22.01 Fall 2016, Problem Set 1

September 14, 2016

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

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1 (50 points) Retracing Chadwick's Discovery of the Neutron

In these questions, you will recreate some of James Chadwick's logic as he hypothesized and proved the existence of the neutron. Read the papers provided, "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: http://atom.kaeri.re.kr/

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?

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 (50 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). 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 (15 points)

Calculate the energy in ***Joules*** released from burning 1kg of coal, natural gas, uranium, and deuterium. Use the CRC Handbook of Chemistry and Physics, available through the MIT Libraries site (libraries.mit.edu), 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 Table of Nuclides to find the nuclear binding energies for your answers. Neglect electrons entirely for simplicity.

2.2 Accelerator Energetics (20 points)

A common tool to provide data on nuclear reactions and to perform irradiations is the electrostatic accelerator. These work by accelerating charged particles through a large, static electric field. We consider here an accelerator that provides a 1.7MV potential drop over 2m for doubly charged iron ions $\left(Fe^{+2}\right)$, which enter the accelerator at ~zero kinetic energy into the accelerator from an ion source.

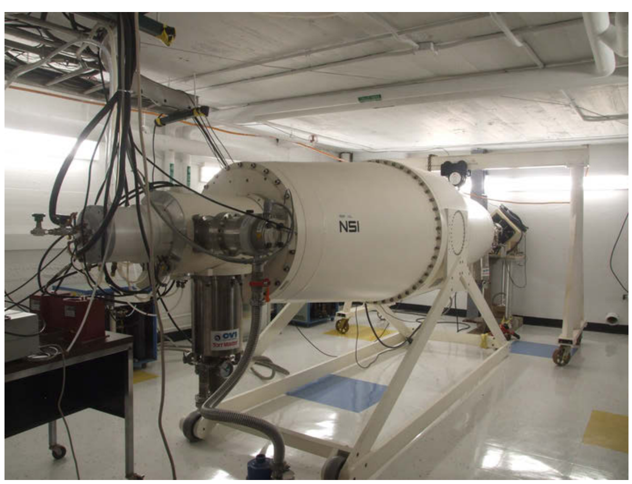
2.2.1 What will be the kinetic energy of an iron ion in eV, as it exits the accelerator?

2.2.2 What will be its *total mass* (not its rest mass) as it exits the accelerator?

2.2.3 If the ion source injects 2mA of current, what is the total number of particles leaving the accelerator per second?

2.2.4 What is the total power, in Watts, associated with pulling 2mA of current through 1.7MV of electrostatic potential? Where does this power go?

Here is a picture of DANTE, the accelerator in question. It lives in the basement of NW13.



2.3 Mass-Energy Equivalence (20 points)

From special relativity, the total mass (m) of a moving particle can be expressed as follows:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma m_0 \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1}$$

where m_0 is its rest mass, v is its velocity, and c is the speed of light.

2.3.1 What is the particle's mass at the following speeds: 1 $\frac{m}{s}$, 1 $\frac{km}{s}$, 1 $\frac{Mm}{s}$, 0.9c, 0.99c, c?

2.3.2 Derive an expression for the particle's kinetic energy (T) in terms of its total and rest masses.

2.3.3 Show that the particle's momentum (p) can be described in terms of its kinetic energy and rest mass as follows:

$$p = \frac{1}{c}\sqrt{T^2 + 2Tm_0c^2} \tag{2}$$

Start with the total relativistic energy of a moving particle:

$$E = \sqrt{p^2c^2 + E_{rest\,mass}^2} \tag{3}$$

2.3.4 Radioactive decay typically proceeds with the emission of ˜1 MeV particles. For the case of an alpha particle, a beta particle, a neutrino, and a neutron of kinetic enregy 1 MeV, which ones must be treated in a relativistic manner? You will have to look up the rest masses of each particle in your answer. Note that the neutrino was only proven to have mass last year!