9. Atoms, Heat, and Light

Reading: Re-read section 3.1. Then read sections 5.3-5.5 (you already read 5.1-5.2) and sections 8.1-8.3.

Atoms

Basic constituent of all everyday matter.

Nucleus made of protons and neutrons. Surrounded by a "cloud" of electrons.

The diameter of the nucleus is roughly 100,000 times smaller than the diameter of the electron cloud. (!)

The mass of a proton is 1.67×10^{-27} kg. (In other words, it takes 6×10^{26} — 600 trillion-trillion — protons to get 1 kg.)

The mass of a neutron is almost exactly the same as a proton, larger by just 0.14%.

The mass of an electron is 1/2000 of the proton mass.

Protons have positive electric charge. Electrons have negative electic charge. Neutrons have no electric charge (they are "electrically neutral").

Opposite charges attract, like charges repel.

Electrons are held in an atom by electrical attraction to the protons of the nucleus.

The nucleus is held together by the *strong nuclear force*, which overcomes the electrical repulsion of the protons.

Typically an atom is electrically neutral, with the same number of protons and electrons.

However, electrons can sometimes be stripped off an atom (by atomic collisions, for example) to create an electrically charged *ion*. Under some conditions an atom can acquire an extra electron to create a positively chared ion.

Atoms form bonds by sharing electrons, making molecules.

The chemistry of an atom is thus determined by its number of protons, which determines the number of electrons the atom would "like" to have.

There are only about 90 stable chemical elements because electrical repulsion makes nuclei with more than 100 protons unstable. (And some nuclei with less than 100 protons are unstable enough that they don't live long.)

Typically, the number of neutrons is similar to the number of protons. An exception is hydrogen, whose nucleus consists of a single proton.

However, many chemical elements have *isotopes*, nuclei with the same number of protons (hence the same chemistry) but different numbers of neutrons (hence different mass).

Deuterium is an isotope of hydrogen that has one proton and one neutron in the nucleus. (Tritium has one proton and two neutrons.)

Protons and neutrons are themselves made of particles called quarks. Electrons (and quarks) appear to be fundamental particles, not "made of" anything elese.

Heat

The energy of motion of a particle or object of mass m moving at a speed v is $\frac{1}{2}mv^2$. (This equation is only accurate for $v \ll c$.)

Heat is the "disordered" energy of a collection of particles (which may individually be atoms, molecules, photons, or a mixture).

Each individual particle has energy, but the particles are not moving coherently.

In a gas, where atoms/molecules move independently, heat energy consists of random motions, which are redirected frequently by collisions. For air at room temperature, the typical molecule velocity is ~ 300 m/s, but with roughly a factor of two spread.

(Not coincidentally, this is the speed at which sound waves travel in room temperature air.)

In a solid, where atoms/molecules are bound together by chemical bonds, these atoms/molecules are vibrating, again with a typical speed of ~ 300 m/s at room temperature.

If I throw a baseball, then it also has *ordered* energy of motion, $\frac{1}{2}m_{\text{baseball}}v^2$. If I could throw it at 300 m/s, then its ordered energy of motion would be equal to the heat energy of its random atomic motions.

If I drop a bowling ball: gravitational energy is converted to energy of motion, which is eventually converted to heat energy (with sound waves along the way).

Temperature and Absolute Zero

Temperature quantifies the average random energy of atoms or molecules; higher temperature means more energy.

There is a (predictable) spread of atomic/molecular energies at each temperature, above and below the average.

There is a temperature of "absolute zero" where atoms/molecules have the minimum possible energy.

(Because of effects of quantum mechanics, "minimum possible" turns out not to be zero in all cases.)

On the Celsius temperature scale, water freezes at 0°C and boils at 100°C, and absolute zero is -273°C.

On the Farenheit scale typically used in the U.S., absolute zero is -459°F.

For thinking about physics or astronomy, it is most convenient to start the temperature scale at absolute zero.

We therefore use the Kelvin scale, which starts at absolute zero.

Water freezes at 273°K. Room temperature is about 300°K.

Matter and photons

A distribution of photons can also have a temperature that describes the average energy of the photons.

Matter (a lump of stuff, a cloud of gas) can usually absorb and emit photons. If the matter is hotter than its surroundings, it will emit more than it absorbs, and vice versa.

Shorter wavelength photons have higher energy, so hotter matter will emit shorter wavelength photons.

At room temperature, the typical photon wavelength is about 0.01 millimeters (10^{-5} m), which is infrared radiation.

Your body is constantly emitting infrared photons and absorbing infrared photons from the environment.

More generally, the characteristic photon wavelength is

$$\lambda_c \approx 0.01\,\text{mm} \times \left(\frac{300\,\text{K}}{T}\right),$$

where T is the temperature in degrees Kelvin.

Expansion and cooling

If hot material expands, it cools off, converting disordered heat energy into ordered energy of expansion.

Conversely, compressing material heats it up, increasing the energy in disordered motion.

As the universe expands, it cools. In the past, it was hotter. When it was highly compressed, it was very hot.

Since photon wavelengths stretch as the universe expands, the temperature of the photons also drops.

Brief history of a hot universe

We'll give more details later, but here is a sketch:

When the universe was about half a million years old, the temperature was about 3000 K, hot enough to break apart atoms.

Before this, we had free electrons and nuclei instead of neutral atoms.

Free electrons are good at scattering light, so before this time the universe was opaque, like a fog.

When the universe was a few seconds old, the temperature was about 10 billion K, hot enough to break apart nuclei.

Before this, there were protons and neutrons, not bound into nuclei.

(Still earlier, even the protons and neutrons were broken into quarks.)

Consequences:

Most of the helium in the universe formed during the first three minutes, when the temperature cooled enough to allow nuclei to form.

The universe is filled with photons left over from its hot early phase, now cooled by the expansion to 3 K (three degrees above absolute zero). These photons are seen today as the cosmic microwave background.