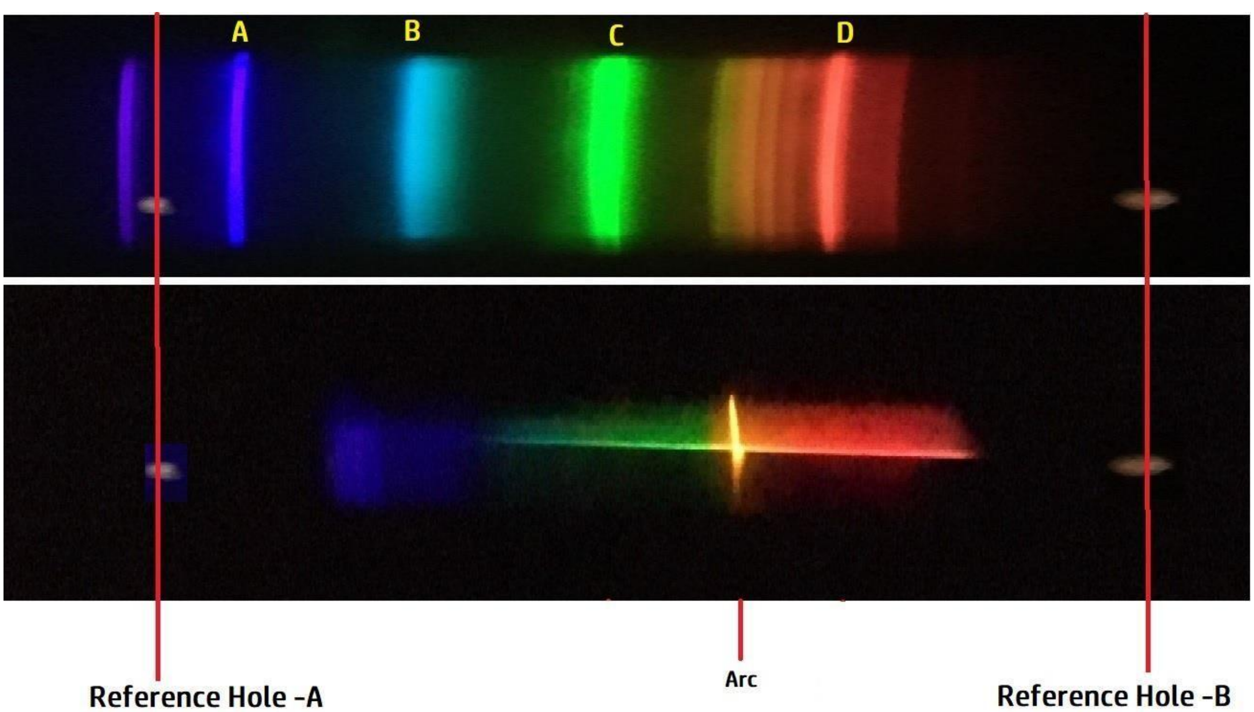
National Aeronautics and Space Administration

Advanced Experiments with Plasma



Advanced Experiments with Plasma

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Acknowledgments

This resource was developed by the NASA Heliophysics Education Activation Team as part of its program of creating and disseminating resources for teachers and Learners that describe the major concepts in Heliophysics – the study of how the sun interacts with Earth and the solar system through its gravity, radiation and space weather influences.

We would like to thank Ms. Rachel Geiter and her student testers for their help in field testing these activities H1, H3, H4, H5 and H6 and providing hands-on feedback for improving them.

Cover art: Spectrum of the plasma from an electric candle lighter and a reference spectrum from a CFL lamp. (Credit: The Author).

Introduction

This Guide is part of a 3-book set of experiments and activities that introduce Learners to plasma, the fourth state of matter, with many hands-on experiments designed to explore the various aspects of this substance. The strategy of these books is to first introduce Learners to the basic properties of plasmas by having them apply criteria defining plasmas to common objects that they see around them.

The “*Introductory Experiments with Plasmas*” book is an introductory exploration of their world that does not require any new observations. In the second book, “*Explanatory Experiments with Plasmas,*” learners create a simple diffraction grating spectroscope and use it to explore different light sources at home and outside to examine how plasmas produce a different type of light than heated bodies such as incandescent bulb filaments.

Finally, in the advanced exploration phase, “*Advanced Experiments with Plasmas,*” Learners will create plasma under various controlled conditions by building simple devices that generate sparks. Most of the experiments at the Advanced level require the purchase of inexpensive components. **Although experiments HS1-HS6 have been classroom tested, the remaining experiments are included for Hobbyists and have not been classroom tested, although Teachers may find them useful nonetheless.**

Information for teachers is also provided to indicate how the content aligns with a variety of science, math, and engineering standards. Although this Guide can be used by life-long learners, it is designed to be a reference for teachers looking for interesting experiments in magnetism, or students looking for science fair project ideas. Each experiment provides a list of materials, and a step-by-step guide to setting up and conducting the experiment. There are also guiding questions and occasional math problems to help quantify the output of the experiment. The Advanced experiments (HS1-HS20) engage learners by having them work directly with common, everyday sources of plasma, and then by creating simple devices for producing plasmas and detecting them via their radio emission.

Unless otherwise cited, all figures and illustrations are courtesy of the First Author.

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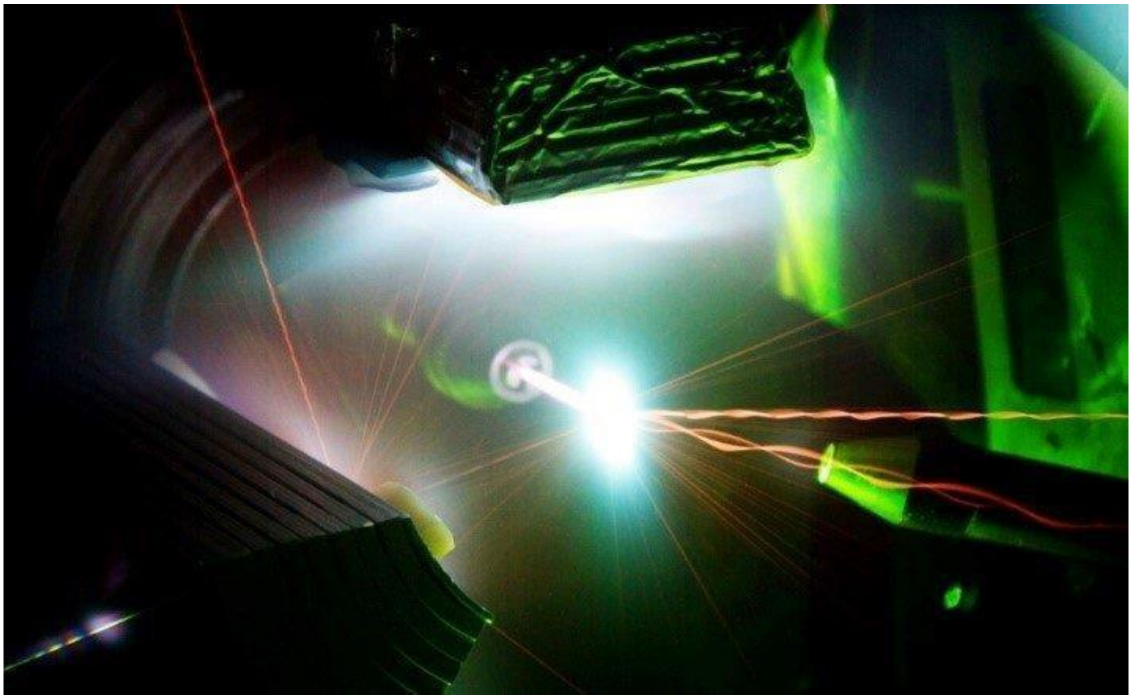


Figure 1. Invisible infrared light from the 200-trillion-watt Trident Laser enters from the bottom to interact with a one-micrometer thick foil target in the center of the photo, generating a ball of glowing plasma. (Credit: Joseph Cowan and Kirk Flippo, Los Alamos National Laboratory)

I. Notes for Educators

Chapters 1-6 provide background information for educators, including a set of problems that can be used to practice with students prior to conducting the experiments. Each experiment provides the educator with an overview of the experiment, student learning objectives, and additional problems that can be used to assess students' knowledge and skills in STEM. All of the experiments model *Science and Engineering Practices* described in the NGSS guidelines, including analyzing and interpreting data and using mathematical and computational thinking. Other assessments can be added by the educator as part of the student's experiment portfolio, including science journaling and engaging in research.

These experiments can be conducted during class, or can be done at home, with parent supervision as needed. The experiments require approximately one class period of time (~45 minutes), with some exceptions. Most experiments take advantage of common household materials, but issues of equity may require students to work in pairs or make other arrangements to borrow the equipment. All of the experiments model *Science and Engineering Practices* described in the NGSS guidelines, such as analyzing and interpreting data, and using mathematical and computational thinking

Advanced Concepts:

Structure and Properties of Matter (NGSS: PS1.A) - Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons. When an atom loses (gains) electrons, it becomes positively (negatively) charged and is called a positively (negatively) charged ***ion***.

- ➢ The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states. The lighter elements in the periodic table can fuse together to form heavier elements during a process called ***nuclear fusion***. During this process a large amount of energy is released. For example, hydrogen atoms in the core of the Sun fuse together to form helium atoms, which is how the Sun releases energy.

Types of Interactions (NGSS: PS2.B) - Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects.

- ➢ Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields.
- ➢ The ***plasma*** state of matter consists of particles (***ions*** and ***electrons***) which have uncompensated electric charge. Charged particles within a plasma cause their own electric and magnetic fields and interact with each other at a distance via electromagnetic forces. If an external electric or magnetic field is applied to a plasma, the charged particles within the plasma follow the direction of these fields. This is how plasmas can be confined within a fixed volume in space (for example, inside a laboratory machine).

Definitions of Energy (NGSS: PS3.A) - Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. That there is a single quantity called energy is due to the fact that a system's total energy is conserved, even as, within the system, energy is continually transferred from one object to another and between its various possible forms.

- ➢ At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and heat.
- ➢ At the microscopic scale, all of the different manifestations of energy can be modeled as a combination of energy associated with the motion of particles (kinetic energy) and energy associated with the configuration or relative

position of the particles (potential energy). In some cases, the relative position energy can be thought of as stored in fields (which mediate interactions between particles). This last concept includes radiation, a phenomenon in which energy stored in fields moves across space.

Conservation of Energy and Energy Transfer (NGSS: PS3.B) - Conservation of energy means that the total change of energy in any system is always equal to the total energy transferred into or out of the system.

- ➢ Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems.
- ➢ Mathematical expressions, which quantify how the stored energy in a system depends on its configuration and how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior.

The Universe and Its Stars (NGSS: ESS1.A)- The star we call our Sun is changing and will burn out over a lifespan of approximately 10 billion years.

- ➢ The study of stars' light spectra and brightness is used to identify compositional elements of stars, their movements, and their distances from Earth.

II. The Plasma State

- ❖ **How was plasma discovered?**
- ❖ **What is a plasma?**
- ❖ **What are some examples of plasmas and how they form?**

A Bit of History

How was the plasma state first discovered, and who came up with such an odd word? Plasmas were probably discovered accidentally by the ancient Greeks who experimented with creating sparks by rubbing amber with fur. They did not have a word for what the composition of these sparks was. Going back even further than that, humans marveled at lightning bolts since long before recorded history.

The recognition that a plasma consisted of a mixture of electrons, ions, and neutral matter didn't really come into its own until the late 1800's when the basic principles of magnetism and electricity were being worked out by physicists. Between 1860 and 1875, physicists such as William Crookes, Johan Hittorf, and Heinrich Gessler were experimenting with discharging electrical currents through tubes of various gases. They noticed a glow forming as the current passed through the gas on its way to the cross-shaped anode.

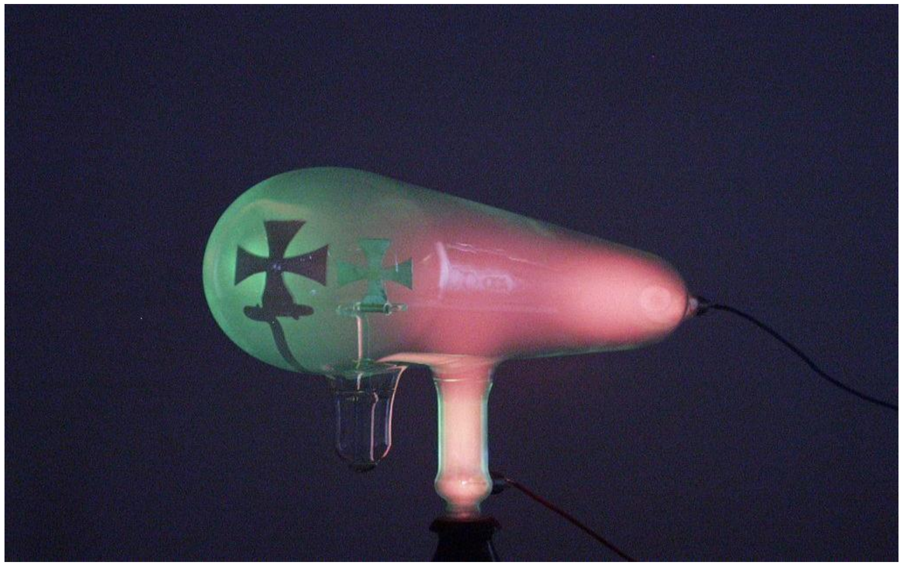


Figure 2. Crookes tube showing glow. (Credit: Wikipedia/Zátonyi Sándor)

Plasma was first identified in the laboratory by Sir William Crookes. Crookes presented a lecture on what he called "radiant matter" to the British Association for the Advancement of Science, in Sheffield, on Friday, 22 August 1879. Systematic studies of plasma began with the research of Irving Langmuir and his colleagues in the 1920s. It was Langmuir who introduced the term "plasma" as a description of ionized gas in 1928:

> *"Except near the electrodes, where there are sheaths containing very few electrons, the ionized gas contains ions and electrons in about equal numbers so that the resultant space charge is very small. We shall use the name* ***plasma*** *to describe this region containing balanced charges of ions and electrons."*

It is thought that he came up with the term *plasma* because this medium transports electrons through space, analogous to how blood plasma transports red and white blood cells.

Basic Description of the Plasma State

Matter is composed of atoms. Each atom has a positively charged nucleus surrounded by negatively charged electrons. When the number of positive and negative charges are equal, the atom has no charge at all. It is called a neutral atom. This is the normal state of matter that you see around you in the form of solids, liquids, and gases. Solids are composed of atoms that are held together tightly to form crystals. Liquids are collections of atoms at higher temperatures that still feel each other's electric forces but can't completely break away. With a bit more heat, you create a gas, which is a collection of atoms that have enough energy to spend most of their time far away from each other. If you were to draw a diagram of where the atoms are in each of these states it would look like this:

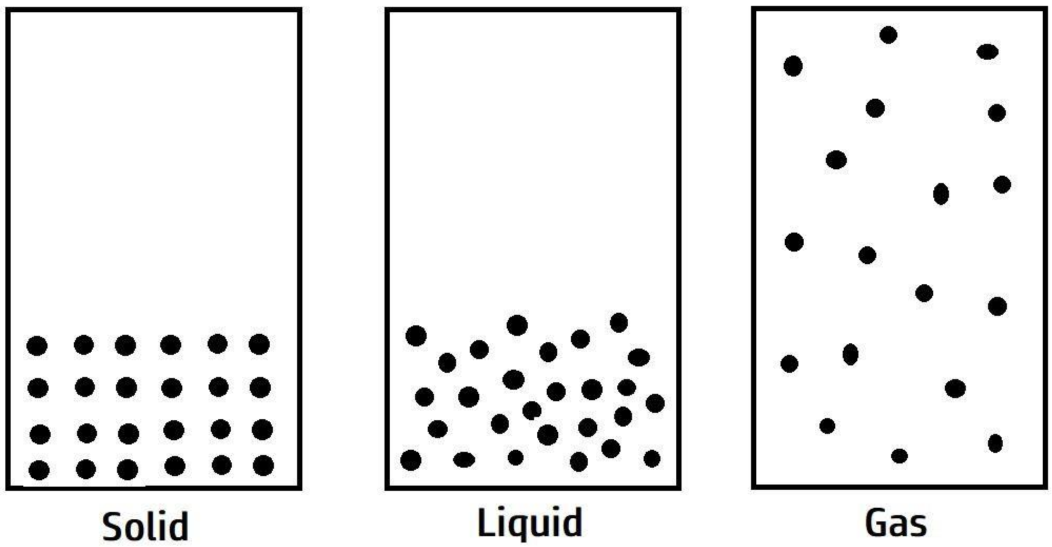


Figure 3. Illustration of how atoms are distributed in the three basic states of matter.

As the temperature increases from left to right in the figure, the atoms arrange themselves into the forms we know as solid, liquid, and gas. This is all well-and-good so long as the atoms do not collide too violently. If they do break apart, you get a new form of matter called a plasma.

A plasma is a form of matter that has been heated so that the individual atoms collide violently. Normally, you just get a very hot gas when you heat matter. If you start with a block of ice and heat it, you eventually get steam as its gaseous form. But when the temperature is high enough the collisions cause atoms to break apart. This happens because the electrons that make up atoms can be pulled out of the atoms during a collision. The result is that you get a gas that contains some normal atoms, but also some atoms that have lost one or more of their electrons (called ions), and then you have the electrons themselves buzzing around. This new collection of atoms, ions and electrons is called the plasma state, or just a plasma.

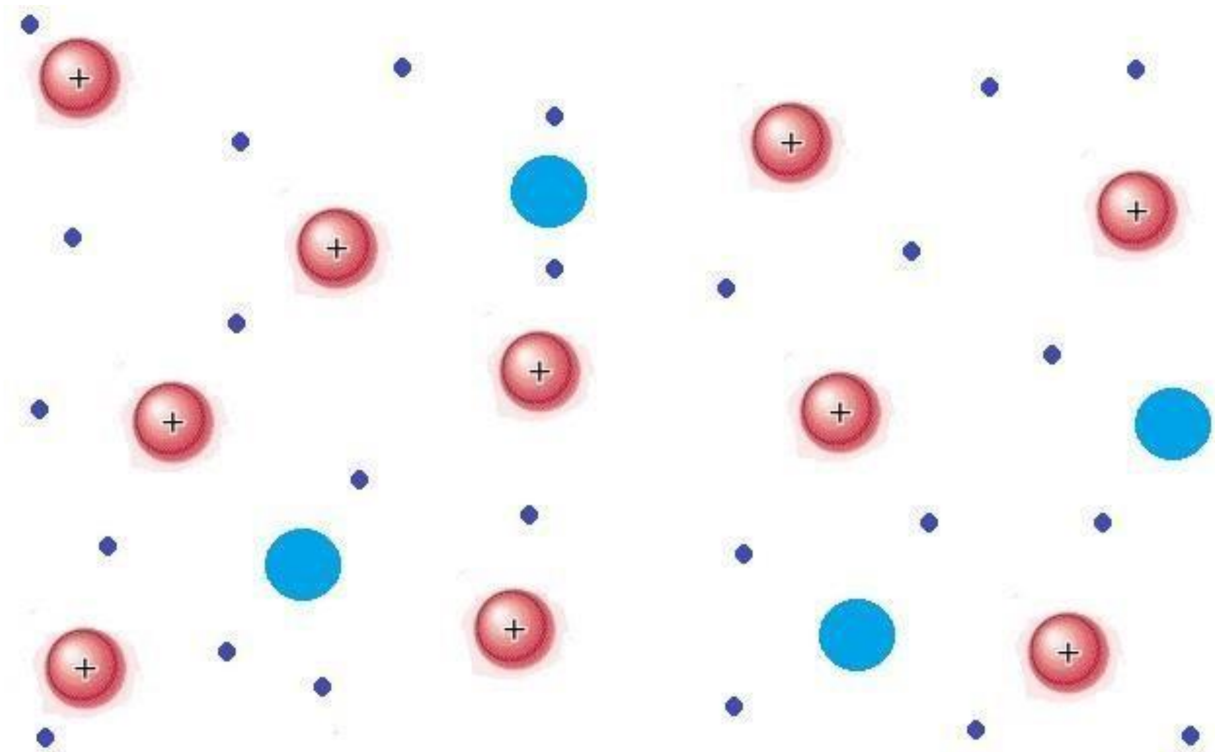


Figure 4. Illustration of a plasma. The dots are the free electrons. The red circles are the positively charged ions that contributed the electrons. The blue circles are the non-ionized neutral atoms that remain in low-temperature plasmas. They will be absent in fully ionized hot plasmas.

Although the name seems exotic and a bit mysterious, plasmas can be found everywhere, including in your kitchen, in your car, and in a lightning storm. The entire Sun is just one big ball of plasma! Once you know what to look for, you can find plasma in many unusual places in your everyday life. The one place you will NOT find them is inside your bloodstream. The plasma in your blood is a completely different thing. It just happens to have the same name.

Advanced Description of the Plasma State

Matter consists of atoms that affect each other through interatomic forces due to their weak charges. When the kinetic energy of the atoms is very low, the interatomic forces lock the atoms firmly into a crystalline structure to form a solid.

By adding additional kinetic energy to the atoms by heating them, the atoms are no longer firmly locked into a lattice via the interatomic forces but can move around - although they do not get very far from each other. They still feel their interatomic forces but do not have enough energy to overcome these forces entirely. This describes the liquid state of a substance.

By adding enough kinetic energy to the atoms, the atoms can finally move to very large distances from each other where the interatomic forces are extremely weak. The atoms can interact with each other through direct collisions, but they have too much energy to be captured back into a liquid or solid state. This describes the state of matter called a gas. The next change-in-state requires an understanding of the composition of atoms.

Atoms are composed of neutrons and protons held together in the nuclei of atoms, surrounded by a cloud of electrons. The number of protons in the nucleus determines the number of positive charges in the nucleus – one for each proton. The number of protons in the nucleus, called the atomic number, determines the type of element in the Periodic Table. In normal, neutral atoms, the number of protons is exactly balanced by the number of electrons so that the atoms are electrically neutral. They have no net charge.

This situation can change if the atoms in the gas are heated to very high temperatures. Under these conditions, the atoms collide so violently that some of the kinetic energy of the collision is imparted to the electrons in the atoms. This can cause one or more of the electrons to be ejected. What is left behind are atoms lacking one or more electrons, which gives them a net positive charge. The atom has been 'ionized', and we call these charged atoms 'ions'. Meanwhile, the ejected electrons have enough kinetic energy to remain free particles. The gas now consists of a mixture of neutral atoms, ions and electrons, which is a defining property of a plasma.

Simply having ions present in a gas is not enough to classify it as a plasma. For instance, ordinary liquid water contains H_2O molecules, but also hydrogen ions (free protons) and hydroxyl ions (OH^-). The pH of water is a logarithmic measure of the number of hydrogen ions it contains such that the higher the pH the more hydrogen ions are present and the higher the alkalinity of the water. But water does not contain free electrons. The excess electrons are bound to the OH molecule giving it a negative charge.

The presence of free electrons as well as ions is a defining characteristic of a plasma. There is no universal energy (temperature) at which a gas turns into a plasma. The critical energy depends on the elements in the gas and the density of the gas. Each element has its own cloud of electrons, and the energy required to remove one of the electrons varies from element to element. For example, for a gas of pure hydrogen, the temperature has to be well over 6,000^o C before more than 90% of the atoms are fully ionized.

Common Types of Plasmas

Typically, plasmas form whenever gases are heated to several thousand degrees or more. Sometimes this can happen in a very small region of space no bigger than a rice grain. At other times, an entire galaxy of stars can become embedded in a plasma. How they are formed depends on just how quickly a gas can be heated and how rapidly the electrons can be removed by recombining with the ions. Here are a few common examples of plasmas.

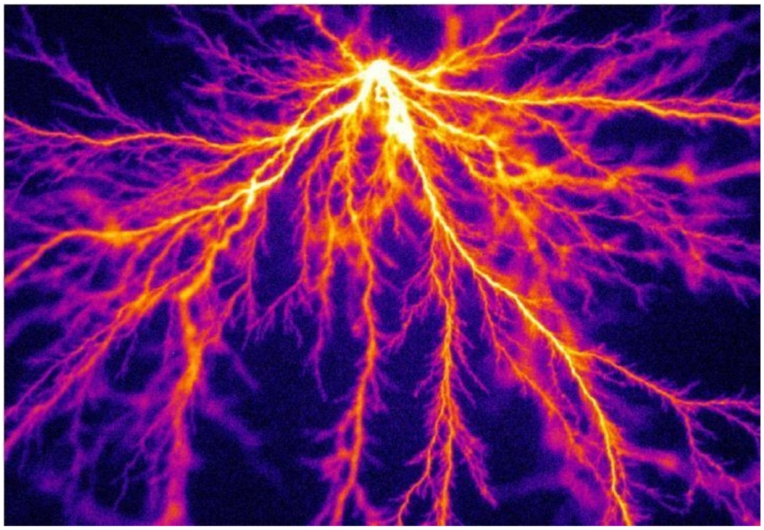


Figure 5. Example of discharge streamers forming on an anode (top) and discharging onto a metal, grounded plate (bottom). (Credit: Ebert et al,2011)

Sparks

Anything that makes a spark is making a plasma. A spark is created whenever a gap forms in an electrical circuit. This gap usually prevents an electrical current from flowing in the circuit because the air within the gap is such a good insulator. In an electrical circuit with an air gap, the two ends of the wire are connected to the battery or source of electricity. Because electrons flow from the negative to the positive side of a battery, one end will contain a surplus of electrons making it negative, but the other end will be attached to the positive side of the battery where there is a deficit of electrons. In an open circuit, electrons from the battery have flowed right up to the end of the wire at the gap and are accumulating there, creating an electric field across the gap.

This build-up of charge is harmless so long as the electric field is weak, but if you increase the voltage in the battery, the accumulated electric charges on the negative side of the gap (called the anode) becomes so large that they start to ionize the air atoms close to the wire’s surface. This ionization causes a plasma to form, which then begins extending towards the attractive, positively charged cathode. This process doesn't just form a cloud of plasma. The plasma forms into very thin streamers. As the electric field across the gap increases by, for instance, adding more batteries to the circuit, the ends of these streamers get closer and closer to the cathode until one of them, called the leader, finally makes contact. The result is an avalanche of the electrons in the plasma to rush into the cathode and complete the electrical circuit. Each kind of gas has its own critical voltage when a spark will form across a gap of a given width. Physicists and engineers call this the breakdown voltage, and it is measured in units of volts.

Actually, it is the strength of the electric field in volts per meter that determines when a spark will occur. For ordinary air at sea level, the critical electric field strength is about 75,000 volts per inch (3 million volts/meter or 3,000 kilovolts per meter).

One common place that relies on producing electric sparks is in your automobile engine. It uses 'spark plugs' to detonate the gasoline vapor to run the engine. The gap in a typical sparkplug is about 0.035-inches so the minimum voltage your car needs to provide is 75,000 V/inch x 0.035 inches = 2700 volts, which is the breakdown voltage for that gap. This voltage comes from the coil of wire in the car's ignition coil (called a step-up transformer) that increases the 12 V battery voltage by about 220 times.

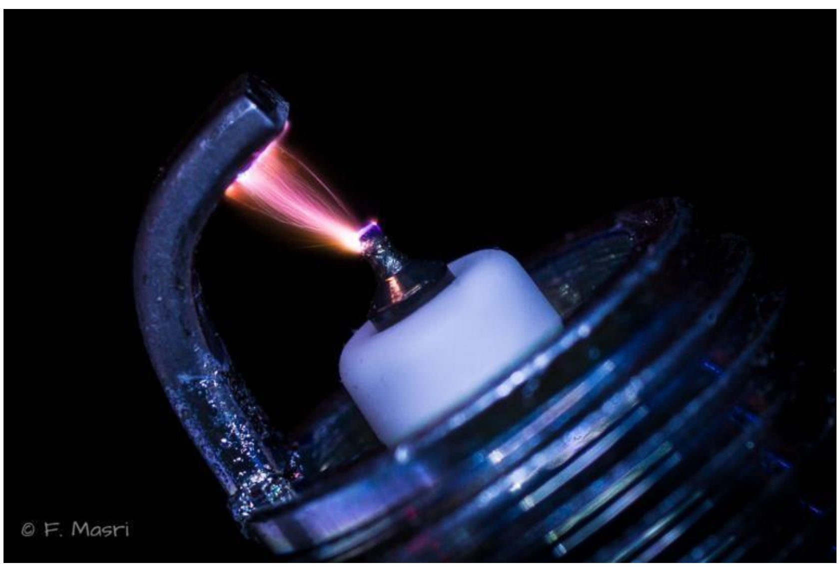


Figure 6. A spark produced by an automobile sparkplug. (Credit: Chris, MyGarage.com)

Other than for operating cars, sparks are a nuisance, but they have one property that can make them useful. Each time a spark discharges, it produces a burst of radio waves that travel outwards at the speed of light. By starting and stopping a series of sparks, you can send a message. Called Spark Gap Transmitters, these were the cutting-edge technology of the 1900's and used in ship-to-shore communication. The famous HMS Titanic used just such a transmitter to carry Morse code messages, including on the night it fatefully struck an iceberg

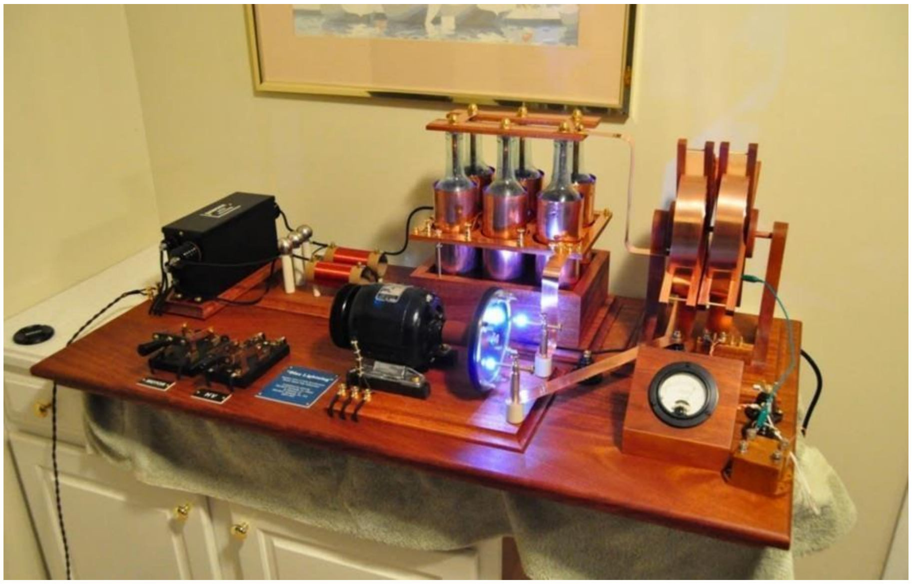


Figure 7. A spark gap transmitter. The blue glow is the plasma arc produced by the powerful battery circuit. These transmitters have been illegal to operate since 1934 because they interfere with other frequencies used by modern radio receivers. (Credit: Ian Poole; DxZone.com)

Lightning

Sparks are a great source of plasma if you only want a few cubic millimeters worth, but for the really big quantities involving thousands of cubic meters, nothing beats a good old-fashioned lightning strike. Scientists think that the initial process for creating charge regions in thunderstorms involves small hail particles called graupel that are roughly one quarter millimeter to a few millimeters in diameter and are growing by collecting even smaller supercooled liquid droplets. These get segregated through a process of updrafts and downdrafts so that the bottom surface of the cloud becomes highly negative.

The accumulation of negative charge at the base of the cloud causes negative charges in the ground to be repelled and so the ground builds up a large positive charge consisting of ions. This separation of positive and negative charges across the gap between the cloud and ground produces a large voltage difference of hundreds of thousands of volts. The negative charges start to flow down to the ground along a number of invisible paths called leaders. At the same time, the positive ions flow up from the ground in their own invisible leaders.

Eventually, one pair of the positive and negative leaders becomes so close together that the voltage between them exceeds the air's breakdown voltage and a lightning 'spark' discharge occurs to equalize the charge excess between the cloud and ground. This happens in a channel about 20 meters in diameter and up to 10 km long where the atmosphere will be heated to over 25,000°Celsius. An individual lightning bolt can carry 10,000 amperes of electrical current at over 100 million volts. In its brief 0.1 seconds of existence, it can generate as much as one trillion watts. In terms of its equivalent explosive power, 25 tons of exploded TNT produces the same amount of power over the same amount of time. In a lightning bolt, much of this energy appears as a pressure wave that travels super-sonically away from the plasma channel, which is why you hear the typical boom of a thunderclap. The same process causes the crackle or pop sound of electricity in an ordinary spark.

Figure 8. Example of lightning strokes during a storm. (Credit: Wikipedia/Nelumadau)

Stars

The coolest stars called brown dwarfs have surface temperatures of only a few thousand degrees, but some of the hottest stars tip the temperature scale at over 50,000°C. This range by itself is more than enough to keep the surface gases in stars in the plasma state. The interiors of stars are even hotter and can reach over 500 million °C. So, every star you can see in the sky is literally a massive ball of plasma. In fact, if you were to take an inventory of all the visible matter in our Milky Way galaxy, 99.9% of the mass would be in the form of plasma and not ordinary 'neutral' matter.

An important feature of plasma is that it is electrically charged. When a plasma is in motion, it acts like an electric current and generates its own magnetic field. The balance between the forces produced by these magnetic fields and the gravity of a star lead to many different kinds of phenomena such as solar flares, prominences, and the ejection of clouds of plasma called coronal mass ejections. The interaction between plasma, magnetic fields and gravity accounts for essentially all of the interesting details we see on the surface of our Sun. Without these dynamic phenomena, there would be no Sunspots, or even a magnificent corona to see during a total solar eclipse.

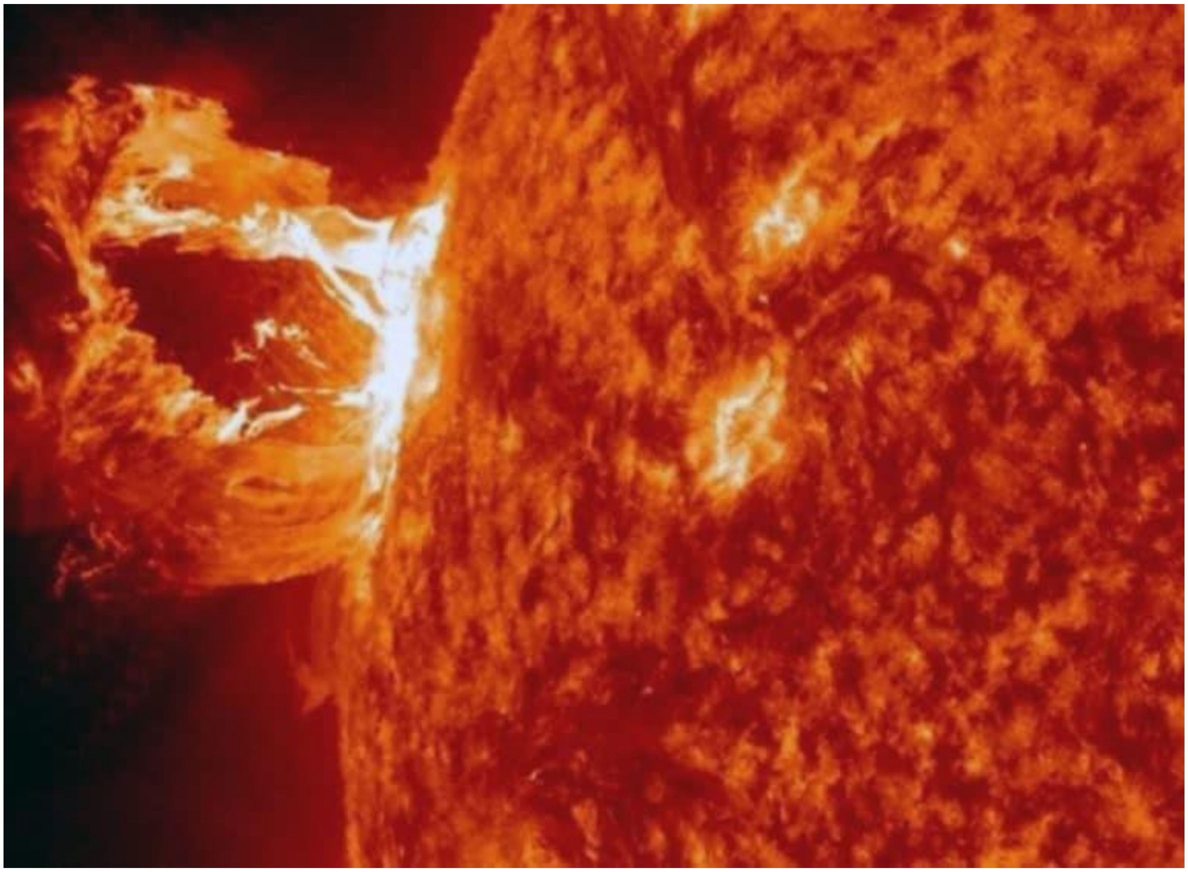


Figure 9. A coronal mass ejection produced by magnetic fields on the Sun reconnecting to form a cloud of plasma over 100,000 kilometers in diameter and traveling at 1,000 km/sec. (Credit: NASA/SDO).

The Universe

More than 99% of all the visible matter in our universe is in the form of a plasma of one kind or another. Within galaxies, this plasma resides in the individual stars, but a very dilute plasma also exists between the stars. Astronomers call this the interstellar medium (ISM). There are three different kinds. There is an exceptionally hot ISM with temperatures of over 1 million degrees Celsius that is heated by supernova. This medium emits x-rays that can be detected from earth and is spread across the sky. It is very dilute and consists of fewer than 100 ions per cubic meter of space. The second medium called the Warm Intercloud Medium is at a temperature of about 10,000^{o}Celsius. It is also mostly ionized, but because its density is one hundred times higher than the Hot Interstellar Medium, it is able to cool down to lower temperatures. It is kept hot by collisions between the winds of gas blown out by stars, and by the energy of the ultraviolet light from billions of stars.

Figure 10. Star cluster and nebula of Westerlund-2 taken by the HST. (Credit: NASA/HST)

When massive stars form and evolve, they produce huge amounts of ultraviolet radiation. This radiation carries more than enough energy to ionize hydrogen atoms into a plasma state. Regions around these massive stars are filled with this ionized plasma to form what astronomers call HII (pronounced H Two) regions (HI is the symbol for neutral hydrogen while HII means that its single electron has been stripped away). We can detect these HII regions around massive stars because they produce beautiful, multi-colored nebulae that glow in shades of red (hydrogen), blue (nitrogen) or green (oxygen).

All Together

When taken together, plasmas form a complicated system of matter that spans a huge range of temperatures and densities. This diagram shows many familiar objects and phenomena and the kinds of plasmas they produce. Neon signs, fluorescent lights and ordinary candle flames cover the mid-range of density and temperature near 1,000° C and 1000 trillion ions per cubic meter. The lower left corner is populated by very dilute and cool plasmas including the beautiful aurora borealis. The upper right, on the other hand, is reserved for exotic plasmas such as the cores of stars where matter is being converted into energy by nuclear fusion.

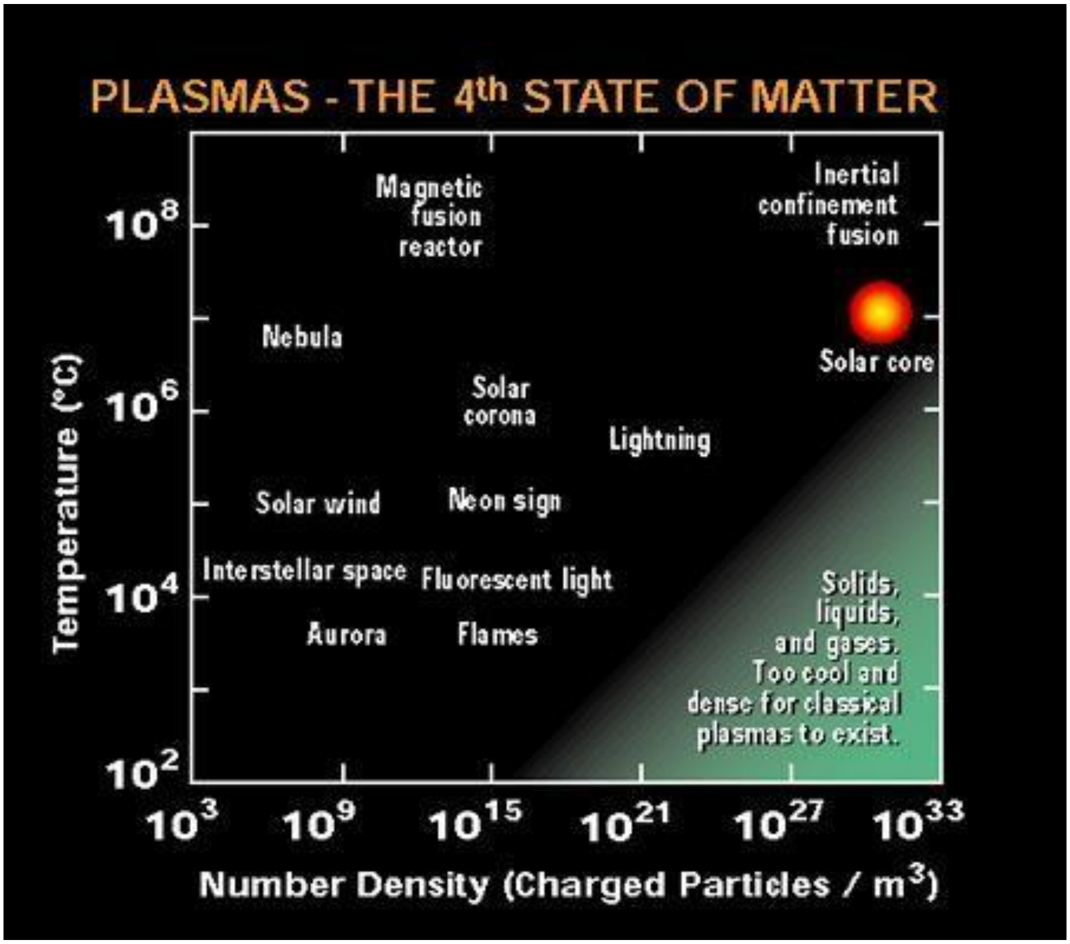


Figure 11. The plasma state of matter encompasses a wide variety of densities and temperatures. [Courtesy of the Contemporary Physics Education Project]

Words to Use with Students about Plasma

<u>Current</u> – A flow of charged particles such as electrons and is measured in units called amperes.

<u>Discharge</u> – The sudden release of electric charges into a current that forms a spark.

<u>Ion</u> – An atom in which one or more of its electrons has been removed so that the atom has a positive charge.

Ionization- The process of giving electrons in an atom enough energy to escape their atoms.

III. Basic Plasma Safety

- **Is plasma dangerous?**
- **How can I safely experiment with plasma?**

Under the conditions that students will be observing and working with plasmas, they will not be harmful. They will be inside sealed lamps, or in the form of sparks, and they will not last long enough or have sufficient volume to be a hazard.

Each experiment will provide specific commentary on any safety issue involved in the process of creating and observing plasmas. Typically, any safety issue will not involve the plasma itself but the process of creating the plasma for observation.

Creating plasmas will involve using batteries and other electronic devices for which ordinary safety practices will suffice. Some devices described in these experiments may involve voltages in excess of 10,000 volts such as commercially available plasma globes, which are completely sealed and not a hazard. In some instances, learners will work with electric candle lighters whose plasmas are 2 to 3 mm long with temperatures above 2,000 °C. These should **NOT** be touched to avoid a severe burning hazard. Specific warnings will be provided for each experiment at this level as appropriate.

IV. Electric Shocks

Electric discharges or ‘sparks’ are an easy way to produce small amounts of plasma. Shocks are a common part of our everyday experience, but most are rarely felt. Sometimes, however, the act of shuffling across a carpet and touching a doorknob is enough to produce a momentarily painful shock. Because some of the Advanced experiments involve the intentional and controlled creation of sparks to investigate their plasma states, it is worth describing the human health issues related to sparks and shocks.

In this chapter, many misconceptions about shocks will be addressed. The overriding principle will be that many things in our environment are potentially deadly, but common sense behavior insulates us from much of this potential danger. For example, no one intentionally ingests razor blades, or decides to jump out a window in a high-rise apartment. This is why packs of razor blades do not carry notices for them being an ingestion hazard. Apartment windows do not carry stickers on every window that suggest jumping out a window could be a hazard. With electricity and sparks, however, the situation is a bit more complicated.

❖ Ohms Law relates voltage, current and resistance.

The basic operating principle is that it isn't the voltage that will injure or kill you but the current. There are three components to electricity: voltage, current, and resistance. To understand this, we can imagine a waterfall. Voltage corresponds to the energy gained by the water as it falls. The taller the waterfall, the more energy the water delivers to the ground as it impacts. The amount of water going over the top of the fall measured in gallons per second is equivalent to electrical current in this analogy. Clearly, a slight trickle of water over the fall will not hurt someone standing at the bottom, but a lot of water could crush someone at the base. Finally, if there are rocks, ledges or other protrusions sticking out into the water from the wall, this will slow down the water reducing its current, but the same number of gallons of water will still make it to the bottom over a longer time. In electricity, you can increase the flow of current by increasing the voltage. You can also decrease the current by increasing the resistance in the wire, just as adding more obstructions to the wall of a waterfall will reduce its flow rate to the bottom. A mathematical formula that relates voltage, current and resistance is called Ohms Law and is stated as

$$I = \frac{E}{R}$$

where E is the voltage in the circuit measured in volts, R is the resistance in the wire measured in ohms, and I is the resulting current measured in amperes. With algebra there are other relations as well such as E = I*R and R = E/I.

Case 1: A current of 0.10 amperes (10 milliamps or 10 mA) causes involuntary muscle contraction that will prevent you from releasing your grip on a wire and eventually lead to electrocution. This current can come about if you have a voltage of 100 volts and a resistance of 10000 ohms since I = E/R = 100/10000 = 0.01 amps (10 mA).

Case 2: But it can also come about if you have E = 100,000 volts and R = 10,000,000 ohms.

A normal dry human body has a resistance of 100,000 ohms so would not be electrocuted in the first case. But during a lightning storm, if struck by lightning in the second case, would almost surely be electrocuted except under very special conditions.

❖ What is electricity?

By its own name, electricity (*elektron* in Greek) is the current of electrons flowing through a conductor. When $1.6x10^{18}$ of these electrons pass a given point in one second, this is called one ampere. With a battery, one pole is positive, and one pole is negative. This means that the negative side of the battery has a surplus of electrons, which have a negative electric charge. The positive pole has a deficit of electrons, giving it a positive polarity. When a conductor is connected between the positive and negative poles, electrons will move out of the negative pole, through the conductor, and into the positive pole of the battery. What is confusing is the terminology used by physicists versus the terminology used by engineers. Physicists follow the electrons described above and this is called the Electron Flow convention. Engineers over time have adopted the Electron Current convention, which says that electrical current flows from the positive to the negative side of a battery opposite to the direction of electron flow. So long as you consistently use one or the other, there is no difference in designing circuits.

❖ Electrons do not flow through a conductor like water through a hose.

Electrons are always present as free particles inside a conductor, but they travel the way water moves in a fireman's bucket brigade. As one electron enters the conductor from one end of the wire, it displaces one electron in an atom, which then jumps to the next atom and displaces the electron there, and so on until at the other end of the wire a single electron emerges. Although the movement of the electrons from atom to atom, called the drift speed, is only about 1 mm/sec, the electric wave this produces travels at nearly the speed of light, which is why you never notice a delay between turning on a switch and the light going on.

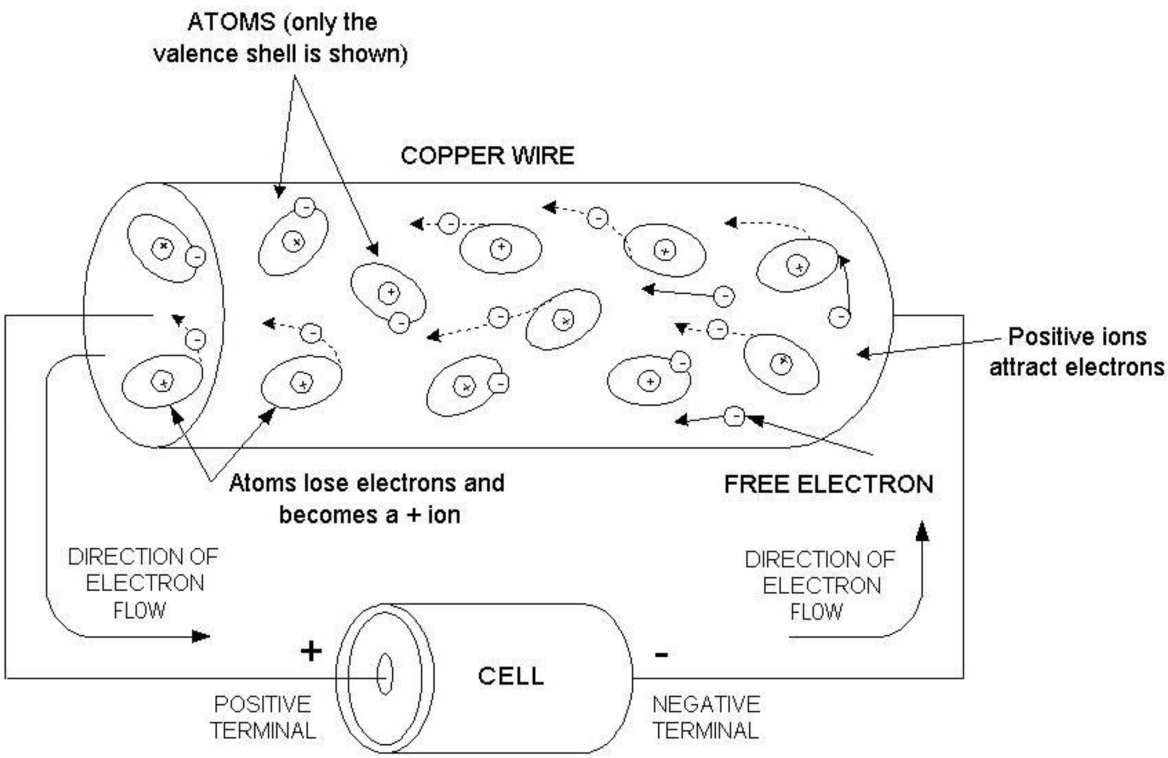


Figure 12. How electrons flow in a circuit. (Credit: Louis Frenzel; NutsVolts.com)

Health and safety effects

All physical phenomena such as radiation, light brightness, and temperature have limits on them that depend on how humans will react to the various levels that are possible, both under laboratory conditions and environmental conditions. Of relevance to our discussion about sparks and shocks is, what are the limits to voltage and current that humans can be exposed to before significant health situations arise? To understand how these limits come about, we have to understand how electricity affects the human body.

Since the advent of industrial-scale electricity in the late 1800's, we have had lots of experience with people getting shocked and electrocuted from which to draw conclusions. Here is some of what we have learned.

❖ Not all electricity is bad

Human bodies and most living organisms rely on biologically generated electricity to perform many vital living functions. One of the most familiar of these is the transmission of information along the neurons in our nervous system. A single neuron acts like a battery that discharges to produce an impulse. Typical electrical properties[1] for a single neuron are 70 millivolts, 1 nanoTesla, 100millisec, and a few nanoamperes.

❖ It does not take much current to kill you

We are largely protected from external electrical currents by the fact that the resistance of our bodies is quite large. In practical terms, if you touched a common 120 V AC outlet and were perfectly dry, the current through your body would be about I = 120/10000 = 0.012 Amps (12 milliamps). This is enough for you to feel the shock but is below the 20-mA threshold where your muscles would freeze and prevent you from letting go. However, if you were wet and standing in a puddle of water, your body resistance would be as low as 300 ohms. The current would be (120/300 = 0.4 Amps or) 400 milliamps. This is more than enough to freeze your muscles, make your heart muscle fibrillate, and quickly cause electrocution.Every year there are over 30,000 electricity-related injuries[2] and 300 to 1,000 deaths[3]. Studies show that virtually all electrocutions are accidental, occur mostly during the rainy season, and involve people between the ages of 20 and 30[4].

Table 1. Common sources of sparks and their hazard level

Current (mA)	**Energy (mJ)**	**Conditions**	**Example**
1	1	Threshold of shock perception	Carpet and balloon shocks; van de Graaf generator
8 to 15	10	Painful shock but muscle control is retained	Police Taser or cattle prod
15 to 20	50	Painful and can't let go	Stun gun - prolonged strike
20 to 50	100	Severe shock. Breathing difficult	Low-power car spark plug
50 to 100	300	Extreme shock. Some fatalities	High-end car spark plug
100-200	500	Severe ventricular fibrillation; possible death.	Home 120V- wet, standing in water; Stun gun prolonged strike
>200	1000	Severe burns. Heart stops. Death	Lightning strike, wet ground, barefoot.

1 https://www.pnas.org/doi/10.1073/pnas.0603219103

2 https://www.ncbi.nlm.nih.gov/books/NBK448087/

3 https://www.electrocuted.com/safety/statistics/

4 https://ejfs.springeropen.com/articles/10.1186/s41935-018-0103-5

Common forms of electricity and how to interact with them safely

The range of currents and voltages we can be exposed to in the modern age is enormous, and results in differing safety issues in each instance. Table 1 shows a variety of situations and technologies that are available as potential shock and/or electrocution sources. The sources of information in this Table can be found in this book's Reference section.

The important thing to recognize is that not all combinations of voltage and current are harmful. For instance, the 25,000 volts you gain as you shuffle across your carpet only produces a 1 mA spark, which is harmless although annoying. Even a 200,000-volt shock from a van de Graaf generator is harmless. Although it can carry up to 4 mA, the shock duration is so brief that it delivers very few joules of energy under normal circumstances. All of the spark-generating experiments in the Advanced section rely on high-voltage but low current discharges that are strong enough to be felt (1 mA) but are not strong enough to cause involuntary muscle contractions (10 mA). All sparks will have a duration measured in microseconds so that too little electric charge will be transferred to cause physiological injury.

As with all electrical experiments, the learner must maintain a high resistance- to-current flow by not working in wet clothes or being in contact with water. Do not provide a current pathway through your heart by touching a spark or electrical device with your left hand while holding a grounded item with your right hand. Use rubber-soled shoes where possible to increase your body resistance above 1 million ohms. Figure 13 shows several common pathways for current traveling through the body and passing through the heart. Case C is where you are washing dishes and switch on the garbage disposal while holding the faucet. If you use a Ground-Fault-Interrupt (GFI) switch, this hazard is in most cases eliminated. With rubber-soled shoes under dry conditions, Cases A, B and E can also be essentially eliminated as risks.

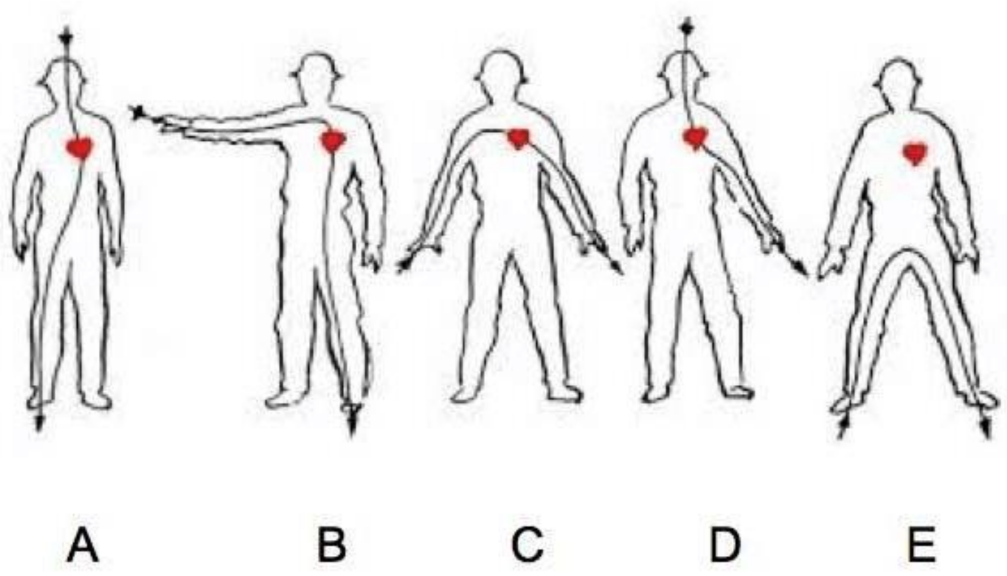


Figure 13. Common electrical pathways through the body. A and B are for the case where one or the other foot is grounded (in water). C and D are for one of the hands grounded. E is for the case of a nearby lightning strike where current travels through the ground. (Credit: Manuel Bolotinha; electricaltechnology.org)

V. Sparks

In Chapter II we looked at several things that produce sparks. In this chapter we will look at this process in more detail because it will help us understand just how sparks are created and why plasma is usually involved.

In simple terms, a spark is a flow of electrons from one place to another, not through a conducting wire but through free air. Most of the time, air is a very good insulator. It provides enormous resistance to the flow of charged particles in an electrical current. But let’s take a look at Ohms Law I = E/R, where I is the current, E is the voltage and R is the resistance. If you make the voltage high enough, any resistance can be overcome, and a current will flow. For instance, imagine an insulator with a resistance of R = 1 million ohms. If you had a voltage of 10 million volts, you could still get 10 amperes of current to flow through it.

A spark can form anywhere you have an electrical circuit connected to a voltage source, but where there is an air gap in the circuit like Figure 14. This diagram shows the voltage source as a battery.

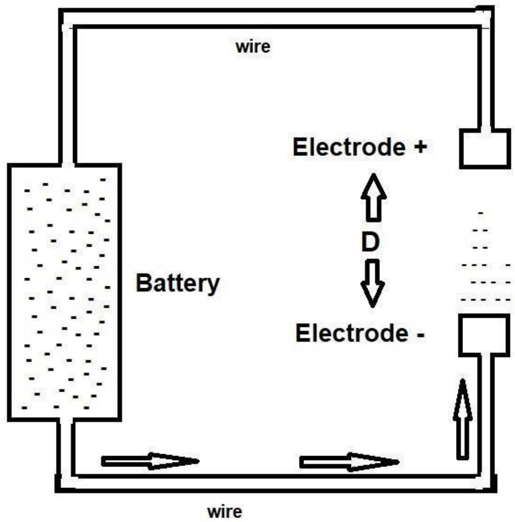


Figure 14. Cartoon sketch of an open circuit with an air gap of size D in width.

If the battery has a voltage of 10,000 V, that means that the electrodes at the ends of the wires also have a voltage difference of 10,000 V across them. Current flows because the electrons in the wire migrate to the positive side of the battery, and as they do, electrons from the negative side of the battery enter the wire and replace the ones that have moved out. But with an air gap, there is no current moving through the wire at all. Instead, because of the large voltage difference between the electrodes, the electrons near the negative electrode move out of their atoms and start to form a cloud just outside the electrode's surface.

These electrons are moving fast because they feel the voltage difference and like water over a waterfall, they want to flow out of the wire. They cannot get very far at first but as they slam into the atoms of air in contact with the electrode, they ionize these atoms, which releases more electrons into the cloud. This cloud contains a mixture of electrons, neutral atoms and ions and is a plasma. The electrons also stimulate other atoms not to lose their electrons but to give off light. This produces a greenish glow (oxygen) or a bluish glow (nitrogen) depending on the energy of the interaction. We can see these plasma glows is in a phenomenon called corona discharge, which is also called Saint Elmo's Fire.

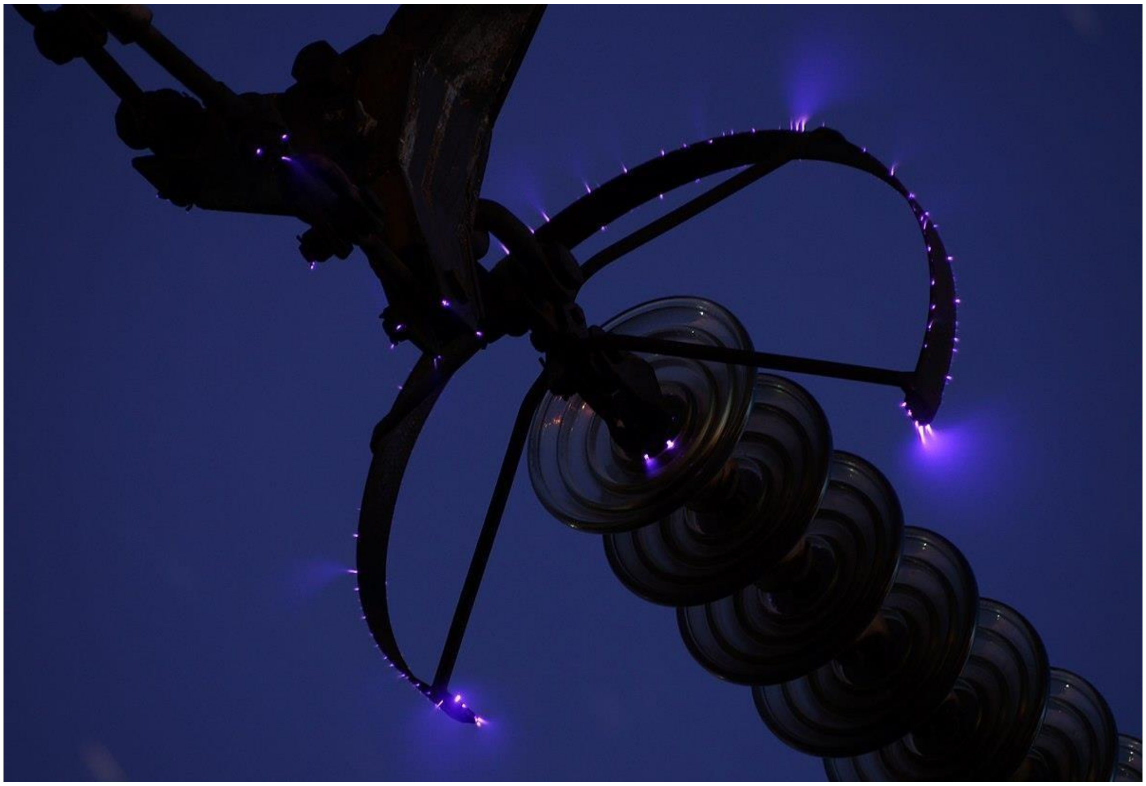


Figure 15. Corona discharge. (Credit: Wikipedia)

Under a large voltage difference between ground and an overhead thunder cloud, conducting objects give off this glow. Also, you can see these glows near high-voltage transmission lines among the insulators and connectors of the tower suspending the cables as shown in Figure 15. The plasma glows are the first stage in creating a spark, but if the voltage is too low you may not see them at all.

Once the ionization starts to happen near the negative electrode, called the cathode, it will start to grow farther and farther from the surface along many different ‘fingers’. Eventually, under the action of the electric field between the electrodes, one of these fingers will touch the distant positive electrode, called the anode, and this starts a massive rush of electrons through the anode and the attached wire, back to the battery to complete the circuit. The higher the voltage, the stronger will be the current flow and the ‘spark’ that results. The plasma current heats the gas it passes through it and lowers its density. The low-density region collapses under the pressure of the atmosphere to cause a pressure wave that produces the crackle you hear when the spark occurs. This is a random process so instead of hearing a definite sound at a specific frequency, you hear a random mixture of frequencies because the cavities are very different sizes.

Why do these sparks happen sometimes and not all the time? Because ordinary air is a very good insulator. It takes a lot of voltage to overcome the resistance of air as an insulator. The amount of voltage you need depends mostly on the width of the gap shown as ‘D’ in Figure 13. If you want a spark to jump across a one-centimeter gap, you need a voltage difference of 30,000 volts. But if you want a spark to cross a gap of 1 millimeter, you only need 1/10 the voltage or 3,000 volts. This value of 30,000 V per cm is called the breakdown voltage for air and is usually written as 30 kV/cm. From this number, you can calculate the voltage you need for any gap width since V = (30 kV/cm) x D where D is in centimeters. For instance, a candle lighter that uses a spark, has a gap width of about 0.1 to 1 mm so it needs to create a voltage from its battery between 300 to 3000 volts. This can be done using devices called capacitors and transformers.

VI. Advanced Experiments

These experiments require that the Learner work with electrical sparks to generate small quantities of plasma for study. A detailed explanation is given about why sparks occur and how they produce plasma. The practical consequences of producing sparks are also described in terms of the design of high-voltage power lines, car engines, and radio communication.

Learners will actively engage with the creation of plasma under a variety of controlled experimental conditions.

- ❖ **Review Chapter III about the nature of sparks as a health and safety risk.** The sparks generated in these experiments are all non-hazardous, although they may be surprising and painful in the same way that strong carpet static discharges can be. Do **NOT** attempt to prolong contact with these sparks because they produce plasmas with temperatures above 2000 °Celsius and can create pinpoint burns that feel like a heated sewing needle placed against the skin**.**

❑ Experiment HS1 - Creating plasma with sparks

Overview: Sparks are a discharge of electricity that heats the local air to thousands of degrees. This allows some plasma to form in the discharge channel of the spark.

Objective: Learners will observe the process of arc discharge using an electric candle lighter and explain how it happened and why it is plasma.

Assessment: Learners will calculate the breakdown voltage of a spark across a gap of a given width. Large gaps require larger voltages than smaller gaps.

Background:

As described in Chapter V, the breakdown electric field for air at sea level is 30 kV/centimeter (3 kV /mm). A spark will form if the electric field across a gap (measured in volts per meter) exceeds this limit. For example, if a circuit has a voltage of about 3,000 volts, a spark will form if there is a gap in the wire only 1 millimeter long. For humid air (summer) the threshold can be as low as 1,000 volts/mm while in dry air it can be as high as 5,000 or even 10,000 volts/mm. This math has other applications as well. High-voltage transmission lines are connected to the tower framework through ceramic insulators. These insulators have to be longer than the spark gap length, otherwise the transmission cables will catastrophically short to ground through the metallic tower framework.

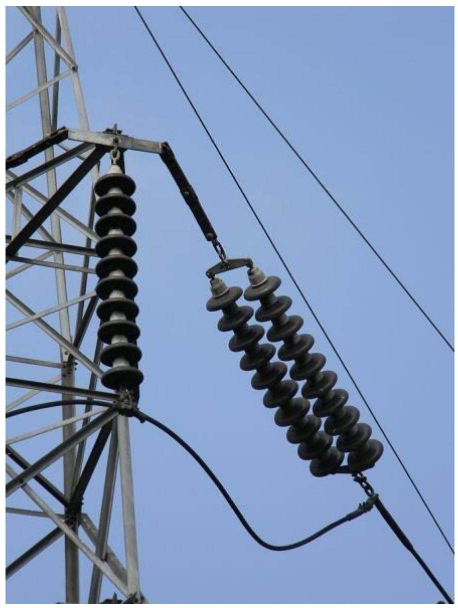


Figure 16. The length of insulators on high-voltage power lines like the ones on this 132-kV line is determined by atmospheric breakdown voltages. (Credit: Wikipedia/Biswarup Ganguly)

This experiment will allow students to experiment with electrical arcs under controlled conditions and generate plasmas within the arcs.

Materials:

- ➢ Electric candle lighter.
- ➢ Millimeter ruler.
- ➢ Candle.
- ➢ Diffraction grating (1000 lines/mm).
- ➢ Optional: Spectroscope/spectrograph from Experiment M3/M4.

Procedure:

Step 1) Follow the directions for the electric candle lighter and charge its battery.

Step 2) Turn on the lighter to display the plasma arc and make sure you are familiar with its operation. Do **NOT** touch the arc. Its temperature is over 1,000 °C (1,800 °F).

Gathering Data:

Step 3) In a darkened room, light the candle. Hold the diffraction grating over one of your eyes facing the candle and look through it. You will see the candle to the left side and a spectrum to the right side. Note that the candle produces a rainbow of colors but that some colors such as yellow are brighter than the others. In fact, the yellow color shows an image of the candle itself!

Step 4) Switch on the arc and place it in a vertical orientation.

Step 5) Look at the arc through the diffraction grating and rotate the grating so that the spectrum is horizontal. Note that the arc produces an image of itself as a bright yellow color.

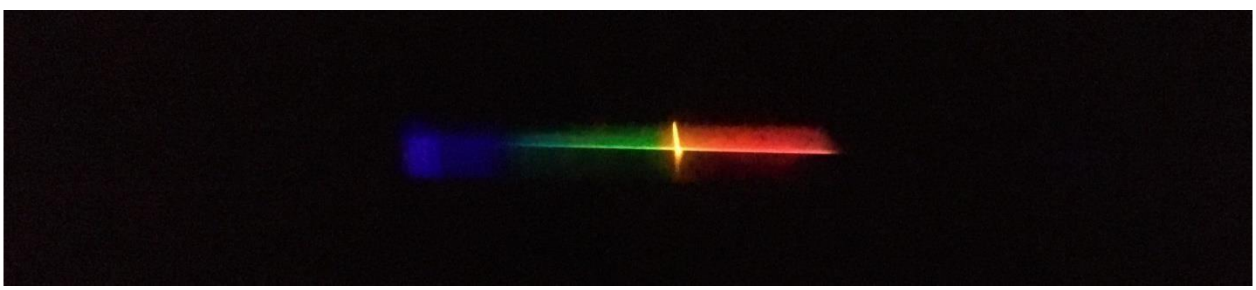


Figure 17. Arc spectrum showing the very bright yellow line produced by the electric arc plasma.

Step 6) Measure the gap between the electrodes in the lighter. If the breakdown field strength is 3,000 kilovolts/meter, how many volts are needed in the lighter circuit to form the spark? Answer: If the gap is 4mm wide or 0.004 meters, the voltage is 3,000 kV/m x 0.004m = 12,000 volts.

Explanation:

As a candle burns, wax the chemical process produces hot gases at over 1,200 °C as Figure 17 shows. The chemical reaction, called combustion, consumes oxygen from the atmosphere and produces heat and byproducts like carbon dioxide and other carbon-rich molecules. The process also produces light from the excited molecules and atoms. As you get farther from the wick, the carbon-rich compounds in the form of very hot soot particles are heated so that they emit the carbon spectrum shown in

Figure 18 with the brightest emission coming from the 'yellow' part of the spectrum. Here the particles are 'yellow-hot'. The hottest part of the candle is at its tip or 'veil' where temperatures are near 1,400 °C (2,550 °F). This is at the threshold where you can have a mixture of electrons, ions and neutral atoms, but it is a very dilute plasma. So, the part of the candle that you see is mostly NOT a plasma but is instead made of hot soot particles.

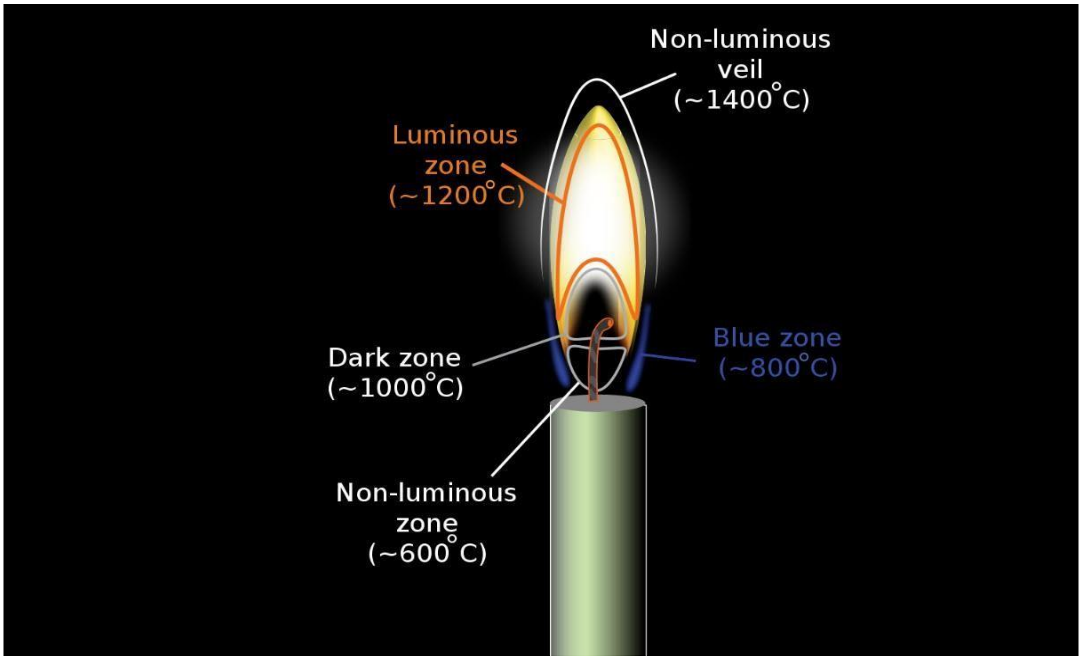


Figure 18. The parts of a candle flame and their temperatures.

Figure 19. The spectrum of an ordinary candle.

But the plasma arc also had a rainbow of colors with a bright yellow line, as shown in Figure 17. If the plasma arc from the lighter is not burning soot, why does its spectrum look so similar to a candle's? The electrodes in an electric lighter are carbon-tipped electrodes to withstand the high temperature, so when the arc is discharged, the arc has a mixture of carbon atoms and compounds of carbon and atmospheric oxygen and nitrogen mixed-in, so it produces a similar yellow glow as a candle flame!

Figure 20. Electric arc lighter with plasma. The plasma is contained in the blue arc between the electrodes.

This experiment can also be performed during a lightning storm during each flash viewed through the diffraction grating. The best results will occur for a single, vertical stroke to avoid confusion with the overlapping spectra from multiple strokes at different orientations. The temperature of the plasma is over 20,000°C so it will emit light across the entire 'rainbow' spectrum.

Assessment:

Learners will see and explain the difference between a candle flame spectrum and a plasma arc spectrum.

Question: Learners will calculate the breakdown voltage of a spark across a gap of a given width. Large gaps require larger voltages than smaller gaps. They will observe the process of arc discharge using an electric candle lighter and explain how it happened and why it is plasma.

Answer: Sparks are a discharge of electricity that heats the local air to thousands of degrees. This allows some plasma to form in the discharge channel of the spark.

Question: What is the difference between a candle flame spectrum and a plasma arc spectrum?

Answer: Both spectra show a rainbow of colors from heated gases, but the arc shows a bright yellow line due to excited carbon atoms in the plasma.

❑ Experiment HS2 - Plasmas conduct electricity

Overview: Plasma is not just a hot gas but one in which a mixture of electrons and ions exist. These can be used to conduct electricity.

Objective: Learners will be able to create a simple device that can demonstrate the electrical conductivity of plasma and describe what they see.

Assessment: Learners will discover and describe how a plasma completes an open electrical circuit by filling in the gap with electrons that can complete the current flow in the wire across the air gap.

Background:

Unlike an ordinary gas, a plasma contains charge carriers, with electrons being negative and ions being positive. This means that a plasma can act like a conductor and transmit a flow of electricity. This is one of the defining features of a plasma. This experiment will create a gap in a copper wire and use an electric plasma candle lighter to replace the gap with a plasma. An ohm meter will be used to show that a current can flow across the gap using the plasma as a conductor. Alternatively, a lamp is inserted in the circuit and will turn on when the plasma completes the circuit.

Materials:

- Electric arc/plasma candle lighter.
- One piece of 22-gauge bell wire (about 2 feet long)
- On-off switch.
- 1x 100-ohm ½-watt resistor.
- Volt-Ohm meter.
- 6-volt ‘lantern’ battery.
- 2x 8x32 3-inch machine screws.
- 8x 8-by-32 nuts.
- 8x 1/8 by ¾-inch metal washers.
- Hand drill with 1/8-inch bit.
- Small wrench to match 8/32 nuts.
- Wire cutter.
- Candle.
- Sharp box cutter knife or equivalent.
- 6” x `2” x 3/8” craft plywood or equivalent wood for a stable base.

Procedure:

Step 1) Drill two 1/8-inch holes about 1-inch back from the edge of the board and about 2-inches apart to accommodate the 8/32 bolts.

Step 2) On each bolt, thread two washers up to the head of the bolt and secure with one of the nuts.

Step 3) On each bolt, thread one nut about ¾-inch from the end of the bolt and thread one washer.

Step 4) Place each bolt through the corresponding drilled holes and secure the end of the bolt on the underside of the board with a washer and nut. Tighten the nut to secure the two bolts firmly to the board.

Step 5) At the midpoint of the wire, pass the wire between the pair of washers at the top of each bolt and use the wrench to secure the washers so that the wire is immobile. There should now be an equal amount of free wire on each side of the bolts.

Step 6) With the wire cutter, snip the wire between the two bolts to form two separate wires.

Step 7) With the knife, carefully strip about ¼-inch of insulation from each end of the wires between the two bolts.

Step 8) Push the bare wire ends together.

Step 9) Remove about 1-inch of insulation from the ends of each wire.

Step 10) Attach one wire to the positive side of the lantern battery.

Step 11) Attach the 100-ohm resistor to the other wire by simply twisting the two ends together. No solder required.

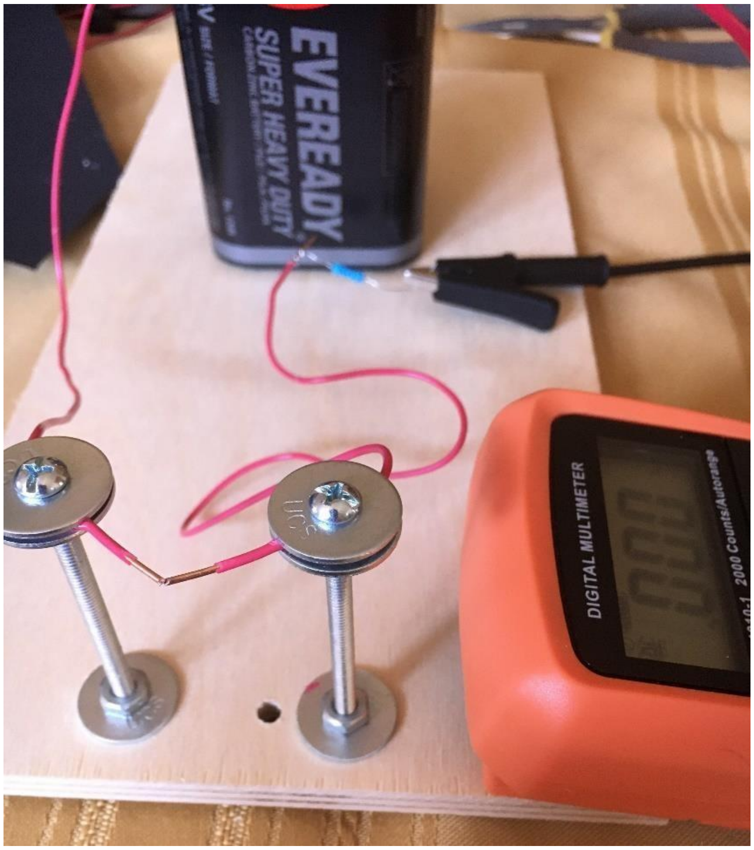


Figure 21. This shows the basic setup. The two-screw 'pylons' support the copper wire gap firmly. The battery, resistor and ammeter are connected in series, and the display shows 0.0 amperes flowing because the gap between the wires in the pylons is open.

Gathering Data:

Step 11) Turn on the volt/ohm/amp meter.

Step 12) Select the 'Ampere' scale for DC current measurements.

Step 13) Clip one of the meter leads to the negative battery terminal.

Step 14) Clip the second lead from the meter to the free end of the resistor.

Step 15) Verify that current is flowing through this circuit by noting that the amperage is not zero but with a 6-volt battery and a 100-ohm resistor should show about 6 Volts/100 Ohms = 0.063 amperes. You may need to adjust the bare ends of the wires between the two bolts to verify continuity.

Step 16) Carefully separate the two wires so that the circuit is interrupted. Make sure that ends are as close together as you can make them without completing the circuit. Ideally, they should be about the thickness of a piece of paper apart to form a gap.

Step 17) Turn on the electric arc lighter and verify that an arc is being produced.

Step 18) Turn on (or pulse) the electric arc lighter, and without touching the exposed wires in the gap, place the visible arc so that it fills the gap between the wires. You should notice that the ammeter indicates a current flow each time the arc successfully fills the gap with its plasma.

Optional: While running the experiment, set up your smartphone on a tripod to record a movie showing the display of the meter and the plasma/gap in the same frame. Then you can study the results afterwards frame-by-frame to see how when the plasma is present, the ammeter displays changes from '0000' or no conduction to a non-zero display when plasma is conducting. A still from such a movie is shown below.

Figure 22. When the plasma arc is present, each electrode creates a plasma link to the exposed copper nearest it. This creates a conducting pathway from the copper wire to the lighter's electrode, across the gap of the lighter where a second plasma connection is present. From that point to the opposite copper wire a third arc forms a three-way conducting path between the two copper wires.

The upside-down ammeter display shows that the circuit with the plasma arc coupling is drawing 52 milliamperes (0.052 amps) which is nearly the maximum measured with a fully-copper pathway of 0.065 amperes. So, the plasma is an extremely good conductor of electricity - at least as good as ordinary copper wire.

Candle flames and plasma

Instead of the electronic arc lighter, light the candle and place it under the gap. What did the ammeter show? What you should notice is that a candle flame causes no current to flow in the wire, which means that the flame is too cool to produce a significant plasma. There are many interesting online discussions about whether all or part of candle flames are actually plasma. Generally, common candle flames have temperatures too low for there to be much plasma in them.

Explanation:

The plasma in the gap is electrically charged and is completing the conduction of the charge carriers in the electrical current between the wire ends.

Assessment:

Learners will have detected the flow of current through the circuit when the plasma is present, confirming the criterion that plasma conducts electricity. They will use evidence from their experiment to explain how they know plasma conducts electricity.

Question: Explain how a plasma conducts electricity.

Answer: Plasma is not just a hot gas but one in which a mixture of electrons and ions exist. These can be used to conduct electricity. A plasma completes an open electrical circuit by filling in the gap with electrons that can complete the current flow in the wire across the air gap.

❑ Experiment HS3 - Detecting electromagnetic energy from a plasma sphere

Overview: 'Plasma ball' lamps produce electric fields that can be detected by the sparks they produce and by affecting fluorescent lamps nearby. These are not magnetic fields but are electrical fields. When combined, electromagnetic fields produce light and radio waves that travel through space.

Objective: Learners will detect and measure the electrical fields surrounding a plasma ball.

Assessment: Learners will explain how plasmasphere lamps maintain plasma with electromagnetic energy.

Background:

Plasma requires a continuous input of energy to maintain it. This can be in the form of electromagnetic energy. Plasmasphere lamps are available in many novelty stores and can serve as an example of plasma being maintained by electromagnetic energy.

Plasmaspheres consist of a center electrode and a cavity filled with a gas such as argon at low pressure. The surface of the sphere is metalized glass and provides the other electrode between which the plasma will be generated. When a high voltage electrical source (3,000 to 5,000 Volts) is applied to the inner electrode, plasma forms in the inert gas filling the interior of the globe (mixtures of argon, neon, xenon, etc.). The crumpled foil inside the electrode provides a variable patina of electric fields on the electrode's surface. Streamers of plasma form from this diffuse plasma that cause continuous discharges to stretch from the inner electrode to the outer grounded sphere as streams of electrons find the shortest path through the plasma to the ground. When you touch the outer surface, some filaments preferentially discharge in the direction of your finger, which provides a better ground path than the surface of the globe.

The globe is also emitting electromagnetic energy at high frequencies in order to maintain this plasma. This electromagnetic field can be detected by using your voltmeter as a radio receiver.

Materials:

- A plasma sphere.
- A voltmeter.
- A fluorescent lamp – compact fluorescent lamp (CFL).
- A copper penny.
- An insulated screwdriver.
- 2x2-inch piece of aluminum foil.

Procedure:

Step 1) Turn on the plasma sphere

Gathering Data:

Step 2) Place the CFL tube close to the surface of the sphere. You should see the lamp start to glow. As you move the tube away the glow in the tube should diminish rapidly.

Figure 23. An example of a fluorescent CFL lamp being excited by the electromagnetic field of the plasma sphere without any physical contact between the lamp and the sphere.

Step 3) Turn on your voltmeter (Called a Volt-Ohm Meter or VOM) and set it for the DC scale shown in Figure 24.

Step 4) Clip the Common Ground test probe to a water pipe or metal faucet so that the VOM is connected to a good earth ground shown in Figure 25.

Figure 24. Setup of a typical VOM dial for 'DC voltage' selection. The 'COM' lead goes to the faucet ground. The 'Input' lead goes to the aluminum foil.

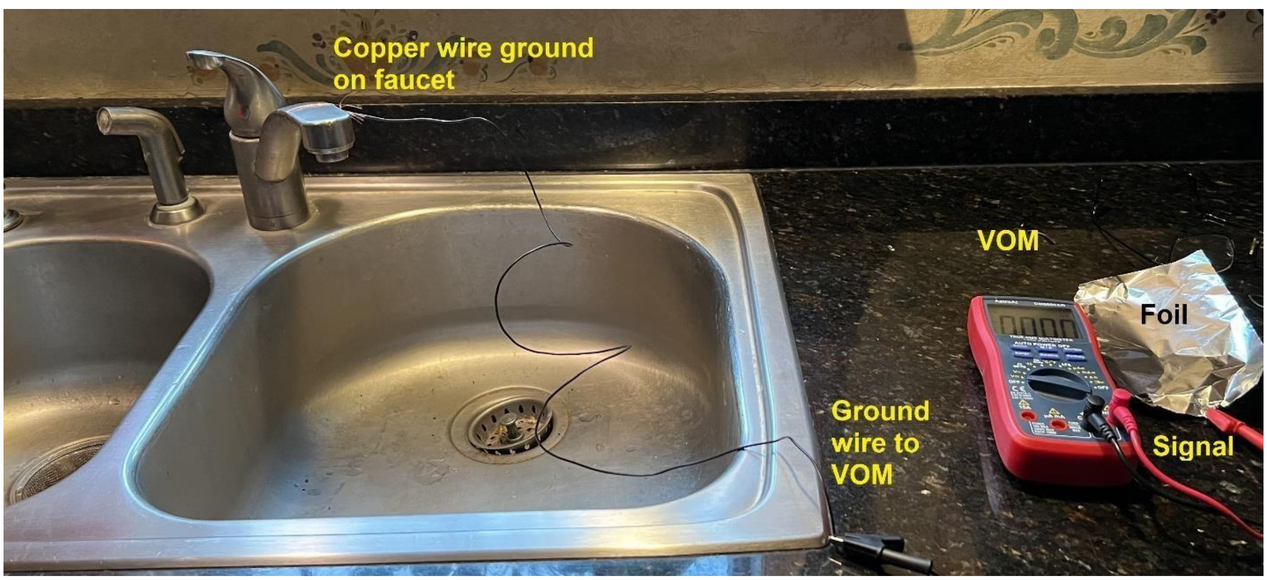


Figure 25. Set up for VOM. Ground wire (black) from VOM attached to the faucet with a twisted bare copper. Signal wire (red) connected to aluminum foil.

Figure 26. The aluminum foil attached to the VOM Input lead serves as an antenna to capture some of the electromagnetic energy from the central plasma ball electrode. The VOM reads about 2 volts on the DC scale.

Step 5) With the other test 'Input' or 'Signal' lead, clip it to the 2x2-inch piece of aluminum foil to make an antenna, then move it towards the operating plasma sphere as shown in Figure 24 and note the change in voltage. With the plasmasphere off the voltage should read 1 millivolts or lower. With the plasmasphere on it should read from 0.1 volts to 3.0 volts depending on distance from the globe, and the globe's power level.

Step 6) With the plasma ball turned off, place a copper penny at the top of the spherical ball.

Step 7) Turn on the plasma ball and move the tip of the screwdriver close to the exposed surface of the penny. As you tap the penny with the tip of the screwdriver you should see sparks appear and disappear.

Explanation:

If you can create a spark between the plasma globe and a sharp conductor like the tip of a screwdriver, why aren't there sparks all along the surface of the globe all the time? The reason is that it takes an electric field with a strength of 3000 Volts/mm to ionize ordinary air. Without a nearby conductor to ground to create a gap, the electric field outside the globe is too weak to spark by itself.

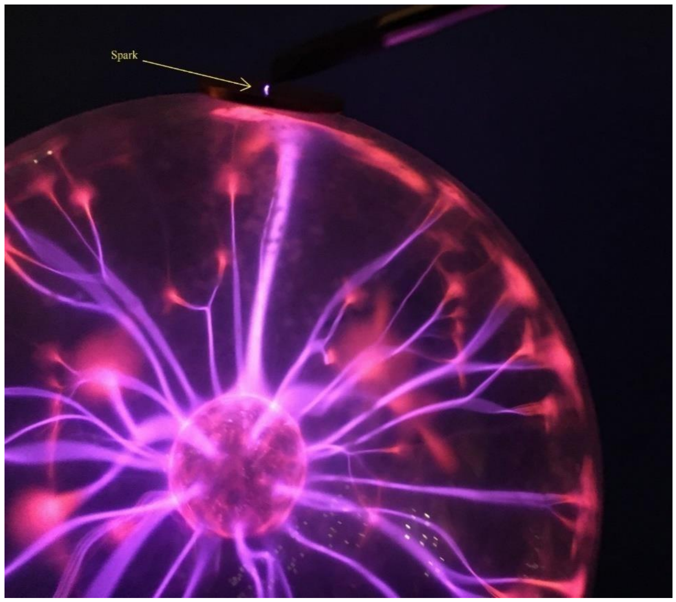


Figure 27. Spark photographed in a smartphone camera's burst mode using camera's automatic set up and focus

The electric field of the plasma ball reaches beyond the glass dome and into the air surrounding the plasma ball. This electric field can easily be detected using a CFL. As you increase the distance between the CFL and the globe, the intensity of the light will decrease. This demonstrates that the electric field decreases in strength with radial distance.

Assessment:

Learners will explain how plasmasphere lamps are able to maintain plasma with electromagnetic energy.

Question: Explain how plasmasphere lamps maintain plasma with electromagnetic energy and how this happens in space.

Answer: 'Plasma ball' lamps produce electric fields that can be detected by the sparks they produce and by affecting fluorescent lamps nearby. These are not magnetic fields but are electrical fields. When combined, electromagnetic fields produce light and radio waves that travel through space.

❑ Experiment HS4 – Analyzing sparks with a spectroscope

Overview: Sparks create plasma, which is a form of gas that produces light through the individual spectral lines that are unique to each element. Plasma does not produce a rainbow spectrum at all wavelengths from red to blue.

Objective: Learners will develop a spectroscope or spectrograph that reveals the spectra of some common plasmas.

Assessment: Learners successfully create a faint-light spectroscope and use it to distinguish a plasma from an ordinary heated solid or gas via its spectral lines and explain what this means.

Background:

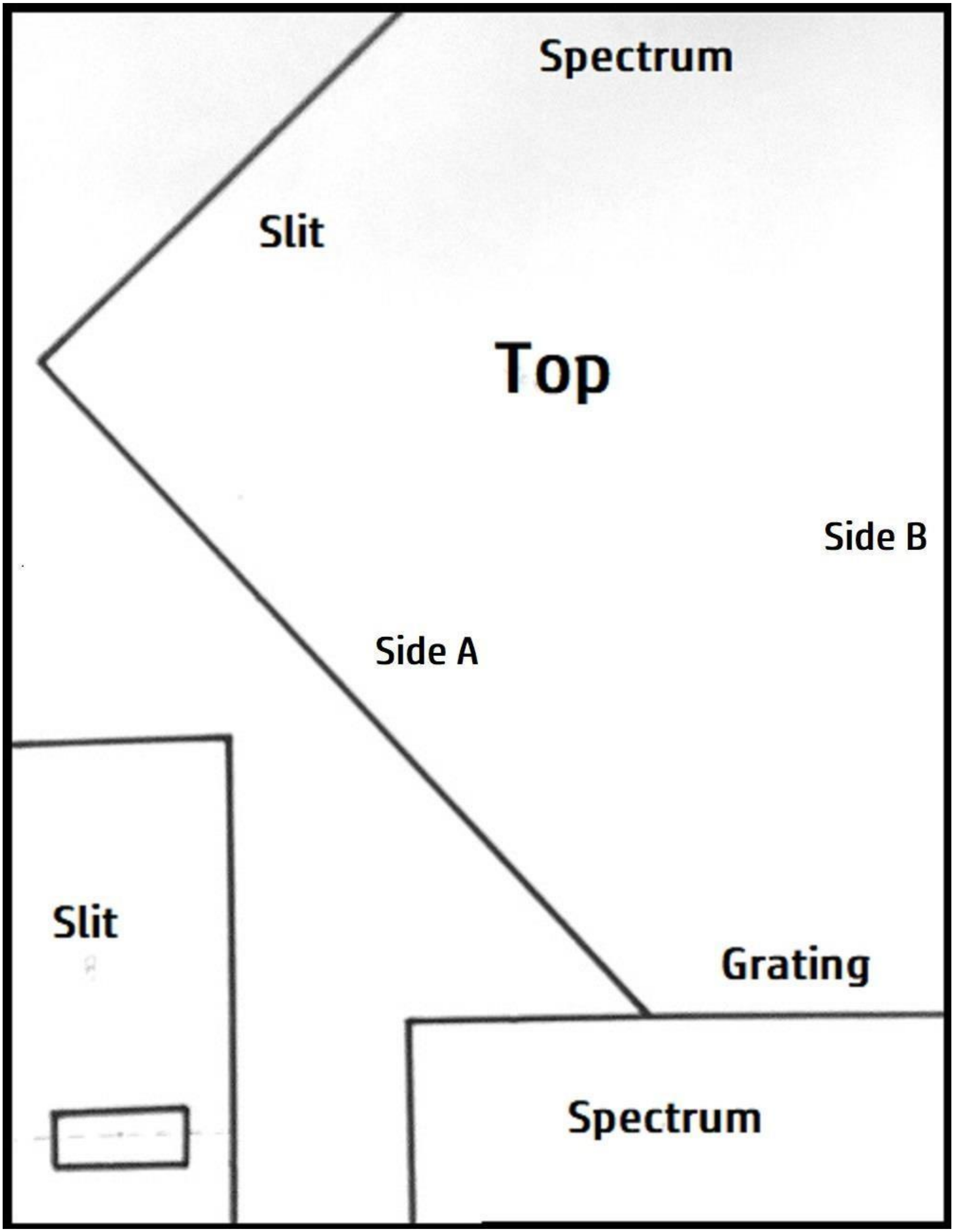
A plasma is a low-density gas that produces light, but the light only occurs at the specific wavelengths associated with each element. These 'spectral lines' can be used as fingerprints to remotely identify the atomic composition of a plasma. Ordinary heated objects such as the tungsten filament in a light bulb produce light at all wavelengths from red to blue, which results in what is called a continuous spectrum. A spectroscope can be used to distinguish between a plasma and an ordinary heated object.

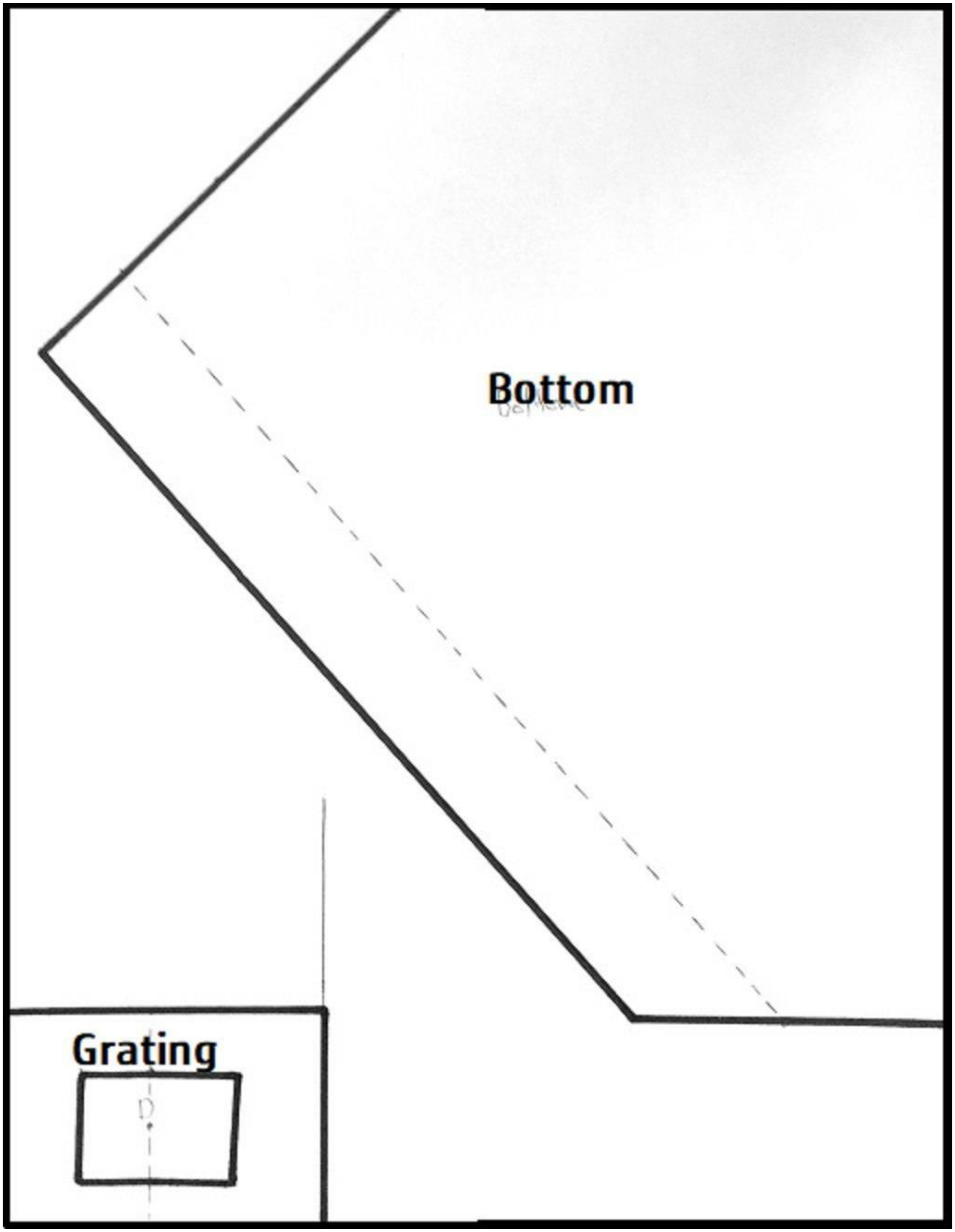
The light from a plasma such as one produced by a spark is too faint to be easily studied with a simple diffraction grating. Instead, a concentrating lens must be added to the design used in Experiment M1 and M2 to amplify the light. Other design changes also have to be made to reduce scattered light inside the device.

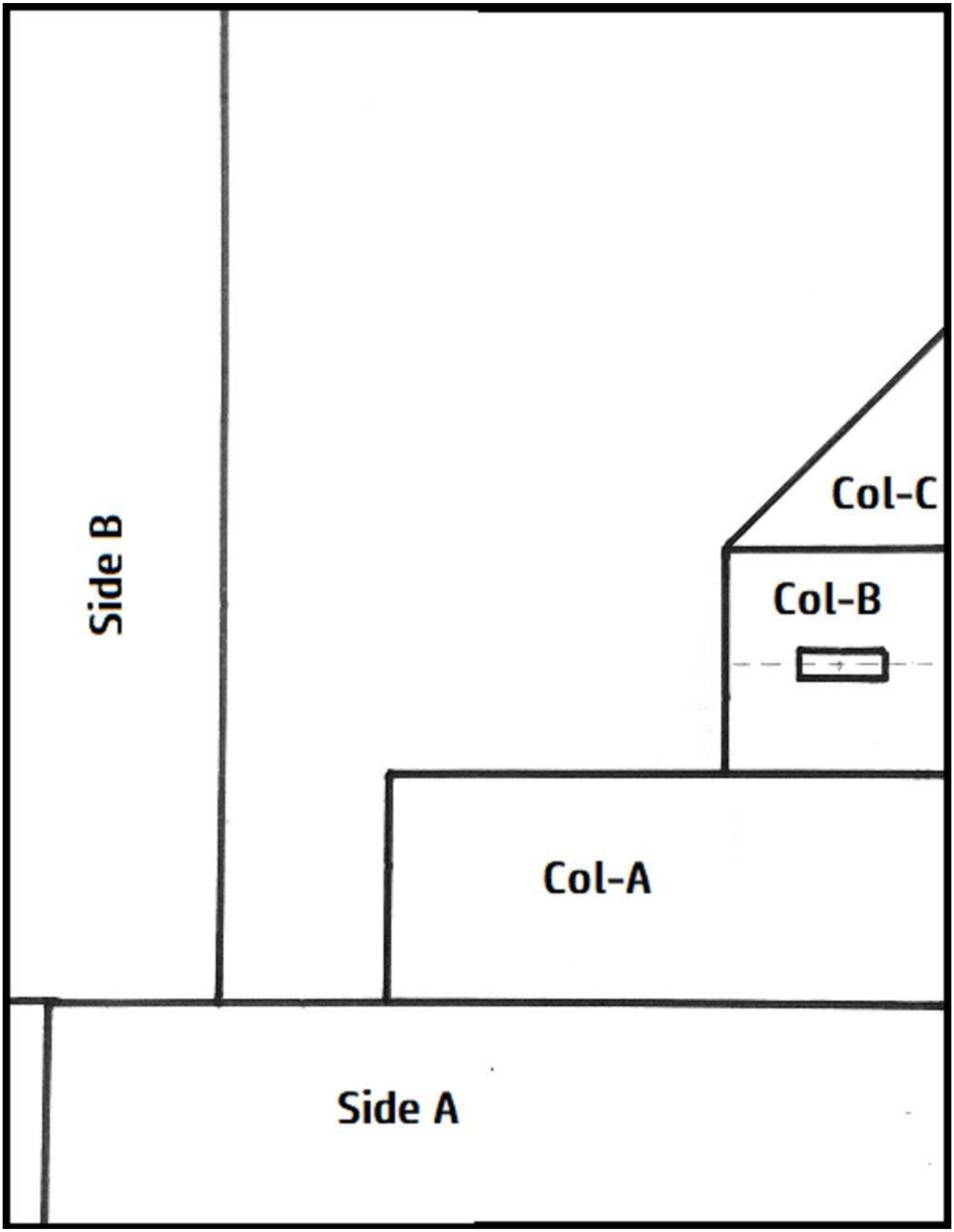
Materials:

- One - 2” x 2” diffraction grating (1000 lines/mm preferred).
- One – Large pizza box 14” x 18” x 2”.
- One - 20.5 mm x 108.5 mm FL, Plano-convex lens, uncoated.
- Two - Utility knife blades (5-blade pack $2.79) or Two safety razor blades (better).
- Sharp box cutter or similar knife to cut foam board or cardboard cleanly.
- Metric 'Millimeter' ruler.
- One – Bottle of glue for paper.
- One roll - Black 'Duct Tape' (1.88-inch x 20 yards $6.99) or other <u>opaque</u> tape.
- Small nail, awl, or other similar tool for punching holes.

Next three pages: Figure 28, Figure 29, Figure 30


Spectrum
Slit
Top
Side B
Side A
Slit
Grating
Spectrum


Bottom
Grating


Side B
Col-C
Col-B
Col-A
Side A

Procedure:

Step 1) Print Figure 28, Figure 29 and Figure 30 full sized on standard laser printer paper. The black border should extend to the edges of the 8 1/2x11 paper sheet.

Step 2) Cut out each piece along the solid lines. Figure 31 shows the pieces in their approximate orientation. Note that the holes on the Grating and Slit pieces have also been cut out.

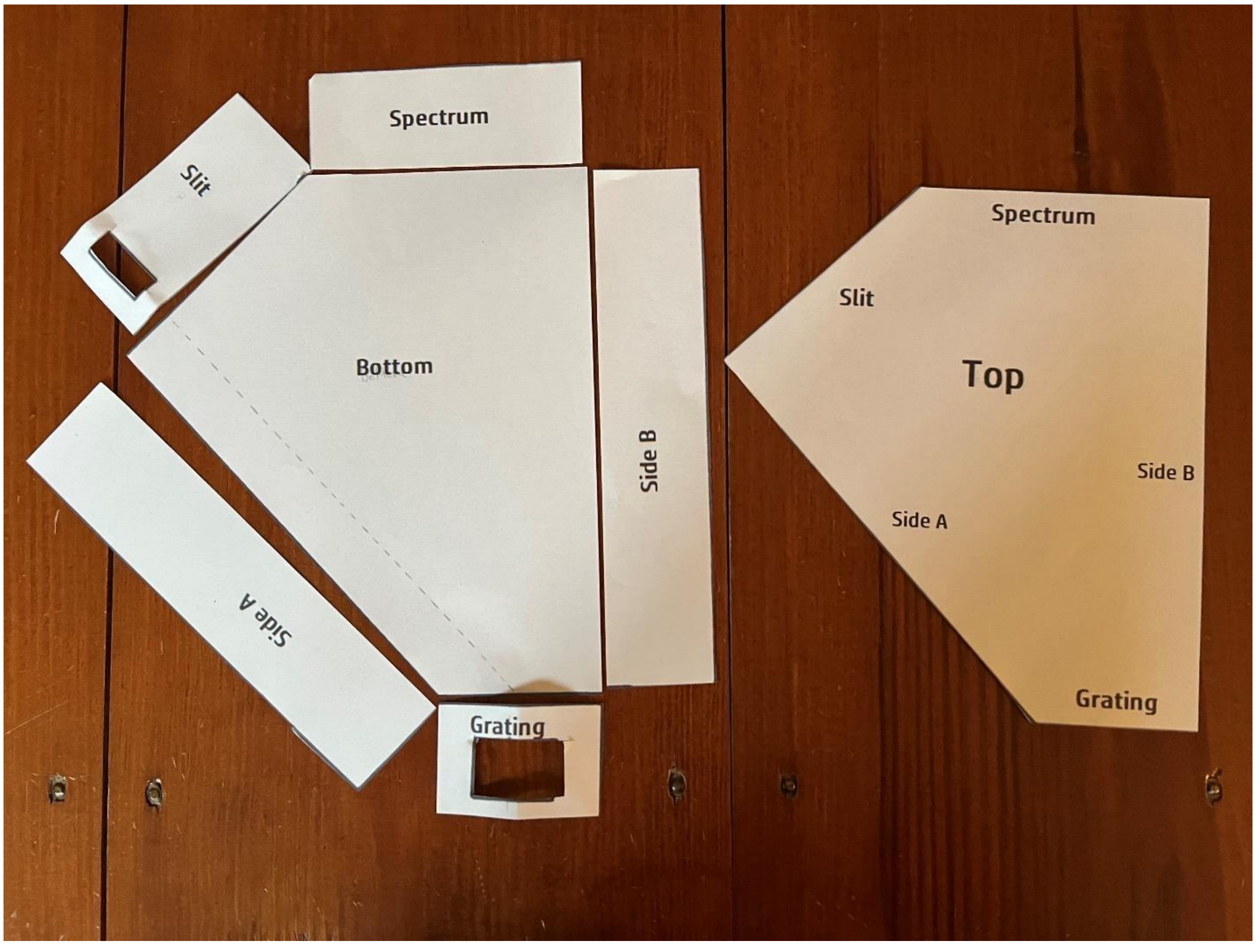


Figure 31. The cut-out patterns for the components of the spectroscope box.

Step 3) Place each of the pattern pieces on the pizza box cardboard and carefully trace its shape.

Step 4) With a sharp knife or boxcutter, carefully cut along the inscribed lines and punch out each piece for the spectroscope case. The Grating, Slit, and Col-B pieces should have cut-out rectangular holes. To minimize cutting, note that many large pizza boxes (14” x 14” x 2”) have sides that are the perfect width (2”) for the walls of the spectroscope box. As you cut each piece, make sure that you label it according to the pattern name.

Step 5) Use ordinary scotch tape to assemble the spectroscope as shown in Figure 32. Starting with the Bottom piece, attach the Grating, Side A, Slit, Spectrum and Side B pieces to the bottom piece first, then bend each piece to its vertical position and tape each piece to its neighbor. Once the sides are secure, go over all the seams with Black tape. This allows joints to be made light tight. You might want to position the pieces so that the commercial text and logos on the box are on the inside faces when assembled so that the outside is clean cardboard.

Figure 32. Partially assembled spectroscope box using pizza box cardboard.

Step 6) Optional: To reduce reflections, cover the inside surfaces of the box and the top piece with black paper. You can also use black paint, but do not use glossy paint. It should have a matte finish and be non-reflective.

Step 7) Attach two utility knife blades or single-edged razor blades to the slit entrance piece to form a narrow gap <1mm wide as shown in Figure 33.

Step 8) Attach the diffraction grating to the outside of the grating piece as shown in Figure 31. Make sure that the grating is mounted so that the spectrum is horizontal not vertical. Check this by looking through the grating at a bright light.

Figure 33. The installed left) knife-edge slit and right) diffraction grating installed

Step 9) As shown in Figure 34, draw a horizontal line across the Spectrum wall along the midpoint of the long axis. With a sharp awl, punch a reference hole A on the Spectrum face that is 30mm along the horizontal mid-point line from the left edge. Punch a second reference hole B 70mm to the right of the first one on the same horizontal line in the direction of the Slit.

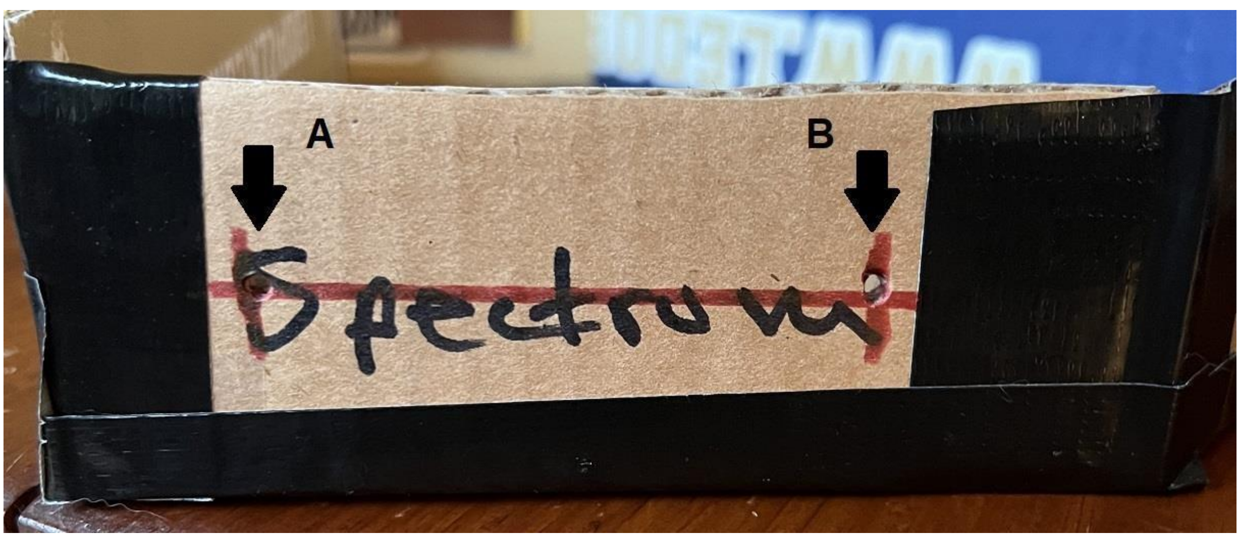


Figure 34. Facing the Spectrum Wall from the outside, punch two reference holes A and B.

Step 10) Temporarily attach the top piece to spectroscope box

Step 11) Point the entrance slit towards a light source. Look through the grating and make sure there are no other entry cracks for light to leak into the interior of the box. You should only see one bright spectrum. You should also see two bright spots to either side of the spectrum from outside light entering through the Reference Holes A and B. Enlarge these holes to make them visible. Add tape to any places where the light leak is occurring. The finished spectroscope should look like the view in Figure 35.

Figure 35. Completed spectroscope box.

<u>Building the collimator</u>:

In order to study the light from faint sources, the light entering the slit has to be amplified and collimated into a parallel beam and then focused on the grating. This is done by placing the large (20.5 x 108.5 mm) plano-convex lens between the slit and the grating.

Step 12) Open the spectrometer box and draw a line from the center of the grating to the center of the slit shown in Figure 36. This is the optical axis for the light arriving at the grating and is the center line for where the lens needs to be placed between the grating and the slit. The collimator lens has to be positioned so that its center is the same as the center of the slit and the grating along the optical axis. This means we have to build a small rectangular box to hold the lens. The focal length of the lens is 108.5 mm.

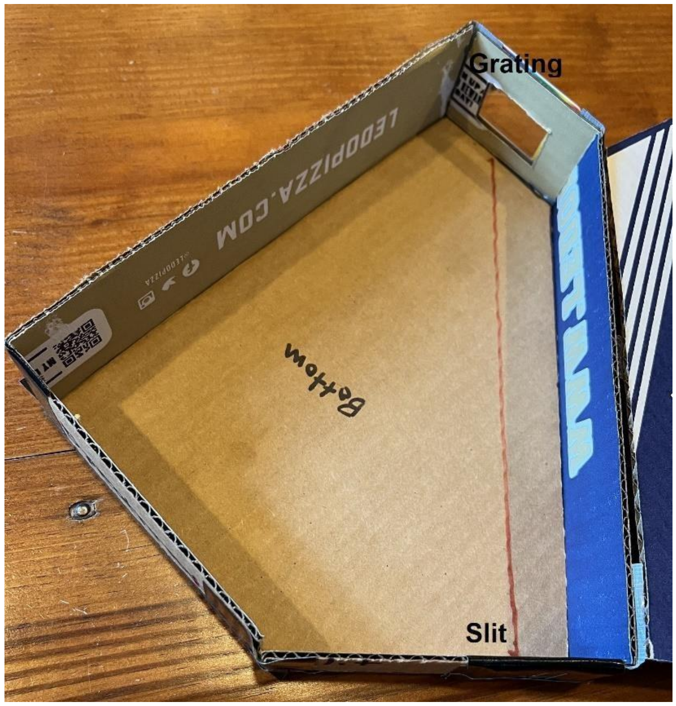


Figure 36. Optical axis of the spectroscope drawn as a red line.

Figure 37 shows the geometry of the grating, slit and the lens along the optical axis. We have to create a small box that will ensure that the lens is positioned accurately and does not move.

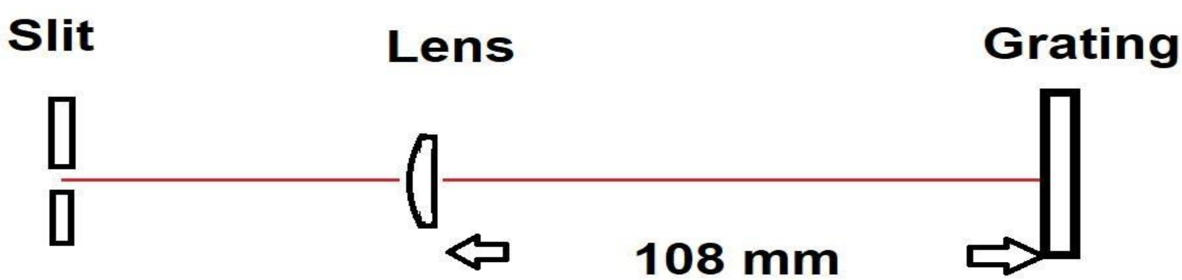


Figure 37. Optical geometry of the collimator lens, slit and grating.

Step 13) Cut out five pieces of cardboard. Note that the depth of the spectroscope box is 45 mm 'tall'.

1) Base and Top: 2 pieces 50mm wide x 130mm long

2) Lens Wall: 50mm wide x 45mm tall

3) Side Walls: 130mm long x 45mm tall.

Step 14) Place the Base inside the spectroscope box so that its short dimension is flush against the slit wall. The long dimension should be along the optical axis and centered on the optical axis. Draw a line on the base along the optical axis.

Step 15) From the center of the grating, measure a distance of 108mm along the optical axis and mark the base with this point. Remove the base and trim it so that its face is now at the mark. On the Base, mark this side 'Lens'. For example, if the mark is 5mm from the edge, trim the base so that it measures 125mm x 50mm. Trim the Top and Side Walls to this same length.

Step 16). On the Lens Wall, Place the Lens Wall against the base and mark the location of the Optical Axis. Draw this line from top to bottom of the Lens Wall.

Step 17) Place the Lens Wall against the inside face of the Grating and mark the center of the Grating on the vertical line of the Lens Wall. The completed Lens Wall marking is shown in Figure 38.

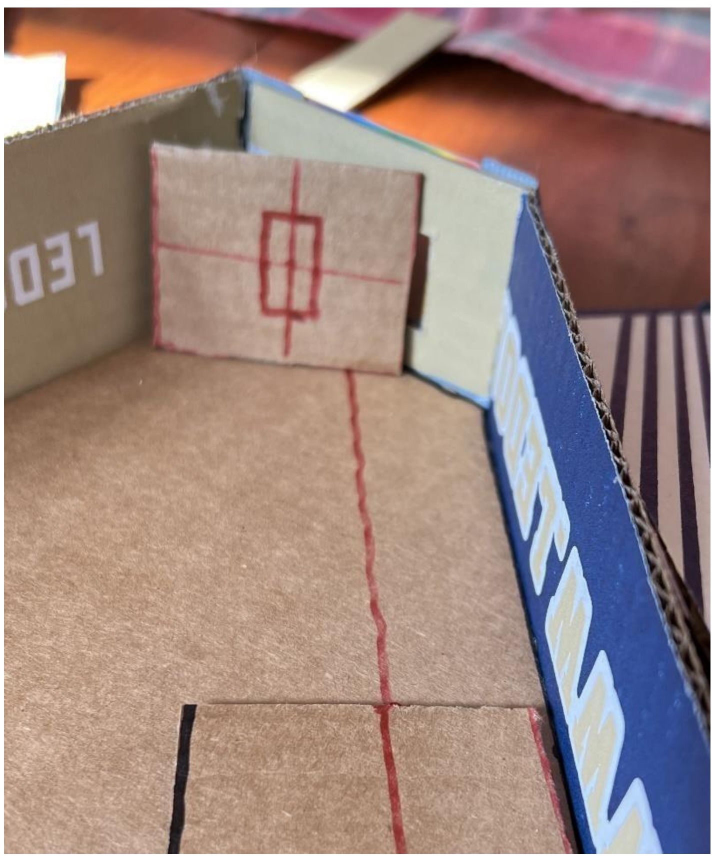


Figure 38. Lens Wall with vertical reference line for Optical Axis and horizontal center line for the center of the Grating. Also shown are the markings for the 5mm x 10mm window.

Step 18) Cut a rectangular hole at the center of the Wall that is about 5mm wide x 10mm long. When placed against the 'Lens' side of the Base, the long axis of the opening will be perpendicular to the Base.

Step 19) Mark one side of the Lens Wall as 'inside'. Apply two pieces of double-sided tape on either side of the rectangular opening on the Inside face with the tape flush with the edge of the opening.

Step 20) Identify the flat side of the plano-convex lens and, with the flat side facing the tape, center the lens over the opening and press it into the tape to secure it.

Step 21) Attach the Lens Wall to the Base so that the Inside face of the Lens Wall faces inside the collimator box and towards the Slit. The flat side of the lens will face the Grating.

Step 22) Attach the two side walls to the Lens Wall and the Base to form a rectangular box.

Step 23) With the top of the spectroscope box open, and facing the slit, insert the collimator box so that the lens is farthest from the slit and placed snugly in the corner of the box. Check that the optical axis line drawn through the lens is aligned with the axis of the spectroscope formed by the slit entrance and the center of the grating window. When completed, the installed collimator box should look like Figure 39.

Figure 39. Installed collimator. Note the alignments of the red reference lines for the optical axis and lens centering.

Step 24) Attach the collimator box cover, and the top of the spectroscope box.

Step 25) Return to your test area where you have a CFL lamp and table set up. Turn on the lamp and point the spectroscope slit at the lamp and look through the grating. If the spectrum does not appear, open the top of the spectroscope and shift the collimator box by pivoting it at the grating end and rotating it slightly at the Lens wall side-to-side by a few millimeters until the spectrum appears when you sight through the grating. You can do this by holding the collimator box in your left hand while looking through the grating. You may have to shift your head vertically. If you do not see the spectrum, remove the collimator box and move the spectroscope until the spectrum appears, then re-insert the collimator box and repeat the process.

If you cannot get the collimator to work, simply remove it and use the spectroscope in the normal fashion. This will however limit you to observing only very bright lamps and spectra and not the fainter electrical sparks.

Optional but recommended:

(To add a smartphone for photographing the spectra)

Step 26) Attach the spectroscope to a cardboard box with the Grating Wall flush with the box wall.

Step 27) Place the spectroscope on a table elevated by books and point the Slit at a fixed lamp with a CFL bulb. Move the spectroscope until you see the bright spectrum through the Grating. Firmly secure the spectroscope to the stand with tape and a few books on top so that it does not move.

Step 28) Move your smartphone around until you see the spectrum on your camera display. Note the orientation of the smartphone case. You can use scraps of cardboard to make a U-shaped docking area so that in the future you simply need to slide your smartphone securely into the 'U' to start taking pictures. With the smartphone camera attached, your spectroscope now becomes a spectrograph!

Gathering Data:

Test the spectrograph by pointing it at a CFL lamp to view the bright spectral lines. The result should look like Figure 40. The tilt of the lines is caused by the axis of the entrance slit not being exactly perpendicular to the floor of the box. Plasmas often produce spectra that have one of more individual lines of emission rather than a continuous rainbow of colors. This is because at a high enough temperature, atoms will still hang on to their electrons, but the electrons will emit light at specific wavelengths. If this is happening, the gas will also be just hot enough to produce a plasma consisting of ions, electrons, and the neutral atoms, which are now emitting light from their excited electrons. The surface of our sun is a plasma at a temperature of 6000^{o} C, but only 4 atoms out of 10,000 are actually ionized!

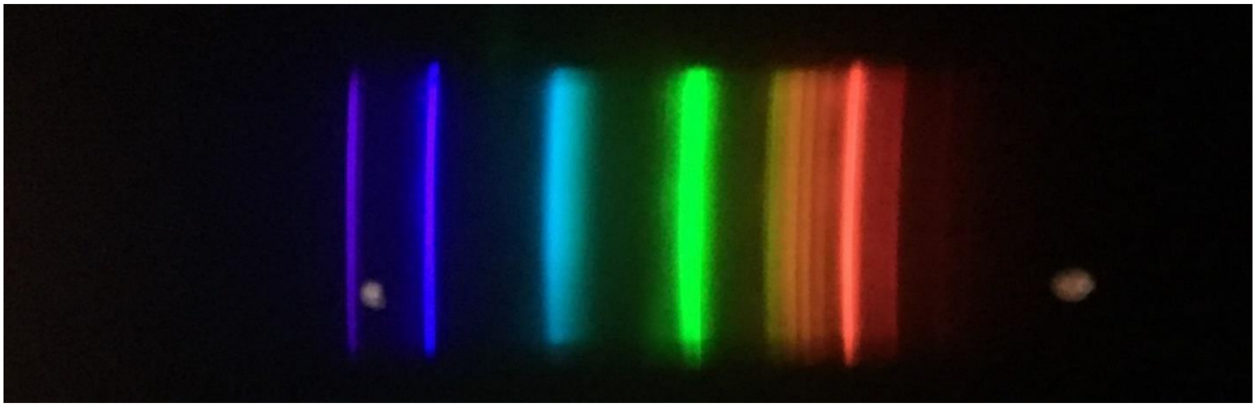


Figure 40. The spectrum of a CFL tube, which also shows the two Reference Hole bright spots.

Explanation:

The lens added to the design of the spectroscope from Experiments HS1 and HS2 allow the light entering the spectrograph slit to be collimated (rendered into parallel rays) and then focused onto the diffraction grating window. This helps to make the lines brighter so that fainter emission can be studied. By making the slit much narrower (0.2-mm) than in the earlier design (1-mm), this helps to increase the sharpness of the spectral features.

Figure 41. CFL spectrum showing First (Blue to red lines in left half of image) and Second Orders (blue and green lines in right half of image).

Diffraction spectra are defined by their ‘orders’. Starting from the slit, to either side you will see a complete spectrum from blue to red. It will be very bright. Still further away from the slit you will see the same spectrum but stretched out. This is the Second Order spectrum and astronomers use it to examine spectral lines in more detail. Figure 41 shows the bright First Order spectrum to the right-side of the slit which is outside the picture beyond the left-hand edge. You can also see the first three lines in the First Order spectrum but spaced farther apart and in more detail, especially in the green line, which you can now see is a double line.

Students will have assembled and tested their own spectroscope with a collimator lens and also created a spectrograph by adding a smartphone camera. The execution of the construction should result in a clean, professional-looking device, especially if you use foam board instead of cardboard. The key ingredients are:

1. Reducing stray light inside the box so that only the main spectrum is displayed.
2. Getting the slit, lens, grating and camera lens to align on the same optical axis.

Assessment:

Learners will explain how their faint-light spectroscope was able to distinguish a plasma from an ordinary heated solid or gas via its spectral lines.

Question: Explain how their faint-light spectroscope was able to distinguish a plasma from an ordinary heated solid or gas via its spectral lines.

Answer: This spectroscope design reduces stray light and aligns the slit, lens, grating, and camera to the same optical axis.

❑ Experiment HS5 – Spectroscopic study of plasma in a CFL light

Overview: Plasmas produce light emission at specific wavelengths characteristic of the elements they contain. These elements can be identified using a spectroscope.

Objective: Learners will be able to identify elements in a common plasma using a spectroscope.

Assessment: Learners will study the spectrum of a CFL and identify the elements present in the plasma.

Background:

Compact Fluorescent Lamps (CFLs) are a popular lighting technology that replaces less energy efficient incandescent bulbs that have been used for over a century. Incandescent bulbs produce light by passing an electric current through a tungsten wire. The wire heats up to over 2,300 °C and emits light. CFLs pass an electric current through a gas that is excited to produce ultraviolet light. This light strikes the glass of the bulb which is coated with a fluorescent material that gives off the light that you see. The gas inside a CFL is classified as a weak plasma with only about 1% of the atoms ionized and is also called a glow discharge plasma[5].

[5] https://link.springer.com/referenceworkentry/10.1007/978-3-319-00176-0_3?noAccess=true

Materials:

- ➢ One-CFL lamp.
- ➢ Spectrograph from previous experiment.

Procedure:

Step 1) Set up the CFL lamp and the spectrograph so that the entrance slit is pointed at the lamp

Step 2) Turn-on the CFL lamp and orient the spectrograph so that a bright-line spectrum appears on the camera screen

Step 3) Take a picture of the spectrum. A typical example is shown in Figure 40.

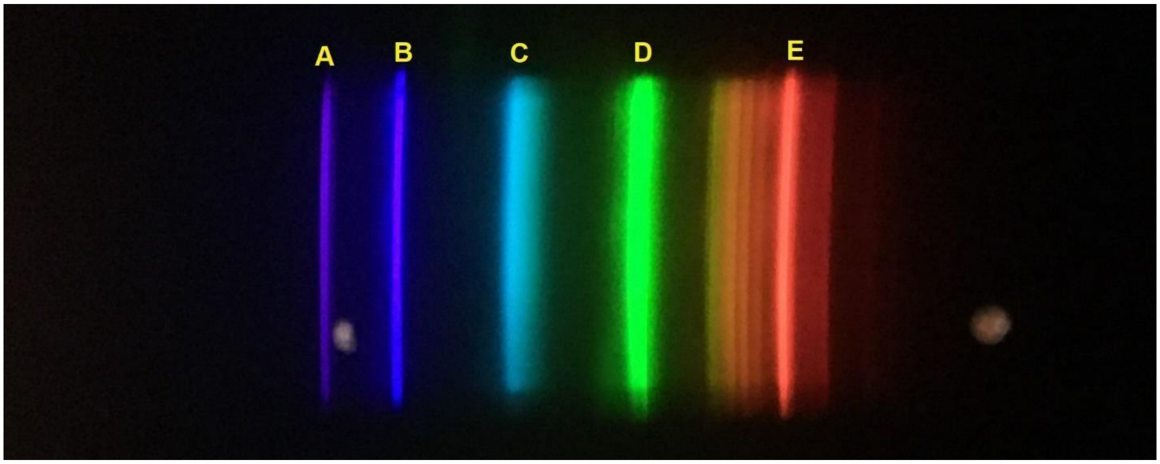


Figure 42. Spectrum of a CFL lamp. Note the Reference Holes appear as bright spots to the left of the blue spectral line and to the right of the red lines that complete the First Order spectrum.

Gathering Data:

From a catalog of spectral line wavelengths from known elements (see Wikipedia: https://tinyurl.com/34cvhtva or https://tinyurl.com/2c6czj6j), in Figure 42, the bright blue line on the left labeled B has a wavelength of 437 nm from the element mercury. The bright orange-red line labeled E has a wavelength of 611 nm from the element europium.

Step 4) Print your CFL spectrum on a piece of paper.

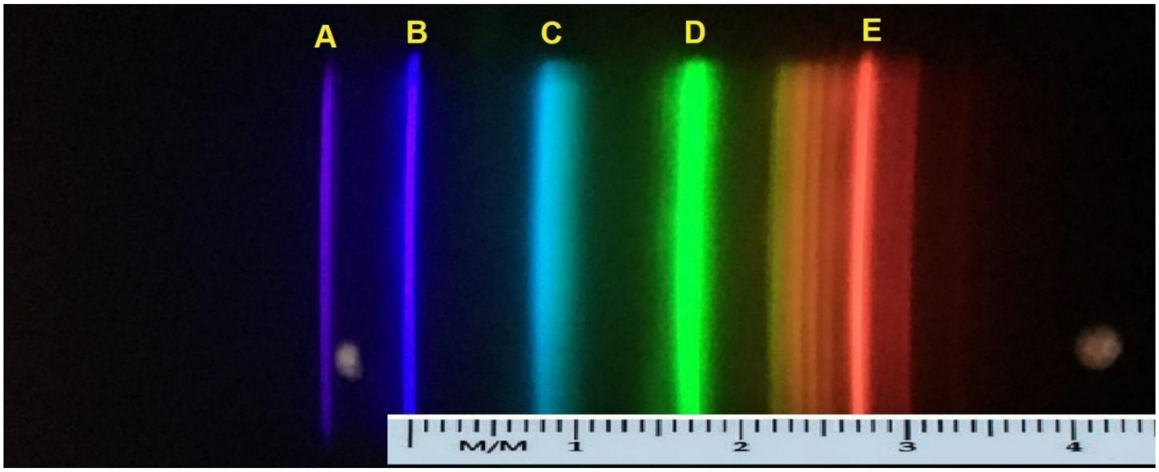


Figure 43. Measuring the distance between the two lines in the spectrum.

Step 5) As shown in Figure 43, with a millimeter ruler, measure the distance in millimeters (mm) between lines B and E. The example shows a measurement of 27 mm.

Step 6) Calculate the wavelength difference between the blue and yellow line from the information above. (Example 611nm – 437 nm = 174 nm).

Step 7) Calculate the scale, S, of the spectrum by dividing the wavelength difference in nanometers (nm) in Step 6 by the number of millimeters measured in Step 5. Working example: S = (174 nm)/27mm = 6.4 nm/mm. Note: the unit for S will be nanometers per millimeter.

Step 8) Measure the horizontal distance between the Blue Line, B, and each identifiable line in the First Order spectrum (A, C, D). Enter these measurements in Table 2 Column 2.

Table 2. Data

(1)	(2)	(3)	(4)	(5)
Line	Distance (mm)	Distance (nm)	Line (nm)	Identification
A	-5	-32 nm	406 nm	Mercury
B	0	0	438 nm	Mercury
C	8	51	489 nm	Terbium
D	17	109	547 nm	Mercury
E	27	173	611 nm	Europium

Table 3. Catalog of CFL lines and their identifications.

Element	Wavelength (nm)
Mercury	405 nm
Mercury	437 nm
Terbium	490 nm
Terbium	544 nm
Mercury	546 nm
Terbium	577 nm
Europium	611 nm
Argon	760 nm

Step 9) Beginning with the Blue Line at B= 438 nm, calculate the distance of each line from the Blue Line using the measured millimeters in Column 2 and the scale factor S, and enter the answers in Table 2 Column 3. (Example from Figure 43. Line A is at -5mm so wavelength = 438 -5x6.4 = 406 nm).

Step 10) Now add the distance in Column 3 to the wavelength of the reference Blue Line to get the estimated wavelength of each line and enter the answers in Table 2 Column 4.

Step 11) From the identifications for the common CFL lines in Table 3, find the nearest cataloged line to your wavelength estimates in Table 2.

Explanation:

Mercury vapor is a source of UV light and terbium, and europium are elements used in the phosphor of the CFL glass to convert UV into light that appears white to human retinae.

Assessment:

Learners will do the scaling calculations and verify from their spectra the common elements found in a CFL lamp.

Question: Explain how a weak plasma is produced in a CFL.

Answer: CFLs pass an electric current through a gas that is excited to produce ultraviolet light. This light strikes the glass of the bulb which is coated with a fluorescent material that gives off the light that you see. Mercury vapor is a source of UV light, and terbium and europium are elements used in the phosphor of the CFL glass to convert UV into light that appears white to human retinae. The gas inside a

CFL is classified as a weak plasma with only about 1% of the atoms ionized and is also called a glow discharge plasma.

❑ Experiment HS6 – Spectroscopic study of plasma in an electric arc

Overview: Learners use a spectroscope to identify the elements present in the plasma from an electric arc.

Objective: Learners will be able to identify the unknown material in the spectrum of the plasma from an electric arc.

Assessment: Learners successfully use a spectroscope to identify the dominant element in the plasma of an electric arc lighter.

Background:

Electric candle lighters create a spark across a 4 mm gap that can be used to light the wick on candles. The arc has a temperature of about 2,000°C and is capable of producing a plasma. The arc is produced by creating a voltage difference of 12,000 volts across the gap (3,000 V/mm), which exceeds the breakdown voltage of the atmosphere. In this experiment we will examine the chemistry of this plasma with a spectrometer to identify what elements are present.

Materials:

- Spectrograph.
- CFL lamp.
- Electric candle lighter.
- Millimeter ruler.

Procedure:

Step 1) With the CFL lamp lighted, point the spectrograph at the lamp and confirm the spectrum seen in Experiment HS7.

Step 2) Take an image of the emission line spectrum.

Step 3) Turn off the CFL lamp.

Step 4) Place the electric lighter tip about 5mm outside the slit of the spectrometer so that the arc will be parallel to the slit.

Step 5) With the camera on, flick the lighter on and move it around so that a spectrum can be glimpsed on the camera display. This will be rather difficult and may require a partner.

Step 6) Take a picture of the spectrum with the smartphone camera. Alternatively, with the video mode on the camera operating, move the arc around until a spectrum flashes on the display screen. Download the video and use a video editor to grab a frame from the video that shows the spectrum at its best visibility. An example is shown in Figure 44.

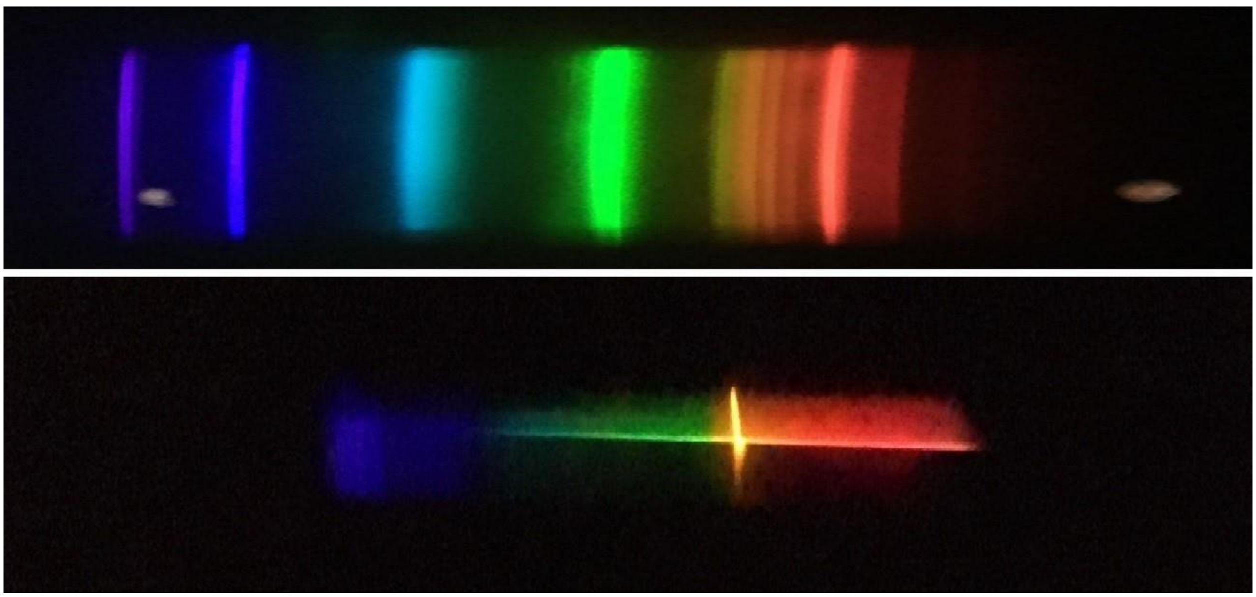


Figure 44. Spectrum of the CFL tube (above) and plasma arc (below).

The spectrum consists of a rainbow spread of colors from the oxygen and nitrogen in the air, plus a bright line with the same color as the arc. Call this the Arc Line. We don't know what elements this line corresponds to and will attempt to identify them in this experiment.

Gathering Data:

Step 7) Use an image editor to import the CFL and the arc spectra into the same image with the CFL spectrum below and the Arc spectrum above. Make sure that the Reference Holes in the two spectra line up vertically. Print this composite image so that the image fills up the full width of the paper.

Step 8) Draw two vertical lines onto the lower white space of the paper that show where the Reference Holes are.

***METHOD 1* - Using Excel and linear trendline regression:**

Step 9) From Experiment HS5, identify the wavelengths of the lines in the CFL spectrum and label them. Fill out column 2 in Table 4 with the wavelengths of these lines in nanometers (nm).

Table 4. Data for CFL spectrum

Spectral Line	Wavelength	Distance (mm)
A-blue	438 nm	
B-turquoise	488 nm	
C-green	545 nm	
D- red	610 nm	

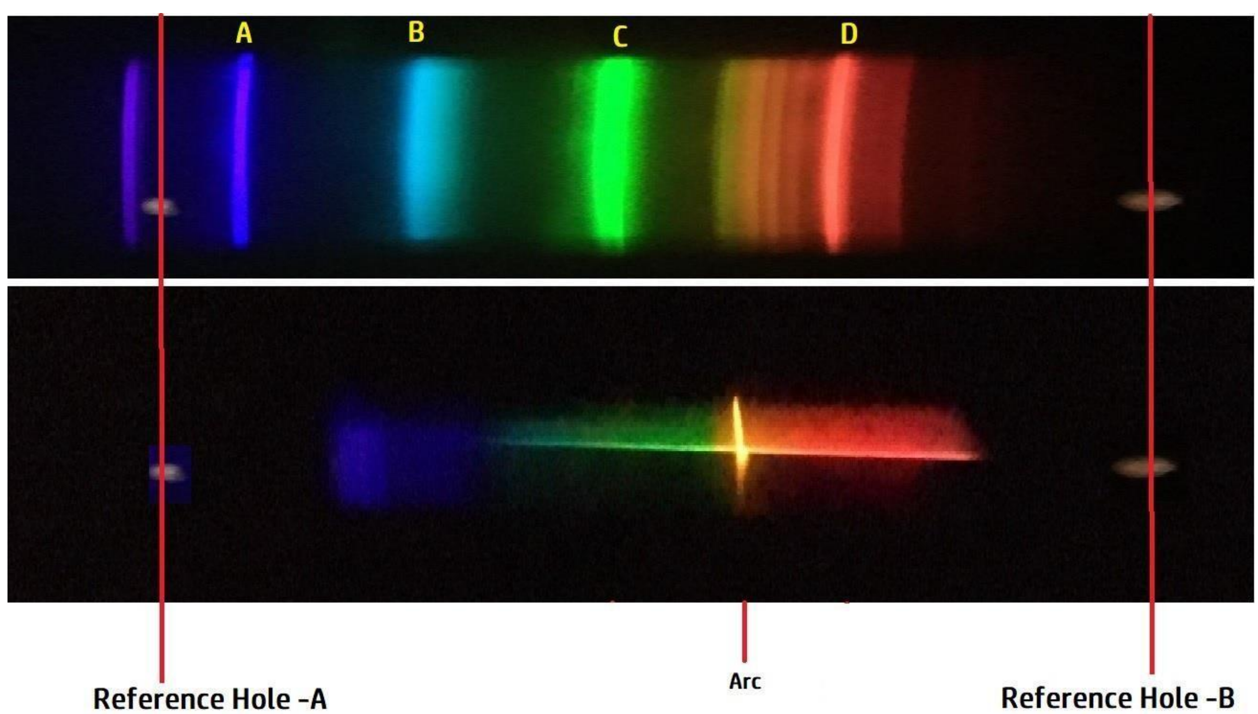


Figure 45. Labeled reference lines in the CFL spectrum. See Table 1.

Step 10) Measure the distance from the Reference Hole-A to each of the lines in Table 4 in millimeters. Note these measurements in Table 4.

Step 11) Using Excel, create two columns of data with the information in Table 4. Graph these data. See Figure 46 as an example.

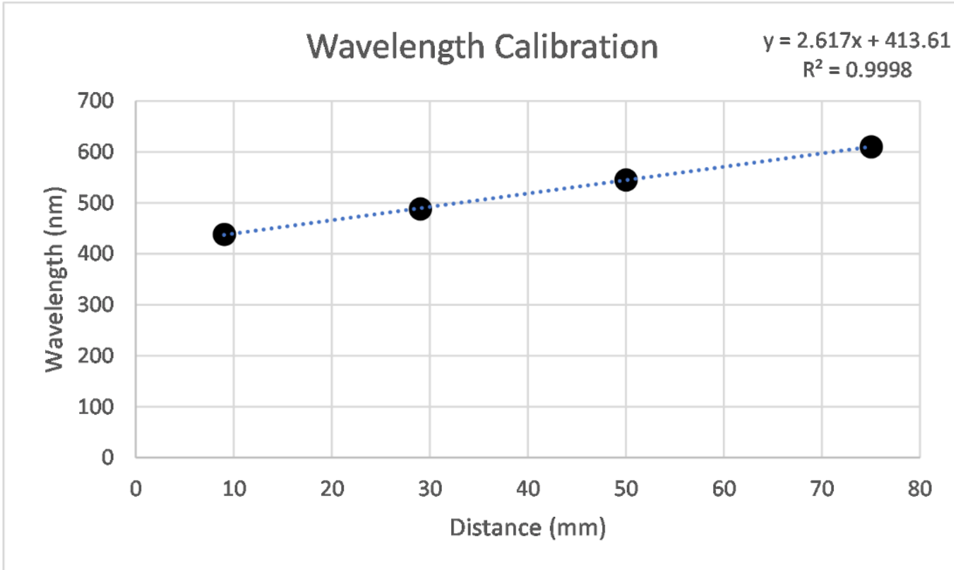


Figure 46. Calibration of CFL spectrum and spectrograph scale.

If you use the 'Add Trendline' feature with 'Linear' selected, it should show a straight line through the points with a fitted equation of the form Y = mx + b. The value for m gives the scale of the image in nanometers per millimeter where x is the measured distance from Reference Hole-A to the line of interest. In the Figure 45 example, m = 2.6 nanometers/millimeter with the Reference Hole-A (0 mm) corresponding to a wavelength of 413 nm.

Step 12) On the same image as Figure 45, measure the distance in millimeters from the Reference Hole-A mark (0 mm) to the center of the Arc line.

Step 13) Use the linear equation fitted from the data to predict the wavelength of the arc line. Example, if the equation is y = 2.6X + 413 and you measured X = 65 mm, then y = 2.6(65) + 413 = 582 nm.

***METHOD 2* - Using simple proportions:**

Step 1) From your study of the CFL spectrum in Experiment HS5 and your data from Table 4, draw two vertical lines across both spectra for a pair of spectral lines that straddle the Arc Line. The line towards the blue-side of the spectrum is called Reference-A and the line on the red-side is called Reference-B.

NOTE: *This step is done to minimize any curvature in the scale across the region of interest in the spectrum.*

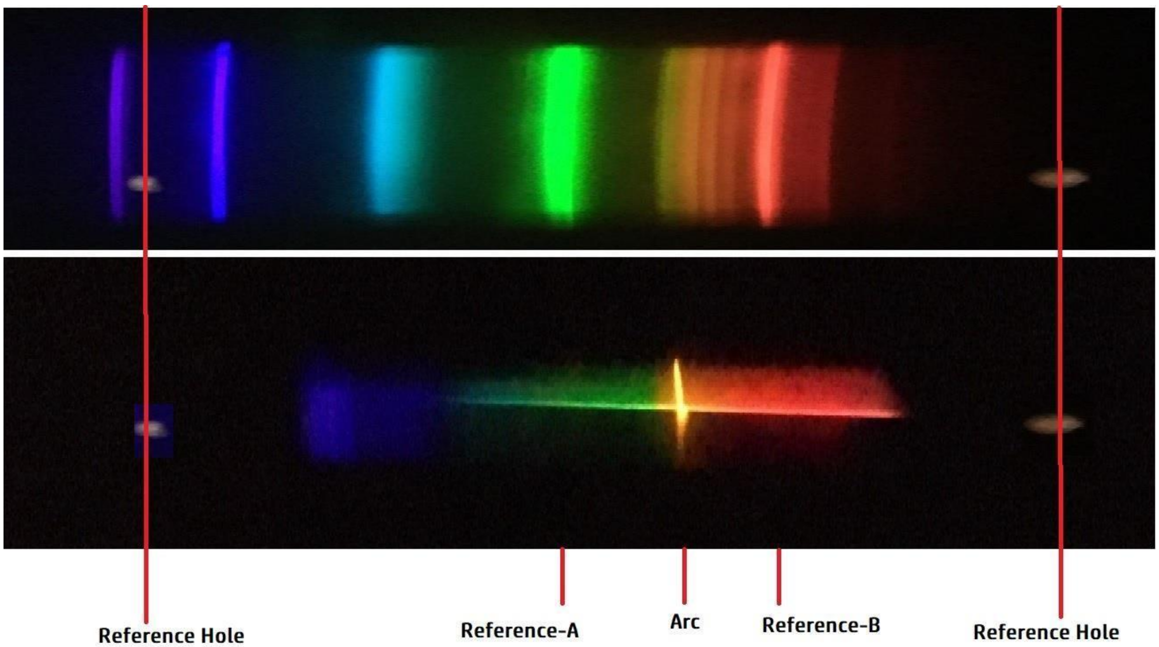


Figure 47. The CFL and Arc spectra aligned vertically with the Reference Holes.

Step 2) Measure the distance in millimeters between Reference-A and Reference-B in millimeters. Call this Dm.

Step 3) Calculate the known difference in wavelength between Reference-A and Reference-B in nm units. Call this Dw

Step 4) Calculate the scale factor of these spectra from S = Dw/Dm in units of nanometers per millimeter (nm/mm)

Step 5) We will now find the wavelength of the Arc Line. To do this, measure the distance in millimeters from the Reference-A line to the Arc Line and call this Da.

Step 6) Multiply Da by S to get the offset in wavelength between Reference-A and Arc Line, call this OFFSET in units of nm.

Step 7) Add OFFSET to the known wavelength of Reference A to get the estimated wavelength of the Arc Line in nm units.

Step 8) Consult Table 5 to identify the possible candidates for the Arc Line.

Worked Example: In Figure 47, Reference-A is the green mercury line at 546 nm. Reference-B is the Europium line at 610 nm. The difference is Dw= 64 nm. The measured separation is Dm= 26mm so S = 2.5 nm/mm. The distance between Reference-A and the Arc line is 15 mm, so this is OFFSET=15 mm x2.5 nm/mm = 38 nm. Then the estimated wavelength of the Arc line is 546 nm + 38 nm = 584 nm.

Note: Method 1 and Method 2 should lead to very similar answers for the wavelength.

Table 5. Candidate elements and the wavelengths of their prominent spectral lines.

Element	Wavelength (nm)
Hydrogen - blue	490 nm
Oxygen - green	550 nm
Carbon - yellow	600 nm
Nitrogen – red	640 nm

Example: For the examples above, the estimated wavelength was 584 nm. This is close to the yellow carbon line in Table 5 (differs by about 16 nm) but farther from the other candidates (oxygen line = 34 nm and Nitrogen line = 56 nm).

Explanation:

Although there are many different spectral lines produced by elements, each has a prominent line in the visible spectrum that is easy to detect if the element is present. The diffraction grating spectrometer and careful calibration of the wavelength scale should allow the Learner to estimate the wavelength of the Arc line and match it with one of the elements in Table 5.

Assessment:

Learners will up the calibration spectrum, calculate the wavelength scale factor, and estimate the wavelength of the Arc line if present and explain why this is important.

❑ Experiment HS7 – Spectroscopic study of plasma in a plasma globe lamp

Overview: Learners use a reference spectrum of a CFL lamp to determine the element/s present in the plasma within a plasma sphere lamp.

Objective: Learners compare a calibrated spectrum against an unknown spectrum to identify the elements present in an inaccessible plasma.

Assessment: Learners will be able to calibrate their spectroscopes and use them to identify the element/s that make up the plasma.

Background:

Spectroscopes and spectrographs are the 'miracle instrument' of astronomers that enable them to identify the elements in distant gas clouds that are inaccessible from earth. Each element produces its own set of 'fingerprint' spectral lines. These patterns can be used to identify their presence in distant objects in the universe. They can also be used to identify the primary elements that make up a plasma under laboratory conditions such as within plasma globe lamps.

Materials:

- Plasma Globe lamp.
- Spectrograph.
- Flashlight.
- Towel.
- CFL Lamp.

Procedure:

Step 1) In a darkened room, set up the spectrograph as you did with Experiment HS5 and take a reference image of the spectrum of the CFL lamp. Make sure that the lines are as crisp as possible and that only enough light enters the spectrograph so as not to over-illuminate the spectral lines. The reference spots to either side of the spectrum should be clearly seen.

Step 2) Turn off the CFL lamp and place the plasma globe as close to the entrance slit of the spectrograph as possible.

Step 3) Attach the smartphone camera to the grating viewing window and turn on the camera. Set the camera at its manual mode and adjust the settings so that the exposure time is about 0.5 seconds and the ISO is about 1500.

Step 4) Turn on the flashlight and position it so that some of the light covers the two entrance holes for the reference spots on the Spectrum window. Check the camera display for the two reference spots.

Step 5) Cover the plasma globe and the spectrograph with the towel so that the light from the flashlight does not enter the slit area. This will also serve as a 'photographer's hood to reduce the stray light on the camera display. The camera display should clearly show the reference spots and with the plasma glob on, you should see occasional flashes of spectral lines appearing between the two reference spots.

Gathering Data:

The data-gathering operation is the most difficult. A strong spectrum only appears when one of the plasma filament bright spots on the surface of the globe is exactly on the axis of the slit. The plasma filaments are too faint to be detected in this way.

Step 6) Take a rapid sequence of images with your camera spanning about 15 seconds or about 30-50 images.

Step 7) Remove the camera from the spectrometer and scroll through the images until you find several in which a faint spectrum appears between the two reference spots. Download the selected images to your laptop and delete all the unused/unusable images from this data run. An example of such an image is shown in Figure 48.

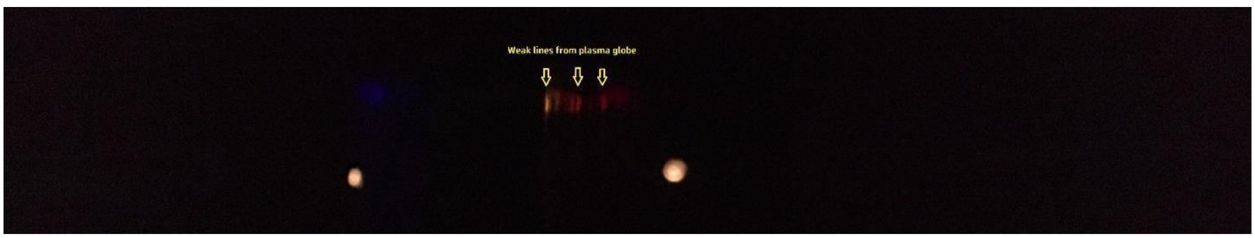


Figure 48. Example of the spectrum of a plasma globe bright spot. Arrows indicate some of the plasma globe spectral lines

Step 8) Using your photo editor, create a composite of the CFL spectrum and the Plasma globe spectrum with the CFL spectrum on top and the plasma globe spectrum on the bottom. Carefully align the spectra so that the reference spots line up vertically as shown in Figure 49.

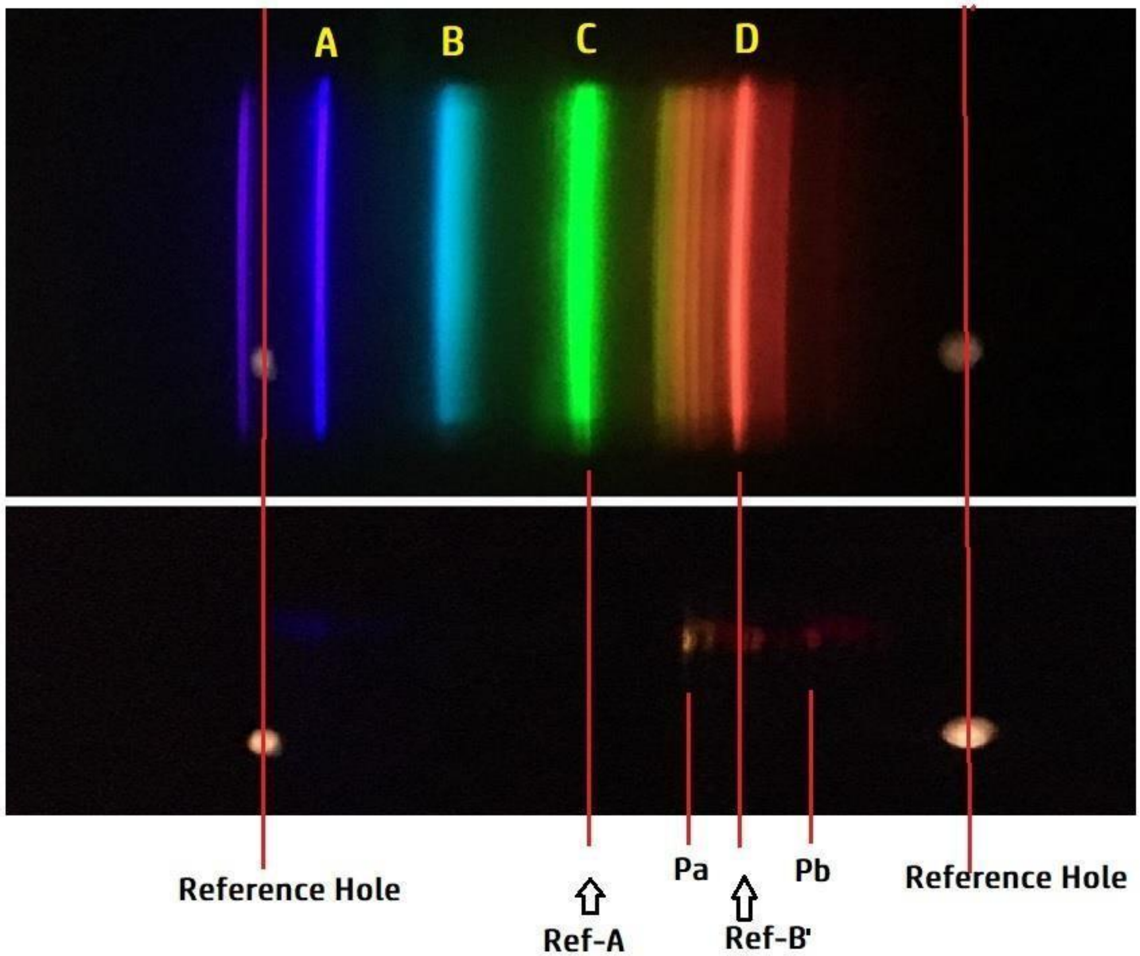


Figure 49. Aligned CFL and plasma globe spectra. The faint spectrum of the plasma globe plasma is seen between the lines labeled Pa and Pb.

Step 9) From Experiment HS8, Method 2, determine the calibration equation for this data.

Step 10) With a millimeter ruler, measure the distance between Reference Hole-A and the Arc line in millimeters. Compute the estimated wavelength of the Pa line from the linear equation.

Step 11) Repeat the process for the Pa line and other lines in the plasma spectrum that you find.

Step 12) Compare the wavelengths of the lines you have identified with Table 6 and choose an element whose lines are the closest match. Example 590 nm in Step 10 is close to a bright neon line and the helium line, but helium does not have the additional 'red' lines (Pb etc.) at longer wavelengths which better-match the plasma spectrum.

Table 6. Some common bright lines of elements found in low-temperature plasmas

Element	Wavelength (nm)
Nitrogen - blue	500 nm
Helium - yellow	588 nm
Argon - red	748 nm
Neon - yellow	588 nm
Xenon - blue	470 nm

Figure 50. Neon spectrum http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/atspect2.html

Figure 51. Argon spectrum http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/atspect3.html

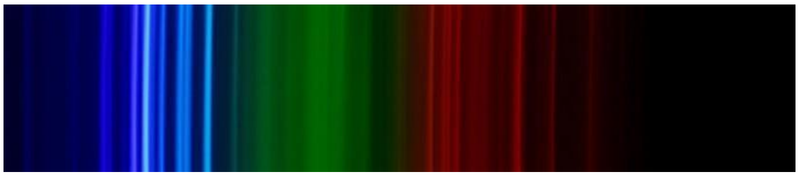


Figure 52. Xenon spectrum https://fineartamerica.com/featured/xenon-spectra-ted-kinsman.html

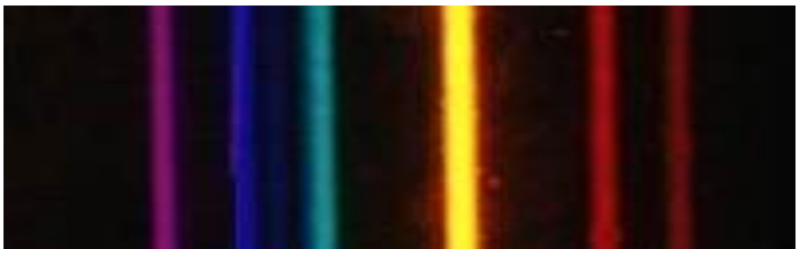


Figure 53. Helium spectrum http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/atspect.html

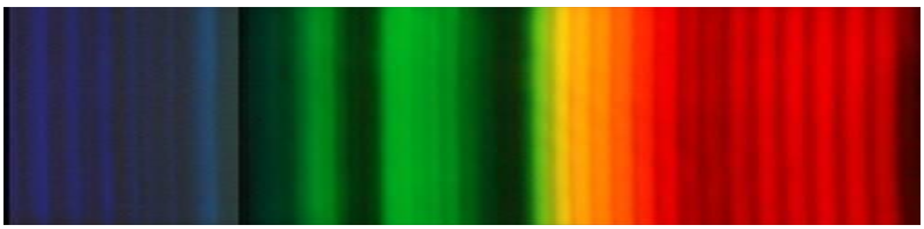


Figure 54. Nitrogen spectrum http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/atspect.html

Explanation:

Spectroscopes allow the spectral lines of individual elements to be discerned and used as 'fingerprints' to identify their presence in other systems. This requires carefully calibrating the spectrograph against a standard set of known spectral lines to establish the wavelength scale and offsets. This usually involves using regression equations that are polynomials because spectrographs produce a generally non-linear scale due to optical distortions and diffraction effects.

Assessment:

Learners will determine the wavelength of one or more lines in the plasma globe spectrum and match the lines to a specific set of candidate elements uses as the gas inside the globe. Common gasses include neon, argon, and xenon.

❑ Experiment HS8 – Spectral line studies with DIY gas discharge tubes

Overview: Learners explore how common sources of plasma produce spectral lines at specific wavelengths that identify the atoms common to the plasma.

Objective: Learners will use their own spectroscope to identify the spectral lines of elements in a plasma.

Assessment: Learners use a spectroscope and create a neon lamp circuit in order to identify the spectral lines in a neon plasma, along with other common light sources.

Background:

Many demonstrations of how different plasmas produce distinctive spectral lines involve the use of gas discharge tubes. Commonly, these involve the noble gases such as neon and helium, but also include oxygen, nitrogen and other elements. These tubes, and the transformer to operate them, typically cost $30.00 each and the transformer an additional $200.00, making them prohibitively expensive for many learners and home hobbyists. This experiment will demonstrate the design of a DIY plasma demonstration system that costs less than $50.00. It relies on off-the-shelf commercial lamps that can be found in many hardware stores.

Materials:

- Compact Fluorescent Lamp – 60w, 2700K.
- Black Light CFL.
- Table lamp with lamp shade removed.

- Neon glow lamp - Memotronics A3C / NE-2U Package of 10, $4.99 with resistors.
- Screwdriver.
- Terminal block for 6 circuits - $9.99 at most hardware stores.
- 6” x 12” x 3/8” craft plywood (Any hardware or craft store).
- Small, ¾” wood screws size 6x.
- Scrap 2-prong, 6-foot, 110V extension cord.

Procedure:

Step 1) Remove the lamp shade from the table lamp and place on a table.

Step 2) Screw-in the CFL lamp and turn on the lamp.

Step 3) Use the smartphone spectrograph created in Experiment HS1 to photograph the spectrum of the CFL lamp. For best results, place the spectrograph on a second table at a distance of about 10 feet, and place books or other shims under the spectrograph so that the spectrum shows the clearest lines. Use other books or weights to firmly secure the spectrograph in this orientation.

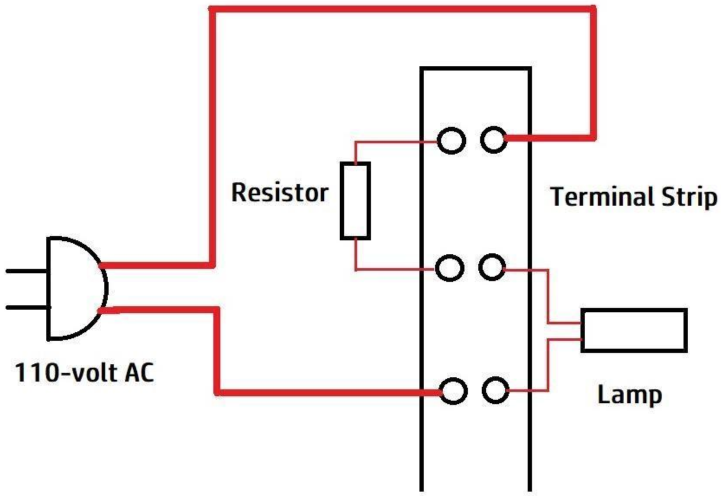
Step 4) Remove the CFL lamp and replace it with the Black Light. Take a photograph of its spectrum.

Neon Glow Lamp Setup

Step 5) Mount the terminal strip on the wood base using screws. Only two required for stability.

Step 6) Snip off the receptacle end of the cord and prepare the two wires by removing 1” of insulation from both wires. About 6” of separated wire are needed.

Step 7) Follow the placements and connections shown in Figure 55. Make all connections using the terminal block and secure the wires tightly.



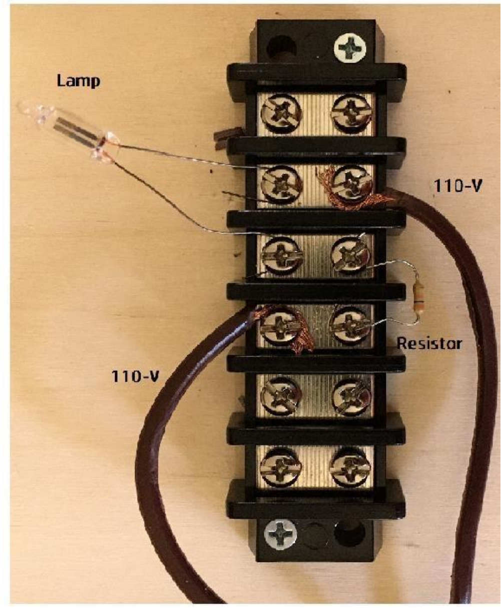


Figure 55. Circuit for neon lamp. Left is the diagram; Right is an example of the hookup scheme.

Step 8) Plug in the cord and the neon light should immediately illuminate. Do not touch the terminal block when the cord is plugged in to avoid an electrical shock.

Step 9) Unplug the cord and carefully twist the lamp so that it is in a vertical orientation.

Step 10) Place the lamp as close to the entrance slit of the spectrograph as possible.

Step 11) Plug in the cord and turn on the lamp. Move the spectrometer until a spectrum appears. You may have to perform this step in a darkened room for the best contrast.

Step 12) Take a photograph of the spectrum of the neon lamp.

Gathering Data:

Step 13) Download the spectra of the three light sources to your laptop.

Step 14) Use a program such as ‘Paint’ or ‘Photoshop’ to combine the three best spectra, one from each light source, into one image in which the spectra are stacked vertically and the two reference spots are lined up vertically. This may require some horizontal stretching and cropping of each individual image to get the reference spots to line up. The result should look like Figure 56. The spectra for the black light and the neon light have now been rendered to the same horizontal scale as the known CFL spectrum.

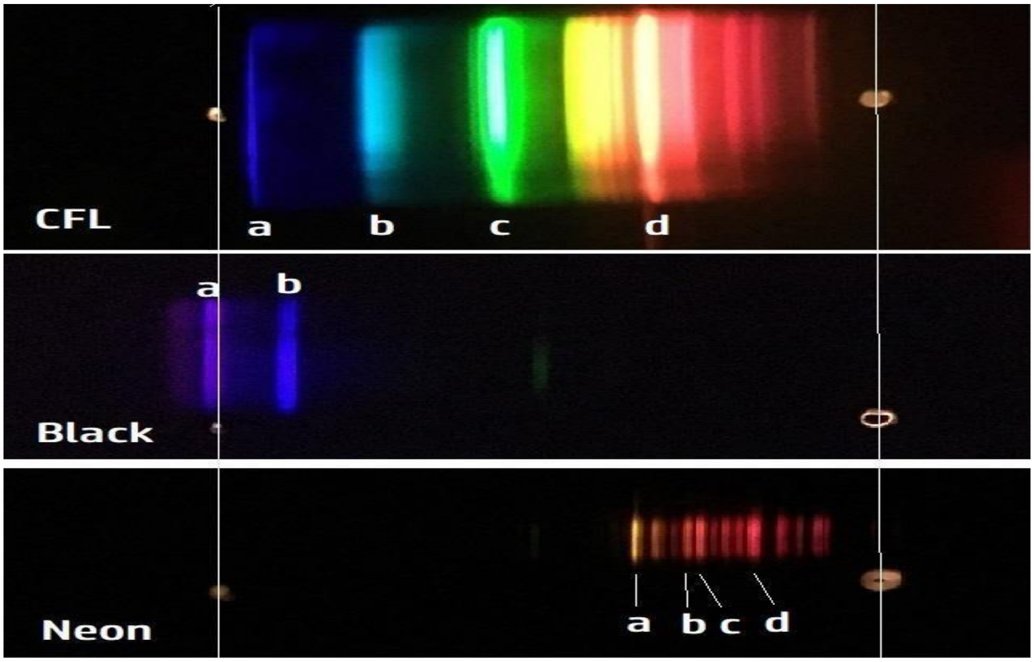


Figure 56. Example of the stacked spectra. Notice that the centers of the reference spots illuminated by an external flashlight or ambient light all fall vertically along the parallel guidelines.

Step 15) –The wavelengths of the lines in this spectrum are shown in Table 1. For each line, measure its distance in millimeters from the left-hand guideline and enter the values in the table. Use Figure 56 as a guide to labeling the lines for each element.

Table 7. CFL reference lines

Spectral Line	Wavelength	Distance (mm)
A-blue	438 nm	4
B-turquoise	488 nm	18
C-green	545 nm	31
D- red	610 nm	48

Step 16) – Scale calculation: Compute the difference in wavelength, Dw, between a pair of lines and the difference in millimeters, Dm, between the same pair of lines from Table 7. Compute the image scale factor S=Dw/Dm in nanometers per millimeter (nm/mm). This is the wavelength scale of the CFL spectrum, and it is also the same wavelength scale for the other spectra.

Step 17) – Offset calculation: From the A-line of the CFL spectrum, use its distance from the reference line in millimeters, Dr, to calculate the wavelength of the reference line from R= 438 nm – (Dr x S). Because the wavelength scale is increasing to the right, you have to subtract Dr x S to find the wavelength of the left-hand reference line which will be at a shorter wavelength than Line-A.

Step 18) – Measure the locations of the lines in the other spectra using the millimeter ruler and enter your answers in Table 8 column 2.

Step 19) – Calculate the wavelengths of the lines by using the formula: W = R + (Dm x S). The value for R is the wavelength of the reference line from Step 15. The product of Dm and S gives the difference in wavelength between the reference line and the line in Table 8. Enter your answer in column 3.

Step 20) – Compare your answers in Column 3 with the expected wavelength of these lines in Column 4.

Table 8. Spectral lines of black light and neon light

Line	Distance Dm	Wavelength (nm)	Actual value (nm)
Black - a			420 – europium coating
Black - b			463 – mercury vapor
Neon - a			585
Neon - b			609
Neon - c			614
Neon - d			640

Explanation:

Compact fluorescent Lamp (CFL) - A CFL tube is filled with a gas containing low pressure mercury vapor and noble gases at a total pressure of about 0.3% of the atmospheric pressure. A pair of electrodes, one at each end of the tube, is heated by a current and emits electrons, which excite the noble gases and the mercury gas by impact ionization. The collisions in the mercury plasma of free electrons, ions and atoms cause the electrons in the atoms to be bumped up to higher energy levels and then fall back while emitting light at two UV emission lines (254 nm and 185 nm). This UV radiation is then converted into visible light by exciting the fluorescent coating on the inside of the glass envelope of the lamp. The chemical composition of this coating is selected to emit in a desired spectrum.

Black Light CFL - This lamp is identical to an ordinary visible-light CFL, however the coating on the outside of the glass does not allow much of the light with wavelengths longer than about 500 nm to exit the lamp. The majority of CFL 'black lights' are actually regular white CFL bulbs dipped into a coating that filters all non-violet light. The mercury inside these bulbs creates ideal UV light. The coating filters all of the white light except violet. Only about 6% of light makes it out of the bulb. This causes the 'blue light' effect that stimulates other materials to emit at these wavelengths. However, if the material does not naturally emit or absorb at these wavelengths, it will remain black and invisible. Many organic compounds emit and absorb at these UVA wavelengths, which is why they 'fluoresce' when illuminated by a black light.

Neon glow lamp - Neon lights are found everywhere including holiday decorations and commercial advertising. They work in much the same way as the mercury-based CFL lamps do, in this instance by having neon atoms stimulated to emit radiation, but in this case most of the light is emitted in a small number of lines, this time in the red part of the spectrum. Because the gap between the electrodes in a neon sign is measured in centimeters, it takes over 15,000 volts to get this arcing to happen from end-to-end in the tube, so you need a special 'neon-sign transformer' to boost the voltage from 120 to 15,000 volts.

The basic principle for neon glow lamps is much simpler. The neon gas is placed inside a very small, sealed glass bulb in which two electrodes are exposed to the gas. When the electrodes are energized, they produce a current across the gap between them in which the neon atoms are present. The neon atoms are excited by the flowing electrons to produce light at their characteristic wavelengths, which are in the red part of the spectrum. The gap is only a millimeter or less wide, so much less voltage is needed to form the arc and the plasma compared to the much-larger neon signs that can be meters in length.

Gas Discharge Tubes (Not used in this experiment)

The following two forms of plasma light are available on streetlights (high-pressure sodium) and in many commercial parking lots (mercury vapor lamps). Because they are hazardous to use indoors in a classroom or in other settings, they will not be offered for experimentation. These can be studied outdoors at night using the same measurement procedures as the previous light sources.

Mercury vapor lamp

Figure 57. Example of the spectrum from a mercury vapor lamp. (Credit: Wikipedia)[6]

CFL and other fluorescent lamps use a current of electrons to excite mercury atoms to emit UV light, which is then absorbed by a coating to emit the light we see. The mercury plasma itself is invisible. A mercury vapor 'gas discharge' lamp uses an electric arc through a pressurized gas of mercury atoms to directly produce the light we see without the need of a fluorescent screen or coating. The plasma is confined

[6] https://commons.wikimedia.org/wiki/File:Mercury-vapor_lamp_spectrum_PNr%C2%B00026.jpg

to a small quartz tube and is surrounded by a larger glass casing to reduce the intense ultraviolet light and heat that is produced. These lights are hugely efficient and are used to light up large venues such as stadiums and parking lots. These lamps have to be 'pre-started' for about 10 minutes or so by first vaporizing the mercury gas inside the quartz tube. When this is finished, and the gas has increased in pressure from about 2 to 20 times sea-level pressure, the electric arc begins to discharge continuously through the gas to form the light-emitting plasma. Because plasmas are so efficient in conducting electricity, as the lamp continues to operate, its resistance decreases. If it were not for a device called a 'ballast' the lamp would quickly overheat and destroy itself.

The strongest lines in the spectrum are found at 184, 253 and 365 nm (UV A and UV C), as well as the visible lines at 404 (violet), 436 (blue), 546 (green), 578 (yellow orange) and 650 (red)[7]

High pressure sodium lamp

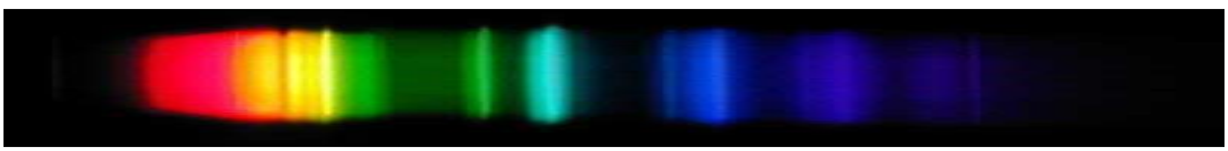


Figure 58. Example of a high-pressure sodium light spectrum. (Credit: Wikipedia)[8]

The operating principle is the same as for mercury vapor lights except that sodium produces only two spectral lines under low-pressure conditions, and many more lines under high-pressure operation. They are used for street lighting, and because the yellow sodium spectral is so bright, these streetlights have a yellow-orange color. They are in widespread use around the world; however, astronomers prefer low pressure lighting in cities because the two strong sodium lines can be easily blocked by telescopes. The numerous lines in the high-pressure lamps produce more of a natural sunlight spectrum but are much harder to filter out by astronomers conducting research near urban and urbanizing areas. High-pressure sodium lamps are fairly

[7] https://en.wikipedia.org/wiki/Mercury-vapor_lamp

[8] https://commons.wikimedia.org/wiki/File:Spectrum-hp-sodium.jpg

inexpensive, costing $17.00 for a 150-watt light[9]. A low-pressure sodium lamp at the same wattage might cost as much as $135.00 or more[10].

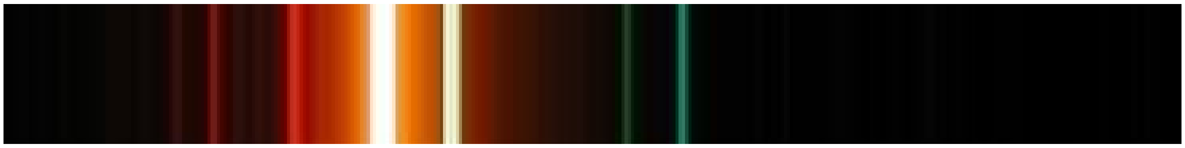


Figure 59. Example of low-pressure sodium light. The brightest line is at a wavelength of 589 nm and is actually a pair of lines called by astronomers the H and K-lines. (Credit: Wikipedia)[11]

Assessment:

With the aid of a spectrograph, the learner will explore and explain different kinds of plasma using conventional lamps and light sources. Distinct lines for each light source will be measured using the calibrated spectrum of a CFL.

9 https://www.amazon.com/Sunlite-03635-LU150-MOG-Pressure/dp/B004QWYMG6/ref=sr_1_3_sspa?crid=3K0M8WHPYN56&keywords=high+pressure+sodium+lamps&qid=1649271623&sprefix=high+pressure+sodium+lamps%2Caps%2C58&sr=8-3spons&psc=1&smid=A25GCJCNZU2KLL&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzNURLQ1YwUFVWWDRUJmVuY3J5cHRlZElkPUEwNTg0Mjc0M0c2QjFaTk1IODlQVCZlbmNyeXB0ZWRBZElkPUEwMDI4NDI2MzBJTVBGSk1KWldMNyZ3aWRnZXROYW1lPXNwX2F0ZiZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=

10 https://www.amazon.com/Philips-321539-135-watt-SOX135-Pressure/dp/B002E7WXD4/ref=sr_1_4?crid=JPM0X3UOPXOC&keywords=low+pressure+sodium+lamps&qid=1649271558&sprefix=low+pressure+sodium+lamps%2Caps%2C58&sr=8-4

11 https://commons.wikimedia.org/wiki/File:Low-pressure_sodium_lamp_700-350nm_widened.jpg

❑ Experiment HS9 - Creating plasma radio waves with CFL lamps

Overview: Plasmas also emit electromagnetic radiation in the radio spectrum. These radio waves can be detected with a simple AM or short-wave radio.

Objective: Learners will use a smartphone to record sound amplitude across the AM band and compare with a CFL lamp operating and turned off to see the quantity of radio noise produced.

Assessment: Learners will study and explain the amount of radio noise from a device and note its intensity changes across the AM radio band.

Background:

The plasma in a spark causes radio noise across many different frequencies from 30,000 to 30 million Hz. The movement of the electrons in the plasma is generally the source of the electromagnetic waves that combine to create the broad-spectrum radio noise. This is unavoidable because electrons will emit EM radiation whenever they are accelerated or decelerated such as in a collision with atoms and other ions in the plasma.

Sparks are a ubiquitous feature of modern technology. Each time a switch is opened or closed, a small spark can be created that produces EM signals. This includes various components of motors, generators, computers and things as simple as the static electric 'shock' you get when you shuffle across a carpeted floor and touch a metal doorknob. Most of these sparks carry less than 1 milliamp of current and cannot even be felt at all but can be devastating to exposed computer circuitry.

This experiment will investigate a CFL lamp as a source of radio noise and use a simple radio to detect and study them. In order to create a permanent record of radio noise, we will use a smartphone equipped with a sound-measuring app. The app will record the sound level of the noise at the speaker of the radio and produce a .csv formatted data file that can be exported to your laptop for further study.

Material:

- AM radio or one with long-wave bands below 530 kHz.
- Smartphone with a sound recording app that produces a .csv data file.

Procedure:

Step 1) On your phone, download a sound-recording app such as *Physics Toolbox* (iOS, Android) or *Decibel-X* (iOS). Create several test recordings, save them, and be familiar with how to export the .csv file to your laptop via email transfer and download.

Step 2) Obtain a portable radio and tune it to the low end of the band near or below 530 kHz. Find a compact fluorescent lamp (CFL) in your house and put the radio close to the bulb. Turn the bulb on. Place the CFL lamp about one foot from the radio. As you scan the radio across its band, you should hear locations where loud buzzing or humming occurs. Turn off the CFL lamp to check that the noise vanishes. The loud static noise is from the sparks used to excite the mercury vapor in the tube.

Step 3) Turn the radio volume control so that the loudest radio station is comfortably loud.

Step 4) Move the tuner to the lowest end of the radio band.

Gather Data:

Step 5) Start the smartphone sound app recording data and place the smartphone's microphone close to the radio speaker.

Step 6) Slowly and at a uniform pace, tune the radio from its lowest frequency to its highest frequency. When completed, stop the sound data recording and download the .csv file to your laptop.

Step 7) Open the .csf sound file in Excel and plot the column of data corresponding to the decibel values (dB) of the sound level. They will typically range from about 35 dB (very quiet) to 80 dB (very loud). For the *Physics Toolbox* app, this data is in Column B at 0.5second intervals.

Step 8) Turn the CFL bulb off and repeat Steps 3 – 7.

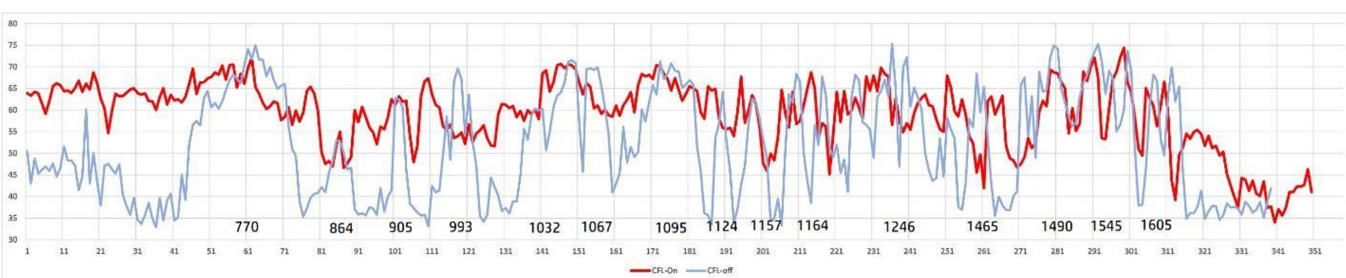


Figure 60. Radio spectrum with CFL off (blue) and CFL on (red) and stations labeled with frequency in kilohertz.

Step 9) You now have two plots: one for CFL-on with the noise, and one for CFL-off with no CFL noise. You can plot both of these together on the same plot by copying the data from one file into a separate column of the other file and then highlighting both columns to plot them together. An example is shown in Figure 60 using *Physics Toolbox* data.

Step 10) Return to the radio with the CFL lamp on and again scan through the band, identifying the frequencies of the detected radio stations and the locations where the CFL noise was present. Use this data to label the plots in Step 9 shown in Figure 60.

Explanation:

CFL lamps produce radio frequency noise caused by an electrical component called the ballast[12]. The ballast takes the 110v from your wall and steps it up to nearly 1000 volts to spark the mercury vapor into a plasma state. Because the resistance of the plasma decreases as it heats up, once the plasma is ignited, more and more current will flow until the tube is burned out. To control this effect, the ballast is designed not only to create the plasma but to regulate the current flowing through it.

Older ballasts used a simple resistor to control this and operated near the frequency of the line voltage of 50-60 Hz. You could often see the flickering of fluorescent lamps at this low frequency. Modern electronic ballasts operate between 20,000 to 80,000 times per second. This on/off switching causes electromagnetic radiation at frequencies between 40kHz and 80KHz, and all harmonics of these frequencies. The result is that radio noise[13] from CFL tubes appears across the standard Long-Wave (140-250 kHz), AM (560kHz to 1600 kHz) and short-wave bands (below 9Mhz). The worst noise appears near 40 kHz, which is far below most amateur radio channels.

Assessment:

Learners study and explain the amount of radio noise from a device and note its intensity changes across the AM radio band.

❑ Experiment HS10 – Moving plasma with magnetism

Overview: Magnetic fields can cause charged particles to move via the Lorentz Force. This force depends on the strength of the magnetic field and the speed of the charged particles in the electric current.

Objective: Learners will explore how magnetic fields can move the charged particles in a plasma.

Assessment: Learners demonstrate that electric currents in discharge arcs can be moved with magnetic fields.

[12] https://www.electrical4u.com/electronic-ballast/

[13] http://www.arrl.org/files/file/RFI/Light_Bulbs.pdf

Background:

Plasma spheres are known by many different names, but you see them in many craft and novelty stores or stores where electronic gadgets are sold. The principle was invented by Nicola Tesla in his investigations of high voltage alternating current. They consist of a center electrode, usually hollow and filled with crumpled metal to provide a variable electric potential on the surface of the electrode.

When a high-frequency (30,000 Hz) and high voltage electrical source (3,000 to 5,000 V) is applied to the inner electrode, plasma forms in the inert gas filling the interior of the main globe (mixtures of argon, neon, Zenon, etc.). Streamers of plasma form from this diffuse plasma that cause continuous discharges to stretch from the inner electrode to the outer grounded sphere as streams of electrons find the shortest path through the plasma to the ground. When you touch the outer surface, the minute change in the capacitance of the outer surface causes some filaments to preferentially discharge in the direction of your finger, which provides a better discharge ground than the freely floating surface.

The globe is emitting electromagnetic energy at high frequencies in order to maintain this plasma. This electromagnetic field can be detected by using your voltmeter as a radio receiver.

Materials:

- A plasma sphere.
- A voltmeter.
- A fluorescent lamp – compact fluorescent lamp (CFL) or aquarium tube.
- A copper penny.
- An insulated screwdriver.
- 2x2-inch aluminum foil.
- Xenon flash tube $7.00 (IFK-120 Strobotron) https://tinyurl.com/5ct9j3sv ➢ One alligator clip.
- 10-feet of 22-gauge insulated 'bell' wire or equivalent.
- Neodymium disk magnet. 30mm x 2mm, $9.49 (https://tinyurl.com/5ct9j3sv) Pack of 8

Safety Note: Never pull neodymium magnets apart. Instead, slide them apart and make sure that they are stored with a thick, non-magnetic spacer in between them. All small neodymium magnets such as the ones used here present an uncomfortable pinching hazard if they are not used carefully. **NEVER** swallow pairs of these magnets. This will cause severe internal injuries that can be fatal.

Procedure:

Step 1) Turn on the plasma sphere.

Step 2) Place the CFL tube close to the surface of the sphere. You should see the lamp start to glow. As you move the tube away the glow in the tube should diminish rapidly.

Figure 61. An example of a fluorescent CFL lamp being excited by the electromagnetic field of the plasma sphere without any physical contact between the lamp and the sphere.

Step 3) Turn on your voltmeter and set it for the AC scale.

Step 4) Clip the Common Ground test probe to a water pipe or metal faucet so that it is connected to a good earth ground.

Step 5) With the other test lead, clip it to the 2x2-inch aluminum foil to make an antenna, then move it towards the operating plasma sphere and note the change in voltage.

Figure 62. The aluminum foil attached to the VOM test lead serves as an antenna to capture some of the electromagnetic energy from the central plasma ball electrode. The VOM reads about 0.2 volts on the DC scale.

Step 6) With the plasma ball turned off, place a copper penny at the top of the spherical ball.

Step 7) Turn on the plasma ball and move the tip of the screwdriver close to the exposed surface of the penny. As you tap the penny with the tip of the screwdriver you should see sparks appear and disappear.

If you can create a spark (plasma) between the globe and a sharp conductor like the tip of a screwdriver, why aren't there sparks all along the surface of the globe all the time? The reason is that it takes an electric field with a strength of 3,000 volts/mm to ionize ordinary dry air. In this set-up, that voltage is created between the penny (high voltage) and the tip of the screwdriver (ground) when it is brought very close to the globe.

The most difficult thing to demonstrate is that magnetic fields can affect plasma using common and safe ingredients. Ideally, by bringing a very strong neodymium magnet close to the filaments in the plasma sphere, you should be able to make them wiggle. You can get them to move, but this isn't because the magnet is affecting them directly. Instead, when you bring a very strong magnet close to the plasma sphere, you are affecting the high-voltage transformer itself, causing the plasma to dim. In Step 7 we saw that there is an electrical field around the plasma globe that can be used to strike a spark. This electrical field can create a weak plasma inside a xenon flash lamp.

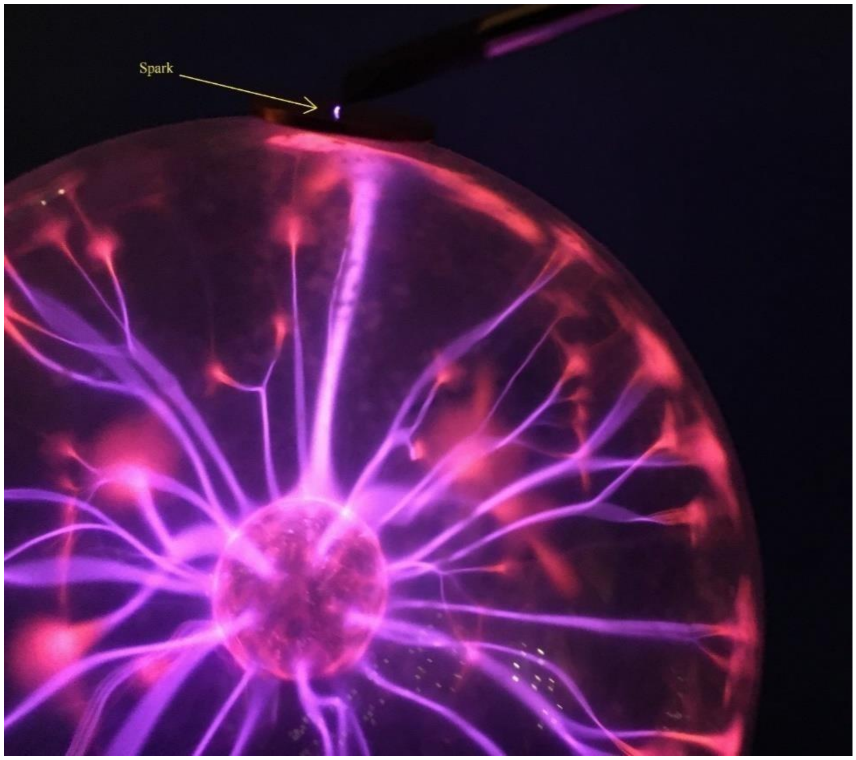


Figure 63. Spark taken in burst mode with a smartphone using camera's automatic set up and focus

Step 8) Attach the alligator clip to one end of the wire. Attach the other end to a copper water pipe to create a 'ground' line.

Step 9) Attach the ground line alligator clip to one electrode of the xenon lamp.

Step 10) Secure the xenon lamp to the black card by taping the ground wire to the card and use a small piece of tape to secure the bottom of the lamp where the electrodes are to the card.

Step 11) Turn on the plasma sphere, and with the card in contact (tangentially) with the globe, slide the flash lamp across the globe until a bright glow appears inside the tube. You should also observe a faint filament that connects one electrode with the other part-way or fully around the loop of the lamp. Figure 64 shows an example of this. To make this configuration more stable, use DVD disk cases or books on each side of the plasma globe to create a horizontal surface. Place the card on this surface so that the xenon lamp touches the plasma globe at a tangent point where the electrical field will be the most intense. Secure the card in place by taping it to the stack of DVD cases.

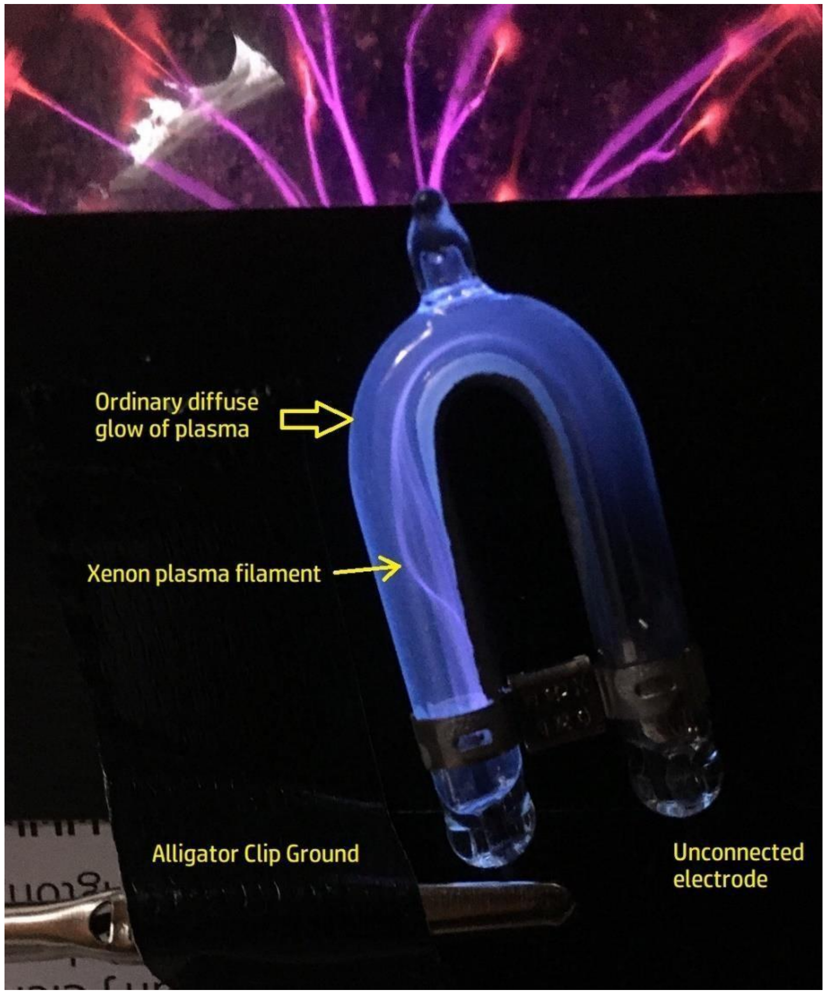


Figure 64. A Xenon lamp filament activated by an electric field near the plasma globe.

Step 12) This step requires some patience and a magnet with a suitable strength and concentration. The best magnets for this are neodymium alloy magnets because they have very strong magnetic fields and occupy a small area making them very concentrated. Figure 65 shows an example of the kind of motion to be expected. Figure 65A shows the position of the filament when the magnet is far from the tube. Bringing the magnet so that it nearly touches the tube causes the filament to move slightly away from the magnet shown in Figure 65B. Under extreme conditions, you can even get the filament to vanish and the tube to completely darken as the plasma is pushed into the glass walls of the tube.

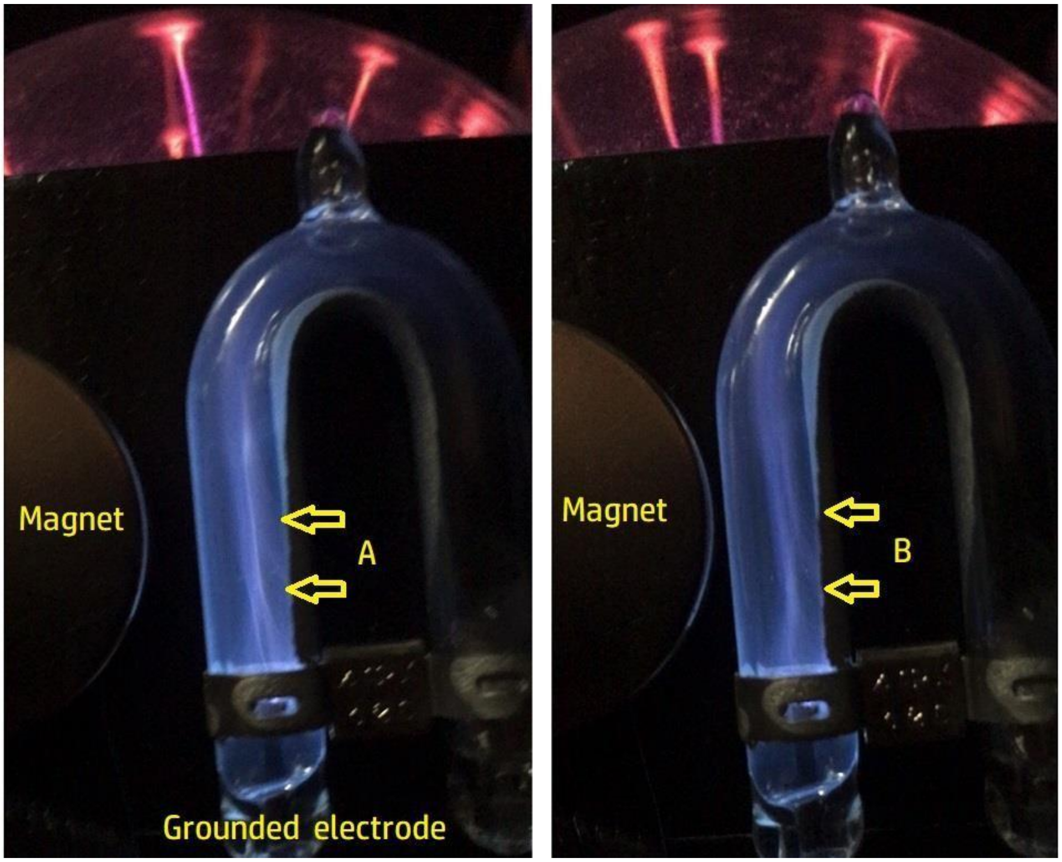


Figure 65. Motion of xenon plasma filament under the action of a magnetic field. Note the filament shift between A and B.

Explanation:

The magnetic force on a plasma is given by Lorentz's Law: F = q*v*B where q is the charge of the plasma, v is the speed of the charged particles in the plasma in multiples of the speed-of-light, and B is the magnetic field strength.

Plasmas can usually be controlled by magnetic fields, but in order to witness deflections of plasma, the charges must move for long enough times. A plasma ball operates on a high-frequency alternating voltage, so the slow-moving charges in the low temperature filaments do not have much time to move a measurable distance in one cycle and get deflected. In a plasma light, the filaments are not electrically charged enough and move too slowly for this effect to be seen, using a typical (ferrite-iron) toy magnet. We need a stronger magnet (neodymium-alloy), a much denser plasma (higher q) that is moving faster (higher v) to more easily see this effect.

Assessment:

Learners will demonstrate and explain how magnetic forces can steer the direction of charged particles in plasmas.

❑ Experiment HS11 - Plasma discharge in high-voltage power lines

Overview: High-voltage power lines carry alternating current, and their magnetic fields can be detected from a distance of tens of meters. This can cause interference on electrical devices.

Objective: Learners will be able to: Describe the properties of a magnetic field

Assessment: Learners make a smartphone measurement of the ground-level magnetic field from a high-voltage power line and use a simple formula to derive the current flowing in the power line using the measured magnetic field.

Background:

Although residential power lines outside your home carry insufficient currents to be detectable at ground level, high-voltage power lines have their three-phase lines separated by enough distance that you can usually stand under one of them unlike in the residential power line set up. These lines carry hundreds of kilovolts and hundreds of amperes of electricity. These electric currents can be detected using your smartphone and also electromagnetic field (EMF) meters.

High-voltage transmission lines are located on tall towers and have various configurations depending on their voltage and the number of circuits they carry. A set of high-voltage power transmission lines from the Dickerson Generating Station crosses River Road in Maryland just outside Poolesville as shown in Figure 66 . The Dickerson Generating Station is an 853-megawatt coal-fired generating plant owned by NRG Energy. The three-phase lines are physically separated so that you can be close to one of these lines and far from the others so that only the current in the closest line is dominant.

Materials:

- ➢ Smartphone with magnetometer app that graphs data.
- ➢ An app that works as a clinometer to measure elevation angles of targets.
- ➢ 1x EMF meter such as the GQ EMF-390 ($127.00), which measures both the RF and electric field intensity, or Erikhill EMF Meter ($39.99), which measures electric fields (V/m^2).

Procedure:

Step 1) Find a safe location where transmission lines pass over a roadway, a park or some other accessible location. You need to be able to stand directly under the lines to make the measurements.

Step 2) Start up the magnetometer app and check that you see at least one of the magnetic components exhibiting a rapid sinusoidal change. Point the smartphone (Y-axis) perpendicular to the direction of the powerline. The X axis of the smartphone should be parallel to the powerline. Start the data recording and storage in a spreadsheet.

Step 3) Use your EMF meter to measure the electric field strength (V/meter) and if available, the radio frequency (RF) emission (mW/m^2) under the transmission line.

Figure 66. Transmission towers on River Road in Poolesville, Maryland. The tower on the right carries three 500,000-volt (500 kV) transmission lines.

Author's example: The app Physics Toolbox was used to record the magnetic field of this cable from directly underneath as shown in Figure 67. The sample interval was 0.1 seconds (10 Hz).

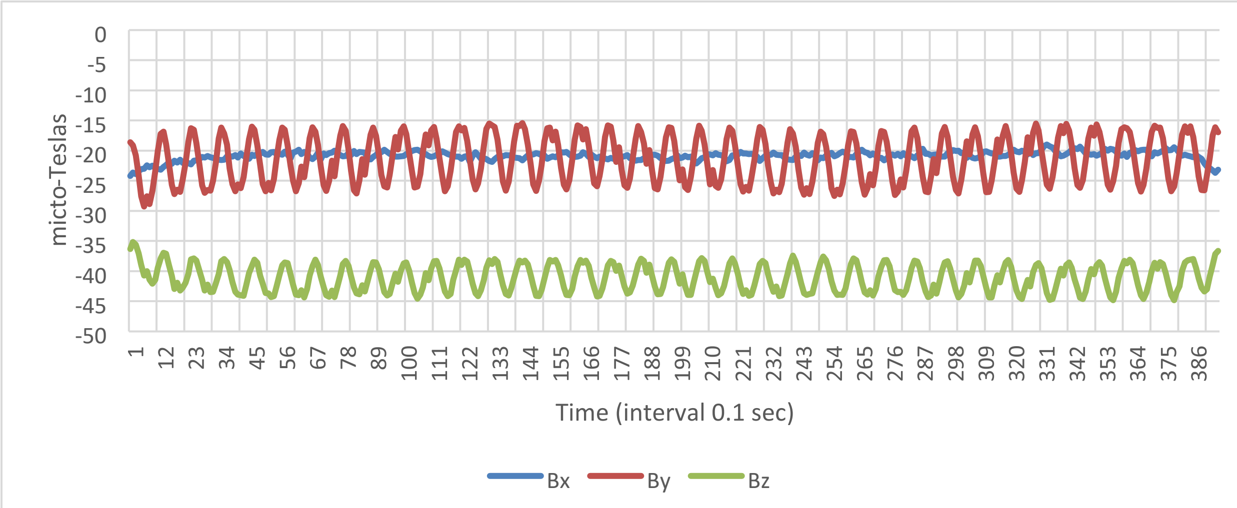


Figure 67. Plots of periodic changes in magnetic field under a high-voltage transmission line.

Gathering Data:

The magnetic field of a wire carrying a current is circular so that for this roadway geometry, standing directly below the 500 kV wire, the principal field axis should be purely in the horizontal (By - Bz) plane with no variation perpendicular to the roadway along the wire's axis (Bx). Because the current in the wire oscillates at about 60 Hz, the field strength along the roadway (By) and along the vertical axis (Bz) should oscillate as the current flow oscillates from +Imax to -Imax, which is what the figure shows. For comparison, a record of the local geomagnetic field shown in Figure 67 was made at a distance of 65 meters shown below, which has the components Bx=-17.4 μTesla, By=17.2 μTesla and Bz=-47.5 μTesla for a value |B|=53.4 μTesla. The traces are flat showing no measurable influence of any local time-varying magnetic systems.

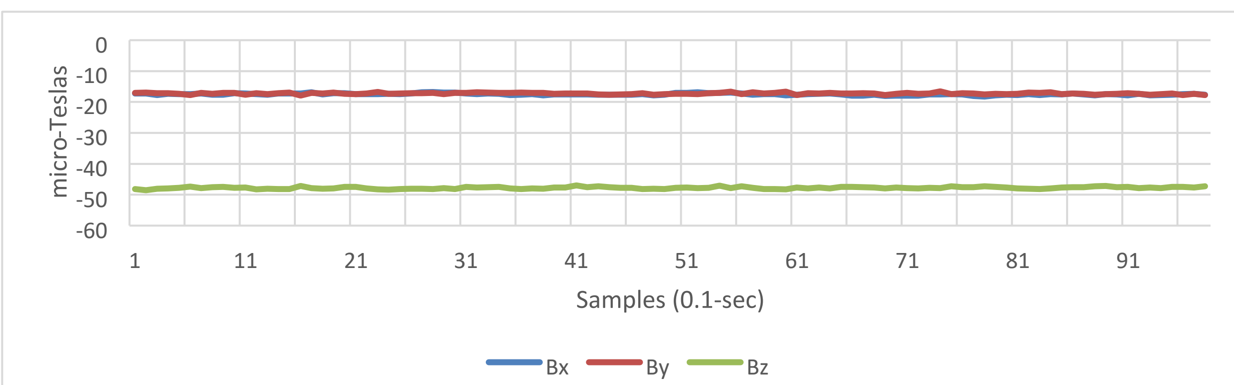


Figure 68. At 65 meters there is no trace of the changing magnetic field.

Table 9 summarizes the relevant features. The magnetic field values were determined by placing the long axis of the smartphone (Y) along the center of the roadway, which is perpendicular to the line. The smartphone X axis is perpendicular to the roadway in the horizontal plane, while the Z axis is along the local zenith-nadir axis. Because the magnetic fields change with the oscillating current, the amplitude, B, of the magnetic field in each direction varies according to B(t)=B cos(2pωt) where ω=1/60 where '60' is the frequency in Hertz.

Table 9. Sample measurements

	Field due to current (μTesla)		
Bx (along powerline)	0.3	0	0
By (perpend to powerline)	4.6	0	0
Bz (local zenith-nadir)	2.1	0.15	0
|B|=	**5.1**	**0.2**	**0**
Roadway Distance	0 m	50 m	65 m
Distance to wire	7 m	50.5 m	65.4 m
Distance in multiples of initial height (7m)	1	7	9

EMF measurements:

The electric field under a 500 kV transmission line that is 20 feet (6 meters) above your head can be as high as 1000 V/m^2. At a distance from this line beyond 100 meters, the electric field will typically be lower than 1 V/m. If you don't hear the crackling of arc discharges, the RF intensity may be very low at 0.001 mW/m^2, however if you hear this crackling sound, the RF intensity may be as high as 1.5 mW/m^2.

Figure 69. A common utility pole transformer bank for three-phase electrical distribution. The main supply of 6,000 volts is carried by the three lines at the top of the pole. Below these lines will be one or more transformers to step down this voltage to 240 volts for use in your home. You will not hear crackling of electricity in these lines or at the utility poles because the electrical fields are below the break-down field of the atmosphere (3000 V/mm). You may hear the crackling sound if there are defective parts on the utility pole especially in the transformers and capacitors. (Credit: Wikipedia)

Explanation:

The high-voltage lines carry over 300 kV of electricity. At ground level, the resulting electric field from this line can be over 3,000 V/mm. Arc discharges, called corona discharges, are common near the transmission towers because there are many locations where the electric field can exceed 3,000 V/mm and cause sparking. This is the noise you hear in the 'crackling' of the electricity. This crackling produces radio-wave emission that you can hear on your AM radio, and you can measure using an 'RF' meter. The sound of this crackling is a giveaway that plasma is being created in the arc discharges.

Figure 70. Corona discharge on corona ring of 500 kV overhead power line. The picture was taken at night with a camera on a tripod using a 200mm lens, ISO 200 and a 90-second exposure. (Credit: Wikipedia)

Assessment:

Learners detect the changing magnetic field in a transmission line and relate this to the existence of strong electrical currents that can produce corona discharge plasma.

❑ Experiment HS12 – Plasma near a high-voltage transmission line

Overview: Electromagnetic energy is required to produce the conditions for forming a plasma.

Objective: Learners will be able to use the electric field of a high-voltage transmission line to stimulate the production of plasma in an ordinary fluorescent lamp.

Assessment: Learners will explain why a plasma is produced in an ordinary fluorescent lamp.

Background:

High-voltage transmission lines above 300,000 volts (300 kV) produce electric fields at ground level that can exceed 1000 volts/meter. This is enough energy to cause the mercury inside fluorescent lamps to produce a bright glow as the atoms are ionized and generate a weak plasma.

This experiment will demonstrate plasma production through this mechanism.

Materials:

- Plasma globe lamp.
- Fluorescent tube.
  Philips Soft White 30w 36-inch T12 ($9.98).
  Philips Cool White 54w 46-inch T5 ($9.98).
- Compact Fluorescent Bulb.
- Smartphone camera.

Procedure:

Step 1) Turn on the Plasma Globe and place the fluorescent tube and CFL close to the globe. You should notice the mercury vapor in each lamp beginning to glow as you bring each bulb close to the glass. This shows that the electric field outside the plasma globe is strong enough to cause plasma to form inside the fluorescent tube.

Step 2) Find a transmission line of at least 300 kV close to your home. At twilight, hold each of the fluorescent bulbs in a vertical orientation under the closest transmission line overhead.

Gathering Data:

The best result for the fluorescent bulb is to place one end in contact with the earth to ‘ground’ one end of the tube and hold the other end vertically with one finger placed on the metal electrode. This will cause the tube to glow brightly along its entire length. Alternately, hold the tube vertically in the air by its glass envelope and the tube will glow brightly between your grounded hand and the top of the bulb.

The CFL will also glow, but this will be more difficult to see and will require holding the bulb by its glass envelope overhead and moving it around until you see the lamp flicker.

Take a selfie or other type of photo of your glowing lamp with your smartphone. This is best done with the help of a friend. Figure 71 shows some examples taken with an older iPhone 6s, but more modern low-light-level cameras such as the Pixel 3 and iPhone 12 will produce much better images under these lighting conditions. You may even see stars in the sky!

These images were shot under the 500 kV transmission line of the Dickerson power plant as the line crossed River Road in Maryland near Poolesville.

Explanation:

The electric field at ground level is about 1000 volts/meter so that for a lamp about 3-feet in length there is about 1000-volts of voltage difference between the ends of the bulb. This is enough to get the mercury vapor to partially ionize so that the gas inside the tube consists of neutral mercury atoms, mercury ions and free electrons, which constitutes a plasma.

Assessment:

Learners will explain why a plasma is produced in an ordinary fluorescent lamp.

Figure 71. A) is the Philips Soft White 30w bulb held at arms-length in the air. Note the silhouette of the two transmission towers in the background. The one on the right is the 500-kV circuit. The one on the left is a lower-voltage transmission line whose ground-level electric field was insufficient to cause the plasma to glow. B) shows the 30w Philips bulb held horizontally with the twilight sky and the moon in the distance. An attempt at some artistry in creating the picture under low light level conditions. C) is the 54w Philips soft white bulb which glows much more brightly due to its increased mercury vapor content. D) is an ordinary CFL bulb held in the air at a spot where the brightness is the greatest. It took several minutes of walking around and holding the lamp above my head to find this 'sweet spot'.

❑ Experiment HS13 – Building a simple plasma spark detector

Overview: Sparks and lightning are two forms of plasma that generate broadband radio wave interference (called RFI). This interference can be used to detect sources of plasma.

Objective: Learners will be able to construct an electronic device that detects the RFI from plasma.

Assessment: Learners can explain how RFI and a DIY lightning detector can be used to detect sources of plasma and use it to detect common sources.

Background:

Lightning is a dramatic source of plasma, and a dramatic generator of radio frequency interference (RFI) each time a lightning stroke appears. There is enough EM energy generated by the plasma that these lightning discharges can be heard on AM radios from many miles away. This principle is used by 'Lightning Detectors' that can be purchased commercially to warn you of an approaching storm.

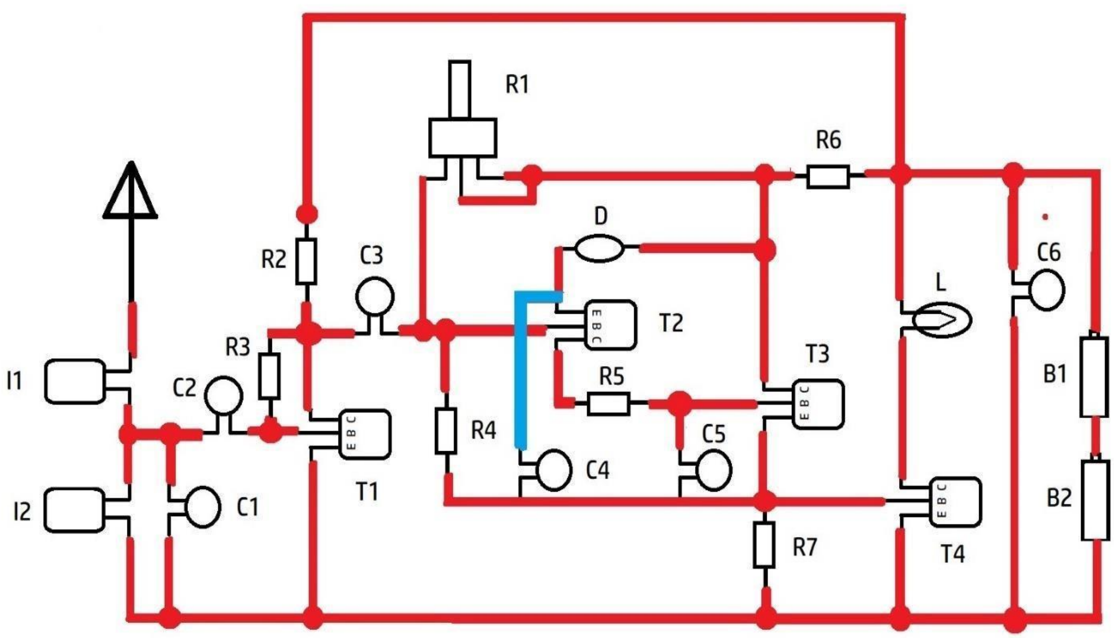


Figure 72. Circuit diagram of lightning detector showing components and electrical connections. The blue line is a 'jumper' across the connection to the base 'B' of transistor T2.

In this experiment, we will build a simple lightning detector and use it to study the RF emission from electrical discharges from a variety of sources. It is based upon a design published at EasyCircuit.com (https://tinyurl.com/3fy7dva4) and shown as a component view in Figure 72.

This is a simple radio receiver that operates at a frequency of 300 kHz just below the AM radio band, which is where the RFI from plasma arcing is most intense. The flasher is biased to not flash until a burst of RF energy, amplified by the 2N3904, is applied to the base of the 2N4403.

The receiver requires familiarity with assembling electrical components based on a diagram. Some soldering may also be required but can be avoided using a breadboard kit.

Materials (See Figure 72 for symbols and identifications):

- C1= 680 pF, 300 VAC (Cat: 81-DE6B3K681KN3AE01 $0.69)
- C2, C3= 0.01 mF, 50V (Cat: 594-K103M15X7RF5TL2 $0.27 each)
- C4 = 100 mF, 25V (Cat: 710-860010473007 $0.13)
- C5 = 0.005 mF, 3kV Disc Cap. (Cat: 594-S502M75Z5UR83L0R $0.73)
- C6 = 5 mF, 50V Electrolytic (Cat: 75-TE1303-E3 $4.51)
- D = 1N914 (Cat: 512-1N914 $0.10)
- I1 = 10 mH (Cat: 580-18R106C $1.42)
- I2 = 330 mH (Cat: 652-RLB0914-331KL $0.50)
- L = 2.5-volt, 0.3 A lamp (Cat: 560-8732 $1.11)
- R1 = 20k potentiometer (Cat: 179-PT01-D120D-B203 $0.79)
- R2 = 3.9 kW (Cat: 71-MBA02040C3901FC10 $0.40)
- R3 = 180 kW (Cat: 594-MBB02070C1803DC1 $0.41)
- R4 = 22 kW (Cat: 71-RL07S-G-22K/R $0.59)
- R5 = 2.2 kW (Cat: 279-CBT25J2K2 $0.66)
- R6 = 47 W (Cat: 71-RL07S470GTR $0.52)
- R7 = 2.7 kW (Cat: 71-CMF072K7000JKR6 $0.62)
- T1, T3, T4 = 2N4401 (Cat: 512-2N4401TA $0.39) each)
- T2 = 2N4403 (Cat: 512-2N4403TF $0.39)
- AA battery holder for 2 cells: (Cat: 534-2462 $1.29)
- Bread boarding kit (Amazon.com - Bojack or equivalent $12.99)
- B1, B2 = 1.5-volt, AA batteries ($0.75 each)

For convenience, all component parts were ordered at mouser.com. The catalog number and prices are shown in the list. The total cost for materials (not including shipping) is under $18.00. Including the breadboard kit, the cost is about $31.00.

Figure 73 shows the components laid out before assembly. The bread board is the rectangular object at the top. It measures 5cm x 16.5 cm. It is a good idea to unpack each component and label it on a piece of paper such as in Figure 66. This prevents mis-identifying some components since many do not have markings on them to help with identification.

A significant savings occurs if you build your own breadboard kit by tapping nails into a piece of wood and soldering the components to the nails at the points indicated by the round junction symbols in Figure 72. Simply copy the figure onto a piece of plywood and place nails at each junction point. Make proper allowance for the lengths of the component leads. Figure 72 is not drawn to scale.

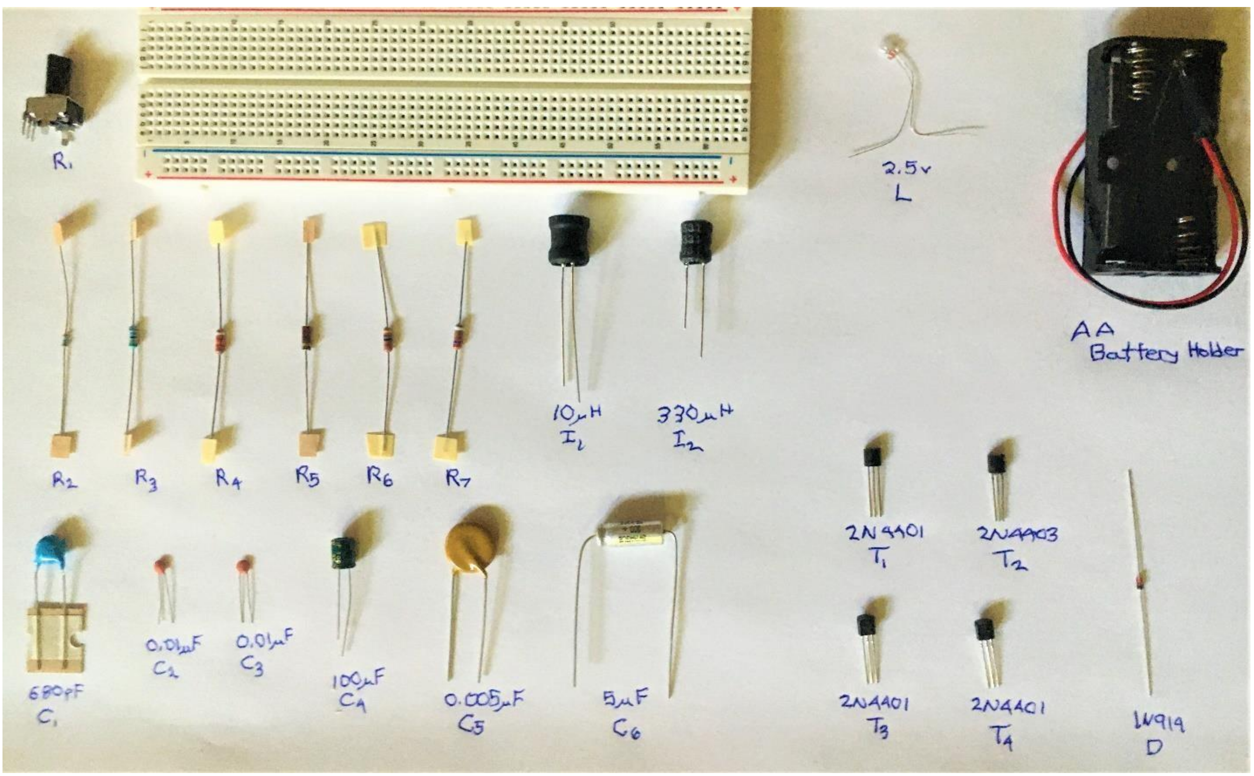


Figure 73. The components to the detector shown as they appear along with their values and indices (e.g. R1, R2, ... C1, C2 ...) that appear in Figure 72.

Procedure:

Step 1) Bread board construction will be a challenge because of the design of many breadboards. For example, in Figure 74, the *Bojack* breadboard has parallel rows of holes that are electrically tied together. The rows are indicated by numbers and the columns by letters: a-j. In each row, all holes from a-j can be used to represent the connections entering one point in the diagram in Figure 72. The challenge is to place the components on the board in a way that takes advantage of this feature given the size of each component. Figure 75 shows how L1, L2, C1 and C2 are connected.

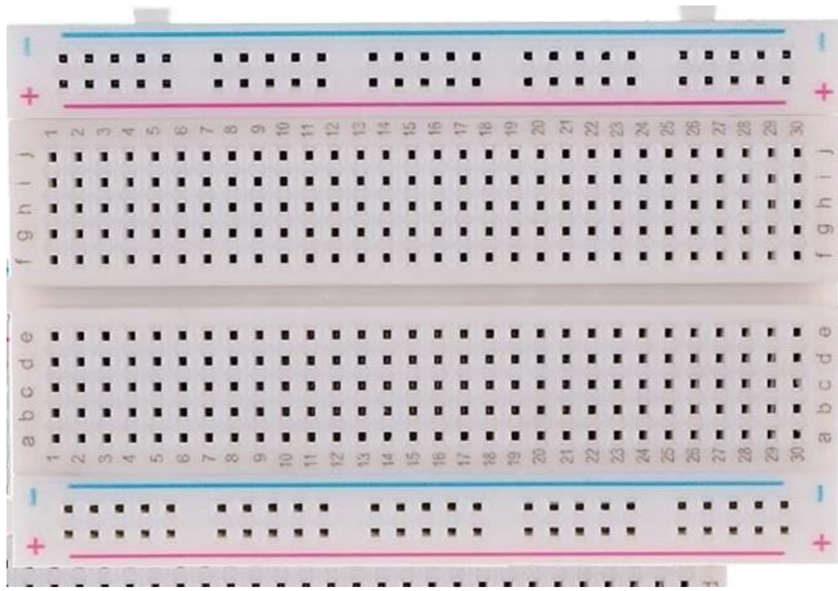


Figure 74. Bojack breadboard rotated 90 degrees for convenience. Each numbered row is electrically tied together but not to the '+' and '-' power strips. The power strip holes are all tied together with the same polarity.

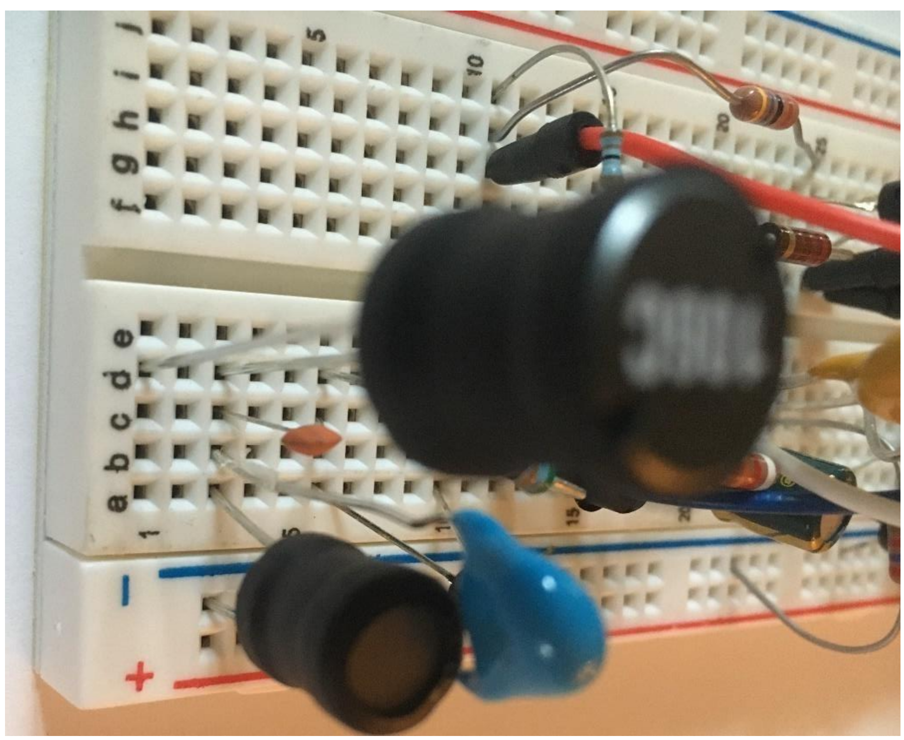


Figure 75. Breadboard with components assembled.

In row #3, the components that share the same connection are L1 (d3), L2(d3), C1(b3) and C2(c3). The row marked '+' is the positive side of the battery and we see that the component L2 is connected to this 'power strip'. The capacitor C1 is also connected to this '+' power strip in the adjacent hole which is blocked from view in this photograph.

A degree of advanced planning is required to have all the components connected correctly and you may have to remove and replace the same component several times as you build up the circuit.

Step 2) The capacitors C4 and C6 are electrolytics which means they are polarized and must be inserted with their positive ends facing the top of the diagram. The polarity is written on the case of the capacitor.

Step 3) The 2N4401 and 2N4403 transistors have three leads each and are numbered as follows:

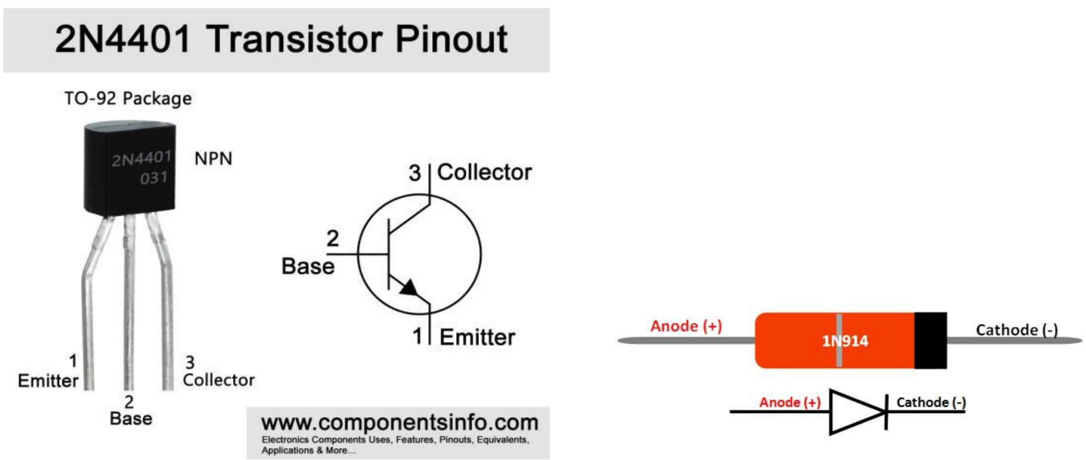


Figure 76. The pin assignments for the 2N4401 and 2N4403 transistors and the 1N914 diode.

Step 4) The diode, D, is polarized and must be inserted with its black-banded end (negative end) directed towards the 2N4403 transistor T2.

Step 5) Be careful soldering the diode and the transistor because they can be heat damaged with common soldering irons. Use a 'heat sink' if available. For bread boarding kits, no soldering is needed. Simply insert the leads into any convenient holes. Figure 77 and 78 show examples of this device assembled on a solderless bread board.

Step 6) Make sure you check and re-check the connections. Working with breadboards and very small components is a challenge and it is not uncommon to place a component in the wrong hole or to fail to firmly insert components for proper electrical contact. Be very careful that the transistors and diodes are inserted properly.

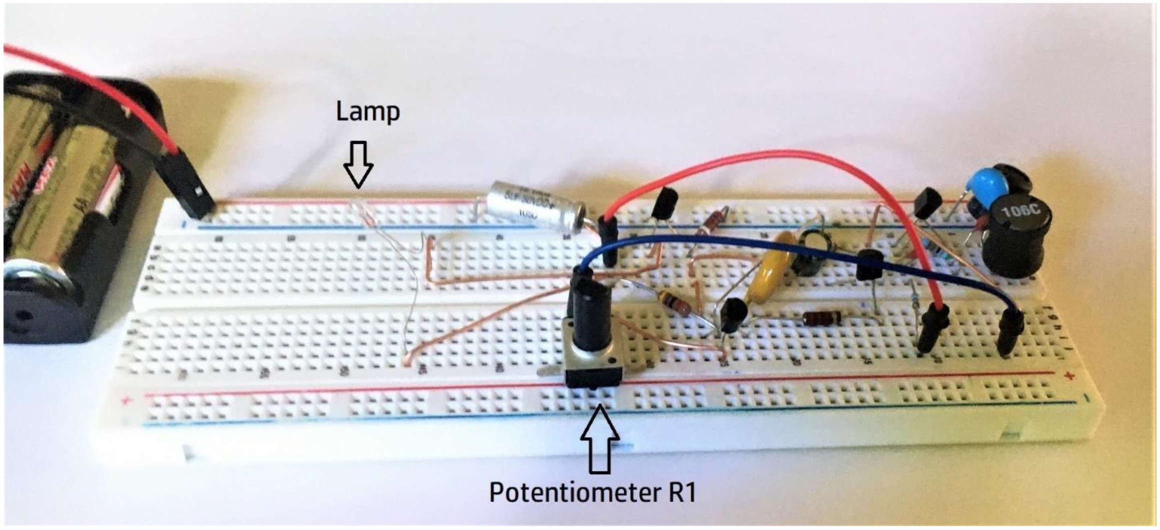


Figure 77. Example of the lightning detector assembled on a bread board.

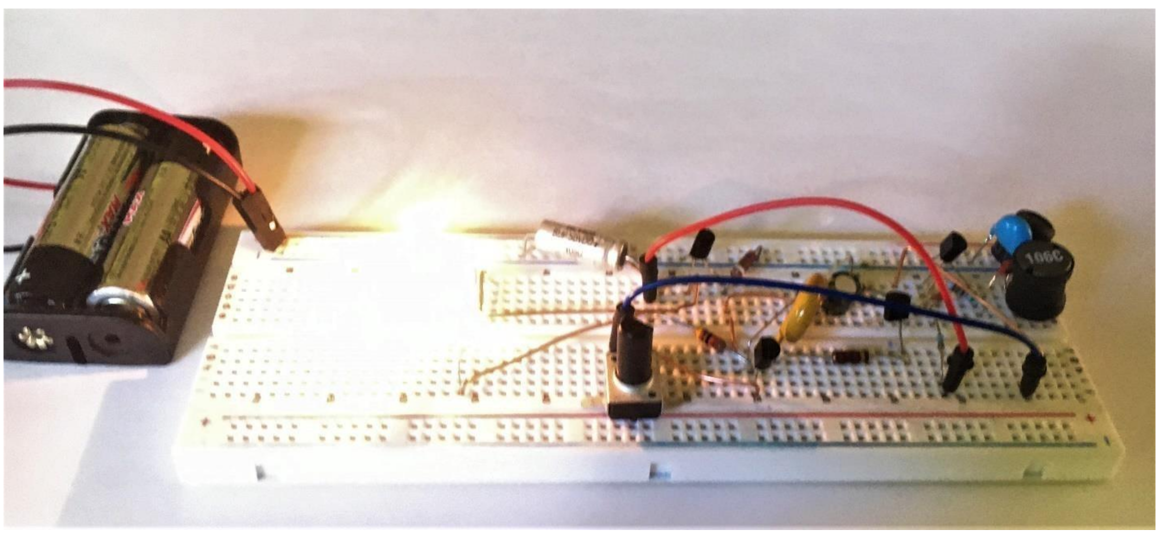


Figure 78. Lamp activated during test, but with no antenna attached on right end of board.

Step 7) Insert the batteries in the battery holder. The lamp should immediately turn on as you rotate the potentiometer (R1) knob. Figure 78 shows the lamp turned on during this test. If you cannot get the lamp to turn on for any setting of R1, re-check all of your connections. Common errors include not installing the electrolytic capacitors C4 and C6 properly and not installing the diode properly. Also, pay close attention to the transistor pin assignments in Figure 76.

Step 8) A short 60-cm antenna should be attached to the inductor I1 as shown by the triangular symbol in Figure 72. It need not be straight but can be curled into a loose spiral.

Step 9) When you have determined that the unit works, mount the board inside a box, which can be made from common foam board. The lamp should protrude from the top, and the shaft of R1 should be accessible. The antenna can be run through a small hole in the top of the box. Figure 79 shows an example of such an assembly.

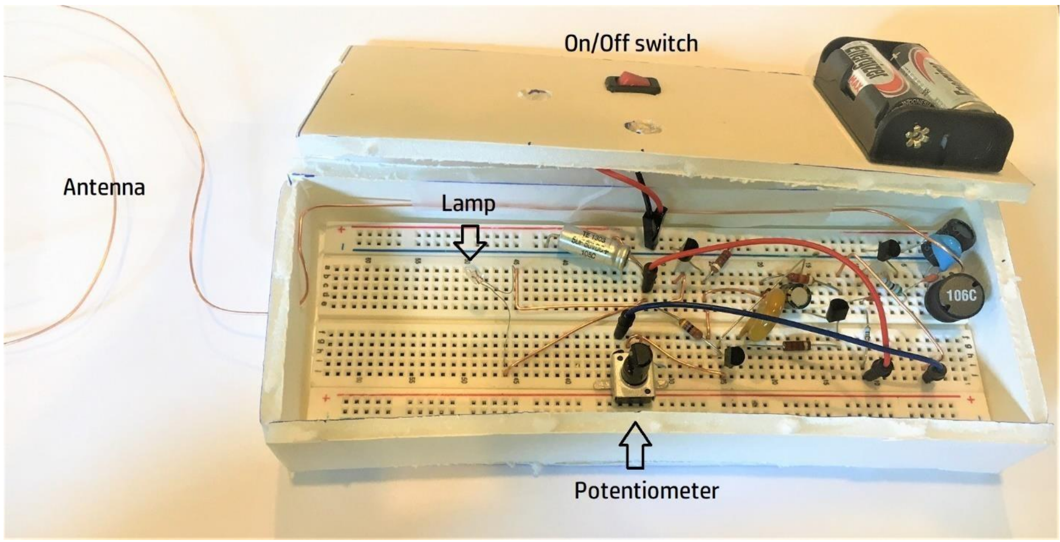


Figure 79. Detector mounted in a compact foamboard box.

Step 10) Adjust the potentiometer R1 until the regular flashing stops. When properly adjusted, the lamp will occasionally flash when large motors or appliances switch on and off. An approaching storm will produce multiple flashes for individual strikes within 10 km.

Step 11) Tune an AM radio to the bottom of the dial to monitor the pulses that the lightning detector is receiving.

Step 12) Increased sensitivity may be achieved by increasing the antenna length.

Step 13) The receiver draws about 0.3 milliamps when in operation. Common AA batteries supply about 2500 milliamp Hours, so this device using AA batteries should be able to operate continuously for 7500 hours (312 days). Higher battery drain rates occur during frequent stormy events due to the increased lamp activity. An on/off switch near the batteries can be added so that the device can be switched off when the device is not being used between storms. This will allow dozens of storms to be monitored without exhausting the batteries.

Gathering Data:

Step 14) Set the sensitivity of the detector so that the lamp flashes slower than once every 5 seconds.

Step 15) Create a table of possible sources of electric discharges, note their loudness on an AM radio, and also note the flashing of the detector lamp. Table 10 shows some examples. An EM power meter has been used to calibrate the RFI signal in terms of radio flux (Watts/m^2) for some common sources. All sources are in the milliwatts/m^2 range. Other sources such as arc welders will generate much more RFI power, and the plasma detector should be able to detect them at distances greater than a few meters. Note that the Laptop does produce RFI but the switching that produces plasma is at megahertz frequencies. There is little RFI in the 400 kHz band region so no rapid flashing will result. Table 10. Calibrating the Plasma Detector

Source	**RFI Power (mW/m^2)**	**AM @ 500kHz**	**Plasma Detector**
Crackling trans. line	2	Loud buzzing	At 30 meters-no signal
CFL lamp	2	Loud crackling	Bringing antenna wire within 1 cm of the lamp causes very rapid flashing
Laptop	5	Normal noise	No rapid flashing
Plasma sphere	10	Loud buzzing	Flashing period at 1 per sec at 1.5 meters and lamp continuously on at 1 meter or closer.
Local T-storm	10	Loud crackles with each bolt	

Explanation:

The detector receives EM radio energy from the antenna (microvolts) at the base of the impedance-matching inductor L1, and with L2 and C1 only passes the oscillations in this energy slower than about 338kHz. The capacitor C1 (680 pF) and the coil inductor L2 (330 mH) for what is called an LC filter that resonates at a frequency of

$$f = \frac{1}{2\pi\sqrt{L\,C}} = \frac{1}{6.242\sqrt{(330x10^{-6})(680x10^{-12})}} = 338\ kHz$$

All the other energy is shunted to the negative battery ground in the circuit. C2 acts to suppress any DC signal and passes the 338 kHz signal to the pre-amplifier defined by T1. The output from the preamplifier at the collector ‘C’ of T1 is passed through capacitor C3 to further remove any DC noise and passed to the base of T2 for the second stage of amplification. The amplified output of T2 appears on the transistor's collector 'C' where it is fed to the base 'B' of transistor T3 for the third stage of amplification. The output from T3 is then fed to the base of transistor T4 for the fourth stage of amplification. The output from T4 is then large enough to drive the lamp. The input AC signal detected by the antenna and amplified by T1 is rectified into a DC signal by the diode, D. The variable resistor R1 is placed between the input base of T1 and the output collector of T2, and its resistance causes T1 and T2 to oscillate at a frequency determined by the input signal from the antenna. The resistor R1 is set so that the circuit barely oscillates.

When a signal is present at the output collector of the T1 preamplifier, the small added signal pushes the oscillator to oscillate at a faster rate. The result is that the lamp turns on and off with a flashing period related to the input power of the 400 kHz signal. Any strong EM radio signal at 338 kHz or lower will set off the detector because it cannot discriminate between RF power from lightning or RF power from a local radio transmitter in the waveband below a frequency of about 400 kHz.

Assessment:

Learners can explain how RFI and a DIY lightning detector can be used to detect sources of plasma and use them to detect common sources.

❑ Experiment HS14– Exploring the Ionosphere through radio propagation

Overview: The ionosphere is a layer of plasma in the upper atmosphere that can be used to reflect radio broadcasts from the ground to distant parts of earth. The changing density of the ionosphere between day and night can be detected using an AM or shortwave radio.

Objective: Learners will be able to explain why nighttime is best for listening to distant radio stations by describing the properties of the ionosphere plasma.

Assessment: Learners will describe how radio propagation is affected by ionospheric plasma density.

Background:

The Ionosphere is an electrically charged layer of Earth's atmosphere located above an altitude of 60 km. It was proposed in the early 1900s by Arthur Kennelly and Oliver Heaviside as they explored why Marconi's long-wavelength radio waves could travel far beyond the line-of-sight distance between a transmitter and a receiver. It was actually discovered in 1924 by Edward Appleton for which he received the 1947 Nobel Prize. This layer consists of a mixture of neutral atoms of oxygen and nitrogen, their ions and free electrons making this a plasma at lower altitudes in the so-called D and E-regions. At higher altitudes in the F-region, hydrogen and oxygen dominate with the lighter hydrogen atoms being produced by the ionization of water molecules in the lower atmosphere – a process called photoionization.

Although the exact composition and density of this plasma changes in a complex way between the D and E-regions, at an altitude of about 200 km, there are about 1000 oxygen (O_2) and nitrogen (N_2) ions per cc, 1,000,000 electrons/cc and the neutral molecules of O_2 and N_2 constitute about 1 billion molecules/cc. The fraction of ions and electrons is only 1/1000 of the neutrals so this is a very weak plasma[14]. Nevertheless, the low density of electrons provides a very effective mirror for radio waves, and this allows what radio operators call Skywave Propagation to occur.

The density of electrons and the structure of the ionosphere are not fixed in space and time because there are a number of phenomena that cause physical changes in the strength and location of the ionosphere. In the daytime, the solar wind compresses the ionosphere so that only nearby radio stations are reflected by this mirror, which is now close to the ground. At night, the solar wind is no longer compressing the ionosphere and so its base is pushed to higher altitudes so that more distant radio stations can be heard via Skywave Propagation.

Another modification to the ionosphere occurs as the sources of the ionization change. Ultraviolet light from sunlight causes photoionization of the oxygen and nitrogen molecules. This means that the number of electrons in the local ionosphere varies with the seasons (fewer in winter, more in summer), with latitude (lower at high latitudes and higher near equator), and with the time of day (higher at noon, lower at sunset and sunrise).

At night, the E layer weakens because photoionizing sunlight is no longer present. After sunset an increase in the height of the E layer increases the range to which long-wavelength radio waves can travel by reflection from the layer. This region is known as the Kennelly–Heaviside layer, or simply the Heaviside layer. Because the F2 layer remains intact by day and night, it is responsible for most skywave propagation of radio waves and long-distance high frequency (HF, or shortwave) radio communications.

[14] M.C. Kelley, Ionosphere, Encyclopedia of Atmospheric Sciences, 2003 Figure 2 - https://www.sciencedirect.com/topics/chemistry/ionosphere

Although the E and F-layers act like mirrors at certain wavelengths, the D-layer is more problematic. As the ionization in the D-layer increases, it can actually absorb radio signals if they are above a specific frequency. This happens because the density is high enough for the electrons to be pushed around by the EM fields in these shortwave (high-frequency) radio waves causing the radio-waves to lose energy as they do work against the electrons. D-layer ionization is at its highest point during solar flares and during the peak of the sunspot cycle every 11 years. A common example of the D layer in action is the disappearance of distant AM and short-wave radio stations in the daytime.

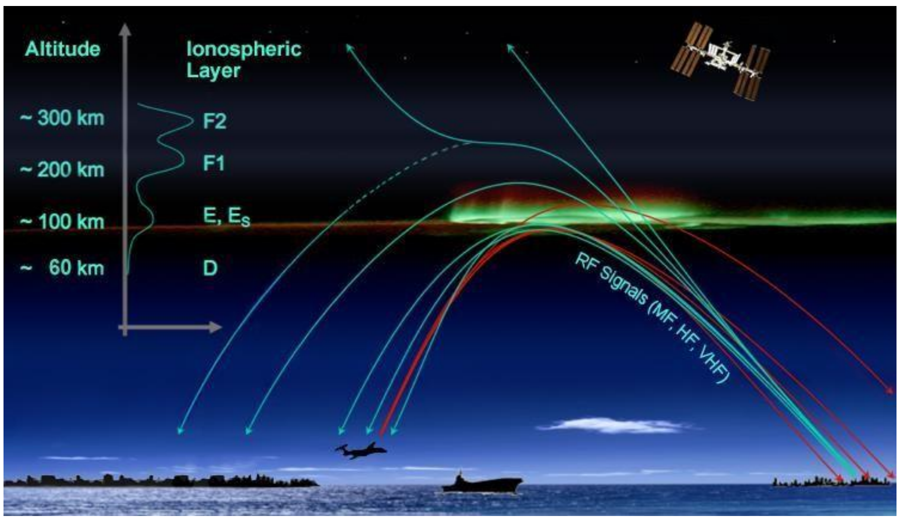


Figure 80. A diagram showing the structure of the ionosphere and some examples of radio-wave propagation paths. (Credit: US Navy)

Materials:

Short-wave radio – For best results, obtain a radio that includes a few of the short-wave bands such as the 31-meter and 19-meter bands (See Table 11). For best results and sensitivity, use an outdoor aerial such as an 18-30 meter, 18-gauge insulated copper wire suspended at each end about 15-feet (5 meters) above the ground. Use a ground wire attached to an indoor copper water pipe, or outdoor ground spike at least 3-feet deep. Make sure that during lightning storms the antenna wire is taken down to prevent lightning discharge into your radio and the possibility of fire damage. Consult online guides to erecting short-wave antennas for more details on how to create a sensitive SW receiver set-up. Some examples of inexpensive SW radios include

- Grundig S350DL ($130.00 or eBay $70.00)
  - Three bands: SW1 (2.9-8.5 MHz); SW2 (7.9- 17.5 MHz) and SW3 (16.9-28.7 MHz)

- ➢ TECSUN R-9012 ($23.00) Twelve bands from 75 meters to 13 meters.

The radio should be operable with either batteries or with a plug-in wall transformer. Also, it is recommended that you use a pair of headphones with the radio to hear faint stations more clearly.

Table 11. Examples of short-wave bands[15]

Wavelength (Meters)	**Frequency (MHz)**	**Comments** SW1, SW2, SW3 (Color coded by Grundig wavebands)
49 m	5.9–6.2	Good year-round night band; daytime (long distance) reception poor
41 m	7.2–7.45	Reception varies by region—reasonably good night reception, but few transmitters in this band target North America.
31 m	9.4–9.9	Most heavily used band. Good year-round night band; seasonal during the day, with best reception in winter.
25 m	11.6–12.1	Generally best during summer and the period before and after Sunset year-round
22 m	13.57–13.87	Substantially used in Eurasia. Similar to the 19 m band; best in summer.
19 m	15.1–15.83	Day reception good, night reception variable; best during summer.
16 m	17.48–17.9	Day reception good; night reception varies seasonally, with summer best.
13 m	21.45–21.85	Erratic daytime reception, with very little night reception.

[15] https://en.wikipedia.org/wiki/Shortwave_bands

AM radio – For best results, use an AM radio with an analog tuning dial that allows continuous coverage across the AM band from 530 kHz to 1600 kHz. Do not use the AGC (Automatic Gain Control) feature. Instead, set the volume control to half its maximum range so that weak stations can be heard. The AGC feature will boost the volume of weaker stations, and this will interfere with your being able to qualitatively judge their distance/reception compared to nearby (louder) stations.

In this experiment we will study the diurnal changes in shortwave propagation.

Procedure:

Step 1) This experiment will be very sensitive to many sources of radio-frequency noise (RFI) also called QRM by radio 'Hams'. If you are inside your house, stay as far away from laptops, TVs, WiFi routers as possible. These can generate as much as 6 mW/m^2 to 500 mW/m^2 of radio frequency power, which will be detected as broad-band noise across your tuning band. It should not be too difficult to find locations in your house or basement where the RF power is below 0.1 mW/m^2. To find these locations, use your radio on battery power and extend its antenna to full length. Walk around the house until you find locations where you no longer hear loud RFI sounds.

Step 2) Set up your outdoor antenna and ground so that it is convenient to where you will be working in your RFI-quiet location. The wires can be passed through a nearby window. Keep the distance between the antenna and radio as short as possible so that the cable from the antenna to the radio does not itself act like an antenna and pick up additional RFI inside your home.

Step 3) Connect the antenna and ground lines to the radio through the jacks that are usually provided for these wires on the back of the radio.

Step 4) The radio should be provided with a plug-in transformer so that you can operate the radio with ordinary house current. These wall transformers step down the electricity from 120 VAC to about 6 VDC. Try to operate your radio as far from the wall transformer as the connecting cable will allow. Transformers produce 60-cycle hum, which can be heard on both AM and SW bands.

Step 5) Adjust the volume control of the radio so that it is about 1/3 of the way to its maximum setting. Keep this volume level fixed as you explore the radio bands.

Step 6) Attach headphones to the radio if they are available. Headphones allow you to concentrate on detecting faint stations. Radio Hams call this activity 'DXing'.

Gathering Data:

Step 7) Turn on the radio and, beginning with the AM band, set the tuner at its lowest frequency near 530 kHz. Slowly scan the tuner through its entire band range and note each station that you can hear by entering its data into a table such as Table 2. Use a convenient station loudness scale such as:

- Faint – Station fades in and out but words not discernable
- Weak – Station can be heard but fades in and out; language discernable
- Strong – Station may fade in and out but remains reasonably loud; language discernable
- Loud – Station does not fade and is very loud. There may be duplicates of this station heard across the band in the vicinity of the main frequency.

Also note whether there are duplicated stations heard at this frequency, whether the signal is steady or drifts 'in and out' of detection, and the language being spoken, which might help identify the country of origin. Also note any additional information that could identify the station such as its call sign, mentions of geographic locations, or advertisement info.

Step 8) Repeat your band DXing for each of the available SW bands on the radio. Examples are in Table 12 and 13.

Step 9) Repeat Steps 7 and 8 a few hours after sunrise, at Noon, and a few hours before sunset. Also conduct this scanning in the late evening about 4-5 hours after sunset. This Daytime /Nighttime data can be included in your scanning tables as shown in the examples of Table 12,13 and 14. Use the 24-hour clock (e.g. 3:00 pm local time is 15:00) to record your times.

Table 12. AM Band data (517 kHz – 1752 kHz)

Freq. kHz	Language	Comment	09:00 Daytime	15:00 Daytime	22:00 Nighttime	05:00 Nighttime
544	English					weak
568	English	WWRC -MD	loud	loud	strong	loud
588	English	CNBC - FNN	loud	loud	loud	loud
604	English				weak	weak
618	English	WFAN multiple	strong	loud		weak
628	English	Dup 618 WSBN		loud	loud	weak
635	English			loud		
653	English				strong	

669	English			weak		
678	English		faint	weak	strong	weak
690	Spanish	+English	weak	strong		
703	Spanish	+English		faint	strong	
708	English					weak
725	Spanish			faint		
740	English				weak	
751	English		weak			weak
759	English				weak	
780	English	WABC -NY	loud	loud		loud
815	English			weak		weak
823	English				weak	strong
840	??			faint		
862	English	WFSI + French	strong	strong	strong	
868	English	multiple	weak	weak	strong	
883	English	WCBS -NY				strong
902	Spanish	WACA - MD	loud	loud	strong	strong
914	English	multiple		strong		
938	English	multiple		weak		
958	??	Japanese?			strong	
983	English	WTEM -DC	loud	loud	loud	loud
1007	English				strong	
1021	English					weak
1049	Spanish	WBQH -MD	loud	loud	strong	loud
1069	Spanish					weak
1083	??	multiple		faint		
1088	??				strong	
1093	English	multi	strong	strong		
1110	English	Charlotte NC				strong
1124	English	multiple		strong		
1142	English					loud
1154	English			strong		
1161	English	Dup of 1093	strong	strong		loud
1206	English			loud		
1219	English		faint			
1260	English	WRCW -VA	loud	loud	loud	loud
1300	??	multi		loud		
1310	English			weak		
1342	English	WYCB - DC	strong	strong		strong
1373	English	Dup of 1339				strong

1422	Spanish			strong		
1462	Spanish	Dup of 1422	loud	loud		
1499	English	WFED -DC	loud	loud	loud	loud
1540	Spanish		loud	loud		
1563	Spanish			weak		
1578	Spanish	multi	strong	weak		
1590	Spanish					weak
1599	Spanish		loud	strong		strong
1675	English				strong	loud
1713	??			faint		
1731	Asian				strong	
1742	English		strong	strong		

Table 13. SW1 Band data (2948 kHz – 8511 kHz)

Freq. kHz	Language	Comment	09:00 Daytime	15:00 Daytime	22:00 Nighttime	05:00 Nighttime
3218	English				loud	strong
3336	Time code				loud	strong
3926	English				strong	strong
4115	Spanish					strong
4175		Rock			strong	
4237	Time code				strong	
4456	Time code				strong	
4464	Time code				strong	
4846	English				loud	loud
4979	English					strong
5000	Time code				strong	
5027	English					strong
5086	English	Alabama			loud	
5117	Spanish				strong	
5163			faint			
5196	Asian	Japanese?			loud	
5893	English				loud	strong
5940	English				loud	strong

5946	English					strong
5978	English					strong
6024	English					strong
6034	Spanish				loud	
6074	English		weak	strong		strong
6107	Asian				loud	
6119	English					strong
6203	English					strong
6424	Spanish	Dup 6453	loud		strong	
6582	English		strong			
6593	English				strong	loud
6600	English	Dup 6593			strong	
6684	English					weak
6938	Time code				strong	
7334	Spanish		loud		loud	
7340	Spanish	Dup 7334			loud	
7368	Spanish	Dup 7334	loud		loud	
7397	Spanish		strong			
7499	English		strong		strong	
7503	Chinese				loud	
7510	English				loud	
7570	Spanish	+English			weak	weak
7678	Spanish				weak	
7693						faint
7729	Spanish				weak	
7773					weak	
7850	Time code		strong	strong	strong	
8012					weak	
8120					weak	
8277	Spanish				weak	
8345	Spanish				weak	
8417	Spanish	+English		faint	strong	
8421	Spanish		loud			
8500	Spanish				weak	

Table 14. SW2 Band data (7871 kHz – 17450 kHz)

Freq. kHz	Language	Comment	09:00 Daytime	15:00 Daytime	22:00 Nighttime	05:00 Nighttime
8421	Spanish	+English	strong	loud		
8487					weak	
8669	Asian	Chinese?			strong	
9030	English			strong		
9067	English		weak		faint	
9329	British	WLC		loud	strong	
9333	Spanish					
9396	English		strong		strong	strong
9942		Rock		strong		
9958	English	Canada?			strong	strong
9979	English		strong	weak		
10000	Time code					strong
10762	Spanish				strong	
10844			faint			
10916	English				weak	
11251		Dup 12161		weak		
11780	Spanish					weak
11826	English				weak	
12161	English			weak		
12767				faint		
12791	Spanish		weak			
12832	English	_+Spanish	strong		strong	
12932	English			strong		
13119					strong	
13684	French			weak		
13702	Spanish		weak			
13741	Spanish		weak		strong	
13850	English		strong	strong		
14093	Time code		strong	strong	strong	
14231	Spanish		strong			
14857	British	Dup 15771		loud		
15003	Time code				strong	
15144	Spanish		weak	faint		

15771	British		loud	loud		
15828	English		weak	strong		
16943	Spanish			loud		

Explanation:

AM Band: From Table 12 we see that there are slightly more identified stations in this band during the daytime than at night (62 vs 50) and that the day and night tally of faint or weak stations is about the same (18 vs 15). This is a reflection of the fact that AM stations can appear or disappear because of daily programming schedules. There is also the fact that AM stations tend to be very local to the listener. This means that the broadcast travels with the line-of-sight Ground Wave rather than using the ionosphere Sky Wave.

Shortwave band SW1: From Table 13 we see a dramatic change from the AM band. Even though the AM band is populated by commercial operators, the SW band also includes a variety of non-profit and even Ham radio operators. There is a dramatic difference between daytime and nighttime programming (11 vs 56) and the greater number of weak or faint stations that are detected (3 vs 12). Also, unlike the weak and faint AM stations that tend to use Ground Wave propagation and have a steady sound, in the SW band the weak and faint stations often fade in and out of detectability. This fading is a direct consequence of Sky Wave propagation in which the SW reflectivity of the ionosphere changes causing the received signal to increase and decrease its sound level (received power) as the plasma's electron density changes. These weak and faint stations tend to be the farthest away in geographic distance, however, some may be relatively close-by but simply transmitting at lower power.

Shortwave band SW2: From Table 14 we see a different type of change between daytime and nighttime stations. There were more daytime stations detected than nighttime (28 vs 18) and more of the daytime stations were weak or faint (12 vs 5). This pattern is the reverse of the SW1 band results. An important distinction between the SW1 and SW2 bands is that the overall noise level contributed by artificial sources, called RFI, was much higher for SW1 in the daytime than for SW2 so that stations were undercounted in SW1 in the daytime. The propagation mechanism is still the same, with more Sky Wave transmission from distant stations relying on the ionosphere.

Your tabulations are likely to differ from the above examples depending on the amount of RFI in your environment. International stations are highly desirable for study because their distances are confirmable to be far enough away that only Sky Wave propagation will occur. This makes them especially sensitive to ionospheric changes.

Assessment:

Learner will explain how radio propagation by skywave is affected by ionospheric plasma density.

❑ Experiment HS15 – Ionosphere propagation and the plasma state

Overview: The plasma density of the ionosphere determines the critical frequency below which radio waves will be reflected back to the ground.

Objective: Learners will be able to use their AM or short-wave data to identify the critical frequency where radio propagation is changing and relate this to the density of the plasma.

Assessment: Learners will be able to quantitatively describe how plasma density affects radio propagation.

Background:

Why does the ionosphere act like a mirror to reflect some radio signals but not others? A plasma acts like a pane of glass. It reflects EM radiation at low frequency but transmits EM radiation at high frequency. A pane of glass reflects low frequency infrared waves back into the house but transmits optical radiation at higher frequencies. This condition of reflection/transmission varies with the density of the electrons in the plasma.

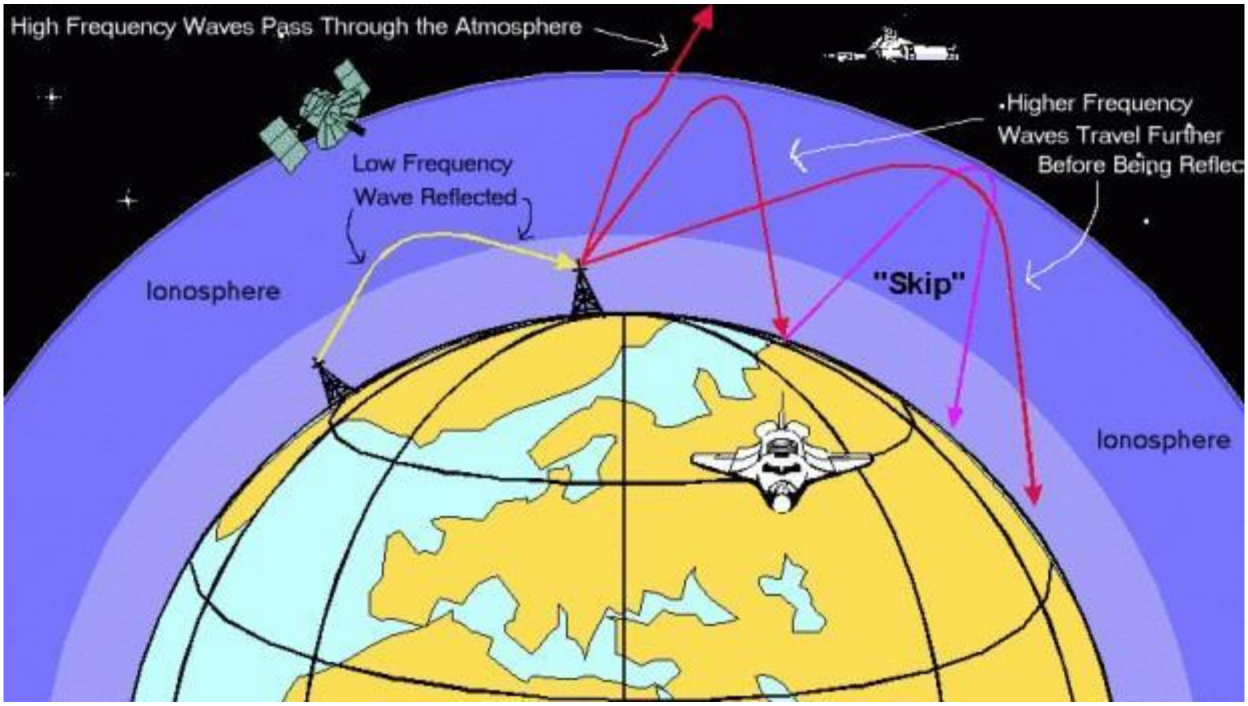


Figure 81. Whether the ionosphere reflects or transmits radio waves depends on their frequency and on the density of the electrons in the ionosphere. (Credit: NOAA)

The critical frequency is determined by the frequency of the plasma. This frequency is the plasma's natural resonance frequency and depends on its density. For a radio signal above the critical frequency, the electrons in the plasma cannot move fast enough to re-radiate the radio signal and so the radio signal passes through the plasma. At lower frequencies, the electrons in the plasma have enough time to move and set up an electric field that reflects the incoming radio wave. The mathematical formula that gives the critical frequency for a signal is given by $n = 9\sqrt{N}$ where n is the frequency in Hz and N is the electron density in electrons/m3.

Under average conditions, the ionosphere has a density of about 10^{11} electrons/$m^{3,}$ so the critical frequency is about 2850 kHz or 2.8 MHz. From Experiment HS14, the AM band (500-1700 kHz) is well-below this critical frequency so AM-band radio waves will be reflected. For SW1 (2900-8500 kHz) and SW2 (7800-17500 kHz, however, the radio signals may be reflected and/or absorbed and transmitted into space depending on the exact conditions of the ionosphere. This is why, for distant stations, you hear the stations fade in and out in volume as the electron density changes and the critical frequency increases and decreases.

What does Earth look like from space high above the ionosphere? If a transmitter was pointed at the International Space Station with an operating frequency in the AM band, the signal would not reach the ISS before being reflected back to the ground. At frequencies in the SW2 band, however, you would be able to detect the transmitted signal.

Also, because FM stations and TV stations operate above 80 MHz, the ionosphere is almost completely transparent to these signals. That is why the FM and TV stations have to be on the line-of-sight to the receiver in order to be detected. You cannot use the ionosphere to 'bounce' the signal over the horizon. That is also why TV signals have to be sent to orbiting satellites to be re-directed back to your satellite dish.

In this experiment, we are going to DX a distant SW station and monitor its loudness (received power). The station will be selected so that it is fading in and out, which means that its transmission frequency is close to the critical frequency for the plasma at the reflection point. We will use its frequency to measure the density of the plasma in the ionosphere.

Materials:

Short-wave radio with bands at (2900-8500 kHz) and/or (7800-17500 kHz).

Procedure:

Step 1) Set up the short-wave radio as you did for Experiment HS14. Determine the UT time at which you want to start your DX program.

Step 2) Consult an international program listing for SW broadcasters and identify a selection of stations broadcasting at your current UT time and that are located more than 1000 km from your location. In North America, stations in Europe, Canada or South America are ideal. Examples of program guides can be found at Short-wave.info (https://www.short-wave.info/) and hfradio.org (http://hfradio.org/english/). Try to select stations that are transmitting at more than 50,000 watts.

Step 3) Using your list from Step 2, tune in to each station and find one or more whose signal is fading in and out of reception.

Gathering Data:

Step 4) Fill out Table 1 with the information for each station. Use a distance calculator such as distance.to in order to determine the approximate distance between your station and the transmitter. (https://www.distance.to/Washington,DC,USA/Oman)

Step 5) Use the formula $N = n^2/81$ to determine the approximate electron density of the ionosphere at the reflection point where n is in Hertz and N is in electrons/m^3. Enter the logarithm of your answer for N into Table 15 to the nearest tenth (e.g. 11.578 becomes 11.6).

Table 15. Example of a table of detected stations and measurements

Frequency (kHz)	Station	Location	Distance (miles)	Time (UT)	DX	Log(N)
11761	WCBC	Alaska	3,500	14:10	Weak	12.2
15140	Radio Oman	Oman	7,300	14:20	Weak	12.5
15745	Sri Lanka	Sri Lanka	8,900	14:25	Weak	12.5
6025	Patria Nueva	La Paz	3,900	02:02	Strong	11.7
7378	Radio Romania	Romania	4,800	01:48	Strong	11.8
9485	Lokalradio	Germany	4,100	02:09	Weak	12.1

Step 6) Repeat the measurements for stations at nighttime and daytime.

Explanation:

The calculated N values should be very close together in value, but the daytime values should be higher than the nighttime values for N because without solar photoionization, the nighttime ionosphere has a lower electron density than the daytime ionosphere.

Assessment:

The Learner will quantitatively describe how plasma density affects radio propagation.

❑ Experiment HS16 – Using your AM and SW radio as a plasma detector

Overview: Plasmas produce electromagnetic radiation at many different frequencies depending on their temperature. A simple AM or short-wave radio can be used to find sources of low-temperature plasma that emit at radio frequencies.

Objective: Learners will be able to use a radio to discover sources of plasma in their home environments.

Assessment: Learners describe how plasmas produce radio waves and find examples of plasma using a simple radio.

Background:

In Experiment HS11, we used a radio to study the RFI produced by common sources of plasma such as CFL lamps. The broad-band RFI could be detected across the entire AM band. In this experiment, we will search for many different kinds of RFI that indicate plasma being produced under many different circumstances in our environment.

Materials:

- Shortwave or AM radio

Procedure:

Step 1) Set up your radio in battery mode.

Step 2) In an outdoor location far from neighboring houses, turn on your radio and scan through its AM and SW bands. Locate any regions of the band where you hear no radio stations and natural radio 'static' noise that sounds like hissing or crackling. As you scan the band, this radio noise will increase and decrease in volume but should sound the same otherwise.

Step 3) Note places in the radio band where you hear odd sounds that do not sound like broadcasting stations (music, talking etc.) or natural radio noise detected in Step 2. They could sound like periodic beeps, crackles or even humming.

Step 4) Repeat Step 3 inside your house and identify any new sources of unnatural RFI that you didn't hear outdoors

Step 5) Select one of these indoor RFI sounds and move your radio from room to room until you find places where the sound is loudest. Is there an obvious electrical device at this location such as an active computer, lamp, router, plug-in wall transformer, dimmer switches, LED and CFL lights, or TV?

Step 6) With your portable radio, take a trip in your car and identify places in your neighborhood, town or city where RFI noise is loudest. You can also use your car's AM radio and tune across its band to study these noises. Examples of places where you will find RFI are near high-voltage transmission lines, electrical utility sub-stations, wind farms, and cell towers.

Gathering Data:

For each distinct sound you are able to identify with a specific kind of source (WiFi router, laptop, desktop, CFL etc.), determine the range of frequencies over which you can hear its distinctive noise and enter it in your data table. If possible, turn the source on and off and see if it changes the RFI sound you are hearing such as a laptop or a fluorescent lamp. An example of the gathered data is shown in Table 16.

Table 16. Sources of RFI

Source	Time of Day	Frequency ranges	Type of Sound
CFL lamp			
Laptop computer	When on	AM, SW1, SW2	Loud periodic chatter and buzzing
TV area with WiFi	When on	AM, 4268-5700, 8200-12000	Buzzing and periodic beeps
Wall transformer	When on	520-530, 6001748, 3676-8494, 7865-16192	Loud buzzing and rhythmic beeping
Air purifier	When on	13600-17400	Rapid distinct pulses from spark discharge
LED lights-dimmer switch	When on	AM, SW1, SW2	Loud buzzing when nearby

Are there any RFI sounds that you cannot identify with a physical source? Do a Google search under 'Radio Frequency Interference' and related search terms to see if you can identify these unknown sources. Some radio users have reported that internet Data Centers produce RFI that can be heard for many miles. In another example, NASA's $912 million Soil Moisture Active-Passive satellite could no longer gather data from Kerrville, Texas because this area produced RFI that corrupted the scientific data. When FCC investigators searched this area on the ground, they found a rancher using a faulty wireless TV camera to monitor cattle. The RFI produced by this camera could be detected 400-miles away in space by the SMAP satellite[16].

Explanation:

A general feature of any device that employs a switch is that the surge of electrons across the gap in the form of a discharge arc as the switch is opened or closed causes the electrons to emit EM radiation. When switches are opened or closed slowly as a single event, they produce a 'pop' that can be heard on a radio. A lightning bolt is similar to a switch that produces a powerful arc, and this produces a much louder 'crackle' that can be heard across the radio spectrum as well. There are many other electrical systems that have switches that open and close hundreds or even billions of times a second, and these produce a constant level of RFI in the radio spectrum, which have their own distinctive sounds.

[16] https://whyy.org/segments/our-gadgets-increasingly-crowd-the-radio-spectrum-theyre-crowding-out-sciencetoo/

Assessment:

Learners describe how plasmas produce radio waves and find examples of plasma using a simple radio.

❑ Experiment HS17 – Solar Flares and the Ionosphere

Overview: A solar flare causes the density of the plasma in the ionosphere to change. This results in a decrease in the propagation of shortwave radio waves and the 'fade-out' of distant radio stations.

Objective: Learners will be able to detect shortwave fade-out during a solar flare event.

Assessment: Learners explain how short-wave fadeouts occur and how they are related to solar flare events.

Background:

During the 20th century, both long-wave and short-wave transmissions were often corrupted by what were called 'fade-outs'. These were caused by solar flares whose x-ray energy was enough to ionize the lower ionosphere, in particular the D-region. As a result, long distance transmissions were stopped because only local signals could use the ionosphere to 'skip' from the transmitter to the receiver.

This experiment will reexamine this phenomenon during significant solar flares that occur during the current sunspot cycle.

Materials:

➢ An AM or preferably a shortwave radio.

Procedure:

Step 1) On your laptop/computer, visit a solar activity service such as spaceweather.com or the NOAA Space Weather Prediction Service (swpc.noaa.gov). Book mark the main page for quick access.

Step 2) Visit this service periodically and see whether a significant solar flare is expected to occur in the next 24 hours and upset radio communications on the day-time side of earth. These flares will be rated as R3 (about 175 per sunspot cycle lasting for an hour); R4 (About 8 per sunspot cycle lasting one to two hours) and R5 (one per solar cycle lasting for many hours). These flares will also be indicated by X-class x-ray flares reported on these space weather services.

Gathering Data:

Step 3) If a daytime flare has just occurred from your daytime location, scan through your AM and short-wave bands as you did in Experiment HS16 and check each of the stations that you detected when no flare was occurring. Even better, redo your HS16 observations the day after the flare event at the same time of the day. This lets you correct for stations dropping out because of their programming schedule.

Step 4) You should notice that many/most of the weaker stations that you detected under no-flare conditions have dropped out. Some of the medium-strength stations may also have become weak stations.

Explanation:

When a strong X-ray flare occurs in the daytime from your location, the energy travels at the speed of light and penetrates Earth's atmosphere all the way down to the D-layer of the ionosphere. Normally, this layer has low ionization and permits long and short-wave signals to travel through it and be reflected by higher-up layers. But the increased ionization by the flare turns this layer into a bright mirror that reflects signals back to earth and also absorbs their energy. This causes only local stations to be heard and other stations to rapidly fade out in strength.

Assessment:

Learners explain how short-wave fadeouts occur, and how they are related to solar flare events.

❑ Experiment HS18 – NASA / RadioJOVE: Exploring Type III Radio Bursts

Overview: Solar events called Type III radio bursts are releases of energy that accompany the ejection of coronal mass ejections.

Objective: By monitoring the change in frequency with time of these bursts, learners can model how the density of the plasma changes in time.

Assessment: Learners create a model for a solar Type III radio burst that describes the density change in the solar plasma during the event.

Background:

Type III solar radio bursts are the Sun's most intense and frequent radio emissions. Type III bursts usually are long-lasting, intense bursts seen in low-frequency observations made from space. They are caused by streams of electrons traveling from close to the Solar surface out to 1 AU (1 AU is the average distance from the Sun to Earth, or about 93 million miles).

In most events, the Type III emissions are reported some 5 to 10 minutes after the start of the associated X-ray flare and have starting frequencies in the 500 to ~100 MHz range that often get lower in time. The electron beam interacts with the plasma near the solar surface and excites a Langmuir wave. These are high frequency waves in the plasma itself. Langmuir waves that scatter off ions result in radiation at a plasma frequency defined by the formula (Equation 1):

$$f = \sqrt{\frac{Ne^2}{4\pi^2 m\epsilon}}$$

where N is the density of electrons in the plasma in electrons/m^3; e is the electric charge given by 1.6×10^{-19} Coulombs; m is the mass of an electron given by 9.1×10^{-31} kg; and ε is the permittivity of free space 1.85×10^{-12}. For example, if $N = 5 \times 10^{12}$ electrons/m^3 the frequency is just 44 MHz (megahertz). Here's a sample problem that shows how astronomers use the Langmuir formula to study the evolution of a plasma cloud near the Sun.

A solar physicist uses a radio telescope to detect a major Type III radio burst at a frequency of 500 MHz. She watches as the signal shifts steadily downwards in frequency to 20 MHz. What is the change in plasma density between these observations? Explain what might be happening to the plasma cloud as it travels? Answer: With a little algebra, we get Equation 2:

$$N = f^2 \frac{4\pi^2 (m\epsilon)}{e^2}$$

So, for $f = 500 \times 10^6$ Hz, $N = (500 \times 10^6)^2 (0.002)$ = **5×10^{14} e/m^3**. For $f = 20 \times 10^6$ Hz, N = **8×10^{11} e/m^3**. What is happening is that the plasma cloud is expanding as it travels, which is causing the density of the particles to decrease as the volume is increasing.

Gathering Data:

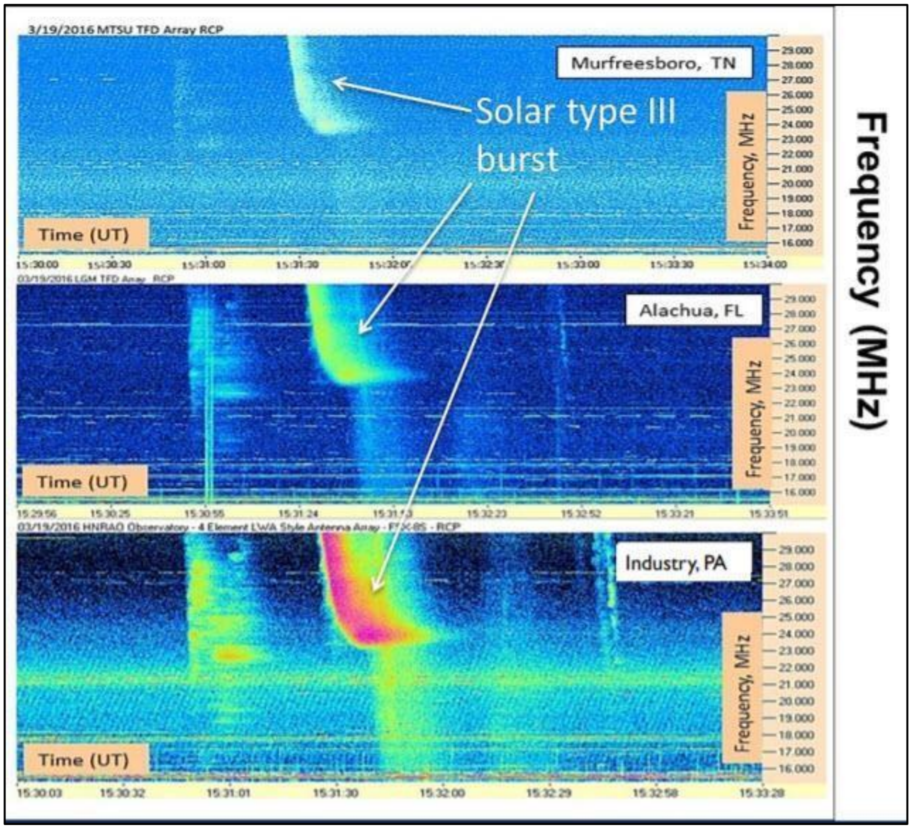


Figure 82. Example of several radio bursts showing their start at high frequency followed by a fast decline to lower frequencies. (Credit: RadioJOVE)

The frequency of the radio burst detected by the RadioJOVE program is shown in Figure 82 in units of MHz from 16.0 to 30.0 MHz (vertical axis). The time is shown on the horizontal axis from 15:30 to 15:33 UT. Create a graph with time in seconds on the horizontal axis and density along the vertical axis using the frequency to calculate the density from Equation 2. Can you create a story that describes what happened to the cloud?

Assessment:

Learners create a model for a solar Type III radio burst that describes the density change in the solar plasma during the event.

❑ Experiment HS19 - Modeling a solar flare event using energy conservation

Overview: Solar events called magnetic reconnections provide the raw energy that generates solar flares and other dynamic events on the solar surface and in the corona.

Objective: Learners will use energy conservation principles together with defining equations for magnetic, thermal, kinetic and gravitational energy to study a solar flare event.

Assessment: Learners create an energy model for a solar flare and predict whether or not it can launch a coronal mass ejection.

Background:

Energy stored in magnetic fields can be released in events called magnetic reconnection. This energy can be quantified and used to provide the input for other forms of energy on the Sun's surface such as moving plasma around at high speeds or heating it to very high temperatures. This mathematical experiment uses energy conservation to explore how several forms of energy are partitioned in a solar flare outburst. An example of a major solar flare seen by the SDO spacecraft on March 6, 2012, is shown in Figure 83.

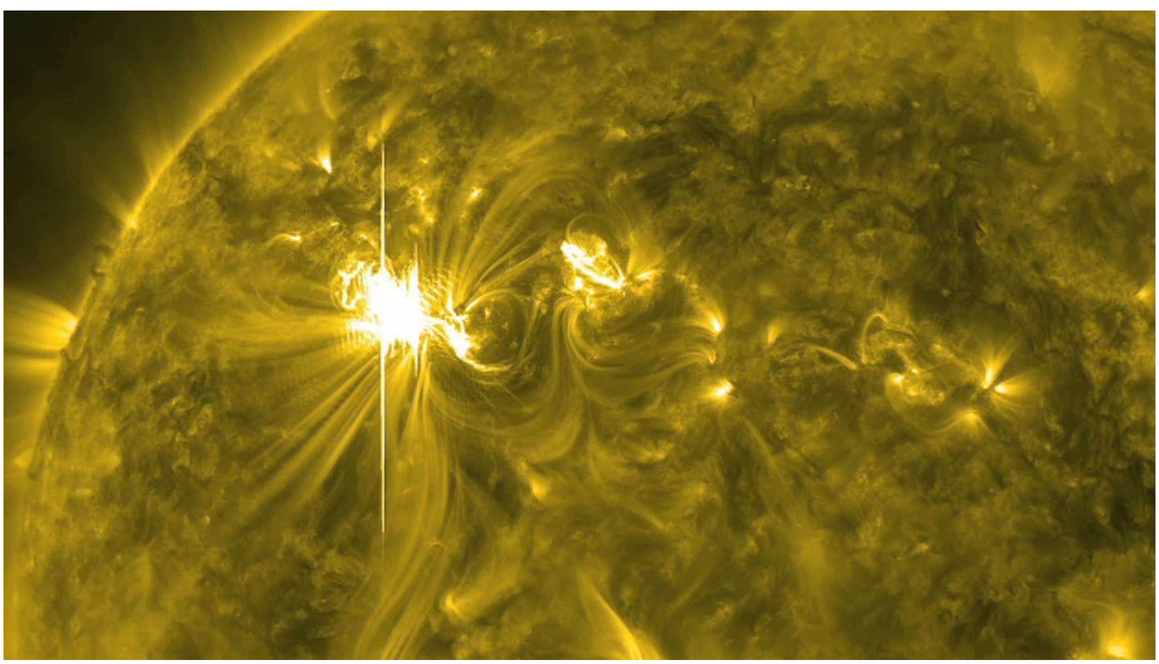


Figure 83. Major solar flare seen on March 6, 2012.

Materials:

Below are a set of equations that give the energy in joules of each of these forms.

Magnetic Energy: where B is in Teslas, and the volume V is in m^3

$$\mathrm{Em} = \frac{10^7\, V\, B^2}{8\pi}$$

Thermal Energy: where N is the gas density in particles/m^3, V is the volume in m^3, T in kelvins and k is Boltzmann constant = 1.38×10^{-23}

$$\mathrm{Et} = \frac{3}{2} N\, k\, T\, V$$

Kinetic Energy: where m is the total mass of the gas cloud in kg, and s is the cloud speed in m/s.

$$\mathrm{Ek} = \frac{1}{2} m\, s^2$$

Gravitational Potential Energy: Eg = GMm/r where M is the mass of the Sun in kg, m is the mass of the gas cloud in kg, r is the distance to the cloud from the center of the Sun in meters, and Newton's constant of gravity G = 6.67×10^{-11}.

$$\mathrm{Eg} = \frac{GMm}{r}$$

Procedure:

Suppose a solar flare is produced by the reconnection of a tangled magnetic field at the surface of the Sun and within a volume with an area of 1,000km x 1,000 km and a thickness of 100 km. Simplify all of the energy equations by evaluating the given constants, area and volume. If the mass and radius of the Sun are 2.0×10^{30}kg and 7.0×10^{8} m respectively.

Step 1) Magnetic Energy = $10^7 B^2 V/8\pi$ so Em = $4.0 \times 10^{22} B^2$ joules

Step 2) Thermal Energy = 3/2 N k T V so Et = 2.0×10^{-6} NT joules

Step 3) Gravitational potential energy = GMm/r so Eg= 1.9×10^{11} m joules.

Gathering Data:

Step 4) If the magnetic field in the reconnection region has a strength of 0.5 Teslas, what is the total available magnetic energy in this volume of space? **Answer: Em = $4.0 \times 10^{22} (0.5)^2 = 1.0 \times 10^{22}$ joules.**

Step 5) The plasma in this volume of space consists of hydrogen (m=1.6×10^{-27} kg) at a density of 2×10^{-7} kg/m^3, and is heated to a temperature of 1,000,000 K. What is the total thermal energy of the gas? **Answer: The gas density N = $2 \times 10^{-7}/1.6 \times 10^{-27}$ = 1.3×10^{20}atoms/m^3 then Et = 2×10^{-6})(1.3×10^{20})(1,000,000) = 2.6×10^{20} joules.**

Step 6) What is the available kinetic energy of the plasma found by subtracting the thermal energy from the magnetic energy. **Answer: E = Em – ET = 1.0×10^{22} – 2.6×10^{20} so the available energy is E= 9.74×10^{21} joules.**

Step 7) What is the gravitational potential energy of this volume of gas? **Answer: mass = 2×10^{-7} kg/m^3 x (10^6m x 10^6m x 10^5m)= 2×10^{10} kg so Eg = 1.9×10^{11} (2×10^{10}) = 3.8×10^{21} joules.**

Step 8) Does the plasma produced by the reconnection event have enough energy to escape the solar surface? **Answer: Yes because Eg < E. The plasma has ($9.74 \times 10^{21}/3.8 \times 10^{21}$) = 2.6-times the required escape energy from the solar surface.**

Explanation:

On the surface of the Sun, many phenomena occur that involve magnetic fields, such as sunspots, flares, and coronal mass ejections. The raw energy for most of these events is supplied by magnetic fields that get tangled up by the convecting motion of the surface plasma. Energy is stored in magnetic fields. When the fields change their shape, this energy can be released through a process called magnetic reconnection and used to heat the plasma to high temperatures releasing x-rays. This energy release can also cause violent currents to flow that produce kinetic energy. This kinetic energy can be large enough to eject the matter from the Sun's surface as a prominence or a coronal mass ejection. By using conservation of energy principles and following the flows of energy through their various forms, astronomers can explore a variety of phenomena near the Sun's surface.

Assessment:

Learners create an energy model for a solar flare and predict whether or not it can launch a coronal mass ejection.

❑ Experiment HS20 – Modeling a plasma with the Saha-Boltzmann

Overview: We are going to study how a gas of hydrogen atoms changes its ionization with temperature. For hydrogen, these atoms become ionized when the single electron has an energy of 13.6 eV or $U=2.2x10^{-18}$ joules.

Objective: Learners will program a spreadsheet to create an ionization-fraction curve.

Assessment: Learners will explain how density and temperature work together to define the properties of plasma.

Background:

Plasma is a unique state of matter that can take many forms depending on its temperature. At low temperatures, few atoms are ionized so the plasma has a very low density of ions and electrons. At extreme temperatures, a plasma can contain few, if any, neutral atoms and consist entirely of ions and electrons. In the 1920s, physicists Meghnad Saha and Maxwell Boltzmann studied the theoretical process of creating plasma from heated gases and came up with the 'Saha-Boltzmann Equation'[17]

$$\frac{N\,Y^2}{(1-Y)} = 2.4x10^{21}\,T^{\frac{3}{2}}\,e^{-\left(\frac{U}{kT}\right)}$$

Y is the fraction of atoms that are ionized (values from 0.000 to 1.000); **N** is the density of neutral atoms (number/m^3); **T** is the plasma temperature in kelvins; **U** is the ionization energy of the atom in joules, and **k** is Boltzmann's constant ($1.38x10^{-23}$ in MKS units).

This equation shows that for the same temperature and density, gases consisting of different elements can have different quantities of free electrons due to the changes

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[17] The constant $2.4x10^{21}$ comes from evaluating $2(g1/g)(2\cdot mk/h^2)^{3/2}$ where $h = 6.6x10^{-34}$ JoulesHz, $m = 9.1x10^{-31}$ kg and $k = 1.38x10^{-23}$ Joules k. Also for hydrogen atoms, g1=0.5 and g = 1. See Wikipedia 'Saha ionization equation' for more details.

in their ionization energy, U. For instance, hydrogen has an ionization energy of 13.6 eV, but helium has a value of 24.6 eV. This means that for a mixture of these gases, the helium plasma would have a much-lower fraction of its atoms ionized than would hydrogen.

We are going to study how a gas of hydrogen atoms changes its ionization with temperature. For hydrogen, these atoms become ionized when the single electron has an energy of 13.6 eV or $U=2.2\times10^{-18}$ joules.

Materials:

- ➢ Laptop with Excel spreadsheet.

Procedure:

Step 1) Simplify the Saha-Boltzmann equation by evaluating it for the fixed constants $U = 2.2\times10^{-18}$ and $k = 1.38\times10^{-23}$:

Equation 1:

$$\frac{N\,Y^2}{(1-Y)} = 2.4x10^{21}\,T^{\frac{3}{2}}\;e^{-\left(\frac{159420}{T}\right)}$$

Step 2) As a test case, we are going to study the hydrogen plasma at the surface of our Sun, which has a temperature of T=5778 k. Evaluate the right-side of this equation for this solar photospheric temperature.

Equation 2:

$$\frac{N\,Y^2}{(1-Y)} = 2.4x10^{21}\,5778^{\frac{3}{2}}\;e^{-\left(\frac{159420}{5778}\right)}$$

Equation 3:

$$\frac{Y^2}{(1-Y)} = \frac{2.1x10^{15}}{N}$$

Step 3) The density of hydrogen gas at the solar surface is about N=1.5x10^{20} atoms/m^3. Simplify Equation 3 by evaluating the right-side.

Equation 4:

$$\frac{Y^2}{(1-Y)} = 0.000014$$

Step 4) Write Equation 4 as a quadratic equation:

Equation 5:

$$Y^2 + 0.000014Y - 0.000014 = 0$$

Step 5) Solve Equation 5 for the positive root of Y using the Quadratic Formula (Equation 6) where A = +1, B=+0.000014 and C = -0.000014:

Equation 6:

$$Y = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

Answer: Y = 0.0037. This means that at a surface temperature of 5778 k, the fraction of ionized hydrogen is only 37 hydrogen ions per 10,000 neutral atoms!

Collecting Data:

Step 6) Open a blank spreadsheet.

Step 7) In Column A fill the cells with temperatures starting at 5000 k and ending at 12,000 k in intervals of 100 k.

Step 8) Select a density, N, for the plasma.

Step 9) In Column B calculate the value for the exponential factor for each temperature.

Step 10) In Column C calculate the constant in Equation 4 for each temperature.

Step 11) In Column D, solve the Quadratic Equation, Equation 6, for the positive root of Y.

Step 12) Using Excel tools, plot the values in Column D against the temperature values in Column A. Example is shown in Figure 84.

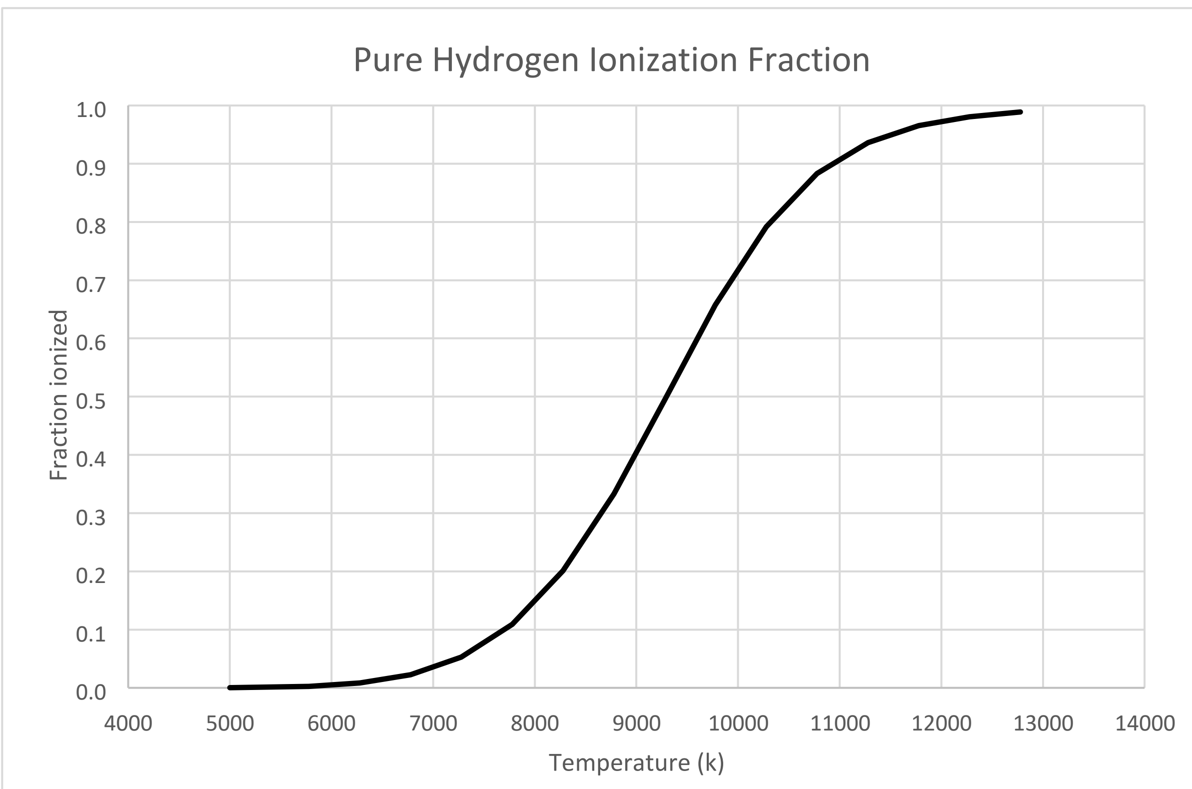

Figure 84. Plot of ionization fraction under solar surface density conditions. Note that for the Sun, T=5778 k and the ionization fraction is under 1% but for stars with surface temperatures above 12,000 k the ionization fraction is nearly 100%.

Step 13) Assuming that the surface densities are about the same, rank these stars in terms of increasing surface ionization fraction and plasma density: Alpha Centauri A (6,000 k), Capella (5,200 k), Sirius (15,000 k), Altair (7,500 k), Castor (10,000 k), Pollux (4,100 k) and Deneb (9,100 k)

Step 14) The hydrogen on the surface of a star can be detected by the spectral lines its single electron emits as it makes transitions between the energy levels in the atom. Based on the ionization fraction, rank the stars in Step 13) in terms of the brightness of their hydrogen lines.

Explanation:

The fraction of atoms that are ionized in a plasma depends on the temperature and density of the plasma. Temperature controls the speeds of the electrons, ions and atoms. Electrons have over 1800 times less mass than hydrogen atoms so that for the same amount of energy (temperature) they travel much faster than the atoms. The density controls how far apart the ions are in the plasma. If an electron can collide with an ion and be captured by it, the ion once again becomes a neutral atom. If the density of atoms is low enough, the time between ionizing collisions can be very long so that there is plenty of time for the faster-moving electrons to be captured. This will keep the plasma at a low level of ionization. If the density is high enough, even fast-moving electrons (high temperature) will not be captured for very long because the collisions between atoms and ions are occurring so rapidly. Figures 84 and 85 show what happens as you keep the atom density fixed while increasing the temperature. At low temperature, the atoms when they collide have barely enough energy to ionize the atoms into ions, so the electron fraction is very low. At higher temperatures, the collisions produce electrons at higher rates and the time for the electrons to vanish and combine with the ions becomes shorter because at these densities the atoms collide more frequently to produce electrons.

Stars with the highest surface temperatures have the highest ionization fractions. At temperatures above 10,000 k, almost all of the surface hydrogen has been ionized. With these stars, spectral lines are only produced by the neutral hydrogen atoms. That means that as the surface temperature increases, there are fewer neutral hydrogen atoms present, and the hydrogen spectral lines become progressively weaker.

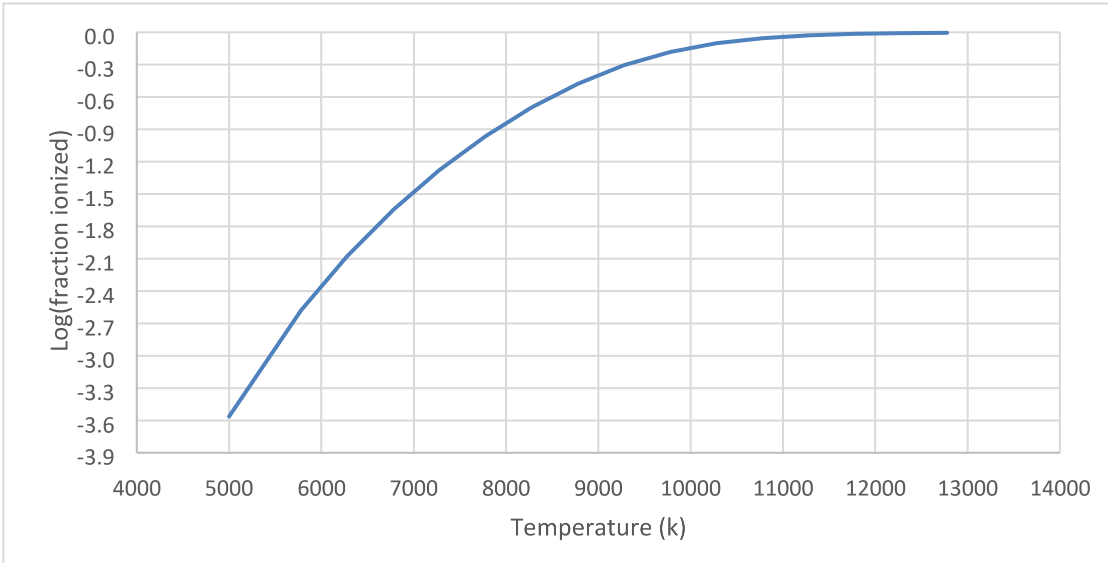

Figure 85. Same data as for Figure 84 but where the logarithm base-10 is used for the ionization faction.

Assessment:

Learners will program a spreadsheet to create an ionization-fraction curve and explain how density and temperature work together to define the properties of a plasma.

Notes

Electrical shock effects by amperage:

https://www.elcosh.org/document/1624/888/d000543/section2.html

- 0.25 mA – lower limit for sensation - https://www.hydroquebec.com/safety/electricshock/consequences-electric-shock.html
- mA: slight tingle
- 5 mA: Slight shock felt. Disturbing, but not painful. Most people can "let go." However, strong involuntary 'surprise' movements can cause injury
- 10-30 mA: Painful shock. Muscular control is lost. This is the range where "freezing currents" start. It may not be possible to "let go."
- 50 – 150 mA: Extremely painful shock, respiratory arrest (breathing stops), severe muscle contractions. Flexor muscles may cause holding on; extensor muscles may cause intense pushing away. Death is possible.
- >1,000 mA: Ventricular fibrillation (heart pumping action not rhythmic) occurs. Muscles contract; nerve damage occurs. Death is likely.

More than 99% of the body's resistance to electric current flow is **at the skin**. Resistance is measured in ohms. A calloused, dry hand may have more than **100,000 Ω** because of a thick outer layer of dead cells in the stratum corneum. **The internal body resistance is about 300 Ω**, being related to the wet, relatively salty tissues beneath the skin. The skin resistance can be effectively bypassed if there is skin breakdown from high voltage, a cut, a deep abrasion, or immersion in water. At **500 V or more, high resistance in the outer layer of the skin breaks down.[3] This lowers the body's resistance to current flow** greatly. The result is an increase in the amount of current that flows with any given voltage. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2763825/

Police Taser – 3.65 mA and 50,000 volts: https://taserguide.com/how-many-amps-in-a-taser/

Stun Gun - 4.5 mA and 80 megavolts: https://www.tbotech.com/rechargeable-runt-stun-gun.htm

Cattle prod – 5 mA, 4000 volts: https://www.amazon.com/Pet-Control-HQ-Electric-Cattle/dp/B07BBMF8D3

Dog collar – 400 to 6,000 volts: https://petdogsworld.com/how-many-volts-in-a-dog-shock-collar/

7mA to 50 mA - https://topdogtips.com/dog-shock-collars-science/

Electric fence – 1000 to 10,000 volts: https://hypertextbook.com/facts/2001/NicoleCastellano.shtml

500 mA to 6000 mA: https://hypertextbook.com/facts/2001/NicoleCastellano.shtml

Lightning bolt – 300 million Volts; 30,000 amps

https://www.weather.gov/safety/lightningpower#:~:text=A%20typical%20lightning%20flash%20is,120%20Volts%20and%2015%20Amps.

Carpet shock: 25,000 volts: https://www.livescience.com/4077-shocking-truth-static-electricity.html

1,500 to 35,000 volts: https://wihausa.tools/electrostatic-discharge/

1 microamp: https://www.lsu.edu/science/chemistry/other/chem_demo/Demo-6-Energy.pdf

Tesla coil – 50,000 V one mA: https://www.lsu.edu/science/chemistry/other/chem_demo/Demo-6Energy.pdf

Van De Graff generator: 4cm spark; 120,000 volts:

https://spark.iop.org/collections/van-de-graaffgenerator

Dried clothes in dryer – 30,000 volts

Spark duration: 1 microsec - https://en.wikipedia.org/wiki/Static_electricity

10 to 100 nanoseconds: https://eprints.qut.edu.au/63476/1/Yi-chuan_Su_Thesis.pdf

IEC 479-2:1987 states that a discharge with energy greater than 5000 mJ is a direct serious risk to human health. IEC 60065 states that consumer products cannot discharge more than 350 mJ into a person.

The maximum potential is limited to about 35–40 kV, due to corona discharge dissipating the charge at higher potentials. Potentials below 3000 volts are not typically detectable by humans. Maximum potential commonly achieved on human body range between 1 and 10 kV, though in optimal conditions as high as 20–25 kV can be reached. Low relative humidity increases the charge buildup; walking 20 feet (6.1 m) on vinyl floor at 15% relative humidity causes buildup of voltage up to 12 kilovolts, while at 80% humidity the voltage is only 1.5 kV. https://www.staticelectricity.com.au/truth-vs-fact

0.2 microseconds - https://apps.dtic.mil/sti/citations/AD0721000

Charge decay time:
T = R x C   Humans have C= 100-300 pF   R=100,000 ohms so T =   E = ½ C V2 joules

Creating harmless sparks: https://www.exploratorium.edu/science_explorer/sparker.html

Van de Graaf Classroom safety: http://amasci.com/emotor/safe.html

Sparks from rubbing a balloon: https://physics.stackexchange.com/questions/366902/voltage-chargein-a-negatively-charged-balloon

$Q = 10^{-6}$ coulomb; $C = 100$ pF, and $V = Q/C = 10^{-6}/100\text{x}10^{-12} = 10{,}000$ volts $E = 0.5CV^2 = 0.5\,(100\text{x}10^{-12})(10000)^2 = 5$ milli Joules.

https://www.osti.gov/servlets/purl/1422965

https://books.google.com/books?id=o6ONAgAAQBAJ&pg=PA59&lpg=PA59&dq=shock+safety++mJ&source=bl&ots=u7DP4gXTdV&sig=ACfU3U1tGCGFf9NI96_HXkrLzQqZYM6fqw&hl=en&sa=X&ved=2ahUKEwjS1LycsMn2AhVLlYkEHTHcDzQQ6AF6BAg2EAM#v=onepage&q=shock%20safety%20%20mJ&f=false

Note: Col 1 and 2 from http://www.appstate.edu/~brian/tec-1023/misc/shockadvisory.pdf

Spark plug mA - https://pages.championpowersports.eu/assets/Beru/ti-07-ignition-coils-gb-2013lowres-0.pdf

Spark plug - 200-300 mJ: https://www.onallcylinders.com/2013/09/16/monday-mailbag-what-isignition-voltage-millijoules-resistance/

Spark plug 50 – 100 mJ: https://www.w8ji.com/ignition_systems.htm

Shock energy 250 mJ: https://www.ee.iitb.ac.in/course/~emlab/assets/shocks.pdf

Shock energies - https://physics.stackexchange.com/questions/177961/what-is-the-voltage-of-anaverage-carpet-static-shock-can-you-make-it-lethal

Energy:
https://books.google.com/books?id=9EozDwAAQBAJ&pg=PA111&lpg=PA111&dq=shock+discharge+ene
ne
rgy+joules&source=bl&ots=FP_OqcGGJT&sig=ACfU3U0FRp0iYGVRY7uauH7HtkUtdGwaSA&hl=en&sa=
X&
ved=2ahUKEwitjdzfs8n2AhWykIkEHdFECLo4HhDoAXoECCYQAw#v=onepage&q=shock%20discharge%2
0 energy%20joules&f=false

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https://nasa.gov/goddard/
www.nasa.gov

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