Atomic Structure and the Properties of Matter (Chapter 11)

Introduction
Suppose I begin by posing the situation of breaking large rocks or boulders with a sledged hammer. One finds that
Boulders $\rightarrow$ rocks $\rightarrow$ stones $\rightarrow$ pebbles $\rightarrow$ gravel $\rightarrow$ sand $\rightarrow$ powder ...
If I continue along this process of breaking things down, will I keep going on forever getting infinity smaller as I go? The answer is “NO” according to physics. There is a limit.

PowerPoint
Atoms
- Microscopic irregularities look like mountains with canyons
- Walls of canyons look as if they are oscillating
- Greater detail of walls shows that the surface consists of hazy blobs, mostly spherical, making up long chains of complicated structures
- As you brace yourself for impact with a spheroid, you are surprise to enter a whole new universe – empty and vast. You are inside an atom which is as empty as the solar system. You occasionally see a speck whirling past you at unbelievably high speeds and at the center is a very dense core called the nucleus.
- As you approach the nucleus, again you brace yourself for impact but again enter a “new solar system.” Inside this nucleus are protons and neutrons.
- As you brace for impact with a proton or neutron, again, you enter a small solar system that has smaller particles called quarks. As far as particle physics is concerned, this is the end of the line.

Power of Tens
Applet [http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/]

Scale of the Universe Applet: [http://scaleofuniverse.com/]

All matter is made of tiny building blocks. Even though the atom is not the smallest constitute of matter, for the purposes of this class I will consider it the smallest.

History lesson
In the earliest days of science people wandered how far the idea of breaking of objects to it fundamental elements would go on. “Does it ever end?” Hundreds of years ago, people had no way of finding out, and therefore, carried on with philosophical speculations. Not until “modern chemistry” in the late 1700’s did people begin to get indirect evidence of the basic order in the combinations of things. The “real proof” that there were atoms was given by Einstein in 1905. He calculated what kind of motion there ought to be in Brownian motion – the idea of heat is due to atomic motion using conservation of energy/momentum. Many of the “heavies” in physics at the time didn’t believe in atoms until Einstein’s work.

What is an atom?
All matter is made up of tiny building blocks called atoms. Atoms have a nucleus (composed of protons and neutrons) and outside the nucleus are electrons. The study of chemistry only focuses on how electrons interact from atom to atom, whereas the nucleus is like nuclear reactors or carbon/lead dating. The most ionic image of the model of the atom

Atoms-1
Unfortunately, this image is completely wrong and everybody knew it was wrong when it was created in 1911. Here is a quick history of the atom: In the 1911 Rutherford model, the atom consisted of a small positively charged massive nucleus surrounded by a much larger cloud of negatively charged electrons. In 1920 Rutherford suggested the nucleus consisted of positive protons and neutrally-charged particles, suggested to be a proton and an electron bound in some way. Electrons were assumed to reside within the nucleus because it was known that beta radiation consisted of electrons emitted from the nucleus.

**The Periodic Table**

Everything is made up of atoms: jello, nuclear waste, basketballs … Only a small number of atoms (relative at least to the number of objects that they make up) make up the whole universe.

**Analogy:** Only 3 light colors are needed to recreate all of the colors that one observes on a TV or computer monitor. Note that this is thousands of colors.

When it comes to atoms (or elements), **only 118 atoms** are needed to make-up the infinite number of objects in the known universe. 118 is a very small number in comparison with the number of objects they make up. Of the 118 atoms, it turns out that

92 occur naturally
26 are unstable and must be produced artificially

What is meant by unstable is that the nucleus is not capable of “holding on” to its structure and decays (breaks apart) or suddenly changes into a different animal. However, there are currently experiments being conducted as we speak on trying to increase the number of atoms. One example is at the Bevatron in Berkeley.

![Periodic Table of the Elements](image)

Element 117 was discovered in 2010 by bombardment of berkelium with calcium. See Wikipedia for the up-to-dated periodic table.

We should be careful when we say the word “Universe” because it really means one thing but it is used in two ways. There is the Universe and the Observable Universe.
The periodic table only tells us about the 4% of the universe (i.e., the observable universe) and we immediately find that we, us humans and life here on Earth, is extremely rare. Only 0.03% of the universe is made of heavier elements that make us.

**Atomic Structure and Forces**

**Goals**

1. To determine the atomic structure of an element. That is, be able to determine the number of protons, neutrons, electrons, the number of energy levels and if it is the most common isotope.

2. Understand that the planetary model of the atom is unstable, and therefore, not the correct model of the atom.

**1. Atomic Structure**

1. Almost the entire mass of an atom lies within the nucleus. Why?
   
   The nucleus is made up of protons and neutrons, not electrons. Electrons are outside the nucleus and they live in energy levels (also called shells or orbitals. If we compare the mass of the proton, neutron and the electron, here is what we find: the neutron and proton have the same mass but are 1800 times heavier than the electron. That is, to balance the mass of a single neutron (or proton), you would need to balance it with 1800 electrons.

   \[
   m_{\text{proton}} = m_{\text{neutron}} \approx 1800m_{\text{electron}}
   \]

   So all the mass of the atom lies inside the nucleus and we can ignore the mass of the electrons (for our purposes).

**Spectra Notation**

The two most important numbers that describe the atom are the atomic mass and the atomic number.

- The atomic mass represents the number of protons and neutrons in the nucleus. The reason for this is

  \[
  \text{Atomic mass} = \text{mass of nucleus} + \frac{\text{mass of electrons}}{\text{very little mass}} = \text{mass of nucleus}
  \]

  \[
  A = \text{Atomic mass} = \text{mass of the protons & neutrons} = \text{number of the protons & neutrons}
  \]

- The atomic number is the number of protons inside the nucleus

  \[
  Z = \text{Atomic number} = \text{number of protons}
  \]

When one looks at the periodic table, these two numbers are shown. It is customary to write these two atomic numbers using **atomic spectra notation**:

\[
\begin{align*}
\text{Atomic mass} & = X \\
\text{Atomic number} & = Z
\end{align*}
\]

Examples:

\[
\text{\textsuperscript{4}\text{He}} \rightarrow \begin{cases} A = 4 & \rightarrow 4 - 2 = 2 \text{ neutrons} \\ Z = 2 & \rightarrow 2 \text{ protons} \end{cases}
\]

\[
\text{\textsuperscript{238}\text{U}} \rightarrow \begin{cases} A = 238 & \rightarrow 238 - 92 = 146 \text{ neutrons} \\ Z = 92 & \rightarrow 92 \text{ protons} \end{cases}
\]

ii. The **main characteristic that distinguishes an atom** is the **number of protons** in the nucleus. That is, all helium atoms are defined by the two protons found with the nucleus, regardless of any other detail.
iii. Elements that are listed in the periodic table are electrically neutral. That is, there are an equal number of protons and electrons. So the helium atom has 2 protons and 2 electrons, whereas Uranium which has 92 protons, also has 92 electrons.

iv. The number of atomic shells of an atom is determined by the row number that the element lives in. For example, the helium atom lies in the first row and only has 1 shell, where its two electrons are located. On the other hand, Uranium lies in the 7th row, so it has 7 atomic shells where is 92 electrons are located.

v. Neutrons and Isotopes
There was a famous physics (Rabbi) who ask the follow question when talking about the neutron: “who ordered that?” This question was one of the most challenging and important questions in the first half of the 20th century, which finally lead to the picture of the atom we know today. Ultimately, neutrons distinguish the types of isotopes. Each element has multiple isotopes (same number of protons but different number of neutrons). In fact, the atomic mass values listed on the Periodic table are derived from averaged over all of the observed isotopes masses. However, for many of the isotopes (especially for elements higher up in the Periodic table but not true for elements lower in the table), the atomic mass values given on the Periodic table is likely to be the most commonly found in nature. Assumption: always assume that the most common isotope found in nature is the one on the periodic table. Although this is not correct, we will make this assumption. There are lots of important isotopes.

\[
\begin{align*}
\text{Hydrogen} & \rightarrow 1^1\text{H} \quad \text{common isotope} \\
\text{Helium} & \rightarrow 4^4\text{He} \quad \text{common isotope} \\
\text{Carbon} & \rightarrow 6^{12}\text{Ca} \quad \text{common isotope} \\
\text{Uranium} & \rightarrow 92^{235}\text{Ur} \quad \text{common isotope}
\end{align*}
\]

Video Superfluid Helium

2. Atomic forces
The stability of the entire atom is determined by two forces: the electrical force between the nucleus and electrons as well as the electric force within the nucleus and (ii) the strong nuclear force between the protons and neutrons inside the nucleus. As we will see, the stability of the atom is determined by the constant struggle between these two forces inside the nucleus.

Electric Force
There are two types of electric charge: positive (the charge of a proton) and negative (the charge of the electron).

If an object is neutral, it means that there are equal amounts of positive and negative charges such that the sum of these is exactly zero. This is exactly what happens inside of the neutron; the sum of positive and negative charges inside sum to zero. Since the nucleus is made of protons and neutrons, the nucleus is positively charged. Electrically charged objects will experience an attractive electric force when their charges have opposite signs where is they have the same sign, the charges will feel a repulsive electric force.
What holds the atom together? The electrical attraction between the positive nucleus and the negative electrons is what binds them together to form an atom. So the standard image that most people have of the atom is that the electrons are circling the nucleus similar to a planetary system (that is, the nucleus plays the role of the sun and the electron the earth). However, there is a very serious problem with this picture. An electron that is accelerating (note that an electron orbiting the nucleus is accelerating since it is changing direction) will give off light and reduce its energy. As a result, the electron will continually lose energy and spiral in towards the nucleus until it crashes into the nucleus and the atom stops existing. However, since scientist know that atoms exist, the model of the atom with electrons orbit the nucleus like little planets is NOT correct. A model that works extremely well is the quantum Mechanical model of the atom. In a nutshell, this model states that electrons live in energy levels and do not radiate energy when they are in these energy levels. Therefore, the electrons are stable in these configurations. The details, unfortunately, are beyond the scope of this course.

Strong Nuclear Force
When one looks closely at the nucleus from an electrical viewpoint, there is a problem. Since the nucleus has a collection of positively charge protons, the electrical repulsion between the protons inside the nucleus should "blow apart" the nucleus. However, it is observe that the nucleus is fairly stable for the majority of the atoms in the periodic table. So why is the nucleus not blowing apart? There must be another force that prevents this – this force is called the Strong Nuclear Force. It is sometimes referred to as the glue that bounds the nucleus together. The strong nuclear force binds protons-to-protons, protons-to-neutrons as well as neutrons-to-neutrons.

To make it clearer, let’s go through the periodic table and build-up nuclei to see how these two forces interact with each other.

- Hydrogen (\(^1\text{H}\)) has 1 proton and 0 neutrons in the nucleus. No surprising it is the most stable of all elements in the periodic table. Note that there are no competing forces.
- Helium (\(^2\text{He}\)) has 2 protons and 2 neutrons in the nucleus
- Repeat with \(^{24}\text{Mg}\) and \(^{157}\text{Ba}\)
- Uranium (\(^{238}\text{Ur}\)) has 92 protons and 146 neutrons in the nucleus

Explain how a nuclear bomb is really an electrical bomb.
If time, talk about the 3 major types of nuclear decays.

PROPERTIES OF ATOMS
The Size, Quantity, and Age of Atoms
Atoms are extremely small. It is impossible to comprehend just how small they really are. To get a feel for their smallness, the average size of an atom is a few Fermi (femtometer) = \(10^{-15}\) m and the electrons is known to be at least smaller than \(10^{-20}\) m. What do these numbers mean?

- Comparing the size of the atom to apple is comparable to comparing the apple to the size of the earth. Clearly, the atom is a very tiny object.
- The number of atoms required to fill an apple is equivalent to asking the question how many apples are required to fill the whole earth.
Clearly, atoms are very tiny and therefore, enormously numerous. There is a special number called Avogadro's number \( \approx 10^{23} \) atoms that is an indicator of how numerous atoms are in fixed quantities called moles. As we all known, water is made up of the water molecule \( \text{H}_2\text{O} \). In one gram of water, there are \( \approx 10^{23} \) water atoms.

**DEMO** Show a gram of water.

- The number of water droplets in all the lakes and rivers of the world is less than \( 10^{23} \).
- The number of leaves on every bush and tree in the whole world is less than \( 10^{23} \).

**Size of the Atom**

The nucleus of the atom has a diameter of about \( 10^{-15} \) meter, whereas the atomic diameter is about \( 10^{-11} \) meter. This means that the nucleus has a diameter 10,000 times smaller than the atom. The great amount of empty space in an atom can be illustrated by the following analogy. Imagine the nucleus to be the size of a golf ball. Then on this scale the first electron shell would be about one kilometer from the golf ball, the second shell about four kilometers, the third nine kilometers and so on. If you find that hard to visualize then try this. The period at the end of this sentence, (depending on your monitor and the font you are using), is probably about \( 1/2 \) a millimeter in diameter. If that period represents the nucleus then the electrons in the first shell would be orbiting with a diameter about 50 meters around you. In fact, the actual diameter of an atom is very small and it would require some two hundred million of them side by side to form a line a centimeter long.

In order to talk about the **radius** of an atom, we have to make an arbitrary decision about where the **edge** of the atom is. It is arbitrary because the electron orbitals **do not end sharply**. Nevertheless, we can do like we did with the 3D contour plots of the orbitals and just arbitrarily choose the **radius** that the **electron spends 90% of its time inside**. The electrons spend 90% of the time inside the black line. Using this definition consistently, we can look at the **trends** of the atomic radii as a function of position in the periodic table. That trend is...

![Diagram of atomic radii](image)

In general the size of the atom depends on how far the outermost valence electron is from the nucleus. With this in mind we understand two general trends...

- **Size increases down a group**
  - The increasing principle quantum number of the valence orbitals means larger orbitals and an increase in atomic size.

- **Size generally decreases across a period from left to right**
  - To understand this trend it is first important to realize that the more strongly attracted the outermost valence electron is to the nucleus then the smaller the atom will be. While the number of positively charged protons in the nucleus increases as we move from left to right the number of negatively charged electrons between the nucleus and the outermost electron also increases by the same amount. Thus you might expect there to be no change in the radius of the outermost electron orbital since the increasing charge of the nucleus would be canceled by the electrons between the nucleus and the outermost electron.
electron. In reality, however, this is not quite the case. The ability of an particular inner electron to cancel the charge of the nucleus for the outermost electron depends on the orbital of that inner electron. Remember that electrons in the s-orbital have a greater probability of being near the nucleus than a p-orbital, so the s-orbital does a better job of canceling the nuclear charge for the outermost electron than an electron in a p-orbital. Likewise, an electron in a p-orbital does a better job than a d-orbital. Thus as we move across a given period the ability of the inner electrons to cancel the increasing charge of the nucleus diminishes and the outermost electron is more strongly attracted to the nucleus. Hence the radius decreases from left to right.

When astronomers estimate the age of the universe, experimentally they come up with the number of about 15 billion years old. As far as we are concerned, this is an infinite amount of time by any scale. The constituents of atoms – electrons, protons, and neutrons (only inside atoms), are known to have lifetimes are at least the age of the universe. Remember that an average adult dies, on the average, around 70 years. Atoms are ageless, that is, they have been around forever! Atoms are being recycled from one object to another. In fact, since atoms are so numerous, in every single breath that you take in, you’re breathing in everyone atoms. I mean everyone atoms whoever existed in the past. So you can breathe easy since your are breathing in Einstein atoms, Galileo’s, Marie Curie … However, you are also breathing in the atoms of Jack the Ripper, Son of Sam, Richard Ramirez …

Tell story of Orchard elementary school

**How atoms are made?**

Hydrogen makes up 90% of all the matter in the universe. Scientists believe that hydrogen is the origin atom, just like Adam & Eve. There is something really interesting about hydrogen: what is meant by empty space is that there exist only one hydrogen atom per 1 m³. Space is not really empty but pretty dam close it. If the human race is to ever travel to another galaxy, rockets would not be able to carry their fuel simply because there is not enough room. For example, in the Cassini probe, they had to use the slingshot effect in order to get to Saturn – the technology is not currently available to fly a rocket directly to Saturn. It would run out of fuel before. There is a theoretical rocket called the rambust engine that would use hydrogen as it fuel which it would collect as it travels through space. A version of a rambust engine was tested a year or two ago where the rocket reached 25 mock speed (18,000 mph).

When one looks at all the other atoms except for hydrogen, one finds that they are made (1) inside of stars and (2) supernovas.

Inside of a star, the temperatures and pressures are extremely high. They are so high that if one takes two hydrogen atoms, this intense pressure literally fuses them together to create new atoms – Helium, the second atom on the periodic table. Then hydrogen and helium atoms are fused to produce Lithium, the third atom on the periodic table. This process occurs again and again until it reaches lead (Pb).

**Radio Report**

The process of fusing atoms together is called **nuclear fusion**. To produce atoms heavier than lead, a star goes through a evolution process where it gets to the point that it does not burn hydrogen anymore, but instead starts burning helium. When this occurs, the sun will start expanding it size and reach it final size to around the orbit of the earth. We don’t have to worry a lot about this since it will occur around 10 millions from now. At this point, the sun is get heavier atoms above lead,
Nuclear physicists want to replicate this process here on earth. There are two main projects: a world project that will be in France and the NIF (talk about NOVA). Why is this a good thing? Whether one wants to emit it or not, the only green solution is nuclear power currently – with the emission of CO$_2$ gases into the atmosphere, one can foresee a future in which global warming or climate change could bring civilization to an end as we know it.

There are only 5 atoms needed to make-up all living matter: Hydrogen, Nitrogen, Calcium, Oxygen, and Carbon.

**How were the elements of the Periodic Table made?**

The matter of everyday is made up of electrons, protons and neutrons. The question is why? There is a periodic table of particle physics called the Standard Model:

![Image of the Standard Model](image)

Collisions between high-energy particles (e.g., LHC) tell us how the universe was when it was newly born. The cosmological model that describes the expansion of the universe, not the creation, is called the (inflationary) big bang model. Here is the model in a nutshell: the universe starts out as a "singularity," a complicated big bang occurs and the universe starts expanding. Very early in the age of universe, the energy density is extremely high. From Einstein’s energy relationship,

\[ E^2 = (pc)^2 + (mc^2)^2 \]

(E = mc$^2$ is not a complete statement). Energy (potential and kinetic) is converted into mass, which brings us to the SM particle table. When the energy density was very high, all of these particles where created. The table shows two classes of particles: matter particles (fermions) called leptons & quarks and force carriers (bosons). The matter that was born in the Big Bang consisted of all kinds of quarks and leptons.

**Key point: nature seeks the state of lowest energy, which translates (in this case) to the state of lowest mass particles.** So starting with heavy quarks (c, s, t, b), which are highly unstable, they “died out” or decayed within a fraction of a second, leaving only the up and down quarks. In a similar manner the heavy leptons (\( \mu \), \( \tau \)) were also unstable and decayed, courtesy of the weak force, leaving only electron as survivors from the lepton family. In this whole decay process, lots of neutrinos and electromagnetic radiation (CMB) were produced during this process, and these particles continue swarming throughout the universe some 14 billion years later (that is, these are the
particles of the CMB). These heavier particles play no obvious role in the matter that we normally find on Earth.

As a result, all of the matter that is stable is electrons, up and down quarks, neutrinos and photons. It is these particles that make up the observable universe (only 4% is visible). So the electrons, up and down quarks were the survivors while the universe was still very young and hot. As it cooled, the quarks stuck to one another, forming protons and neutrons. Once protons and neutrons are formed, there are three ways to produce atoms: (i) Big Bang, (ii) Stellar, and (iii) Supernova nucleosynthesis.

1. **Big Bang nucleosynthesis.** 300,000 years after the big bang, the first 4 elements on the periodic table (H, He, Li and Be) are produced through fusion in a time period of 3 minutes, as the universe cooled. There are rather specific thermal requirements for these processes to occur, so there was only a short time window in which these elements could have formed. That is, fusion can only produce significant amounts hydrogen (75%), helium-4 (25%), and trace amounts of deuterium (0.1%), lithium and beryllium within the first three minutes of first light. (In fact, there is a book written by one of my favorite science writers, Steven Weinberg, called The First Three Minutes.) These are very firm predictions by the various big bang models and have been measured very well with COBE and WMAP (Wilkinson Microwave Anisotropy Probe), as well as with several nuclei collider. This time period is 300,000 years after the big bang, and 3 minutes after first light.

With these light elements born, the mutual gravitational attraction among themselves gathered into large clouds that eventually produced the first stars. As they bumped into one another and interacted in the heart of these stars, the protons and neutrons built up the seeds for the production of heavier elements. This leads us to the next stage of atom building – stellar nucleosynthesis.

2. **Stellar nucleosynthesis.** Inside of stars, the fusion process continues with protons and other light nuclei in the cores of stars. It was here that heavier nuclei would be cooked over the next billions of years. This is something separate from big bang cosmology, since stars didn’t form until millions of years into the universe’s lifetime. Not *all* elements are formed in stellar nucleosynthesis. There are specific "chains" of nuclear reactions that occur, and only the elements that are produced by those reactions will exist in a star in appreciable quantities. Most stars produce their energy using either the proton-proton chain (in lighter stars) or the CNO cycle (in heavier stars), both of which consume hydrogen and form helium. Once most of the hydrogen has been consumed, the star’s temperature will increase and it will start to fuse helium into carbon. When the helium runs out, it will fuse carbon into oxygen, then oxygen into silicon, then silicon into iron. (Of course the actual process is more complicated – see Wikipedia for details.) Several other elements are produced or involved along the way, including neon, magnesium, phosphorous, and others, but lithium is not among them.
3. **Supernova nucleosynthesis.** Some stars became unstable and exploded, ejecting heavy atomic nuclei (elements heavier than iron) into space. Supernova nucleosynthesis is the fusion of atomic nuclei due to the high-pressure, high-energy conditions that arise when a large star explodes in a type II supernova. There are certain similarities between this and big bang nucleosynthesis, namely the high temperatures and pressures, but the main difference is that an exploding star will have "reserves" of heavy elements built up from a lifetime of nuclear fusion. So instead of just forming a lot of helium as occurred just after the big bang, a supernova will form a whole spectrum of heavy elements. In fact supernovae are the only natural source of elements heavier than iron, since it actually requires an input of energy to produce those elements as fusion products. Supernova 1987A verified this model of production of heavier elements.

**Interesting point:** if you look at my wedding band on my finger it is made of gold, which was clearly mined here on earth. However, the earth nor the sun is capable of making gold because it doesn’t have enough high temperatures and pressures to do it. So the only conclusion that one must arrive at is that the sun is a second generation star. That is, there was at first a massive star in our neighborhood of our galaxy that went supernova, which in turn seed our solar system. With these cosmic seeds, it is believed that some 5 billion years ago our solar system was formed whose atoms were from that long-dead supernova that make you, me and my gold wedding band today.

In summary, the Sun is carrying on today what the universe did at large long ago. Atoms cannot survive inside the depths of the Sun, and nor could they in the early universe. It was not until some 300,000 years had elapsed that the universe had cooled enough for these nuclei to entrap passing electrons and make atoms.

Question: why does the earth have an iron/nickel core? Iron and nickel can’t be made by the earth; it does have the internal pressure to make. Our sun is a second generation star that seeded this solar system. Since the first generation star was a large star, it already had iron and other heavy elements. When the star went supernova, since it is already starting with heavy elements, it fuses elements together to make heavier beyond iron.
http://sol.sci.uop.edu/~jfalward/physics17/chapter14/chapter14.html

Atoms