Atoms and Spectra

Relativity and Astrophysics
Lecture 11
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Outline
- Bohr Model of the Atom
- Electronic Transitions
- Hydrogen Atom
- Other elements – Spectral signatures
- 21-cm Hydrogen line

Prelim
- Wednesday, Sept. 23
- Closed book and notes, will cover material through last Friday
- Should know
  - Spacetime interval, fundamental postulates of Special Relativity, simultaneity and other issues raise by relativity
  - Will have both qualitative and quantitative questions
  - Lorentz Transformation equations will be provided (if needed)
- You may want to bring a calculator

My office hours are:
- Monday: 02:00 – 04:00 pm
- Tuesday: 11:00 – 12:00 am

If you can’t make these, set up an appointment.
Where does light come from?

- It had been known during the 19th century that accelerated charges produce light, and hence emit energy.
- If we picture an electron as in orbit around the nucleus, it should radiate light.
  - Changing direction is acceleration!
  - But if the electron radiated, it would lose energy and soon spiral into the nucleus.
- The world would collapse instantly!
  - Fortunately it doesn’t.
  - What is wrong with this picture?
- Enter Quantum Mechanics (QM)
  - Quantum Mechanics was developed during the revolution which occurred in physics from 1900 - 1930.
  - Both Special Relativity and General Relativity were developed during this time.

The Bohr Model of the Atom

- Niels Bohr 1913:
- Formulated 3 rules regarding atoms.

1. Electrons can only be in discrete orbits.
2. A photon can be emitted or absorbed by an atom only when an electron jumps from one orbit to another.
3. The photon energy \( E \) equals the energy difference between the orbits.

\[
E = hf = \frac{hc}{\lambda}
\]

since \( c = \lambda f \), and \( f = c/\lambda \).
Quantum Numbers (Q.N.)

- An electron can reside in one of many orbits.
- \( n \) = number of orbit = Principal Q.N.
- \( n = 1 \) is the lowest energy state.
- If \( n > 1 \), then the atom is “excited.”

Electronic “Orbits” in an Atom

Atomic Energy Levels

Energy Level Diagram

A schematic representation of the orbital energy levels.
Electronic Transitions

- An **electron transition** occurs when an electron moves between orbits.
- When **absorption of a photon** occurs, an electron goes up, e.g. from \( n=1 \) to \( n=2 \).
- **Emission of a photon** occurs when an electron moves down, e.g. from \( n=2 \) to \( n=1 \).

Spectra from Atoms

- A **spectrum** is the intensity of light seen from an object at different wavelengths.
  - e.g. done by spectroscopy with a prism.
- Individual atoms, like H, show **spectral lines**, i.e. For H, these are the Balmer lines in the visible.
- For a “Conversational” lecture on spectral lines see [http://www.colorado.edu/physics/2000/quantumzone/](http://www.colorado.edu/physics/2000/quantumzone/)
The Spectrum of Hydrogen

- H has one electron => simplest spectrum.
- Discrete emission and absorption lines
  - Need a photon of the correct energy to move up a level.
- Spectral lines occur in ultraviolet, visible, infrared, and radio.
- Visible lines called Balmer lines.

![Hydrogen Energy Level Diagram]

- Note the discrete “lines” where there is emission.

Hydrogen Energy Level Diagram

- The energies in atoms are usually expressed in electron volts (eV).
  - 1 eV = 1.6 x 10^{-19} J
- For instance, the energy difference between n = 2 and n = 1 in H is 10.2 eV.
- Since $E = \frac{hc}{\lambda}$, $\lambda = 1216$ Å

### Lyman Lines - Ultraviolet
- Lyα: $n=2 \rightarrow 1$, $\lambda = 1216$ Å
- Lyβ: $n=3 \rightarrow 1$, $\lambda = 1026$ Å
- Lyγ: $n=4 \rightarrow 1$, $\lambda = 973$ Å
- ...

### Balmer Lines - Visible
- Hα: $n=3 \rightarrow 2$, $\lambda = 6563$ Å
- Hβ: $n=4 \rightarrow 2$, $\lambda = 4861$ Å
- Hγ: $n=5 \rightarrow 2$, $\lambda = 4341$ Å
- ...

Ground State = Lowest Energy Level
Hydrogen Balmer Spectrum: Revisited

Balmer Lines - Visible
- Hα: n=3 → 2, λ = 6563 Å
- Hβ: n=4 → 2, λ = 4861 Å
- Hγ: n=5 → 2, λ = 4341 Å
- ...

Notes: (1) The energy levels get closer together as the quantum numbers get larger.
(2) The greater the difference between the quantum numbers, the larger the energy of the photon emitted or absorbed.

The “Continuum”

The ionization energy of hydrogen is 13.6 eV. To ionize an electron from the ground state (n=1) of hydrogen requires photons of energy 13.6 eV or greater. => λ < 912 Å

The energy of an electron in the continuum is not quantized (it’s continuous).

An electron in the continuum has escaped from the proton.
- This can happen if the Hydrogen atom absorbs a photon with energy (hν) greater than 13.6 eV.
- And the hydrogen atom is “ionized.”
If a photon has enough energy, it can ionize an atom, i.e. promote an electron into the continuum.

An atom becomes an ion when one or more electrons have been removed.
- Adding an extra electron also creates an ion but this is much more difficult and rare.

Neutral HeI
Once ionized HeII
Twice ionized HeIII

Astronomers use the following notation to indicate the ionic state of an atom.

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Meaning</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>neutral</td>
<td>HeI, OI</td>
</tr>
<tr>
<td>II</td>
<td>once ionized</td>
<td>HeII, OII</td>
</tr>
<tr>
<td>III</td>
<td>twice ionized</td>
<td>HeIII, OIII</td>
</tr>
</tbody>
</table>

Notes (on ionization):
- It takes progressively more energy to remove successive electrons from an atom.
- That is, it is much harder to ionize HeII than HeI.
- Note: You can not have HeIV!
Solid materials have a continuous spectrum rather than a discrete one (somewhat like white light).
This is different from individual atoms.
Examples:
- Tungsten filament light bulb - continuous
- Fluorescent lamp - discrete
Spectral Signatures: Astronomy’s Rosetta Stone

- Spectral signature:
  - Each ion has a unique set of spectral lines associated with it.
  - This is of fundamental importance to astronomy, allowing the identification of elements clear across the galaxy and universe.
  - With spectral signatures we can identify oxygen, carbon, iron, etc.

- In addition these signature provides information on:
  - Chemical composition of the stars
  - Abundances of the elements
  - Physical conditions of the gases
    - Densities and Temperatures

Hydrogen 21-cm Radiation

- An important spectral line in astronomy for measuring the gas between stars is the 21-cm line of Hydrogen.
- This is in the radio part of the spectrum.
- The $n = 1$ level (ground state) of $H$ is actually “split” into 2 levels separated by a very small energy.

- This splitting is due to the fact that the electron and proton have intrinsic spin, i.e. they behave like small magnets.
- When the North poles are aligned the energy is higher than when they are not.
A 21-cm photon is emitted when poles go from being aligned to opposite (a spin flip).

This emission from a small number of H-atoms is very weak, but hydrogen is very plentiful in space.

We see lots of this radiation from our Galaxy and others. (Line first detected in 1951)

Note – the lifetime of the 21-cm hydrogen upper state is about $10^7$ yrs, whereas the lifetime of the $n = 2$ state is $10^9$ seconds!