Quantum Physics
& From Ideas to Implementation

Underlying concepts in the syllabus
What is Quantum Physics?

- Wave-particle duality: Tells us that energy comes in packets, particles are wave-like.
- Systems have resonant energy levels defined by the constraints of the medium.
- The quanta are the energy gaps between these levels
Resonant energy

• Electron orbitals would not work in classical mechanics
• Quantum mechanics describes electrons as a standing wave, which collapses into a point upon being measured.

Electron orbitals would not work in classical mechanics - the electron would emit synchrotron radiation and lose energy, soon colliding with the nucleus.

Instead Quantum mechanics describes electrons as a standing wave. It is a probability wave - where the amplitude is high you are more likely to find an electron.

When you make a measurement of the electron’s position, it will be found at only one location, but there will be no pre-defined position at which you can be certain of finding it.
We are all waves

- Not longitudinal or transverse - probability!
  - E.g. probability to be in a certain position when measured
- Uncertainty principle
- As a wave matter can interfere with itself to become more or less probable
- or can become a standing wave.

When we attempt to make a measurement, quantum mechanics tells us that there is not a certain result. There are a few different possible results, each with their own probability, but for any given measurement you can’t predict which of those results it will be. Over the course of a bunch of measurements they will appear in the right distribution, but for an individual one, you can’t be sure.

A wave of course oscillates between negative and positive - but what does this mean? A negative probability doesn’t make much sense to our intuition. The measurable quantity - probability - is the square of the probability amplitude. This is similar to light, where the quantity our eyes detect - intensity - is the square of the light wave’s amplitude. The consequence of having an amplitude which can be negative is that there can be destructive interference, or waves cancelling each other out.

The uncertainty principle comes into this measurement issue. When making measurements of of related quantities - e.g. time and frequency (equivalent to energy), or position and velocity - you cannot determine both accurately. The more accurately one measurement becomes, the greater the uncertainty in the other. (this uncertainty is very small, and not detectable at macroscopic levels, e.g. exactly where I am in the room.)
Standing waves

Stable energy states of matter are standing wave frequencies of the material. e.g. the Bohr orbitals are circular orbits, where electron probabilities form a standing wave.
A system has a number of these...
Quantum mechanics - the maths

To find the resonant modes solve the Schrodinger equation

\[ H\psi = E\psi \]

- \( H \) = Description of system (Hamiltonian)
- \( E \) = Energy of system
- \( \psi \) = probability distribution (wavefunction)

The Hamiltonian \( H \) describes the system, its size, shape, and all the other characteristics that affect its energy. Mathematically it is an Operator. \( E \) is a number, and \( \psi \) is a function.

There are multiple values of \( E \) (called eigenvalues), each with a corresponding \( \psi \) (wavefunctions or eigenfunctions). These are the different resonant modes of the system, \( E \) is the energy of a mode, while \( \psi \) is the probability distribution.
Three dimensional wave

Electron orbitals:
• We are all 3-D waves

These orbitals are the solutions (wavefunctions) to the Schrödinger Equation for the electrostatic field provided by the nucleus
Resonance

Lots of little bits of energy add up to a lot

- A system can only absorb energy to move it between levels
- Otherwise no energy absorbed - Forbidden energy!

http://susiebright.blogspot.com/2007/10/would-you-like-.html

Large Pendulum

Coupled pendula
Emission too

- Systems can only emit energy that corresponds to an energy jump too.

www.answers.com/topic/bohr-model
Resonance and wine glasses
Photoelectric effect

- The important quantum part of the photoelectric effect is that the light is quantised,
- And the electron interacts with only one photon, absorbing all its energy.
Dark Space & striations

• In dark space Electrons don’t have enough energy to knock gas molecules to an excited state
• Below resonance level = no energy absorbed by gas

Electrons leave cathode at zero velocity and speed up as they move towards anode (i.e. roll down potential “hill”). Takes some time to speed up enough to knock gas molecules into higher state.

If they collide with a molecule before then they don’t lose any energy because the molecules can’t absorb it - it’s not enough energy to get them to their first excited level. If the molecules can’t absorb the energy then the electrons can’t give it away - i.e. it is a completely elastic collision.

Until they have travelled far enough down the potential hill to have enough energy to knock a molecule up to its first level. Then the electron gives ALL its energy to the molecule, and has to start again. Hence the second dark space. As the pressure increases these clear striations get smeared out.
Energy bands

• All the atom energy levels combine to form the band
  – Many different levels very close together
  – Because of Pauli exclusion principle (Fermions) these levels cannot be identical levels

• The Band Gap or Forbidden Energies are the areas between these levels:
  – Every atom has band gaps - between levels!
Atomic vs solid state energy states

The diagram on the left is for an atom, with very well defined energy levels. All the space in between is “forbidden energy” or a band gap.

If you put a lot of these atoms together to form a solid then suddenly you have a whole lot of atoms all with the same energy levels. This is forbidden by the Pauli exclusion principle, and so all the energy levels adjust themselves slightly to form a band of states that is almost continuous.

Note: The Fermi energy is the energy level to which the levels are filled at thermal equilibrium. This of course depends on the temperature.
An LED shows exactly how the current travelling through a diode crosses from one type of doped semiconductor to the opposite, e.g. from a P-type material to an N-type material. In the P-type material, holes are the charge carriers (travelling left to right in the below diagram), while in the N-type, electrons are the charge carriers, which, because they have the opposite charge, travel in the opposite direction (right to left in the below diagram).

At the junction of the two semiconductors, electrons from the conduction band recombine with holes in the valence band. As the electrons fall into the lower energy valence band, they give out energy in the form of electromagnetic radiation; the energy of each photon of the radiation is equal to the energy of the band gap.

By doping to different concentrations of dopant (usu ~ 1:10,000 - 1:1,000,000) you can change the height of the band gap, and hence change the colour of the LED.
A solar cell is a LED operating in reverse. Instead of current making a light, light makes the current flow, by splitting an electron away from a hole. This raises the electron into the conduction band where it can run off to make a current.

Of course the energy the solar cell wants to absorb is the band gap energy, i.e. monochromatic light. But sunlight is not monochromatic. We’ll see in the following slides what this means for the efficiency of solar cells.
If you have incident light with energy that is greater than the band gap, the light will be absorbed as usual. However the electrons will end up in a higher energy state in the conduction band than they need to be, so they will decay down to the lowest energy state in the conduction band, giving off their extra energy as heat.

It’s well known that solar cells produce heat as a by-product and this is why.
If you have incident photons with energy LESS than the gap, they are not absorbed. The diagram shows a momentary excitation, which instantly decays. This happens very quickly (within the time of the heisenberg uncertainty principle) and is termed a virtual excitation. Because it cannot reach the upper band, no energy at all can be absorbed. This virtual excitation decays instantly giving all the energy back to the light field, as if it had never touched it.
Superconductors and band gap

• In a superconductor the levels all collapse to be identical (electrons become bosons)
  – Now the gap is much larger
  – Electrons don’t have enough energy to reach an upper state: they can’t lose energy!
  – Their momentary excitation of the lattice - a virtual phonon
  – cf normal conductor: resistance = phonons = heat
Above critical temp, current experiences resistance just as it does in a normal conductor. This is the electron colliding (interacting with) the lattice. As it collides, the electron loses energy, transferring it to the lattice, which begins to vibrate.

Just as the quantum of light is a photon, the quantum of vibration (be that heat or sound) is a phonon.

In other words, the electrons add phonons to the lattice. Although they are often thought of as sound waves, it’s actually heat; this is how a lightbulb filament glows hot - from all the phonons bouncing around!
Below the critical temperature the electron pairs begin to act as bosons, which means they no longer obey the Pauli exclusion principle. So all the levels which were stacked on top of each other collapse to be at the same level.

Suddenly the gap has become a whole lot bigger! So the energy provided by the electrons colliding with the lattice is no longer enough to excite the lattice out of the ground state. Note that at the lower temperature the energy of the electrons is smaller as well, which is going to make it even harder to get to the higher level.

As we have said all along today, if you can’t get to the upper state (i.e. a resonance) then nothing will be absorbed at all. This means the electrons cannot get rid of their energy, because they can’t excite the lattice. Electrons losing no energy equates to a perfect current, no resistance!

(Note the energy from the levels collapsing is a possible source of the energy required to lift the magnet off the surface of the superconductor in the Meissner effect.)
In Summary

- Energy transitions - (emission or absorption) only happen when the incident energy matches a resonant energy state (energy level) of the medium.
- If they don’t match, there is no absorption, AT ALL.

Quantum perfection!