March 26th, 2015

P340: Homework Assignment No. 4; from Atoms to the Universe

DUE DATE: Fri, April 10th, 2015

Please note that late assignments will not be marked

(1) NUCLEI and STARS:

(i) Nuclear Fission: Explain how nuclear fission works - show how it is that the effective potential energy for a proton in the vicinity of an atomic nucleus is formed, and what the energy levels of the proton are inside the nucleus. Then explain nuclear fission as a tunneling process, and what explain what happens to the proton after it has tunneled.

Now explain the process of induced nuclear fission, and how this leads to chain reactions in both nuclear reactors and atomic bombs

(ii) Nuclear Fusion and Nucleosynthesis: How does Nuclear fusion work? This is also a tunneling process - explain what happens, and where the energy comes from and goes to; and then how it is that in stars, a succession of heavier and heavier nuclei are formed as the star ages. To do this you need to explain why it is that the rate of fusion of H and He nuclei, as well as heavier nuclei, increases extremely rapidly as we increase the temperature.

(iii) White dwarfs and Supernovae: Now lets consider the life cycle of a star. We are going to compare 2 stars - one is the sun, and the other is a supergiant, with an initial mass of 30 solar masses. How do these 2 stars form, and then what happens to each of them as its life goes on, and how do they finish their lives? Describe in as much detail as you can the last part of this process, and what is left afterwards in each case.

(2) ATOMS, MOLECULES, CHEMISTRY, and BIOLOGY:

(i) Energy Levels and transitions: Consider what happens when one brings an electron up near to a proton. Show the energetics of the system, and describe how it is that the electron can lose energy to then form a H atom. Pictures are essential here.

Now, once the atom is formed, the electron can be either in the ground state $|\psi_o\rangle$, with energy E_o, or in excited states $|\psi_n\rangle$, with energies E_n. Suppose the energies of the lowest states, compared to the energy of a free electron, are $E_o = -16eV$, $E_1 = -4eV$, $E_2 = -1.5eV$, and $E_3 = -1.0$ eV, where energies are measured in 'electron volts' (eV). Suppose that the electron initially finds itself in the state $|\psi_3\rangle$. There are actually 4 possible pathways it can then use to get to the ground state - what are these, and what are the energies of the emitted photons for each pathway?

(ii) Atomic and wave-functions: The old dream of Demokritos was finally realized in the quantum theory of atomic and molecular structure. Explain how it is that we get atoms with lots of different "shapes" governed by quantum mechanics. Show, in a diagram, the shapes of some of the 'wave functions' which lead to these shapes, for a simple H atom. Then explain how it is that when we look at heavier atoms, the electrons fill up different 'energy levels' and give different electronic structures for these atoms.

(iii) Molecules and Life: Now explain how it is that by 'sharing' electrons (through tunneling), a set of atoms can lower their total energy. This then leads to chemical bonding. Why do we think of the bonds as having a direction?

The formation of ever more complex structures in Nature relies on the presence of an external energy source, and to a great extent on the process of catalysis. Explain how it is that on interstellar grains, complex molecules form with the help of these 2 mechanisms.

On Earth, once long carbon chain molecules had formed, it became possible for 'vesicles' to form, which allowed the development of cellular structures. Explain what these vesicles are, and how it is that they formed the basis for cell structure.

(3) THE QUANTUM UNIVERSE

(i) The Big Bang: How do we know the Big Bang occurred? Describe the clinching piece of evidence discovered in 1964, and why it provides really strong proof. In order to do this, you need to describe how it was, as the universe cooled, it very abruptly became transparent some 400,000 years after the Big Bang, to release the radiation which we now see as the microwave background.

Current ideas about the Big Bang involve the "inflation mechanism". What is the inflationary theory of the universe, and in what way does tunneling operate in this mechanism?

(ii) Dark energy, Dark matter, and the Formation of the Galaxies: We now know that 96% of the mass of the universe is in the form of dark energy and dark matter. Discuss how these dark components of the universe interacted, early after the Big Bang, with ordinary matter (ie., nucleons, electrons and radiation) to then cause the formation of the galaxies. How did the supermassive galaxy M87 then evolve? What do you think will happen to the objects in our galaxy when it collides with the Andromeda galaxy M31 in roughly 5 billion years?

(iii) Quantum Gravity: The biggest mystery in modern physics is - how can we effect a marriage between quantum mechanics and General Relativity? So far only limited progress has been made, leading to the development of theoretical ideas like Hawking radiation, Unruh radiation, and the field of 'quantum cosmology'.

Write a short essay on this fundamental problem. Imagine you are writing a 400-word article for a newspaper, wherein you want to explain (i) what is Hawking's result of Hawking radiation, what is a 'quantum black hole', and how we can think of Hawking radiation as a kind of tunneling process; and (ii) what is the fundamental problem that Hawking's result is trying to address, and why anyone should care about solving the problem (this last part is important!).