TABLE OF CONTENTS

INSTRUCTOR’S KEY

Overview:

PLASMA

Since recorded time, there have been few scientists who could also be called prophets. However, Sir William Crookes most certainly fits both categories. In 1879, long before the concepts of atomic structure was proposed by Niels Bohr or harnessed by companies like General Electric for use in fluorescent lamps, Crookes told an audience at a meeting of the British Association for the Advancement of Science:

> ***In studying this Fourth state of Matter we seem at length to have within our grasp and obedient to our control the little indivisible particles which with good warrant are supposed to constitute the physical basis of the universe... We have actually touched the borderland where Matter and Force seem to merge into one another, the shadowy realm between Known and Unknown, which for me has always had peculiar temptations. I venture to think that the greatest scientific problems of the future will find their solution in this Border Land, and even beyond; here it seems to me, lie Ultimate Realities, subtle, far-reaching, wonderful (Crookes, 1879a).***

Sir William Crookes was a brilliant and aggressive entrepreneur credited with discovering the concept of ionization in 1898. Today, we know that the phenomena Crookes referred to is actually an ionized gas. Atoms consisting of a nucleus containing protons, neutrons, and electrons that orbit the nucleus. Atoms have the same number of charges protons (+) and electrons (–) so that they are electrically neutral. When an electron is stripped away from the atom, an ion is formed, which has a positive charge. This ion will then react to any electrostatic or magnetic fields that it encounters. The free electron is also affected by fields and travels in the opposite directions and polarity than the positive ion. It is easier to create ions in a gas due to its lower density as opposed to liquids or solids.

While the description of plasma includes ions in a gaseous form, true plasma exhibits a “collective behavior” in which elements of plasma exert a force on one another even at large distances. Not all ionized gases are called plasmas, they must contain enough charged particles so the electromagnetic field produced by them influences the movement of each individual electron and ion. This means that parts of plasma will affect other parts due to its electromagnetic properties, rather than local collision events. Plasmas stay, on average, electrically neutral by containing a sufficient number of electrons to balance the positive charge of ions. The ions and electrons are dissociated from each other as if they did not know each other. In fact, they will neutralize each other if the external energy excitation source if turned off or its energy effects are diminished, usually by distance from the energy source.

The word “plasma” comes from Greek meaning something molded or fabricated. Even though this may be hard to appreciate, the internal and external electromagnetic forces that bound it mold plasma.

Given this broad definition, measurable properties of plasma include its density, electrostatic and magnetic field effects, temperature, and gas species. All conventional plasmas consist of a distribution of ions, excited gas, and neutral gas.

The method for creating plasma starts with the ionization process. Ions are typically created using high voltage, which causes electrons in the atom’s outer orbits to be stripped away. These electrons accelerate through the low-density gas and collide with neutral atoms that create more unbounded electrons and ions. Both are then accelerated in larger numbers. The flow of ions and free electrons is an electrical current and gives rise to an accompanying magnetic field. In an electric discharge, ions (positive) flow in one direction while the electrons (negative) flow in the opposite. An externally applied external electric field either collects electrons or ions depending on the polarity of the electric field. If one applies an external magnetic field around the plasma, the ions and electrons will follow the field lines with the electrons going in one direction and the ions in the other. Plasma is unlike the other states of matter (solid, liquid, and gas). It appears to be a fourth state of matter with atoms becoming simplified parts (electrons and ions) and existing in a dissociated state.

Where is this plasma found in our environment? It has often been said that 99% of the matter in the universe is in the plasma state; that is the form of an electrified gas with the atoms dissociated into positive ions and negative electrons. For example:

- Stellar interiors and atmospheres.
- Gaseous nebulae.
- Much of the interstellar hydrogen.
- Van Allen radiation belts.
- Solar wind.

In our everyday lives, experience of plasmas include several more examples:

- Flash of a lightning bolt.
- The Aurora Borealis and Australia Australis.
- The conducting gas inside a florescent tube or neon sign.
- Welding arcs.
- Gas lasers.

Engineering applications of plasmas includes:

- Surface etching.
- Material processing in the microelectronic industry.
- Plasma chemical processing.
- Synthetic diamond production.
- Fusion research for energy production.

One of the most common uses of low energy plasmas is for lighting. Florescent lights use plasma to bombard impurity mercury atoms which are excited and release ultraviolet light. The ultraviolet light, in turn, excites the coating material to give off visible light or “fluoresce.” This process produces light in an efficient manner from the phosphorous at low temperatures. Neon lights use the direct electrostatic excitation of the neon atom at low pressure in a glass tube. The light is given off when the ionized atom recombines with a free electron. The electron gives up its energy, moving to a lower orbit, when recombining with the ion. The release of this energy is through a photon at a specific visible light frequency (red). (See the chapter on the electromagnetic spectrum for a more detailed description.)

One of the uses for higher energy plasma is for etching microprocessor chips. The high velocity and small size of the atoms are used to bombard chip surfaces to remove material between microscopic conductors. Synthetic diamonds are also produced by laying down carbon atoms in a diamond lattice structure via the addition of radio frequency energy to catalyze the diamond producing process.

Fusion energy research uses very hot plasma. Controlled thermonuclear energy is the attempt to use plasma to get ions to a high enough energy to collide and fuse. When their nuclei fuse, a large amount of energy is released. We all know of the large energy release associated with hydrogen bombs, which fuse light atoms and thus the fusion process was created on earth and sought to be controlled. Scientists are studying ways to harness this energy release in a controlled and safe manner. These high-energy plasmas have very high temperatures that are greater than 300×10^6°C. (The temperature of the sun is on the order of 10×10^6 °C.) Magnetic fields contain the plasma (remember, an ionized gas is trapped by a magnetic field line), “holding” the plasma away from the vacuum chamber walls. Electromagnetic waves and ion beams are used to heat this plasma to high enough temperatures to get the ions to collide with enough energy that they will fuse.

When this fusion takes place, energy is released and new elements are formed. Scientists put into the plasma, isotopes of hydrogen, deuterium, and tritium; helium is produced as a by-product. The reason the light atoms are used is that they take the least amount of energy to accelerate to very high velocities. Harnessing the fusion process in producing energy will also lead to humankind’s creating new elements using the basic building blocks of nature. Mankind will have unlocked the process which transpires in the stars in the universe and may even find ways to create elements that we now have to dig out of the earth.

The process of putting together lower mass elements to form higher mass elements may someday become reality. This leads us onto the next step in plasma and fusion — nucleosynthesis.

The Process of Nucleosynthesis

Once this universe arrived, by means of the “Big Bang,” the only abundant elements present were hydrogen and helium. Clumps of hydrogen and helium would eventually form galaxies and stars and through the internal processes by which a star “shines,” higher mass elements formed inside the stars. Upon the death of a star, these high-mass elements along with even more massive nuclei were thrown out into space to join with a star or celestial body. The conditions inside a star that allow the formation of the higher mass elements is like a tug of war between gravity and the energy released by the star. Gravity creates a force causing a star to collapse, and the energy released by nuclear reactions flows outward, producing thermal pressure that opposes gravity.

In the beginning, essentially all matter was in the form of two elements — hydrogen and helium. Their relative abundance (by weight) was 75% hydrogen and 25% helium. Eventually by compressions due to gravity in the core of the new-star, the temperature of this clumped together material became hot enough to form a phase of matter called a plasma. The temperature and density continued to increase until they reached the “fusion point.” Up until this moment, all the collisions between nuclei were like marbles bouncing off each other. Once the conditions reached the flash point, some of these smaller nuclei fused giving off more energy causing the star to shine.

There are a number of possible pathways for hydrogen fusion in a star, but the primary reaction mechanisms are the PROTON-PROTON CHAIN (p-p chain), or the CARBON-NITROGEN-OXYGEN CYCLE (CNO cycle). The proton-proton chain occurs under lower temperature and pressure than the carbon-nitrogen-oxygen cycle. As time passes, though, the fusion process causes helium to accumulate in the core. The increase in the number of helium nuclei begins to interfere with the hydrogen nuclei collisions and causes a reduction in the rate of hydrogen fusion. This reduces the thermal pressure, and the star will begin to contract.

If the temperature reaches 100,000,000 K, helium nuclei begin to fuse. Carbon nuclei form through reactions called the Triple Alpha Process. The release of energy through this process increases the thermal pressure of the core to the point where it overcomes gravity and this increases the size of the star. The star, a red giant, begins to glow red. (When our sun reaches the red giant stage, it will almost reach the earth.) When this happens, carbon nuclei pull toward the center, just as the He nuclei in an earlier stage, creating a carbon core. On our size sun, this is as far as it goes because of the limited mass of the star. There is not enough gravitational force (due to the lack of mass) in the star to create the temperature and density where carbon nuclei can fuse into heavier nuclei.

On stars of higher mass, enough carbon would compress so that the temperature and density are high enough that carbon nuclei fuse into neon nuclei. The number of element layers stratified by mass that form depends on the initial total mass of the collapsing nebula. This is because the main force that produces fusion is gravity, which depends on the initial mass of the star or density of light elements in the local area.

Further core/shells produce:

1. Neon fusing to oxygen.
2. Oxygen fusing to silicon.
3. Silicon fusing to nickel (this product is radioactive and decays to form iron). Stars that reach this stage are red super-giants.

As the fusion process continues, the amount of iron increases in the star center, the center contracts, and the temperature increases. When the temperature reaches the iron fusion point, the nuclear reactions differ from the previous reactions. Iron nuclei are the most stable of all atomic nuclei and when they undergo nuclear reactions, they absorb energy rather than release it. Iron nuclei are then broken down into alpha particles, protons, and neutrons and compressed further. Eventually, the outer layers of material rebound off the compressed core and are thrown outward. Following the collapse of the inner core, the star's outer layers pull into the center. A collision between the core layers and the collapsing layers occur. This process creates a supernova, which ejects a large quantity of neutrons that are absorbed by surrounding nuclei. Once captured, the neutron decays into a proton causing the atomic number of the element to increase creating still heavier elements.

The process of element formation is possible through the repeated collapse and expansion of stars. Each phase is different from the one before it, involving heavier and heavier elements.

From the simplest to the most complex elements, stars hold the secrets and the answers to the formation of the matter in the universe. Fusion appears to be an answer for the world population's energy production needs, as well as the factor that produced most of the matter that we see around us. All these processes start with an initial plasma formation.

This chapter contains several aspects of plasmas and specific labs to demonstrate and convey the concepts and principles of characteristics in a simple manner. The concepts and associated activities are:

No.	Concept	Activity
1	Nucleo Synthesis	Where do the elements come from?
2	Mass to Energy Conversion	$E=mc^2$
3	Mass to Energy Conversion	Fusion Cookies
4	Nuclear Repulsion	Desk Top Fusion
5	Mean Free Path	The Science of Nothing
6	Ionization	Atomic Act
7	Magnetic Confinement	Magnetic Field Effects
8	Plasma Heating	Plasma Density Model

INSTRUCTOR'S GUIDE
ACTIVITY 1 — WHERE DO THE ELEMENTS COME FROM?

Purpose

To have students understand the fusion concept of nucleosynthesis — how new elements are created.

Objective

After completing this activity, students will be able to:

1. Describe how fusion produces new elements.
2. Define nucleosynthesis.

Time

30 minutes.

Required Equipment and Supplies

1. Periodic Table of the Elements.
2. Pencil or pen.

Theoretical Background

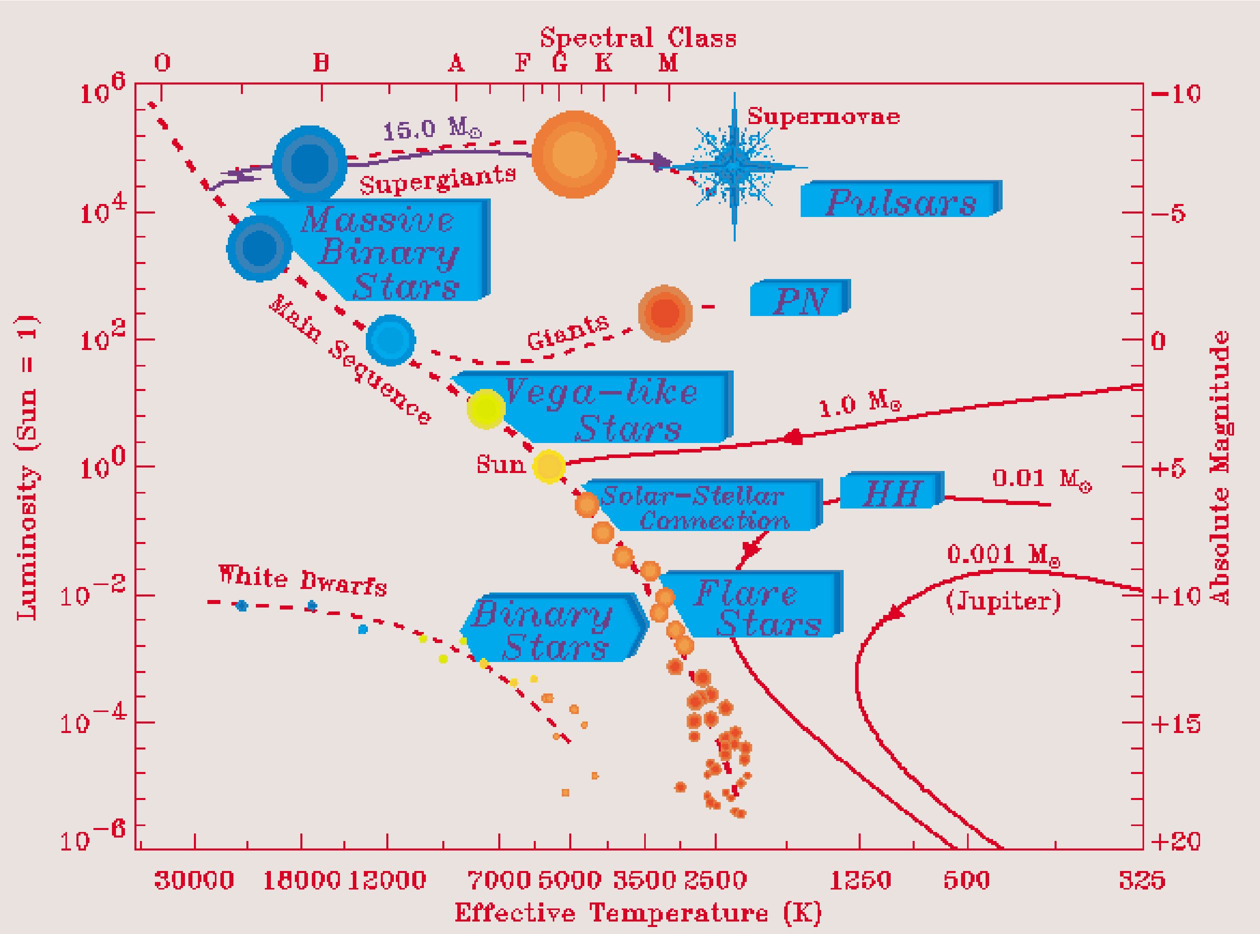
Nucleosynthesis — The Production of New Elements through Stellar Fusion

All stars go through a "life cycle." They are born in a cloud of dust, use up their nuclear fuel, and, depending upon their mass, end up possibly as a neutron star, white dwarf, or black hole. The Hertzsprung-Russell diagram depicts what the anticipated life history of a star will be depending on its initial mass (Fig. 1). As a star begins life, dust and gases (mainly H and He) are squeezed together ever more tightly by gravity until the temperatures and pressures strip electrons off of the nuclei producing a plasma. The temperature and pressure continue to rise eventually overcoming the electrostatic repulsion of the nuclei, and the thermonuclear engines of fusion are ignited. It is this process of nuclear fusion taking place in a star which creates new elements. There are several processes which take place in stars to produce new elements.

Hertzprung-Russel (HR) Diagram

The diagram below shows an example of a Hertzprung-Russel (HR) diagram. The first such diagram was plotted by Ejnar Hertzsprung in 1911 and (independently) by Henry Norris Russell in 1913. It is a "two-dimensional" plot for the observed stars and represents one of the greatest observational syntheses in astronomy and astrophysics! The important things to note about such a diagram is that:

- Most of the stars in the solar neighborhood fall on a well-defined "Main Sequence."
- There are a few "Red Giants."
- There are a few "Blue Supergiants."
- There are a few very faint stars near the bottom left of the diagram — these are the white dwarfs.



The various boxes on the diagram illustrate the general areas that are studied at Rutherford Appleton Laboratory in order to gain a greater understanding of how stars are born, live their lives, and finally die.

The Proton-Proton Chain

Initially, a star will have a huge amount of hydrogen and some helium. Stars of one solar mass or less will fuse hydrogen into helium in a process called the proton-proton chain. Four hydrogen atoms are necessary to produce one atom of helium through this process. In this reaction, two protons are converted into neutrons, positrons and neutrinos are released, and the end product is helium. However, if the original mass of the four atoms of hydrogen is taken and compared to the resulting helium, 0.007 of the mass will be gone — converted into energy according to $E = mc^2$. The sun converts 3636 kg of matter into energy every second!

The CNO Cycle

If the initial mass of a star is greater than one solar mass, it will typically use another reaction sequence called the CNO cycle for fusion. Typically, stars in the FO spectral class (see Fig. 1) use the CNO cycle. In this complex set of reactions, carbon and hydrogen initially interact, go through reactions involving nitrogen and oxygen, and finally produce carbon and helium. The net result is the same as the proton-proton chain. Hydrogen is converted into helium and 0.007 of the reactant mass is lost as energy.

Alpha (He Nucleus) Reactions

As a star uses up its hydrogen, it will begin to use other elements for fusion if temperatures reach sufficiently high levels. The star will begin to go through triple alpha reactions and alpha capture. In a triple alpha reaction, three helium nuclei combine to form one carbon. In stars undergoing alpha capture, an element combines with a helium nucleus, thereby converting it into a new element ($C + He \rightarrow O$). In very massive stars, ever higher temperatures will be created resulting in the production of ever heavier elements on the Periodic Table. The heaviest element which can be produced by stable fusion reactions is iron. Heavier elements than iron are produced through supernova explosions and other disruptions of the stable fusion process. It is these super massive stars which enrich element diversity in the galaxy.

Setup

None.

Hints and Tips

Make sure students understand that only the number of protons makes the difference in elements. That is why this activity does not include neutrons.

Name: Class: Date:

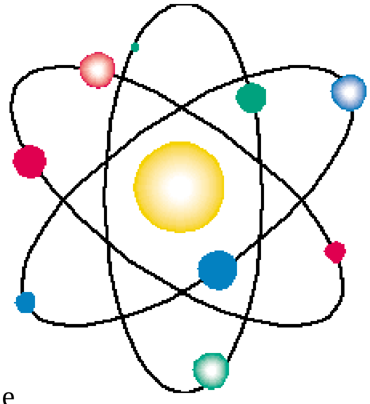
ACTIVITY 1
WHERE DO THE ELEMENTS COME FROM?

Purpose

In this activity, you will use the Periodic Table of the Elements to determine some of the sequences of nucleosynthesis in a star.

Introduction

Although stars are huge in size, the process which powers them takes place at the nuclear level. Deep inside a star, the process of fusion is creating new elements. There are three parts to an atom: the electrons (–), the protons (+), and neutrons (+). The protons and neutrons are located in the nucleus while the electrons orbit around the nucleus. In the nuclear reactions of fusion, the electrons have been stripped away by the enormous temperatures producing a plasma. The nuclei in this plasma are then free to interact in nuclear reactions. When the number of neutrons in an atom changes, but the number of protons remains the same, an isotope is produced. However, if the number of protons (atomic number) is changed, a new element is produced. The process of fusion changes the number of protons — thereby creating new elements. The process of creating new elements is called nucleosynthesis. Through the years, the sequence of nucleosynthesis has been worked out.



Required Equipment and Supplies

1. Periodic Table of the Elements.
2. Pencil or pen.

Setup

None.

Procedure

1. Obtain a copy of the Periodic Table of the Elements.
2. Study the sequence of elements being produced in a star on the activity page.
3. Using your Periodic Table of the Elements, fill in the missing elements and their atomic number (protons). Please note that the neutrons have been left out.
4. Fill in the Going Further section with the missing elements.

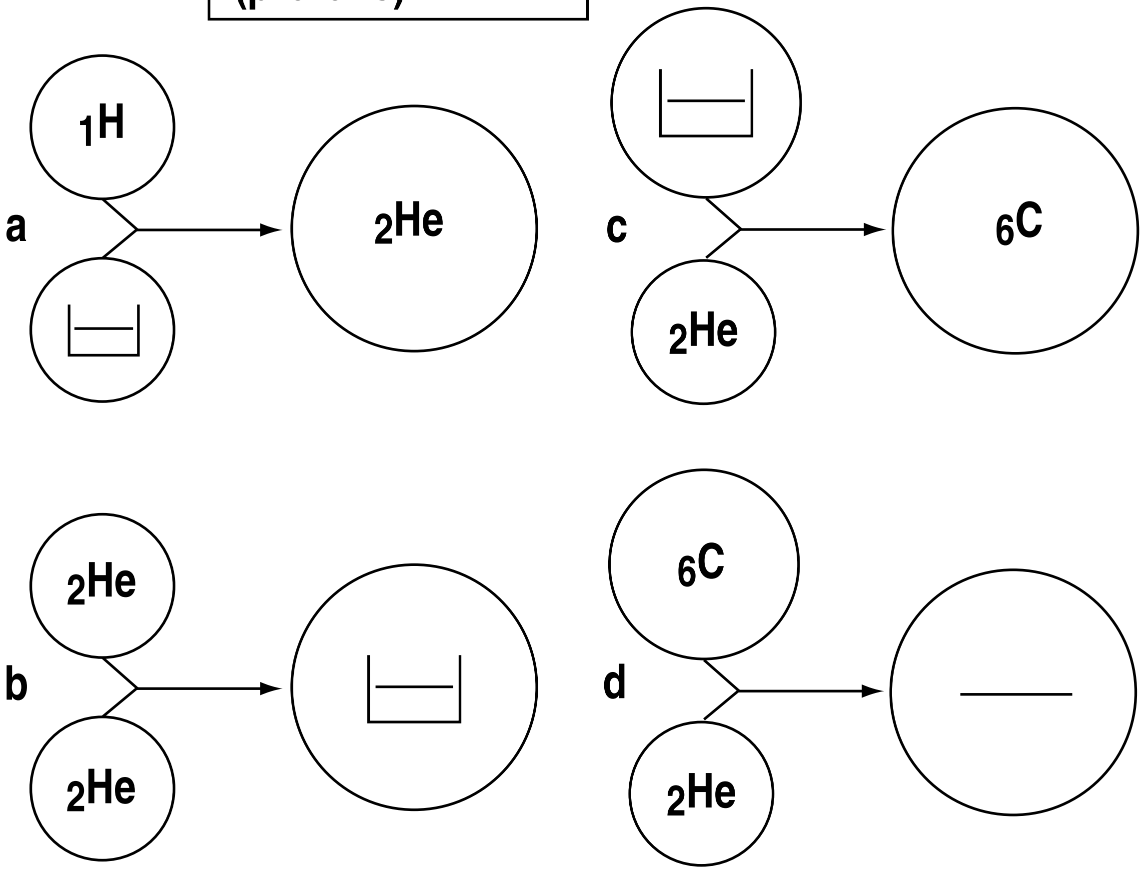
Questions

5. Which process produces new elements in stars?
6. Where did the elements in the earth — and yourself — come from?
7. Which part of an atom has to change for a new element to be produced?

Activity Page

3

$_1$H → element
atomic number
(protons)



INSTRUCTOR'S GUIDE
ACTIVITY 2 — HOW MUCH ENERGY IS PRODUCED DURING THE FUSION PROCESS?

Purpose

To have students manipulate the equation E= mc^2 and do energy calculations.

Objective

After completing this activity, students will be able to:

1. Manipulate the E= mc^2 equation to solve for mass.
2. Calculate fusion energy equivalencies for gas and oil.

Time

30 minutes.

Required Equipment and Supplies

None.

Theoretical Explanation

In a typical chemical reaction involving electrons, the mass of the reactants and products will be equal. The law of conservation of matter states that all matter before and after a reaction can be accounted for — even in an explosion. However, in some types of reactions involving the nuclei of atoms — nuclear reactions — matter can be directly and completely transformed into energy. In the classic equation $E = mc^2$, Einstein states the equivalence of matter and energy. Matter can be transformed into energy, and vice versa. Typically, only those working with in high energy physics are accustomed to seeing matter converted directly into energy, or electrons — matter — suddenly appearing from energy.

The amount of energy contained in matter is stunning. Since the mass of an object is multiplied by the speed of light (3.0×10^8 m/sec) squared, even a small amount of matter contains an enormous amount of energy. During a fusion reaction which involves two hydrogen atoms being fused together to form helium, 0.0038 of the initial mass will be "lost" or transformed into energy.

To gain an appreciation of the amount of energy produced during the fusion reaction, it is necessary to understand some terms used to describe energy.

Whenever a force moves an object through a distance, work is done.

$$\text{Work} = \text{Force} \times \text{distance} \qquad W = Fd$$

Force is measured in Newtons. A Newton is defined as kilogram × 9.8 (acceleration of gravity).

Work is then measured in Newton-meters also called a joule. The joule can also be converted into a more familiar measurement of heat — the calorie. There are 4.186 joules per 1.000 calorie. A calorie is the amount of heat necessary to raise the temperature of 1 g of water by 1°C.

Example: How much energy is released when 4 g of H are converted into He?

$$H + H \rightarrow He$$

Mass before reaction = 4g **Mass after reaction = 3.9848 g**

How much mass was converted into energy during the reaction? = 0.00152g.

$E = mc^2$ → Where : **E is measured in joules**

m is measured in kg

c is the speed of light = 3.0×10^8 m/sec.

$$\text{Energy (joules)} = 0.00000152\ \text{kg}\ (3.0 \times 10^8\ \text{m/sec})^2$$

1.368×10^{11} joules of energy = the equivalent of 100 tons of TNT!!

or in terms of calories = 3.268×10^{10} calories = enough to power your body for 45 years at 2000 Kcal per day!

Setup

None.

Hints and Tips

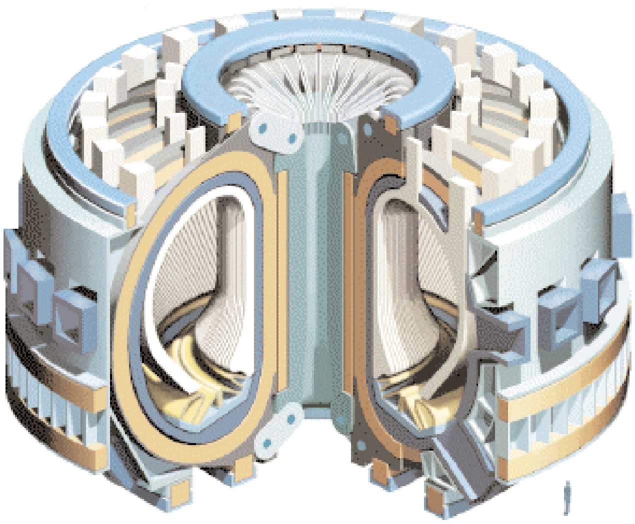
For the two calculations assigned to the students, first have them manipulate the equation $E = mc^2$ to solve for m → $m = E/c^2$. The number of joules is given, and the speed of light is known. Students can then solve for the mass. Remind students that they are solving for the actual mass of matter converted into energy.

ACTIVITY 2
HOW MUCH ENERGY IS PRODUCED DURING THE FUSION PROCESS?

Purpose

To have students manipulate the equation $E = mc^2$ and do energy calculations.

Introduction



Scientists and engineers are now attempting to recreate the power source of stars on earth. Isotopes of hydrogen obtained from water are pumped into a machine called a tokamak. The gas is heated to 150 to 200 million Kelvin. When the atoms are heated to these temperatures, the electrons are removed from the nuclei changing the gas into a charged plasma which can be constrained by magnets. When the positively charged nuclei are heated enough to overcome their repulsion, they fuse and a new element is formed. During this reaction, a small amount of matter (0.0038) is "lost," or converted completely into pure energy. The equation $E = mc^2$ can tell us how much energy is produced during the fusion process.

To gain an appreciation of the amount of energy produced during the fusion reaction, it is necessary to understand some terms used to describe energy.

Whenever a force moves an object through a distance, work is done.

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1.368×10^{11} joules of energy = the equivalent of 100 tons of TNT!!

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Setup

None.

Procedure

1. Use the equation $E = mc^2$ to calculate the kilogram of fusion fuel which would have to be converted into energy to equal the amount of energy in 1000 kg of coal and oil. You will have to manipulate the equation to solve for m (mass). See if you can determine how to calculate the actual total mass of fusion fuel that would have to be used.

Coal		Oil			Fusion Fuel Converted into Energy (mass in kg)
Mass (kg)	Energy (joules)	Mass (kg)	Energy (joules)	Actual Mass of Fuel	
1.8×10^9	2×10^{17}(a)	1.18×10^9	2×10^{17}	551 kg	2.21
1000 kg	1.11×10^{11}				
		1000 kg	1.69×10^{11}		

(a) Enough energy to light a 100-watt light bulb for 634,195 years or 100,000 100-watt light bulbs for 6.3 years.

Questions

2. Write the equation $E = mc^2$ to solve for m.

3. On a percentage basis, how much more fuel efficient is fusion than coal and oil?

Overall

1. Which process produces new elements in stars?

2. Which process converts mass into energy?

3. Why do you think fusion is a difficult process to achieve on earth?

INSTRUCTOR'S GUIDE
ACTIVITY 3 — THE SCIENCE OF NOTHING

Purpose

To demonstrate the effects of density on the mean-free path of atoms in a gas and have the students quantify this by measuring and graphing the results.

Time

1 to 2 hours maybe broken down into two sessions.

Theoretical Explanation

A collisionless plasma is a low density plasma in which the mean-free path between particle collisions is much larger than the distances over which collective processes take place. This means that the collective processes are much more important in determining the behavior of the plasma than collisions between its atoms. Every gas has a characteristic mean-free path that describes the average distance a particle in the gas will travel before it encounters another particle. It depends upon the density of the gas (n) (absolute pressure) and the cross sectional area of the particles. The mean-free path is inversely proportional to the density., In order to have a relatively large distance between collisions, the gas density must be low. Therefore, low pressures/densities are required for plasmas to be heated to fusion temperatures/velocities. Otherwise, the gas particles would not be accelerated enough to reach fusion velocities so that they can overcome the electrostatic forces of the nucleus when they collide.

Molecules travel with a spectrum of velocities in straight lines and collide with the container walls and also collide (elastically) with one another. This motion of the molecules is described numerically with the aid of the kinetic theory of gases. The formula for the mean-free path is:

$$\text{MFP (cm)} = 1/(4\pi\eta b^2)$$

Where: η = particle density/cm^2 (number density)

b = atomic radius in meters

And $\eta = PV/RT \times 6.02 \times 10^{23}$

Where P = Pressure in Torr (1 atm = 760 Torr) (1 Torr = 133 pascal a nd 1.33 millibar)
V = 1 liter
R = 0.0821 liters atm/mol K
T = degrees Kelvin (273 ∞ K = 0 ∞ C)
Avagadro's number = 6.022E23 atoms/mole

It follows that the mean-free path is inversely proportional to the number density of molecules η and, therefore, to the gas pressure P at a constant temperature.

Note: For this exercise, the temperature is constant.

1. The mean-free path is related to the density of the gas. Typical mean-free paths are used to describe gas collision lengths in vacuum systems and plasmas. The lower the pressure in a vacuum chamber, the more space between atoms, resulting in a longer the mean-free path.

2. In a plasma, an atom is ionized and accelerated. It holds this energy until it collides with another object — either the wall or another gas molecule. By increasing its mean-free path, the particle can be accelerated to higher velocities before it collides with another particle. If the velocity is high enough, it will overcome the nuclear electrostatic forces and fusion of atomic nuclei will occur upon which a large amount of energy is released in the form of a high energy neutron. Thus the importance of a mean-free path in plasma applications such as fusion.

3. Have the students find on the mean-free path chart below the corresponding pressures associated with the mean-free paths found in the density circles.

GASSIM — www.ozemail.com.au/~imesoft/gassim.htm — Windows Program

A molecular simulation program for demonstrating aspects of kinetic theory and statistical mechanics. An understanding of the microscopic behavior of a system often leads to greater insight and understanding of its macroscopic properties. Gassim simulates the motion of up to 1000 hard "2–D spherical" molecules of one or two different species and brings the microscopic world of an ideal gas to life with rapid simulations that will catch the interest of students at all levels.

ACTIVITY 3
THE SCIENCE OF NOTHING

Purpose

To demonstrate the effects of density on the mean-free path of atoms in a gas and have the students quantify this by measuring and graphing the results.

Introduction

Space is defined as the absence of matter and, conversely, matter is the absence of space. In plasma physics, a vacuum chamber is required to provide a space free of matter so that exact and pure quantities of material can be added as required for the intended purpose. Making this space free of material results in more space between the particles, resulting in a longer path between atomic particles and, thus, atomic collisions. This activity demonstrates the concept of mean-free path for several gas pressures and densities. Note: mean-free path = average clear path between atoms.

Some molecular diameters:

Species	**Molecular Weight (g/mol)**	**Diameter ($\times 10^{-10}$ m)**
H_2	2.016	2.74
He	4.002	2.18
H_2O	18.02	4.60
N_2	28.02	3.75
O_2	32.00	3.61
Ar	39.94	3.64

Required Equipment and Supplies

1. Enclosed density graphics.
2. Centimeter ruler.
3. Pencil/Pen.
4. Graph paper.

Assembly

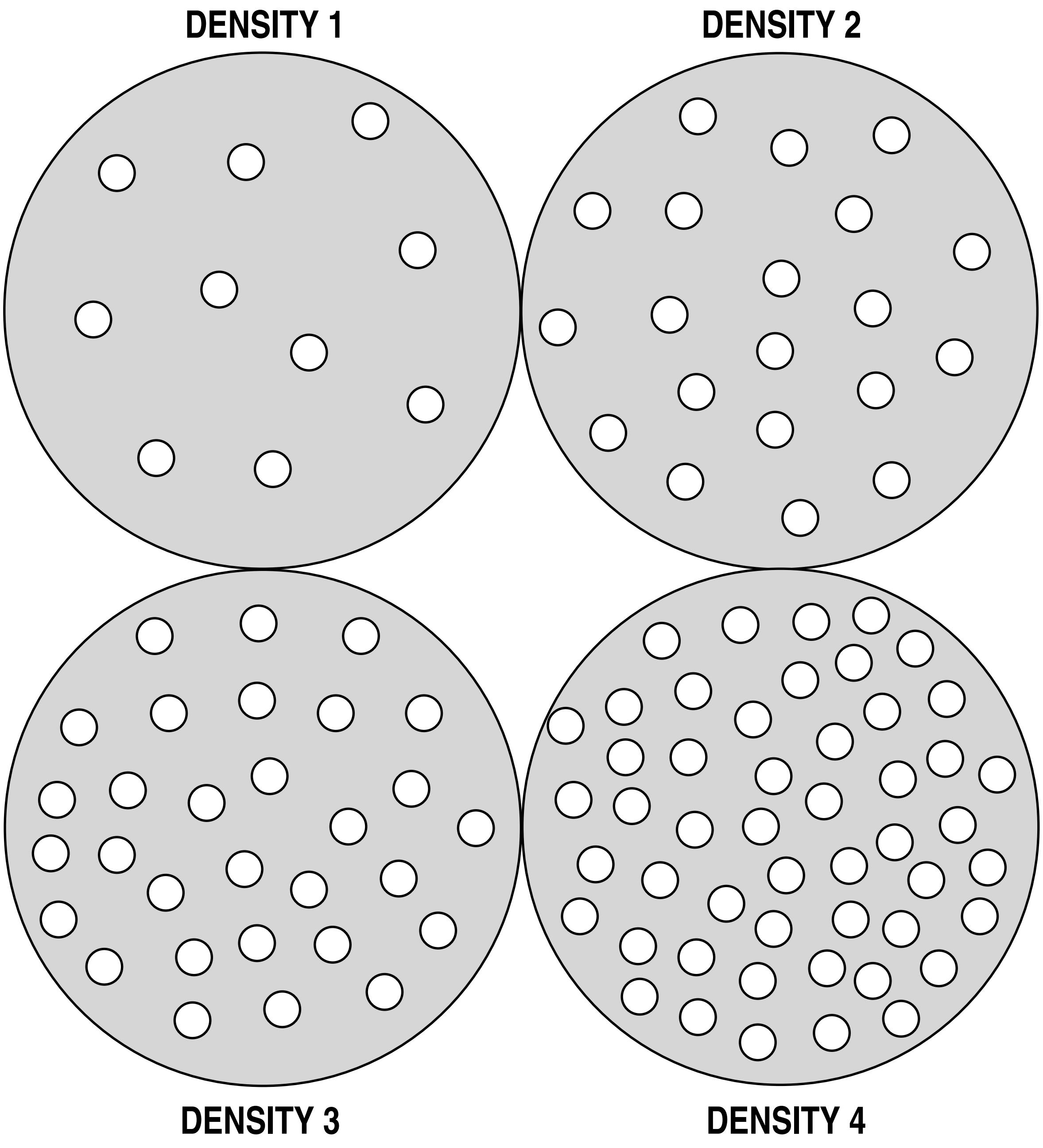
None.

Procedure

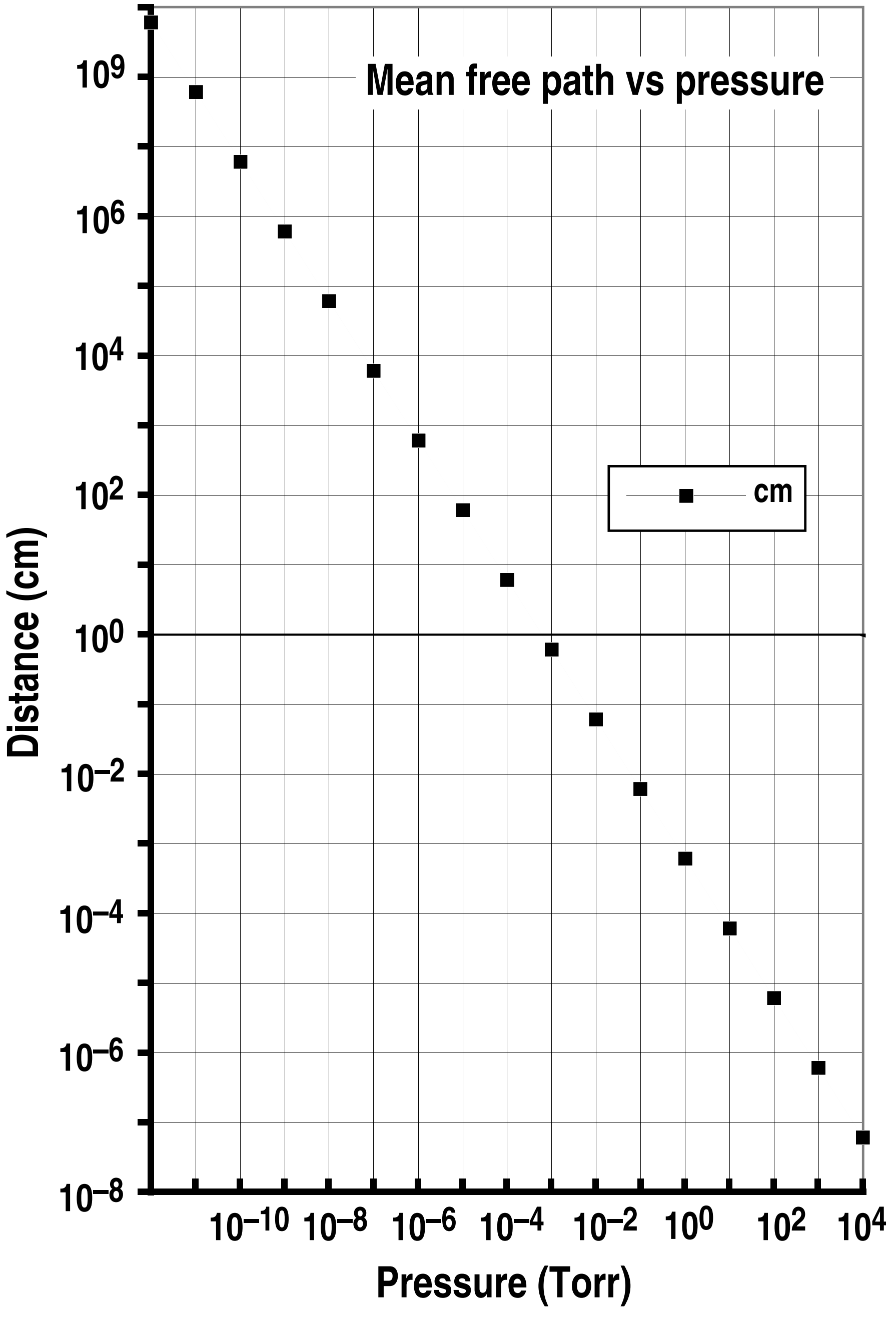
1. In the density pictures, draw a straight line using the ruler from one small circle to another. Do this 10 times from different small circles with the larger circle. The small destination circles can have more than one line drawn to it.
2. Measure the lines and mark the length next to each one.
3. Transfer the measurements to the table in the appropriate column for each density picture, do not mix picture data, and do not repeat data.
4. Complete the table for total and average.
5. Graph the results, and compare average length with the pressure chart. On the chart, make the y axis the mean-free path and the x axis the four categories below. Plot the corresponding mean-free path length and draw a line through the points. On a separate y axis (right side), label the right side of the graph **density**. Plot the corresponding densities and draw a line through them.
6. Determine what pressures are represented on the density circles.
7. Discuss your results.

Using the table below fill in the length of the respective lines.

Line No.	Picture 1	Picture 2	Picture 3	Picture 4
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
Total				
Mean (average)				
Density no./circle				


DENSITY 1
DENSITY 2
DENSITY 3
DENSITY 4

MEAN-FREE PATH



Questions

1. What is the relationship between the mean-free path and particle density?

2. What pressures do the mean free paths represent?

3. Where would you find these pressures in the universe?

4. Why is the average path used instead of just a single path to characterize the free path length at certain densities?

5. What would you expect to happen to the mean-free path if the small circles were increased in size within the same bounding circle?

6. What property would the enlarged small circles represent?

INSTRUCTOR'S GUIDE
ACTIVITY 4 — ATOMIC ACTS

Purpose

To demonstrate the process of ionization and the formation of light.

Time

10–15 minutes.

Theoretical Explanation

Light (a photon) is given off when an electron at a higher energy loses this energy in the form of a photon. This occurs when the electron rejoins an atom and is absorbed into its electron shell — not when an electron is stripped from its atom. This is an important point and should be pointed out how common light is in our world and only happens when electrons loose energy.

The first ionization energy is the minimum amount of energy required to remove the most loosely bound electron from an isolated gaseous atom to form an ion with a 1+ charge. Ionization energies measure how tightly electrons are bound to atoms. Note that ionization requires energy to remove an electron from the attractive force of the nucleus. Low ionization energies indicate ease of removal of electrons and, hence, ease of positive ion formation (an atom missing one of its electrons).

Name: Class: Date:

ACTIVITY 4
ATOMIC ACTS

Purpose

To demonstrate the process of ionization and the formation of light.

Introduction

An ion is simply an atom where the number of protons is not equal to the number of electrons. Typical unionized atoms have an equal number of protons to electrons. Ionization occurs when an electron is pulled away from the atom’s nucleus usually by an external energy. This may be through several means such as mechanical, electrical, chemical, radiation, collision, and magnetic. This activity dramatizes the ionization of an atom by having the student become the atomic particles.

Required Equipment and Supplies

1. Markers.
2. Paper.

Setup

1. Make paper labels with “nucleus/proton,” “ion,” “electron,” “energy,” and “photon” written on them in large letters.

2. Put a “+” and a “–“ symbol on opposite sides of the blackboard at the front of the class.

3. Give each student a copy of the script below.

Procedure

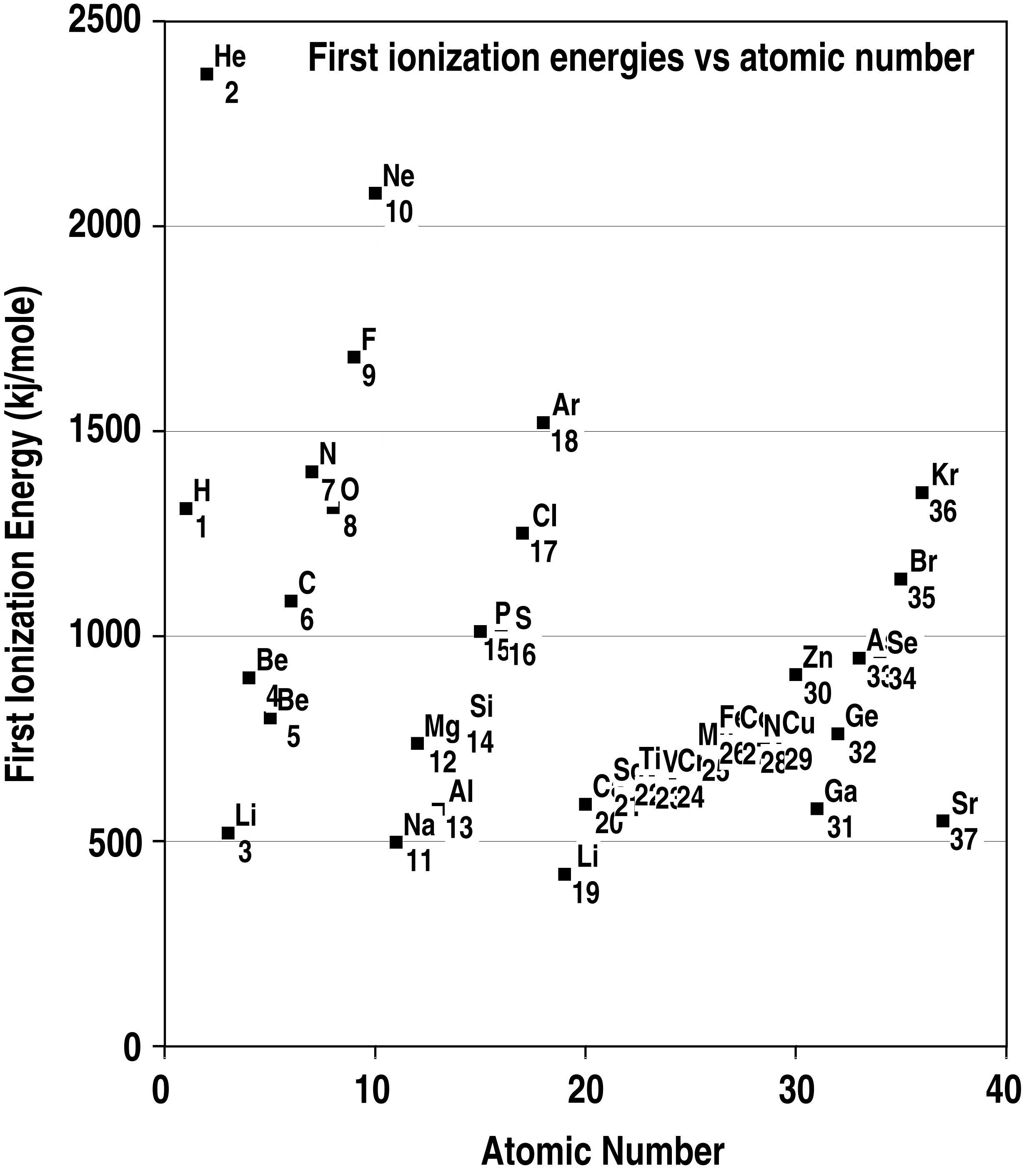
Atomic Acts Script

Actors	Action
Atoms 1, 2, 3	— Hold nucleus/proton sign on chest and hold electron sign out away from your body so the class can see both signs. (Simulate an atom — 1 proton + 1 electron = hydrogen.) — Stand in front of the class smiling — appearing happy and well balanced.
Energy	— Hold your "energy" sign towards the front of the class and appear powerful. — Hold the crumpled photon paper up in your other hand (do not let the class see it). — From the edge of the front of the class, go up to Atom 2 and take the electron sign away from the Atom and move off to the side of the class.
Atom 2	— When the electron is taken from you, flip the nucleus sign over to display the ion label. You are now positively charged and will be attracted towards the negative "–" sign on the blackboard. Act like you miss the electron and are being pulled toward the "–" sign.
Atoms 1, 3	— Stay where you are and appear happy and not affected by the ion or the charge signs on the board.
Energy	— Once you have picked up the electron, move about and act like you miss the ion and move towards the "+" sign on the board.
Teacher	— Point out the relationship of the significance of the charges on the board (ion + electron) and their relationships. Point out that the neutral atoms are not affected by the charges.
Energy	— Once you have appeared to loose energy, move slowly back to the ion and give back the electron. Then immediately throw the balled up photon paper to the class.
Atom 2	— Act happy that your electron has returned to you and that you are balanced again.
Teacher	— Ask whoever caught the photon paper to open it and show what is printed on it to the class. Point out that photon (light) is only given off when an electron looses energy. This photon is then moved to a lower energy orbit around an atom which may be ionized, but does not have to be.
All Players	— You may now return to your seats.

Questions

1. What element do the students represent?
2. What charge does the ionized atom have?
3. What pulls the electron back towards the ion?
4. What happens when the electron goes back with its proton?
5. What speed is the photon traveling when it is given off by the electron recombining with the ion?

ION CHART


First ionization energies vs atomic number
First Ionization Energy (kj/mole)
Atomic Number
0
500
1000
1500
2000
2500
0
10
20
30
40
H 1
He 2
Li 3
Be 4
Be 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
Li 19
20
24
25
29
Zn 30
Ga 31
Ge 32
Se 34
Br 35
Kr 36
Sr 37

INSTRUCTOR'S GUIDE
EXPERIMENT 1 — FUSION COOKIES

Purpose

To simulate a fusion reaction by using a microwave oven to cook cookie dough and have students measure the amount of mass "lost."

Objective

After completing this activity, students will be able to explain the following:

1. How heat will fuse two lighter atoms into a heavier atom — a new element.
2. Why during this fusion process, a small amount of matter is lost — converted into energy.
3. Microwaves can be used to heat fusion fuel.

Skills Required

Microwave oven operation. Analytical scale operation.

Time

45 minutes.

Required Equipment and Supplies

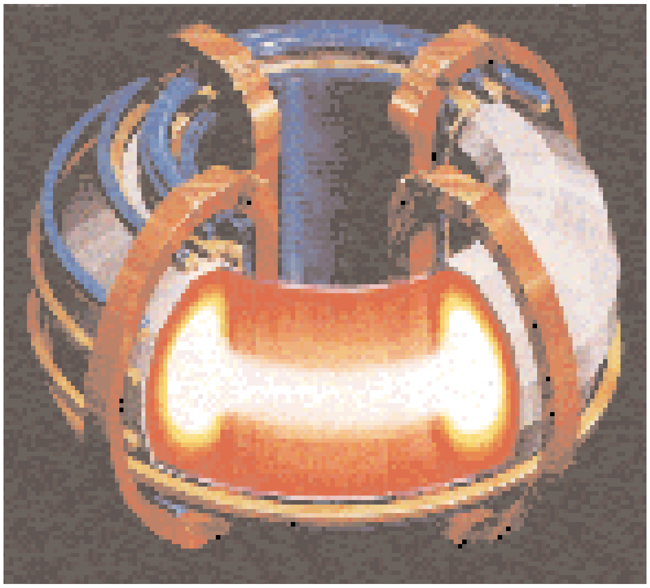
1. Commercial cookie dough in tube. (Homemade dough can be substituted.)
2. Microwave oven.
3. Electronic or triple beam balance.
4. Bread board.
5. Wax paper.
6. Plastic knife.
7. Scissors.

Theoretical Background

In a fusion reaction, two light atoms combine or fuse at very high temperatures to form a heavier atom (new element) and release energy ($E = mc^2$). The fusion process accounts for the creation of all elements beyond hydrogen in the universe. In addition, during a fusion reaction, a small amount of matter is "lost" or converted into pure energy. This energy powers the thermonuclear engines of the sun and stars and provides the energy for almost all life on earth.

For 40 years, researchers around the world have studied methods to control thermonuclear reactions. There was early optimism that taming fusion would be as easy as controlling fission (the splitting of atoms). This early optimism soon gave way to the sobering reality that controlling fusion would be accomplished only after many years of painstaking research, technological advancements, and engineering breakthroughs.

Why the difficulties in achieving fusion? The answer lies within the atom itself. Practically all physical matter on earth is composed of one of the three "common" states of matter — solid, liquid, or gas. In these states, electrons revolve around nuclei composed of neutrons and protons. In the rest of the universe, however, the most common state of matter is plasma — it makes up the sun and stars. In a hydrogen plasma at approximately 100 million Kelvin, the electrons have been stripped away from the central nucleus creating a hydrogen ion. At these extremely high temperatures, the hydrogen nuclei finally overcome their natural electrostatic repulsion and through a series of steps fuse together to form helium (alpha particle) thereby releasing an energetic neutron which carries away heat. During this process, a small amount of matter (approximately 38 parts out of 10,000) is converted completely into energy. As Einstein's equation $E = mc^2$ indicates, even a small amount of matter can produce an enormous amount of energy. The massive gravitational field of stars confines and sustains their fusion reactions, but confining hot plasmas on earth has proved to be a daunting scientific and engineering challenge.



One of the methods used to confine fusion on earth is the tokamak, first designed by the Russians. A tokamak is in the shape of a torus or a "doughnut." Isotopes of hydrogen — deuterium and tritium — are introduced into the hollow torus. Various methods are then used to heat the plasma which include neutral beams, lasers, microwaves, and resistive heating.

The physical characteristics of a plasma (it is charged and conducts electricity) allow it to be constrained magnetically. Since no physical material can withstand the 100 to 200 million Kelvin fireball of a fusion reaction, powerful magnetic fields surrounding the torus are used to keep the plasma in place.

The simulation shows:

1. Two pieces of cookie dough fusing into one cookie with enough heat.

   In real fusion, two lighter elements fuse together through heat and pressure.

2. Loss of mass when the cookie dough cooks and water is lost.

   In real fusion, 0.4% (0.004) of the initial mass is "lost" as mass is converted into energy.
3. Use of a microwave to heat the cookie dough.

   Microwaves are actually used to help heat fusion fuels to millions of degrees in tokamaks.

Procedures

1. While commercial cookie dough which comes in tubes is recommended because of ease of use, any homemade dough will work.

2. Have students use plastic knives to cut the dough from the tube.

3. A mass of cookie dough of approximately 15 g is sufficient to get good results, i.e., the loss of mass will be very apparent after cooking in the microwave oven.

4. We have recommended the use of a microwave oven for this activity because (1) convection ovens are typically not found in many schools anymore, (2) it cooks the dough in 20 to 30 seconds compared to 10 to 15 minutes in a convection oven, and (3) it is actually used to heat fusion fuel in a tokamak. The "fusion" cookie which results from cooking in the microwave will be cooked and edible, but it may not look very edible.

Hints and Tips

1. "Fusion Cookies" is a simulation and therefore represents an analogy to the real fusion reaction.

While there are several similarities between baking cookies and the fusion reaction, students must realize what is analogy and what is real. Keep reminding students to use the science terms throughout the activity. Otherwise, students who are asked what they learned from this activity will answer, "We nuked cookie dough in the microwave." Have students creatively name their new element — microwavium, meltedcookieum, nukedcookieum, etc.

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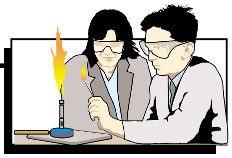


EXPERIMENT 1
FUSION COOKIES

Purpose

To simulate a fusion reaction by using a microwave oven to cook cookie dough and have students measure the amount of mass "lost."

Introduction

In a fusion reaction, two light atoms such as hydrogen combine or fuse at very high temperatures to form a heavier atom and release energy. The fusion process accounts for the creation of all elements in the universe beyond hydrogen. In addition, during the fusion reaction, a small amount of matter is "lost"or converted directly from matter into energy. This energy powers the thermonuclear engines of the sun and stars and provides energy for almost all life on earth. While only 38 parts out of 10,000 in a fusion reaction are converted into energy, this still produces an enormous amount of energy. As Einstein's equation $E = mc^2$ indicates, even a small amount of matter converted into energy produces a huge amount of energy.

Example: $E = mc^2$

E = energy (joules)

m = mass

c = speed of light (3×10^8 m/sec)

If a one gram (1 g) raisin were converted completely into energy:

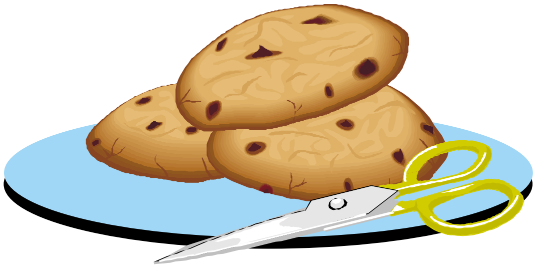
$$\begin{aligned} E &= 1\ \text{g} \times c^2 \\ &= 10^{-3}\ \text{kg} \times (3 \times 10^8)^2 \\ &= 9 \times 10^{13}\ \text{joules} = 10{,}000\ \text{tons of TNT !!!!} \end{aligned}$$

In this activity, you will be using cookie dough to simulate a fusion reaction.

Skills Required

Microwave oven operation. Analytical scale operation.

Required Equipment and Supplies



1. Commercial cookie dough in tube = atomic material.
2. Microwave oven.
3. Electronic or triple beam balance.
4. Bread board.
5. Wax paper.
6. Plastic knife.
7. Scissors.

Setup

None.

Procedure

1. Cut 2 squares of wax paper, 10 cm on each side.
2. Cut a 5-cm wide slice of the tube of "atomic material" on the bread board.
3. Find the mass of the "atom" and record in Table 1.
4. Place the "atom" 1 cm from the edge of one of the wax paper squares.
5. Repeat steps 2 through 4 for a second "atom."
6. Place the two pieces of wax paper close together so that the "atoms" are 2 cm apart.
7. Place both "atoms" on a plate and cook in a microwave oven for 1 minute.
8. After 1 minute, remove the "new element" and let it cool for 2 minutes.
9. Find the mass of the "new element" and record in Table 1.
10. Add the masses of the "atoms" before cooking and record in Table 1.

	Mass Before Cooking	Mass After Cooking
Atom 1		■
Atom 2		■
Total Combined Mass		
Difference between before and after cooking		

Questions

1. Compare the 2 masses of “atoms” before cooking and the “fused new element” after cooking. What happened to the mass?

2. By what percentage did the mass of the “atoms” change?

   Calculating the percentage change:

   Mass after cooking — Combined mass before cooking × 100 = % Change

   Combined mass before cooking

3. How does the change in mass of the cookie dough compare to the actual change of mass in a fusion reaction?

4. What causes the real change of mass during the cooking of the cookie dough?

5. — How is the cookie fusion like a real fusion reaction? List three ways.
   — How is it different? List three ways.

INSTRUCTOR'S GUIDE
EXPERIMENT 2 — MAGNETIC FUSION ON YOUR DESK

Purpose

To demonstrate by analogy nuclear electrostatic forces and how temperature is related to the kinetic energy of a gas.

Time

Overall — 45 minutes.

Theoretical Explanation

The thermal activity of a gas is described by its temperature measurement which is really an indication of its velocity/energy. This is represented by the height that the upper magnet is raised. The upper ring has a potential energy given by PE = mgh at its drop point which is converted into kinetic energy ($KE = 1/2\ mv^2$) as the magnet falls towards the lower magnet. The two magnets click lightly when the kinetic energy is just greater than the magnetic energy that holds them apart. Since Kinetic Energy = Potential Energy (ignoring frictional components), the gravitational pull and mass of the upper magnet are constant, then the height needed to overcome the magnetic repelling force is proportional to that magnetic repelling force.

The plasma analogy demonstrated is that atomic nuclei are held apart by nuclear electrostatic forces similar to the repelling force of the like poles of a magnet. The click is the point where they would fuse to form another element. (Double-stick tape would have a more dramatic effect by making the magnets stick tightly together.)

Required Equipment and Supplies

Assembled as one unit:

1. 10-inch long wooden dowel, o.d. sized approximately 1/16 inch smaller than the ring magnet i.d. (*The wooden dowel can be pressed or glued into the wood block hole.*)
2. 2 × 2 × 3/4 inch wood block with dowel o.d. sized hole drilled through center.
3. Two ring magnets (~$2.00 for a pack of five at Radio Shack).
4. Double-sided tape (if desired).

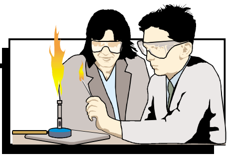
Setup

Assemble the wood block and dowel.

Hints and Tips

The magnets need to slide down the dowels easily. A 5/16 inch dowel with a 3/8-inch i.d. ring magnet work well. Tape could be used instead of marking the dowel with a marker so it could be used over by a new group. If neither of the above are available, listening for a light clicking sound when the magnets contact each other will work also.

Name: Class: Date:



EXPERIMENT 2
MAGNETIC FUSION ON YOUR DESK

Purpose

To demonstrate by analogy nuclear electrostatic forces and how temperature is related to the kinetic energy of a gas.

Introduction

In fusion technology, the goal is to push two atoms together with enough force to make them stick together. In order to do this, the nuclear electrostatic forces holding the atoms apart must be over come. This is no easy task. If it were easy, we would find the atoms in the world clumping together and our physical mass would become smaller since the atom is made up of mostly empty space.

In order to fuse atoms together to produce fusion, a gas is heated to a very high temperature. This temperature is really a measure of the velocity of the gas. This concept is explored in the experiment described below.

Required Equipment and Supplies

1. 10-inch long wooden dowel.
2. One wooden base 2 × 2 inches with (1) 5/16-inch diameter through hole in middle.
3. Two ring magnets with a 1–3/8 inch diameter nominal through hole
4. Double-sided tape (if desired).

Setup

Put the dowel into the hole in the wooden base. Place the magnets together and determine the sides that repel each other. Mark them both with a + sign.

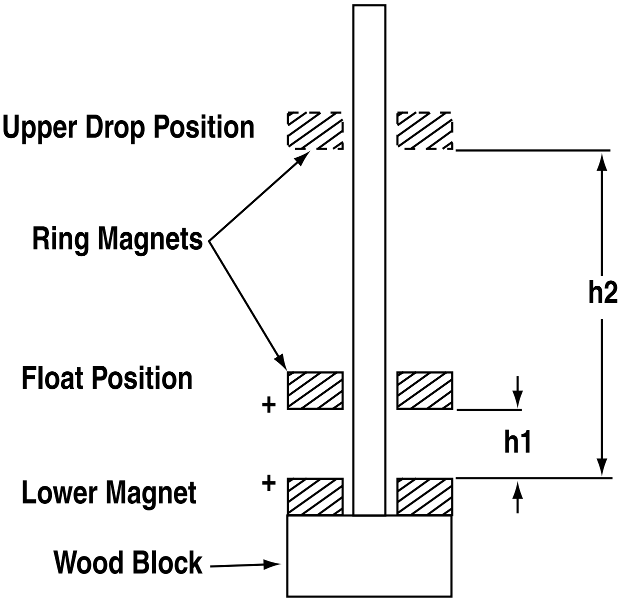
Procedure

1. Put one magnet over the dowel so that its + side is up. Place another magnet over the dowel with its + side down and let it "float" above the lower. You now have a levitating magnet.

2. Measure the distance (meters) between the adjacent magnet faces (h_1).

3. Carefully raise the upper magnet (~1 inch) and drop it onto the base magnet.

4. Raise the upper magnet (~1 inch) and drop it. The upper magnet should bounce on the repelling magnetic field. Keep raising the upper magnet and dropping it until a light clicking is heard between the magnets. Mark this point on the stick (on the lower surface of the raised magnet) and measure the distance to the lower magnet (upper face).



Desktop Fusion Assembly

5. Determine the mass of the upper magnet.

Now you have enough information to calculate the magnetic forces of both of the magnets used in this experiment. Notice that the gravity force on the upper magnet is constant, whether it is falling or stationary and hovering over the lower magnet.

6. Calculate the magnetic repulsion force. Use

   $PE = mg \times \Delta h$ PE = Potential Energy
   $\Delta h = h_2 - h_1$ (meters)
   m = mass (kg),
   g = acceleration due to gravity (m/sec^2).

   Let PE = KE = Fd

   KE = Kinetic Energy
   F = force of magnet's repulsion
   D = distance the Kinetic Energy work is performed = h_1

   With the results of the PE calculation, calculate the magnetic forces.

   $F = PE/h_1$

The result found is the force of two magnets repelling each other. Try different arrangements with magnets stacked to see if the magnetic forces change as you add them. To determine the forces of each arrangement, the above procedure needs to be repeated with a new calculation.

Notice that h_1 is the distance that the energy from the falling magnet is absorbed and work performed. The hovering distance is similar to the room temperature electrostatic repulsion distances that atoms have except they are much closer. The falling magnet is similar to an atom at an elevated temperature at which the atoms move at higher velocities and have more energy to move through the repulsing electrostatic atomic forces.

Questions

1. What does the repelling force of the magnets represent?

2. What does the increased height of the magnet represent in fusion science?

3. What would happen if two magnets were stacked in a series on the bottom?

4. Calculate the velocity of the upper magnet, when it meets the lower magnet's force field by using equality PE = KE, and KE = 1/2 mv^2. Remember you have to transpose the formula to solve for v.

INSTRUCTOR'S GUIDE
EXPERIMENT 3 — IONS AND MAGNETIC FIELDS

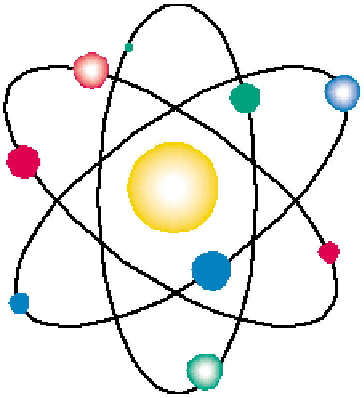
Purpose

Observation of magnetic field effects on magnetic material and by direct analogy plasma magnetic field interactions.

Time

15–30 minutes.

Theoretical Explanation



Magnetic materials will align themselves to a magnetic field by aligning the atomic magnetic poles along the field lines. Ions in a plasma also follow magnetic field lines except that they rotate around them as they move along them. Scientists use this electromagnetic property in magnetic fusion to trap the gas ions so that they cannot come into contact with the vacuum vessel, which would cool the gas or melt parts of the vessel wall. The 3–D view of the magnetic field should be pointed out since most field views use a 2–D model.

Safety Note: This lab requires fine pieces of steel wool (not iron filings). To produce fine steel wool "dust," special precautions such as eye and breathing protection should be employed.

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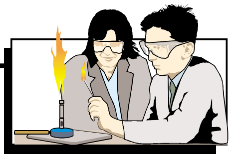


EXPERIMENT 3
IONS AND MAGNETIC FIELDS

Purpose

Observation of magnetic field effects on magnetic material and by direct analogy plasma magnetic field interactions.

Introduction

Magnetic materials align themselves to a magnetic field. Ions in a plasma do the same thing — they follow the field lines. In the following lab, steel wool fibers (ions) are used to show the 3–D magnetic field lines of a magnet and how the fibers will mimic ions at a much slower speed and follow magnetic field lines.

Required Equipment and Supplies

1. Baby oil/mineral oil bottles (any size).
2. Steel wool fibers (0000-very fine) added.
3. Cow magnet or other medium strength magnet.

Setup

Remove the labels from the baby oil bottle. Grate the steel wool into very fine fibers by rubbing against sandpaper backed by a wooden block. Collect the fibers on a piece of white paper with a folded crease down the center. After about a teaspoon of fibers have been rubbed off, gently and without clumping, let them slide down the crease into the oil. Try not to push the fibers with our fingers since this tends to mash them together. If the fibers clump, a pencil can be used to remove it.

Once they have entered the oil, re-seal the bottle and tape the lid shut. It is now ready for mixing. Using a circular motion mix the solution.

Various viscosity of oils can be tried. For longer delay times in the particle movement, thicker viscosity of oils is better.

Procedure

1. Swirl the steel wool fibers around in the bottle so that they are evenly distributed.

2. While holding the bottle up to a white background, slowly bring the magnet to the side of the bottle until the fibers start to orient themselves to the magnetic field. Stop at this point and observe how the fibers align themselves and travel down the magnetic field lines. Ions in a plasma follow field lines in the same manner.

3. Try several orientations. Try holding the magnet quickly against the side of the bottle. Compare this to a more delayed removal of the magnet from the side of the bottle. Notice the three-dimensional aspects of the field lines. To produce the best effect, start with an even distribution of the fibers within the solution before introducing the magnetic field.

Questions

1. What causes the particles to follow the field lines?

2. What kinds of field lines does the magnet produce?

3. What kind of atoms are similar to the steel wool particles?

4. What kind of atoms would not be affected by the presence of a magnetic field?

INSTRUCTOR'S GUIDE
EXPERIMENT 4 — PLASMAS

Purpose

Observe how a simulated styrofoam atomic plasma can be created to model real plasma behavior.

Objective

After completing this activity, students will be able to:

1. Describe the forms of matter.
2. Describe what happens as a plasma is formed.

Time

10 minutes for demonstration. 10 minutes for students to answer questions.

Theoretical Background

Practically all physical matter on earth is composed of one of the three "common" states of matter — solid, liquid, or gas. In these states, electrons revolve around nuclei composed of neutrons and protons. Chemistry is possible because elements share or exchange electrons. However, by far the most common state of matter in the universe is plasma — the fourth state of matter. More than 99% of the visible universe is a plasma. In a plasma, electrons have been stripped off of their nuclei and are free to move independent of the nuclei; a plasma is essentially a sea of charged particles. Since the nucleus is positively charged and the electrons are positively charged, they will feel the affect of a magnetic field. If a charged particle moves through a magnetic field, it will feel a force. This will cause the particle to spin around the magnetic field line. A good example is the Northern Lights (Aurora Borealis) which is caused by the charged particles from the Sun which are trapped by the Earth's magnetic field and spiral along until they crash into the Earth's atmosphere.

Plasmas and Fusion

Deuterium and tritium, isotopes of hydrogen, are introduced into a chamber shaped like a doughnut (tokamak). As this fusion fuel is heated to millions of degrees, the electrons separate from the nuclei they are circling. Since the resulting plasma is now charged, it can be controlled magnetically., The plasma will continue to spiral around the field line and stay inside the magnetic bottle formed by the magnetic field. This is the idea behind the tokamak — a donut-shaped device surrounded by magnets which control the flow of the 100 million Kelvin plasma inside.

Required Equipment and Supplies

1. Shoe box.
2. 4 × 6 cm screen mesh (enough to cover the box).
3. Eight 1-1/4 inch Styrofoam balls.
4. Eight 3/4 inch Styrofoam balls.
5. Eight pins.
6. Two different colors of bright paint.
7. Hair dryer with a cool setting.

Procedure

1. Paint Styrofoam balls of equal size the same color (Diagram 1).
2. Remove the lid from the shoebox.
3. Cut a hole 4 × 4 cm in the bottom of the box (Diagram 2).
4. Cut out 1/4-inch metal screen mesh so that it fits over the shoe box and the hole in the bottom of the box (Diagram 2).
5. Pin the small Styrofoam balls onto the large ones. Approximately 1 cm of pin should protrude to hold the small Styrofoam balls onto the large one (Diagram 3).
6. Place the "atoms" into the bottom of the box.
7. Place the screen over the box.
8. Using a hair dryer with a cool setting, blow air into the box.

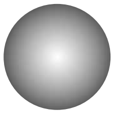
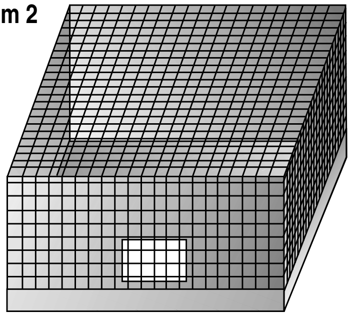


Diagram 1

Diagram 2



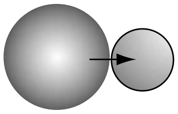


Diagram 3

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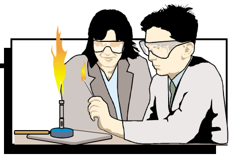

EXPERIMENT 4
PLASMAS

Purpose

Observe how a simulated styrofoam atomic plasma can be created to model real plasma behavior.

Introduction

Practically all physical matter on earth is composed on one of the three “common” states of matter — solid, liquid, or gas. In these states, electrons revolve around nuclei composed of neutrons and protons. Chemistry is possible because elements share or exchange electrons. However, by far the most common state of matter in the universe is plasma — the fourth state of matter. More than 99% of the visible universe is a plasma. In a plasma, electrons have been stripped off of their nuclei and are free to move independent of the nuclei; a plasma is essentially a sea of charged particles. Since both the nucleus and electrons are positively charged, they will feel the affect of a magnetic field. If a charged particle moves through a magnetic field, it will feel a force. This will cause the particle to spin around the magnetic field line. A good example is the Northern Lights (Aurora Borealis) which is caused by the charged particles from the Sun which are trapped by the Earth’s magnetic field and spiral along until they crash into the Earth’s atmosphere.

Plasmas and Fusion

If the magnetic field line can be coupled into a closed configuration like a donut shape, the plasma will continue to spiral around the field line and stay inside the magnetic bottle formed by the magnetic field. This is the idea behind the tokamak — a donut-shaped device surrounded by magnets which control the flow of the 100 million Kelvin plasma inside.

In this demonstration, you will see how a plasma is produced.

Teacher Demonstration

Required Equipment and Supplies

1. Shoe box.
2. 4 × 6 cm screen mesh (enough to cover the box).
3. Eight 1-1/4 inch Styrofoam balls.
4. Eight 3/4 inch Styrofoam balls.
5. Eight pins.
6. Two different colors of bright paint.
7. Hair dryer with a cool setting.

Procedure

1. The teacher will put the eight hydrogen atoms in the plasma chamber.

2. The teacher will place the hair dryer over the hole and turn it on.

3. Observe the action of the "atoms."

Questions

1. What do the large Styrofoam balls represent? the small Styrofoam balls?

2. What happens to the "electrons" and "nuclei" as they are "heated up" in the chamber? Why?

3. What is the resulting mixture called?

4. What is the most common form of matter? Where is it found?

ACTIVITY 1
WHERE DO THE ELEMENTS COME FROM?

Answers

3. a. $1H + 1H \rightarrow 2He$
   b. $2He + 2He \rightarrow 4Be$
   c. $4Be + 2He \rightarrow 6C$
   d. $6C + 2He \rightarrow 8O$

Going Further

4. a. $C + C = Mg$
   b. $O + N = P$
   c. $Ne + Li = Al$

5. fusion

6. nucleosynthesis through fusion

7. proton.

ACTIVITY 2
HOW MUCH ENERGY IS PRODUCED DURING THE FUSION PROCESS?

Answers

1. — 1000 kg of coal = 0.000001234 kg of fusion fuel converted into energy.
   — Actual mass of fusion fuel = 0.031 g.
   — 1000 kg of oil = 0.000001883 kg of fusion fuel converted into energy.
   — Actual mass of fusion fuel = 0.047 g.

2. $m = E/c^2$

3. — Coal = 1000 kg = 1000/0.000001234 = 810,372,772 times as efficient.
   — Oil = 1000 kg = 1000/0.000001883 = 531,067,445 times as efficient.

Activity 2 — How Much Energy is Produced During the Fusion Process?

ACTIVITY 3
THE SCIENCE OF NOTHING

Answers

1. The mean-free path is inversely proportional to the particle density.

2. Check the mean-free path to pressure correspondence on the accompanying chart.

Unit	Nm^{-2} (pascal)	mbar	bar	torr
1 Nm^{-2} (= 1 Pascal)	1	1E–2	1E–5	7.5E–3
1 mbar	100	1	1E–3	0.75
1 bar	1E–5	1E3	1	750
1 torr	133	1.33	1.33E–3	1

3. The pressures below 10^{-4} Torr would be found in space, stars, fusion reactors, plasma processing tanks, and outer reaches of earths atmosphere.

4. The mean-free path is a statistical representation and average of a population of atoms, similar to the average grade of students in a class.

5. The mean-free path would be shorter.

6. The increase in diameter of the small circles represents an increase in molecular diameter and, typically, mass of the gas.

GASSIM — www.ozemail.com.au/~imesoft/gassim.htm — Windows Program

A molecular simulation program for demonstrating aspects of kinetic theory and statistical mechanics. An understanding of the microscopic behavior of a system often leads to greater insight and understanding of its macroscopic properties. Gassim simulates the motion of up to 1000 hard “2–D spherical” molecules of one or two different species and brings the microscopic world of an ideal gas to life with rapid simulations that will catch the interest of students at all levels.

ACTIVITY 4
ATOMIC ACTS

Answers

1. hydrogen
2. positive charge
3. opposite electrostatic charge
4. 186,000 miles/seconds. The speed of light.

EXPERIMENT 1
FUSION COOKIES

Answers

1. The mass will have decreased.

2. Answers will vary according to the mass of dough used — typically 3 to 5 g of mass will be lost as water vapor. Indicate to students what is really happening with the dough versus actual fusion.

3. The mass change in the cookie dough will be much larger due to water loss.

4. Water is lost when the dough cooks causing the dough to change mass. No actual mass is lost, however; the law of conservation of mass is reinforced!!

5. See “The simulation shows” above.

EXPERIMENT 2
MAGNETIC FUSION ON YOUR DESK

Answers

1. The repulsion of the magnets represents the nuclear electrostatic forces that cause like charges to repel. The nucleus is filled with positively charged protons that repel each other.

2. The height of the magnet when released represents the increased temperature/kinetic energy needed to overcome the nuclear electrostatic forces in a fusion reaction.

3. If two magnets were stacked in series on the bottom and one magnet was in repel mode on top, the lower magnetic field would add and double the repelling force on one side. The gap between the magnets will get larger, given that the force increased but the weight load of the upper magnet stayed constant. This would be indicative of a larger mass atom having more protons with a larger electrostatic force.

4. Using $mgh = 1/2\ mv^2$, solve for the velocity at which the upper magnet encounters the lower magnets force field. Let $PE = KE = 1/2\ mv^2$ and v can then be solved by transposing the formula into $v = \mathrm{SQRT}(2 \times PE/m)$. Remember that PE is transformed into KE through the acceleration of gravity.

EXPERIMENT 3
IONS AND MAGNETIC FIELDS

Answers

1. The magnetic force pulling on the steel wool's magnetically aligned molecular structure — like any other magnetic material.

2. Magnetic field lines of force.

3. Ions of any gaseous element usually in a plasma state.

4. Neutral atoms of any gaseous element — in or out of a plasma state. (Plasma also contains a small amount of neutrals.)

EXPERIMENT 4
PLASMAS

Answers

4. Nuclei; electrons.

5. They come apart. The electrons become too energetic to remain around the nucleus.

6. The resulting mixture is called a plasma.

7. The most common form of matter is a plasma. Plasmas are found in stars and fusion devices such as tokamaks and inertial fusion machines.