PHYS 340 ("From Atoms to the Universe"): FINAL EXAM

(Tuesday, April 26th, 2011)

12.00 - 2.30 pm, Room Hennings 301

This exam will last 2 hrs and 30 mins. The only material allowed into the exam will be pens, pencils, and erasers. No notes of any kind are permitted, nor any calculators.

There are 2 sections. Students should answer THREE QUESTIONS ONLY from section A, and TWO QUESTIONS ONLY from section B. No extra marks will be given for extra questions answered. The questions in section A should take roughly 15-20 minutes to answer, and the questions in section B roughly 45-50 minutes to answer.

SECTION A

A1: Give a brief discussion of the way in which Galileo's work upset the established Aristotelian view of the universe at the time. You should explain what the Aristotelian view was and how it had arisen, and then explain what observations and ideas of Galileo were so crucial to its overthrow.

A2: Two of the most striking predictions from Einstein's theory of gravitation are (i) black holes, and (ii) an expanding universe.

For each of these two predictions, explain one astronomical observation or set of observations which gives evidence confirming them.

A3: Describe the famous 2-slit experiment for light. Explain what you would see in this experiment, depending on whether one or two slits are open, and on whether the light intensity is weak or strong (this gives a total of 4 different possible cases). You will find diagrams very helpful here - make them clear.

A4: What is the microwave background; and where, precisely, does it come from?

The surface of the sun is at a temperature of 6,000 K, emitting light with maximum intensity around a wavelength of 5,000 $\mathring{A}$ (ie., 5 $\times 10^{-7}$ m). Assuming that the wavelength of maximum intensity varies inversely with the temperature, what is the typical wavelength of the microwave background (whose temperature is roughly 3 K)? And given that the velocity of light $c = 300{,}000$ km/sec, what is the wavelength of microwave background radiation?

A5: The main reason that epicycles were originally invented to describe planetary motion was to explain the apparent retrograde motion of planets in the sky.

Taking the planet Mars as an example, show how the modern picture of planetary motion explains retrograde motion - you should use a picture to explain your argument.

A6: What are Kepler's three laws of motion for the planets? Explain how these laws were an advance over what Copernicus had argued was the correct description of planetary dynamics.

SECTION B

B1: TUNNELING The theme of this question is the physics of tunneling processes in quantum mechanics, and the way in which these are responsible for much of what we see around us.

(i) According to the uncertainty principle, an uncertainty in position of Δx implies an uncertainty in energy $\Delta E \sim \hbar^2/2m(\Delta x)^2$.

Now suppose the energy uncertainty comes from thermal fluctuations (which cause a system to fluctuate between states of different energy). A hydrogen atom, whose mass $m_H \sim 2 \times 10^{-27}$ kg, will at room temperature have a quantum uncertainty in position, coming from its thermal energy, of 1 $\mathring{A}$, ie., $\Delta x \sim 10^{-10}$ m. Using this information, estimate the quantum position uncertainty of a bacterium at the same temperature (so that the energy uncertainty is the same), but whose mass is 10^{12} times greater than the Hydrogen atom.

Then consider a pair of Carbon atoms. Suppose the electrons in the outer shell are confined to a diameter of 2 $\mathring{A}$ in the atom, where their ground state energy is 4 eV (where "eV" signifies an 'electron volt', a measure of energy). They spread over a length of 4 $\mathring{A}$ when the 2 atoms bond. From the uncertainty principle, what is the energy of one electron lowered by doing this? What is the significance of this result for chemistry?

(ii) Nuclear fission is also a tunneling process. Explain how nuclear fission works for a heavy nucleus, using diagrams; you will need to explain the roles of the strong and electrostatic force here.

(iii) Nuclear fusion powers the stars. Explain how nuclear fusion works for a pair of colliding alpha particles (ie., ^{4}He nuclei, each containing 2 protons and 2 neutrons). Then explain how a combination of fusion, radiation, and gravitational processes determine the life cycle of a massive star like Rigel or Deneb, from the time it begins to collapse from a molecular cloud, to its ultimate demise.

(iv) Finally, what is the current theory of how the Big Bang occurred as a tunneling process? Explain both the tunneling event and its aftermath, and the observational evidence we have for it.

B2: GEOMETRY and PHYSICS The focus of this question is our evolving ideas of space, time, and geometry, and their relationship to matter.

(i) Explain briefly how Plato thought of an ideal geometrical form in his theory of Forms. Then consider, as an example, a triangle - what are the defining properties of an ideal "Triangle", in Euclidean geometry, and what is the relationship of this to the triangle we might draw on a piece of paper? Finally, what can you say about the internal angles of a Euclidean Triangle, and if one of these is a right angle, about the area of the triangle?

(ii) According to Newton, space and time were to be thought of as *receptacles* for material objects. Explain in detail Newton's 'rotating bucket' argument, designed to show that space was 'absolute', and could thus be given definite properties in the absence of matter.

(iii) After Einstein we understood that the unified object known as 'spacetime' was itself a field, with its own dynamical properties. Explain what is meant by curved space, and how it is possible to determine whether a space is curved by making measurements of the geometry 'from within' (instead of going outside it). Explain in particular how one would measure the area enclosed by a circle, and the internal angles of a triangle, for the example of a closed 2-dimensional surface (like a balloon or a sphere); and say what results you would get for these quantities. Diagrams are useful here.

Now discuss in what sense we can think of spacetime as a field. To do so, compare the effect that both static and moving electric charges have on the electromagnetic field, with the corresponding effects occurring for the spacetime field in the presence of static or moving masses; and also explain what is the effect of these two fields on charges and masses.

(iv) While there is so far no direct evidence for gravitational waves, the binary pulsar has given very good evidence for their existence. Explain what this evidence is, and how it confirms the theory of gravitational waves.

B3: LIGHT This question is concerned with the nature of light, as understood in particle mechanics, as the excitation of a field, and finally, in quantum mechanics.

(i) Describe an experiment in which one sees simultaneous refraction and reflection of light. You should draw a figure to show how this works and what one would see.

Now describe how Newton explained this result using a particle theory of light; and how Huyghens explained it using a wave theory. Again, pictures are essential.

What were the main objections that each had against the ideas of the other?

(ii) Explain how it is that an electric charge, oscillating in time, can generate an electromagnetic wave. You should explain how the magnetic and electric fields interact with each other to do this.

(iii) Apart form the usual example of 2-slit interference, light shows other interference properties. Polarized light waves can propagate with their directions of magnetic and oscillations fixed. Show a diagram of how this works, and then consider the following situations:

(a) Light polarized vertically can pass through polarised glass whose polarisation plane is also vertical, but not if the plane is horizontal. Explain how this works with reference to the atomic structure of the glass.

(b) Now imagine vertically polarised light passing through 2 sheets of polarised glass. What would you see if their polarisation planes were both vertical, if the first was vertical and the second horizontal, and if the first was vertical and the second oriented at 45^o (halfway between horizontal and vertical)? Explain your answers.

Imagine trying to explain these phenomena by imagining light is a particle that is somehow oscillating perpendicularly to its direction of motion. Try to give such an explanation, for situations (a) and (b) above, and explain where such an explanation would then have to go wrong.

(iv) In quantum mechanics, the interaction between light and matter can be explained simply by referring to emission and absorption of light by atoms and molecules. Consider a molecule in which the energy of the 'ground state' $|0\rangle$, of an electron bound in the molecule, and of the first three electronic excited states $|1\rangle$, $|2\rangle$, $|3\rangle$, are $E_o = -7.5$ eV, $E_1 = -3.5$ eV, $E_2 = -1.5$ eV, $E_3 = -0.5$ eV, respectively, where the energies are measured relative to the lowest energy of an unbound electron, and "eV" refers to an electron volt (a measure of energy).

Show in a picture these 4 energy levels in this system, and how one can get transitions between these 4 states. Now find the energies (measured in electron volts eV) of the six possible transitions between these levels (ignoring the transitions to unbound states). Finally, what would one see if (a) one shone light through a cold gas of these molecules, and (b) one heated up the gas to high temperatures?

B4: CLASSICAL and QUANTUM MECHANICS This question compares and contrasts Newtonian Mechanics and Quantum Mechanics, by looking at a pair of interacting bodies.

(i) Galileo did several experiments to show how forces acted on bodies to change their motion, including rolling balls down inclined planes, and colliding balls on horizontal planes. Explain how one of these worked, describing how Galileo would have done the experiment, how he would have measured lengths, times, and velocities, and what results he would have found.

(ii) Explain Newton's 2nd and 3rd Laws of motion. Then, using the possibility of experiments involving interacting masses, explain how the concept of mass is defined.

Now explain Newton's Law of universal Gravitation. To show how it works, then consider a situation in which two masses orbit each other. Describe how gravitation forces them to orbit one another. How can we determine the ratio of the 2 masses by looking at their orbits?

(iii) An electron and a positron have the same mass but opposite charge. If they are allowed to meet they mutually annihilate to form a pair of photons which are emitted in opposite directions and each with the same helicity (ie., they are both spinning in the same sense - clockwise or anticlockwise - about the direction of propagation of the photon).

What sort of quantum state would we write for the pair of photons after they have been created? Show a picture of the situation before and after they are created.

(iv) We can set up a situation in which one of the photons meets a detector which, if the photon is in a positive helicity state, will, after a time t, electrocute a cat. What is the quantum state of the system of 'cat plus photons' before time t has elapsed, and then after t has elapsed? If we believe quantum mechanics applies to this situation, what does this tell us about what we should take to be 'physically real' in the system of 'cat + photons'?

END of EXAM