e = 2v_\alpha$, thus from momentum conservation $\Delta E_\alpha = T_e = \frac{1}{2}m_e(2v_\alpha)^2 = 2m_e v_\alpha$ or $\Delta E = 4Em_e/m_\alpha$.

8. Although it is not as strong as the Nuclear force, Coulomb interaction plays a major role in determining the viability or the rate of many nuclear and radiation phenomena. Name some of these phenomena and explain briefly what is the role of the Coulomb interaction.

Coulomb interaction, as we just saw, plays a major role in scattering of charged particles from electrons and nuclei. Also, through the Coulomb barrier, it determines which radioactive decay is viable or not – and its rate. This is the case of alpha decay vs. C-12 or other types of decay. Also, the Coulomb barrier makes it hard to fusion two nuclei together (fusion is then possible only at high energies) and it requires to bombard fissile nuclei with neutrons for fission to start.

9. True or False: Uranium is much more effective than water in thermalizing neutrons because the scattering cross section in Uranium is of order ten times larger than the neutron-hydrogen cross section.

   Since the energy lost in a neutron-hydrogen collision is much more than in a Uranium-neutron collision, this statement is false. This is reflected in the fact that we need only 18 collisions with ^1H for thermalization while 2200 with U.

10. Above what energy can we observe pair production in the interaction of the the e.m. field with matter? Why?

    We need an energy $E \geq 2 \times m_e c^2 \approx 1.022$MeV (or twice the rest mass of the electron).

Problem 2: The life of Polonium I: Alpha decay vs. Spontaneous fission *10 points*

Consider the isotope of Polonium, $^{211}_{84}$Po. This is a very unstable nucleus.

a) What is the Q value of the alpha decay? What is Q for spontaneous fission (e.g. into two Molybdenum fragments)?
$Q_\alpha = (m_{Po} - m_{Pb} - m_\alpha)c^2 = 8$*MeV*, $Q_f = (m_{Po} - m_{Mo-106} - m_{Mo-106})c^2 = 141$*MeV*

b) Do you expect spontaneous fission to be a competing decay process for alpha decay? Why? Give some simple quantitative argument to support your answer.

Hint: m(Po-211)=196526 MeV/c^2, m(Pb-207)=192790 MeV/c^2, m(α)=3728 MeV/c^2, m(Mo-105)=97726 MeV/c^2, m(Mo-106)=98659 MeV/c^2.

Even if fission seems to be more energetically favorable, the Coulomb barrier is much lower for alpha decay, as the product $Z_{Pb}Z_\alpha \ll Z_{Mo}^2$, thus the probability of tunneling through the barrier is much less for the fission process.

Problem 3: The life of Polonium II: Shell Model *12 points*

We now focus on the alpha decay of $^{211}_{84}$Po and its products.

a) The product of the alpha decay is Lead-207 ($^{207}_{82}$Pb). Based only on filling the levels of the shell model (see the level scheme attached), what is the spin/parity assignment of this nuclide?

We have 125 neutrons, with the last unpaired neutron in the $i\frac{13}{2}$ level. Thus the spin should be $\frac{13}{2}$ and the parity $\Pi = (-1)^l$ with $l = 6$, then even parity.

b) The level $i\frac{13}{2}$ is part of the shell which gives rise to the magic number 126 while the level $i\frac{11}{2}$ is in the next shell. What part of the nuclear interaction is responsible for this splitting? Calculate the energy splitting between the levels.

The spin-orbit couplings splits the two levels. The splitting can be calculated from $V_{so} = \frac{V_{so}^0}{\hbar^2}\hat{\boldsymbol{l}} \cdot \hat{\mathbf{s}}$. The dot product is in turn calculated from $J^2 = (\hat{\boldsymbol{l}} + \hat{\mathbf{s}})^2 = \hat{\boldsymbol{l}}^2 + \hat{\mathbf{s}}^2 + 2\hat{\boldsymbol{l}} \cdot \hat{\mathbf{s}}$ from which we have:

$$\hat{\mathbf{l}} \cdot \hat{\mathbf{s}} = \frac{1}{2}(\hat{\mathbf{J}}^2 - \hat{\mathbf{l}}^2 - \hat{\mathbf{s}}^2) = \frac{\hbar^2}{2}[J(J+1) - l(l+1) - s(s+1)]$$

where $s = \frac{1}{2}$ and $l = 6$ and $j = l \pm \frac{1}{2}$. We then have for the two cases $J = \frac{11}{2}$ and $J = \frac{13}{2}$:

$$\hat{\boldsymbol{l}} \cdot \hat{\mathbf{s}} = \frac{\hbar^2}{2}[\frac{11}{2}(\frac{11}{2}+1) - 6 \cdot 7 - \frac{3}{4}] = \frac{\hbar^2}{2}[\frac{143}{4} - 42 - \frac{3}{4}] = -\hbar^2\frac{7}{2}$$

and

$$\hat{\boldsymbol{l}} \cdot \hat{\mathbf{s}} = \frac{\hbar^2}{2}[\frac{13}{2}(\frac{13}{2}+1) - 6 \cdot 7 - \frac{3}{4}] = \frac{\hbar^2}{2}[\frac{195}{4} - 42 - \frac{3}{4}] = \hbar^2\frac{6}{2}$$

Notice you did not need to calculate that. Simply, you could have calculated the difference in energy: $\Delta E = \frac{\hbar^2}{2}(\frac{13}{2}\frac{15}{2} - \frac{11}{2}\frac{13}{2}) = \hbar^2\frac{13}{2}$

c) Another characteristics of the nuclear force makes the naive spin/parity assignment you gave in question a) improbable. A rearrangement of the nucleons in the shell gives a lower energy, resulting in which spin/parity assignment?

The pairing force tends to pair up nucleons of the same type. This pairing lowers the energy and the energy gain is much more pronounced the larger the angular momentum. Thus, we expect that a neutron will jump to the $i\frac{13}{2}$ level to leave only pairs in that level. The remaining unpaired neutron is likely to be in the $3p\frac{1}{2}$ level (which has very low j and is still close in energy to $i\frac{13}{2}$.)

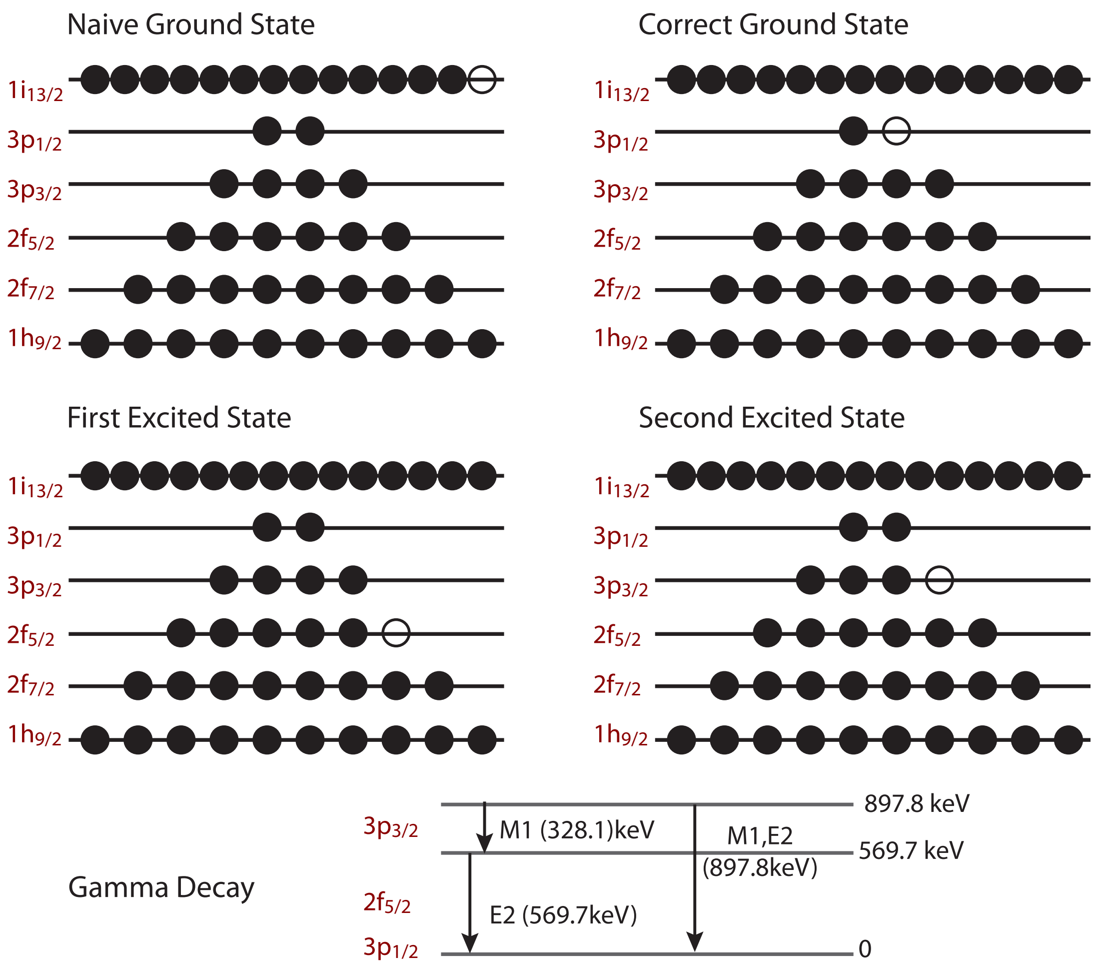

Figure 1: Unclosed shell filling for ground and excited states (open circle indicate a missing neutron). Related gamma decay levels.

Problem 4: The life of Polonium III: Gamma decay *16 points*

Following the alpha decay from ^{211}Po, ^{207}Pb is left in an excited state with spin/parity $\frac{3}{2}^-$ and energy 897keV. The nucleus decays from this state by gamma emission to the ground state.

a) What are the permitted multipoles and which multipoles are most likely to be observed? Give the approximate ratio of the two most probable decay mode rates.

Considering the transition from $\frac{3}{2}^-$ to $\frac{1}{2}^-$, we have no change in parity and possible angular momentum given by $\frac{3}{2} \pm \frac{1}{2} = \{2, 1\}$. Thus we have an E2 or M1 transition. It is known that the ratio between the rates of these two transitions is usually about 10^{-3}. This is confirmed by using the rates given in the appendix:

$$\frac{\lambda(E2)}{\lambda(M1)} = \frac{7.3 \times 10^7 A^{4/3} E^5}{5.6 \times 10^{13} E^3} \approx 10^{-4}(207)^{4/3} 0.9^2 \approx 1.6 \times 10^{-3}$$

Considering the transition from $\frac{3}{2}^-$ to $\frac{13}{2}^+$, we have change in parity and possible angular momentum given by $\frac{13}{2} - \frac{3}{2} \leq l \leq \frac{13}{2} + \frac{3}{2} = \{5, 6, 7, 8\}$. Thus we have E5, M6, E7,M8 transitions, with E5 the most probable. It is known that the ratio between the rates of the two strongest transitions (E5 and M6) is usually about 10^{-7}.

b) Detection of gamma rays with lower energies (328keV and 569keV) indicates that there is an intermediate level between the $\frac{3}{2}^-$ excited state and the ground state. The observed multipoles are M1 (associated with the energy 328keV) and E2. With the help of the selection rules and of the shell structure, find the spin/parity of this intermediate level and its energy above the ground state.

Because the two transitions have different energies, they must arise from the decay between different energy levels. Thus one will be associated with the decay from the excited to the intermediate level and the second from the intermediate level (first excited level) to the ground state (see also figure 1). Also, you must ensure that both these transitions respect the selection rules in a consistent way when finding the spin-parity of the intermediate level. The transitions observed, E2 and M1, imply no change in parity, thus the parity of the intermediate level must be odd. Thus we are looking for a state with l odd, and we can then focus on the $N = 5$ shell levels, which have l odd, without needing to look in the higher shell. If the M1 transition were from the intermediate level to the ground state $\frac{1}{2}^-$, the level spin parity could only be $\frac{3}{2}^-$, but this is not possible (since we already know that that is the second excited state). Thus, the order of the transitions is M1 from $\frac{3}{2}^-$ to the intermediate level and E2 from that level to the ground state. Finally to have a $\Delta l = 1$ from $\frac{3}{2}^-$ and $\Delta l = 2$ to $\frac{1}{2}^-$ the only possible intermediate level is $2f\frac{5}{2}$. From the gamma energy, this level is predicted to be 569keV above the ground state.

Notice that considering the ground state to be $\frac{13}{2}^+$ would have led to a contradictory result here.

c) Based on your previous answers and what you found in Problem 3, draw a scheme of the unclosed shell for ^{207}Pb showing the level occupancy for the ground state and the two first excited states (involved in the gamma decay) that explain the various spins and parities you found.

See Figure 1

Problem 5: The life of Polonium IV: Radiation products *10 points*

a) What is the stopping power of the emitted alpha particles in Polonium? Do you need to worry a lot about their effects on nearby people?

The stopping power is $-\frac{dE}{dx} = (2\pi r_e^2 \frac{Z_\alpha^2}{\beta^4} \ln\Lambda) n_e 2m_e v_\alpha^2 \approx 40$barns $\times 84 n_{Po} m_e c^2 \beta^{-2} = 40 \times 10^{-24}cm^2 \times 84 \times 2.5 \times 10^{22}cm^{-3} \times 0.511$ MeV $\beta^{-2} \approx 42\beta^{-2}$MeV/cm. β can be calculated from the Q value you found in Problem 2, assuming that the speed is non-relativistic: $Q = \frac{1}{2} m_\alpha v_\alpha^2 = \frac{1}{2} m_\alpha c^2 \beta^2$, from which $\beta^2 = 2Q/(m_\alpha c^2) \approx 16/4000 = 4 \times 10^{-3}$. Finally we have $-\frac{dE}{dx} \approx 10^4$MeV/cm thus the alpha will most probably be stopped inside the Polonium.

A second way to calculate this is the following: From $-\frac{dE}{dx} = \sigma_c n_e \Delta E$, with $\Delta E = 2m_e v_\alpha^2 = 4E m_e/m_\alpha \approx 480.511/4000$MeV $\approx 4 \times 10^{-3}$MeV. And $\sigma_c = (2\pi r_e^2 \frac{Z_\alpha^2}{\beta^4} \ln\Lambda) = 2(4\pi r_e^2)10/\beta^4 = 20/\beta^4$barns, and with $\beta^2 \approx 4 \times 10^{-3}$ (see above) $\sigma_c \approx 1.2510^{-18}$cm^{-2}.

b) What interaction(s) will be most probable for the gamma rays emitted in the Pb decay ?

Given the high energy of the gamma rays, Compton scattering is the most probable reaction.

c) What is the maximum energy lost in such a scattering?

The change in the wavelength $\Delta\lambda$ for Compton scattering was provided in the appendix: $\Delta\lambda = \frac{4\pi\hbar}{m_e c}$. Then $\lambda' = \lambda + \frac{4\pi\hbar}{m_e c}$. In terms of frequencies, we have $\frac{2\pi c}{\omega'} = \frac{2\pi c}{\omega} + \frac{4\pi\hbar}{m_e c}$. This gives $\hbar\omega' = \frac{m_e c^2 \omega}{m_e c^2 + \hbar\omega}$. The energy lost is then $\Delta E = \hbar\omega(\frac{m_e c^2}{m_e c^2 + \hbar\omega} - 1) = -\frac{2\hbar^2\omega^2}{m_e c^2 + 2\hbar\omega}$. Notice that even if $\omega \propto 1/\lambda$ of course $\Delta\omega = \omega' - \omega \neq \frac{2\pi}{\Delta\lambda}$.

Problem 6: Deuteron *12 points*

A simple model for the Deuteron is a square well with depth V_0 and width R_0 (here we neglect the spin effects). It is known from experiments that the bound state has angular momentum $l = 0$ (that is, the state with $l = 1$ is unbound).

a) Use this knowledge and simple arguments requiring the wavefunction to "fit" in the well, to find the range of parameters V_0 and R_0 consistent with the experimental evidence.

You can take the neutron and proton mass to be both $mc^2 = 938$MeV, $\hbar c = 200$MeV fm and consider the angular momentum potential at the minimum distance $V_l = \frac{\hbar^2 l(l+1)}{\mu R_0^2}$.

Hint: Note that this experimental evidence does not set a range for V_0 and R_0 *separately*.

For the deuteron to be bound in the center of mass square well, we need the wavefunction to fit inside the well. This happens if the wavelength of the wavefunction is such that it has a negative slope at the boundary, or when $\lambda/4 \approx R_0$.

This sets the wavenumber to $k \approx \frac{\pi}{2R_0}$. The wavenumber is limited from above by the condition that the total energy is negative, or the kinetic energy is less than the potential depth: $\frac{\hbar^2 k^2}{2\mu} < V_0$. At the same time, we know that the states with $l \geq 1$ are unbound. This means that $\frac{\hbar^2 k^2}{2\mu} > V_0 - \frac{\hbar^2 l(l+1)}{\mu R_0^2}$. With $k = \frac{\pi}{2R_0}$, we have then the conditions: $\frac{\hbar^2 \pi^2}{8\mu} < V_0 R_0^2 < \frac{\hbar^2}{\mu}\left(2 + \frac{\pi^2}{8}\right)$. This sets a range of allowed values for the product $V_0 R_0^2$.
Now, $\mu = m/2 = 938/2$MeV. Then the range is

$$\frac{\hbar^2 c^2 \pi^2}{8\mu c^2} < V_0 R_0^2 < \frac{\hbar^2 c^2}{\mu c^2}\left(2 + \frac{\pi^2}{8}\right) \quad \rightarrow \quad \frac{(200MeV fm)^2 \pi^2}{4 \times 938MeV} < V_0 R_0^2 < \frac{(200MeV fm)^2}{938/2MeV}\left(2 + \frac{\pi^2}{8}\right)$$

$$\frac{9 \times 10^4 MeV fm^2}{938} < V_0 R_0^2 < \frac{24 \times 10^4 MeV fm^2}{938} \quad \rightarrow \quad 100MeV fm^2 < V_0 R_0^2 < 270MeV fm^2$$

b) Show that if the excited state with $l = 1$ is unbound, then also the first radial excited state with $l = 0$ is unbound.
The first radial excited state should have $\lambda' = \lambda/3$ to fit inside the well. Then the kinetic energy is $E_k = \frac{\hbar^2 k'^2}{2\mu} = \frac{9\hbar^2 k^2}{2\mu} = \frac{\hbar^2}{\mu R_0^2}\frac{9\pi^2}{8}$. Because $\frac{9\pi^2}{8} > \left(2 + \frac{\pi^2}{8}\right)$, $E_k > V_0$ and the state is unbound for any combination $\{V_0, R_0\}$ such that $V_0 R_0^2 < \frac{\hbar^2}{\mu}\left(2 + \frac{\pi^2}{8}\right)$.

Problem 7: Mass Parabola and Beta Decay *10 points*

The semi-empirical mass formula (SEMF) gives an expression for the binding energy as a function of the mass number A and the proton number Z:

$$B(Z, A) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{sym}\frac{(A-2Z)^2}{A} + \delta a_p A^{-3/4}$$

a) What terms in the SEMF arise from the "liquid drop model" that considers the nucleus as a uniformly dense drop of a fluid composed by nucleons and which ones arise from quantum-mechanical considerations? (Explain briefly)
The first three terms assume that the nucleus is a uniformly dense fluid (the Coulomb term is calculated assuming a uniformly charged sphere). The last two terms instead take into account quantum-mechanical considerations. The asymmetry term takes into account the fact that if we increased the number of neutrons – in order to decrease the number of protons and thus the Coulomb repulsion – these would have to occupy higher energy levels because of the Pauli exclusion principle, leading to an higher total energy. The pairing term describes the tendency of nucleons to pair up, to achieve zero angular momentum (and thus reduce the spin-orbit interaction).

b) Consider the nuclear mass as given by the SEMF for $A = 65$. What is the shape of the curve $M(Z, A = 65)$?
At fixed, odd A (for which the pairing term is zero), the binding energy variation is given by the Coulomb and symmetry term: $B(Z) \sim cst. - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{sym}\frac{(A-2Z)^2}{A}$. When considering the function $M(Z, A)$ both these terms describe parabola as a function of Z (see figure 2).

c) The minimum mass is reached for $Z_{min} \approx \frac{A}{2}\left(1 + \frac{1}{4}A^{2/3}\frac{a_c}{a_{sym}}\right)^{-1} \approx 29$. This correspond to the isotope $^{65}_{29}$Cu. Sketch the shape of the curve $M(Z, A = 65)$ and show approximately on the plot the Masses of $^{65}_{29}$Cu and of its neighboring isotopes ^{65}Ga, ^{65}Zn, ^{65}Ni and ^{65}Co.
The Z number for each of the isotope is found from the periodic table and we can make an approximate sketch.

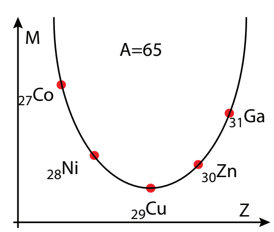

Figure 2: Mass formula

d) Since $^{65}_{29}$Cu is the nuclide that is more tightly bound, it is the only stable nuclide. By what process(es) do the other nuclides decay toward the stable nuclide? Write the reactions involved, making sure to show all the decay products.
Beta decay is responsible for achieving the stable configuration. More precisely, the isobars with $Z > 29$ will try to loose protons and transform them into neutrons, decaying by β^+ or electron capture. The isobars with $Z < 29$ will decay by β^- processes, converting neutrons into protons:

$$^{65}_{27}Co \rightarrow ^{65}_{28} Ni + \beta^- + \bar{\nu}$$
$$^{65}_{28}Ni \rightarrow ^{65}_{29} Cu + \beta^- + \bar{\nu}$$

$$ {}^{65}_{31}Ga \rightarrow^{65}_{30} Zn + \beta^+ + \nu \quad \text{or} \quad {}^{65}_{31}Ga + e^- \rightarrow^{65}_{30} Zn + \nu $$
$$ {}^{65}_{30}Zn \rightarrow^{65}_{29} Cu + \beta^+ + \nu \quad \text{or} \quad {}^{65}_{30}Zn + e^- \rightarrow^{65}_{29} Cu + \nu $$

Appendix: Useful Formulas

Relativistic energy: $E = \sqrt{p^2c^2 + m^2c^4}$
SEMF coefficients: $a_v \approx 15.5$MeV, $a_s \approx 16$MeV, $a_c \approx 0.7$MeV, $a_{sym} \approx 23$MeV, $a_p \approx 34$MeV.
Spin-orbit interaction $V_{so} = \frac{V_{so}^0}{\hbar^2}\hat{\mathbf{l}} \cdot \hat{\mathbf{s}}$ (you can consider V_{so}^0 a constant).
Fermi's Golden Rule: $W = \frac{2\pi}{\hbar}|\langle\psi_f|V|\psi_i\rangle|^2\rho(E_f)$
Gamma Decay: Estimates for the rates of different electric multipoles (energies in MeV):

- $\lambda(E1) = 1.0 \times 10^{14} A^{2/3} E^3$
- $\lambda(E2) = 7.3 \times 10^{7} A^{4/3} E^5$
- $\lambda(E3) = 34 A^2 E^7$
- $\lambda(E4) = 1.1 \times 10^{-5} A^{8/3} E^9$
- $\lambda(M1) = 5.6 \times 10^{13} E^3$
- $\lambda(M2) = 3.5 \times 10^{7} A^{2/3} E^5$
- $\lambda(M3) = 16 A^{4/3} E^7$
- $\lambda(M4) = 4.5 \times 10^{-6} A^2 E^9$

Cross Sections
Differential cross-section: $\frac{d\sigma}{d\Omega} = \frac{r(\vartheta,\varphi)}{4\pi I_a n}$ Doubly differential cross section: $\frac{d^2\sigma}{d\Omega dE_b}$
Coulomb : $\sigma_c = 2\pi r_e^2 \frac{Z_\alpha^2}{\beta^4} \ln\Lambda$ (with $r_e = \frac{1}{4\pi\epsilon_0}\frac{e^2}{m_e c^2} \sim 2.8 fm$ –or $4\pi r_e^2 \sim 1$barn– and $\ln\Lambda \sim 10$)
Stopping power: $-\frac{dE}{dx} = \sigma_c n_e \Delta E$. Rutherford's $\frac{d\sigma}{d\Omega} = \left(\frac{zZe^2}{4\pi\epsilon_0}\right)^2 (4T_a)^{-2} \sin^{-4}\left(\frac{\vartheta}{2}\right)$
Rayleigh: $\sigma_R = \frac{8}{3}\pi r_e^2 \frac{\omega^4}{\omega_0^4}$ Thomson: $\sigma_T = \frac{8}{3}\pi r_e^2$
Compton: $\sigma_C = \sigma_T \frac{m_e c^2}{\hbar\omega}$, with a change in the photon's wavelength: $\Delta\lambda = \frac{2\pi\hbar}{m_e c}(1 - \cos\vartheta)$.
Number of collisions to reach neutron thermalization

^1H	^2H	^4He	^{12}C	^{238}U
18	25	43	110	2200

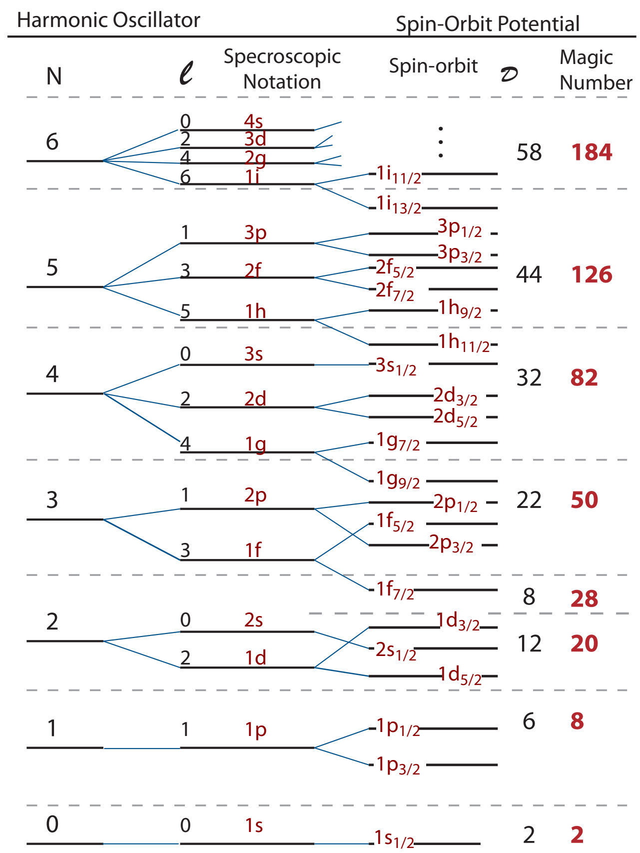

Figure 3: Shell Model

The Periodic Table of the Elements

1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Figure 4: **Periodic Table of the elements** 1 amu ≈ 937 MeV/c^2.

22.02 Introduction to Applied Nuclear Physics
Spring 2012