22.01, Problem Set 1

Complete all the assigned problems, and do make sure to show your intermediate work.

You may work together on *all* of these problems, though each student must (1) submit their own written/typeset copy and (2) state with whom they worked.

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1 (35 points) Retracing Chadwick's Discovery of the Neutron

Learning Objective: The goal of these problems is for you to trace how competing hypotheses led to the discovery of the neutron, by refusing to break the laws of energy and mass conservation.

In these questions (5 points each), you will recreate some of James Chadwick's logic as he hypothesized and proved the existence of the neutron. Read the two papers on the Canvas site, "Possible Existence of a Neutron" and "The Existence of a Neutron," and answer the following questions.

1. What made James first hypothesize an uncharged particle with the mass of a proton?
2. What was the competing hypothesis to explain the observed results?
3. Write the nuclear reaction of alpha particles (helium nuclei) bombarding beryllium. You may want to look up the stable isotope of Be here: https://pripyat.mit.edu/KAERI/
4. Why would a neutron have greater "penetrating power" (range) through matter compared to charged particles? What does a neutron not interact with?
5. On p. 694 of the second paper, Chadwick states that "The source of polonium was prepared from a solution of radium by deposition on a disc of silver." How could polonium be produced directly from radium? Look at the KAERI Table of Nuclides (MIT local mirror) or the IAEA Chart for clues, using ^{224}Ra. Click on "Decay Radiation" and "Daughters" for the IAEA chart.
6. On p. 698 of the second paper, Chadwick states that "the mass of the neutron is equal to that of the proton..." Is this true? What are the masses of the proton, neutron, and electron? Is the mass of Rutherford's "neutron," consisting of a proton and an electron, equal to the neutron's mass? Why or why not (where does the energy discrepancy come from)? Why couldn't Chadwick discern between the masses of these two particles?
7. On pp. 701-702, why is the kinetic energy of ^{11}B not accounted for, and what does it mean for kinetic energies to be given in "mass units?" Convert these "mass unit" energies to energies in electron volts (eV). What is the approximate kinetic energy of ^{11}B in eV at room temperature?

2 (65 points) Getting Used to Nuclear Quantities

In these questions, you will calculate a number of quantities related to nuclear reactions and power generation. You will have to look up certain reactions and values from *primary sources* in the literature (books, papers, databases). Try starting from a place like Web of Science (available from the MIT Libraries at https://libraries.mit.edu/) instead of Google or worse. As we saw in class, the internet is rife with misinformation and rounding errors. Make sure to state which values you look up or assume, and *cite your sources* using proper citation methods.

These calculations are useful, especially when arguing the benefits and costs of nuclear power. If you can derive them quickly and by yourselves, you don't have to rely on as many other sources of information to make your point.

2.1 Relative Power Densities and Nuclear Reactions (25 points)

Learning Objective: These problems will get you used to calculating order-of-magnitude energy releases from chemical and nuclear reactions, so you can compare them and see why we want to use nuclear power in the first place.

Calculate the energy in ***Joules*** released from burning (oxidizing) 1kg of coal, natural gas, uranium, and deuterium. Use the CRC Handbook of Chemistry and Physics, available through the MIT Libraries site, to find chemical binding energies (otherwise known as enthalpies of formation, or ΔH_0^f) data for your answers. Now repeat this calculation for the nuclear fission of uranium into ^{90}Sr and ^{145}Xe (two typical fission products), and the nuclear fusion of ^{2}H with ^{3}H. Use the KAERI or IAEA Table of Nuclides (link on the Canvas site) to find the nuclear binding energies for your answers. Neglect electrons entirely for simplicity. To summarize the quantities we're looking for:

1. Energy in Joules from oxidizing 1kg of coal. You'll need to find & cite the percentage of carbon in coal.
2. Energy in Joules from oxidizing 1kg of natural gas (assuming it's pure methane, CH_4)
3. Energy in Joules from *chemically* oxidizing 1kg of uranium metal
4. Energy in Joules from *chemically* oxidizing 1kg of deuterium gas
5. Energy in Joules from nuclear fission of 1kg of ^{235}U (you will have to pick two fission products plus 2-3 neutrons)
6. (5 points) Energy in Joules from nuclear fusion of 500g of ^{2}H and 500g of ^{3}H. Hint: One of these will be a limiting reagent.

2.2 (40 points) Excess Mass and Binding Energy

Learning Objective: These problems will drill you in calculating and verifying nuclear binding energies, test your knowledge of the meaning of excess mass, and teach you how to use computer tools to automate tedious calculations if you don't already know how to do so.

For these problems, you'll be verifying a few quantities from the Table of Nuclides by hand, and explaining what they mean. That means the answers are in the Table of Nuclides, you just have to show where they come from and why. Consider the the isotopes of fluorine ranging from $^{16}_{9}$F to $^{22}_{9}$F, and the isotopes of copper ranging from $^{60}_{29}$Cu to $^{68}_{29}$Cu. It is *highly* suggested to use a spreadsheet like Excel or Gnumeric to help complete these problems, to avoid lots of tedious writing and calculator punching. If you do, then be sure to upload your spreadsheet of calculations to the Canvas site, or export the page as an image/PDF. Otherwise we can't give you partial credit!

1) Using the isotopes of fluorine, explain what the *excess mass* (Δ) physically represents, and why it is almost always positive. Why/when is it negative, and what does a negative excess mass physically mean?

2) Verify the stated values of excess mass and binding energy using nothing but the stated masses in *amu*, and the numbers and individual masses of the protons, neutrons, and electrons present.

Next, consider the the isotopes of copper ranging from ${}^{60}_{29}\mathrm{Cu}$ to ${}^{68}_{29}\mathrm{Cu}$. It is *highly* suggested to use a spreadsheet like Excel or Gnumeric to help complete these problems, to avoid lots of tedious writing and calculator punching. If you do, then be sure to upload your spreadsheet of calculations to the Canvas site, or export the page as an image/PDF. Otherwise we can't give you partial credit!

3) Calculate the Q-value (energy gained or lost) for each of the above isotopes absorbing a neutron, via the following nuclear reaction: ${}^{A}_{29}Cu + {}^{1}_{0}n \longrightarrow {}^{A+1}_{29}Cu + Q$. Is each reaction *exothermic* or *endothermic*, and how do you know?

4) Plot the *binding energy per nucleon* $\left(\frac{BE(A,Z)}{A}\right)$ vs. the natural log of the half life $\left(ln\left(t_{1/2}\right)\right)$ of each copper isotope. Is there a pattern, and do you see any significant deviations? Why or why not?

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