TOPICS to be COVERED in 2004 EXAM (P340)

A good guide to the sort of questions that will be on the exam is provided by the previous exams- the same pattern of short and long questions will be maintained. Not all of the topics in the notes and slides will be covered in the exam- the following is a guide to what will be covered. Note that the exam does, amongst other things, try and test how you have in your own mind made the link between different themes in the course. There will be very little in the way of calculations in the exam, and any that are there will involve grade 5-6 level mathematics- and there is no need to remember any numbers, all relevant numbers will be given in the exam.

(1) ANCIENT GREEKS

All the relevant material in the notes. Basic facts about the pre-Socratics; the roots of Plato's ides in those of Parmenides and Heraclitus. The basic ideas of atomists like Democritus- how matter was to be understood in the phiulosophy of the atomists. Basic facts about the philosophy of Pythagoras. The beginnings of Greek mathematical ideas, and why these were important for philosophy. The axiomatic approach of Euclid- how a logical system is constructed. How meaning is given to the objects defined in an axiomatic system.

The ideas of Plato. The contrast between the ideal world of forms, and the world of appearances. The most important thing is to understand the arguments which led him to this picture. A basic understanding of how mathematical forms are understood in this theory, and how these are to some extent a blueprint for the whole theory. An understanding of the weaknesses of the theory of forms. The ideas of Aristotle- his way of avoiding the reliance on an abstract world of forms.

The most important thing to understand in all of this is the basic arguments in the Greek work- the historical details are less important. You will know you have really understood them when you have your own versions of them.

(2) RENAISSANCE

The role of Copernicus, Tycho Brahe, and Kepler in breaking the 'Aristotelian' mold. Contrast between the older Ptolemaic picture and the Keplerian picture of elliptical orbits, etc. Understanding of what Kepler's results were.

Early discussions of how 'science' should be done, and how knowledge of the world is to be gained. The empirical views of Bacon (later taken up by Newton), contrasted with the rationalist views of Descartes, Spinoza, etc. Some understanding of the philosophical arguments of these people, the historical development of their ideas, and how they were linked to the scientific developments occurring at the same time. How philosophers dealt with the question of empirical evidence, and how slowly a view emerged of what ingredients were involved in a successful theory, and how theory related to experiment.

Revolutionary role of Galileo in changing our view of how science should be done, in making the role of experiment central. Some knowledge of the experiments done by Galileo and what he deduced from them- and in what way these contradicted the orthodox views of the time. Also, some knowledge of what astronomical observations Galileo made, how he made them, and what they demonstrated.

The crucial change made by Newton- the explanation of the motion of the planets (Kepler's results) and the dynamics of objects on earth, using his 3 dynamical laws plus the universal law of gravitation. The philosophical and empirical assumptions made by Newton in formulating these (action at a distance, etc). The meaning of quantities like mass, acceleration, and force in Newton's framework.

Ideas about the nature of light in the time of Newton and Huyghens. The wave theory of Huyghens, and the particle theory of Newton. Evidence for each picture, from experiments on reflection and refraction. The role of optical inventions (telescope, microscope, etc) in the development of science.

The most important things in all of this are to understand (i) what is new in the approaches of the scientists in this period- both in their philosophical approach, and in the new picture of the world;(ii) to understand the details of the new mechanics, what principles it was based on and what was the meaning of the new terms introduced; and (iii) to understand the crucial role of experiment and observation in the revolution.

(3) FIELDS

The basic idea of a field (without mathematics). The existence of electric fields, acting in a vacuum (shown by the forces between + and - charges in space) and magnetic fields (shown by experiments on moving charges (electric currents), so that currents act on each other through a vacuum. How magnets have magnetic fields because of atomic currents in them. How changing a magnetic field causes an electric field, and vice-versa. In all of this, only a qualitative understanding is necessary. How it was demonstrated finally that light is just a wave (shown in 1801 by Thomas Young, by demonstrating interference), and how it was later shown (by Hertz) that light is just a wave in the electromagnetic field. Understand that there is a whole spectrum of EM waves, from gamma rays at the high frequency, short wavelength end, to radio waves at the low frequency, long wavelength end of the spectrum.

A qualitative understanding of the idea of non-Euclidean geometry, in which areas, angles, etc, do not obey the usual rules. How one can establish whether one is living in a Euclidean geometry, without 'going outside' the geometry, by making measurements inside it. Some simple historical facts about the developments of General Relativity (equivalence principle, expanding universe, light bending, big bang, etc), and how this has given us our modern picture of the universe. The existence of black holes (in which matter has collapsed under gravity to a point) and of superdense neutron stars. How gravitational fields are equivalent to curved spacetime, and vice-versa.

The most important things to understand here are (i) the basic ideas involved in a field, what is its 'logical status' as an independent physical entity (it is invisible, and can only be detected by its influence when disturbed, but its effects are very widespread); (ii) some of the 'facts' about the EM field, which show its existence; and (iii) an understanding of what it means to probe a 'geometry' from within, and what is the evidence for Einstein's picture.

(4) The QUANTUM REVOLUTION

This is a very large topic, made all the more complex because we are living in the middle of the quantum revolution, making it hard to evaluate. There are essentially 3 main aspects to quantum mechanics, viz., (i) the basic experimental facts about quantum systems; (ii) the conceptual side of quantum mechanics; and (iii) the application of quantum mechanics to explain the real world. Some of the basic features of the quantum world that we were able to cover are as follows:

(i) Experimental Features:

The wave-particle duality, as shown in, eg., the 2-slit experiment, using either light (photons) or elctrons. A clear discussion of exactly what is seen in this experiment, under different conditions. Interference experiments with matter (eg., electrons) show that, just like light, it shows interference and diffraction, ie., has wavelike properties. One should understand why in classical physics this is impossible- why a particle cannot behave like a wave.

The existence of spin, which is 'quantized', ie., which can only come in discrete values. The elctron spin can only take 2 values, viz., 'up' and 'down' along some direction. This is shown in experiments like the Stern-Gerlach experiment.

The existence of *discrete* bound quantum states (ie., a set of states with well-defined energies, separated by energy gaps), which are confined in some region of space, bound in a potential well. For example, the discrete electronic states which exist around the nucleus in an atom.

Quantum tunneling- as shown in, for example, the escape of particles from the strong binding forces holding the nucleus together, ie., out of the nuclear potential well.

The wavelength λ of a quantum wave, and how it is related to the momentum $p = mv$ (where v is the velocity), by $\lambda = h/p$. Thus fast particles have short wavelength. The frequency ν of oscillation of a quantum wave, and how it is related to the energy E of the system, by $E = h\nu$. Thus rapidly oscillating waves have high energy.

(ii) Conceptual Aspects of Quantum Mechanics

Probability amplitudes- the whole idea that the quantum 'wave function' does not represent anything more than a *probability* that a system will be found in a state- and that this is *all there is.* How this works in a simple example like the 2-slit experiment- in which the wave amplitude merely tells us the *probability* that the photon or electron will be found at some point.

The uncertainty principle- a fact about waves. If we try and confine the wave to a small volume of space, then its momentum (and hence velocity and energy) become very uncertain- in the same way, if one has a wave with a very precise wavelength (and hence a precisely defined momentum and velocity) then it will have a very uncertain position, ie., it will be spread over a very large region of space.

Another fact about waves- that they spread out wherever they can. This is embodied in the Feynman idea that all possible paths will be followed by the probability waves, and the final result is given by summing all of the possibilities. One can see this in experiments by passing particles through multiple slit systems. Another way of understanding this is:

The basic idea of *superposition of states*; that if we add together 2 quantum states we get another one. Understand this in a few simple cases- adding 2 waves together to get a superposed wave pattern (eg., in the 2 slit experiment);

or adding together 2 spin states to get a 3rd one. How this leads to very counterintuitive results- for example, that a state which is a superposition of a particle in one place and a particle in another is legitimate.

(iii) Applications of quantum mechanics

We did not cover many of the applications at the end of the notes. This material is not important for the conceptual or philosophical side of quantum mechanics, but is interesting nonetheless. The most important things covered in detail were:

The structure of the atom: The energy levels of the hydrogen atom, which are the energies of the bound states of the electron in the attractive potential well of the nucleus. How the electron can make transitions from one level to another by either emitting or absorbing a photon of the right energy. The way in which the absorption of light by atoms in a gas gives us spectral lines (in, eg., the spectra of stars), and the historical role this played in the discovery of quantum mechanics. The 'shape' of the electron states in an atom, with 'lobes' pointing in particular directions. How this leads to chemical bonds, by sharing of electrons between atoms, and the huge variety of molecules and crystal structures in nature, including biological molecules.

The photoelectric effect- how photons of sufficiently high energy kick electrons out of a metal. The role this played in the discovery of quantum mechanics, via Einstein's postulation of photons to explain it.

The nature of the atomic nucleus- Rutherford's discovery of the nucleus by the scattering of fast particles, and our present understanding of nucleons (protons and neutrons) as bound together by the short-ranged 'strong' force to form the nucleus. Radioactivity, discovered by the Curies, explained by the tunneling of nucleons out of the potential well caused by the strong force. Nuclear fission caused by break up of heavy nuclei, fusion by the fusing of light nuclei, fission induced by neutrons, chain reactions, etc. How this powers the stars. How when stars run out of fuel, they either explode as supernovae if they are massive (then collapsing to a neutron star or a black hole), or slowly cool to white dwarves if they are light (like the sun).

The range of sizes in the universe, from the very small (sub-nuclear) level, to the very large scale of the universe. Some understanding of how we can observe phenomena at these different size scales.

NB: Topics that will NOT be covered include entanglement, quantum measurements, quantum philosophy, and the details of the early universe, superfluids and superconductors, and macroscopic quantum phenomena.