National Aeronautics and Space Administration

Exploratory 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 sixth-grade testers for their help in field testing these activities and providing hands-on feedback for improving them.

Cover art: Demonstration of electrical current flowing through a plasma created by an electric candle lighter. (Credit: The Author).

Introduction

This Guide is an introduction to plasma, the fourth state of matter, with many hands-on experiments designed to explore the various aspects of this substance. The strategy of this book 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. In this Exploratory phase, 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.

Introductory 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. In this Guide covering experiments M1-M4, learners engage with the plasma state more directly than in the companion guide, *Introductory Experiments with Plasmas,* by building a simple spectroscope and using it to distinguish between ordinary hot gases and heated matter that give off light, and plasmas. In experiments M5-M7 they will create simple sparks under controlled conditions and explore their spectra.

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

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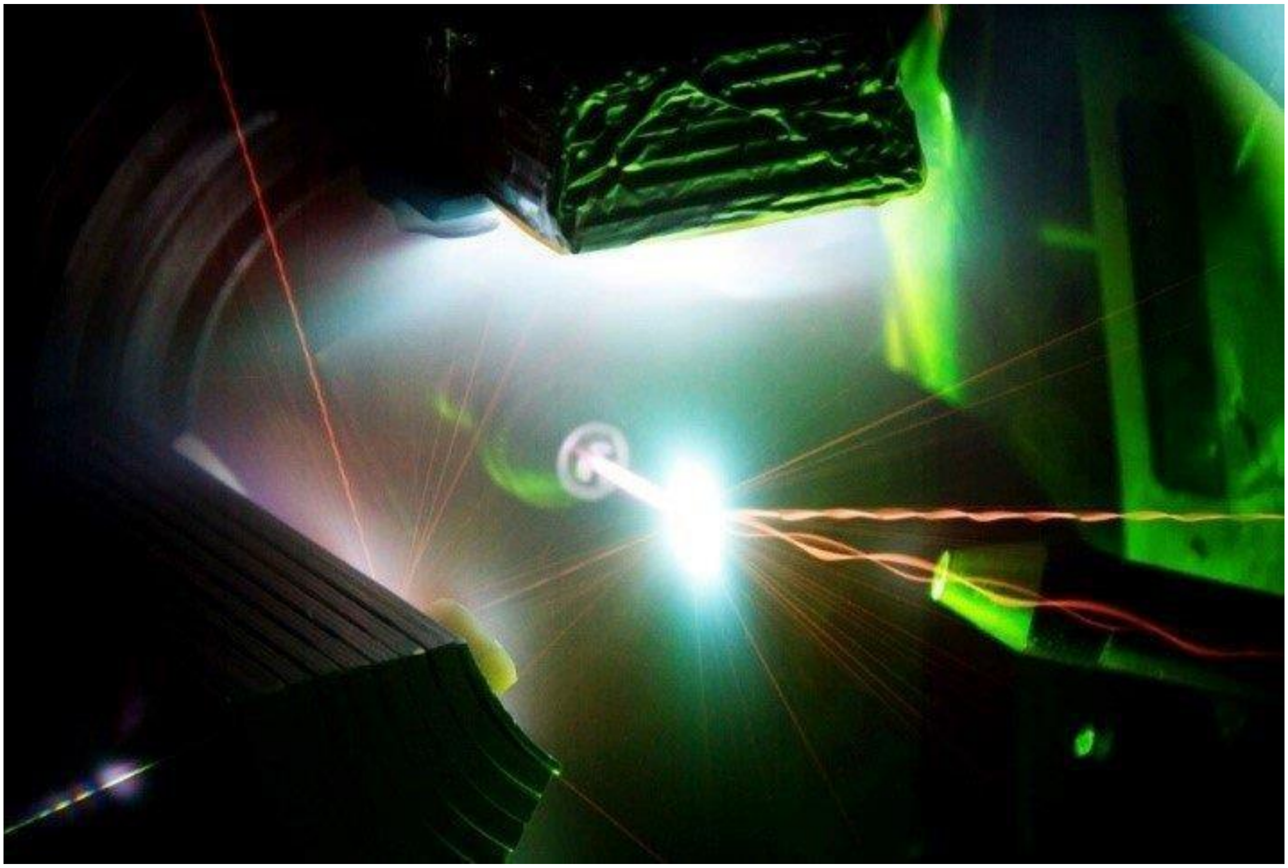

Figure 1. Invisible infrared light from the 200-trillion-watt Trident Laser enters from the bottom to interact with a one-micrometer thick foil target in the center of the photo, generating a ball of glowing plasma. (Credit: Joseph Cowan and Kirk Flippo, Los Alamos National Laboratory)

I. Notes for Educators

Experiments M1-M4 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.

Exploratory Concepts

MS-PS1-1 Developing and Using Models to describe the atomic composition of simple molecules and extended structures. [Clarification Statement: Emphasis is on developing models of molecules that vary in complexity. Examples of simple molecules could include ammonia and methanol. Examples of extended structures could include sodium chloride or diamonds. Examples of molecular-level models could include drawings, 3D ball and stick structures, or computer representations showing different molecules with different types of atoms.] [Assessment Boundary: Assessment does not include valence electrons and bonding energy, discussing the ionic nature of subunits of complex structures, or a complete description of all individual atoms in a complex molecule or extended structure is not required.]

MS-PS1-4 Develop a model that predicts and describes changes in particle motion, temperature, and state of a pure substance when thermal energy is added or removed. [Clarification Statement: Emphasis is on qualitative molecular-level models of solids, liquids, and gases to show that adding or removing thermal energy increases or decreases kinetic energy of the particles until a change of state occurs. Examples of models could include drawing and diagrams. Examples of particles could include molecules or inert atoms. Examples of pure substances could include water, carbon dioxide, and helium.]

MS-PS3-2 Develop a model to describe that when the arrangement of objects interacting at a distance changes, different amounts of potential energy are stored in the system. [Clarification Statement: Emphasis is on relative amounts of potential energy, not on calculations of potential energy. Examples of objects within systems interacting at varying distances could include: the Earth and either a roller coaster cart at varying positions on a hill or objects at varying heights on shelves, changing the direction/orientation of a magnet, and a balloon with static electrical charge being brought closer to a classmate's hair. Examples of models could include representations, diagrams, pictures, and written descriptions of systems.] [Assessment Boundary: Assessment is limited to two objects and electric, magnetic, and gravitational interactions.]

Structure and Properties of Matter (NGSS: PS1.A) Substances are made from different types of atoms, which combine with one another in various ways. Atoms are made of positively charged core, called ***nucleus***, surrounded by negatively charged particles, called ***electrons***.

- ➢ Atoms in solids, liquids, or gases have equal amounts of positive and negative charge, which is why their total charge is zero. When an atom attains excess positive (or negative) charge by gaining (or losing) negative electrons, it is called a positively (or negatively) charged ***ion***. ***Plasmas*** are made of ***ions*** and ***electrons***.
- ➢ Gases and liquids are made of molecules or inert atoms that are moving about relative to each other. Atoms or molecules in a gas are widely spaced except when

they happen to collide. Much like atoms in gases, ions and electrons in ***plasmas*** move relative to each other and are widely spaced except when they collide, but they also interact with each other at a distance through electric forces.

Types of Interactions (NGSS: PS2.B) Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved and on the distances between the interacting objects.

- Unlike atoms and molecules in gases, ions and electrons in plasma interact with each other, not only by collisions, but also at a distance through electric forces.
- Forces that act at a distance (electric, magnetic, and gravitational) can be explained by fields that extend through space and can be mapped by their effect on a test object (e.g. a charged object such as a ball). Ions and electrons are particles that have uncompensated (positive or negative) charge. Such particles can be moved by electric and magnetic forces. This is why plasmas, which are made of ions and electrons, can "feel" electric and magnetic fields extending through space.

Energy: Definitions of Energy (NGSS: PS3.A) Motion energy is properly called kinetic energy; it is proportional to the mass of the moving object and grows with the square of its speed. A system of objects may also contain stored (potential) energy, depending on their relative positions.

- For example, potential energy is stored in the chemical bonds that hold atoms in molecules, while the motion of individual atoms or molecules give rise to their kinetic energy. When the chemical bonds between atoms in molecules break, that potential energy is released.

Energy: Relationship Between Energy and Forces (NGSS: PS3.C) When objects collide, the contact forces transfer energy so as to change the objects' motions. Particles in plasma move very fast because they have a lot of energy. Sometimes, when fast particles collide, they can merge (or fuse together) to form new particles. A lot of energy is produced when particles fuse together. This process is called fusion. At other times the collisions cause the particles to split apart. This is called ionization, and it produces plasmas.

Electromagnetic Radiation (PS4.B) Atoms of each element emit and absorb characteristic frequencies of light. These characteristics allow identification of the presence of an element, even in microscopic quantities. (secondary)

The Universe and Its Stars (NGSS: ESS1.A) Earth and its solar system are part of the Milky Way galaxy, which is one of many galaxies in the Universe. The Sun is a star. Like all stars in all galaxies in the Universe, the Sun is made of plasma gas. In fact, scientists have calculated that 99.999% of all visible matter in the Universe is in the plasma state.

Earth and the Solar System (NGSS: ESS1.B) The solar system appears to have formed from a disk of dust and gas, drawn together by gravity. To be precise, the gas is in the plasma state. This disk of dust and plasma gas is one example of what is called a dusty plasma.

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).

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 have 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.

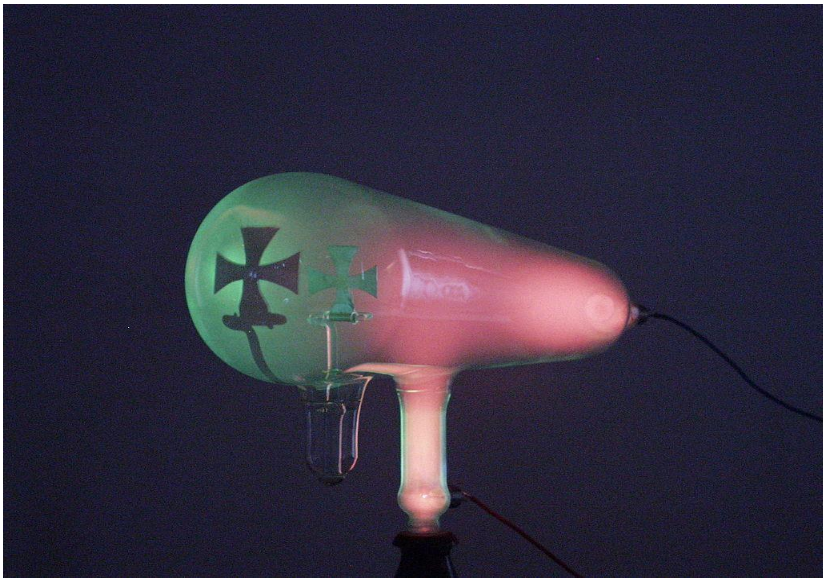

Figure 1. Crookes tube showing glow. (Credit: Wikipedia/Zátonyi Sándor)

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. 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. Finally, with a bit more heat, a gas 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:

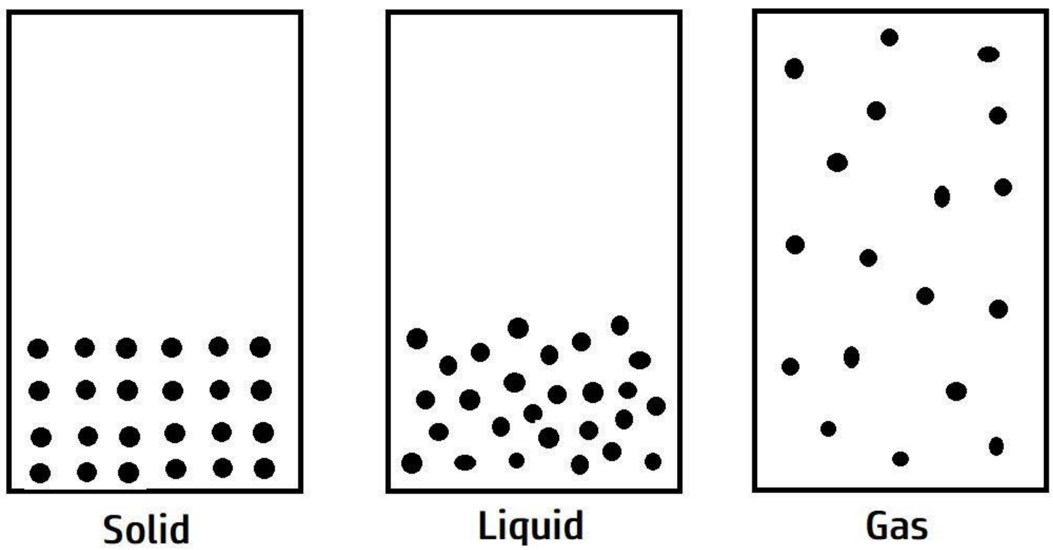

Figure 2. Illustration of how atoms are distributed in the three basic states of matter.

As the temperature increases from left to right in the figure, the atoms arrange themselves into the forms we know as solid, liquid and a 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.

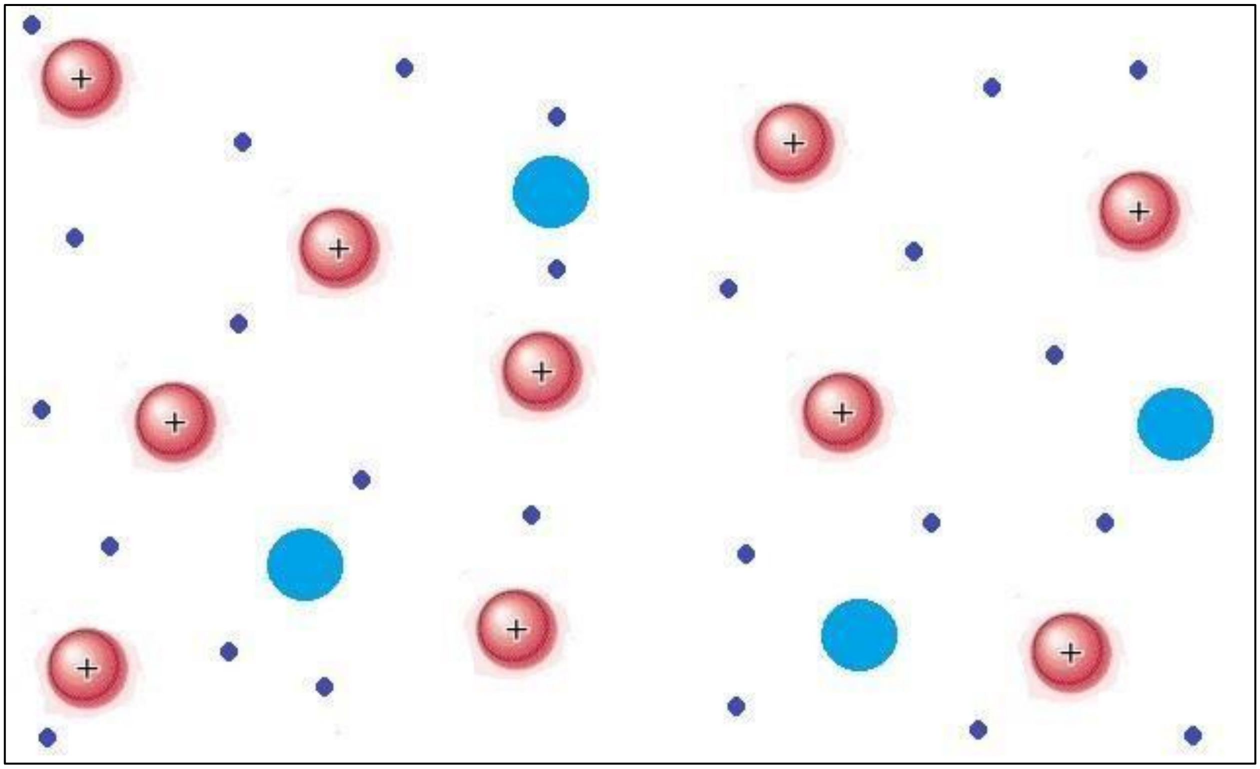

Figure 3. Illustration of a plasma. The dots are the free electrons. The red circles are the positively charged ions that contributed the free electrons. The blue circles are the non-ionized neutral atoms that remain in low-temperature plasmas. They will be absent in fully ionized hot plasmas.

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 electric forces due to their charges. When the kinetic energy of the atoms is very low, the electric forces lock the atoms firmly into a crystal structure to form a solid state.

By adding additional kinetic energy to the atoms by heating them, the atoms are no longer firmly locked into the crystal via the electric forces but can move around - although they do not get very far from each other. They still feel the electric forces between them 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 in the liquid state, the atoms can finally move to very large distances from each other where the electric forces are very 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 a 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, also determines the type of element it is 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. If there are six protons in the nucleus with 6 negative charges, there are six electrons in the cloud with six negative charges. The total charge is exactly zero. In chemistry and physics, we call this a neutral atom.

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.

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 space, say, 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.

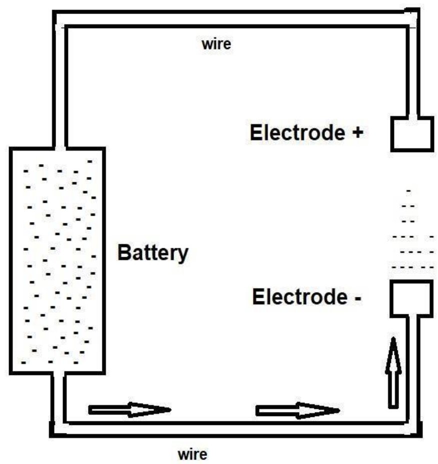

Figure 4. The battery is the source of negative charges (electrons). The figure shows the buildup of negative charges in a spark gap.

Sparks in gas stoves and outdoor grills

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 shown in Figure 4, the two ends of the wire, called electrodes, are connected to the battery or source of electricity. Because electrons flow from the negative to the positive side of a battery, one electrode will contain a surplus of electrons making it negative (called the anode), but the other end will be attached to the positive side of the battery where there is a deficit of electrons (called the cathode). 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.

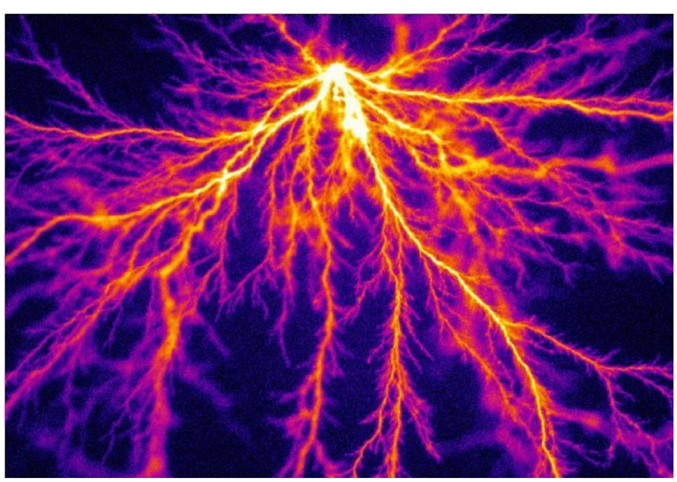

Figure 5. Example of discharge streamers forming on an anode (top) and discharging onto a metal cathode, grounded plate (bottom). (Credit: Ebert et al, 2011)

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 becomes so large that they start to ionize the air atoms close to the electrode's surface. This ionization causes a plasma to form, which then extends towards the attractive, positively charged cathode. This process doesn't just form a single cloud of plasma. The plasma forms into very thin streamers shown in Figure 5. 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 a split-second 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 at which 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/meter). For example, if you had a 10,000 V battery and the gap was one meter wide, the electric field would be 10,000 volts/ 1 meter. This is too weak to actually produce a spark because you need 3,000,000 volts/meter. But if you narrowed the gap to 1 millimeter (which is 0.001 meters) the electric field would be 10,000 volts/0.001 meters or 10,000,000 volts/meter. This is more than enough to produce a spark.

One common place that relies on producing electric sparks is in your automobile engine. It uses 'spark plugs' like the one shown in Figure 6 to ignite 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. If the gap is too big, the ignition coil can't produce enough voltage across the gap to reach the 75,000 volts/inch needed to produce the spark and the car will not run. This is why auto mechanics spend so much time getting the spark gap correct.

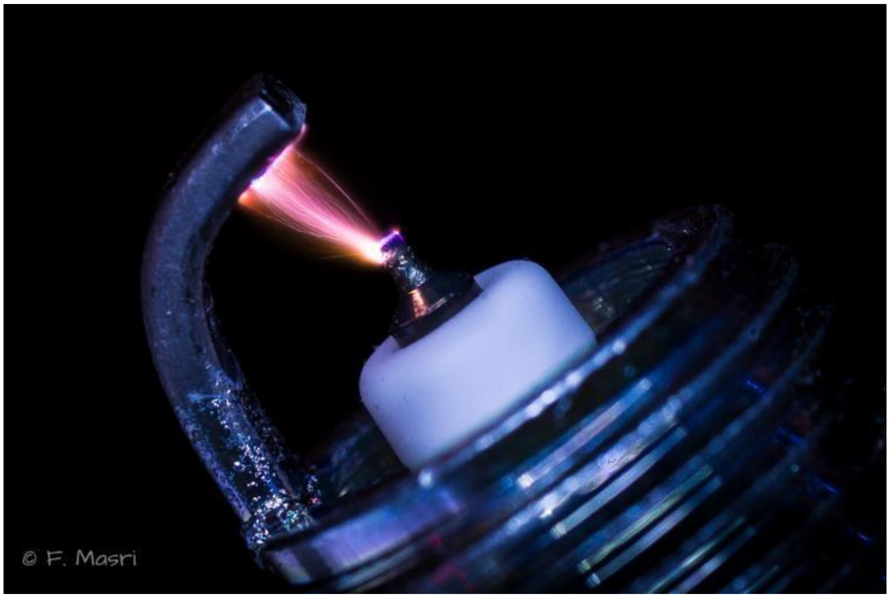

Figure 6. A spark produced by an automobile sparkplug.

Other than for operating cars, sparks are mostly a nuisance, but they do 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 (like the one in Figure 7), 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 after it fatefully struck the 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^{o}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 life, 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^{o}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.

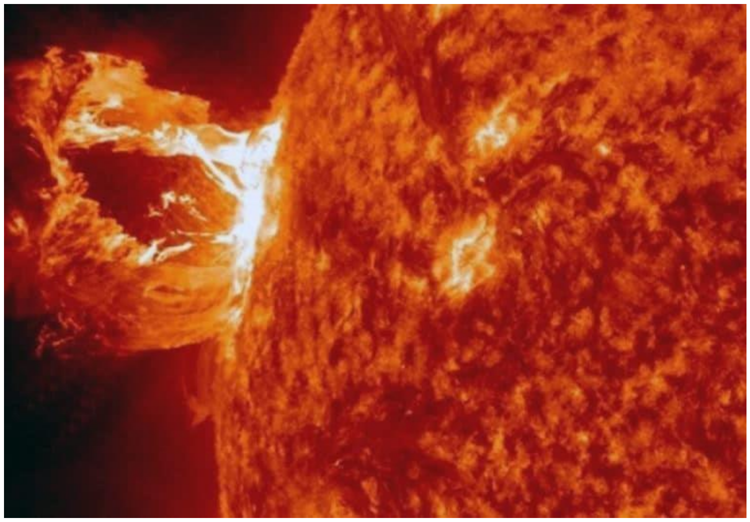

Figure 9. A coronal mass ejection produced by magnetic fields on the Sun reconnecting to form a cloud of plasma over 100,000 kilometers in diameter and traveling at 1,000 km/sec. (Credit: NASA/SDO).

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 in the space between the stars. 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 throughout the galaxy. 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. 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).

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

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.

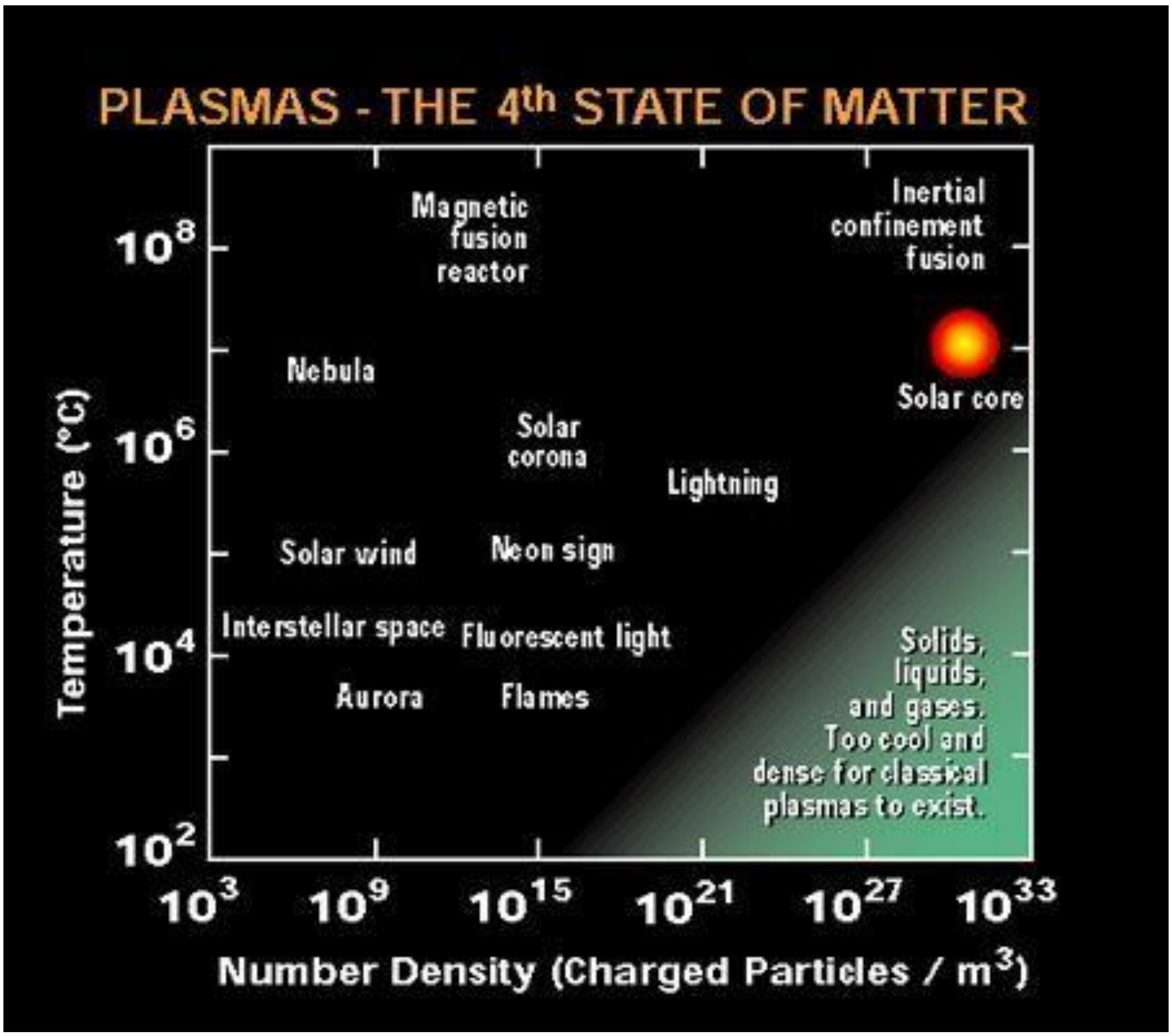

Figure 11. The plasma state of matter encompasses a wide variety of densities and temperatures. [Courtesy of the Contemporary Physics Education Project]

Words to Use with Students about Plasma

Charge – A property of matter that can be either positive or negative.

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

Diffraction – The bending of light that causes light to form patterns of bright and dark regions. When a wave crest meets another wave crest it reinforces itself to produce a brighter crest. When a crest passes over a trough, however, the waves cancel producing no light. This property of light interfering with itself when reflected is how diffraction gratings work to produce a light spectrum.

Discharge – The sudden release of electric charges into a current, which then forms a spark.

Electron – An elementary particle of matter that has a negative charge and is usually found inside atoms.

Ion – 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.

Spectroscope – An instrument that displays the spectrum of a light source.

Spectrograph – An instrument that photographically records the spectrum of a light source.

Spectrometer – An instrument that works like a light meter to measure the intensity of the light across a spectrum.

Spectrum – A pattern of electromagnetic radiation in which the radiation is sorted by its increasing wavelength from blue (short wavelength) to red (long wavelength). It can sometimes look like a rainbow, but for other sources it can look like individual bars of color whose pattern depends on the element emitting the light.

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, plasmas will not be harmful. They will be inside sealed lamps, or as sparks, 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.

At the Exploratory level, learners will observe plasmas that emit light, which means that they might possibly be bright enough to produce a temporary persistent image if students stare at the light source long enough. The same warning that would be relevant to working with ordinary light sources such as reading lamps, car headlights, or flashlights would also apply here. Students will be creating spectroscopes, which involves cutting cardboard with sharp knives or scissors.

IV. Exploratory Experiments

The previous activities described in the companion guide *'Introductory Experiments with Plasmas'* introduced the learner to the basic criteria that the plasma state satisfies so that they can identify them in their environment. The activities did not require any physical contact or interactions with the plasma but relied on remote observations only. These Exploratory experiments take the study of common plasmas to the next level by creating an instrument called a spectroscope that can distinguish plasma from ordinary states of hot matter.

A spectroscope is an instrument that splits light into a 'rainbow' of colors sorted from the shortest (blue) to the longest (red) wavelengths. Most heated forms of matter produce a full rainbow of colors. Plasmas however produce only limited numbers of individual 'lines' of light at specific wavelengths. The pattern of lines is unique to each element, so from these lines you can identify which element is the primary element in the plasma. Here are some examples of the kinds of light you might find in your home that display continuous emission (incandescent and LED) and line emission (fluorescent).

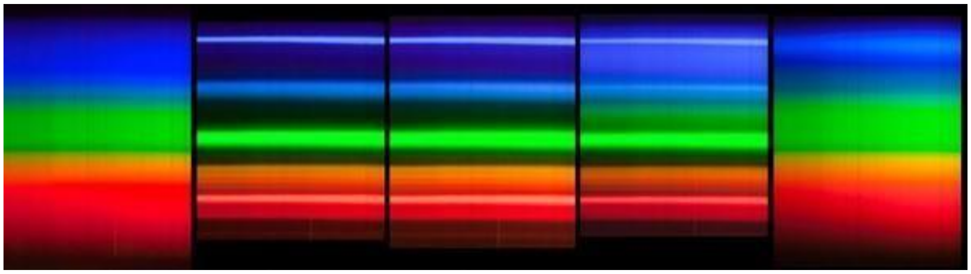

Figure 12. The far-left spectrum is of an ordinary incandescent lamp that produces light by heating a tungsten wire. The middle three spectra are from fluorescent bulbs showing the light emitted by excited argon atoms at only a few wavelengths. The far-right spectrum is from an LED light, which is popular because it requires low voltages and gives a warmer, natural light spectrum similar to sunlight.

❑ Experiment M1 - Creating a simple spectroscope

Overview: A spectroscope acts like a prism to sort light into a spread of wavelengths ordered by their lengths. Ordinary heated bodies produce a continuous rainbow of colors while plasmas only produce light at specific wavelengths. Spectroscopes allow the user to discriminate between plasmas and other sources of light.

Objective: Learners will build a simple spectroscope using a diffraction grating and cardboard and use it to identify spectra for different light sources

Assessment: Learners will explain how a spectroscope can be used to discriminate between plasmas and other sources of light.

Background:

A spectroscope consists of a slit through which the light passes, and a prism or diffraction grating that sorts the light according to increasing wavelength. Some sources of light, called black bodies, produce some light at all wavelengths. This is called a continuous spectrum, which resembles a rainbow of colors. Red wavelengths are longer than blue wavelengths with the other colors in between. Some gases produce light at only a small number of specific wavelengths. Each element in the gas produces its own pattern of 'fingerprint' spectral lines, which can be used to identify them. Plasmas tend to produce spectral lines when they consist of a small number of pure elements such as neon, argon, hydrogen, or oxygen. If a spectroscope shows that a light source consists of individual spectral lines, the light source is a plasma. If a light source shows a rainbow of colors, the light is probably produced by a heated material and is not a plasma. The exception being the Sun, which is a plasma so dense that it resembles a solid body in the way that it produces its light.

Diffraction Gratings:

A prism has a triangular shape, and the angle of the vertex determines how far the incoming light will be deflected into a spectrum. A diffraction grating is a piece of plastic or metal that is ruled into thousands of grooves per inch. Each ruling forms a miniature prism that causes a spectrum to be created of the incoming light and displaced by an angle that depends on how the grating was cut. Diffraction gratings come in two kinds. Transmission gratings are transparent, and you look through them to see the spectrum. Reflection gratings are covered with silver and reflect the spectrum. If you see jewelry that produces a colorful rainbow, this is an example of a reflection grating although the quality is nowhere near as good for a scientific-quality grating.

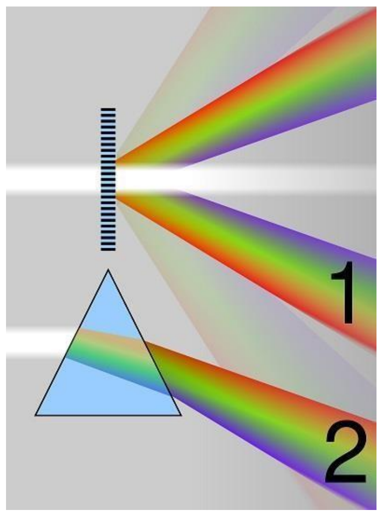

Figure 13. Comparison of a prism and a diffraction grating.

One of the interesting things about a transmission grating is that the spectrum is actually created inside your eye. It is not projected onto a screen. You can test this yourself by just looking through the transmission grating at a light source. The spectrum seems to be suspended in mid-air and is not somehow projected onto a distant surface.

The most important thing about transmission gratings is that the spectrum does not appear in the direction of the light source but is shifted about 20^{o} to either side. When we design a spectroscope, we take advantage of this shift by placing the slit to one side of where we want the spectrum to appear as we look through the grating. This is shown in Figure 14.

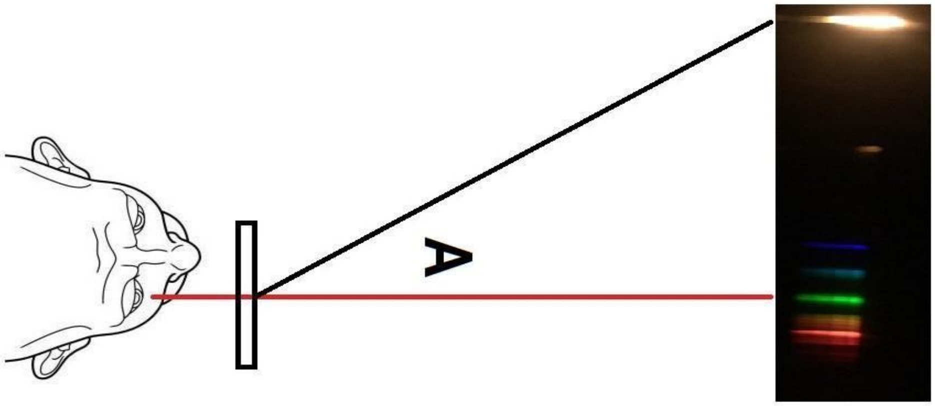

Figure 14. The basic diffraction grating geometry.

The basic geometry of the diffraction grating spectroscope is shown in Figure 14. Light passes through the narrow slit and reflects off the diffraction grating. When you look through the grating along the red 'sight line' at an angle A to the slit line, you will see the spectrum of the light. The angle is about 20^{o}.

Box Construction:

We are building the spectroscope by creating a slit on one end of the box and a hole for the grating at the other end. How big should the box be? It doesn't really matter. All that matters is that the box has to fit the two lines in Figure 14 at an angle of about 20^{o}. The grating has to be mounted one to two inches from the one corner of the box, and the grating has to be mounted about 6 cm from the opposite corner of the opposite wall. The box also needs to be deep enough that it fits the 4 cm x 4 cm grating. You can use a cereal box, or any box from the frozen-foods section of a supermarket. In the example below, we will use a medium-sized pizza box. That is because the cardboard is a heavier stock than cereal boxes, and will produce a better, more stable result in the construction of the smartphone spectrograph in Experiment M2.

Some spectroscope designs use a paper towel or toilet paper roll, with the slit on one end and the grating on the other. This results in an uncomfortable experience where you are looking straight at the bright light through the slit, but the fainter spectrum is off to the left or right and so you have to tilt the cylinder horizontally to see it. The design here allows the spectrum to form directly in front of the diffraction grating but with the entrance slit offset to the left to match the geometry in Figure 14.

Materials:

- Serrated steak knife for cutting (sawing) the stiff pizza box cardboard.

- Black tape such as duct tape or plastic electrical tape.
- 2x2-inch diffraction grating 1000 line/mm (Sources: Rainbow Symphony: $12.95 for pack of 10; $20.00 for package of 50; Or get a roll 6”x60” and cut into 2x2 squares $18.89)
- Medium-size pizza box.

Procedure:

Medium-sized pizza boxes vary in size but try to get something at least 30 cm x 30 cm x 4 cm. Most establishments are happy to give you a spare, empty box with your order. This box is the core of the spectroscope. The stiff cardboard is essential for keeping the geometry as fixed as possible while the spectroscope is in use .

Step 1) Examine Figure 15 which shows the layout and orientation of a medium-sized pizza box. Many pizza boxes have four sides but where the corners of one side have been trimmed diagonally so that the box has a more rounded shape. Place this side facing you. Usually, the printed logo is oriented in the same way. This near side will be the Grating Side. The far side will be the Slit Side.

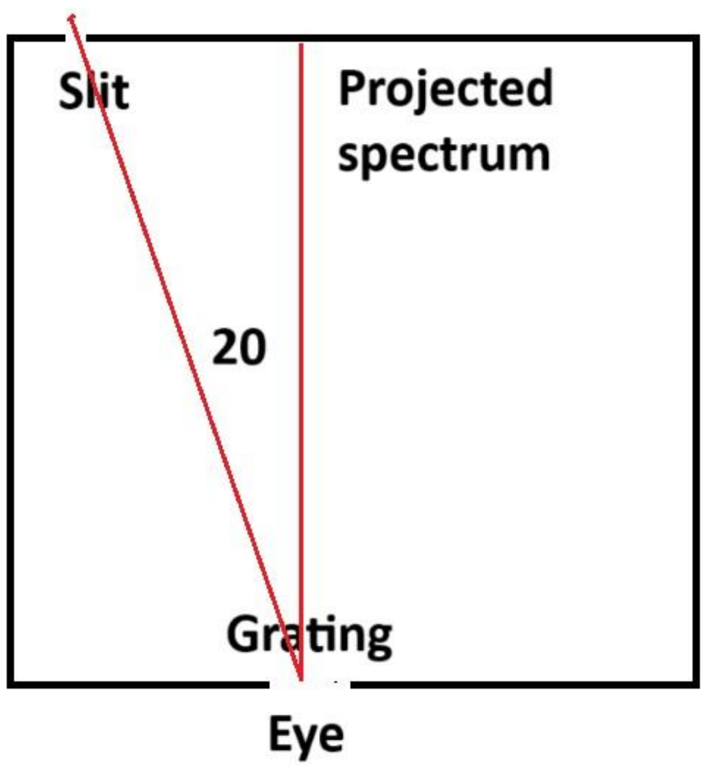

Figure 15. Starting layout of the 14”x14”x2” spectroscope box with the locations of the Grating and the Slit indicated.

Step 2) Beginning with the Grating, you want to install it on the side of the box directly below the arrow shown in Figure 15. To do this, tip the box on its Slit edge so that the Grating face is facing upwards. Cut a rectangular hole 3 cm wide just below the arrow through both the outside wall and the inside wall of the lid. The hole should be centered 13 cm from the right edge of the box.

Step 3) In a darkened room, turn on a lamp and orient the grating so that the spectrum of the lamp is from left to right horizontally. This is usually along the long axis of the rectangular grating in a cardboard mounting.

Step 4) Carefully trim the cardboard mounting for the grating along the horizontal direction so that it just fits the width of the box. Tape the grating over the opening you cut in the side of the box as shown in Figure 16.

Figure 16. Grating trimmed and installed on the wall of the box.

Step 5) Flip the box over to the Slit side facing you, with the top of the box facing up and the area marked 'Slit' in Figure 16 on your right.

Step 6) Cut a rectangular hole that is 2 cm wide centered 2 cm from the right edge of the box, and that extends to the top and bottom edge of the box as shown in Figure 17 (left). Don't worry if the edges are a bit ragged. It will not matter when the Slit is fully installed because the tape will cover the edges.

Step 7) We need to create a narrow slit about 1 millimeter wide that will run vertically from the top of the opening to the bottom. The easiest way to do this is to take two pieces of black tape and carefully tape them across the opening vertically so that they are spaced about 1-millimeter apart at their edges. This is shown in Figure 17 (right). The opening should be directly below the arrow marked in Figure 15, which is 25 mm from the right side of the box. It is best to use black electrical tape to do this, which will seal the hole from light leaks and provide a rigid edge for the slit. You can also tape a piece of heavy gauge aluminum foil over the opening and then, with a sharp knife, carefully cut a vertical slit. Once the slit is cut, do not touch it or the opening will be damaged.

Figure 17. Installing the Slit. Left) Cut a 25 mm wide hole. Right) Cover the hole with tape to form the Slit.

Step 8) Find a bright lamp, preferably a Compact Fluorescent Lamp, and point the Slit at the lamp while looking through the Grating window. Directly ahead you should see the spectrum of the lamp. As you look through the grating, you should be able to see the slit to the left filled with the bright lamp although it may not cover the full height of the slit.

Step 9) Look through the Grating and check that there are no light leaks along the edges of the walls. Use the black tape to cover the edges to make the box light tight.

Gathering Data:

Point the slit end of the box at a ceiling light and look through the grating end. To the right of the slit you will see a rainbow spectrum. If you carefully place your smartphone camera lens against the grating window you can adjust your camera to take a picture of the spectrum. An example of the many different spectra you will see is shown in Figure 18.

Assessment:

Students describe different light sources in terms of the spectra they observed in their spectroscope. If they did not use a smartphone camera, have them take notes or draw what they saw for each light source .

Question: Explain how a spectroscope can be used to discriminate between plasmas and other sources of light.

Answer: A spectroscope acts like a prism to sort light into a spread of wavelengths, ordered by their lengths. Ordinary heated bodies produce a continuous rainbow of colors while plasmas produce light only at specific wavelengths. Spectroscopes allow the user to discriminate between plasmas and other sources of light.

Question: What spectra did you see for each light source? (draw or describe) Answers will vary.

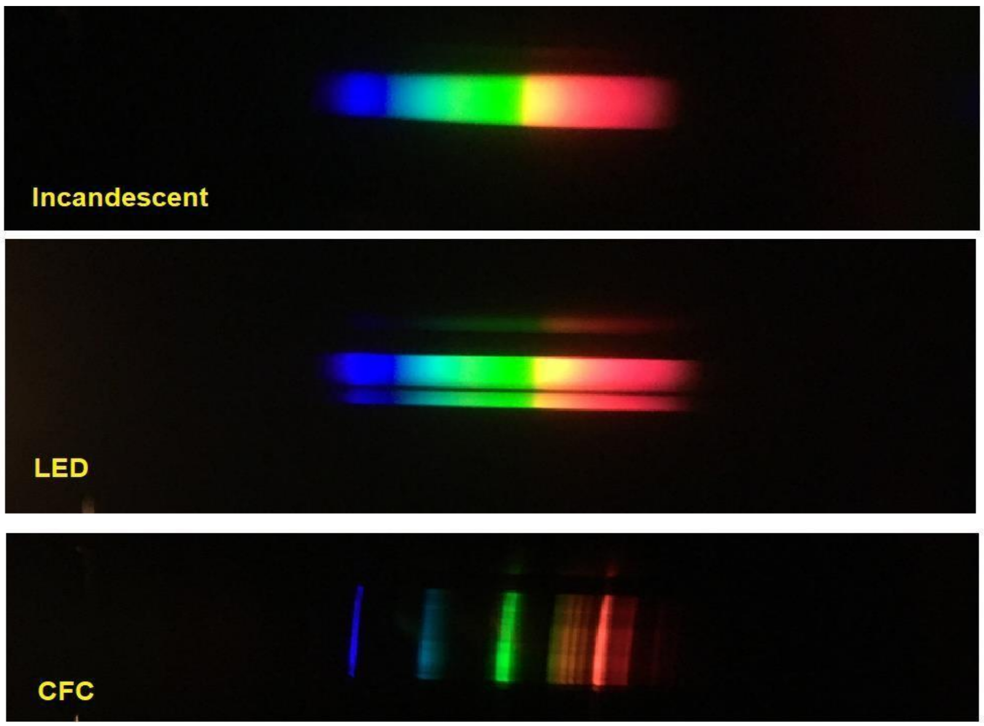

Figure 18. Examples of spectra from three common light sources: *Top* - Ordinary incandescent bulb. *Middle* - LED light. *Bottom* - Compact fluorescent light.

❑ Experiment M2 - Constructing a simple smartphone spectrograph

Overview: Spectroscopes reveal the spectrum of a light source, while a spectrograph lets you record this spectrum photographically for later study.

Objective: Learners will adapt the design of their spectroscope so that a smartphone camera can be used to photograph the spectrum.

Assessment: Learners will create and demonstrate the capture of a spectrum with their smartphone and explain why this is important for studying spectra more accurately.

Background:

The spectra of objects viewed through a spectro**scope** are so complex that they can be very hard to draw or remember accurately. Spectro**graphs** are instruments that record the spectrum of an object photographically. This lets the scientist/learner study the spectra more accurately and to create an atlas of spectra that can be used to identify other unknown sources of light.

Materials:

- Spectroscope from previous experiment.
- Smartphones.
- A small plastic bag to fit the smartphone.
- Small cardboard box.
- Three pieces of scrap cardboard.
- Hot glue and hot glue gun.
- Pair of scissors and a box cutter.
- Packing tape or other similar wide tape.
- Pen or pencil.
- Bright reading lamp with shade removed.

Procedure:

Step 1) Attach the box to the spectroscope from Experiment M1 so that the Grating-side is flush with one face of the box and the box is centered below the Grating as shown in Figure 19. The purpose of the box is to provide a stable, elevated stand for the spectroscope when it is on a tabletop, and to provide a large flat surface for attaching the smartphone. Attach the box using tape or hot glue.

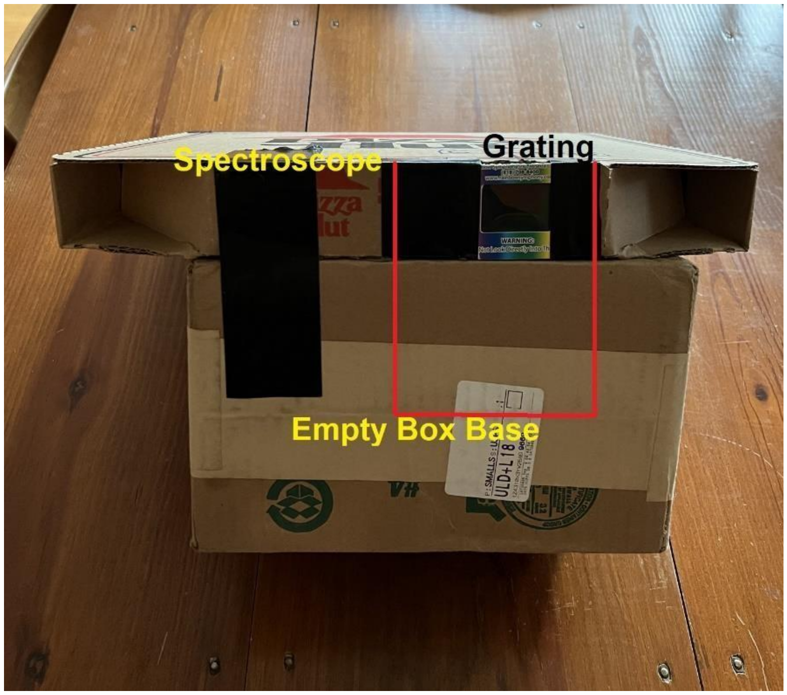

Figure 19. Example of a box mounted to a spectroscope. Area marked within red lines is reserved for the smartphone so that the camera lens is centered on the Grating.

Step 2) Fully charge your smartphone so that you have plenty of time to make adjustments during the experiment

Step 3) Turn on the reading lamp and, on a nearby tabletop, point the Slit of the spectroscope so that an image of the lamp's spectrum appears through the Grating. Place several books on top of the spectroscope so that it does not move when the smartphone is being adjusted at the Grating. See Figure 20 for an example.

Step 4) Turn your smartphone on and start up your camera app.

Step 5) Adjust your camera app so that it does not use its flash

Step 6) With the app running and the Back Camera enabled, hold the camera lens up to the grating and position it so that a spectrum appears on the camera display. With the pen/pencil, trace the edges of the smartphone onto the cardboard as shown in Figure 21. Remove the smartphone from the Grating and then return it to the Grating positioning it inside the marked lines. Take a picture of the spectrum. This helps to confirm that the smartphone orientation is correct.

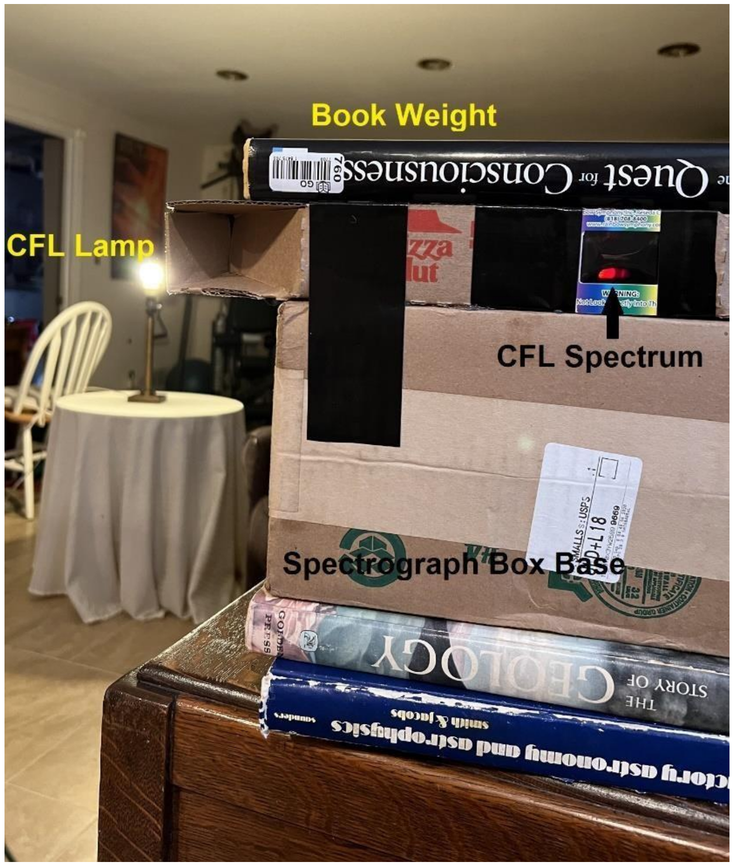

Figure 20. Camera alignment set up. Note spectrum of CFL lamp visible in Grating window.

Figure 21. Lines marked to outline smartphone placement, highlighted with a black Sharpie Marker.

The next thing we need to do is to create a U-shaped holder for the smartphone whose inside dimensions match the lines drawn on the box. Smartphones are about 9 mm thick, so we need some construction material with this thickness. We will use salvaged cardboard from scrap boxes, which can be cut with a pair of scissors.

Step 7) In the example in Figure 22, the inner lines going to the top of the box match the size of the smartphone case. On a piece of cardboard or foam board, mark a rectangle with these dimensions. Mark the lines for a second rectangle that is 25 mm wider all around than the inner dimensions with one of the sides coincident with the top edge of the inner rectangle.

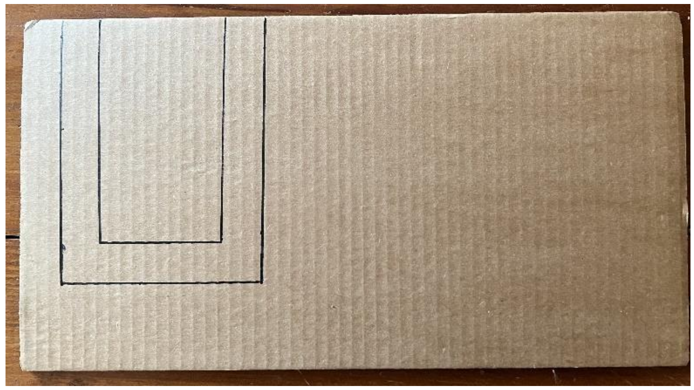

Figure 22. Example of U-holder markings on scrap cardboard.

Step 8) Carefully cut out the inner rectangle for the smartphone and the outer rectangle to form the mounting flange so that you are left with a U-shaped cardboard shape. Although scissors can cut the cardboard, it is best to use a box cutter to avoid deforming the shape. Cut out the inner rectangle first, then trim out the outer edge.

Step 9) If the cardboard has a 3 mm thickness, cut out two more of these U-shaped flanges.

Step 10) Place the bottom U-shape on a flat surface and insert the smartphone (in a plastic bag). If the smartphone doesn't fit, use your scissor to trim the inside edges until they fit snuggly.

Step 11) Place the second U-shape for the middle layer on top of the first layer and trim until it fits snugly around the smartphone. Remove this middle layer, carefully run a bead of hot glue around the bottom U-shape along its center line and press the middle-layer U-shape on top of this bead.

Step 12) Repeat Step 11 for the top layer. Once again, do not use so much hot glue that the compressed bead touches the plastic bag around the smartphone.

Step 13) Hot glue the flanges onto each other to form a single flange with a thickness of 9 mm to match your smartphone case. Make sure the inner edges where the smartphone case will be inserted are flush with each other. If not, trim each U-shape individually so that it fits the case and then glue it onto the previous layer.

Step 14) Place the flange on a table and insert the smartphone into the opening. It should fit snuggly but not so that you have to force it into place and bend the U-shaped flange. Trim inside edges as needed. See Figure 23 for an example.

Figure 23. Example of a completed 3-layer U-shaped flange.

Step 15) With the spectroscope and box at the edge of a table so that the Grating face is parallel to the table, run a bead of hot glue along the centerline of the U-flange and press it firmly onto the Grating area using the guidelines you drew as the inner edge of the flange as shown in Figure 24.

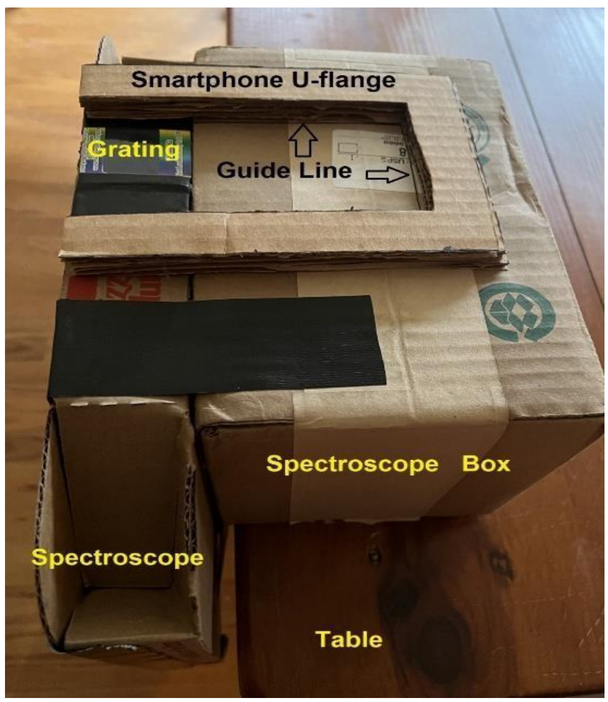

Figure 24. U-flange installed in the grating area using guidelines.

Step 16) Return to your test station in Step 3 Figure 20, and with the camera operating on your smartphone, slide it into the U-flange. There should be adequate friction to keep the smartphone inserted without manual intervention.

There are a number of different camera apps to choose from. Best results are obtained from apps that let you adjust the speed of the imager (ISO) and the exposure speed (1/15th sec). An example of this shown in Figure 25 is called ProCam (Apple: $14.00).

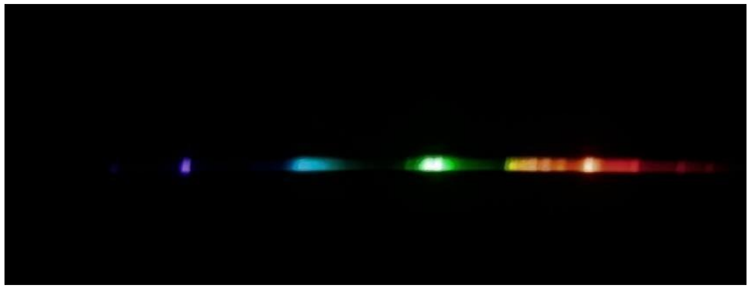

Figure 25. Example of CFL spectrum with ProCam and spectrograph. This is a view with a zoom feature to enlarge the details in the spectrum.

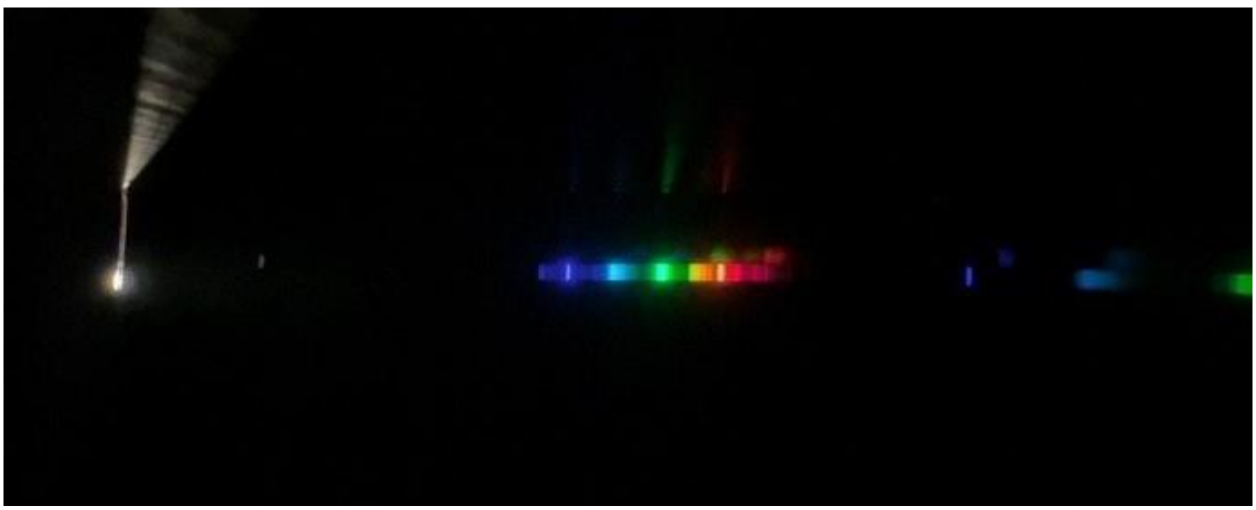

Figure 26. Example of CFL spectrum with TimeStampCamera app (Apple: *free*). Note the wide-angle view lets you use the image of the lamp through the slit on the far Left, and the spectrum in the center

At this point, your spectroscope and box with the attached smartphone can be carried to other locations to take pictures of spectra. This instrument is now called a spectro**<u>graph</u>** because it can photograph spectra. Point the spectrograph slit towards the light source and its spectrum should appear on the camera screen. The images can be downloaded to your laptop and can be cropped to isolate the spectrum. Make sure you label the image file with the kind of light you were looking at. A table like the one below can be used to collect and compare data.

Gathering Data

Table 1. Sampling locations for the spectrograph study

Type of light	Location	File Name
Gold-colored streetlight	Across from 9710 Park Avenue, Kensington	StreetLight1.jpg

Assessment:

Learners should be able to complete the spectrograph and orient it so that it works with their smartphones and take a series of pictures of different light sources. Ask them to share and compare their images and data tables. Draw conclusions about spectra in their environments and explain how this improves their observations.

Question: Create and demonstrate the capture of a spectrum with their smartphone and explain why this is important for studying spectra more accurately.

Answer: Spectroscopes reveal the spectrum of a light source, while a spectrograph lets you record this spectrum photographically for later study.

❑ Experiment M3 - Using a spectroscope to investigate indoor light sources

Overview: Learners will use their spectroscopes to investigate the spectral 'fingerprints' of a variety of light sources in their homes.

Objective: Learners will see how light sources have different spectra depending on how their light is produced. For unknown light sources, they will determine what the light source is by using the spectral 'fingerprints' from known light sources.

Assessment: Learners will identify the spectral fingerprints of common light sources.

Background:

Objects that emit or reflect light produce unique spectra that can be used to identify them, and to deduce how the light is produced. Some light sources that depend on a heated filament produce a continuous rainbow of colors. Other light sources that involve heated gases or plasma may produce only a limited number of colors and may even produce separate lines of color.

Materials:

- Spectroscope from Experiment M1.
- Notepad.
- Crayons or colored pencils or markers that include red, blue, green, orange, yellow.

Procedure:

Step 1) Spectroscopes work best when there is no stray light entering the slit. Turn off all other lights in a room so that only the light being studied is illuminated.

Step 2) Point the spectroscope slit at a light source and note its spectrum. Does it have a rainbow of colors? Does it only have individual, vertical bands? Does it have a mixture of bands, lines, and a rainbow?

Gathering Data:

Step 1) On your notepad, draw the spectrum you saw and note the kind of light it was, based on the bulb used. Example: Incandescent, fluorescent, LED, flashlight, flame, etc.

Students may also photograph the spectra at home using the smartphone spectrograph from Experiment M2.

Step 2) Visit as many different light sources in your apartment or house as you can. Are you able to predict what kind of light it is just by looking at the spectrum?

Step 3) Create a gallery of drawings or photos of the different light sources to form a spectral atlas. For example, in Figure 27, various kinds of lighting in a home were examined. Only the first one produced by a CFL lamp actually has significant plasma and is included in List A. The other sources in List B such as incandescent reading lamps, or LED lights have a very different spectrum and are not hot enough to produce plasma.

List A: Light sources that DO contain plasma:

- Electric sparks
- Lightning
- Aurora
- Neon signs
- Plasma balls
- CFL lamps
- Fluorescent lamps
- Halogen car headlights
- Gas-discharge lamps
- Theater stage lights
- Welding arcs (Oxy-Acetylene torches)

List B: Light sources that do NOT contain plasma

- Glowing lava
- Candle flames
- Flashlights -incandescent
- All incandescent lamps
- LED lights
- Fireworks sparklers

Assessment:

Learners should be able to create an atlas of at least three different kinds of spectra. In the classroom, the teacher can turn on a lamp at the front of the class and have students use their atlases to identify what kind of light it is: LED, incandescent, CFL, etc. Below is an atlas of common spectra photographed using the spectrograph in Experiment M2.

Question: Learners will identify the spectral fingerprints of common light sources (may create an atlas of three different kinds of spectra (e.g., incandescent, fluorescent, LED)

Answer: Learners will see how light sources have different spectra depending on how their light is produced. For unknown light sources, they will determine what the light source is by using the spectral 'fingerprints' from known light sources.

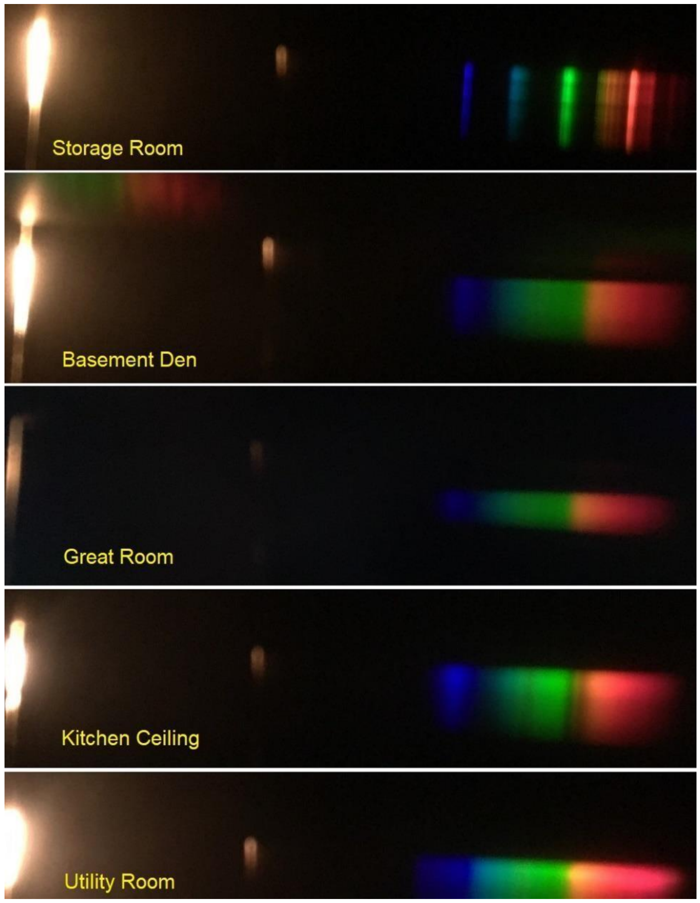

Figure 27. Different lights in a typical home. The bright light on the left is the light through the slit.

- The Storage Room uses 60-watt Compact Fluorescent Lamps (CFL), which heat a gas and ionize it to a plasma to produce only specific kinds of light from the argon gas. These lines are called the spectral lines of the element argon, and their wavelengths are unique to this element.
- The **Basement Den** and **Great Room** both use 65-watt Light-Emitting Diode (LED) lights. These are designed to simulate ordinary sunlight, and they have spectra that closely resemble ordinary sunlight rainbow colors.
- The **Utility Room** uses standard 60-watt incandescent lights that produce a continuous rainbow spectrum from a heated filament.

➢ The **Kitchen Ceiling** uses 65-watt LED lamps but has a glass made from a compound that blocks light at certain wavelengths, which are seen as the dark bands between the red and green areas.

❑ Experiment M4 - Using a spectroscope to investigate outdoor light sources

Overview: Learners will use their spectroscopes to investigate the spectral 'fingerprints' of a variety of light sources outside their homes.

Objective: Learners will see how light sources have different spectra depending on how their light is produced. For unknown light sources, they will determine what the light source is by using the spectral 'fingerprints' from known light sources.

Assessment: Learners will identify the spectral fingerprints of common outdoor light sources.

Background:

At home, learners were able to study sources of light that you could easily touch, turn off, and turn on. Astronomers use spectroscopes and spectrographs to study remote objects in space that they cannot travel to or manipulate. But the spectral patterns they see under laboratory conditions 'at home' can be used to identify what distant objects are made from and how their light is produced. This experiment shows how to use spectroscopes and spectral atlases to identify light sources from streetlamps, parking lots, store ceilings, and other unreachable sources.

What to expect.

The most common kind of spectrum is one that looks like a rainbow from red to blue. This is what you get from any heated object that is solid and at a temperature of a thousand degrees or more. Examples include the tungsten filaments in incandescent bulbs. The sun's spectrum is also a rainbow, which you can indirectly observe by looking at a white sheet of paper in full sunlight.

Caution: NEVER look directly at the sun with the spectroscope. Even through the tiny slit, its brightness will damage your eye.

Any object that is reflecting the sun's light will also share the sun's spectrum including the surface of the full moon. Stars also have a similar spectrum to the sun but are too faint for your spectroscope to view without a telescope to amplify the light onto the slit.

Figure 28 shows examples of spectra for the sun, moon and stars. The sun and moon have almost identical spectra while the stars can differ a lot. The hot star produces a lot of blue and ultraviolet light while the cool star produces hardly any or none. The hotter a star is, the bluer the light it produces.

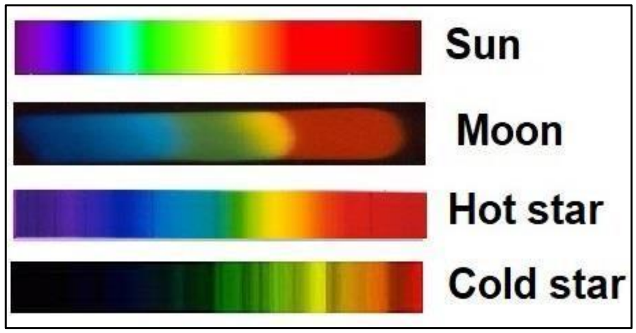

Figure 28. Example of astronomical spectra.

There are many kinds of artificial light sources that produce almost rainbow-like spectra. They are designed this way so that the light they produce mimics natural sunlight. These light sources use different kinds of filters to block some of the wavelengths while letting others pass. With the right choice of filters, you can turn just about any light source into something that resembles our sunlight. Some light sources, however, are designed for underwater life and so often have lots of blue in their spectrum compared to indoor lighting. Lots of blue light tends to make the illumination look cold, as in ordinary fluorescent lighting, and this can irritate some people's eyes. Figure 29 shows an example of aquarium lighting compared to other common lighting.

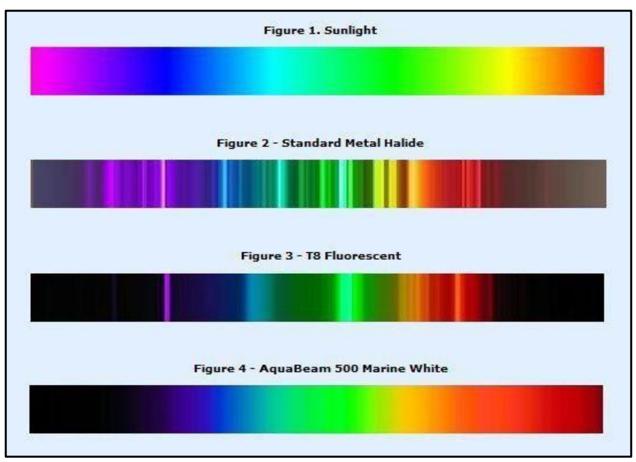

Figure 29. Examples of aquarium lighting and other sources

Materials:

- ➢ Spectroscope from Experiment M1, or spectrograph from M2
- ➢ Spectrum Atlas from Experiment M3
- ➢ Notebook

- Colored crayons, markers or pencils: red, orange, yellow, green, blue
- Parents or siblings with access to a car, bus or other transportation.

Procedure:

Step 1) Wait until nighttime after sunset when most commercial lights have been turned on.

Step 2) With your spectroscope and notebook, visit a location close to a light source.

Gathering Data:

Step 3) Use your spectroscope to form a spectrum and consult your atlas to identify its type: Incandescent, CFL, LED, etc. If the spectrum is not in your atlas, draw a careful figure of its appearance using crayons, markers, or colored pencils.

Step 4) Note the location of this light so that you can return to it later. Note any house address, business establishment, cross street, etc.

Step 5) Visit many different kinds of light sources in your neighborhood. Streetlights that have a yellow glow are sodium-vapor lamps commonly found on major boulevards. Lights that have a harsh blue light are mercury vapor lights commonly found in parking lots or on car headlights. Neon lights are often used for advertising a store's name and are found in business districts or 'downtown'.

Step 6) Create an atlas of the outside lights you studied, labeling each one with its location and what kind of light it was from your spectrum atlas. You can use sketches with colored crayons or take smartphone photographs and crop them. Are there any lights that you could not identify and whose spectra you have never seen before? An example of a photographic atlas of some common outdoor lights is shown in Figure 30, 31 and 32 together with a normal photo of their appearance.

Figure 30. Example of a ‘yellow’ street light spectrum. These are sodium-vapor lamps in which the sodium plasma glows brightly as a yellowish light. The brilliant yellow line of the element sodium is visible in the spectrum.

Figure 31. Most parking lots have brilliant white lights and use what are called mercury-vapor lighting. The spectrum is designed to mimic the Sun’s spectrum and produce a rainbow of colors. Other similar lights are car headlights, and outdoor home security lights.

Figure 32. Neon signs produce only limited spectral lines as the neon plasma is heated. Each of the spectral lines takes the shape of the gas emitting the light, which is why the lines in the figure are wavy and not straight.

Assessment:

Test the students' knowledge of the most common types of outdoor lights by showing their spectrum. Challenge them to find pictures or use their spectroscope on mercury-vapor, sodium-vapor, or neon lights.

Question: Learners will identify the spectral fingerprints of common outdoor light sources.

Answer: Learners will see how outdoor light sources have different spectra depending on how their light is produced. For unknown light sources, they will determine what the light source is by using the spectral 'fingerprints' from known light sources.

Question: Explain how astronomers use spectroscopes to study remote objects in space.

Answer: The spectral patterns they see under laboratory conditions 'at home' can be used to identify what distant objects are made from and how their light is produced.

❑ Experiment M5 - 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:

Usually, air is a very good insulator. That means it is very hard for an electrical current to flow across a gap in a piece of wire. But sometimes, when the battery voltage is high enough, electrons enter this gap as shown in Figure 33. With enough voltage, the electrons make it all the way across the gap to the other side of the gap and the electrical circuit is completed. When enough electrons cross the gap at the same time you get a spark, and there is a crackling sound of heated air like you hear when a stroke of lightning occurs. This spark is actually a miniature lightning bolt!

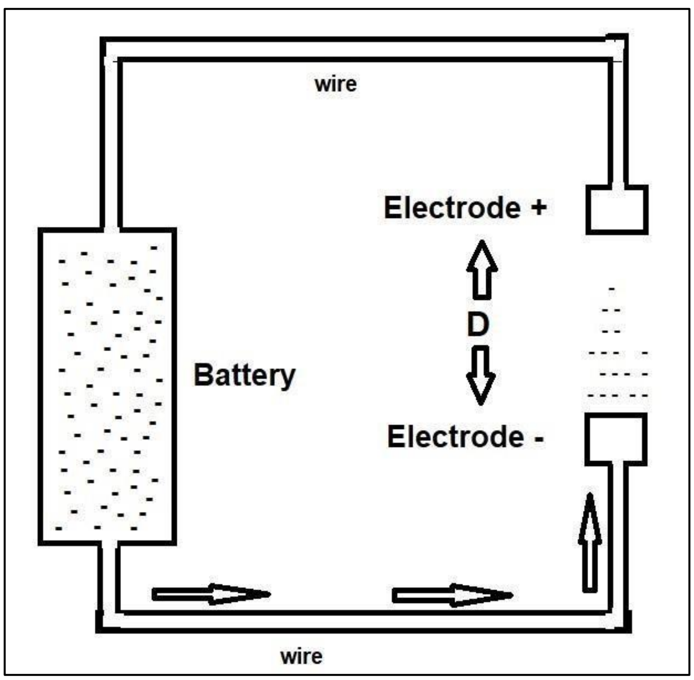

Figure 33. How a spark starts to form between two electrodes. The dashes represent negatively charged electrons.

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

Materials:

- ➢ Electric candle lighter or other similar models.
- ➢ 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^{o} C (2,000^{o}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.

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. The spectrum will show a rainbow spectrum because of the hot electrodes on either end of the gap but will also show an image of the spark as a bright yellow color.

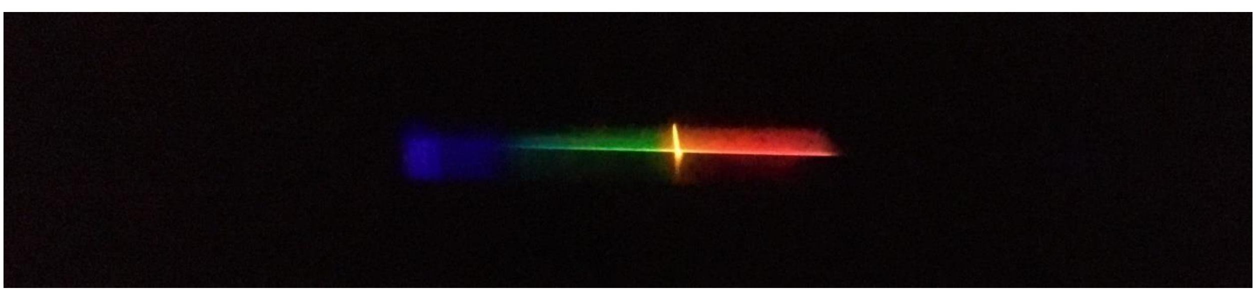

Figure 34. An example of a spectrum from the arc.

Explanation:

As a candle burns, wax the chemical process produces hot gases at over 1,200^{o} C as Figure 35 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 34 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 hot soot particles.

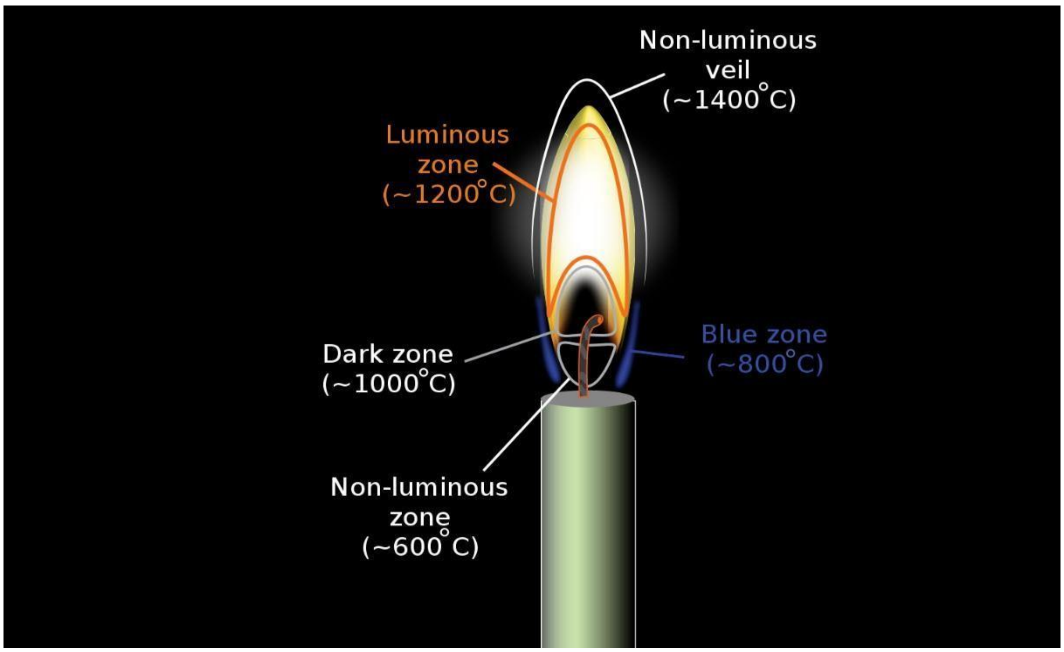

Figure 35. The parts of a candle flame and their temperatures.

Figure 36. The spectrum of an ordinary candle.

But the plasma arc like the one in Figure 37 also had a rainbow of colors with a bright yellow line. 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 to a candle flame!

Figure 37. 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°Celsius 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 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: The candle flame has a rainbow of colors from red to blue while a spark may have a rainbow too from the hot carbon in the electrons, but also shows a bright yellow line produced by the arc.

❑ Experiment M6 - Microwaving aluminum foil to make a plasma torch

Overview: Plasma is a high-temperature substance that is above the vaporization temperature of many ordinary solids. This fact is used in industry to create plasma torches to cut metal quickly.

Objective: Learners will be able to safely observe mini-plasma torches at work with aluminum foil.

Assessment: Learners will find holes punched by plasma sparks when aluminum foil balls are unwrapped and explain why this happened.

Background:

Plasma is a very high temperature ‘gas’. We usually think of a gas as a loose collection of particles, but a plasma is a collection of charged particles that can be focused into a narrow beam. Because plasma torches used in industry have temperatures over 5,000^{o}C, they can cut through many kinds of metals with ease. Everywhere their particles touch, the material is quickly heated to thousands of degrees and immediately melted or turned into a gas – a process called vaporization. Some very strong metals like titanium are very difficult to cut without a diamond saw, but an inexpensive plasma torch can cut titanium very easily, and into very intricate patterns as shown in Figure 38. Plasma torches use high-density beams of particles to do the cutting. An ordinary spark or arc is an example of a low-density plasma. Although low-density plasmas are also very hot, they may not have enough concentration to cause damage. But spark discharges can be concentrated enough to vaporize thin aluminum foils.

Figure 38. Example of an industrial plasma torch cutting steel. The plasma has a temperature of 15,000°C and cuts through metal like a hot knife cuts through butter .

Materials:

- Microwave oven
- 12 cm x 12 cm square of aluminum foil

Microwave Safety

Many people have concerns that creating sparks in a microwave oven will damage the oven. This is not the case if reasonable precautions are taken. A major study led by the European Aluminum Foil Association (EAFA) shows that aluminum containers are perfectly suited for microwave cooking when only a few guidelines are followed. No hazardous results or damage to ovens were found in the more than 200 food portions that were heated in aluminum foil containers or packs containing aluminum foil. The Fraunhofer Institute conducted the heating procedures with the microwave ovens set at maximum power and there were no cases of damage to the microwave ovens or danger to the users.

(See: https://www.alufoil.org/aluminium-foil-and-microwave-ovens)

1) Keep the object in the center of the oven.

2) Do not let any part of the aluminum touch the inside of the oven.

3) Only one aluminum object in the oven at a time.

4) To minimize sparks, the object should not have any sharp edges or corners that can concentrate the charges being built up by the microwaves. Metal spoons are OK, but forks, knives and aluminum crumpled with sharp edges will lead to sparking.

Repeated sparking where the spark touches the inside surface of the oven will cumulatively damage the oven. Each spark leaves a microscopic hole in the lining. This eventually compromises the precise way in which the microwaves are reflected inside the oven.

Procedure:

Step 1) Crumple the aluminum foil into a loose ball. Sparks will form wherever the aluminum foil comes to a sharp point close to another piece of aluminum where the spark can jump to. If you crumble the ball tightly enough to form many corners but not so tight as to flatten the corners, you should be OK.

Step 2) Place the crumpled aluminum at the center of the oven. Do not let it touch the walls. Make sure it is supported by the glass shelf and not in contact with any plastic or metal.

Step 3) At full power setting, set the timer for 15 seconds.

Collecting Data:

Step 4) Turn on the microwave but keep your finger on the 'Pause' button.

Step 5) After 10 seconds one or more flashes will appear within the foil ball. Immediately hit the pause button to stop the microwave. The bright flashes are the production of plasma across narrow gaps where two corners of the foil are closest together in the crumpled ball. If your crumpled foil does not have enough sharp corners, you will not get enough sparks. Unfold the foil and recrumple it and repeat this step until you see a few arcs form. You may need to use a fresh piece of foil.

Step 6) Retrieve the aluminum foil, carefully unfold it, and flatten it. There will be pairs of holes burned through the aluminum foil wherever the spark and its plasma were formed. The aluminum was vaporized in the burst of light at a temperature of 2,467° Celsius.

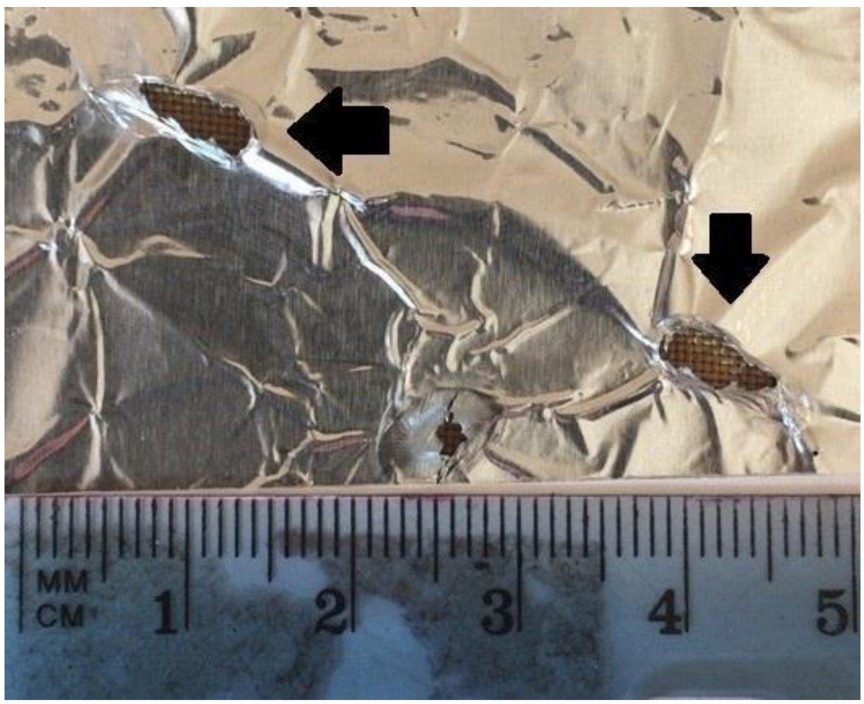

Figure 39. Example of holes in aluminum foil. Black arrows show the holes where the aluminum was evaporated.

Explanation:

In the crumpled aluminum shown in Figure 39, there will be edges that are adjacent to each other and close enough to form a gap across which a spark can jump. Electric charges flow across this gap. The discharge momentarily heats the aluminum to its vaporization temperature forming a pin-point plasma fireball of aluminum vapor, which dissipates in the oven cavity when the microwave is shut off. Over many, many sparks, the aluminum atoms in the vapor will gradually coat the inside of the microwave oven but will not be noticeable if only a small number of sparks are produced.

Figure 40. Crumpled aluminum showing spark and details. The yellow circles show places where adjacent corners are closer than one millimeter. This is where sparks will form.

Assessment:

Learners will explain how the demonstration showed that plasmas have very high temperatures and can melt or vaporize metal.

Question: How does plasma cut metal?

Answer: Plasma is a very high temperature 'gas', which at high enough density can be used to cut metal by evaporating the metal at the point of contact. Although low-density plasmas are also very hot, they may not have enough concentration to cause damage. But spark discharges can be dense enough to conduct enough energy to a metal to vaporize it wherever the arc makes contact

❑ Experiment M7 - Creating plasma in a microwave oven...with a grape!

Overview: A spark is produced any time two conducting surfaces are close enough that a large amount of electric charge is present. This charge will cause a current to flow creating a spark.

Objective: Learners will discover and explain how a common grape, under the right conditions, can produce sparks and plasma.

Assessment: Learners will create a spark between two grapes and understand why the spark occurs.

Background:

Sparks are static electric discharges that are familiar to anyone who has shuffled across a rug and touched a doorknob. The basic idea is that electric charges accumulate on your finger, and as it gets close to a grounded doorknob, the electrical field between the finger and doorknob exceeds the breakdown field of the air as an insulator. The excess charges then travel through this gap as a spark.

If you place two grapes in a microwave oven so close together that they nearly touch, charges will build up on the surface of each grape until the breakdown voltage is reached and a spark occurs in the narrow gap between the grapes. What has happened is that the moisture from inside the grape has built up charge and when these two moist areas are brought close together a spark results. The moisture is just a charge carrier to accumulate the charges more efficiently than just the bare skin of the grape by itself. That is why the tops of the grapes are trimmed to expose the moist pulp.

Materials:

- 1 large grape
- 1-microwavable plate
- 2-plastic spoons, or 2 chopsticks
- 1-transparent, microwavable drinking glass (not plastic)
- Sharp knife

Procedure:

Step 1) Open the microwave oven and remove the rotating base. Movement of the grapes will make it harder for the sparks to form because of the changing intensity of the microwave energy they are encountering.

Step 2) Clean the interior of the microwave.

Step 3) Place the plate on the bottom of the microwave

Step 4) Trim the spoons or chopsticks to about 3-inch lengths. These will form the support for the glass enclosure and allow a gap near the base to avoid gas pressure building up when the sparks form.

Step 5) Place the trimmed spoon handles parallel to each other about 2-inches apart at the center of the plate as shown in Figure 41.

Step 6) Holding the grape so that its longest axis is vertical, trim about 2-3 mm off of the top end. This exposes the moist pulp of the grape to the microwave energy and lets charges more easily collect in the moisture.

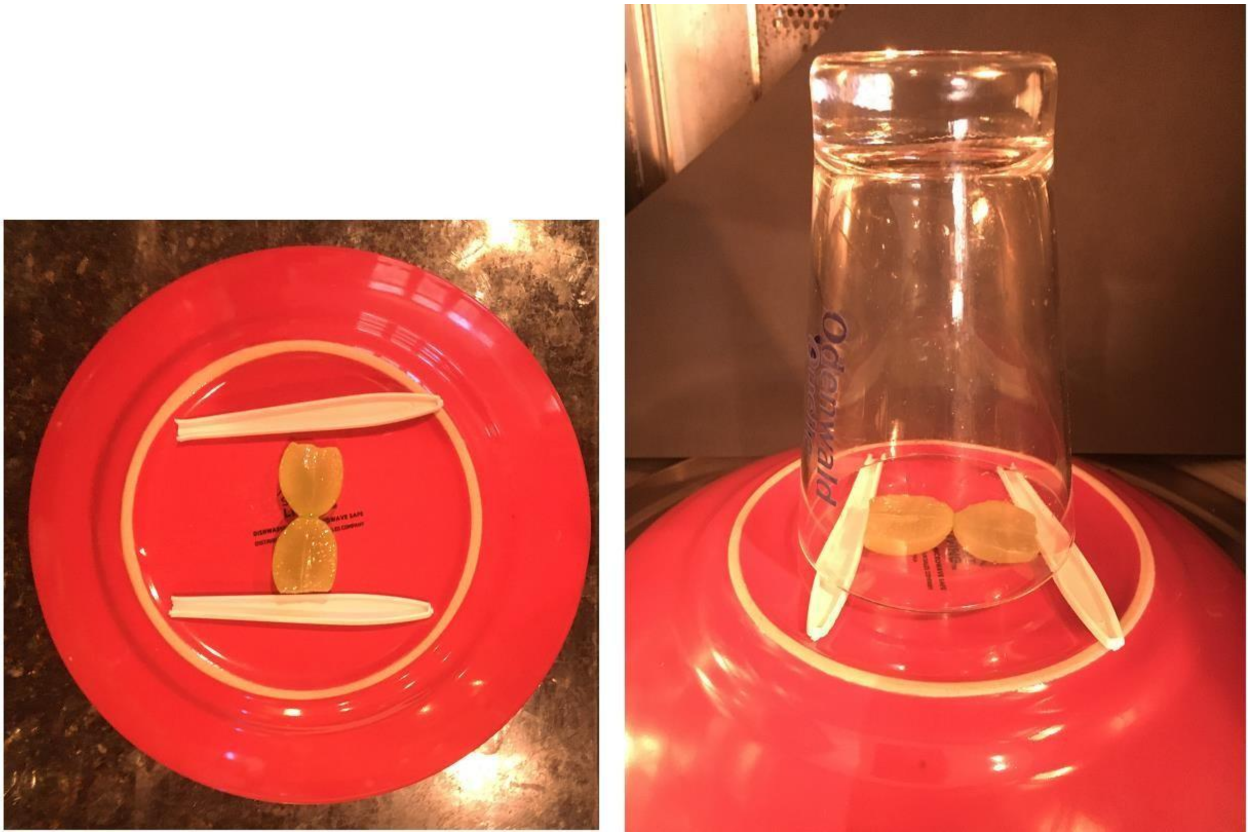

Figure 41. Example of the orientation of the cut grapes and glass enclosure.

Step 7) With the knife, cut the grape in half but leave the grape halves still touching at their bases.

Step 8) Place the halved grape with cut side facing upwards between the two spoon handles.

Step 9) Place the transparent glass cup or glass with its open side facing down on top of the spoon handles so that there is an air gap as shown in Figure 42.

Gathering Data:

Step 10) Set the microwave for full power at 15-seconds. Within a few seconds a spark will form between the grapes.

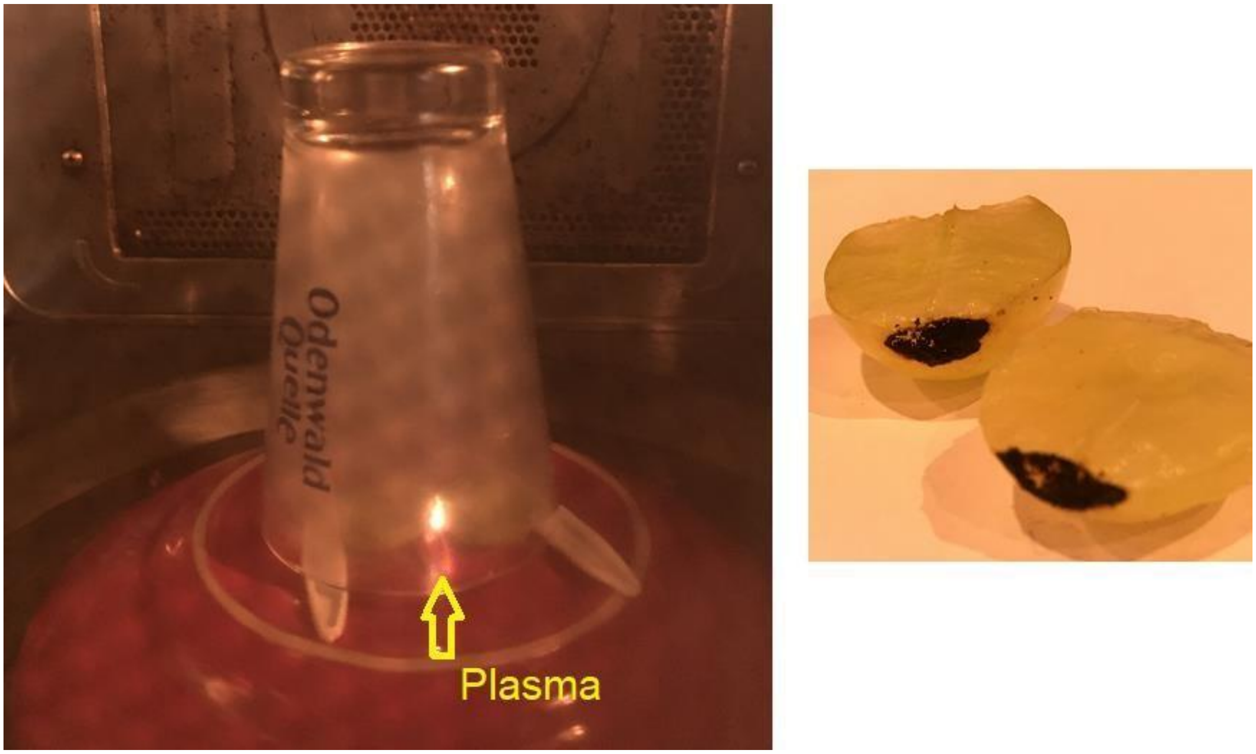

Figure 42. Example of a plasma discharge and the burning damage produced on the grape afterwards.

Explanation:

Microwave energy causes charges to collect on the moist pulp within each grape. To collect charges quickly, grapes are used because they have smaller surfaces and can collect charges more quickly than other kinds of fruit. Where the surfaces are closest, the spark that is produced creates the plasma. This initial spark may be hard to see directly because it will cause the grape skin to start burning to produce the more brilliant flame you see.

Assessment:

Learners will have explained why sparks form based on evidence from their grape experiment.

Question: Explain why two grapes in a microwave will create a spark.

Answer: If you place two grapes in a microwave oven so close together that they nearly touch, charges will build up on the exposed grape pulp until a spark occurs. This spark of plasma will produce the flame you see, which is the burning of the grape skin.

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