

# Unit 5

## The Quantum World

### Introduction

*All these fifty years of conscious brooding have brought me no nearer to the answer to the question, "What are light quanta?" Nowadays every Tom, Dick, and Harry thinks he knows it, but he is mistaken.*

– Albert Einstein

Our everyday experience with both light and matter turns out to be woefully inadequate for describing how light and matter behave at the scale of atoms. Quantum mechanics told us that light is not simply the stream of electromagnetic waves described by Maxwell, but made of small packets of energy called *photons*. Quantum theory also shows that tiny particles, like electrons, do not have well-defined positions but are instead smeared out in space as waves—their location can only be described probabilistically. In this unit we'll explore these weird aspects of the microscopic world, how it affects the behavior of some human-sized objects, and some cutting-edge applications that have grown out of this elegant theory.

### ***What Will Participants Learn?***

Participants will be able to:

1. Describe both the particle and wave behaviors of light and matter, and give examples that display both behaviors at the same time.
2. Provide at least one example for each of the following tenets of quantum mechanics: *quantization*, *wave-particle duality*, and *the uncertainty principle*.
3. Explain the processes used in cooling and trapping atoms to temperatures near absolute zero.
4. Explain how the probabilistic nature of light and matter waves affects measurement of quantum mechanical phenomena and contrast with classical measurement.

### ***What's in this Unit?***

**Text:** Unit 5: *The Quantum World* covers the field of quantum mechanics and some of its applications. Developed early in the 20th century to solve a crisis in understanding the nature of the atom, quantum mechanics has laid the foundation for theoretical and practical advances in 21st century physics. The unit details the reasoning that led to an awareness of the particle nature of light, including the *photoelectric effect*, *interference effects*, and *blackbody radiation*. The *wave nature of matter* is also explored, including the *de Broglie wavelength* of matter, *interference of matter waves*, *wavefunctions*, and the *Heisenberg uncertainty principle*. Applications to *laser cooling*, *atom traps*, and *atomic clocks* are described.

**Video:** The program explores how two scientists and their teams are using laser cooling to explore how matter behaves on the atomic level. Laser cooling allows scientists to

cool atoms to extremely low temperatures and to trap them within a tiny space. Through this technique Martin Zwierlein and his team at the Massachusetts Institute of Technology produce exotic forms of matter by controlling the interactions of atoms and their external environment. At NIST/Boulder, cooling and trapping of single mercury ions have enabled David Wineland and his team to create what is currently the world's most precise clock, as well as to test some of the fundamental laws of physics.

**Video Extra:** John Lowe of the National Institute for Standards and Technology (NIST) discusses atomic clocks.

**Interactive Lab:** *Laser Cooling*. Learn the basics of how to manipulate atoms with light, and cool a hot atomic beam to a few millionths of a degree above absolute zero.

#### Activities:

- The Hook: How To Make Something Really Cold? (10 minutes)
- Activity 1: Watch and Discuss the Video (50 minutes)
- Activity 2: The Photoelectric Effect (optional)
- Activity 3: The Wave/Particle Nature of Light (35 minutes)
- Activity 4: Matter is a Wave (But What's "Waving?") (40 minutes)
- Back to the Classroom (15 minutes)

(*Note:* There is likely to be a large variation in participants' familiarity and comfort with the topics in this unit. In order to meet all possible needs this unit covers a broad range of material. You may wish to gauge participants' understanding through emailed questions prior to the session. Depending on participants' background experience and preferences, you may wish to expand on *Activity 2: The Photoelectric Effect* (and de-emphasize *Activity 3: The Wave/Particle Nature of Light*), or eliminate *The Photoelectric Effect*. If participants need a review of the photoelectric effect, 15 minutes may be sufficient. If they need to learn it in depth, more time may be needed.)

**Nature of Science Theme:** *Measurement & Observation*. You may wish to display the *Measurement & Observation* icon during the session and remind participants of the central ideas of this theme. We cannot always trust our direct perception and must confirm our observations via measurement. Thus much, if not all, scientific evidence relies on indirect measurement. A variety of tools allow scientists to probe aspects of the natural world that are beyond our human abilities to perceive.



## Exploring the Unit

Before the session: As participants enter, ask them to post their question about quantum theory on the wall or a bulletin board. Encourage them to peruse the questions as they get settled. Tell them to keep their question in mind, and encourage them to speak up about their questions at the appropriate time in the session.

### *The Hook: How To Make Something Really Cold?*

Time: 10 Minutes.

#### Materials:

- Ping-pong balls (about 15)
- 5 marbles
- An enclosure, such as a hula-hoop



(Note: You may use different types of balls depending on your available materials)

Throw about 10 ping-pong balls into the enclosure and shake so that they move in random directions. Explain that these represent the molecules of a gas.

Ask participants, how can we make this gas hotter? Participants may suggest a variety of mechanisms, such as putting it in an oven or compressing it. These can be modeled by shaking the hula-hoop to make them move faster. Discuss the fact that temperature is a measure of molecular motion, or the kinetic energy of the molecules.

Ask participants, how can we make this gas colder? They may suggest a variety of mechanisms, such as waiting for the atoms or molecules to slow down, putting it in a refrigerator, or the laser cooling from the reading. Defer the discussion of laser cooling. If they suggest waiting for the atoms to slow down and stop (through friction) remind them that frictional forces heat the system. If they suggest the molecules will slow down and stop on their own without friction, recall Newton's laws. If anyone suggests grabbing the ball to stop it, point out that the heat of a hand (or other object) will add energy to that molecule.

Ask, what has to be true for a substance to reach zero temperature? Discuss as a group. Some participants may be confused as to how a substance can be gaseous when it is cold—explain that this is possible at low enough pressure. Molecules are still moving, even if they've been slowed to a near stop in a refrigerator—nothing gets to absolute zero. So, how do we slow them down further? Roll a marble at the moving ping-pong ball to slow it. Now, discuss the idea of laser cooling from the reading. Roll several marbles at the ping-pong balls to represent a laser. Particles of light (photons) hit particles of matter that can only absorb certain energies of light.

You may wish to display some of the applets from Physics 2000 (<http://www.colorado.edu/physics/2000/index.pl>) on laser cooling, or the *Interactive Lab: Laser Cooling*.

Take-home message: Laser cooling manipulates motion on the atomic scale, and relies on the fact that light is made of photons of particular energies, and the fact that atoms only absorb light of a particular energy.

Explain that in this unit, we will be discussing the particle nature of light and the wave nature of matter, both of which are exactly backwards from what you're used to. In the next unit, we will explore phenomena using laser cooling.

## **Activity 1: Watch and Discuss the Video**

Time: 50 Minutes.

If participants are watching the video in class, have them view it now. You may wish to show the *Video Extra* for Unit 5 (on atomic clocks) here. Remind them of the guiding questions listed in *Between Sessions* from the previous unit.

1. If the position of an electron is probabilistic, then how can atomic clocks measure time with such precision?
2. What's quantum about these experiments? List as many aspects of the experiments as you can.



You may wish to display some of the applets from Physics 2000 (<http://www.colorado.edu/physics/2000/index.pl>) on laser cooling, optical molasses, magnetic trapping, and evaporative cooling to answer participants' questions after the video.

An atomic clock can measure time precisely because it is measuring the period of oscillation of an electron between energy levels, *not* its position. Its energy is very well-defined even though its location is not.

Gather participant responses to Question 2 into different groups: particle nature of light, wave nature of light, particle nature of matter, wave nature of matter. For example, "energy levels of electrons in atoms" would belong in "wave nature of matter." Remark that we don't need quantum mechanics to explain the wave nature of light or particle nature of matter—those can be explained classically. But we do need quantum mechanics to explain the particle nature of light and the wave nature of matter, and we will be exploring those ideas in this unit.

## ***Activity 2: Photoelectric effect (optional)***

**Purpose:** To use thought experiments and simulations to understand the photoelectric effect and how it supported the idea that light was made of quantum packets called *photons*. Participants will compare and contrast classical and quantum predictions for the photoelectric effect with experimental observations. This is recommended for participants who are not as deeply familiar with quantum mechanics and the photoelectric effect, though even those who think they understand this phenomenon may have underlying misconceptions.<sup>1</sup> For those who only need a review, the clicker questions are highly recommended.

**Materials:**

- Digital projector
- PhET "Photoelectric Effect" simulation ([http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric\\_Effect](http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect)).  
(*Note:* You do not need to be connected to the internet to run the simulation. You may click "download" to download and run the simulation locally on your machine.)

### **1. Classical frequency dependence**

#### ***To Do and To Notice***

Experiments in the late 1800's showed that if light is shone on a metal, electricity is produced. Let's imagine that this happens because the light "heats up" the metal, giving electrons energy so that they can jump off.<sup>2</sup> How would participants expect:

- (a) The frequency, or color, of the light to affect how many electrons jump off the metal?

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<sup>1</sup> For a comprehensive study, see

[http://www.colorado.edu/physics/EducationIssues/papers/McKagan\\_etal/photoelectric.pdf](http://www.colorado.edu/physics/EducationIssues/papers/McKagan_etal/photoelectric.pdf). In particular, students at the undergraduate level often (a) believe that  $V=IR$  still applies, (b) confuse intensity and frequency of light (and thus photon energy), (c) are unable to predict a  $I$ - $V$  graph of the experiment, and (d) cannot relate photons to the photoelectric effect.

<sup>2</sup> You might use the following analogy: Imagine waves hitting a beach, where the shore is lined with pebbles. The pebbles are scattered by the waves as they hit the shore. How would you expect the frequency of those water waves to affect: (a) The number of pebbles scattered by a particular wave front? (b) The speed or energy that the pebbles fly away with?

(b) The intensity of that light to affect how many electrons jump off the metal?

### What's Going On?

Classically, one would expect that the frequency of waves hitting the metal would have no effect on the electrons released from the metal—only the intensity would matter. But we can see from the PhET simulation that the frequency of the light waves hitting the metal affects both the number of electrons released from the metal and how quickly they move. Thus, we need a quantum explanation.

## 2. Actual frequency dependence

### To Do and To Notice

Demonstrate the PhET simulation and its basic properties, or ask a participant to do so. What happens when the light intensity changes? What happens when the light frequency changes? Then, discuss the homework questions as a group. Use each question as a starting point for exploration and discussion of the topics, rather than searching only for a correct answer.

Clicker/Discussion Question: Frequency dependence<sup>3</sup>

Which of the following graphs most accurately represents your prediction for the initial kinetic energy of the electrons ejected from the metal, based on your experiments with the simulation?

A.

B.

C.

D.

E. something different



### What's Going On?

Best answer is (D). Because of the quantized nature of light, one photon can promote only one electron above the *work function* (the amount of energy needed to eject the electron from the metal). You may want to introduce atomic *potential energy well*

<sup>3</sup> This question and the following questions are from the University of Colorado Modern Physics course developed by C. Wieman, K. Perkins, and S. McKagan, <http://per.colorado.edu/modern>. This question also appeared in McKagan et al., Am. J. Phys., 77, 87 (2009).

*diagrams* here if participants struggle with the idea of work functions. What happens when photons of different energies hit an electron in this well?

Thus, using conservation of energy, a complete response is:

- Energy in = Energy out
- Energy of photon ( $hf$ ) = Energy to eject electron ( $W$ ) + Kinetic Energy ( $KE$ ) of ejected electron
- So  $KE = hf - W$  (for a *single photon*; otherwise,  $KE = nhf$ )
- Thus, until  $hf = W$ , electrons are not ejected
- After that point, the  $KE$  rises linearly with  $f$ . Thus, answer ( $D$ ) is correct.

### 3. Probabilities

#### *To Do and To Notice*

Clicker/Discussion Question: Probability of electron ejection

Imagine we're running the photoelectric effect simulation with very low light intensity that uniformly illuminates the surface. We observe an electron only pops out every few seconds. **Why does that particular electron pop out?**

- Because that is where the light hit the metal
- That electron had more energy than any of the others so it was the easiest to remove
- No physical reason, that electron just got lucky and won the "escape from metal" lottery
- There must be some other physical reason but I am not sure what it is
- There is a physical reason that is not listed above and I think I know what it is



Prompt participants to think about the "Quantum Wave Interference" simulation.

#### *What's Going On?*

Answer is (C). "Uniformly illuminated" means that the probability of a photon being absorbed at every location is the same, but we can't know where that photon will land until it's detected.

Take-home message: The photoelectric effect provides substantial evidence that light acts like a particle and that electrons have fixed energy levels within an atom.

Explain that these ideas of probability and measurement will be explored further in the next activity.

### ***Activity 3: The Wave/Particle Nature of Light***

Time: 35 Minutes.

Purpose: To use the PhET simulation "Quantum Wave Interference" to explore the idea that light and electrons are both a wave (that can go through both slits in a double slit



experiment) and a particle (that hits the screen at a single location). This is a challenging set of concepts, and we recommend that facilitators look at the summary of common student difficulties on these topics at <http://www.colorado.edu/physics/EducationIssues/modern/>.

**Materials:**

- Digital projector
- PhET “Quantum Wave Interference” simulation ([http://phet.colorado.edu/simulations/sims.php?sim=Quantum\\_Wave\\_Interference](http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference)).

**To Do and To Notice**

Show participants the PhET simulation and demonstrate a few key features on the first two tabs (or ask a participant to do so), particularly how both electrons and photons show a double-slit interference pattern indicative of wave behavior. What happens when the particles build up over time? What does this resemble? Focus on the photon interference pattern first.

Ask participants the following series of clicker/discussion questions. Be sure to have them discuss with their neighbors before discussing as a large group.

Clicker/Discussion Questions:<sup>4</sup>

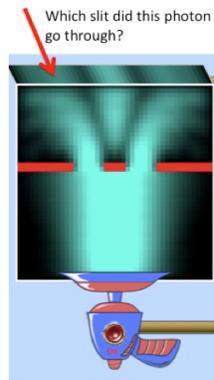
1. **If you shoot a photon through the two slits to hit the screen it:**

- Cannot hit in the middle because the block is in the way
- Hits at a random location, with an equal probability of hitting anywhere on the screen
- Must hit at the maximum of the interference pattern
- Has a chance of hitting anywhere on the screen, but on average a better chance at hitting where the interference pattern is brightest
- Will hit anywhere that it can travel in a straight line from the gun to the screen

Discuss with respect to *Measurement & Observation*.

2. Consider a photon to the left of center as in the image. **Which slit did it go through?**

- Left
- Right
- Both
- Neither



<sup>4</sup> These questions and the following question are from the University of Colorado Modern Physics course developed by C. Wieman, K. Perkins, and S. McKagan, <http://per.colorado.edu/modern>.

Clicker/Discussion Questions continued:

3. **What do you visualize when you think about a photon traveling through space?**

- A. A particle of light with a specific energy traveling in a straight line:



- B. A particle of light with a specific energy traveling along a sinusoidal path:



- C. A weak bit of electromagnetic wave with a specific amount of energy traveling along a straight line:



- D. A particle of light with a specific energy traveling along side an electromagnetic wave:



- E. None of the above. I think about it in a different way.



**What's Going On?**

1. Best answer is (D). The nature of physical measurement is fundamentally inexact in the world of quantum mechanics. Randomness is inherent in the natural world. We can predict particle behavior based on probabilities rather than the deterministic equations of classical mechanics. Physical behavior is governed by randomness and probability. Yet, the probability distribution itself *is* deterministic, and can be calculated and predicted with very high degrees of accuracy.
2. Best answer is (C). Light goes through both slits as a wave. But when it interacts with the screen, all the energy ends up in one spot, so it acts like a particle. This is why the interference pattern will show up even if only one photon goes through at a time; each photon interferes with itself. Demonstrate the second tab ("Single Particle") and ask participants to notice what happens when the wave front hits the screen. Discuss as a group.<sup>5</sup>
3. People have many visual models in their heads. Physically, the best answer is (C) which incorporates both the wave view and the particle view, though many undergraduates choose D.<sup>6</sup> A particle is a "chunk" of an electromagnetic wave.



<sup>5</sup> For common questions asked during this simulation, see "Common student difficulties" at <http://www.colorado.edu/physics/EducationIssues/modern/>.

<sup>6</sup> See college course materials at <http://www.colorado.edu/physics/EducationIssues/modern/>.

The energy of a photon is contained in the frequency of oscillating electric and magnetic fields.<sup>7</sup>

Take-home message: Light behaves as a wave, and has a fundamentally probabilistic nature. The bright areas of the interference pattern tell us where a photon is most likely to hit the screen (as a particle) but it goes through both slits (as a wave).

When do we actually need to worry about the particle nature of light? It's only important when our detection system is good enough to see individual photons, such as in the photoelectric effect, the inner workings of lasers, molecular bonding, etc. It doesn't matter for heating and optics.

## ***Activity 4: Matter is a Wave (But What's "Waving"?)***

Time: 40 Minutes.

Purpose: Participants will explore the probabilistic interpretation of the wave equation.

Materials:

- PhET "Quantum Wave Interference" simulation at [http://phet.colorado.edu/simulations/sims.php?sim=Quantum\\_Wave\\_Interference](http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Wave_Interference). (Note: You do not need to be connected to the internet to use these simulations. You may click "download" to download and run the simulation locally on your machine.)

### **1. PhET Simulation "Quantum Wave Interference"**

***To Do and To Notice***

Show the PhET "Quantum Wave Interference" simulation and choose "electrons" to be fired from the gun. Demonstrate properties of the simulation as for light waves.

***What's Going On?***

We know that electrons act like particles. But the fact that they produce an interference pattern also tells us that they act like waves.

### **2. Probabilities**

***To Do and To Notice***

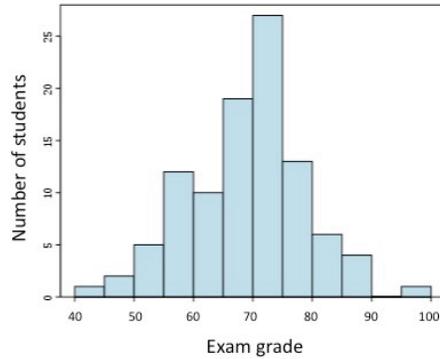
Tell participants you will now explore the interpretation of these matter waves.

The following is a distribution of all student exam grades in a class. Ask participants, if I pick a student at random, which grade range is he/she most likely to have?

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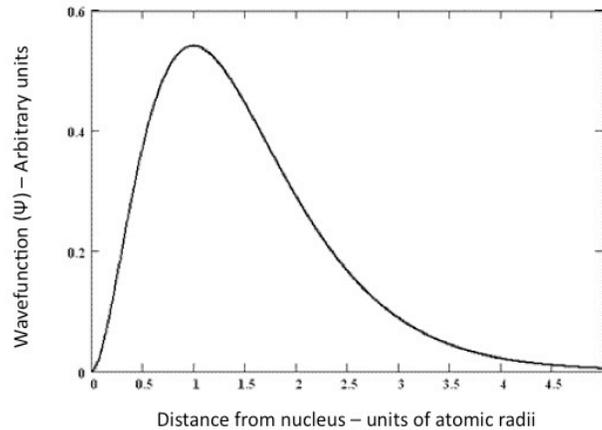
<sup>7</sup> Some participants may be curious how energy only depends on frequency, and not intensity, as a higher wattage light bulb is more intense and puts out more power. The important distinction is between the energy carried by a *beam* of light versus the energy in a single *quantum particle* of light. The energy of a quantum particle (a photon) depends on its frequency. But a beam of light carries many photons, and the energy of the beam is the sum of the energy of each photon. Thus, a higher wattage light bulb emits more photons, each of which carries energy corresponding to its individual frequency,  $E=hf$ .



**Grade distribution**

(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

The following is the electron wavefunction or probability wave of an electron in the hydrogen atom. Ask participants, if we measure the location of the electron at a random time, how far is it most likely to be from the nucleus?

**The n=1 hydrogen wavefunction in one dimension**

(Available in the online resource: *Facilitator's Guide High Resolution Graphics*)

### ***What's Going On?***

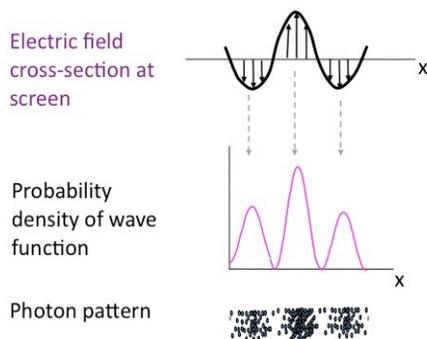
A student picked at random is most likely to have a grade between 70 and 75. But there is a probability that they will have a grade that is higher or lower than that.

An electron picked at random is most likely to be found at a distance of one atomic radius. But there is also a probability that the electron will be further or closer than that.

If a student or electron is picked at random, there is 100% probability that they will have a grade or location that lies on the curve shown (i.e., with a grade between 0 and 100).

The height of an electron wavefunction represents the probability of finding an electron at that location. This is closely related to the interference pattern for light—the intensity of the pattern on the screen is a measure of the probability of detecting a photon at that location. (In particular, the square of the height of the wave represents the probability but that's not crucial here). Remind participants of the earlier clicker question: “If you shoot a photon through the two slits to hit the screen, it... has a chance of hitting anywhere on the screen, but on average a better chance at hitting where the interference pattern is brightest”. Below is a graphical representation of this correspondence between

probability and intensity. Discuss the similarities between the two interference patterns and their quantum interpretations.



Photon probability distribution versus intensity

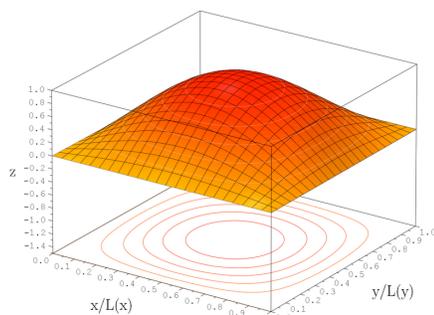
### 3. Representations of probability

#### *To Do and To Notice*

Show participants the  $n=1$  hydrogen wavefunction once again. What does this look like in two dimensions? In three? Discuss as a group. Help participants make the connection between this activity and the spherical shape of the S-orbital.

#### *What's Going On?*

Below are some sample images.



The  $l=0, n=1$  hydrogen wavefunction (s-orbital) as a two-dimensional "hump" and a three-dimensional "cloud"



#### *Going Further*

Consider the  $n=2$  orbital of hydrogen. Given what participants know about the Bohr model of the atom (i.e., that the  $n=2$  orbital is further from the center of the atom than the  $n=1$ ), sketch the wavefunction in 1-D, 2-D, and 3-D. The 3-D image should show a spherical shell of high probability at a larger radius. Given what we know about the shape of the p-orbitals in 3-D, (i.e., two lobes like a figure eight), draw the p-orbital on a 1-D graph. It should have two humps on either side of the origin, like camel humps.

## 4. Measurement and Uncertainty

### *To Do and To Notice*

What does this probabilistic description of electrons mean about the ability of physics to predict results? What about the nature of measurement in physics? How do we answer questions like, “What is the exact position of a particle?” Relate your discussion to the double-slit interference pattern from the PhET simulation and to the Uncertainty Principle.



Consider the *Heisenberg uncertainty* relation. The more precisely we know the momentum (i.e., wavelength) of a particle, the less certainly we know its precise location. Lead participants through the following thought experiment. Imagine a beach on a calm day. A single tall wave comes and crashes on the shore. You know precisely where it was as it approached the shore, and when it reached it. But what was its wavelength? Without a periodic set of waves, it's impossible to talk about the wavelength (and thus momentum, for a de Broglie wave) of the wave. Now imagine a series of about 20 regularly spaced waves, crashing on the shore at equal intervals. These waves have a definite wavelength (and thus momentum). But when did the wave, as a set, hit the shore? The more precisely the wavelength is known, the less precisely the location of the wave is known.

If any of participants' questions from the beginning of class have not been addressed, discuss them now.

### *What's Going On?*

Heisenberg answered the question “What is the exact position of a particle” by saying, “I do not need to answer such a question because you cannot ask such a question experimentally.” Such a question cannot be subjected to experiment, and so it is no longer a scientific question. Unless a thing can be measured, it has no place in a theory. Classically, ideas about exact momentum and position of particles are allowed and can be predicted, deterministically. Quantum mechanically, they cannot. Quantum mechanics can only make probabilistic, not definite, predictions. (For further discussion of these ideas, see: *The Feynman Lectures on Physics, Volume 1* and *Volume 3*.)

Take-home message: Matter is a wave, but not the kind of wave that physically moves up and down through space. It is a probability wave, and the height of the wave represents the probability of measuring the particle at that location. The spread of the wave represents the uncertainty in the position of the particle.

## Back to the Classroom

Time: 15 Minutes.

Following is a list of high school topics and standards that are relevant to this material. See <http://strandmaps.nsd.org/> for a visual representation of science standards and benchmarks.

- **Where might this unit fit into your curriculum?** Brainstorm a list of topics with participants. You may share additional items from the list below, as you see fit.
- **What do your students know about this topic?** Brainstorm with participants.
- Optionally, you may ask participants to **find one or more of the relevant topics on the Science Literacy Maps**, and explore related ideas and misconceptions.

## Topics and Standards

**Energy.** Energy appears in many forms (such as kinetic and potential). The total amount of energy remains constant if no energy is transferred into or out of the system. Thermal energy in a system is associated with the disordered motions of its atoms or molecules.

**Atoms and Molecules.** Atoms are made of a positively charged nucleus surrounded by negatively charged electrons.

**Size and Scale.** Natural phenomena often involve sizes, durations, or speeds that are extremely small or extremely large.

**Waves and Light.** Wave behavior can be described in terms of how fast the disturbance spreads, and in terms of the distance between successive peaks of the disturbance (the wavelength). Light acts like a wave in many ways. The wavelength of light varies from radio waves, the longest, to gamma rays, the shortest.

**The Mathematical World.** Students should be able to estimate probabilities of outcomes in familiar situations on the basis of history or the number of possible outcomes. How probability is estimated depends on what is known about the situation. Estimates can be based on data from similar conditions in the past or on the assumption that all the possibilities are known. The larger a well-chosen sample is, the more accurately it is likely to represent the whole.

**Nature of Science.** A scientific model is judged, in part, by its power to predict the outcome of experiment. Theories shift as new observations show inconsistencies or flaws in the previous model. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations.

## Classroom Resources

**Physics 2000.** A great set of clear, interactive tutorials on many aspects of atomic and optical physics, including two-slit interference, laser cooling, magnetic trapping, and Bose-Einstein condensation. Click “What is it” to see a list of all applets, and “Table of Contents” for an index of all topics. <http://www.colorado.edu/physics/2000/index.pl>.

**PhET Simulations.** Interactive simulations and teaching activities for a variety of quantum phenomena and related topics. including: Wave Interference; Quantum Wave Interference; Photoelectric Effect; and Blackbody Spectrum. <http://phet.colorado.edu>

**The Challenge of Quantum Reality**, from the Perimeter Institute. An excellent and very detailed teacher’s guide with lesson plans, curriculum links, hands-on activities, worksheets, and homework. Includes an excellent activity on the nature of models. [http://www.perimeterinstitute.ca/Perimeter\\_Explorations/Quantum\\_Reality/The\\_Challenge\\_of\\_Quantum\\_Reality/](http://www.perimeterinstitute.ca/Perimeter_Explorations/Quantum_Reality/The_Challenge_of_Quantum_Reality/).

**Workshop tutorials for physics.** Short interactive inquiry-based group activities for a variety of topics, including quantum and atomic physics, from the University of Sydney Physics Education Research Group. [http://www.physics.usyd.edu.au/super/physics\\_tut/contents.html](http://www.physics.usyd.edu.au/super/physics_tut/contents.html).

**Videos on Teachers' Domain about quantum mechanics.** Including a segment on whether electrons are particles or waves, the uncertainty principle, and the development of quantum mechanics.

<http://www.teachersdomain.org/collection/k12/sci.phys.fund.quan/>.

**Visual Quantum Mechanics** from Kansas State University. Includes research-based interactive visualizations. Instructional units developed as part of the project are available for about \$200, though a free sample on light emission is available.

<http://web.phys.ksu.edu/vqm/software/online/info/summaryOfVqm.html>.

**Research on Teaching and Learning Quantum Mechanics.** A set of nine papers from NARST in 1999 is available for download with good information on student difficulties in learning quantum mechanics.

[http://web.phys.ksu.edu/papers/narst/QM\\_papers.pdf](http://web.phys.ksu.edu/papers/narst/QM_papers.pdf).

**Measuring Planck's constant.** A hands-on activity from the Perimeter Institute to measure Planck's constant ( $h$ ) using LED's and a few simple electronics.

[http://www.perimeterinstitute.ca/en/Outreach/Plancks\\_Constant/Measuring\\_Planck%27s\\_Constant%3A\\_Introduction/](http://www.perimeterinstitute.ca/en/Outreach/Plancks_Constant/Measuring_Planck%27s_Constant%3A_Introduction/).

**Introductory college level materials** in quantum mechanics (and other courses) from the Physics Education Research Group at the University of Illinois. Includes helpful lecture notes and clicker questions (Quantum Mechanics starts on Lecture 20 of the algebra-based materials). Free registration required to download.

<http://research.physics.illinois.edu/PER/Materials.htm>.

**Quantum Physics Labs from the Center for Nanoscale Systems.** Several quantum-related labs including the Bohr Model Game, The Phantastic Photon and Light Emitting Diodes, as well as several on wave phenomena, interference, and nanophysics. You can't order the kits if you haven't gone through their institute, but you can use their online lab manuals.

<http://www.cns.cornell.edu/cipt/labs/lab-index.html>.

**Public lectures** from the Kavli Institute for Theoretical Physics. A variety of public lectures by notable scientists on topics in quantum mechanics.

<http://www.kitp.ucsb.edu/outreach/public-lectures/past-lectures-talks>.

**Hands-on activities** from the Exploratorium's Paul Doherty.

- Energy levels. Model the energy levels of an atom with a stool or other object, noticing how it will fall to its "ground state" when tilted.  
<http://www.exo.net/~pauld/activities/energylevelmodel/energylevelmodel.html>.
- Bohr Model of an Atom. Model the energy levels of an atom using potential wells and strips of paper.  
<http://www.exo.net/~pauld/activities/energylevelmodel/bohratom.html>.
- Two Slit Interference Model. Model two slit interference with physical representations of waves on strips of paper.  
[http://www.exo.net/~pauld/summer\\_institute/summer\\_day8interference/twoslitinterferencemodel.html](http://www.exo.net/~pauld/summer_institute/summer_day8interference/twoslitinterferencemodel.html).
- Fundamental Frequency. Show resonant frequencies with a phone cord, demonstrating how certain wavelengths can fit on a length of string.  
[http://www.exo.net/~pauld/summer\\_institute/summer\\_day10waves/harmonic\\_phonocord.html](http://www.exo.net/~pauld/summer_institute/summer_day10waves/harmonic_phonocord.html).

**Concept map of quantum mechanics** at HyperPhysics has summaries of the main ideas of quantum mechanics and how they are interrelated.

- <http://hyperphysics.phy-astr.gsu.edu/hbase/quacon.html#quacon>

- <http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/statcn.html#c1>

**Good explanations of laser cooling and underlying principles** on the Nobel Prize website for 1997. [http://nobelprize.org/nobel\\_prizes/physics/laureates/1997/illpres/](http://nobelprize.org/nobel_prizes/physics/laureates/1997/illpres/).

**Videos on new types of atomic clocks** developed by NIST  
[http://www.nist.gov/public\\_affairs/clock/clock.html](http://www.nist.gov/public_affairs/clock/clock.html).

**Absolute Zero.** An activity guide intended for middle school students that would also be appropriate at the high school level, including demonstrations on superconducting levitation, the meaning of absolute zero, and Bose–Einstein condensation.  
<http://www.compadre.org/portal/document/ServeFile.cfm?ID=8053&DocID=718>.

## Between Sessions

### FACILITATOR

You may wish to share the *Classroom Resources* section of the next unit with participants for their homework.

You may wish to share the learning goals of the next unit from *What Will Participants Learn?* with participants in preparation for the next session.

Assign each participant to write a one or two paragraph summary of either Jenny Hoffman’s or Debbie Jin’s experiment. If possible, allow them to post these summaries in an online forum to spur discussion out of class.

### PARTICIPANTS

**Text:** Read Unit 6: *Macroscopic Quantum Mechanics* for the next session.

#### Further exploration:

1. **PhET Models of the Hydrogen Atom** at [http://phet.colorado.edu/simulations/sims.php?sim=Models\\_of\\_the\\_Hydrogen\\_Atom](http://phet.colorado.edu/simulations/sims.php?sim=Models_of_the_Hydrogen_Atom). (See also the teacher tips for this simulation).
  - a. How is de Broglie’s view of the electron different from Bohr’s view? What is the purpose of the three different views of the de Broglie electron?
  - b. How is Schrödinger’s model of the atom different from de Broglie’s? You may want to refer to the simulation.
2. **Physics 2000.** Go through the interactive tutorial and applets on Bose–Einstein condensation. Click “what is it” to see all applets, and “table of contents” for a list of topics. The following two links are particularly relevant: [http://www.colorado.edu/physics/2000/bec/what\\_is\\_it.html](http://www.colorado.edu/physics/2000/bec/what_is_it.html), and [http://www.colorado.edu/physics/2000/bec/what\\_it\\_looks\\_like.html](http://www.colorado.edu/physics/2000/bec/what_it_looks_like.html).
3. **Interactive Lab** associated with this unit: *Laser Cooling*. Learn the basics of how to manipulate atoms with light, and cool a hot atomic beam to a few millionths of a degree above absolute zero.

**Video:** Watch the Unit 6 program and write a one or two paragraph summary of either Jenny Hoffman’s or Debbie Jin’s experiment (you should have been assigned to one

experiment or the other by the facilitator). In your paragraph, try to imagine you are telling the story of their experiment to someone who is learning about it for the first time. (Even better, actually tell the story of the experiment to a family member or a colleague. Their questions will help you understand the material better.) Be sure to include what they are trying to discover/measure, and how their experiments relate to the topic of “macroscopic quantum mechanics.”