Chapter 1: Introduction to atoms and light

Learning goals: By the end of this chapter, you should understand
- that atoms have discrete energy levels, and we can think about electrons as waves to understand why these energy levels are discrete.
- knowing either the frequency of a laser, the wavelength of a laser, or energy of a photon tells you all three. All three quantities are related by fundamental constants, so knowing one of them allows you to calculate the other two.

1.1 What is atomic physics?

Before we discuss atomic physics, we should first ask a more fundamental question: What is physics? We are all taking this course, which is a physics course, so let’s start with a broad mission statement. Before you read further, pause and think for a few minutes. If someone was to ask you, “What is physics?”, how would you respond? My answer is on the next page. Here is a comic to fill up the rest of this page 😊

Credit: XKCD Comics: https://xkcd.com/2100/
My answer: Physics is a branch of science that is trying to understand the universe. We do this through physical concepts and often explain those concepts using the language of mathematics.

All subfields of physics focus on a particular portion of the universe. For example, plasma physicists are trying to understand … wait for it … plasmas, a.k.a. ionized gasses. Atomic physicists\(^1\) are trying to understand the world of atoms, which I like to refer to as the world of the super super small.

These subfields can also have subfields. PHY242 is a brand-new course that is focused on providing a research experience in the field of spectroscopy, a subfield of atomic physics. Actually, spectroscopy can be thought of as both a subfield and a tool. As a subfield, it is using atom light interactions to try and understand the world of the super small. But it can also be thought of as a tool. The end goal is to understand how atoms work, and spectroscopy is just a tool to accomplish this goal. The important thing for this class is that spectroscopists use light to interact with atoms with the end goal of understanding the world of the super small.

Atomic physicists also start at one of the simplest systems and build up complexity over time. One of our simplest systems is a single electron bound to a single proton (a.k.a. a hydrogen atom). More complicated systems include helium (2 electrons and 2 protons), lithium (3 electrons and 3 protons), and europium (63 electrons and 63 protons). Arguably, nuclear physicists (physicists trying to understand the interactions inside the nucleus), have simpler systems to understand, but our math is easier\(^2\). Other fields of physics start with complicated systems and either “build up” or “build down” in complexity. For example, condensed matter physics, which includes subfields like superconductivity, have incredibly complex systems!

A few important reminders about atomic physics that you might have heard about before:

- Atoms are composed of three types of particles: protons, neutrons, and electrons.
  - Protons and neutrons form the nucleus and electrons orbit around the nucleus.
- Molecules are made from multiple atoms.
- The theoretical (mathematical) framework that describes the world of the super small is known as quantum mechanics.\(^2\)
- Atoms can be in a gas phase, liquid, or a solid. Most of atomic physics works in the gas phase to avoid the complexity of liquids and solids. In liquids and solids, atoms are bonded to one another, which makes the system more complicated.
- Spectroscopists use light to interact with and learn about the world of the super small.

In this class, we are going to think about a single, isolated Europium atom. The atoms will be in their gaseous form so we don’t have to worry about how two atoms interact in a molecule. One of the most important things to note right now is that we want to know general properties of the

\(^1\) In the last half of the 20\(^{th}\) century, atomic physics combined with molecular physics and optical physics. If you Google to find more, the branch of physics in now known as atomic, molecular, and optical physics. We use the acronym AOM physics: [https://en.wikipedia.org/wiki/Atomic,_molecular,_and_optical_physics](https://en.wikipedia.org/wiki/Atomic,_molecular,_and_optical_physics)

\(^2\) A more complete conceptual model of atomic physics is known as The Standard Model of Particle Physics: [https://en.wikipedia.org/wiki/Standard_Model](https://en.wikipedia.org/wiki/Standard_Model)

The mathematical framework of the Standard Model is known as quantum field theory: [https://en.wikipedia.org/wiki/Quantum_field_theory](https://en.wikipedia.org/wiki/Quantum_field_theory)
Europium atom. For example, we want to know the energy separation between two atomic states (more on this below) of a single, isolated atom. We don’t care about these properties in a magnetic field, an electric field, or even a laser field. Imagine a single Europium atom in the middle of outer space, completely in the dark, and far from any other object. We want an experiment that helps us figure out these general properties. If a scientist knows the general properties, they can then calculate or estimate what would happen to that property if the atom was, for example, put in a magnetic field. The important thing is that we provide the general information that can then be used by theorists, other experimentalists, and engineers later on.

To start the class, I will pose two general questions:
1. How do we understand the world of atoms and molecules?
2. How do we know that we know what is going on?

The simple answer to both questions is that we have a theoretical framework to work from. That framework has concepts built into it. We experimentally test that theoretical framework. If the experiments agree with theory, we say we understand what is going on. If experiment and theory don’t agree, the theory was wrong, and we conclude that we don’t understand some aspect(s) of the theoretical framework. Science is really that simple! Either experiments agree with theory, or they don’t. Even better, the theory should make predictions that we, as experimentalists, can go check. If theory and experiment agree, we give each other high fives. If they don’t, life gets really, really exciting because we have something new to explore.

Our theoretical framework is quantum mechanics. As mentioned in the footnote on the previous page, quantum mechanics has a more modern and complete version called the Standard Model of Particle Physics (more on this later in the semester). The Standard Model came about because, while quantum mechanics did a great job describing the world of the super small, it didn’t do a perfect job. In other words, quantum mechanics isn’t complete (it doesn’t describe everything). The Standard Model is also not complete, but it is more complete than quantum mechanics. For example, the Standard Model doesn’t know how to describe lots of things we observe in real life like General relativity (gravity), dark matter, dark energy, and baryon asymmetry. So, we test it over and over again. In this class, we are studying the Europium atom. In the future, these measurements can be used to validate the theory.

1.2 Conceptually understanding the atom

We are not going to discuss the Standard Model right now. We are going to keep things a bit simpler and discuss, conceptually, the atom. Over the semester, we will add to our conceptual model to make things more complete. So, what does quantum mechanics say about the atom?

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3 That question might take a few times to read!
4 Or the experiment was wrong. But when there is a disagreement, the experimental setup is scoured over and other groups will redo the experiment to make sure the experiment is indeed correct.
5 The Standard Model predicts there should be equal amounts of matter and antimatter. But our astronomical observations indicate there is much more matter than antimatter. So where is all the antimatter? This problem is known as baryon asymmetry: https://en.wikipedia.org/wiki/Baryon_asymmetry
6 You can read more about the things missing from the Standard Model here: https://en.wikipedia.org/wiki/Standard_Model#Challenges
**Important Concept:** Electrons in atoms behave more like waves than particles.

**Definitions:**
- **Wavelength:** The distance between any two points on a wave ($\lambda$). This is the lowercase Greek letter lambda.
- **Frequency:** The number of oscillations per second ($f$).

Extra fun: One of the first experiments to hint at this behavior is the double slit experiment. Wiki: [https://en.wikipedia.org/wiki/Double-slit_experiment](https://en.wikipedia.org/wiki/Double-slit_experiment)
YouTube video by the amazing Don Lincoln from FermiLab: [https://www.youtube.com/watch?v=nmxwVU88Bd8](https://www.youtube.com/watch?v=nmxwVU88Bd8)

This is a really hard concept to wrap our brains around, but experiments seem to indicate this idea is correct. An electron in an atom is not like the moon orbiting the earth. It is more like a standing wave on a string or sound modes from a drum head.

**YouTube videos:** Watch these videos before continuing.
- Standing waves on a string: [https://www.youtube.com/watch?v=gr7KmTOrx0](https://www.youtube.com/watch?v=gr7KmTOrx0)
- In class, we are going to do the above demo.
- Standing waves on a drum head: [https://www.youtube.com/watch?v=v4ELxKKT5Rw](https://www.youtube.com/watch?v=v4ELxKKT5Rw)

**Summary:** If you have a wave that is interfering with itself, the wave can either be constructively interfering with itself or destructively interfering with itself. Depending on the geometry (i.e. drum head, wave on a straight string, wave on a circular string, etc), the standing wave condition is slightly different, but typically something like $L \approx n\lambda$ where $L$ is the length of the string, $\lambda$ is the wavelength of the wave, and $n$ is an integer or half integer (depending on the geometry).

Ok, so electrons are behaving more like waves. They even have their own wavelength just like a standing wave on a string. Why are standing waves important here? The conceptual answer is that the electron is orbiting the nucleus and interfering with itself. Unless the standing wave condition (the circumference of the orbit is an integer multiple of the wavelength of the electron) is met, the electron will destructively interfere with itself, which according to quantum mechanics means the electron will not exist. Think about that for a minute. What we are actually saying here is that if the electron does not constructively interfere with itself, it will destructively interfere itself out of existence. Electrons don’t normally just disappear! So, the electrons can only exist with certain energies, specifically these standing wave energies. Just like the 2nd mode in the standing wave on a string requires more energy than the 1st, the higher energy “states” of an electron have more modes.
We call the energies an electron can have “energy levels” or “energy states” and describe them like in diagrams like this:

![Energy Diagram](image.png)

The lowest energy state is called the ground state. States with more energy modes are called excited states.

**Summary statement:** Electrons in atoms can have only specific energies. As an analogy, the lowest energy an electron orbiting a nucleus can have is like the lowest mode on a string (1 bump). The next lowest energy is like having two bumps on the string, etc.

**Important comment:** We often say the ground state energy is 0. This is not true! Think about the lowest energy mode of a standing wave on a string. That lowest energy mode has energy! The ground state of an atom also has energy. In experiments, we measure the energy difference between the ground state and excited states. For this purpose, we assign the lowest energy state to be 0 so that everything is measured with respect to that state.

Your goal for this class is to measure the energy difference between the ground state of Europium and one of the excited states to as high precision as possible (more on precision in future classes).


Picture from wiki:
1.3 Photons and spectroscopy

Ok, so that is our goal. How do we do it?  
Answer: Spectroscopy! We shine a laser onto the atoms and look at the interaction.

But first, we need to talk about lasers. Light, including laser light, is composed of tiny particles called photons.\(^7\) As an analogy, think about a stream of water. The water looks continuous, but it is actually made up of tiny water molecules. The same thing with light. Light is composed of tiny particles we call photons. Each photon has an energy just like each individual water molecule has energy.

We aren’t going to prove the following statement with math, but it is very important:

**Important statement:** If a photon of light has the exact energy as the energy difference between the ground state and an excited state, the atom will absorb that photon and move an electron to an excited state. If the photon of light *does not* have the exact energy as that energy difference, the atom will ignore the photon completely.

This is like trying to excite the 2\(^{nd}\) mode on a string from the 1\(^{st}\) mode. If you don’t give the string the exact amount of energy you will get destructive interference on the string. If we don’t give the electron the exact amount of energy to go from the ground state to an excited state, it cannot do so! If it did, the electron would destructively interfere itself out of existence.

**Restating that in terms of an actual experiment:** We are going to smoothly scan the energy of the photons in time. If the energy of the photons does not match then energy difference between the ground state and an excited state, the laser light will pass right through the atoms with no losses. If the energy of the photons does match that energy difference, light will be lost from the laser. Experiments that match the above description are known as absorption spectroscopy experiments. We, as experimentalists, simply monitor the power of the laser after it passes through an atomic sample. As we scan the energy of the photons in the laser, if the power in the laser drops, the atoms absorbed light from the laser and we just learned what energy is required to excite the atoms from the ground state to an excited state.

**Common misconception:** Power is not the same thing as energy. Power is the amount of energy transferred per unit time. Here is a nice YouTube video on the difference:  
[https://www.youtube.com/watch?v=N7arlSaKYWA](https://www.youtube.com/watch?v=N7arlSaKYWA)  
I like his last line, “Energy is an amount of something you need to get things done, whereas power is a measure of how quickly you get things done.” For a laser, which is composed of photons, each photon has an energy. The total energy coming out of the laser in 1 second is the power of the laser beam. In math form, the power of a laser is:

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\(^7\) Lots of folks think Einstein won the Nobel Prize in physics for special relativity. He did not. He actually won it for the photoelectric effect: [https://en.wikipedia.org/wiki/Photoelectric_effect](https://en.wikipedia.org/wiki/Photoelectric_effect)  
Before this, light was thought of as just a wave. After this, light was thought of as a wave composed of tons of little particles we call photons. I may be biased, but Einstein’s explanation of the photoelectric effect was the most important discovery of the 20\(^{th}\) century.
\[ P = \frac{N E_{ph}}{1 \text{ second}} \]

where \( N \) is how many photons left your laser in 1 second and \( E_{ph} \) is the energy of a single photon. Imagine you have a 1 Watt laser and a 10 Watt laser that has photons with the same energy. The 10 Watt laser emits 10 times as many photons per second as a 1 Watt laser.

1.4 Math

**Definitions:**
- **Wavelength:** The distance between any two points on a wave (\( \lambda \)). Units are m, cm, or nm.
- **Frequency:** The number of oscillations per second (\( f \)): Units are \( \frac{1}{s} = \text{Hz} \) (Hertz).
- **Speed of light:** \( c = 299,792,458 \text{ m/s} \approx 3 \times 10^8 \text{ m/s} \)
- **Planck’s constant:** \( h = 6.626 \times 10^{-34} \text{ Js} \) (Joules times seconds)

A Joule is the SI unit of energy.

It turns out, the energy of a photon, wavelength of the laser light, and frequency of the laser light are all related to each other using the formula \( c = f \lambda \). This formula comes from the theory of electricity and magnetism. The energy of the photon is related to the frequency of the laser by the formula \( E_{ph} = hf \). This equation was what won Einstein the Nobel Prize in Physics.\(^7\)

The most important thing to emphasize here is that we have multiple ways to state the same property of a photon. This is such an important concept, the entire first homework set is dedicated to this idea.

1.5 The most important equation in all of science

Questions + repetition + critical thinking = mastery

Don’t be afraid to ask questions. Don’t be worried about asking for clarification. Don’t expect to remember or understand every single concept the first time you read or hear about it. Mastery is not a short journey. Developing critical thinking skills is not a 5 minute activity that you figure out after watching a 3 minute YouTube video. Practice deep learning,\(^8\) keep a growth mindset,\(^9\) and have fun 😊

If there is a topic you want to know more about, I can provide you with more on that topic. If you, for example, want to explore something more in depth because you find it interesting, we should let that happen. I replace homework problems for learners all the time. For example, if you told me, “Prof. Will, I would really like to learn more about the photoelectric effect”, I would give you readings on the photoelectric effect and tell you to do a few problems on that topic instead of HW problems 5-7 below.

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\(^7\) https://en.wikipedia.org/wiki/Deeper_learning
\(^8\) https://en.wikipedia.org/wiki/Deeper_learning
\(^9\) https://en.wikipedia.org/wiki/Mindset#Fixed_and_growth_mindset
Homework 1

<table>
<thead>
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<td>Frequency</td>
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<td>Hertz (1/second)</td>
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</table>
| Speed of Light      | c           | meters/second | m/s                 | 299,792,458 m/s  
|                     |             |               |                     | ≈ 3 × 10⁸ m/s     |
| Planck’s Constant   | ℏ           | Joules seconds | J s                 | 6.626 × 10⁻³⁴ Js  |

\[ c = f \lambda \]
\[ E_{ph} = hf \]

1. What is the frequency of light for a laser that has a wavelength of 462.8 nm \((462.8 \times 10^{-9} \text{ m})\)? Your final answer should have 4 significant figures.
2. Using the two formulas above, derive a formula for the energy of a photon in terms of only constants and wavelength.
3. Assess the formula you found in question 2 by finding the energy of a photon two different ways using the numbers from question 1. The first way is using the formula \( E_{ph} = hf \). The second way is using the formula you found in question 2. Physicists are trained and known for assessing everything. It is what makes us special 😊
4. In atomic physics, energy is often measured in the units of \( \text{cm}^{-1} \). The method of calculating energy in these units is to first find the wavelength in centimeters, and then take the inverse. In equation form, this is

\[ E(\text{cm}^{-1}) = \frac{1}{\lambda(\text{cm})} \]

Note in the above formula the variables include the units to remind us to use wavelength in centimeters; the formula does not say \( \lambda \) times cm. Using the wavelength given in question 1, find energy in units of inverse centimeters.
5. The equation in question 4 can be confusing. Energy has units of Joules and not inverse length! Why are atomic physicists comfortable with using energy in this weird unit? There are multiple correct answers here.
6. Using questions 1-5, make a list of all the different ways to convey the same exact information as \( \lambda = 462.8 \text{ nm} \).
7. It actually isn’t only atomic physicists. Astronomer, nuclear physicists, and a good number of chemists also use energy in inverse centimeters. Other chemists and condensed matter physicists prefer to use electronVolts (eV). Virtually no one uses the SI unit (Joules)! Any thoughts why?

A final comment: while speaking to one another or giving a talk, spectroscopists will use wavelength or energy in units of inverse centimeters. However, published values are always energies in units of inverse centimeters. There is something called the NIST database that compiles all of the known energy levels and their measured energies. Here is the NIST page for Europium: [https://physics.nist.gov/PhysRefData/Handbook/Tables/europiumtable5.htm](https://physics.nist.gov/PhysRefData/Handbook/Tables/europiumtable5.htm)

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10 You have a lot of reading in the first week of class, so the first week’s homework is a little easier than normal. There are 7 problems, but they are all fairly short. Take a look at homework 2 if you are looking for a more typical homework set.
Don’t worry about what all the columns mean right now; over the course of the semester, we will discuss the other columns. Notice that all of the energies are given with respect to the ground state in units of inverse centimeters. The ground state does not actually have zero energy!! The electron wave has some sort of standing wave structure that does have energy. We measure everything with respect to that ground state energy.