# Physics at the Quantum Level: Big or Small?

*Everything is a harmonic oscillator if you're brave enough.* What does this mean and how is this a joke? Hopefully by the end of this, we will know the answers to these questions. The short answer is *because of quantum field theory.* Whereas the long answer will now follow.

Even before quantum mechanics was conceived, physicists studied the natural world. Starting with James Clerk Maxwell, he consolidated the then-current knowledge on electromagnetism and gave the most complete description (still taught today) of *classical* (this just means not quantum) electromagnetism. The solutions to *Maxwell's equations* are waves – in fact by combining them, one derives the equation happily known as the *Wave Equation*. Faraday took to using the term *field* to describe the electric and magnetic, well, fields. The wave solutions are exactly the electromagnetic waves (think radio waves, microwaves, light etc.) we come across in everyday life.

Despite the great success of the classical theory of electromagnetism, it could not describe effects such as *discrete atomic spectra*. Discrete here means not continuous, that is the numbers can only be fixed distances apart like these integers 1, 2, 3, for example rather than any number in between such as 1.2. An atomic spectrum is a property measured for atoms. It shows the difference in energy between different energy levels in an atom. You may have heard the terms *ground state*, *excited state* etc, these represent the lowest energy (ground) an atom can be at and any energies above this. A classical theory would predict that the energies can be any number above the ground state energy, however this was not observed. They were seen to be discrete or *quantised*.

The solution to this problem came by the hand of Max Planck who treated atoms as *oscillators* (think small springs with a mass on the end bouncing up and down). In doing this, Planck captured the fact that the energy is in discrete values. For simplicity we can choose a spring with frequency 1 and using appropriate units (you can ignore the beginning of this sentence if it doesn't make sense), it turns out the energy of the oscillator, called the *quantum harmonic oscillator*, takes values

$$1/2, 3/2, 5/2, \ldots$$

Or written in a clearer way,

$$0 + ½, 1 + ½, 2 + ½, \ldots$$

These are integers plus ½ and this ½ plays a very important part. The first number represents the lowest energy that this particular oscillator can be which is not 0. Because it is not zero in its lowest energy state, this is what tells us that the two *coordinates* we associate with it, position and momentum, do not have definite values, even in its lowest state – the quantum oscillator is always vibrating unlike a classical spring which can stop vibrating, this makes it special. This lack of definite values means there is always some uncertainty what the momentum and position are, this leads to the Heisenberg uncertainty principle which can be interpreted as "we cannot know the position and the speed of a particle at the same time". We can know one **or** the other but never both for sure at the same time.

Wait, I just used the term particle when we were talking about oscillators – why? Well, the equations that govern many particles look exactly like (or very similar to) the equation for the quantum harmonic oscillator – this doesn't mean that there are actually oscillations happening, but it makes for a mental image to hold onto! There is a small technical caveat that not all theories can be thought of as oscillators, for example in *quantum chromodynamics*, however you could try it if you're brave enough! (this may not work)

So now we have an idea of harmonic oscillators representing particles, the breakthrough in quantum *field* theory is the change in perspective, rather than the particles being the main player in the game, we change that to fields. There are fields for everything, the electron field, neutrino fields and so on and these fields are everywhere in the universe. When *excited states* were mentioned earlier, this translates directly to fields, but we can now interpret these are: particles are excitations in a given field. That is that electrons are excitations in the electron field. A small enough leap tells us that we are made up of excitations in various fields.

There are two basic types of particles called *fermions* named after Enrico Fermi and *bosons* named after Satyendra Nath Bose which have different characteristics. Bosons are the simplest to work with, these are sometimes called *force carriers* since these cause the interactions between fermions. An example of a fermion is an electron and an example of a relevant boson is the photon. An electron is the thing we know from chemistry being associated with the atom but doesn't have to be anywhere near an atom, it can exist on its own. Two electrons can come near to each other and are caused to bounce off of each other in what is called scattering. Imagine two marbles on their own trajectories and they are caused to move off of these trajectories when they come near each other. What happens is the two electrons interact with each other and a photon goes from one to the other. This act of the two electrons talking to each other causes them to deviate from each other.

Fermions exist in *generations* – these are particles that share the exact same properties as the previous but have a larger mass. The electron generations are the electron, the muon and the tau which are all just like the electron. Then there are neutrinos: electron neutrino, muon neutrino, tau neutrino and finally quarks too: the positively charged *up* (just a name) quark with its heavier charm and top quarks, then the negatively charged *down* quark and its heavier strange and bottom quarks in the generations.

One could summarise these as: electron, electron neutrino, up and down quarks plus the extra following two generations. Each of these also has an anti-particle associated, named as
anti-[particle] unless it has a specific name such as "anti-electron" is a positron.

Here are some bosons:
-The gluons which carry the *strong* force between quarks.
-W and Z bosons which are involved in nuclear processes such as *beta decay*, a process where a neutron decays into a proton, an electron and an anti-electron neutrino.
-The Higgs boson which is involved in giving some mass to particles.*

*Yes, some mass. If we know the classic $E = mc^2$, then mass and energy are related. This is just "Energy equals mass times the speed of light squared." Protons and neutrons are made up from 3 quarks each, however their mass is much larger than adding up the masses of those 3 quarks. The 3 quarks are held together by the strong force, which really is very strong and has a so-called *binding energy*, we can think of this exactly as the energy binding together the 3 quarks. By using Einstein's famous $E = mc^2$ applied to the binding energy, we find that this is where most of the mass of protons, neutrons and us come from! The Higgs does however give mass to electrons, quarks, muons etc but these are very small masses.

Back on topic. Fermions obey a special law called the Pauli exclusion principle. To understand this, we need to know that fermions have numbers associated to them called *quantum numbers* which help describe the state of the fermion. The Pauli exclusion principle then tells us that "two or more identical fermions cannot exist in the same quantum state within a quantum system simultaneously". We can have many electrons in the same system such as in an atom. Taking an atom of oxygen, this has 8 electrons which are all identical. Without the exclusion principle because nature is inherently lazy, all the electrons would fall to their ground state because it is the lowest energy and is the easiest to sit in, however then chemistry would then break, and even larger consequences!

Bosons on the other hand don't need to obey such a principle like this!

Now we've spoken about the very big, let's move to the very large: stars. Stars can exist because they find a balance between gravity and nuclear energy. Stars are held together because gravity is pulling all the matter to its centre but then stars don't fully collapse because the pressure within the star balances out gravity. Imagine putting an object in water that slowly sinks but stops about halfway down, the buoyancy of the object balances out the force of gravity, so it no longer sinks. The idea of the *equilibrium* of the situation is the same. The pressure in stars originates from particles bouncing around which generates the pressure. The particles have enough energy to bounce around because the nuclear reactions (due to the weak force) give off energy like how we get nuclear power, the nuclear reactions give off heat which we use to turn turbines – in a star the energy makes particles bounce around giving a pressure!

Once a star uses up its nuclear fuel, this force balancing gravity stops and gravity wins, the star's surface stars to collapse inwards. This is called gravitational collapse. If this happens in a star up to 1.44 times the size of our sun, then the star will collapse into a white dwarf star. Gravity gets balanced again! What balances it? The good old Pauli exclusion principle creates *electron degeneracy pressure*, this is a pressure created by electrons within the star resisting occupying the same state, which Pauli's exclusion principle says they must not. In a star less than 1.44 times the mass of our sun, the star will remain as a white dwarf forever due to this equilibrium, with quantum mechanics and gravity eternally battling out with no winner.

The number 1.44 seems arbitrary but it is called the Chandrasekhar limit. Stars with a mass larger than this will be doomed by their size, allowing gravity to win. Stars more massive than this limit are then fated to end in black holes or neutron stars.

Even though it is easy to think that quantum mechanics is only important at the smallest levels or that it is essentially unimportant, it shouldn't be understated that it is important on scales larger than those at first sight. Ignoring it would leave us in the dark on phenomena such as white dwarf stars.