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The Relationship Between Emission Wavelength and Photon Energy in Metallic Ions

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ABSTRACT

This investigation explores the relationship between emission wavelength and photon energy in metallic ions using flame test analysis. The research question is: How does the observed photon color and predicted metallic wavelength (nm) of different metallic ions impact the energy (J) emitted? The researchers hypothesized an inverse relationship between the variables: as the wavelength increases, the energy emitted will decrease.

To investigate these ideas, wooden splints were soaked in 1.0 M solutions of various metal chlorides and exposed to a flame emitted from a Bunsen burner. The flame colors emitted as a result of the contact between heat and the metallic solutions were qualitatively observed and utilized to estimate frequency and energy.

The processed data later revealed a clear inverse relationship between wavelength and energy, supported by a near-perfect linear correlation. Metals emitting a shorter wavelength (e.g., potassium) exhibited higher photon energies, while those with longer wavelengths (e.g., lithium) showed lower energies. Relatively low percent error values demonstrated reasonable accuracy, though limitations arose from subjective color estimation and inconsistent flame conditions.

In the end, the results support the hypothesis and align with established quantum theory, confirming that photon energy is inversely proportional to wavelength. Beyond this experiment, this relationship has important real-world applications in fields such as spectroscopy, astronomy, and modern technologies, including lasers, fireworks, and medical imaging.

INTRODUCTION

In 1666, Sir Isaac Newton observed that light consists of a spectrum of seven unique visible colors. The spectrum of colors is universally accepted today as the rainbow: Red, Orange, Yellow, Green, Blue, Indigo, Violet (Smithsonian Libraries, 2019). This spectrum can be observed through a diffraction grating, or even in the sky after a storm, when light shines through raindrops that act as prisms that reflect the light. Among the visible rainbow, there are two color ranges that one's eyes cannot see: infrared light, below red, and ultraviolet light, above violet. The observed color of any object depends on the light it reflects; for example, a yellow object appears yellow because it reflects yellow light and absorbs all other colors. White, however, appears white because it reflects all lights equally, producing a white coloration. Black objects absorb all colors and reflect no visible light. Isaac Newton's experiment in 1665 demonstrated the fact that a prism bends “visible light and that each color refracts at a slightly different angle depending on the wavelength of the color” (NASA, 2016).

In the case of chemical light found in fireworks, lasers, and neon signs, atoms and molecules are emitting energy in the form of controlled visible light. Electrons in an atom are most commonly found in the lowest energy level, known as the ground state. When an electron moves to a higher energy level, it enters an excited state through the transfer of energy in the form of heat or electricity (Kancherla et al., 2026). Reaching the peak of this excited state, the electron typically begins to fall, descending back to the more stable ground state. If the energy released to excite the electron matches the energy needed to create visible light, the element produces color. The visible spectrum, showing the wavelengths necessary to produce each color, is depicted in *Figure 1*.

Electrons have many special properties, most importantly, electrons have duality, meaning they can act as particles or as waves (Butto, 2020). In 1905, Einstein concluded that light consists of both particles and waves, suggesting that electrons offer a dual purpose as both (Ouellette, 2005). In some situations, light acts as a particle, and in others, a wave. A wave of light can be measured utilizing wavelength, the distance from one crest of the wave to the next. Red light has long wavelengths, while blue light has short wavelengths. A particle of light, referred to as a photon, is measured by its energy. The energy of a single photon of visible light is minimal; thus, the infinitesimal units of “electron-volts” are used to measure the energy of photons. Photons of red light have low energies, while photons of blue light have high energies. One of Einstein’s most famous results is the discovery that wavelength relates to the energy of the photon (Ouellette, 2005). Einstein suggested this relationship: the longer the wavelength, the smaller the energy.

Additionally, the quantum mechanical model is the modern atomic theory, developed primarily by Erwin Schrodinger in 1926, that describes electrons as probabilistic matter waves rather than particles moving in fixed orbits. The model is built on three foundational quantum concepts: wave-particle duality, the Heisenberg Uncertainty Principle, and the Schrodinger Equation (Camilleri, 2006). Schrodinger primarily asserted that electrons exhibit properties of both particles and waves, thus agreeing with Einstein’s past conclusions. The Heisenberg Uncertainty Principle further suggests that it is fundamentally impossible to know both the exact position and momentum of an electron at the same time due to the duality of electron particles (Hilgevoord & Uffink, 2016). In quantum mechanics, a particle’s position and momentum act as conjugate variables; both are mathematically linked in a way that prevents both from being sharp at the same time (Wave-Particle Duality, Uncertainty Principle, 2025). Furthermore, the Schrodinger Equation, proposed by Schrodinger himself, is a mathematical formula ($H\psi=E\psi$) utilized to calculate the wave function of an electron. Unlike the circular orbits proposed by Niels Bohr, this model uses orbitals, a three-dimensional region of space where there is a high probability (typically ~90-95%) of finding an electron. The collection of these orbitals creates a "cloud" around the nucleus; denser areas represent a higher probability of electron presence (LibreTexts, 2016). Orbitals appear in different shapes based on their energy levels: s-orbitals are spherical, p-orbitals are dumbbell-shaped, and d/f orbitals are more complex multi-lobed shapes. This model is the foundation of modern chemistry, as it accurately predicts atomic spectra, why different elements emit specific colors of light, chemical bonding, how atoms share or transfer electrons, and periodic trends, the organization and behavior of elements (Weiss, 1961).

Spectra can be organized into three specific categories: the continuous spectrum, the absorption spectrum, and the emission spectrum. A continuous spectrum can be produced by thermal emission from a black body, making it extremely relevant to astronomy. Absorption and emission lines exemplify that every atom of a particular element will have the same pattern of lines consistently, and the spacing of these lines is the same in both absorption and emission; however, only emission lines are added to the continuum, while absorption lines are subtracted (A, 1930).

In this experiment, researchers heated wooden splints dipped in solutions of metal salts, observing the production of different colored flames to answer the essential question: how does the observed photon color and predicted metallic wavelength (nm) of different metallic ions impact the energy (J) emitted? By comparing the color emitted by an unknown salt with the known metal salts, researchers were able to accurately determine the identity of the metal salt. This experiment deepened the operator's understanding of wavelength, energy, frequency, and overall visible light because it challenged researchers to compare flame colors and calculate the wavelength, frequency, and energy as a result of the produced color. Researchers hypothesized: if an unknown element burns yellow-green, then the wavelength will be 563nm and the element will be Barium (Keane, 2019; USGS, 2020).

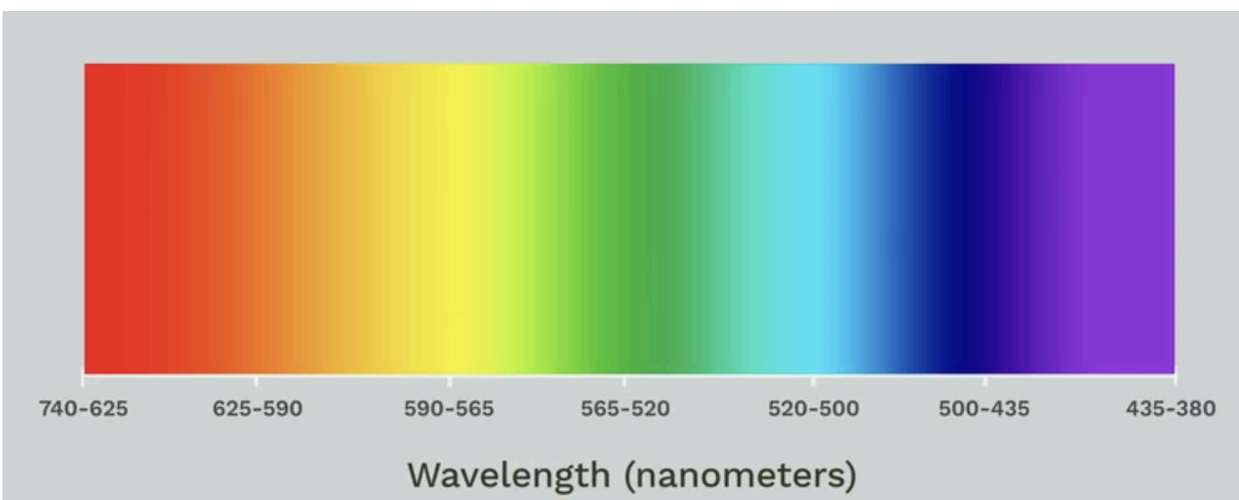

Figure 1: Visible Spectrum (Jones, 2024).

VARIABLES

Independent and Dependent Variables

The independent variable in this experiment is the color viewed by the researchers and the wavelength for that color emitted by a metal. The wavelength is measured in nanometers and will later be converted to meters for further calculations. As a result, the dependent variable is the energy emitted, measured in joules, because it is directly related to the recorded wavelength.

Controlled Variables

Variable	Explanation	Method of control
Room environment (temperature, lighting, etc.)	By keeping the room environment constant, researchers ensured that the data recorded was not affected by confounding variables such as differences in light or temperature. If the temperature varied, the flame color may have changed. If air conditioning was turned on, the flame may have been affected by the circulation of air in the lab. Similarly, if the lighting changed, researchers may have experienced a difference in flame color due to increasing/decreasing visibility.	researchers turned on and kept the lights in the laboratory on, and maintained the classroom temperature set to 22.2°C.
Concentration of all solutions	The concentration was kept constant to ensure that all wooden splints were soaking in equal amounts of solution, thereby preventing splints from being more or less saturated and producing a difference in light brightness or color.	All solutions were measured to be exactly 1.0M.
Set-up	Every group maintained the same setup in order to limit any	All groups were provided with labeled flasks containing each

	irregularities due to a simple functional error.	splint soaking, a Bunsen burner placed on the right-hand side of the lab table, and the same tables for recording data.

Table 1: Controlled variables.

MATERIALS

Item	Quantity and volume
Bunsen burner	1
Wooden splints	9
Lithium chloride solution	1.0 mol/L
Barium chloride solution	1.0 mol/L
Strontium chloride solution	1.0 mol/L
Calcium chloride solution	1.0 mol/L
Copper (II) chloride solution	1.0 mol/L
Sodium chloride solution	1.0 mol/L
Potassium chloride solution	1.0 mol/L
Sodium chloride/potassium chloride mixture	1.0 mol/L
An unknown metal chloride solution	3 1.0 mol/L solutions
Cobalt blue glass	1

Table 2: Materials utilized in the experiment.

EXPERIMENTAL PROCEDURE

1. Soak the 9 wooden splints in the metal salt solutions for 24 hours
2. Label each wooden splint with the names of the salts so that they are not mixed up
3. After 24 hours of soaking, obtain the wooden splints and the Bunsen burner
4. Light the Bunsen burner and open the air vent to obtain a non-luminous flame with two blue cones. Be sure to avoid a yellow flame.
5. Starting with the Lithium chloride solution, carefully place the end of the soaked wooden splint into the top of the inner blue flame.

6. Record the color the solution produces when heated. The color given off by the salt is the initial color observed, not the orange color produced by the burning wood.
    a. To avoid burning the wood, wave the wooden splint through the flame, instead of holding it steady in intense heat
7. Repeat steps five and six with the other 8 salts.
    a. Be sure to record the colors as precisely as possible
8. For the sodium-potassium mixture, observe the flame color produced through the cobalt blue glass to filter out any yellow or orange colors that may be present.
9. If additional observations are needed, dip the wooden splints back into their respective flasks, let them soak for 1 minute, and then return them under the flame.
10. For each color recorded, use the electromagnetic spectrum for visible light (*Figure 1 & Figure 2)* to predict the wavelength in nm.
11. After all the data has been collected and the experiment has concluded, turn off and store the Bunsen burner. Dispose of each of the solutions down the drain (see risk assessment), and properly dispose of the wooden splints in the trash. Wash all glassware with soap and water, then leave to air-dry.

Color	Wavelength (nm)
violet	380–450
blue	450–485
cyan	485–500
green	500–565
yellow	565–590
orange	590–625
red	625–750

Figure 2: (Ye, 2022).

RISK ASSESSMENT

To ensure the safety of all participants, researchers conducted the experiment with proper safety equipment, including goggles and an apron. The goggles were worn at all times, protecting researchers from the possibility of glassware shattering due to heat exposure from the Bunsen burner and the risk of splashing chemicals into their eyes. The goggles also provided extra protection against any fumes emitted by the burning of such substances that may have affected vision. Additionally, the aprons ensured that any spilled solutions or chemicals were kept away from the researchers' clothes and bodies. There are no ethical concerns with this experiment; however, it is essential to note that flushing large quantities of the chemicals could affect the drainage system and the surrounding aquatic environment.

Moreover, the disposal methods for each elemental mixture are listed below. Please note that all elements were of small enough quantity to safely dispose of down the drain, but if larger amounts are utilized, refer to *Table 3* for specifications.

Name	Method of Disposal
Lithium Chloride	Method #27h: Solid barium salts are extremely toxic and should not be flushed down the drain or buried in a landfill. Conversion to an insoluble barium sulfate is the best disposal route.
Sodium Chloride	Method #26a: Neutralization, solid waste disposal, or incineration
Potassium Chloride	Method #26a: Neutralization, solid waste disposal, or incineration
Calcium Chloride	Method #26a: Neutralization, solid waste disposal, or incineration
Strontium Chloride	Method #26a: Neutralization, solid waste disposal, or incineration
Copper (II) Chloride Dihydrate	Method #26a: Neutralization, solid waste disposal, or incineration

Table 3: Proper Disposal Methods for Each Compound According to Disposal Methods (2022)

DATA

Qualitative Data

Qualitative properties are all non-numeric observations recorded about the physical appearance and properties of a specific object. In this experiment, researchers observed that each flame exhibited distinct qualitative properties, as displayed in *Table 4*.

Metal Found in the Salt	Flame Color

Lithium	Red
Barium	Yellow
Strontium	Red
Calcium	Orange-red
Copper	Green
Sodium	Orange
Potassium	Lavender
Sodium and Potassium	Orange
Unknown A	Red
Unknown B	Red
Unknown C	Yellow

Table 4: Qualitative properties of each salt.

Essential Equations

Formulas:
1nm = $1*10^{-9}$m
f = frequency (Hz)
c = Speed of light in vacuum = $3.00*10^{8}$m s^{-1}
λ = wavelength (m)
f = c/λ
E = energy (J)
h = Planck's constant = $6.63*10^{-34}$J s
E = hf

Data Processing/Sample Calculations for Barium:
Wavelength in meters = 580nm*($1*10^{-9}$m) = $5.80*10^{-7}$m
Frequency = f = ($3.00*10^{8}$m/s)/($5.80*10^{-7}$m) = $5.17*10^{14}$Hz
Energy = E = ($6.63*10^{-34}$ J s)($5.17*10^{14}$Hz) = $3.43*10^{-19}$J

Quantitative Data

Quantitative data is all numerical data based on equations, measurements, or estimation (Welcome to Zscaler Directory Authentication, 2026). In this experiment, researchers estimated the wavelength (nm) of each salt and, accordingly, calculated the frequency (Hz) and energy (J) of each salt in relation to its wavelength. These values are illustrated in *Table 5*.

Metal Found in the Salt	Flame Color	Wavelength (nm)	Frequency (Hz)	Energy (J)
Lithium	Red	700.	$4.29*10^{14}$	$2.84*10^{-19}$
Barium	Yellow	580.	$5.17*10^{14}$	$3.43*10^{-19}$
Strontium	Red	730.	$4.11*10^{14}$	$2.72*10^{-19}$
Calcium	Orange-red	625.	$4.80*10^{14}$	$3.18*10^{-19}$
Copper	Green	540.	$5.56*10^{14}$	$3.69*10^{-19}$
Sodium	Orange	630.	$4.76*10^{14}$	$3.16*10^{-19}$
Potassium	Lavender	400.	$7.50*10^{14}$	$4.97*10^{-19}$
Sodium and Potassium	Orange	590.	$5.08*10^{14}$	$3.37*10^{-19}$
Unknown A	Red	722.	$4.16*10^{14}$	$2.76*10^{-19}$
Unknown B	Red	640.	$4.69*10^{14}$	$3.11*10^{-19}$
Unknown C	Yellow	580.	$5.17*10^{14}$	$3.43*10^{-19}$

Table 5: Raw (nm) and Processed (J and Hz) Data of Each Salt

ANALYSIS OF DATA

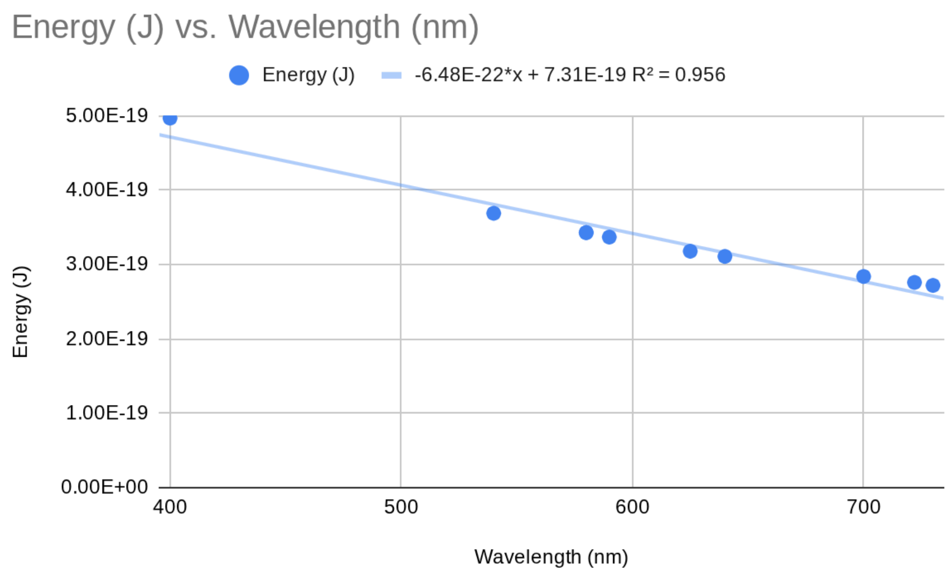

Figure 3: Graph of Energy (J) vs. Wavelength (nm).

Analytical Discussion of Figure 3

The graph depicted in *Figure 3* demonstrates the inverse relationship between energy (J) and wavelength (nm). As the wavelength increases, the energy noticeably decreases, demonstrating the fact that, as the wavelength increases, the space between the waves increases, meaning that the frequency of waves decreases because so much space and not as much energy is involved in each lengthy wavelength. This trend is consistent with the theoretical relationship defined by Plank's equation and the wave equation, where energy is inversely proportional to wavelength. The negative slope of the line of best fit also demonstrates this inverse relationship; as the wavelength increases, the energy decreases.

An R^2 value measures the proportion of variance in the dependent variable, as predicted by the independent variables in the linear regression (Khan Academy, 2017). It is a value between zero and one; the closer the number is to one, the better the fit for the model. The R^2 value approaches 1.00, indicating a strong linear relationship between Energy (J) and Wavelength (nm). It is even equal to one when rounded properly, suggesting that the data collected in this experiment is near-perfect. This suggests that wavelength is a highly reliable predictor of photon energy within the visible spectrum. Furthermore, the concentration of points surrounding the line of best fit, with no outlier data points, visually represents the strong linear relationship between the two variables, meaning the independent variable is a reliable predictor of the dependent variable.

Error Discussions

Percent Error Calculations:
% Error (round to nearest whole number) ={[|actual-experimental|]/[actual]}*100

Accepted Wavelengths (nm) (Santa Monica College, 2017):
Lithium = 670. nm
Barium = 590. nm
Copper (II) = 515. nm

Calculations:
Lithium = {[|670.-700.|]/[670.]}*100 = 4%
Barium = {[|590.-580.|]/[590.]}*100 = 2%
Copper = {[|515.-540.|]/[515.]}*100 = 5%

Accepted Energy (J) Values Calculated from Accepted Wavelengths:
Lithium = $2.97*10^{-19}$ J
Barium = $3.37*10^{-19}$ J
Copper = $3.86*10^{-19}$ J

Calculations:
Lithium = $\{[|2.97*10^{-19}-2.84*10^{-19}|]/[2.97*10^{-19}]\}*100$ = 4%
Barium = $\{[|3.37*10^{-19}-3.43*10^{-19}|]/[3.37*10^{-19}]\}*100$ = 2%
Copper = $\{[|3.86*10^{-19}-3.69*10^{-19}|]/[3.86*10^{-19}]\}*100$ = 4%

DISCUSSION

Given that the percent errors exceeded 1% error, the experimental results should be interpreted with caution. However, due to the fact that the percent errors remained under 10%, it is of note that the experimenters conducted the experiment with relatively low error. The percent error most likely resulted from the fact that researchers estimated the wavelengths instead of accurately calculating them, or even from the fact that the researchers did not record the qualitative observations of each flame color as precisely as possible, leading to small inconsistencies and failures in accurate data collection.

As expressed earlier, and as exemplified in *Figure 3*, the near-perfect R^2 value suggests that the margin of error was extremely small. When errors occurred, the researchers made only minimal mistakes, leading to simple, minuscule errors that did not completely derail the entire experiment or findings.

To further evaluate the accuracy of the results, accepted energy values were calculated using accepted wavelengths according to Santa Monica College (2017) and applying the equation E=hf, where frequency was determined using f=c/λ. These accepted energy values were then compared to the experimental energy values. Initial percent error calculations for energy yielded extremely large values due to a unit inconsistency, where frequency (Hz) was mistakenly compared to energy (J). Since these quantities are not directly comparable, the calculation produced non-physical results. After correcting this error by converting frequency to energy using Planck's equation ($E = hf$), the recalculated percent errors were found to be consistent with those obtained for wavelength. This highlights the importance of dimensional consistency in physical calculations, as incorrect unit comparison can lead to misleading or non-meaningful results.

The percent error between accepted and experimental values was found to be relatively low (ranging from approximately 2% to 5%), closely matching the percent error calculated for wavelength. This consistency indicates that the experimental method was reasonably accurate and that any deviations were systematic rather than random. The remaining sources of error (excluding the simple dimensional inconsistency discussed above) likely stem from limitations in the experimental method, particularly the reliance on visual estimation of flame color to approximate wavelength. Small variations in human perception, differences in lighting, and flame intensity may have introduced minor inaccuracies in wavelength estimation, which subsequently affected calculated energy values. Despite these limitations, the relatively low percent error values suggest that the overall experimental procedure was effective in demonstrating the inverse relationship between wavelength and energy.

CONCLUSION

Overall, this experiment accurately exemplified the importance of wavelength's impact on energy. Researchers discovered and supported the general idea that an inverse relationship exists between wavelength and energy, as depicted in *Figure 3*. Thus, the observed photon color and predicted metallic wavelength (nm) of different metallic ions significantly impact the energy (J) emitted, because, as the wavelength increases, the energy decreases, establishing a direct inverse relationship.

When assessing the experimental investigation, researchers were limited to small amounts of solution in each test tube, which prevented them from being able to resoak and retest the salts' flame color production multiple times. Additionally, researchers were provided with a Bunsen burner and small amounts of instruction, resulting in inconsistent production of both large and small flames that may have affected the burn color of each salt. Furthermore, cobalt glass was not available during this experiment, limiting the researchers to simple guesswork regarding the flame color and, consequently, the wavelength of the sodium potassium mixture. A key limitation of this investigation is the reliance on visual estimation of flame color to determine wavelength. Human perception of color is subjective and can vary based on lighting conditions, individual differences in vision, and environmental factors. This introduces uncertainty in assigning precise wavelength values to observed colors. Future investigations could improve accuracy by utilizing a spectroscope or diffraction grating to directly measure emission wavelengths, thus reducing reliance on subjective observations.

Additionally, these results support the quantum mechanical model of the atom, in which electrons occupy discrete energy levels and emit photons of specific energies during transitions. This aligns with the principles described by the Schrodinger Equation, where electron behavior is modeled probabilistically, and energy states are discrete rather than continuous. Therefore, the inverse relationship between wavelength and energy observed in this experiment reflects the underlying quantum nature of electron transitions.

Overall, the proposed hypothesis is accepted because unknown element C appeared yellow when heated (*Table 5)*, resulting in its 580nm wavelength, thus suggesting that the unknown element was Barium. The hypothesis correctly stated that if an unknown element burned yellow-green, then the wavelength would be 563nm, and the element would be Barium; although the predicted wavelength was incorrect, it is within the accepted range for a yellow-green flame. Thus, the hypothesis is correctly accepted because it accurately described Barium as an element producing a yellow-like flame, and properly used accepted wavelengths from the visible spectrum in *Table 3,* to estimate a proper wavelength.

Finally, this experiment applies to the modern world because visible light and bright colors, as a result of chemical reactions, are present in hundreds of different objects. For example, fireworks and neon signs alike utilize visible light to produce concentrated color and eye-catching displays. Understanding the relationship between wavelength and energy is essential for comprehending and effectively utilizing technologies such as medical imaging, communication, and solar power, as well as understanding phenomena like the color of the stars and the safety of radiation. These applications rely on controlled electron transitions between quantized energy levels, further demonstrating the relevance of the quantum mechanical model in explaining how specific wavelengths and energies of light are produced.

Discovered and proposed in 1666, the visible light spectrum has journeyed far since then. In this experiment, the visible light spectrum exemplifies the inverse relationship between wavelength and energy. Therefore, observed photon color and predicted metallic wavelengths (nm) of different metallic ions directly determine the energy (J) emitted through their inverse relationship.

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