Lecture 11: Atomic Structure

- The patterns of lines in spectra tell us about the composition of the source
- We need to understand atomic structure in order to extract this information

Spectroscopy

- Spectroscopy is the study of the way atoms emit and absorb radiation
- Studies are carried out using a spectroscope to view atomic spectra

- White light produces a continuous spectrum, or continuous spectrum
- Photographs of the spectra are obtained using a spectrograph

Continuous Spectrum

Emission Lines
Emission Lines

- When a gas is heated, it produces bright emission lines in the observed spectrum

- The wavelengths of the lines depend on the composition of the sample

Absorption Lines

- When white light passes through a cool gas, we observe dark absorption lines in the spectrum

- The wavelengths of the lines depend on the composition of the sample
Absorption Lines

Absorption and Emission Lines

- These are the emission and absorption lines of sodium
- They occur at the same wavelengths

Emission lines, absorption lines, and a continuous spectrum can all be produced together in a single apparatus:
Spectroscopy

- We observe that emission and absorption lines are produced at exactly the same frequencies (wavelengths) for a gas of the same composition.
- The locations (colors) of the lines vary with the composition of the sample.
- What is the underlying physical explanation for this phenomenon? - this was a mystery until about 1900.
- This behavior is a reflection of the atomic structure of matter.

**Electron "Orbitals"**

- The "orbits" are really smeared-out clouds called "orbitals".
- Each orbital has a precise energy.
- If the electron changes orbitals, the atom must emit or absorb energy.

**Energy of an "Orbit"**

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**Atomic Transitions Applet**

**Atomic Radiation Applet**
Electrons in an atom can only have certain energies. The energy values are determined by the structure of the nucleus.

An electron of a given energy has a precise mean orbital radius from the nucleus.

Atomic Nuclei

Atomic Structure

The number of electrons in a neutral atom equals the number of protons in the nucleus.

- Hydrogen: 1 proton, 1 electron
- Helium: 2 protons, 2 electrons, 2 neutrons

There are many more energy levels (orbitals) than there are electrons in the atom.

Isotopes of elements have different numbers of neutrons.

The mean orbital radius increases with increasing energy.
The lowest energy is called the ground state of the atom, with energy $E_1$.

If energy is given to an atom, it can be raised from the ground state to a higher energy level:

- The exact amount of energy added is $E = E_2 - E_1$.
- The atom is then called an excited atom.

The energy can be given in two ways:

1. By absorbing radiation with energy $E = E_2 - E_1$.
2. By colliding with another atom or particle.
De-Excitation

- Excited atoms can spontaneously emit a photon:

- Excited Atom

- De-Excited Atom

- The energy of the emitted photon is exactly:
  \[ E_{\text{photon}} = E_2 - E_1 = hf \]

- The corresponding wavelength is given by:
  \[ \lambda = \frac{hc}{E_{\text{photon}}} \]

- Atoms can also collisionally de-excite.

If the excitation is to a high level, then more than one decay route is available.

Emission & Absorption Lines
The energies of the lines are equal to the differences between energy levels in the atom.

Spectrograph 1 sees the continuous spectrum minus the photons that cause the excitation: Why?

The de-excitation photons are emitted in random directions.

Spectrograph 2 sees just the photons produced in the de-excitations:

Thus Spectrograph 2 sees emission lines only.
If enough energy is given to the atom, the electron is completely removed:

Energy can be given via short-wavelength (UV) radiation or via a collision.

Kirchhoff’s Laws (1859)

1. Hot gas at high density or pressure glows with a continuous spectrum:
   - Atomic collisions produce free electrons
   - Free electrons don’t have discrete energy levels
   - We see a rainbow
   - The photons produced have many different energies

2. Hot gas at low pressure produces only bright (emission) lines
   - Collisions excite atoms
   - Electrons drop down to lower energy levels, emitting radiation, which cools the gas
3. Cool gas at low pressures absorbs certain colors, creating absorption lines:

- Radiative excitation followed by radiative de-excitation

Using Spectral Lines to Measure Velocity

- The spectrum of hydrogen gas can be measured with precision in the laboratory

Using Spectral Lines to Measure Velocity

- Suppose that when we observe a star, we see a similar pattern of lines, but with a wavelength shift…
Comparing the observed spectrum with the lab spectrum, we see that this is hydrogen. However, the lines are all shifted to longer wavelengths. Therefore, the star must be receding from us. How can we determine the velocity of recession, $v$, from the observational data? We can use the formula for the Doppler shift to do this.

**Doppler Effect**

- The emitted (rest frame) and observed wavelengths are related by:
  \[ \lambda_{\text{observed}} = \lambda_{\text{emitted}} \left(1 + \frac{v}{c}\right) \]
- where $v$ is the relative speed of the observer and the source
- The observed wavelength is larger than the emitted wavelength if $v$ is positive (receding observer)
- If we know both wavelengths, then we can measure the speed of the source

Using Spectral Lines to Measure Velocity

We can make a table of the observational data:

\[
\begin{array}{cc}
\lambda_{\text{observed}} & \lambda_{\text{emitted}} \\
4341 & 4102 \\
4593 & 4341 \\
5144 & 4861 \\
6945 & 6563 \\
\end{array}
\]

These all give $v = 0.058 \, c = 17,467 \, \text{km/sec}$
• Using the formula

\[ \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{1 + \frac{v}{c}}{1 - \frac{v}{c}} \]

• The data give us

\[ 1 + \frac{v}{c} = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = 1.058 \]

• Therefore we find that the source is receding with a speed of

\[ v = 0.058 \, c \quad \text{or} \quad v = 17,467 \, \text{km/sec} \]

**Doppler Shift**

- This same technique has been used to measure the velocities of material swirling around compact objects
- The measured speed is very close to the speed of light
- This implies that the central object must a black hole

**More Complex Spectra**

- Atoms with higher atomic numbers have more protons, more neutrons, and more electrons
- Therefore they have much more complex spectra:
  
  - H: 1 proton
  - He: 2 protons
  - C: 6 protons
  - O: 8 protons
  - Fe: 26 protons
Many transitions are possible in complex atoms
Each transition between energy levels has a unique energy value
Therefore each transition produces a photon of a specific wavelength
For example, Fe (iron) contributes hundreds of lines to the Solar Fraunhofer absorption spectrum

Molecules are groups of atoms
The energy structure of molecules is much more complex than atoms:
- Electronic transitions produce visible and ultraviolet lines
- Vibrational transitions produce infrared lines
- Rotational transitions produce radio lines
Line broadening occurs when the observed atoms have a large distribution of velocities.

The observed wavelength of the line is shifted by the Doppler effect.
The relative velocity of the atom determines the observed wavelength

- Atom receding
- Atom approaching

When the gas has a high temperature, the atoms are moving with high speed.

- Many are approaching the observer, many are at rest relative to the observer, and many are receding from the observer.
- This produces a distribution of observed wavelengths called thermal broadening.
Thermal broadening produces a bell-shaped curve of brightness:

Rotational broadening

If the star is rotating, then this produces relative velocities too, and therefore Doppler shifts:
Thermal and rotational broadening have a combined effect on the observed profile.