Your Name: ______________________________________

Your lab partner(s): __________________________________

Lab 8: Models of the Hydrogen Atom

(Instructions partially adopted from http://phet.colorado.edu/en/simulation/hydrogen-atom)

Purpose:

- to investigate different models of the hydrogen atom and compare their predictions to the results of simulated experiments
- to recognize the significance of only certain wavelengths being absorbed or emitted by an atom

Equipment: timer PhET hydrogen simulation

Theory: One of the greatest scientific mysteries at the beginning of the 20th century was the structure of the atom. While trying to figure out how the atom was organized, scientists a century ago observed something similar to what you will observe in this lab. While they used real light and atoms for their experiments, we will use simulations to investigate the same questions.

You will first observe a simulated experimental spectrum of hydrogen gas. Based on these observations you will develop your own model of the atom. You will then look at light spectra predicted by the following models of the atom:

- Billiard Ball (Dalton)
- Plum Pudding (Thomson)
- Classical Solar System (Rutherford)
- Shell (Bohr)
- Electron Wave (de Broglie)
- Quantum Mechanical (Schrödinger)

Procedure: The Appendix lists actions (run, restart, etc.) and features (light gun, experimental mode, etc.) alphabetically. Terms defined in the Appendix are given in the **bold** text below.

Part I - Introduction to the Program

1. Go to http://phet.colorado.edu/en/simulation/hydrogen-atom. **Run the program**.
2. Start the **light gun** and select the **monochromatic** light. Observe that the incoming photons are all of the same color. Move the **spectrum slider** from UV to IR. Notice the color of the light beam coming out of the **light gun** and of the photons moving up the screen. Although all UV photons look the same in this simulation, they may have different wavelengths. Decide how you can distinguish between UV, visible and IR photons.
3. Select **white** light and observe the photons. What does white light consist of?

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Part II - Experimental Results for the Hydrogen Spectrum

4. While in the **experimental mode**, **collect data** using **white** light and **medium** speed**.** Watch the photons carefully for at least 1 minute. Describe what is going on in the $\boxed{?}$ box by considering the following:

   What happens to most of the photons? ___________________________________

   What do you think is making some photons scatter? ________________________

   Is every color scattered? ____

   How would you describe the scattering angles of most of the scattered photons? Do any of them scatter at 180^o?

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   How are the colors of incident and scattered photons related?

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5. **Collect data** for at least 4 minutes at **fast** speed using **white light**. Observe as the lines appear in the **spectrometer** box. The line colors correspond to the wavelengths of the emitted photons. If white light is illuminating the box, why are not all ROYGBIV (visible) colors being detected by the spectrometer? Which lines are rising the fastest?

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6. After at least 4 minutes have past, take a **snapshot** of the **experimental spectrum**. Slide the snapshot off to the right of the screen for later comparison with different models.
7. **Stop the data collection**. Maximize the screen to increase the readability. Use the **snapshot** to describe the spectrum, including how many different spectral lines are observed and their colors and relative heights.

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8. Using the **experimental spectrum** estimate the wavelengths of the detected photons. To which parts of the spectrum do they belong? (Is the horizontal axis linear?)

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9. Using the **transitions** window, calculate the energy (in eV) of the photons with the shortest wavelength. To which part of the spectrum does it belong? Show your work.

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10. In the **wavelength slider** box, type "122" for the 122-nm wavelength of the incident photons. **Collect data** at this wavelength, using the **fast** speed setting, until you obtain at least a couple of dots for the wavelength. While the wavelength is selected, are any photons emitted at other wavelengths? (Note: you may need to quickly click on **Start**, then on **white light** to get the program going; then switch back to the **monochromatic light**)

11. Repeat the previous step for 103 nm. Then repeat it for one of the wavelengths listed in the **transitions** box from the visible part of the spectrum. What do you observe?

12. Try a wavelength that is not listed in the **transitions** box. Observe for at least 3 minutes. Are any photons being emitted? Carefully record your observations.

13. Based <u>only on what you observed</u> during the above simulated experiment (not based on what you find on the Internet, read elsewhere, etc.) formulate a model of the hydrogen atom. What characteristics must the hydrogen atom have? Justify each characteristic by addressing which of your observations support that characteristic. For example, if no photons passed through the $\boxed{?}$ box, then you would conclude that the hydrogen atom must have a rigid wall around it.

14. **Stop the data collection** and exit the **spectrometer** window.

15. Now that you have created your own model of the atom, switch from the **experiment mode** to **prediction mode** to observe what other scientists theorized about the atom.

<u>Part III- The Billiard Ball Model</u>

16. Select the **Billiard Ball** model in the **prediction mode.** Turn on the **light gun**, selecting **white light** and **slow** speed**.** Observe which photons scatter by the hydrogen atom and which don't. Does this seem to depend on the color of the photons or on something else? Explain why you would or wouldn't expect preferential scattering of photons of any particular wavelength in this model.

17. **Collect data** for 1 minute using **white light** and **fast** speed. Do you see any spectral lines?

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    What does this model say about the internal structure of the atom?

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    This model was popular for a while. What atomic properties do you think it might have helped explain?

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Part IV - The Plum Pudding Model

18. **Stop the data collection**. Switch to the **Plum Pudding** model. What do the red glob and blue sphere represent? Keep in mind that the proton had not been discovered when this model was proposed.

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19. Turn on the **light gun**, selecting **white light** and **slow** speed**.** How do you know when a photon is absorbed by the electron?

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    Are photons of all colors absorbed, or is the electron selectively absorbing only certain color(s)?

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    How do you know when the electron emits a photon?

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    Are photons of all colors emitted, or only of certain color(s)?

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    Why do you think the colors of photons that are absorbed differ from those that are emitted?

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20. **Collect data** for about half a minute with **white** light at **fast** speed. Take a **snapshot** of the spectrum. How does the spectrum for the **Plum Pudding** model compare to the **Billiard Ball** model? Is this model an improvement to the **Billiard Ball** model? Explain.

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21. How does the **Plum Pudding** model compare to the **experimental spectrum**? What observations are different? What did the **Plum Pudding** model say about the structure of the atom?

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22. Slide the snapshot of the **Plum Pudding** spectrum off to the right for later comparisons.

<u>Part V - Classical Solar System Model</u>

23. **Stop the data collection**. Select **slow** speed. Click on the **Classical Solar System** model. Wow! What just happened? You can observe it again by clicking on the **Classical Solar System** model.

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24. Turn on the **Show electron energy level diagram**. Click again on the **Classical Solar System** model and observe the electron's energy. Describe what happens and why you think it happens.

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Why do you think scientists did not accept this model for very long and searched for a different explanation of atomic structure?

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<u>Part VI - Bohr Model</u>

25. Close the **spectrometer**, **Show electron energy level diagram** and **transitions** windows.
26. Switch to the **Bohr model**. What is happening to the electron

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What do the concentric circles represent?

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What do you think "n = 1" means in the lower right corner of the atomic window?

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Does this value of "n" change during your observation? Why do you think this is the case?

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27. **Collect data** with **white light** at **fast** speed for at least 2 minutes. Observe the electron. What is happening to it?

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28. Take a **snapshot** of the spectrum. Slide it to the right for later comparison. **Stop the data collection**. How well does the spectrum predicted by the **Bohr model** match the experimental spectrum? What are the differences?

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29. Turn on the **light gun**, selecting **white light** and **slow** speed**.** Carefully observe until you are sure of your answers to the following: What happens to the electron when it absorbs or emits a photon.

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30. Are photons of all colors being absorbed and emitted? Which photons are absorbed most often? Which are emitted most often?

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How are the colors of the absorbed and emitted photons related?

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31. Turn on the **Show electron energy level diagram**. Select either **slow** or **medium** speed. Repeat the analysis from the previous step, but this time observe what happens to the energy levels when the electron absorbs or emits a photon. What do n = 1, 2, etc. refer to?

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What are the most common energy transitions? ____________________________

How are the absorbed and emitted photon energies related?

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Which one is the lowest (ground) energy state of the atom?

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Where does the electron spend most of its time and why do you think this is the case?

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32. Observe that the electron moves slower in orbits with higher n values. How can this be when the electron's energy increases with n, as you saw in the previous step?

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33. Look again at the spectral **snapshots** of the **Bohr model**. Is the number of lines the same as in the **experimental** spectrum? Why do you think this is?

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34. Select **monochromatic** light and **slow** speed. Open the **transitions** window, which in this simulation lists energy levels from n = 1 to n = 6. In the **wavelength slider** box, type "122" for the 122-nm wavelength of the incident photons. **Collect data** at this wavelength for half a minute at **fast** speed. In what part of the spectrum are the emitted photons? To which transition(s) do the absorbed and emitted photons belong?

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35. **Reset** the spectrometer. Repeat the previous step for the 103 nm wavelength. Describe the atom diagram and the energy level diagrams. Analyze the colors of the absorbed and emitted photons using the spectrometer and energy level diagram.

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How many spectral lines are there? Explain why. How do these transitions differ from those for 122 nm?

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36. Repeat the previous step and the analysis for the incident light of 97 nm and 656 nm. **Reset** the spectrometer each time. Describe what you observe.

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37. **Stop** and **reset** the spectrometer. Set the light source to a couple of wavelengths not listed in the **transitions** box. What do you observe?

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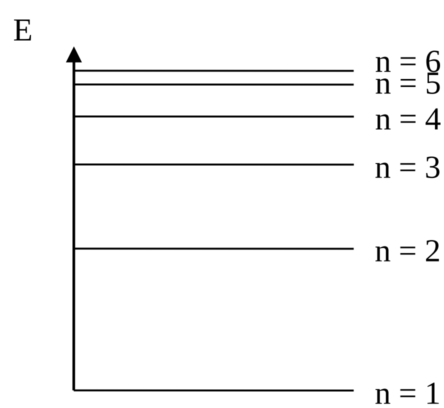
38. In the space below, create a schematic representation of the atom and energy levels to explain what happens. Show at least 6 different excitation/decay sequences that you observe.



39. Does the **Bohr model** explain why only certain electron energy levels exist?

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Part VII - de Broglie Model

40. **Stop the data collection**. Switch to the **de Broglie** model. Close the **transitions** and **Show electron energy level diagram** windows. Observe the atom and describe its similarities and differences with the **Bohr model**. The **de Broglie** model finally explains why only certain electron energy levels exist. Write an explanation in your own words.

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41. **Collect Data** with **white** light and at **fast** speed for at least 1.5 minutes. What is happening to the electron?

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42. Take a **snapshot** of the spectrum. How well does the de Broglie spectrum match the experimental spectrum? How well does it agree with Bohr? Slide the snapshot off to the right for later comparison.

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43. With the **light gun** on, select either **slow** or **medium** speed. Click on **Show electron energy level diagram**. Carefully observe and describe what happens to an energy level when the electron absorbs or emits a photon. Is this different from the **Bohr** model?

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44. Change the **Radial View** to **3-D View**. Describe what you see. Select **Brightness View**. What do the bright and dark spots represent?

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Part VIII - Schrödinger Model

45. **Stop the data collection**. Close the **Show electron energy level diagram** windows. Switch to the **Schrödinger** model. **Collect data** for at least 4 minutes with **white light** at **fast** speed. Observe the atom and describe its similarities and differences with the structure of **Bohr** atom. What new features are incorporated in the Schrödinger model?

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46. After letting the simulation run for at least 4 minutes, take a **snapshot**. What are the main differences between the spectra predicted by the **Schrödinger**, **Bohr** and **de Broglie** models?

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How well does the **Schrödinger** spectrum match the experimental spectrum?

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Slide the snapshot off to the right for later comparison with other models.

47. Open **Show electron energy level diagram**. Select either **slow** or **medium** speed. How is the energy diagram similar to and how is it different from those in the **Bohr** and **de Broglie** models? Do all the transitions occur at the same rate or do some seem more probable than others?

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48. **Stop** and **reset** the spectrometer. **Trap the electron** in the **metastable state** (2 0). Using the selection rules, explain why the electron is unable to spontaneously transition to the ground state (1 0).

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49. **Stimulate the transition** of the electron from (2 0) to (1 0). For the efficiency sake:
   - First select all wavelengths transitions between the ground state and higher states (1 → n). Can any of these wavelengths excite the electron from its metastable state? Explain.

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   - See Notes 1 and 2 under **Stimulate the transition** in the Appendix. In the **wavelength slider**, input the wavelengths that correspond to transitions from the n = 2 level. Do these wavelengths excite the electron from its metastable state? Explain.

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50. Do a research to find out if there are any atomic models that improve on the Schrödinger's model.

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Appendix

Actions (run, reset, etc.) and features (light gun, experimental mode, etc.) are listed alphabetically in the table. Words in the right column written in the *italic* text are defined elsewhere in the left column.

? box	represents a single hydrogen atom in the *experiment* mode
(❚❚)	see *pause*
(❚▶)	see *step*
(▶)	see *restart*
3D view	- found in the pull-down menu in the top left corner of the *atomic window* (*de Broglie model*, only)
Atomic window	a transparent, expanded view of the box of hydrogen gas, displaying various models of the atom
Billiard Ball model	- a model which assumes that an atom is a very tiny hard ball - can be accessed by turning the dial in the gray box in the upper left corner from *experiment* or *prediction*, then selecting the model - the atom is represented as an orange ball in the middle of the box
Bohr model	- developed to explain the spectra of hydrogen-like atoms - can be accessed by turning the dial in the gray box in the upper left corner from *experiment* or *prediction*, then selecting the model
Box of hydrogen	a transparent, expanded view of the box of hydrogen gas with ? *box* when in the *experimental mode* and a model of an atom in the *prediction* mode
Brightness view	- found in the pull-down menu in the top left corner of the *atomic window* (*de Broglie model*, only)
Camera	- a camera-like icon at the bottom of the *spectrometer* box - used to take a snapshot of the recorded spectrum
Classical Solar System model	- assumes that the atom is like our solar system - proposed to explain the results of Rutherford's gold foil experiments - can be accessed by turning the dial in the gray box in the upper left corner from *experiment* or *prediction*, then selecting the model
Collect data	- turn on the *light gun* to start a beam of incoming photons - select either *white* or *monochromatic* light - set the desired *speed* of the simulation (*fast*, *medium* or *slow*) - open the *show spectrometer* box - *reset* and then *start* the spectrometer
de Broglie model	- based on the hypothesis that any moving particle has an associated wave - incorporates the ideas of Planck and Einstein that electrons can exhibit both wave and particle properties
Display the wavelengths	see *display transitions*
Display transitions	- click on Help in the upper left corner, then on *transitions* - transitions in the hydrogen atom and wavelengths will be displayed
Experiment mode	the dial in the gray box in the upper left corner shows whether the *experiment* or *prediction mode* is selected

Experimental spectrum	the *spectrum* obtained in the *experiment mode*
Fast (speed)	- used for fast data collection - see *speed slider*
Light controls	- a blue window below the *light gun* - controls the wavelengths of photons emitted from the *light gun*
Light gun	- the red and blue device (Fig. A) - used to *start* and emit photons when the red button is clicked
Medium (speed)	- used for either observations or data collection - see *speed slider*
Metastable state	- a state from which the electron cannot spontaneously emit a photon, unless it absorbs a photon with exactly the right energy to excite it out of this state - the spontaneous transition does not occur because a selection rule requires that $\Delta\boldsymbol{\ell} = \pm 1$ - an example is state (2 0), n = 2, $\boldsymbol{\ell} = 0$, from which the electron <u>cannot</u> spontaneously transition to the ground state (1 0), n = 1, $\boldsymbol{\ell} = 0$. This is because $\Delta l = 0$ for this transition, which is against the selection rules (allowed transitions).
Monochromatic (light)	selects monochromatic light from the *light controls* box
Prediction mode	- the dial in the gray box in the upper left corner shows whether the *experiment* or *prediction mode* is selected - allows a selection of one of the six atomic models
Pause	- button (▌▌) to the right of the *speed slider* - to pause a simulation
Plum Pudding model	- a model in which a negative electron is free to move through uniformly distributed positive charge - can be accessed by turning the dial in the gray box in the upper left corner from *experiment* or *prediction*, then selecting the model
Radial view	- found in the pull-down menu in the top left corner of the *atomic window* (*de Broglie model*, only)
Reset (the spectrometer)	- button at the bottom of the *spectrometer box* - to reset the spectrometer so it is ready for new data collection
Restart (the spectrometer)	- button (▶) to the right of the *speed slider* - to restart a simulation
Run the program	- go to http://phet.colorado.edu/en/simulation/hydrogen-atom to access the PhET website - click on "Run Now!"; a Java applet will open (Fig. A)
Schrödinger model	- assumes that the electron is a wave - describes the probability that an electron can be found in a given region of space at a given time - introduces quantum numbers, n, *l* and m, which describe the size, shape and orientation of the orbitals of an atom - transition probabilities are based on the overlap between the wave functions; some transitions are forbidden or highly improbable

Show electron energy level diagram	- a clickable box in the upper right hand corner, next to the atomic window - displays electron energy levels and electronic transitions in a given atomic model
Show spectrometer	- a clickable box positioned to the right of the *light controls* box - displays the number of scattered photons as a function of the photon's wavelength
Slow (speed)	- used for careful observations of the electron or photons - see *speed slider*
Snapshot	- a snapshot of the *spectrometer* box display, taken by the *camera* - every time the *spectrometer* box is closed, the snapshots will disappear, but will reappear once the box is reopened
Spectrum	the distribution of EM radiation according to photon's wavelengths
Spectrum slider	- access from the *light controls* box when *monochromatic* is selected - allows a continuous change of wavelengths (energy) of the incoming photons from ultraviolet (UV) to infra-red (IR)
Spectrometer	- displayed when *show spectrometer* is selected
Speed slider	- positioned at the bottom of the screen, below the *atomic window* - regulates the speed of the simulation as *slow*, *medium* or *fast*
Speed (of the simulation)	- can be regulated by moving the *speed slider*
Start (the spectrometer)	- open the *show spectrometer* box - start the data collection by clicking on the start button at the bottom of the box - alternates with the *stop* the spectrometer button
Step	- button (**▌▶)** to the right of the *speed slider* - to incrementally analyze a simulation
Stimulate the transition	- the electron should be trapped and light set to *monochromatic* - select *fast* speed and open the *transitions* box - systematically change the wavelengths in the *light controls* box to the values given in the *transitions* box (see the lab instructions) - <u>Note 1</u>: each time the electron leaves the metastable state, it needs to be returned back to this state; make sure you first change the wavelength in the *monochromatic* view to a value that does not cause any transition (e.g. to 100 nm); then, you can again *trap the electron* in the (2 0) state - <u>Note 2</u>: only wavelengths up to 780 nm can be selected with the *wavelength slider*, so transitions from levels n ≥ 3 cannot be done in this simulation, although they occur in real atoms
Stop the data collection	- turn off the *light gun* - *stop* and then *reset* the spectrometer
Stop (the spectrometer)	- open the *show spectrometer* box, if not already opened - stop the data collection by clicking on *stop* at the bottom of the box (alternates with the *start* the spectrometer button) - *reset* the *spectrometer* so it is ready for new data collection

Transitions	- click on Help in the upper left corner, then on *transitions* - a window will open that will display the wavelengths and transitions in the hydrogen atom (you can slide it out of the way)
Trap the electron	- select the *monochromatic* light and input 103 nm in the *wavelength slider* box - switch to *white* light and select either the *medium* or *fast* speed - turn on the *light gun* on *fast* and wait for the electron to fall into the *metastable state* with n = 2 and ℓ = 0 [this state is labeled as (2 0)] - <u>immediately</u> click on the *monochromatic* light, so the electron remain stuck in this state
Wavelength slider	- appears in the *light controls* box when *monochromatic* light is selected - represented by the white box, attached to the gray slider, and in which a desired wavelength can be typed (in units nm)
White (light)	selects white light in the *light controls* box

Figure A