THIRD YEAR EXAMPLE CLASS SHEET THREE
PHYS30121 Introduction to Nuclear and Particle Physics
Problems 2: Masses, Q Values, Semi-Empirical Mass Formula

1: α Decay

What is the Q value for the α decay of ^{238}Pu, given that the atomic masses of ^{238}Pu, ^{234}U and ^{4}He are 238.049555u, 234.040947u and 4.002603u respectively? Qualitatively speaking, what form does this energy take after the decay has happened?

2: β Decay

^{20}F decays to the ground state of ^{20}Ne in two steps via an excited state:

$$^{20}\mathrm{F} \rightarrow^{20} \mathrm{Ne}^* + \beta^- + \overline{\nu}$$

$$^{20}\mathrm{Ne}^* \rightarrow^{20} \mathrm{Ne}_{\mathrm{gs}} + \gamma$$

Find the atomic mass of the ground state of ^{20}Ne, given the mass-excess of ^{20}F is -17.404 keV/c^2, the maximum β^- energy (the endpoint) is 5.390 MeV and the γ-ray energy is 1.633 MeV, stating any approximations used.

[Hint: If you work in atomic masses, the maximum β energy is (to an approximation) equal to the Q value of the first reaction. The Q value of the second reaction is (to an approximation) equal to the γ-ray energy. Remember that mass-excess is not the same as atomic mass.]

3: Semi-Empirical Mass Formula and Fission

The semi-empirical mass formula can be written as:

$$m(A,Z) = Zm_{1H} + (A-Z)m_n - 15.85A + 18.34A^{2/3} + 0.71\frac{Z(Z-1)}{A^{1/3}}$$

$$+23.21\frac{(A-2Z)^2}{A} \mp 12A^{-1/2}$$

where symbols have their usual meanings and units are MeV.

(a) Use the semi-empirical mass formula to calculate the energy made available when a neutron is captured by (i) ^{235}U and (ii) ^{238}U.

(b) If a nucleus elongates without change in density, which terms alter in the semi-empirical mass formula? Thus explain qualitatively why a uranium nucleus requires around 6 MeV of excitation energy to be able to fission.

(c) Indicate the importance of (a) and (b) to nuclear reactor technology.

4: Semi-Empirical Mass Formula and the Line of Stability

Use the semi-empirical mass formula to show that for a particular isobar (i.e. A constant) the atomic number leading to the minimum mass is:

$$Z_{min} = \frac{m_n - m_{^1H} + a_c A^{-1/3} + 4a_a}{[2a_c A^{-1/3} + 8a_a A^{-1}]}$$

where a_c and a_a are the Coulomb and symmetry coefficients given in the expression above.

Using the values above, show that the line of stability follows $N = Z$ for light nuclei and $N > Z$ for heavy systems.

An extra question if you've managed to get through the others, or a question to save for revision.....best done with a spread sheet.

5: Semi-Empirical Mass Formula and Neutron Emission

A major focus of current research in nuclear physics concerns the properties of exotic nuclei and isotopes can now be manufactured with extreme proton-to-neutron ratios. In very neutron-rich species, neutron emission can occur if the associated Q value becomes positive. Use the semi-empirical mass formula to estimate the mass number of Na isotopes ($Z = 11$, stable isotope $A = 23$) for which neutron emission becomes possible.