Optimising Student Engagement and Results in the Quanta to Quarks Option

Dr Mark Butler
Gosford High School

1) Introduction

The development of the quantum theory in the early 20th Century and the revolution in thinking it caused makes for an exciting unit of study, particularly when it is taught in its historical context. The debates, the wrong turns and the wonderful personalities of the many gifted physicists involved in the early development of quantum theory can be used to engage, excite and delight students.

In this workshop we will look at some of the syllabus outcomes, some of the interesting 'dot points' in the syllabus, mandatory and non-mandatory practical work, preparing students for this option in the HSC and hopefully share some resources and ideas.

2) Key Skills Outcomes in Physics

We have been told over and over again by the Board of Studies that the course outcomes will be examined in the HSC via the content expressed in the 'dot points'. Some teachers have made the mistake of concentrating their teaching on the 'dot points' and all but ignoring the outcomes. It is very important to base teaching on the outcomes and to familiarise students with the terminology used in the outcomes. For example consider the following skills outcomes:

H11:

- **a)** **Dependent** and **independent** variables.
- **b)** **Keeping other variables constant**. (Use of a control.)
- **c)** Ensuring collected data is **valid**.
- **d)** Ensuring collected data is **reliable**.
- **e)** **Repetition.**
- **f)** Carry out a **risk assessment** and address potential hazards.
- **g)** **Destructive** and **non-destructive testing.**

H12:

- **a)** Minimise hazards and wastage of resources, dispose of waste materials appropriately.
- **b)** Use **data loggers** and **sensors.**
- **c)** Access **popular science journals, digital data** and **internet.**
- **d)** Use **computer-assisted analysis.**
- **e)** Identify practising **male and female Australian scientists** and the area of their research interest.
- **f)** Assess **accuracy** of measurements and calculations.
- **g)** Assess **validity** of first hand and secondary information.
- **h)** Assess **reliability** of first hand and secondary information, by referring to a variety of sources.
- **i)** Assess **accuracy** of information in the mass media by referring to scientific journals.

H13

- **a)** Use of pictorial presentations (eg. **Diagrams**)
- **b)** Use of **graphs**, **curves of best fit**.

H14

- **a)** **Justify inferences** and conclusions.
- **b)** Use **models** to **make predictions**.
- **c)** Use **cause** and **effect** to explain phenomena.
- **d)** **Evaluate appropriateness** of different strategies of investigation.

3) Some Important Definitions

The Board definitions are very brief and the following expanded definitions may be of use:

a) ACCURACY: ***Exactness or conformity to truth.***

Texts refer to accuracy in two ways:
a) Accuracy of a result or experimental procedure can refer to the percentage difference between the experimental result and the accepted value. The stated uncertainty in an experimental result should always be greater than this percentage accuracy.
b) Accuracy is also associated with the inherent uncertainty in a measurement. We can express the **accuracy of a measurement** explicitly by stating the estimated uncertainty or implicitly by the number of significant figures given. For example, we can measure a small distance with poor accuracy using a metre rule, or with much greater accuracy using a micrometer. Accurate measurements do not ensure an experiment is valid or reliable. For example consider an experiment for finding g in which the time for a piece of paper to fall once to the floor is measured very accurately. Clearly this experiment would not be valid or reliable (unless it was carried out in vacuum).

b) RELIABILITY: ***Trustworthy, dependable***.

In terms of first hand investigations the board seems to define reliability as repeatability or consistency. If an experiment is repeated many times it will give identical results if it is reliable. In terms of second hand sources reliability refers to how trustworthy the source is. For example the NASA web site would be a more reliable source than a private web page. (This is not to say that all the data on the site is valid.) The reliability of a site can be assessed by comparing it to several other sites/sources.

c) VALIDITY*:* ***Derived correctly from premises already accepted, sound, supported by actual fact.***

A valid experiment is one that fairly tests the hypothesis. In a valid experiment all variables are kept constant apart from those being investigated, all systematic errors have been eliminated and random errors are reduced by taking the mean of multiple measurements. An experiment could produce reliable results but be invalid (for example Millikan consistently got the wrong value for the charge of the electron because he was working with the wrong coefficient of viscosity for air). An unreliable experiment must be inaccurate, and invalid as a valid scientific experiment would produce reliable results in multiple trials.

4) Clarifying some of the Syllabus Content

Even after the recent changes to the syllabus, some of the 'dot points' are still ambiguous or poorly covered in some texts. For example:

- ***Analyse the significance of the hydrogen spectrum to the development of Bohr's model of the atom.***

Planck first introduced the concept of discrete energy levels in fundamental oscillators (molecules). Planck also proposed that the emission and absorption of radiation was associated with a transition between these discrete energy levels and that the frequency of the radiation was related to the energy difference between the level by $E = hf$. Plank however believed light was emitted and absorbed by the oscillators as electromagnetic waves, as Maxwell had described.

Bohr was the first to extend the idea of discrete energy levels to electrons in atoms. When Bohr did this work in 1913 only the Balmer and Paschen series were known (the UV Lyman series was found in 1916, Bracket in 1922 and Pfund in 1924) and when Bohr worked through his theory he would have sought an energy difference equation that would have looked similar to the Rydberg equation. One suspects he worked backwards from the Rydberg equation and in particular from the experimentally determined Rydberg constant to determine the size of the electron's orbital angular momentum quanta (ie $h/2\pi$). The fact that his theoretical model gave a value within 1% of Rydberg's constant is perhaps then not so remarkable. What was remarkable about the model was that it showed how quantum principles could be used to derive Rydberg's equation. To derive Rydberg's empirical relationship from a theoretical model of the atom was a great triumph for the new quantum approach.

- ***Process and present diagrammatic information to illustrate Bohr's explanation of the Balmer series.***

Clearly simple energy level diagrams and schematic diagrams of the transition of electrons between energy levels with the absorption or emission of photons are in the syllabus. Students should realise that the energy difference between levels decreases at higher levels and relate this to why the spectral series of hydrogen each approach a limiting value. They should also be aware that the ionisation of hydrogen refers to an electron transition to the $n = \infty$ energy level and that the probability of transitions between levels (and their population distribution) determines the relative intensity of spectral lines.

- ***Discuss Plank's contribution to the concept of quantised energy.***

You will recall that black bodies (perfect absorbers/emitters) emitted an unexpectedly small fraction of radiation at high frequencies. Classical wave theory predicted that most of the radiation should have been emitted at high frequencies and it was this 'ultraviolet catastrophe' that led to Plank to suggest that energy might be quantised.

Planck was the first to recognise the importance of quantised energy levels in harmonic oscillators (molecules) even though he tended to think it was a mathematical trick rather than a reflection of physical reality.

Planck made two radical assumptions to explain the distribution of radiation emitted by black bodies:

1) Harmonic oscillators (molecules) can only have discrete units of energy $E_n = nE_o$, where $E_o = hf_o$.
2) Energy is radiated by harmonic oscillators only when they change from one discrete energy level to another and the frequency of the emitted radiation is related to the energy difference by $E = hf$.

Note however that Planck still believed light was a classical electromagnetic wave created by oscillating charges. It was Einstein's explanation of the photoelectric effect that introduced the spatial and energy quantisation of electromagnetic radiation (ie photons).

Students often have trouble understanding how Planck's assumptions helped him derive the black body radiation curves, because they think that high frequency (UV) radiation would be produced just as readily as low frequency (IR) radiation if oscillators could change between any energy levels. This is because high school texts usually neglect to mention that the number of oscillators with high energies is much smaller than the number of oscillators with low energies (ie Boltzmann's law $N_n = N_o e^{-nhf/KT}$). Hence the number of oscillators making a transition from n = 20 to n = 0 and releasing high energy, high frequency photons is tiny compared to the number of low energy photons emitted from n = 4 to n = 0 transitions. This is simply because there are far fewer oscillators with an energy of n = 20 than with n = 4.

Planck's work was clearly the foundation of Bohr's atomic model, which also used the transition between quantised energy levels in the absorption and emission of radiation.

- ***Gather, process, analyse and present information and use available evidence to assess the contribution by Heisenberg and Pauli to the development of atomic theory.***

Strangely Pauli and Heisenberg only appear in the 'students:' column and why other equally important quantum pioneers like Schrodinger and Dirac are not included is anyone's guess.

After my students research Heisenberg I talk to them about the **uncertainty principle** and give them some simple examples to illustrate how it operates. I also talk to them about how Heisenberg used **matrix mechanics** to generalise Bohr's 'quasi-quantum' model to a full quantum theory. I then discuss Schrodinger's **wave mechanics** in general terms and explain how the two approaches were later shown to be simply different mathematical techniques for solving the same problem.

Pauli made many contributions, but I concentrate on his **exclusion principal** and his contribution to the **neutrino** in class and suggest students research some of his other contributions independently.

- ***Describe some medical and industrial applications of radioactivity cf Identify data sources, and gather, process and analyse information to describe the use of a named isotope in medicine, agriculture and engineering.***

Notice that the syllabus mentions **medical and industrial** in the 'Students learn to:' column and **medical, agricultural and engineering** in the 'Students:' column.

- ***Discuss the key features and components of the standard model of matter, including quarks and leptons.***

Strangely this dot point omits the third type of fundamental particle, the boson.

As the standard model is very complex an eight-mark question on this dot point would produce some 'interesting' responses.

Teachers are often concerned about how far to go here. Some key features of the standard model include:

- The model combines electroweak theory and quantum chromodynamics.
- Forces are moderated by particles called bosons and all other particles are called fermions.
- Fermions are divided into leptons that are not affected by the strong nuclear force and hadrons that are affected by the strong nuclear force.
- Hadrons are made up from more fundamental particles called quarks.
- There are three types of fundamental particles, leptons, quarks and bosons. There are six types of leptons and six types of quarks, plus their antiparticles.
- The mass of bosons is related to the range over which their related forces operate. (This can be shown using the Heisenberg's uncertainty principle.)
- Hadrons are made up from quarks.

Because the syllabus only mentions quarks and leptons, HSC questions will probably not ask directly about bosons. The specimen HSC paper and 2003 HSC exam asked about the quarks that make up protons and neutrons and I suspect that only 'up' and 'down' quarks (and their charges) will ever be examined. As for leptons, students probably only have to know about electrons and electron neutrinos. I also teach my students about anti-matter, but I doubt that the HSC would ask about antiparticles directly.

- ***Discuss Fermi's initial experimental observation of nuclear fission.***

Some ambiguity here because Fermi and his co-workers are believed to have produced fission experimentally when he bombarded uranium with neutrons in Rome in 1934, but they certainly did not realise that they had split the uranium atom. They did notice several different beta activities in the products but assumed they were due to neutron absorption. Fermi received the Nobel Prize for his work on neutron absorption in 1938 including the production of transuranic elements. The unexpected emission from uranium after it was bombarded with neutrons was simply called the 'uranium problem' and could not be explained at the time.

Fermi experimentally observed fission when he constructed the world's first fission reactor in 1942, but it was not the first observation of nuclear fission.

So even though he did not recognise it as fission, the syllabus writers believed that he observed it first. He may well have produced fission in 1934, but he did not recognise it as such. Fermi believed instead that by bombarding uranium he had created several radioactive transuranic elements.

- ***Discuss Pauli's suggestion of the existence of the neutrino and relate it to the need to account for the energy distribution of electrons emitted in beta decay.***

This often confuses students. The simplest way I have found to explain it is to consider the emission of a beta particle from a nucleus first and show students that if a certain amount of energy is available, conservation of momentum ensures that the nucleus will posses a fixed fraction of this energy after the collision and the remainder will go to the beta particle.

Let M and m be mass of the nucleus and beta particle respectively, Let V and v be the velocity of nucleus and the beta particle after the emission and let E be the mass defect energy available in the decay.

Assuming the nucleus is initially at rest,

$MV = mv$
and hence $V = (m/M)v$
Now $E = 1/2MV^2 + 1/2mv^2$
and substituting for V from the above equation yields,
$E = 1/2M(m^2/M^2)v^2 + 1/2mv^2$
$E = (m/M + 1)1/2mv^2$
Hence the KE of the beta particle($1/2mv^2$) is related to the total energy available by:

$$\mathbf{KE_\beta = 1/2mv^2 = E/(m/M + 1)}$$

Clearly as M, m and E are constants the KE of the beta particle should also be constant.

To understand how the emission of a neutrino can explain the beta particle having a range of energies rather than a fixed energy, I look at what would happen if another particle (neutrino) were emitted at the same time as the beta particle. The energy of the beta particle would then depend on the energy of the neutrino and the relative direction in which the neutrino and beta particle were emitted from the atom.

3) Firsthand Investigations

There are now only two mandatory firsthand investigations in this option:

i) Hydrogen emission spectrum

Observe visible components of hydrogen emission spectrum. Straightforward practical using a hydrogen discharge lamp and spectrometer.

ii) Cloud Chamber

First hand **or** secondary information to observe radiation from a nucleus using a Wilson Cloud Chamber or similar device. We do the first hand experiment, but putting 'cloud chamber' in a search engine will lead you to several sites with photographs and/or video of tracks in cloud chambers.

I supplement these firsthand investigations with several others including:

iii) Modelling the size of atoms and the nucleus.

Usually on the school oval with different sized balls conducted in the last part of a lesson in which students calculate the size of the nucleus and several electron orbital radii for hydrogen.

iv) Moderators

To demonstrate moderators I use a piece of cardboard with a hole in it above the sink. By rolling a pool ball rapidly over the cardboard the ball does not fall into the sink (and drop to a lower energy level), but if it is rolled slowly it falls into the hole. The same thing happens all the time on the greens at golf course courses and in nuclear reactors.

v) Flame Spectra

To complement the examination of hydrogen spectra I use atomisers containing nitrates of several metals to spray a fine mist into a Bunsen flame and use hand spectroscopes to examine the emissions.

vi) Measuring Plank's Constant using LEDs

As this is not a common practical and I will be demonstrating it at the workshop, I have described it in detail.

Introduction

Light emitting diodes (LEDs) produce light over a very narrow wavelength band when current flows through them. An LED does not allow current to flow until a threshold voltage (V_o) is reached. This threshold voltage can be used to calculate the energy released when an electron recombines with a hole, which will be equal to the energy of the photons emitted.

By measuring the voltage across the LED when it just switches on and the wavelength of light emitted by the LED, we can calculate Planck's constant (h). By assuming the energy lost by an electron (qV_o) when it recombines with a hole is equal to the photon energy ($hf = hc/\lambda$), we can write:-

$$qV_o = hc/\lambda \text{ , or}$$

$$\mathbf{h = qV_o\lambda/c}$$

Where c is the speed of light, λ is the emitted wavelength, $q = -1.6 \times 10^{-19}$ C is the charge on the electron and V_o is the threshold voltage.

IMPORTANT **The long terminal on the LED is the positive one. Be sure to connect the LED correctly. The circuit used should limit the current in the LED to < 50mA.**

Equipment

A Battery (3V) or other (smooth) DC power supply.
A rheostat/potentiometer (1kΩ or similar), used as a voltage divider to provide a variable voltage.
Several different coloured LEDs. (Available from any electronics component shop.)

Spectrometer (The emission wavelengths can be measured using a spectrometer or read from the manufacturer's specs. Wavelengths are approximately 630 nm for red, 590 nm for yellow, 520 nm for green and 480 nm for blue.)

Experiment
i) Set up the voltage divider to power the LED.
ii) Black out the room and wait a few minutes for your eyes to become acclimatised to the low light.
iii) Slowly increase the voltage on the LED until it just begins to emit light and record the voltage. Repeat several times and take an average. V_o is in the 1.6-3.0V range for visible LEDs.
iv) If a spectrometer is available measure the wavelength of the light emitted from the LED.
v) Repeat step iii and iv for the other coloured LEDs and present your results in a table.
vi) Calculate Planck's constant for each of the LEDs used and its average value.
(Or plot V_o against $1/\lambda$ and find h from the gradient = hc/q)

vii) Diffraction and interference

Before students can appreciate Bragg's work they need to know about diffraction and interference.

I usually demonstrate diffraction around the edge of a razer blade, Young's double slit experiment and Poisson's spot using a HeNe laser or laser pointer.

To demonstrate Poisson's spot place the laser at one end of the room and a one-cent piece or a similar round disk about half way down the room (so almost all the laser beam falls on the disk). I usually use blue-tak and a piece of wire to suspend it from a retort stand and run the beam near the side of the room for safety. The light diffracted around the disk will show interference fringes and a central bright spot when it falls on the far wall of the classroom. This is worth persisting with because a bright spot in the middle of a shadow always impresses students.

viii) Absorption of alpha beta and gamma rays

Standard practical, written up in many texts.

ix) Plotting half-life

I use two boxes of matchsticks for this with their heads removed and a texta mark on one side. Students throw them on the table spread them out and then remove the texta up matches (decayed atoms) from the sample. They throw again and repeat until all the matches (atoms) have decayed. Each throw represents a time interval. A plot of matches remaining against number of throws gives a good analogy to a radioactive decay curve.
The half-life in number of throws can be deduced simply from the curve.

Students enjoy doing this simple practical and interestingly, very few are capable of guessing or calculating the half-life accurately before they actually do it. Three or four boxes of matches would give an even better curve, but the counting does become a bit tedious.

x) Chain Reactions

There are many ways to do this. I have students place matches into a plasticine base so their heads are near enough together to ignite from one another. Igniting one starts a chain reaction among the rest. Separating the heads by too big a distance prevents a chain reaction from occurring. (Students enjoy doing this, but care should be taken so they do not burn themselves and the experiment should be conducted outdoors to vent fumes.)

4) Preparing Students for the HSC Exam

We use the following strategies at Gosford High School to prepare students for the HSC:

i) Preparation really stars in year ten where our students have a term of Physics (Space flight and the Universe) with a specialist physics teacher and a week of stage 5 physics revision before the SC.

ii) In year eleven and twelve week-by-week programs are provided to students each term, setting out reading and weekly assignments.

iii) Assessment tasks are set and marked by a variety of faculty members. Each question marked completely by one teacher using a marking scheme devised in consultation with all physics staff.

iv) Participation in Physics Olympiad in year eleven encouraged.

v) Non-assessable HSC style topic tests given at the end of each unit.

vi) All our students are required to complete a weekly assignment throughout year eleven and twelve that is handed in and marked each week. In year twelve these are similar to HSC questions.

vii) We run master classes after school each week in term two of year twelve that look at difficult exam questions in each unit and how to write a band six response to these questions. Specific master class lessons also look at how to handle extended response questions, questions on firsthand investigations and questions on research.

viii) One revision day is provided at school in the mid year and October holidays for interested students.

ix) We advise students to write unit summaries and dot point summaries in their own words. We provide booklets that have the dot points on the left hand side of the page and space on the right for students to write their summaries.

x) Students are encouraged to buy booklets of past HSC trial exams and solutions form the faculty and the Success One text.

xi) Syllabus is seen as 'the floor, not the ceiling'. Staff and students encouraged to go beyond the syllabus to ensure a deeper understanding of the material. Practical work and research work beyond the syllabus encouraged and students are encouraged to use more than one textbook.

5) HSC Questions

We emphasise the following points:

i) Read questions carefully and underline the verbs, data given and anything else important in the question.

ii) Think before you write! Well-prepared students will have plenty of time so plan your answers and do not rush.

iii) If the question is a major extended response question, start by defining terms and be sure you answer the question by addressing the verb/s in the question. **Without waffling,**

elaborate your answer as much as possible. No one has lost any marks in physics for writing too much and you are much more likely to achieve a band six if your answers are extensive. (See for example the Board's Standards Package for the length of typical band six answers).

iv) Do not contradict yourself in your answer.

v) If the question requires a calculation; write the data, write the equation/equations, rearrange the equation, substitute the data in, write the answer with units and direction if required and check to see if your answer makes sense.

vi) Plus the usual advice on; multiple choice questions, graphs, tables, variables, reliability and validity etc.