Name: ____________________

Date: ____________________

Section: ____________________

Astron 104 Laboratory #7
Nuclear Fusion and Stars
Chapter 12

Introduction

You are intimately linked to the nuclear fusion that occurs in stars. Life on Earth thrives on sunlight, which originates as energy produced at the center of the Sun as hydrogen is fused to form helium. Even the very atoms and molecules of your body — iron in your blood, calcium in your bones, phosphorous in your DNA — were forged in stars and dispersed to the interstellar medium in spectacular explosions. In this lab, you will explore the creation of heavy elements and release of energy through nuclear fusion in stars.

Learning Objectives

At the completion of this lab, you should be able to:

1. Describe the components of atomic nuclei and the properties of subatomic particles
2. Describe the force between two protons as a function of their separation distance
3. Describe the temperature required for nuclear fusion of hydrogen and heavier elements
4. Describe how nuclear fusion produces energy
5. Describe why iron is the heaviest element that can be made via nuclear fusion in stars

Atomic Nuclei [5 pts each, 15 pts total]

Atomic nuclear are made of combinations of sub-microscopic particles called protons and neutrons. The neutron is slight more massive than the proton, but for now we will ignore that difference and assume the neutron and proton each have a mass of 1 unit. Protons have a positive electrical charge (let's call it +1 unit) and neutrons have no electrical charge.

1. Summarize the compoents of an atomic nucleus by completing the table below:

Name	Mass	Charge
Neutron		
Proton		

The number of protons in a nucleus determines what **element** the nucleus is (and what the material will be when lots of the nuclei are linked with electrons). The number of protons is the **atomic number** of the element. Neutrons add mass to the nucleus without changing what element it is.

2. Many important properties of atomic elements are encoded in the **periodic table**, which might already be familiar from high school chemistry. Use a periodic table to determine the element, mass, and charge for nuclei in the table below. For example, 8 protons and 8 neutrons is an oxygen nucleus with a mass of 16 units and a charge of +8 units.

Protons	Neutrons	Atomic Number Z	Element	Mass	Charge
0	1	N/A	Neutron		
1	0				
1	1				
1	2				
2	1				
2	2				
3	4				
6	6				
7	7				
8	8				

Note that a neutron is not an element by itself, but we include it here for reference.

3. Atoms with the same atomic number but different masses are called **isotopes**. Are there any elements with multiple isotopes in the table above? What elements are they?

Forces and Nuclear Fusion [5 pts each, 65 pts total]

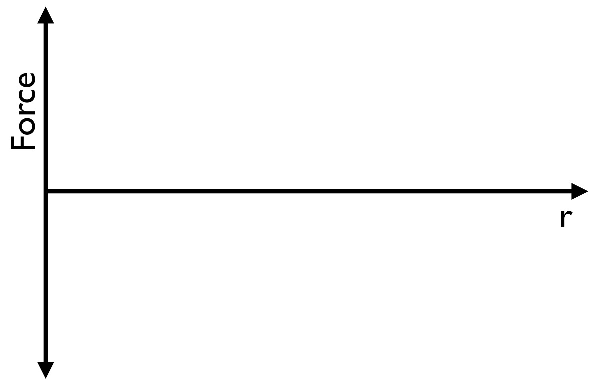
1. Similar to gravity, the repulsive force between two protons (or any two objects with the same type of charge, both positive or both negative) is an **inverse square law**. Write the general form of an inverse square law.

2. Will the repulsive force between two protons become stronger or weaker if the protons are closer together? What if they are further apart?

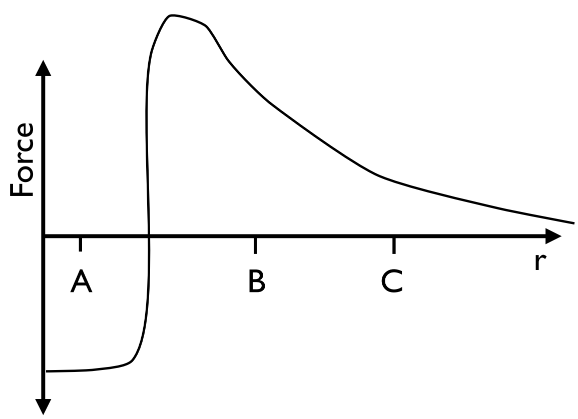
3. Say that the force between two protons a distance r apart is one force unit, F. What is the force between two protons that are $2r$ apart?

4. What is the force between two protons that are $\frac{1}{2}r$ apart?

5. Use your answers above to plot the force between two protons versus their separation distance r. A repulse force is positive, and an attractive force is negative.



6. The plot below shows the force between two protons versus their separation distance r (so one proton is located at $r = 0$).



How is this plot different from your plot?

7. Describe the region on the plot where the force is "negative," both in terms of the separation distance and in terms of the force.

8. What is the force between two protons when the second proton is at a distance of $r = \mathrm{C}$?

9. What is the force between two protons when the second proton is at a distance of $r = \mathrm{B}$?

10. What is the force between two protons when the second proton is at a distance of $r = \mathrm{A}$?

11. Based on your previous answers, describe the forces two protons would feel as you bring them together from a large to a small separation distance.

12. What will happen to the two protons when they get close enough together?

13. Will this be more likely to happen for high or low densities? For high or low temperatures? Why?

Hydrogen Fusion and Energy [5 pts each, 45 pts total]

Nuclear fusion is a series of ractions with the net result of several lighter nuclei transforming into a heavier nucleus and releasing energy. In this section you'll explore how this happens.

1. The most common nuclear fusion process in the Universe is hydrogen fusion: four hydrogen-1 nuclei become one helium-4 nucleus, where the number refers to the mass of the isotope. Using the mass estimate from the previous table, what is the mass of helium-4 compared to the mass of four hydrogen-1 nuclei?

2. We noted above that the mass of a neutron, m_n, is slightly larger than the mass of a proton, m_p. In atomic mass units, or u, their masses are: 1.008665 u for a neutron and 1.007276 u for a proton. What is the percentage difference in mass between a neutron and a proton, $(m_n/m_p - 1)$?

3. To accurately compare the masses of four hydrogen nuclei to one helium nucleus, we need to use more significant figures. The mass of a helium nucleus is 4.001506 u. What is more massive, one helium nucleus or four regular hydrogen nuclei, and by how much?

4. Is ther emore mass before or after the nuclear reactions that transform four hydrogen nuclei into one helium nucleus?

5. One atomic mass unit is equal to 1.66054×10^{-27} kg. How much mass is lost, in kilograms, when four hydrogen nuclei become one helium nucleus?

6. Einstein stated that the energy E, contained in an amount of mass m, is given by mc^2, where c is the speed of light 3×10^8 m/s. Based on this formula, what are the units of E?

7. This unit is also known as one Joule, or J. One Joule is the amount of energy needed to life 1 kilogram by about 10 cm (working against the force of gravity on Earth). How much energy (in Joules) is created from the fusion of one helium nucleus?

8. The Sun produces 4×10^{26} J per second. How many fusion reactions much be occuring per second to produce this much energy?

9. This might seem like a preposterous number, but there are about 10^{57} hydrogen atoms in the Sun! What fraction of the hydrogen atoms in the Sun are fused into helium each second? (One in every 10? Every million? Every billion? More?)

Beyond Hydrogen Fusion [5 pts each, 50 pts total]

You've explored how the forces between two protons depend on distance, but the strength of the force depends on the charges of the nuclei as well, analagous to the force of gravity depending on both the distance between two masses and on their masses.

1. What property of an atomic nucleus plays the role of mass in the analogy with gravity?

2. Will the repulsive force between two helium nuclei be larger or smaller than the repulsive force between hydrogen nuclei? Explain your reasoning. You can use the table earlier in the lab if needed.

3. Does helium fusion require a higher or lower temperature than hydrogen fusion? Explain.

4. As helium builds up in the core of a star, the core of the star shrinks and becomes hotter and denser, and eventually helium fusion begins. Helium fusion creates one carbon nucleus (12.000000 u) from three helium nuclei (4.001506 u each). How much energy (in Joules) is produced in helium fusion compared to hydrogen fusion?

5. Oxygen is also a produce of helium fusion in stars. What elements could fuse together to create oxygen?

6. Each reaction involves a different number of protons and neutrons (jointly called **nucleons**). In order to fairly compare them, we can calculate the **mass per nucleon** for each element, which is the mass of the nucleus divided by the number of nucleons. Use the precise masses provided earlier in this lab to fill out the table below.

Element	**Mass**	**Number of Nucleons**	**Mass per Nucleon**
Hydrogen		1	
Helium		4	
Carbon		12	
Oxygen	15.9994 u	16	

7. How does the mass per nucleon change for heavier and heavier nuclei? What happens to the difference in mass?

8. Iron has 56 nucleons and an atomic mass of 55.845 u. The next element on the periodic table is cobalt, which has 59 nucleons and an atomic mass of 58.933 u. How does the mass per nucleon for cobalt compare to that for iron?

9. In the core of a high-mass star, two silicon nuclei (28 nucleons and a mass of 27.977 u) fuse to form an iron nucleus (56 nucleons and atomic mass of 55.845 u). A silicon nucleus added to an iron nucleus forms strontium (atomic mass of 83.913 u). How is this reaction different from reactions that formed elements lighter than iron?

10. Why is iron the heaviest element that can be produced during nuclear fusion at the core of a star?