Unit 6

Macroscopic Quantum Mechanics

Introduction

A physicist is just an atom's way of looking at itself.
- Neils Bohr

We typically view quantum mechanics as applying to the fundamental particles or fields of Units 1 and 2—not to the objects we find in a grocery store or in our homes. If large objects like baseballs and our dining tables don't behave like waves, why do we bother about their possible quantum nature? More practically, we can ask: If we are supposed to believe that ordinary objects consist of wave-like quantum particles, how does that quantum nature disappear as larger objects are assembled from smaller ones? Or, more interestingly: Are there macroscopic objects large enough to be visible to the naked eye that still retain their quantum wave natures? To answer these questions we need rules for building larger objects out of smaller ones, and means of applying them. These rules are the subject of this unit, and they lead to some surprising macroscopic quantum behavior such as *Bose-Einstein condensates* and *superconductors*.

What Will Participants Learn?

Participants will be able to:

1. Visualize different models of the atom and explain how each model did or did not match experimental observations.
2. Explain how the periodic table is a manifestation of the inner structure of atoms, and how electron energies, spin, and pairing lead to chemical bonding.
3. Describe how quantum mechanics (which operates at the scale of atoms) can have macroscopic effects that are visible to the naked eye. List two or more examples of practical applications of macroscopic quantum mechanics.
4. Compare and contrast the behavior of *bosons* and *fermions*. Explain how fermions can be converted into bosons.

What's in this Unit?

Text: Unit 6 outlines the difference between bosons (integer spin particles) and fermions (half-integer spin particles). The *Pauli exclusion principle* dictates that no two identical fermions can occupy the same quantum state—a fact that leads to the structure of the periodic table as fermions fill up atomic energy levels from the ground state up. Bosons, on the other hand, can occupy the same quantum state, as in a laser, which consists of photons with the same frequency and momentum. Fermionic atoms can be combined to create bosonic atoms, under the proper conditions (extremely cold, low density atoms).[1] This led to the creation of Bose-Einstein condensates (BECs), and new work generating BECs from Fermi gases. These new states of matter exhibit new types of behavior.

[1] Note that fermions combine to create bosons in other contexts without requiring extremely cold temperatures. For example, protons and neutrons are fermions, and combine to create bosonic nuclei and protons; neutrons and electrons are all fermions, but combine to create bosonic atoms.

Video: The program investigates one manifestation of quantum mechanics at the macroscopic scale—superconductivity. In order to raise the critical temperature required to achieve superconducting behavior in materials, two researchers are working to understand what's going on inside these materials. Harvard's Jenny Hoffman and her research team are exploring the problem by using a scanning tunneling microscope to unravel the properties of superconductors, atom by atom. Meanwhile, Deborah Jin, a physicist at the National Institute of Standards and Technology, is looking at the problem from a different angle. She and her group are using ultracold gases, which help build models for how superconductors work using simpler systems that can be manipulated at the quantum level. She describes Bose-Einstein condensates (BECs) and her work on *Fermi condensates*.

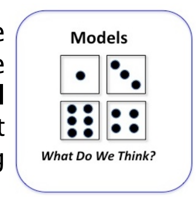
Video Extra: Wolfgang Rueckner of Harvard University demonstrates the *Meissner effect*, where a magnet will levitate above a superconductor as the superconductor expels all magnetic field lines.

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: Superfluid Coffee (10 minutes)
- Activity 1: Models of the Atom (30 minutes)
- Activity 2: Periodic Chessboard (25 minutes)
- Activity 3: Bosons vs. Fermions (10 minutes)
- Activity 4: Bose-Einstein Condensates (20 minutes)
- Activity 5: Watch and Discuss the Video (50 minutes)
- Back to the Classroom (15 minutes)

Nature of Science Theme: *Models*. You may wish to display the *Models* icon during the session and remind participants of the central ideas of this theme. Scientists create models, or hypotheses and theories, to make sense of their observations. Thus, a model is a scientific account of nature. A good model is testable and suggests evidence that would support or refute it. When experimental observations do not match the existing model, scientists do and have changed their ideas about nature.



Exploring the Unit

The Hook: Superfluid Coffee

<u>Time</u>: 10 Minutes.

<u>Materials</u>:

- Mug of coffee or other liquid
- Video of superfluid helium

Have a cup of coffee or other liquid. Stir it. Notice what happens. It has a single vortex, or whirlpool, in the center, and it gradually comes to rest. How would this behavior change if the coffee cup were filled with superfluid Helium-3? Show a video of superfluid Helium (e.g. http://www.youtube.com/watch?v=2Z6UJbwxBZI). You may also wish to show the *Video Extra* for Unit 6 (on the Meissner effect) here.

Explain to participants: In this unit, we will discuss the surprising behavior of ultracold materials, which allows us to observe quantum effects in things that are large enough for us to see, like a superfluid. In a superfluid, there is no resistance to flow, and rotating liquids show surprising behavior, like many quantized vortices on the surface. (*Note:* Bose-Einstein condensates are superfluids; the difference is that the atoms in Helium-3 interact strongly with each other, so their behavior is much more complicated than in Bose-Einstein condensates which remain gaseous.) First, we'll explore our changing model of the basic constituent of matter: The atom.

Activity 1: Models of the Atom

Time: 30 Minutes.

Purpose: In the last unit, participants learned about the wave/particle duality of light and matter. Now, participants see how Schrödinger's probabilistic description of matter wavefunctions leads to a very different model of the atom, which provides greater explanatory power for experimental observations. This activity extends the ideas in Unit 5.

Materials:
- Optional video from Alice and Bob in Wonderland called, "*How can atoms exist?*" http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.
- Optional handout of different models of the atom from the online resource: *Facilitator's Guide High Resolution Graphics.*

1. Bohr Model

To Do and To Notice

Clicker/Discussion Question: Atomic spectra

Gas atoms can absorb and radiate light

A. Of any frequency or color
B. At any frequency lower than that of the light hitting them
C. Only at precise frequencies or colors
D. In the visible part of the electromagnetic spectrum

What's Going On?

Best answer is (C). Atoms can only emit and absorb specific frequencies of light. This is because electrons also exist at fixed energy levels in the atom. Draw the *Bohr model* of the atom from the unit. What's wrong with this model? You may wish to show the 1-minute animated short from Alice and Bob in Wonderland called, "*How can atoms exist?*"

2. de Broglie Waves

To Do and To Notice

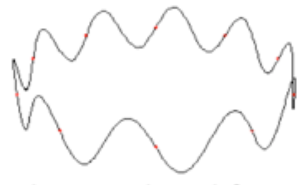
We know that electrons are some sort of wave. How does this lead to electronic energy levels? Imagine a wave that must fit around a ring, as below.

Clicker/Discussion Question: Standing waves on a ring

Imagine a standing wave on a string, but a string with the two ends joined together to create a circle with radius *r*. **What are the restrictions on the wavelength (λ)?**

A. $r = \lambda$
B. $r = n\lambda$
C. $\pi r = n\lambda$
D. $2\pi r = n\lambda$
E. $2\pi r = \lambda/n$

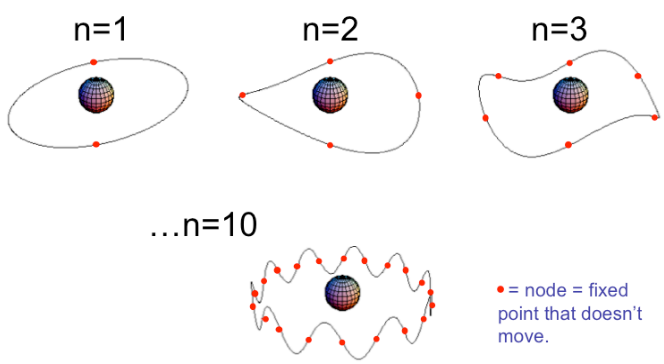
$n = 1, 2, 3, \ldots$



What's Going On?

Best answer is (D). For a given orbital radius *r*, the circumference is $2\pi r$, and to get standing waves without destructive interference you need an integer number of wavelengths[2], $n\lambda$. (*Note:* The particular orbital radius itself is fixed by setting the Coulomb potential energy equal to the kinetic energy of the electron).

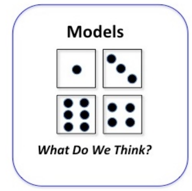
So what would these *de Broglie waves* look like for a single electron atom (e.g., hydrogen)? Thus, de Broglie waves explain energy quantization, at least mathematically. What are the wavelengths of these waves? For photons, $E=pc = hc/\lambda$ gives $\lambda=h/p$. The same relationship between wavelength and momentum can be applied to matter.[3] This is called the de Broglie wavelength: $\lambda=h/p$.[4] Review the models of the atom that we have seen so far.



de Broglie waves for the hydrogen atom[5]

[2] In the absence of any kind of confinement or *boundary conditions*, electron waves can have any energy; they are not restricted to the energy of these standing waves.
[3] Note: The momentum p is different for electrons and photons. For photons, $p=h/\lambda=E/c$ but for electrons and other massive particles, $p=(2Em)^{1/2}$ by using $KE=mv^2/2$.
[4] Note: You may discuss the fact that we don't see everyday objects as waves smeared out in space: As mass increases, the momentum (p) increases and the wavelength becomes incredibly small. Thus, we see everyday objects as located at a definite place in space.
[5] This image is from the University of Colorado Modern Physics course developed by C. Wieman, K. Perkins, and S. McKagan, http://per.colorado.edu/modern. For a thorough study of the use of the Bohr model and atomic models in undergraduate settings, and common student difficulties, see S.B. McKagan et al, "Why we should teach the Bohr model and how to teach it effectively," Phys. Rev. ST Phys. Educ. Res. 4, 010103 (2008).

3. Schrödinger Model



To Do and To Notice

Facilitate a Think-Pair-Share:

- What is "wrong" with the de Broglie model of the atom?
- How many historic models of the atom can you come up with? What is wrong with each of them?
- What were your answers to the homework questions on the PhET 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.

Discuss as a group, including the homework questions. Share the schematic on the next page (or your own version of it) with the class and discuss.

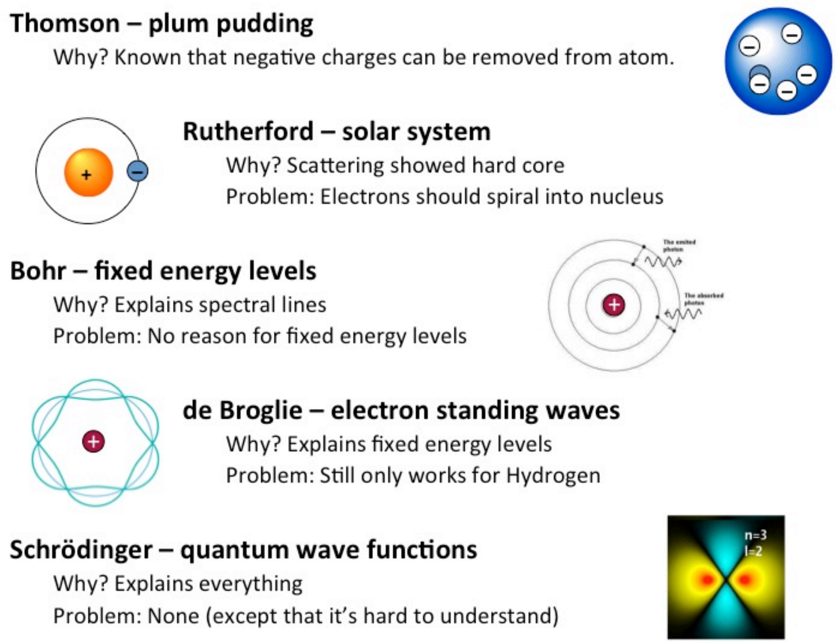
What's Going On?

Discussion points include:

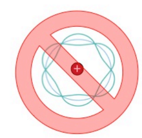
<u>Bohr model</u>: Gives correct electron energies, but postulates fixed energy levels without explaining why the energy levels are fixed. The electron is described as a point particle in space.

<u>de Broglie model</u>: Also gives correct electron energies, and postulates that the fixed energy levels are caused by electrons as standing waves (not an orbiting particle). But these energy levels only work for hydrogen, not for multi-electron atoms, as it is a 1-D model.

<u>Schrödinger model</u>: Also gives correct electron energies, but describes electron as a 3-D probability wave. The quantized energy levels result from boundaries on that wave. Allows us to generalize to multi-electron atoms (as in the next activity).



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



Take-home message: The de Broglie model gives the right answer, but it's the wrong physical model. The electron is not following a circular path around the nucleus. While the energy of the electron is quantized, and the electrons are located in shells (or "clouds"), the location of that electron is probabilistic. Schrödinger's wave equation allows us to calculate the shape of the electron clouds, and the probability of finding the electron at distinct locations within those clouds.

Activity 2: Periodic Chessboard

Time: 25 Minutes.

Purpose: To model the periodic table as a means to compare the Schrödinger model of the atom, quantum numbers, and the nature of fermions to familiar ideas in chemistry. Exploration of the fermionic nature of electrons will then be used to explore the surprising behavior of bosons in the next activity.

Materials:

- Butcher paper
- Colored markers
- 30 small paper or plastic cups
- Copy of the periodic table
- Tape
- Copy of atomic orbital simulation from http://www.falstad.com/qmatom/

To Do and To Notice

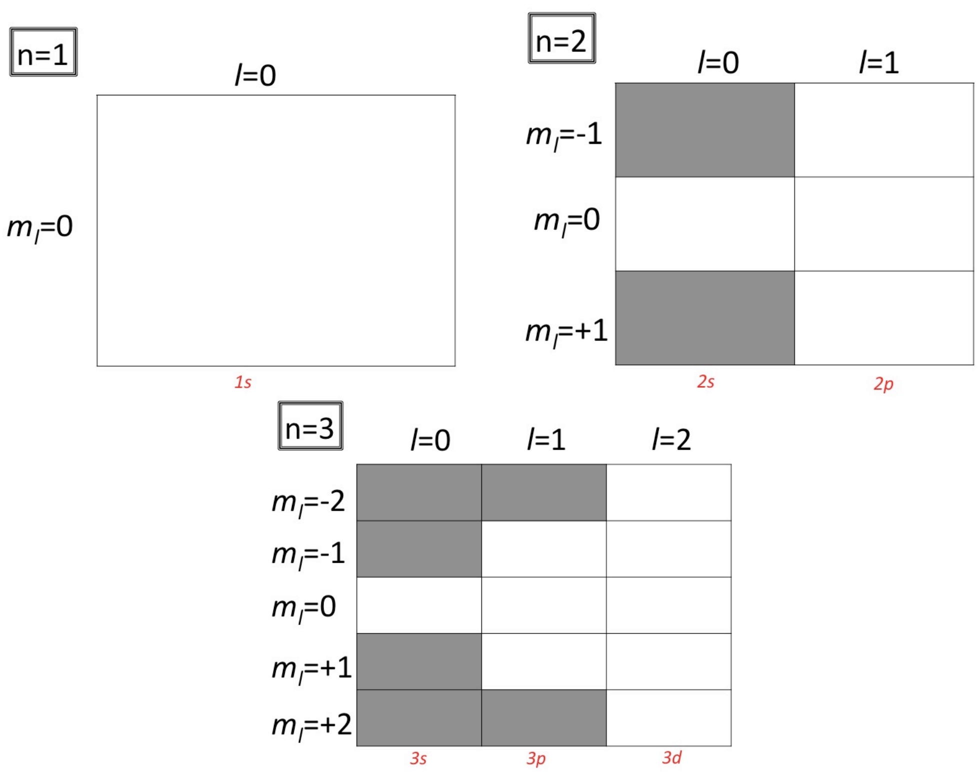
The electronic energy levels in the atoms are solutions to the Schrödinger wave equation, and each one can be uniquely described by four quantum numbers: n, l, m_l, and m_s. This activity will help us link the Schrödinger description of the atom to the chemists' periodic table.

Label three pieces of the butcher paper "n=1", "n=2", and "n=3." Remind participants of the four quantum numbers and their rules:

Name	Symbol	Allowed values
Principal	n	1, 2, 3…
Orbital	l	0, 1, 2…(n–1)
Magnetic	m_l	–l…–1, 0, 1, …+l
Spin	m_s	+1/2, –1/2

As a group, determine the possible quantum numbers available in the n=1, n=2, and n=3 levels. Label the l values along one side and the m_l values along another side. Leave out the m_s values for now. Your final papers may look like the pictures below, or you may choose another layout scheme. Grey squares indicate a quantum number that is not allowed for that level. If you are able, put n=1 on the floor, n=2 on a chair, and n=3 on a table to represent different energy levels.

<u>Optional</u>: You may have participants do this on their own or in pairs and then come to consensus as a group. You may also choose to do only the first two energy levels in the interest of time.



Explain that the cups represent electrons—a right-side up cup is spin = +½, and an upside-down cup is spin = –½. Remind participants that two electrons can't occupy the same quantum state[6] (the *Pauli exclusion principle*). Electrons will fill the lowest energy

[6] Quantum state, wavefunction, and quantum numbers are all different ways of saying the same thing: ψ_{nlm}.

possible without being in the same quantum state. Use a copy of the periodic table and find hydrogen (H), which has one electron.

1. Where should the hydrogen electron be placed on this diagram? It may be in either spin ±½ in the n=1 state.
2. How does this model relate to the observation that hydrogen atoms can only absorb and emit certain frequencies of light?
3. Given that the energy of an electron in hydrogen is $E_n = -13.6 \text{ eV} / n^2$ (where 13.6 eV is the ground state energy of hydrogen), how many different electron wave functions have the energy -(1/9) 13.6 eV?
4. Repeat the placing of cups for helium (He), then for lithium (Li), carbon (C), and neon (Ne). What rules dictate the order in which you place these cups? (*Note:* You may wish to make a diagram of the electron configurations for these elements on the board after placing the cups.)
5. In what ways do helium (He), carbon (C), and neon (Ne) differ from one another?

What's Going On?

Discuss the above questions:

1. A ground state electron in hydrogen will be in the 1s level, either ±½.

2. An electron that absorbs a photon is promoted to the next energy level (demonstrate this by moving one of the cups to a higher energy state).

3. This represents the n=3 level; A total of 9 states have this energy, or 18 including m_s = ±½.

4. Because two electrons can't occupy the same quantum state, they fill from the "bottom up." Electrons must fill the lowest n states, as these represent lower energy values. The lower l values fill next, because those allow the electron to remain closer to the nucleus. So the 1s orbital fills first, then 2s, then 2p. (*Note:* This is another way of stating *Hund's rule*.) Let's see why that is. Show participants the visualization of atomic orbitals for hydrogen at http://www.falstad.com/qmatom/. Use the "real orbitals" and start at n=1, moving to n=2 and n=3. Then change the value of l. (Optional: The changing color represents the phase of the wave—this is what's "waving." The probability density remains the same while the phase of the wave changes.) The quantum numbers m_l and m_s do not represent different energy values, so electrons can have any of these numbers (but not the same one) as they begin to fill those levels. Thus, any electron is defined by the combination of quantum numbers—n, l, m_l, and m_s. Quantum mechanics thus helps explain the periodic table.

5. These elements differ in many ways due to their electron configuration. Helium (He) has a full outer shell, lithium (Li) has one electron in its outer shell, carbon (C) has a half full outer shell, and neon (Ne) again has a full outer shell. These elements differ in many properties, including the *ionization energy*, or energy required to remove an electron. The ionization energy is periodic—it is low for an element with one electron in its outer shell (like Li) and high for an element with a full outer shell (like Ne). As we increase the number of electrons, this pulls electrons closer to the nucleus, so it becomes very difficult to pull electrons away from a noble gas like Ne.

Take-home message: Electrons are described by quantum numbers, and no two electrons in a shell can have the same quantum numbers. This gives rise to the periodic table (which had been described long before quantum mechanics).

Activity 3: Bosons vs. Fermions

Time: 10 Minutes.

Purpose: To explore how bosons do not obey the Pauli exclusion principle, and thus how they behave differently from fermions. Participants will learn how two fermions may be paired to create a boson.

To Do and To Notice

Return to the *Periodic Chessboard.* How would chemistry change if electrons were bosons instead of fermions?

Tape the cups together in pairs. If each electron is spin ½, what then each of these represent spin 0 particles, or bosons. As a group, place the cups to represent helium (He), lithium (Li), carbon (C), and neon (Ne). How do these elements differ from one another now that they're made of bosons?

What's Going On?

Bosons can all occupy the same quantum state (in fact, they like to do so). If electrons were bosons, then they would all occupy the lowest (1s) energy, and have the same quantum state. Helium (He), lithium (Li), carbon (C), and neon (Ne) now would only differ in their mass, total charge, and size. Chemistry would be very boring.

Bose realized that photons with the same energy (or frequency) can have the same quantum state *and* be in the same location. The same is not true of a fermion. If two fermions are in the same physical location (as with electrons in an atom) they cannot have the same quantum state. This is true whether the fermion is an electron or an atom. But we can put several fermions (spin ½) together to make a boson (spin 0). Just as we taped two cups together to make a spin 0 boson, we can put together any fermions (like two atoms) together to make a molecule that is overall spin 0. So, matter can be made of bosons, which will then be able to occupy the same quantum state *and* the same location.[7]

Einstein recognized that *all* bosons should follow Bose's prediction, even bosons made of matter. This is the subject of the next activity.

Take-home message: Bosons can occupy the same quantum state and the same location; fermions cannot. Fermions can be combined into bosons, and show bosonic properties.

Activity 4: Bose-Einstein Condensates

Time: 20 Minutes.

---

[7] If participants are confused about the difference between fermionic atoms and electrons, consider the following. Two electrons are confined to the same location (e.g., the 1s orbital) by an external force (e.g., the *Coulomb attraction* of the nucleus) but must have different states (e.g., spin of ± ½). Two atoms are confined to the same location (e.g., in a matter trap) by an external force (e.g., by a harmonic oscillator potential) but cannot have the same state (an atom has many more states than just that of spin), unless they are bosons.

Purpose: To explore how the de Broglie wavelength of particles can change with motion and temperature, and how this creates indistinguishable particles.

Materials:

- Marbles and an enclosure (from Unit 5)
- Animation of the Bose-Einstein condensation at http://www.colorado.edu/physics/2000/bec/images/evap2.gif
- Optional: Video "Bose-Einstein Condensate" from the BBC with Dan Kleppner: http://www.youtube.com/watch?v=bdzHnApHM9A&feature=related
- Optional: PhET "Quantum Bound States" simulation at http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Bound_States

1. de Broglie Wavelengths

To Do and To Notice

Ask participants the following set of questions and have them discuss in pairs. Then, discuss all questions as a group.

Compute the de Broglie wavelength for (a) an electron and (b) a baseball. Choose reasonable values for the parameters in the problem (for example, the approximate speed of an electron in an atom). The mass of an electron is 9.1 x 10^{-31} kg. Compare these values to the spacing between atoms (which is about 10^{-10} meters). What does this tell you?

Clicker/Discussion Question: Falling stones

A stone is dropped from the top of a building. **What happens to its de Broglie wavelength as it falls?**

A. Increases
B. Decreases
C. Stays the same

What's Going On?

The de Broglie wavelength for both the electron and the baseball is given by $\lambda = h/p = h/mv$. Even if the electron is given a very high speed, its momentum is dominated by its small mass, and its wavelength is longer than that of the baseball[8]. If the speed of the electron is chosen to be around 10^{6} m/s, then the wavelength of the electron is close to the interatomic spacing. The wavelength of the baseball will be around 10^{-34} m; much smaller than the size of an atom. Thus, a baseball does not have observable wave characteristics; its wavelength is too small. This is why the quantum nature of classically sized objects can be generally ignored.

As a stone falls, its velocity increases and so does its momentum. Thus, its wavelength decreases. What does this mean for the de Broglie wavelength of objects as they cool down? Their wavelength increases. So, colder objects have larger de Broglie wavelengths.

[8] For a sample calculation, see http://hyperphysics.phy-astr.gsu.edu/hbase/debrog.html#c4.

2. Can You Tell Them Apart?

To Do and To Notice

Remind participants of *The Hook* activity from Unit 5, *How To Make Something Really Cold?* The marbles (representing atoms) are now moving very slowly. Can you tell them apart? Sure. We can tell one marble apart from its neighbor. But let's think about the marbles as quantum particles. Consider their de Broglie wavelengths. Discuss the following questions as a group: What happens to the wavelength of the atom as it cools? What would its wavefunction look like? Can you sketch it? Interpret that graph physically.

Optional: Show the PhET "Quantum Bound States" simulation at http://phet.colorado.edu/simulations/sims.php?sim=Quantum_Bound_States to demonstrate how energy relates to the number of nodes in the wave function. (Use the first tab, "One Well," and click on different energy levels to see the wave function, or its probability density, in the bottom window. Notice how the wave function broadens if the width of the well is increased. How does that relate to localization?)

Optional: Show the video "Bose-Einstein Condensate" from the BBC with Dan Kleppner (content developer for Unit 5) for a nice visual analogy of Bose-Einstein condensates. http://www.youtube.com/watch?v=bdzHnApHM9A&feature=related.

Show the animation of the Bose-Einstein condensation at http://www.colorado.edu/physics/2000/bec/images/evap2.gif. Before you run the animation, explain: "Electrons in an atom are in a potential well caused by the Coulomb attraction of the nucleus. In the Bose-Einstein condensate, the atoms are in a manmade potential well—a "bowl" of energy. The middle of the image represents the bottom of the bowl. Any atom there is at the lowest possible energy state. Run the animation, and see that a there is a greater density of atoms in the middle (the bottom of the bowl) as the condensate forms. This shows that all the atoms are in the same state—the lowest energy state." Due to common confusion about this image, we recommend that participants make a sketch labeling the x and y axes on this image. The x-axis represents space; the y-axis represents particle density. But there is a hidden variable in the y-axis—energy—such that the middle of the image represents low potential energy.

What's Going On?

As the atom cools, the wavelength of the atom becomes broad. A sketch might look something like the sketch below. The electron is now less localized—it has a probability of being anywhere within the enclosure (though it has a higher probability of being in the center).

Just like electrons within an atom have a lowest possible energy state (the 1s; refer to the *Periodic Chessboard*), atoms within a potential well also have a lowest possible energy state. If the atoms are bosons, then they can all occupy that same quantum state with the lowest energy. The wavefunction depicted above represents the lowest energy quantum state; the next highest energy state would have a node in the middle.

As the wavefunctions of the atoms spread out, they no longer have a well-defined position, and it becomes difficult to tell them apart. They are no longer *distinguishable*—like a photon, these particles have the same quantum state and are in the same location. In the same way that photons in a laser occupy the same quantum state and the same location, these atoms now share the same quantum state. They have become a *superatom*.

Take-home message: As an atom cools, its de Broglie wavelength increases. As a group of atoms cools to absolute zero, their wavelengths overlap and they become indistinguishable.

Activity 5: Watch and Discuss the Video

Time: 50 Minutes.

Have a few participants read their summaries of the experiments in the video and discuss any questions or observations as a group.

If participants are watching the video in class, have them view it now.

How can we apply our understanding to the four applications of supercooled atoms

- Superfluids
- Superconductivity and *Cooper pairs*
- Atomic lasers
- Fermi gases

Superfluids are Bose-Einstein condensates, but harder to manipulate. The atoms in a superfluid are *strongly interacting*—they are much more likely to bump into one another than the atoms in a BEC. This makes them much more complicated to model and to understand.

Superconductors form because electrons pair together as Cooper pairs. Each Cooper pair is a boson, since it is made of two spin ½ particles. Though electrons generally repel one another, they are paired in a superconductor because (a) they are cooled until their wavefunctions overlap and (b) they are confined within a crystal. The electrons in this superconductor flow without resistance. These will be covered in more depth in Unit 8. You may wish to show the *Video Extra* for Unit 5 (on the Meissner effect) here.

Atomic lasers are lasers made of Bose-Einstein condensate atoms. These lasers show interference patterns just as lasers made of light do.

Fermi gases are gases made of fermions. In a BEC, the atoms used are bosons. Debbie Jin and her team try to make fermionic atoms pair up to create bosons (like the fermionic electrons that pair up in a Cooper pair). Those bosons then condense.

Back to the Classroom

Following is a list of high school topics and standards that are relevant to this material. See http://strandmaps.nsdl.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. The total amount of energy remains constant if no energy is transferred into or out of the system (relevant to spectral lines). Energy appears in many forms (such as kinetic and potential). Thermal energy in a system is associated with the disordered motions of its atoms or molecules.

Electricity and Magnetism. In many conducting materials, such as metals, some of the electrons are not firmly held by the nuclei of the atoms that make up the material. In these materials, applied electric forces can cause the electrons to move through the material, producing an electric current. In insulating materials, such as glass, the electrons are held more firmly, making it nearly impossible to produce an electric current in those materials. At very low temperatures, some materials become superconductors and offer no resistance to the flow of electrons.

Atoms and Molecules. Atoms are made of protons, neutrons, and electrons. Atoms are made of a positively charged nucleus surrounded by negatively charged electrons. An atom's electron configuration, particularity the outermost electrons, determines how the atom can interact with other atoms. Atoms form bonds with other atoms by transferring or sharing electrons. When elements are listed in order by the masses of their atoms, the same sequence of properties appears over and over again in the list.

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 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.

States of Matter. Different arrangements of atoms into groups compose all substances and determine the characteristic properties of substances. An enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.

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 formulate and test their explanations of nature using observation, experiments, and theoretical and mathematical models. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations. Scientific investigations usually involve the collection of relevant data, the use of logical reasoning, and the application of imagination in devising hypotheses and explanations to make sense of the collected data. The usefulness of a model can be tested by comparing its predictions to actual observations in the real world, but a close match does not necessarily mean that other models would not work equally well or better.

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. See in particular the links on elements as atoms, the periodic table, and BECs:

- http://www.colorado.edu/physics/2000/elements_as_atoms/index.html
- http://www.colorado.edu/physics/2000/periodic_table/index.html
- http://www.colorado.edu/physics/2000/bec/index.html

Animation of the Bose-Einstein condensation.
http://www.colorado.edu/physics/2000/bec/images/evap2.gif.

The **Nobel Prize website** for Bose-Einstein condensates has some helpful explanations. http://nobelprize.org/nobel_prizes/physics/laureates/2001/public.html.

Absolute Zero from NOVA. A video program and set of activities related to temperature. http://www.pbs.org/wgbh/nova/zero/. Includes an activity guide intended for middle school students that would also be appropriate at the high school level, including some 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.

Alice and Bob in Wonderland. A charming set of 1-minute animated shorts, suitable for classroom viewing, on some of the mysteries of nature. From the Perimeter Institute of Theoretical Physics. Relevant videos include *How can atoms exist?*
http://www.perimeterinstitute.ca/en/Outreach/Alice_and_Bob_in_Wonderland/Alice_and_Bob_in_Wonderland/.

PhET interactive simulation on models of the hydrogen atom
http://phet.colorado.edu/simulations/sims.php?sim=Models_of_the_Hydrogen_Atom.

Public lectures from the Kavli Institute for Theoretical Physics. A variety of public lectures by notable scientists on a variety of relevant topics, including Nobel Laureate Wolfgang Ketterle on BECs. http://www.kitp.ucsb.edu/outreach/public-lectures/past-lectures-talks.

A **physical model of de Broglie's atomic model** from Paul Doherty at the Exploratorium. http://www.exo.net/~pauld/activities/energylevelmodel/bohratom.html.

Physics Central **explanatory websites on Bose-Einstein Condensates** http://www.physicscentral.com/explore/action/state-1.cfm,
http://www.physicscentral.com/explore/pictures/cold-atoms.cfm,
and on Fermi gases http://www.physicscentral.com/explore/action/gas-research.cfm.

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.

PARTICIPANTS

Text: Read Unit 7: *Manipulating Light* for the next session.

Video: Watch the video for Unit 7. Using information from the video, and any external sources, consider the following questions and write some notes or short answers to guide you during discussion in the next session:

1. Why is it useful to create a quantum computer? What are the computing problems that it is trying to solve?
2. What are the challenges or barriers to creating quantum computing?
3. In the video, they call this, "spooky action at a distance." What does this mean? How is this different or similar to the "action at a distance" from Unit 2?
4. What do you think about Dr. Hau, and the implications of her team's work?
5. How do these experiments relate to the double slit experiments from Unit 5?
6. How is quantum entanglement consistent with Einstein's theory of relativity, which states that no information can travel faster than light?