Part 2

Modern atomic model

The modern atomic model is based on Bohr's atomic model, but it can also be applied to more complex atoms (the Bohr atomic model works just fine for a hydrogen atom, but it cannot be applied to atoms with more than one electron since the electron-electron interactions are not accounted for), and of course this current model is also built on wave mechanics.

The current atomic model asserts that, most importantly, there are discrete energy levels in the electron orbitals (an orbital is the volume where there is a probability density of finding an electron, and of course the probability density is worked out using the Schrödinger equation), consequently the electrons' energy values are quantized**.** Henceforth there are also a limited number of possible orbits, not an infinite number of orbits, and hence there is no continuum of energy values which any particular electron can possess. The energy of an electron increases as the further the orbital is from the nucleus of the atom. For all of these rules, an electron does not release any form of energy while in its orbital, as it does not really "orbit" the nucleus as in the earlier Rutherford's planetary model, instead the electron's de Broglie wavelength "fits" inside an "orbit" and so no form of radiation (the primary form of radiation that should not be emitted is synchrotron radiation) is emitted as the electron does not actually "move" in a circular orbit. Also important is that the absorption and release of a wave packet by any electron can "promote" or "demote" that electron to an orbital further or nearer to the nucleus respectively, and the frequency of this wave packet can be calculated by:

$$hf = E_2 - E_1$$

All of these rules results in a unique emission spectra for each element.

Also important in this discussion for electronic structures would be the four quantum numbers:

- n: Bohr's quantum number, and is basically 1 for the ground state, 2 for the next state, and so on and so forth. At the ionization energy level n would be considered as ∞.
- l: Sommerfeld's quantum number, l is actually a collection of values of assigned letters - *s, p, d, f, g*
- m_l : As required by the wave equation, m_l gives the highest possible number of electron orbitals for each of l, be it l_s, l_p, l_d, l_f or l_g
- m_s : Is the spin quantum number, as its name suggests, describes an enigmatic quantum property known as ***spin***. Spin is not the angular momentum of classical physics, but rather it is an intrinsic property of Quantum Mechanics

A combination of these four quantum numbers in the description of a particular electron orbital will allow a solution to be yielded for the Schrödinger wave equation**.**

The Pauli's Exclusion Principle

For a collection of particles that obey the Fermi-Dirac statistics, possesses half-integer spin (described by an anti-symmetric wavefunction) and each particle is identical in all respects, no two such particle can ever be in an identical state. This is the famed Pauli's exclusion principle, and this equation has many direct and crucial consequences in the real world. Pauli's Exclusion Principle is reason for the existence of:

1. Periodic Table: Pauli's Exclusion Principle forces neutrons & protons not to "collapse" into one entity but rather, build up into a divisible object whose wavefunction consists of distinguishable constituent wavefunctions that describe each physical constituent (the neutrons & protons) (under certain conditions the atomic nucleus exhibits singular wavefunction behaviour due to the fact that the "individual" protons and neutrons are so close to one another). This is only for the nucleus, indeed the Pauli's Exclusion Principle is also responsible for the existence of the electron orbitals; as all of the lower possible states in an orbital are filled, another electron can only be accommodated in the next electron orbital, which, of course, would cause that accommodated electron to possess different properties (such as its energy, especially) as compared to another electron in an orbital of smaller distance from the nucleus. If you consider life to be precious, then be thankful for the existence of the Pauli's Exclusion Principle.
2. Fermi Level: This is an energy level (Fermi energy), beyond at which no electrons in a Fermi sea can possess energy; hence this level is at the top of all possible energies in a Fermi sea. The Fermi level allows for a deeper understanding of why electrons do not contribute much to the specific heat* of solids at ordinary temperatures though they "conduct" thermal and electrical energy. The Fermi level also plays an

important role in the band-theory of solids in determining electrical properties. The Fermi energy can be calculated as:

$$E_{Fermi} = \left(\frac{\hbar^2 \pi^2}{2m}\right)\left(\frac{3n}{\pi}\right)^{\frac{2}{3}} \quad (4)$$

*Specific heat (amount of thermal energy required to raise the temperature per unit mass by 1°C) can be calculated by:

$$c = \frac{Q}{m\Delta t}, \quad (5)$$

with Q being the amount of thermal energy added, m being the mass of the sample.

3. Degeneracy pressures: While the above two processes can take place on Earth, this particular effect of the Pauli's Exclusion Principle take place in the heavens. There are two types of degeneracy pressures: electron & neutron degeneracy pressure. Neutron degeneracy pressure is much stronger than its electron counterpart since neutrons are far, far heavier than electrons and when such a gas of neutrons (neutron stars *are* composed primarily of neutrons) is compressed their de Broglie wavelength and correspondingly their energy increases, resisting gravity's crushing power. Hence the Pauli's Exclusion Principle fills up the gap in our knowledge of stellar evolution, of why a body of such a high mass compressed into a volume so small can still exist. As their names suggest, electron & neutron degeneracy pressures support white dwarves & neutron stars respectively, but of course, if the mass of any body exceeds 2 - 3 solar masses and there is no other form of outward pressure (such as degeneracy pressure), gravity alone can crush that body into a singularity as the neutrons' relativistic mass skyrockets, and an event horizon would then form.

Although the Pauli's Exclusion Principle prevents fermions from all occupying exactly identical states some fermions are excluded from this rule as they exhibit bosonic behavior, and examples include helium (helium and the other isotopes of helium can play some interesting tricks at temperatures below ~3.5°K). Hence these examples are capable of forming BECs, so there is really no violation of the Pauli's Exclusion Principle.

Wave-Particle Duality

Quantum mechanics is built very heavily on wave mechanics, hence many familiar terms such as the Laplacian, will appear. Indeed, this is where wave-particle duality comes in. Louis de Broglie came up with this concept after studying the "least-action principle (mechanics)" and "Fermat's principle (optics)". Indeed, even during Newton's time there was already a debate between Sir Isaac Newton & Christiaan Huygens about the exact nature of electromagnetic radiation, whether it was corpuscular or wave-like in nature. Huygens' proof were the results of the famous double-silt experiment (which will become the subject for much of this discussion), and those were the same results that baffled many physicists in the 19th and 20th centuries. After Einstein had showed that light, as well as other forms of electromagnetic radiation had a particulate nature through his Photoelectric equation, there was no doubt an apparent paradox. De Broglie at that time was a little-known French physicist, and whether he received his PhD or not depended on others' acceptance of this equation, and in fact he only received it after Einstein intervened. Now that it is known that energy has a dual nature, and that energy is directly related to matter, might matter not have a similarly dual nature? The answer is yes. In fact, this explains precisely why the nature of the microcosm is entirely probabilistic: at such small distances, the wave [particle], which cannot be localized, spreads out, and this can be described by the probability distribution and amplitude. The Schrödinger equation itself is a wave equation. Of course, there are also other reasons for the probabilistic nature of the microcosm (such as the existence of quantum foam, which causes direct and measurable effects on a physically tiny system, such as energy level fluctuations of an atom of hydrogen).

The Schrödinger Equation & The Wavefunction

The Schrödinger Equation can be said to be one of the most important equations to have ever been discovered, and this equation was discovered by the Austrian physicist Erwin Schrödinger, by a very lucky guess. We cannot go into the exact details of the equation [please accept my deepest apologies] here since if that was to be done Group theory and Calculus would also have to be introduced, however, for a detailed dissection of the Schrödinger equation,

please be referred to: http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/schr.html . The Schrödinger equation is a partial differential wave equation that, using quantum mechanical operators, predict a distribution of the probabilities of a event occurring for a number of events. There are two Schrödinger Equations actually; the time-independent and the time-dependent equations. As their names suggest, the time-dependent equation “predicts” the evolution of that physical system through time. The time-independent equation however, is used to calculate values of energy of that particular physical system, and indeed only certain specific energy values allow for solutions to the time-independent Schrödinger Equation which operates on the wavefunction with the Hamiltonian, and they are named eigenvalues, and correspondingly we have eigenfunctions. Eigenfunctions and eigenvalues are related to the operator of a specific physical parameter by $Q_{operator}\psi_i = q_i\psi_i$, where q_i in this case is the eigenvalue and the eigenfunction is ψ_i , for *I* that is a quantum number characterizing a certain state of the physical parameter. Indeed, the two Schrödinger Equations can also be generalized into one, two, or three dimensions, and correspondingly, there are different coordinate systems in which a certain form of the Schrödinger Equation would be preferred for usage as there may be benefits and there is the factor of suitability. The ***wavefunction*** is acted on by this equation.
The wavefunction could be, but never accurately, visualized as a representation of all essential information regarding a particle in an instant of time. The wavefunction is represented by $\psi([x,y,z],t)$ (this is also the probability amplitude), for *x, y, z* be position in three dimensions and *t* be time. The probability is obtained by the multiplication of the probability amplitude with its complex conjugate as the probability amplitude may be described by a function complex in nature. The wavefunction allows calculations of the particle’s properties via the Schrödinger Equation, but as always the resulting values are only probabilistic. A simple summary of the properties of the wavefunction could be:

1. Is normalized ($\psi^* \psi$ = 1 as the sum over all space and expressed as an integral)
2. Represents all essential and possible information of a physical system
3. Allows for calculations via the Schrödinger Equation with an operator to yield a probabilistic value of the associated parameter
4. Allows for the validation of a probability distribution over space

It is absolutely wrong to envisage the wavefunction as only an interesting, complicated mathematical entity of significance only for physicists, apart from the fact that it can be used to predict probabilistic outcomes for a certain event and that it is directly affect the behaviour of microscopic entities. The wavefunction is much more than that, perhaps this illusion is due to the lack of knowledge, or perhaps due to some intrinsic “sense”, but anyway the fact is that the wavefunction can directly affect the macrocosm, however insignificantly. For example, the wavefunction has been employed extensively to explain the astounding results of the double-silt experiment, in connection with the concept of superposition. The double-silt experiment obviously exists in the macrocosm. Later on of course there would be the famous *gedanken* of Schrödinger’s Cat. Indeed this was the thought experiment that emphasized so much on the reliability of the popular belief among physicists that the reality does not exists till an act of observation / measurement is made on a particular isolated quantum system. As for the definition of observation / measurement, it is any act that perturbs the quantum system, such that the wavefunction is altered or it collapses.
Quantum tunnelling is perhaps one interesting concept in Quantum Mechanics. Put simply, Quantum tunnelling is the tunnelling of a particle through a barrier so that a lower energy state can be achieved, and usually that particle is in a potential well. A classic example of Quantum tunnelling is α-decay in heavy elements such as polonium. George Gamow, Ronald W. Gurney, and Edward Condon independently proposed in 1928 that the reason why the α-particle came strolling out of the nucleus, obviously with an energy value much less than what it should have been for an α-particle that had to smash through the classical Coulomb potential barrier, was Quantum tunnelling. With the probability that the α-particle could be found outside an unstable radioactive nucleus increasing with the decrement of the half-life, there had to be a moment when the α-particle would emerge from the nucleus.
Quantum tunnelling also has some profound implications on the advancement of technology: The discovery of superconductivity and the development of superconducting magnets.
Quantum Mechanics holds a treasure trove of priceless surprises. They await the intrepid.