
QUANTUM (Q)-KIT

Quantum Chemistry:

Laboratory for Secondary Level Students

Teacher Manual



WOMEN SUPPORTING
WOMEN IN THE SCIENCES

Mission Statement

The mission of this laboratory is to teach secondary level students (ages ~12-18) about atoms and matter with hands-on experiments and activities.

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1. Introduction to WS2 Laboratory Kits

1.1. Information about WS2

Women Supporting Women in the Sciences (WS2), an international organization unifying and supporting graduate and professional-level women and allies in science, technology, engineering, and mathematics (STEM), was awarded an American Physical Society (APS) Innovation Fund in 2020 to form international teams to design and distribute low-cost physics and materials science lab kits to primary and secondary school students, predominantly in eastern Africa. The lab kits utilized local resources and included topics that are especially relevant to young girls in order to spur their interest in STEM subjects. From 2020-2023, over 5100 students from eastern Africa at over 40 school sites engaged with our lab kits, with 62% being girls.

WS2 was awarded their second APS Innovation Fund in 2025 to support another Lab Kit Initiative, though this time with a focus on quantum topics. For more information about WS2, please visit our website at ws2global.org.

WS2 is sponsored by the APS Innovation Fund, APS Forum on Education, Northwestern University Materials Research Science and Engineering Center, and Northwestern University Multicultural Student Affairs. WS2 is extremely grateful to the lab kit design volunteers for their hard work and external consultants (SciBridge and Projekt Inspire) for their advising. WS2 also thanks and acknowledges PhysicsQuest (<https://www.aps.org/initiatives/physics-education/physicsquest>) and Quantum Explorations Student Toolbox (QuEST) for example experiments that were used as foundation for the lab kit content.

1.2. Using the Guide

This manual is to be used by the teacher or facilitator of the laboratory kit, and it is similar in content to the student manual but may contain additional material, namely: Fundamental Science Concepts Covered, Practical Skills, Summary of Experiments, Teacher Pre-Lab, and Troubleshooting. These additional sections are intended to provide the teacher with the background and foundation critical for successfully implementing this laboratory kit in the classroom. It is recommended that the teachers of this laboratory kit go through the guide from beginning to end to familiarize themselves with the content prior to teaching the laboratory kit to students. Questions about the content can be directed at any time to ws2global.org@gmail.com, using the subject line "Question about Lab Kit Content".

IMPORTANT NOTES:

- This laboratory kit is intended for use with secondary-level students (ages ~12-18), but depending on the specific students' educational background, the content may need to be modified by the teacher to be made simpler or more complex. The teacher is encouraged to also cover the content at the pace that works best for the students; some younger students may need more time and attention from the teacher and/or facilitator to go through the questions and experiments, while older students may be more independent and require less attention from the teacher and/or facilitator. Thus, the content covered, depth of coverage, and pacing are left to the teacher's and/or facilitator's discretion.
- The content in this lab kit manual may not fit into the specific curriculum of the school in which it is being taught. It is up to the facilitator(s) and teacher(s) whether they would like to introduce new content or skip certain sections that are not applicable to their classrooms.
- In certain areas, modifications to the supply list may need to be made depending on the availability of the supplies in the specific area in which the lab is being taught. We have attempted to list some alternatives in the supply list, but we understand this list of alternatives is not exhaustive.
- In the experiments, the students are split into groups of three to four. If supplies allow, students may instead be split into groups of two.

1.3. Key Vocabulary

- Atom: the smallest unit of an element that retains the element's properties
- Electron: charged subatomic particle that forms "cloud" around atom's nucleus
- Nucleus: dense center of atom consisting of neutrons and protons
- Nanoparticle: a material with a diameter between 2-100 nanometers (nanometer is 1×10^{-9} m)
- Quantum dot: a nanoparticle typically between 2-10 nm in size with unique properties that arise from being so small (like light emission)
- Fluorescence: light emitted by an excited state particle that lasts on the order of nano- to microseconds

1.4. Key Questions

- What are the key features of the Rutherford, Bohr, and quantum mechanical models of the atom?
 - *Answer:* The Rutherford model has a dense nucleus with electrons surrounding the nucleus. This model was created following the famous gold foil experiment. The Bohr model added electron orbits at specific energies around the nucleus. Finally, the quantum mechanical model described the electrons as being found in clouds, or orbitals, with high probability.
- What is a carbon quantum dot and what does it mean to have fluorescence?
 - *Answer:* Carbon quantum dots are small carbon nanocrystals, typically under 10 nanometers in size. These special materials have fluorescence, which means that they emit light by absorbing light, which typically is short-lived.

1.5. Purpose

The purpose of this lab kit manual is to enable students to understand atoms and nanosized matter through theory, demonstration, and experiments. The manual introduces the students to atomic models before discussing quantum dots and the unique ways in which light interacts with them.

1.6. Fundamental Science Concepts Covered

This laboratory kit introduces the topic of quantum chemistry, relevant to numerous fields including Physics, Chemistry, and Biology, to middle and high school/secondary-level students. Specifically, the lab kit encourages students to think about the building block of matter, the atom, and extremely small particles, nanoparticles, through models and experiments. Students will come away with the following key takeaways: (1) atomic models built upon each other, with the current model describing atoms as having a dense nucleus with protons and neutrons and electrons in orbitals; (2) carbon quantum dots can be created through chemical reactions with carbon containing materials and these materials have special properties like fluorescence which means they emit light upon absorbing light of a high enough energy.

1.7. Practical Skills

- Students will understand the structure of the basic building block of matter, the atom, and how atoms form larger entities, like molecules and nanoparticles
- Students will gain experience with basic chemistry, including weighing and heating samples
- Students will connect concepts to everyday experiences at school and home (e.g, glow-in-the-dark objects)

2. Background on Main Topics

2.1. The Atom

The atom is the basic building block of matter, making up everything around us. Atoms essentially are the smallest unit of an element (think of elements on the periodic table, like carbon, nickel, aluminum, and hydrogen) that still retain the element's properties. Atoms are incredibly small and cannot be seen with our naked eyes, but they are extremely powerful in that they determine the properties of everything around us from metal chairs to the air we breathe. Beginning in the 1800s, scientists attempted to describe the atom. In 1808, John Dalton proposed the atomic model theory which described atoms as solid spheres that are small and indivisible. J. J. Thomson built on this model and in 1904 proposed the "plum pudding" model which described an atom as electrically neutral. He said that the atom itself was a sphere of positive charge with negatively embedded electrons, like plums found inside pudding (similar to blueberries or other fruit pieces inside of a cake or muffin), and these opposing charges equal each other. Electrons, which are extremely light, play a key role in how chemical reactions occur and also are the carriers that flow in electricity.

The concept of the atomic nucleus came about in 1911, when Ernest Rutherford described atoms with a dense concentration of positive charge at the center of the atom, the so-called nucleus. Electrons then move about the nucleus and the atom consists of a lot of empty space (Figure 1). Rutherford came up with this description after performing what became famously known as the "gold foil experiment" (see Figure 2). Rutherford and his team aimed alpha particles at a thin gold sheet. Based on the Thomson model, it was hypothesized that these alpha particles would pass directly through the sheet. Mostly these particles passed through the sheet, but occasionally, some bounced back. This was a remarkable finding, and led to Rutherford's famous quote, "It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." This finding led Rutherford to

conclude that atoms have a dense nucleus where most of their mass is concentrated. We now describe the nucleus as containing both protons, which are positively-charged particles that define the identity of an element, and neutrons, which are particles with no charge and have similar mass to protons. For comparison, protons and neutrons are about 2000 times heavier than electrons.

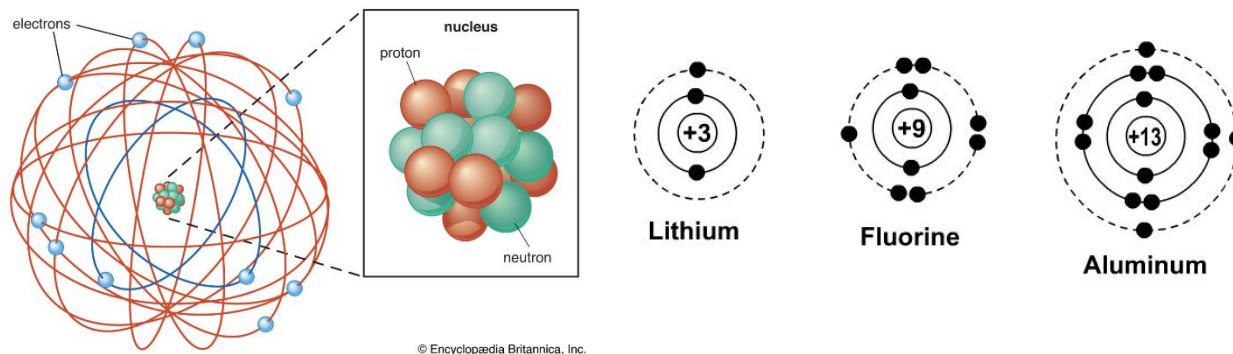


Figure 1. In the Rutherford model of the atom (left), the nucleus is a dense concentration of mass at the center of the atom and there is a lot of empty space. In Bohr model of the atom (right), the electrons orbit the nucleus with orbits that are well-defined sizes and energies. [This Photo](#) by Unknown Author is licensed under [CC BY-SA-NC](#).

Additional refinements to the atomic model concerned electrons. In 1913, Niels Bohr said that electrons orbit the nucleus, and the well-defined orbits have specific sizes and energies (see Figure 1), but this was later improved upon by Erwin Schrodinger in 1926 who said that electrons are really found in clouds, or orbitals, around the nucleus which contains protons and neutrons. The electron orbitals are areas that have a high probability of containing electrons. This model of the atom, known as the quantum mechanical model, is how we still describe atoms today.

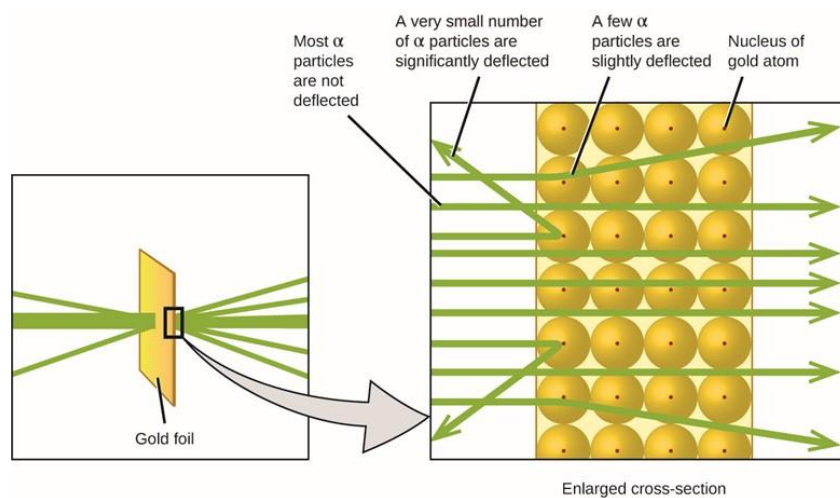


Figure 2. Gold foil experimental schematic. Most alpha particles passed through the gold foil, but a very small number are deflected when they hit the dense nucleus. [This Photo](#) by Unknown Author is licensed under [CC BY-SA-NC](#).

2.2. Quantum dots

Atoms can bond together to form much bigger entities. Consider water (H_2O), which is a molecule that contains three atoms: two hydrogen and one oxygen. More than any other element, carbon has the capability of forming bonds to itself, which can lead to very large molecules that are predominantly carbon and hydrogen, like carbohydrates, proteins, and nucleic acids. Carbon can also bond with itself in an ordered way to make carbon crystals. Examples of carbon crystals are graphite and diamond which are both pure carbon materials. Interesting behaviors can emerge when carbon crystals become very small and are classified as nanoparticles, which are materials with diameters between 2-100 nanometers (nanometer is 1×10^{-9} m). Nanoparticles can be billions of times smaller than the diameter of a hair! Specifically, small nanocrystals of carbon that typically have sizes below 10 nanometers are called carbon quantum dots. Carbon quantum dots (Cdots) were discovered in the early 2000s as a reaction byproduct, and, interestingly, it was soon found Cdots can be produced from various carbon sources (even plant leaves!). Cdots have fluorescence, which means that they emit light by absorbing light, and this emission lasts on the order of nano- to microseconds.

A unique aspect of quantum dots is that their fluorescent emission can be “tuned” simply by changing the size of the particle or its chemical composition. Larger particles emit at longer (redder) wavelengths, while smaller particles emit at shorter (bluer) wavelengths (see Figure 3). The system behaves analogously to the introductory quantum mechanics “particle-in-a-box” model. A crude picture of this is that because the particle size is roughly comparable to the size of the wavelength of light, the particle becomes the “box”, and the system becomes “quantized”, that is, has specific allowed energy levels (this is not exactly true for Cdots, which have broad energy “bands” rather than sharp allowed levels, but the basic ideas still follow). Providing energy to the particle can “excite” an electron from the ground state to an excited state, much as providing electricity to a neon light can excite the neon atoms in the tube. Once excited, the Cdots can glow. Nature in general dictates that systems prefer to be at their lowest energy level (think water running downhill), and one way neon atoms or Cdots can de-energize is to emit their excess energy as light. Neon tubes glow red because the energy of red light corresponds to the energy difference between the excited state energy level and the lower (ground) state level. Just as changing gases in “neon” lamps alters the emitted colors, incorporating other atoms in the Cdots can change the absorption and emission characteristics. It is worth noting that the energy of the light emitted will always be equal to or less than the energy of excitation – that is, the emission will be at longer wavelengths (blue, green or red) than the higher energy light (like ultraviolet) originally absorbed.

Interestingly, some excited molecules or nanoparticles may not emit visible light at all or emit light for a very long time after the excitation is turned off. In the former case, energy could be emitted as heat (i.e., infrared light which we cannot see). The latter case will be familiar to children that have played with “glow-in-the-dark” toys. Neon lamps stop glowing almost immediately after we turn off the power (i.e., fluorescence), but glow-in-the-dark toys work by phosphorescence, where the energy gets trapped in the molecule, and only “leaks” out slowly, meaning the emission is a lot longer lived than in the fluorescence case.

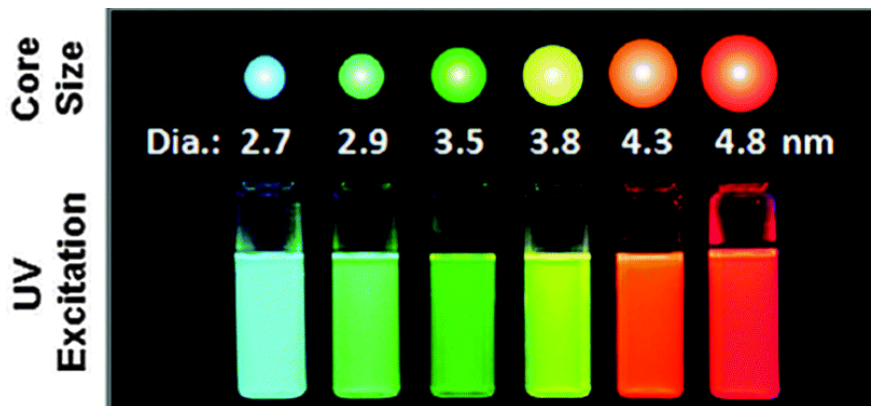


Figure 3. The size of quantum dots is related to the color they emit. Larger quantum dots emit at longer (redder) wavelengths. [This Photo](#) by Unknown Author is licensed under [CC BY-NC](#)

3. Summary of Experiments

This lab kit consists of one activity, one experiment, and one design challenge to understand concepts related to quantum chemistry. This investigation will begin by providing relevant background on atoms, nanomaterials, and fluorescence, before modelling and demonstrating key phenomena. The goals of the experiments and design challenge are the following:

Part I: To model the atom using candy that showcases a dense nucleus of protons and neutrons and electrons surrounding the nucleus

Part II: To showcase fluorescence in carbon quantum dots created from different carbon-containing materials

Design Challenge: To design an application that uses fluorescence in their life

3.1. Supplies List

- Sugar
- Water
- Source of heat (microwave oven, hot plate, stove top, flame)
- Pyrex conical flask
- Clear jar
- Test tubes (or small clear sample holders)
- Parafilm (or plastic wrap)
- Light sources (UV flashlight, green laser, red laser)
- Cotton swabs
- Paper
- Lemon juice
- Spherical-like candies of three colors (or compressed foil balls of three colors)
- Toothpicks
- Dark string (or pipe cleaners)
- Marker

3.2. Safety Information

Before the students begin the laboratory, please take into consideration the following safety concerns:

- Students should never look directly at a UV flashlight or laser point, as this can permanently damage their eyes due to the laser intensity and emission as a tight beam.
- Students should be careful handling hot glassware and should use potholders or protective gloves to move hot glassware.
- Students should not eat or taste items during experiments.

3.3. Teacher Pre-Lab

Teachers can organize the supplies for the experiments and activities ahead of time. For each student or each group of 2-4 students, the materials needed are: spherical-like candies of three colors (at least 8 per group) (or compressed foil/paper balls of three colors), several toothpicks, length of dark string (approximately ~0.5 m) (or ~4-

5 pipe cleaners), paper (at least 2 pieces), 3 test tubes (or clear containers), 3 small pieces of parafilm (or plastic wrap), 3 cotton swabs, and a pen or pencil. There should be light sources (UV flashlight, lasers) that the classroom can share. For Part II, the solutions can be made as a group before being split between groups. A heating source (microwave, hot plate, or oven) should be available for use. For each solution, the following supplies will be needed: 1 Pyrex flask, 1 g of sugar (or 10 g of fresh lemon juice), and water (approximately 60 mL).

Teachers can learn more about Part II by visiting this link to watch the related video: https://www.youtube.com/watch?v=jYG5279Cmx0&list=PLgxD9DiwxLGp_3vj3biSPG88glyU6Vzpz&index=9.

4. Experiments

Note for teachers:

Encourage open discussion and questions from the class when introducing the experiments.

4.1. Part I. Candy Atomic Models

4.1.1. Pre-Activity Questions

1. What subatomic particles are found at the center of the atom (nucleus)?
 - a. Answer: *Protons (positively charged) and neutrons (no charge).*
2. What subatomic particles surround the nucleus?
 - a. Answer: *Electrons (negatively charged).*
3. What are the key features of the Rutherford model of the atom?
 - a. Answer: *Dense nucleus at center of atom and electrons that surround the nucleus. The atom is mostly empty space.*

4.1.2. Materials

- Spherical-like candies of three colors (or compressed foil/paper balls of three colors) (at least 8 of each per group)

- Toothpicks
- Dark string (or pipe cleaners)
- Paper
- Marker

4.1.3. Procedure & Analysis (work in groups of 2-4)

1. Sort out candies of different colors (or create balls of paper/foil that are three different colors).
2. Select 8 candies each of two colors and use toothpicks to join them together in a densely packed nucleus. Set this nucleus on a piece of paper.
 - a. What do these two types of candies represent? Label this on the paper.
 - i. Answer: *Protons and neutrons.*
3. Use two lengths of dark string (or pipe cleaners) and make concentric circles around the nucleus.
 - a. What do these circles represent? Label this on the paper.
 - i. Answer: *Orbits or orbitals.*
4. Select 8 candies of the remaining color and place them on the concentric circles.
 - a. What do these candies represent? Label this on the paper.
 - i. Answer: *Electrons.*
5. Now, place 2 candies on the inner circle and 6 on the outer circle. This represents how electrons fill the outermost orbitals in this element (the first level contains 2 electrons and the second level contains 6 electrons, though it could contain up to 8 electrons total). See Figure 4 for an example of the candy atom model.



Figure 4. Example of the candy atom model with the densely packed nucleus and the electron orbits.

4.1.4. Post-Activity Questions

1. What element did you model in this activity? How do you know? (Hint: you may need to consult a periodic table – see Appendix)
 - a. Answer: *Oxygen. Oxygen has 8 protons, and we know this from the periodic table, which shows oxygen's atomic number is 8.*

2. Was this atom charged in this activity? How do you know?
 - a. Answer: *No, the atom was not charged. This is because the number of positive charges (protons) equaled the number of negative charges (electrons).*

 - b. Extension question: How could you imagine making this atom charged?
 - i. Answer: *If we removed or added an electron, the oxygen atom would be charged. If we removed an electron, the atom would be positively charged, and if we added an electron, the atom would be*

negatively charged. We cannot retain the oxygen atom if we change the number of protons, meaning the oxygen atom will become a different element.

3. What are additional improvements that you could make to your model to more realistically represent an atom? Consider the other atomic models that followed Rutherford. Try these improvements out and record your observations.
 - a. *Answer: Encourage student creativity. A couple of possible options: (1) We could try to represent the quantum mechanical model with electron clouds. Perhaps we could use cotton instead of flat circles in this case. Cotton pieces would represent orbitals and the probabilistic nature of finding electrons. (2) We could also better represent the sizes of the subatomic particles. Electrons are much smaller than protons or neutrons, so we could use a much smaller candy to represent them.*

4.2. Part II. Carbon Quantum Dots in the Kitchen

This section is based on the Secret Nanobits from the Kitchen activity from PhysicsQuest (American Physical Society).

4.2.1. Additional Background

Chemical reactions can convert everyday food items into carbon quantum dots (Cdots). Basically, heating carbon-based samples can cause them to break down and re-form as tiny carbon nanoparticles, in this case Cdots. These materials are fluorescent under certain light with high enough energy, like UV light and some lasers. Once Cdots are formed, they can be used in some simple applications, like “secret” writing.

4.2.2. Pre-Experiment Questions

1. What are carbon quantum dots (Cdots)?
 - a. *Answer: Carbon quantum dots are small nanocrystals of carbon that have sizes typically below 10 nanometers.*

2. What is fluorescence?
 - a. Answer: *Fluorescence is the phenomenon of a material emitting light after absorbing light of high enough energy. This emission lasts on the order of nano- to microseconds.*

3. How does the size of a quantum dot impact its fluorescence?
 - a. Answer: *Larger particles emit at longer (redder) wavelengths, and smaller particles emit at shorter (bluer) wavelengths.*

4.2.3. Materials

- Sugar
- Water
- Lemon juice
- Source of heat (microwave oven, hot plate, stove top, flame)
- Pyrex conical flask
- Clear jar
- Test tubes (or small clear sample holders)
- Parafilm (or plastic wrap)
- Light sources (UV flashlight, green laser, red laser)
- Cotton swabs
- Paper

4.2.4. Procedure (work in groups of 2-4)

The following steps can be completed as a class and then the resultant materials split up and used by smaller groups:

1. Measure 1 g (~1/4 tsp) of table sugar and place in Pyrex conical flask.
2. Add 10 g (10 mL or 2 tsp) water to the container. Stir until sugar is dissolved.
3. Place flask in/on the heat source for about 10 min.
 - a. The time may vary depending on the heat source. In a microwave at 40% power, 10 min is the approximate time.

- b. The product should be dark orange in color and have a “sap” like consistency. The mixture will smell like burnt sugar.
4. Add about 50 g (50 mL or ¼ cup) water to the flask and swirl until the material is fully dissolved.
 - a. The solution should be dark orange (lighter than iced tea). If it is darker than iced tea, add a bit more water. See an example of what this solution will look like in Figure 5.
5. In a separate glass jar, add 1 g (~1/4 tsp) of table sugar and 10 g (10 mL or 2 tsp) of water. Stir until sugar is dissolved.
6. (if supplies allow) Repeat steps 1-4 using fresh lemon juice (10 g or 3 tsp) instead of sugar. Stop heating when the solution gets syrupy and dark (it may take less time than the sugar).



Figure 5. Example of sugar+water solution that has been heated.

The following steps can be completed by smaller groups:

7. Collect three samples in test tubes: sugar+water (heated), sugar+water (unheated), and lemon juice+water (heated).
8. Place parafilm or plastic wrap over the top of the solutions to keep them from being contaminated.
9. In the dark, shine the UV light on the three solutions, one at a time. Record your observations.
10. Repeat step 9 with your other light sources.
11. Saturate cotton swab with the different solutions.
12. On a piece of white paper, use the swab to write letters or draw a shape. You may have to re-wet the swabs. If the writing is wet enough to look dark on the paper, you probably have used enough solution.
13. Allow writing to dry.
14. In the dark, shine the UV light on the three marks. Record your observations.
15. Repeat step 14 with your other light sources.

4.2.5. Results

Solution	What did you observe in the room light?	What did you observe with the UV light?	What did you observe with the green laser pointer?	What did you observe with the red laser pointer?
<u>Sugar+water (heated)</u> Test tube: Marking on paper:				
<u>Sugar+water (unheated)</u> Test tube: Marking on paper:				
<u>Lemon juice+water (heated)</u> Test tube: Marking on paper:				

4.2.6. Post-Experiment Questions

1. What did you observe in the room light with your solutions and markings?
 - a. Answer: *In the room light, we do not see any emission of the solutions or markings.*

2. With the light sources you used in the dark, what did you observe?
 - a. Answer: *The light sources with high enough energy, like the UV flashlight and green laser, likely caused the solutions that contained carbon quantum dots (the heated sugar-water and heated lemon juice-water solutions) to fluoresce. The red laser likely did not have enough energy to cause the fluorescence.*
 - b. Extension question: What does this tell us about the energies of the light sources and how they relate to our Cdots?
 - i. Answer: *Those light sources that caused the heated solution to fluoresce are higher energy than those that did not cause the heated solution to fluoresce. This tells us something about the energy needed to cause fluorescence in our Cdots. The higher energy light sources provided enough energy to excite an electron from its ground state to an excited state, and then the excess energy was emitted as light. The lower energy light sources were not able to do this in our Cdots.*

3. Did you notice any differences in the Cdots made from lemon juice and sugar? How can you explain this?
 - a. Answer: *Students may or may not notice major differences. If there are differences noted, this could be because of the size of the quantum dots or because of the chemical composition.*

4. Were there any sources of error in your experiment that could impact your results?
 - a. Answer: *Encourage students to think broadly about sources of error. The sugar or lemon juice could contain impurities that impact absorption and emission. The other components (water) and glassware are not perfectly clean, so this could always introduce some impurities and error. Not enough heating time would impact the formation of carbon quantum dots.*

5. Design Challenge

The Challenge: Design another application for quantum dots!

We have seen in the previous experiment that quantum dots can fluoresce when they absorb high enough energy light and that the color of the fluorescence can depend on the size of the quantum dot. With these concepts in mind, consider another application for quantum dots that could be useful in your life.

5.1 Design Questions

1. How does the fluorescence color depend on the size of the quantum dot? Are there any other things that could impact the color?
 - a. Answer: *Larger particles emit at redder wavelengths and smaller particles emit at bluer wavelengths. Besides size, chemical composition could also impact the color.*

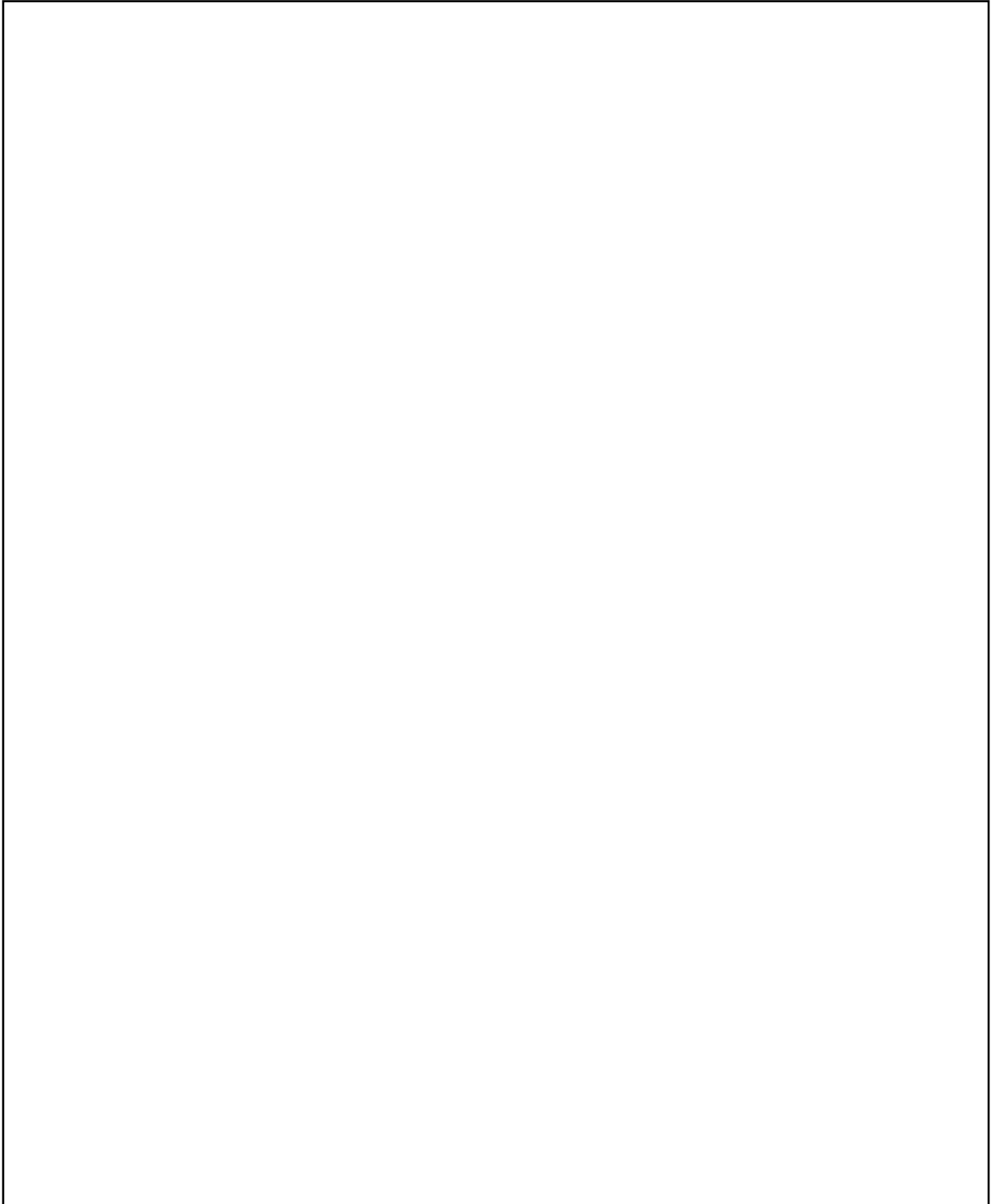
2. How could you potentially change the synthesis conditions of quantum dots to change their fluorescence color?
 - a. Answer: *Students should speculate on what they could do to change either the size or composition of their quantum dots. They could use different starting materials in an attempt to make a quantum dot of a different material. They could add another chemical to alter the composition of their quantum dot. They could try heating longer or shorter times to impact the size of their quantum dots. Encourage creative thinking.*

3. What role does the energy of the absorbed light play in fluorescence?
 - a. Answer: *The absorbed light needs to be high enough energy to cause fluorescence.*

4. How could the properties of fluorescence be used in applications? Brainstorm many ideas and share and discuss with your classmates.
 - a. Answer: *Students should think broadly and imagine many different possibilities. Encourage creativity and open discussion.*

5.2 Design Sketch

Sketch the design of quantum dot fluorescence application below.



6. Sources

Atoms and atomic models:

<https://medium.com/@Intlink.edu/a-timeline-of-atomic-models-cb2607b1da85>

Quantum dots:

PhysicsQuest (2025): The Secret Glow of Nanobit from the Kitchen

United States Naval Academy Chemistry Department, Experiment #490: Synthesis and Properties of Quantum Dots. 2024.

https://intranet.usna.edu/ChemDept/_files/documents/integrated-labs/SC364/2024_Documents/S24_SC364_EXP_490_Quantum_Dots_FV9.pdf
(accessed September 20, 2024).

7. Appendix

PERIODIC TABLE
Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum c 299 792 458 m s⁻¹ (exact)

Planck constant h 6.626 07 × 10⁻³⁴ J s ($h = h/2\pi$)

elementary charge e 1.602 177 × 10⁻¹⁹ C

electron mass m_e 9.109 38 × 10⁻³¹ kg

$m_e c^2$ 0.510 999 MeV

proton mass m_p 1.672 622 × 10⁻²⁷ kg

fine-structure constant α 1/137.035 999

Rydberg constant R_∞ 10 973 731.569 m⁻¹

$R_\infty c$ 3.289 841 960 × 10¹⁵ Hz

$R_\infty hc$ 13.605 69 eV

Boltzmann constant k 1.380 6 × 10⁻²³ J K⁻¹

Physical Measurement Laboratory
www.nist.gov/pml

Standard Reference Data
www.nist.gov/srd

■ Solids
■ Liquids
■ Gases
■ Artificially Prepared

Group	PERIODIC TABLE																Physical Measurement Laboratory				Standard Reference Data				Group												
	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20																
IA	IIA		IIIB	IVB	VB	VIB	VII B	VIII			IX		X		IIIA	IVA	VA	VIA	VIIA	VIIIA																	
1	¹ H Hydrogen 1.008 1s	2		³ Li Lithium 6.94 1s ² 2s	⁴ Be Beryllium 9.0121831 1s ² 2s ²	¹¹ Na Sodium 22.98976928 [Ne]3s	¹² Mg Magnesium 24.305 [Ne]3s ²	¹⁹ K Potassium 39.0983 [Ar]4s	²⁰ Ca Calcium 40.078 [Ar]4s	²¹ Sc Scandium 44.955908 [Ar]3d ¹ 4s ²	²² Ti Titanium 47.867 [Ar]3d ² 4s ²	²³ V Vanadium 50.9415 [Ar]3d ³ 4s ²	²⁴ Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹	²⁵ Mn Manganese 54.938044 [Ar]3d ⁵ 4s ²	²⁶ Fe Iron 55.845 [Ar]3d ⁶ 4s ²	²⁷ Co Cobalt 58.933194 [Ar]3d ⁷ 4s ²	²⁸ Ni Nickel 58.9332 [Ar]3d ⁸ 4s ²	²⁹ Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹	³⁰ Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ²	³¹ Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	³² Ge Germanium 72.630 [Ar]3d ¹⁰ 4s ² 4p ²	³³ As Arsenic 74.921595 [Ar]3d ¹⁰ 4s ² 4p ³	³⁴ Se Selenium 78.9718 [Ar]3d ¹⁰ 4s ² 4p ⁴	³⁵ Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	³⁶ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶	¹³ B Boron 10.81 1s ² 2s ² 2p ¹	¹⁴ C Carbon 12.011 1s ² 2s ² 2p ²	¹⁵ N Nitrogen 14.007 1s ² 2s ² 2p ³	¹⁶ O Oxygen 15.999 1s ² 2s ² 2p ⁴	¹⁷ F Fluorine 18.99840316 1s ² 2s ² 2p ⁵	¹⁸ Ne Neon 20.1797 1s ² 2s ² 2p ⁶						
2	³ Li Lithium 6.94 1s ² 2s	⁴ Be Beryllium 9.0121831 1s ² 2s ²	¹¹ Na Sodium 22.98976928 [Ne]3s	¹² Mg Magnesium 24.305 [Ne]3s ²	¹⁹ K Potassium 39.0983 [Ar]4s	²⁰ Ca Calcium 40.078 [Ar]4s	²¹ Sc Scandium 44.955908 [Ar]3d ¹ 4s ²	²² Ti Titanium 47.867 [Ar]3d ² 4s ²	²³ V Vanadium 50.9415 [Ar]3d ³ 4s ²	²⁴ Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹	²⁵ Mn Manganese 54.938044 [Ar]3d ⁵ 4s ²	²⁶ Fe Iron 55.845 [Ar]3d ⁶ 4s ²	²⁷ Co Cobalt 58.933194 [Ar]3d ⁷ 4s ²	²⁸ Ni Nickel 58.9332 [Ar]3d ⁸ 4s ²	²⁹ Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹	³⁰ Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ²	³¹ Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	³² Ge Germanium 72.630 [Ar]3d ¹⁰ 4s ² 4p ²	³³ As Arsenic 74.921595 [Ar]3d ¹⁰ 4s ² 4p ³	³⁴ Se Selenium 78.9718 [Ar]3d ¹⁰ 4s ² 4p ⁴	³⁵ Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	³⁶ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶	¹³ B Boron 10.81 1s ² 2s ² 2p ¹	¹⁴ C Carbon 12.011 1s ² 2s ² 2p ²	¹⁵ N Nitrogen 14.007 1s ² 2s ² 2p ³	¹⁶ O Oxygen 15.999 1s ² 2s ² 2p ⁴	¹⁷ F Fluorine 18.99840316 1s ² 2s ² 2p ⁵	¹⁸ Ne Neon 20.1797 1s ² 2s ² 2p ⁶									
3	¹¹ Na Sodium 22.98976928 [Ne]3s	¹² Mg Magnesium 24.305 [Ne]3s ²	¹⁹ K Potassium 39.0983 [Ar]4s	²⁰ Ca Calcium 40.078 [Ar]4s	²¹ Sc Scandium 44.955908 [Ar]3d ¹ 4s ²	²² Ti Titanium 47.867 [Ar]3d ² 4s ²	²³ V Vanadium 50.9415 [Ar]3d ³ 4s ²	²⁴ Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹	²⁵ Mn Manganese 54.938044 [Ar]3d ⁵ 4s ²	²⁶ Fe Iron 55.845 [Ar]3d ⁶ 4s ²	²⁷ Co Cobalt 58.933194 [Ar]3d ⁷ 4s ²	²⁸ Ni Nickel 58.9332 [Ar]3d ⁸ 4s ²	²⁹ Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹	³⁰ Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ²	³¹ Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	³² Ge Germanium 72.630 [Ar]3d ¹⁰ 4s ² 4p ²	³³ As Arsenic 74.921595 [Ar]3d ¹⁰ 4s ² 4p ³	³⁴ Se Selenium 78.9718 [Ar]3d ¹⁰ 4s ² 4p ⁴	³⁵ Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	³⁶ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶	⁵⁵ Cs Cesium 132.9054520 [Xe]6s	⁵⁶ Ba Barium 137.327 [Xe]6s	⁷² Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ²	⁷³ Ta Tantalum 180.94788 [Xe]4f ¹⁴ 5d ³ 6s ²	⁷⁴ W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ²	⁷⁵ Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ²	⁷⁶ Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ²	⁷⁷ Ir Iridium 192.222 [Xe]4f ¹⁴ 5d ⁷ 6s ²	⁷⁸ Pt Platinum 195.084 [Xe]4f ¹⁴ 5d ⁹ 6s ¹	⁷⁹ Au Gold 196.966569 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	⁸⁰ Hg Mercury 200.592 [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	⁸¹ Tl Thallium 204.38 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	⁸² Pb Lead 207.2 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	⁸³ Bi Bismuth 208.98040 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	⁸⁴ Po Polonium 209 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	⁸⁵ At Astatine 210 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	⁸⁶ Rn Radon 222 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶
4	¹⁹ K Potassium 39.0983 [Ar]4s	²⁰ Ca Calcium 40.078 [Ar]4s	²¹ Sc Scandium 44.955908 [Ar]3d ¹ 4s ²	²² Ti Titanium 47.867 [Ar]3d ² 4s ²	²³ V Vanadium 50.9415 [Ar]3d ³ 4s ²	²⁴ Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹	²⁵ Mn Manganese 54.938044 [Ar]3d ⁵ 4s ²	²⁶ Fe Iron 55.845 [Ar]3d ⁶ 4s ²	²⁷ Co Cobalt 58.933194 [Ar]3d ⁷ 4s ²	²⁸ Ni Nickel 58.9332 [Ar]3d ⁸ 4s ²	²⁹ Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹	³⁰ Zn Zinc 65.38 [Ar]3d ¹⁰ 4s ²	³¹ Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹	³² Ge Germanium 72.630 [Ar]3d ¹⁰ 4s ² 4p ²	³³ As Arsenic 74.921595 [Ar]3d ¹⁰ 4s ² 4p ³	³⁴ Se Selenium 78.9718 [Ar]3d ¹⁰ 4s ² 4p ⁴	³⁵ Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵	³⁶ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶	³⁷ Rb Rubidium 85.4678 [Kr]5s	³⁸ Sr Strontium 87.62 [Kr]5s	³⁹ Y Yttrium 88.90584 [Kr]4d ¹ 5s ²	⁴⁰ Zr Zirconium 91.224 [Kr]4d ² 5s ²	⁴¹ Nb Niobium 92.90637 [Kr]4d ⁴ 5s ¹	⁴² Mo Molybdenum 95.95 [Kr]4d ⁵ 5s ¹	⁴³ Tc Technetium (98) [Kr]4d ⁵ 5s ²	⁴⁴ Ru Ruthenium 101.07 [Kr]4d ⁷ 5s ¹	⁴⁵ Rh Rhodium 102.90550 [Kr]4d ⁸ 5s ¹	⁴⁶ Pd Palladium 106.42 [Kr]4d ¹⁰ 5s ¹	⁴⁷ Ag Silver 107.8682 [Kr]4d ¹⁰ 5s ¹	⁴⁸ Cd Cadmium 112.414 [Kr]4d ¹⁰ 5s ²	⁴⁹ In Indium 114.818 [Kr]4d ¹⁰ 5s ² 6s ¹	⁵⁰ Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 6s ²	⁵¹ Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 6s ² 6p ³	⁵² Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 6s ² 6p ⁴	⁵³ I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 6s ² 6p ⁵	⁵⁴ Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 6s ² 6p ⁶	
5	³⁷ Rb Rubidium 85.4678 [Kr]5s	³⁸ Sr Strontium 87.62 [Kr]5s	³⁹ Y Yttrium 88.90584 [Kr]4d ¹ 5s ²	⁴⁰ Zr Zirconium 91.224 [Kr]4d ² 5s ²	⁴¹ Nb Niobium 92.90637 [Kr]4d ⁴ 5s ¹	⁴² Mo Molybdenum 95.95 [Kr]4d ⁵ 5s ¹	⁴³ Tc Technetium (98) [Kr]4d ⁵ 5s ²	⁴⁴ Ru Ruthenium 101.07 [Kr]4d ⁷ 5s ¹	⁴⁵ Rh Rhodium 102.90550 [Kr]4d ⁸ 5s ¹	⁴⁶ Pd Palladium 106.42 [Kr]4d ¹⁰ 5s ¹	⁴⁷ Ag Silver 107.8682 [Kr]4d ¹⁰ 5s ¹	⁴⁸ Cd Cadmium 112.414 [Kr]4d ¹⁰ 5s ²	⁴⁹ In Indium 114.818 [Kr]4d ¹⁰ 5s ² 6s ¹	⁵⁰ Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 6s ²	⁵¹ Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 6s ² 6p ³	⁵² Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 6s ² 6p ⁴	⁵³ I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 6s ² 6p ⁵	⁵⁴ Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 6s ² 6p ⁶	⁵⁵ Cs Cesium 132.9054520 [Xe]6s	⁵⁶ Ba Barium 137.327 [Xe]6s	⁷² Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ²	⁷³ Ta Tantalum 180.94788 [Xe]4f ¹⁴ 5d ³ 6s ²	⁷⁴ W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ²	⁷⁵ Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ²	⁷⁶ Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ²	⁷⁷ Ir Iridium 192.222 [Xe]4f ¹⁴ 5d ⁷ 6s ²	⁷⁸ Pt Platinum 195.084 [Xe]4f ¹⁴ 5d ⁹ 6s ¹	⁷⁹ Au Gold 196.966569 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	⁸⁰ Hg Mercury 200.592 [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	⁸¹ Tl Thallium 204.38 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	⁸² Pb Lead 207.2 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	⁸³ Bi Bismuth 208.98040 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	⁸⁴ Po Polonium 209 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	⁸⁵ At Astatine 210 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	⁸⁶ Rn Radon 222 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶		
6	⁵⁵ Cs Cesium 132.9054520 [Xe]6s	⁵⁶ Ba Barium 137.327 [Xe]6s	⁷² Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ²	⁷³ Ta Tantalum 180.94788 [Xe]4f ¹⁴ 5d ³ 6s ²	⁷⁴ W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ²	⁷⁵ Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ²	⁷⁶ Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ²	⁷⁷ Ir Iridium 192.222 [Xe]4f ¹⁴ 5d ⁷ 6s ²	⁷⁸ Pt Platinum 195.084 [Xe]4f ¹⁴ 5d ⁹ 6s ¹	⁷⁹ Au Gold 196.966569 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹	⁸⁰ Hg Mercury 200.592 [Xe]4f ¹⁴ 5d ¹⁰ 6s ²	⁸¹ Tl Thallium 204.38 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	⁸² Pb Lead 207.2 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	⁸³ Bi Bismuth 208.98040 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	⁸⁴ Po Polonium 209 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	⁸⁵ At Astatine 210 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	⁸⁶ Rn Radon 222 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶	⁸⁷ Fr Francium (223) [Rn]7s	⁸⁸ Ra Radium (226) [Rn]7s	¹⁰⁴ Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ²	¹⁰⁵ Db Dubnium (268) [Rn]5f ¹⁴ 6d ³ 7s ²	¹⁰⁶ Sg Seaborgium (266) [Rn]5f ¹⁴ 6d ⁴ 7s ²	¹⁰⁷ Bh Bohrium (271) [Rn]5f ¹⁴ 6d ⁵ 7s ²	¹⁰⁸ Hs Hassium (270) [Rn]5f ¹⁴ 6d ⁶ 7s ²	¹⁰⁹ Mt Meitnerium (268) [Rn]5f ¹⁴ 6d ⁷ 7s ²	¹¹⁰ Ds Darmstadtium (281) [Rn]5f ¹⁴ 6d ⁸ 7s ²	¹¹¹ Rg Roentgenium (280) [Rn]5f ¹⁴ 6d ⁹ 7s ²	¹¹² Cn Copernicium (285) [Rn]5f ¹⁴ 6d ¹⁰ 7s ²	¹¹³ Uut Ununtrium (284) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹	¹¹⁴ Fl Flerovium (289) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	¹¹⁵ Uup Ununpentium (288) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ³	¹¹⁶ Lv Livermorium (293) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴	¹¹⁷ Uus Ununseptium (294) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵	¹¹⁸ Uuo Ununoctium (294) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶			
7	⁸⁷ Fr Francium (223) [Rn]7s	⁸⁸ Ra Radium (226) [Rn]7s	¹⁰⁴ Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ²	¹⁰⁵ Db Dubnium (268) [Rn]5f ¹⁴ 6d ³ 7s ²	¹⁰⁶ Sg Seaborgium (266) [Rn]5f ¹⁴ 6d ⁴ 7s ²	¹⁰⁷ Bh Bohrium (271) [Rn																															