Teaching ideas for Topic 12: Quantum and nuclear physics (HL)

A lot of the material in this topic is new to the course. The main aim of this topic is to give students a more rigorous understanding of the way in which quantum physics answers questions about the micro-scale behaviour of electrons, nuclei and atoms. The wave–particle duality concept is explored through the photoelectric effect (the idea that light behaves like particles) and the diffraction of electrons (the idea that particles behave like waves.) Explaining these two phenomena has been possible with the use of the wave function, a difficult idea for students to deal with because of the many years they have already spent conditioning their thinking into classical ways.

Some useful points to consider are:

- It is advisable not to attempt to teach a university level undergraduate course in quantum mechanics. Although there is little or no exemplar material available (at the time of writing) to suggest to teachers the level of understanding necessary, and hence to answer exam questions, it is thought unlikely that exam questions will explore concepts such as the Schrodinger wave function in more than a qualitative and simple way.
- The nature of radioactive beta decay, as a process that is the result of the weak interaction, is something that some teachers may have introduced in Topic **7**: Atomic, nuclear and particle physics. That it gives rise to the existence of the neutrino (and anti-neutrino) is an important indication of how theoretical models have predicted the existence of other hitherto unobserved particles. In the case of alpha decay, the accompanying of gamma radiation is a good way of helping to explain the discrete nature of the energy levels of a nucleus, and provides another example of how an understanding of one aspect of physics (in this case, the energy levels of electrons in atoms) can help with the understanding of another, similar aspect.
- The mathematical treatment of radioactive decay needs to be done here if it has not already been covered in Topic **7**. The exponential function plays the central role in this, and students should be able to derive for themselves the link between the decay constant (perhaps best thought of as the probability that a given nucleus will decay in the next second, although even this definition is not perfect!) and the half-life. This will also allow students to make calculations on the activity of a sample of radioactive material for any time, not just an integer number of half-lives. It is always worth stressing that the decay constant for a given nuclide is a constant and is not affected by any known other processes.

Ideas for teaching the topic

- A good way to begin this topic is to investigate the photoelectric effect. As the best example of showing that light behaves like particles (or at least localised portions of energy), this is ideal for getting students to accept the quantised nature of energy.
- After the photoelectric effect, and to provide balance, it is a good idea to explore the wave nature of particles. The ideas proposed by de Broglie allow us to give particles an effective wavelength. Students should remember that a phenomenon associated with wave behaviour is interference. So the next thing to show students is the diffraction of electrons by a thin graphite crystal.
- These two ideas together provide the ‘yin and yang’ of describing the behaviour of matter. It is, perhaps, a good time to discuss with students whether it is possible to explain both of these phenomena with only one model or theory. This links nicely with the Nature of science and the state of physics at the moment.
- The Bohr model of the atom resulted from the observations of Lord Rutherford. Although the model has some excellent features (and students need to know what these are), it is worth remembering that it does have some features that have been shown to be inconsistent with

modern thinking. It is also a model that works only for hydrogen. Nonetheless, it is a good starting point for students and is worth exploring in detail. The $1/n^2$ relationship for the electron energy levels, for example, will help students to draw an accurate diagram of energy levels in a hydrogen atom and help them to calculate the photon energies for absorption and for emission.

- This can now be extended by thinking about the electrons as existing inside the atom as standing waves. This approach is powerful, because it can be used to show that electrons cannot exist inside the nucleus (because the wavelength of the standing wave is too small). It is also a good way of showing that, during beta-minus decay, the neutron does not emit an electron that had been inside it!
- In a similar way, it may be good to get students to use the equations that Heisenberg has given us about the uncertainty in energy, momentum, position and time of particles to make simple calculations on their range or lifetime. This is also nicely applicable to sub-nuclear particles and will explain why the strong nuclear force, for example, has a range that is of the order of magnitude of the size of a nucleus.
- When dealing with the concept of a wave function, it is important for students to understand that the square of the amplitude of the wave function is a measure of the probability of finding it in a given place and time. This is, perhaps, easiest to deal with at first by considering the Young double-slit experiment and is nicely explained by Jim Al-Khalili: http://www.youtube.com/watch?v=A9tKncAdlHQ
- Subtopic **12.2**: Nuclear physics requires students to look more closely at the nucleus, its energy levels and the mathematical treatment of radioactive decay. Although this is often done by teachers as a mathematical exercise, it is possible to set up a spreadsheet to model the activity of a sample of radioactive material and allow students to vary the decay constant to see what happens to the resulting half-life.
- The equation that links the nucleon number with the radius of the nucleus can be explored to show that the sizes of nuclear radii do not really vary very much (the cube root of 230 is only just over 6) compared to the mass of the nuclei, and that nuclei have approximately the same densities – this density is what one would expect in a neutron star!

Practical activities

- The photoelectric effect can be demonstrated with a gold-leaf electroscope, a high-tension power pack, a light bulb and an ultraviolet lamp. Charge the top of the electroscope up negatively using the power pack. Then watch what happens when you shine light on it. Light from the normal light bulb will do nothing, whereas when the ultraviolet lamp is used the electroscope will quickly become discharged. With their knowledge of the energy associated with electromagnetic waves of differing frequencies, students should be able to arrive at the idea that the energy from visible light is insufficient to release electrons from the metal surface, and, perhaps more importantly, even when the lamp is left on for a long time, electrons in the metal surface still do not absorb energy from the light in order to escape from the surface.

  This will strengthen the idea that energy is absorbed in quantised amounts and that these amounts depend on the frequency of the incident radiation. This links directly with aim 6 of the group 4 aims. A conservation of energy method will show students that the photon energy is transferred into the work function for the electrons (the energy required for an electron to break free of the metal surface) plus the kinetic energy that the photoelectron acquires. This is nicely shown on the following website: http://www.nationalstemcentre.org.uk/elibrary/resource/4103/photoelectric-effect

- The complementary demonstration to the photoelectric effect for students is the diffraction of electrons. This is the best example of particles behaving like waves. You will need a specialist piece of equipment for this: an electron gun housed within an evacuated glass container that can 'fire' electrons at a piece of graphite crystal. A fluorescent screen inside the glass container will show where the electrons hit the container sides. A circular diffraction pattern will be observed, and students should recognise, from their work in Topic **4**: Waves and Topic **9**: Wave phenomena, that the electrons must be behaving like waves in order for them to produce interference maxima and minima. Changing the accelerating voltage of the electrons will give the electrons more kinetic energy and so their de Broglie wavelength will decrease, producing a diffraction pattern that is smaller. This also links with aim 6 of the group 4 aims.
- If you do not have the equipment to demonstrate the diffraction of electrons through a crystal lattice it is advisable to use a website that shows this clearly, such as: http://www.schoolphysics.co.uk/age16-19/Wave%20properties/Wave%20properties/text/Electron_diffraction/index.html and the CERN page, more suitable for teachers than students: https://project-physicsteaching.web.cern.ch/project-physicsteaching/english/experiments/electron-diffraction-tube.pdf
- The mathematical treatment of radioactive decay can be reinforced using a spreadsheet to model the activity of a sample over a period of time. This can provide an empirical way for students to arrive at the relationship between the decay constant and the half-life. If teachers have used the dice analogy for radioactive decay, as suggested in Topic **7**, changing the decay constant can be done by either allowing dice to have 'decayed' if they show two or more numbers (say, a six or a five) or by using multi-hedral dice. The changed decay constant will produce a changed half-life.
- Please see the available practical notes for further ideas.

ICT

- The two demonstrations, photoelectric effect and electron diffraction, can be shown using pages from internet sites or from YouTube videos. Examples of these are:

  http://physics.info/photoelectric/

  http://www.nationalstemcentre.org.uk/elibrary/resource/4103/photoelectric-effect

  http://www.schoolphysics.co.uk/age16-19/Wave%20properties/Wave%20properties/text/Electron_diffraction/index.html

  https://project-physicsteaching.web.cern.ch/project-physicsteaching/english/experiments/electron-diffraction-tube.pdf
- The idea of a wave function and its link to the probability of finding the wave is nicely explained at: http://www.youtube.com/watch?v=A9tKncAdlHQ
- A spreadsheet can be used to model the activity of a radioactive substance, as described above.

Common problems

- Students can often confuse their ideas about the photoelectric effect with their ideas about electron energy level transitions. Where possible, it is a good idea to keep these two sections separate; students should have already covered the ideas of electrons moving between energy levels causing absorption and spontaneous emission.
- Students will find the use of equations such as $E = hf$ (for electromagnetic waves) and $p = h/\lambda$ (for particles) easily confused. It is important that students can identify the right equations to use, so it is a good idea to spend some time practising this.

- It is worth looking carefully at beta-minus decay and teaching students that although we know the beta-minus particle is a fast-moving electron, it had not existed inside the neutron before the decay occurred. Students can misunderstand this, thinking that the electron was always there inside the neutron, balancing out the positive charge from a proton that was also there.

Theory of knowledge (TOK)

- Explaining the photoelectric effect requires a particle model for electromagnetic waves. Explaining the diffraction of electrons requires a wave model for particles. Both of these models require us to change the way we think about physical phenomena. How important is it for scientists (or, indeed, any other researchers and thinkers) to be flexible in the way they think? How has a lack of flexibility held back our understanding in different areas of our learning? And, how important is our imagination in allowing us to search for new ways of thinking about things? (Einstein is quoted to have said that imagination was more important than knowledge.)
- The search for the Higgs boson is a good example of how a model, obtained from theoretical considerations, predicts the existence of something. But, in searching for this Higgs boson, are scientists led, or misled, by their need to find it? This aspect of looking for something has applications to other areas of knowledge. To what extent, therefore, should we be aware, or concerned, that our desire to find something will find it, even if what we actually find is not the real thing? And when we do observe something that we think is what we were looking for, how can we be sure that we have found it?
- When Schrodinger first proposed the idea of a wave function, there was no clear explanation of exactly what it showed and how it related to observations. Only later, did Born, Heisenberg and Bohr relate the Schrodinger wave equation to a probability wave function (the so-called Copenhagen interpretation of quantum mechanics.) Even to a physicist, some of these ideas are conceptually demanding; to a non-physicist they are worse than speaking in an unintelligible language, because even if the words can be understood, their meaning is too esoteric to make sense. How do scientists decide when not to try to communicate their learning to non-specialists? Is there a moral obligation for scientists to share their learning with others?

International-mindedness

- The collaboration of several distinguished physicists in the 1920s and 1930s showed that in order to make big advances in understanding it is sometimes necessary to bring together different people from different countries to each contribute their thinking towards a greater good. Differences in culture, religion and educational programmes produce differences in the way that people think, and it is the brain-storming between collections of different people that often produces amazing conclusions.