# *Perspectives* - Summer School 2014

## Physics

*From Quarks to Quasars: Quantum mechanics and what it tells us about the Big Bang*

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# From Quarks to Quasars

## Quantum mechanics and what it tells us about the Big Bang

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**Abstract**

In the 20th century, scientists discovered that if atoms were illuminated with white light, very specific wavelengths were absorbed (see Figure 1). The main aim of this tutorial is to use semi-classical quantum mechanics – namely the Bohr model of the atom – to explain how these absorption lines arise. We will then see how a modification to the theory, in the form of Schrödinger's model, accurately explains the concept of atomic orbitals and electron configuration. We conclude by exploring how these absorption lines have enabled us to measure Hubble's constant and the expansion of the universe.

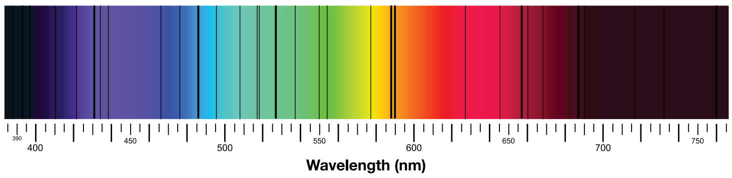


**Figure 1:** Absorption lines on the spectrum of light from the Sun. The dark lines show the wavelengths that are absorbed by atoms in the solar photosphere.

### Reading list

1. *Electrostatic potential energy*: http://hyperphysics.phy-astr.gsu.edu/hbase/electric/elepe.html
2. *Atomic spectra*: http://chemwiki.ucdavis.edu/Physical_Chemistry/Quantum_Mechanics/Atomic_Theory/Electrons_in_Atoms/Atomic_Spectra
3. *Bohr model*: Even if you don't attempt it, you should read through Question 2 on the optional problem set on the next page.

### Required previous knowledge

In addition, students should already be familiar with some ideas from SPM/IGCSE or equivalent Physics and Chemistry courses. In particular, students should have an awareness of the following:

1. *Classical mechanics*: velocity, momentum, Newton's second law, kinetic and potential energy.
2. *Waves*: wavelength, period, amplitude, frequency.
3. *Atomic structure*: protons, neutrons and electrons; shells, electron configuration.

If necessary, students should revise these topics by referring to their school textbooks or online resources. The BBC's *GCSE Bitesize* is a good reference.

**PROBLEM SET**

These are some optional problems for students to attempt as preparation for the tutorial.

**Question 1: Atomic spectra**

Attempt the practice problems given in *2. Atomic spectra* on the reading list.

**Question 2: Classical Bohr model**

The Bohr model describes the hydrogen atom as an electron with negative charge $q_e = -1$ in a circular orbit around a proton of positive charge $q_p = +1$. The potential energy of the electron (see *1. Electrostatic potential energy* on the reading list) is

$$E_p = \alpha\hbar c \frac{q_e q_p}{r} = -\frac{\alpha\hbar c}{r}. \tag{1}$$

Here, $r$ is the distance between the proton and electron, and in non-SI units, Coulomb's constant $k$ can be written as $\alpha\hbar c$. $\alpha$ is called the fine structure constant, $\hbar$ is the reduced Planck constant, and $c$ is the speed of light.

The total energy of the hydrogen atom is the sum of the kinetic and potential energy,

$$E = \frac{1}{2}mv^2 - \frac{\alpha\hbar c}{r}. \tag{2}$$

$m$ is the mass of the electron and $v$ is its velocity.

Using Newton's second law ($F = ma$), it turns out that

$$\frac{\alpha\hbar c}{r^2} = \frac{mv^2}{r}. \tag{3}$$

On the left is the force $F$ from the electrostatic charges, and on the right is just $ma$, where the acceleration $a = v^2/r$ looks funny because we are working with motion in circles rather than straight lines.

By substituting equation (3) into equation (2), show that the energy of the atom is

$$E = -\frac{\alpha\hbar c}{2r}. \tag{4}$$

The negative sign shouldn't alarm you. A negative energy means that the atom is bound together, and that the electron cannot escape.

However, this equation for the energy predicts that the electron can be at any distance $r$ away from the proton. If the atom is in its ground state (has the lowest possible energy), this says that the electron would crash into the proton (the energy is a minimum when $r = 0$). Further, Maxwell's equations for electromagnetism tell us that an electron that's moving in a circle will lose energy. This also suggests an electron will spiral inwards towards the proton.

This cannot be true because obviously atoms exist. In the tutorial, we will see how quantum mechanics resolves this issue.