Teaching ideas for Topic 7: Atomic, nuclear and particle physics

This topic contains a lot of factual information that students need to become familiar and comfortable with. For students following the HL course, teachers may find that the ideas coming from quantum physics in Subtopic **12.1**: The interaction of matter with radiation about the discrete nature of energy in atoms fits in well with the early ideas in Subtopic **7.1**: Discrete energy and radioactivity, whereas Subtopic **12.2**: Nuclear physics fits in with Subtopic **7.2**: Nuclear reactions.

Some useful points to consider are:

- Teachers may find that beginning with the relatively large scale of the physics of atoms and moving to gradually smaller and smaller scales is a good way of working through this topic.
- Students should be aware of the scale of sizes in this topic, so that they can compare them to other sizes of physical phenomena they have met in other areas of the course. For example, the typical size of an atom is about 10^{-10} m, which is comparable to the wavelength of an X-ray (and therefore explains why X-rays can penetrate through matter).
- The mathematical descriptions of radioactive decay are helpful to students, especially the nature of exponential functions, but these are treated only simply in this topic. It is not until the additional HL Topic **12**: Quantum and nuclear physics that students are required to demonstrate an ability to deal with radioactive decay as a mathematical exercise.
- The work on particle physics in Subtopic **7.3**: The structure of matter will be new to most students. New words and some difficult descriptions and definitions will require some time before students will feel comfortable with them. It is tempting for teachers to feel that this section of the topic is more suited to undergraduate studies. Perhaps the introduction of this topic into the core of the course will start to make students more familiar with the unusual language and up-to-date ideas that help to show the dynamic nature of learning in physics.

Ideas for teaching the topic

- Teachers may find it a good idea to begin this topic by thinking about the structure of atoms. For many students, this will be revision. However, there will be some aspects of this part of the topic that are new, and it is important for students to be able to see the observational evidence that allows modern scientists to picture the atom in the way they do. Introducing the idea of electron energy levels may be something that teachers have already hinted at in the work on fields (Topic **5**: Electricity and magnetism and additional HL Topic **10**: Fields), but it is a really good way to start showing that, at the atomic level, energy is quantised.
- When students are ready to move to a smaller scale (it is a good idea for students to think about the typical size of nuclei to be 10^{-15} m – that is, a hundred-thousandth of the size of an atom), it may be a good time to introduce the ideas of why nuclei can be unstable.
- As it is unlikely that students will have experimented with radioactive sources before, it is worth stressing the dangers of radioactive materials and making sure that students follow sensible, health-conscious procedures during their experiments.
- In the same way that Lucretius argued his way to the concept of an atom as an indivisible object, students might like to use a similar argument to see where they end up. This is a good way of introducing the concept of a fundamental particle.
- The ‘rules’ that explain the conservation laws, charge, baryon number, lepton number and strangeness, are important ideas that students must learn. It is worth looking at lots of examples of decay equations and other interactions between particles to help students see how to apply these laws. As interactions between particles are usually the result of forces, the nature of the four forces is an important idea for students to learn. It is also worth pointing out

that the conservation of strangeness does not apply to the weak force and that the involvement of the weak force requires a change in quark flavour.

- Simple Feynman diagrams can be fairly easy for students to understand. Their ability to be rotated, and what this means, is an advanced idea best kept, if at all, for the most able students. The role of exchange particles as the facilitators (sometimes called mediators) of force can be revised nicely with Feynman diagrams.

Practical activities

- The discrete nature of electron energy levels can be nicely demonstrated using some gas discharge tubes and a diffraction grating. The observed emission spectrum from hydrogen should show three easily visible emission lines (the red hydrogen alpha line, the brightest of these, can then be linked to the transition of an electron from energy level $n = 3$ to energy level $n = 2$, as described in the Balmer series. Students can then get a feel for any other emission lines, from other gases, by comparing their wavelengths to that of the hydrogen alpha line. That some atoms have many emission lines in their spectrum should lead students to understanding that those atoms must have complicated electron energy level diagrams allowing many different transitions to occur.
- A cone-like shape, with a profile that models the inverse-square law of repulsion (this has been referred to as a ‘witch’s hat’ in the past) between like-charged objects can be used to model the nucleus in the scattering of alpha particles from gold nuclei, as in the classic Geiger and Marsden experiment supervised by Lord Rutherford. If small ball-bearings or similar are used to represent the alpha particles and rolled towards the cone, their paths can be followed. (If you use some black paper and roll the balls in talcum powder before you roll them, their paths are easily observed.) This links clearly with aim 6 of the group 4 aims.
- Students can produce a graph of all of the nuclides of all the elements, showing the neutron number of the nucleus on the *y*-axis and the proton number of the nucleus on the *x*-axis. This may be done with the use of a database (and students can find such databases on the internet from university or school/college websites, or they can compile their own from their research). Identifying the line of stability and the various regions on the graph that correspond to the decay mode of unstable nuclei is a useful exercise for students to do.
- With a set of radioactive sources and a Geiger–Müller tube and counter, the physics of alpha, beta and gamma decay can be investigated. Investigations involving the relative penetrative properties of the three emissions will produce highly reliable results. Students may also find it interesting to note background radiation counts and what factors might affect this. A number of everyday items will show levels of radioactivity that might surprise some students: bananas, Brazil nuts and fresh prawns, for example, all contain potassium, and the radioactive isotope of this will produce a count that is more than the usual background count. Old-fashioned gas mantles for camping stoves (still available in outdoor and do-it-yourself shops) and Fiesta dinnerware from before 1985 are also mildly radioactive. This links nicely with aims 6, 8 and 9 of the group 4 aims.
- If you are lucky enough to have the specialist kit for observing the radioactive decay of protactinium, students will be able to fulfil the required experiment, 7.1, to measure the half-life experimentally of a radioactive source (see ‘Applications and skills’ section of the IB Physics guide). Modern protactinium generators can be purchased from science equipment suppliers and come complete with everything you need to connect them to a data logger with a voltage input. If you do not have this equipment then it is easy to simulate the radioactive decay of a substance using lots of regular six-sided dice to represent the nuclei of unstable atoms. Use about 300 dice and get students to shake them and see what numbers they give. For each die that has, say a 6, this can represent the decay of this nucleus. These dice are then removed from the simulation. Successive shakes of the dice will make the total number of dice remaining become smaller. If students plot how many dice there are remaining against how

many times they have shaken the dice, they will get a decay curve, from which the 'half-life' of the decay can be found.

- Students need to be able to perform calculations on mass defect and nuclear binding energy. This may be a good use for a database, from which students can calculate the mass defect for a nucleus and from that the binding energy per nucleon. The classic graph showing the binding energy per nucleon plotted against nucleon number will illustrate the regions in which energy can be obtained from the nucleus by the processes of nuclear fission and nuclear fusion. This is helpful to lead on to Topic **8**: Energy production.
- If students are familiar with the 'rules' that govern which quarks can combine together to form hadrons, it is a fun exercise to get students to investigate all possible combinations of quarks and then see if their combinations have a name. If you make lots of coloured circles out of card or laminated paper and cut the circles into thirds (for baryons) or halves (for mesons), students can put these together to form particles.
- Please see the available practical notes for further ideas.

ICT

- There are a number of simulations of Lord Rutherford's classic alpha particle scattering experiment available from various scientific websites. These can be used successfully to revise the experimental observations upon which our model of what an atom is like is based.
- Modelling the decay of radioactive nuclei can be done very successfully with the use of a random number generator that many spreadsheets will have as a standard function.
- A data logger, or virtual oscilloscope program on a PC, can be used with some protactinium generators to measure the activity of protactinium as a function of time, allowing students to measure the half-life of protactinium.
- A database can be used to allow students to draw the graph of binding energy per nucleon against nucleon number.
- Students should be aware of the need for high-specification computing facilities and the ability to record huge amounts of data in particle physics research. This links with aim 4 of the group 4 aims.

Common problems

- Converting between different units used to describe energy is something that students often get confused with. For example, calculations involving the equation $E = mc^2$ should use mass in kilogrammes to produce energy in joules. Other mass units used in nuclear physics are unified atomic mass units, u, and energy units are often expressed in electronvolts, eV, or Mega-electronvolts, MeV. Students may become familiar with the conversion that $1\text{u} \approx 931\ \text{MeV c}^{-2}$.
- The various families of particles and the intersection of these with each other cause some confusion for students. Producing a large poster with these families of particles shown is a useful exercise in helping students to find their way around the 'zoo' of subatomic particles.

Theory of knowledge (TOK)

- Some of the early discoveries in atomic and nuclear physics might have been described as serendipitous (the fortunate result of chance). But is a careful observation (as one might expect from a trained scientist) followed by the curiosity to investigate something further not the real reason for the scientific advances that have occurred? To what extent can a scientist trust his/her 'gut feelings' or intuition when making an observation and noticing something that is unexpected? What other examples are there in physics (or, indeed, in any other area of knowledge) of an unexpected observation leading to a new discovery or a paradigm-type shift in our knowledge?

- Another obvious paradigm shift was the understanding that mass and energy are two aspects of what seems to be the same thing. What other physical phenomena might turn out to be different aspects of the same thing? The grand unified theory (GUT) has so far been able to link the standard model with our ideas of quantum mechanics (excluding gravity as a force), but this has now been surpassed by the theory of everything (TOE): a hope that we will, one day, be able to link all of the various topics within physics together into one all-encompassing explanatory model. Will this mean the end of scientific research?
- Our current understanding is that an electron and a quark are fundamental particles. Is this because we do not have the ability to make an observation on these particles at such a small scale? How has our ability to make better and better observations of physical phenomena helped us to improve our knowledge of the natural world?
- It has been a feature of particle physics research that theoretical physicists have proposed the existence of various particles, and it has been the responsibility of experimental physicists to design experiments that enable such particles to be observed. (The neutrino, for example, had been proposed by Pauli in 1930, but it was not until 1956 that the neutrino was first observed.) The existence of the Higgs boson was proposed long before it had been observed by the work at the European Organization for Nuclear Research (CERN) using the Large Hadron Collider. Is this way of advancing our knowledge different to the usual deductive nature of science? Does this mean that science is changing in the way it progresses?

International-mindedness

- Since the invention of nuclear warheads as a weapon of mass destruction, there has been considerable political collaboration to prevent possible global-scale disasters that might occur should nuclear war become a reality.
- CERN, as a truly international collaboration of scientists, is an excellent example that shows the way that modern large-scale research requires huge amounts of funding, more funding than one country on its own is likely to be willing to make available. Without the agreement of governments in many countries, such research would not be possible.

