

Summary of Important Ideas in Quantum Physics

- 1) The Universe is quantized. Familiar quantities such as energy, momentum, electric charge, mass – possibly even time and space – are not continuous. They occur in discrete quantum units. This fact is not directly observable in day-to-day life because the intervals between the units are incredibly small.
- 2) At the atomic level, the behavior of particles is not classical; i.e., they cannot be described by Newtonian physics. Indeed, “particles” as such do not exist at the atomic level. The “position” of the entities to which we have given names such as “electron”, “proton”, or “neutrino” can only be described in a statistical sense. All that quantum mechanics can tell us about the position of anything is that it has such-and-such relative probability of being here or there as opposed to someplace else.
- 3) The different quantum configurations which subatomic particles occupy are referred to as “states”. A state is characterized by its energy, angular momentum, and other properties. Contrary to common sense, it is not necessary for an electron in a state with 3.4 eV of energy to pass through any intervening energy values if it moves into a state with 13.6 eV of energy. It just disappears from the old state and reappears in the new one. This is the whole point of quantum mechanics: the Universe is quantized. Nothing exists “between” quantum states, because quantum states are All That There Is.
- 4) The energy of electromagnetic radiation (light, radio waves, etc.) is transferred in discrete quantum packets called *photons*, and the energy of the photons is related to the frequency of the electromagnetic radiation by:

$$E = hf, \text{ where } h = \text{Planck's constant} = 6.63 \times 10^{-34} \text{ J-sec}$$

Photons also carry momentum, even though they have no mass. This is given by the formula $p = E / c$.

- 5) If we take the formulas given above for photons, and remember that light is a wave so it obeys $v = c = f\lambda$, we have:

$$p = E / c = hf / c = h / \lambda$$

The wavelength $\lambda = h / p$ is called the de Broglie wavelength, after the physicist who first wrote it down. It is not named after him for this bit of algebra, but rather because he pointed out that *everything* in the Universe must have a wavelength given by this equation, whether it is a massless photon or not.

Note -- we got from $E = hf$ to $\lambda = h / p$ by using $c = f\lambda$. But only photons and other massless particles travel at c , so we cannot go the reverse direction if we are talking about electrons, protons, etc. Light obeys both $E = hf$ and $\lambda = h / p$, but massive particles obey only $\lambda = h / p$.

The size of λ as compared to the size of an object is exactly what determines whether we must use quantum mechanics to describe the object, or whether the much more convenient (but always more approximate) Newtonian physics can be used. Intuitively, the wavelength tells us the size over which a particle's position is “fuzzy”, because a wave packet does not have a precise edge. For a bowling ball, λ is about 10^{-34} meter, which means that the bowling ball is vastly greater than its wavelength. It behaves as a classic Newtonian particle. (Or to put it another way, we only have to worry about quantum mechanics competing with Newton if we try to squeeze the bowling ball into a 10^{-34} meter box.) For an electron, its wavelength is comparable to the size of an atom, and thus we must use quantum mechanics to describe atoms.

- 6) The most easily-observed manifestation of quantum mechanics is the line spectra of excited gases. When an electric current is passed through a low-pressure gas, light comes off which, if viewed through a prism, can be seen to consist of discrete, narrow lines of color. The frequency of the light in these lines corresponds exactly (by $E = hf$) to the energy differences between the quantum levels in the atoms. Electrons “jumping” between levels can only give off (or absorb) photons whose energies are exactly the same as the energy differences between the levels.

7) It is not possible to simultaneously determine the position and momentum of anything with infinite precision. This is known as the Heisenberg Uncertainty Principle. The uncertainty Δx in position and the uncertainty Δp in momentum are related by:

$$\Delta x \Delta p \geq h / 2\pi$$

This can also be written (by doing a little calculus) as:

$$\Delta E \Delta t \geq h / 2\pi$$

which means that you cannot simultaneously know the energy of a particle, and also how long it has had that energy, with infinite precision.

Classically, I can (in principle) measure Δx for a particle to any accuracy I choose. I can also, simultaneously, measure its velocity (and thus its momentum, since $p = mv$) to whatever accuracy I choose by timing it between two points. Thus, $\Delta x \Delta p = 0$ is allowed classically.

But quantum mechanics has no real “particles”, only probability waves. To determine the frequency of any wave to infinite precision, I would need to count an infinite number of wave crests as they pass by. But an infinite number of wave crests implies that the wave stretches from plus infinity to minus infinity – in other words, Δx is infinite because the wave is everywhere. If I constrain the wave to be a “packet” that is confined within some space Δx (like the wave splash from a rock falling in the water), then I cannot have an infinite number of wave crests to count. The smaller I make Δx then the fewer crests there are, and as Δx goes to zero there aren’t any wave crests left at all, so the frequency becomes completely unknown. Since frequency is related to both E and p in quantum mechanics (by the de Broglie and Einstein equations), this means that Δp and Δx cannot simultaneously be made zero. The size of Planck’s constant tells us how much uncertainty the universe can tolerate, that is, how far away it is from a classical Newtonian universe in which $h = 0$.

The $\Delta E \Delta t \geq h / 2\pi$ version of the Uncertainty Principle means that conservation of momentum and conservation of energy can be “suspended” by quantum particles. Strange as it may seem, uncertainty applies even to empty space – how can you know there is nothing there during a given time Δt when it is impossible to know the energy of anything there to better than ΔE ? In fact, it’s not only possible for particles with energy less than ΔE to appear from nothing, a essentially infinite number of them leap in and out of existence every second. (Physicists consider “empty” space to be much closer to a furiously boiling cauldron of quantum soup than to anything empty.)

The critical restriction on such particles is that whatever energy they possess (mainly their rest mass, but also other types of energy), the absolute maximum amount of time they can exist is given by the Uncertainty Principle. Particles whose energy is “borrowed” from uncertainty and cannot exist longer than Δt are called *virtual* particles. The only difference between, say, an electron and a virtual electron, is that the electron possesses its mass-energy and can last forever, but the virtual electron has borrowed its mass-energy from the Uncertainty Principle, and at the end of Δt it must vanish, like Cinderella’s carriage at midnight.

If you run through the numbers, it turns out that a virtual electron cannot exist for longer than about 10^{-21} sec. That may sound impossibly short, but the particles which mediate the strong and weak nuclear forces have lifetimes roughly 200 times shorter even than this.

Note – the Uncertainty Principle does not apply to charge, lepton number, or baryon number. Those are still conserved at all times.

Summary of Important Ideas in Nuclear Physics

1) The nuclei of atoms are made up of protons and neutrons. As a group, they are called nucleons (nuclear physics terminology) or baryons (particle physics terminology). Their physical properties when they are free in space are:

Nucleon	Charge	Mass	Half Life
Proton	+1 e	1.6725×10^{-27} kg	infinite
Neutron	0	1.6748×10^{-27} kg	10.6 minutes

Since like charges repel, the electrostatic repulsive force between the protons in a nucleus is enormous. Nuclei are held together against this repulsion by the strong nuclear force (or strong force, for short). The strong force is one of the four fundamental forces in the Universe. It operates only between baryons, i.e., protons and neutrons. Electrons, photons, and neutrinos are not affected by it.

2) The chemical properties of an element are determined solely by the number of protons in its nucleus. The proton number is the same as the position of the element within the periodic table. Atoms with the same number of protons, but different numbers of neutrons, have exactly the same chemical properties and differ only in mass. Nuclei of the same element (same number of protons) but with differing numbers of neutrons are called isotopes.

3) The strong force, unlike gravity and electromagnetism, is extremely short ranged. You can think of a free neutron passing a nucleus almost like a golf ball on a putting green: either you hit the cup exactly and go in, or you roll past it unaffected. This means that a nucleus can only grow so large, because the strong force is so short-ranged that it more-or-less acts like a chain linking each nucleon to the next – and like a chain, its strength does not change as you add more links. But the electromagnetic force has an infinite range, so all the protons in a nucleus participate in repelling each other. This repulsion rapidly becomes more powerful as you add more protons, so sooner or later the electromagnetic force must overwhelm the “chain-link” attraction of the strong force, and disrupt the nucleus. The heaviest stable element is bismuth, which has 83 protons.

4) Stable nuclei consist of roughly equal numbers of protons and neutrons. Without the presence of neutrons to provide additional strong force, not even two protons can be held together against their electrostatic repulsion, never mind 83. Neutrons, on the other hand, are not stable. Left alone, they will decay into a proton, an electron, and a neutrino. But inside a nucleus, formidably complicated rules of quantum mechanics allow the strong force to “forbid” the neutron’s decay – provided there are enough protons around. So, a nucleus cannot have too few neutrons, or the protons will electrostatically fly apart. But it also cannot have too many neutrons, because eventually the strong force can no longer “forbid” their decay.

5) Actually, it is naive to think of a proton-neutron pair as consisting of a proton, separately, and a neutron, separately. Like everything in quantum mechanics, such a pairing is a probabilistic entity. It is closer to reality to imagine the proton as a black ball, and the neutron as a white ball, and then to visualize them continuously swapping identities so fast that they just blur into two grey balls. There is certainly a proton and a neutron there – but if you try to capture one of them, it’s a 50/50 proposition which you’ll catch.

6) One of the consequences of Item (2) in the Quantum Physics Summary is that quantum particles have a certain probability, albeit usually hyper-small, of appearing anywhere in the Universe. This is the cause behind one type of natural radioactivity, known as α -decay. If a nucleus is very large, or has an excess of protons or neutrons, then the strong force can just barely hold it together. Classically, of course, bowling balls do not roll up hills regardless of whether they are barely sloping or look like Mt. Everest. Quantum mechanically, however, the probability that a quantum particle will leap to the other side of an energy “hill” becomes much larger if the hill is small. In the case of a radioactive nucleus such as uranium, the energy needed to liberate protons or neutrons is small enough that, sooner or later, some will quantum-mechanically tunnel through the strong-force barrier and appear outside the nucleus. Then, they speed away, and this is what we call radioactivity.

7) There are three forms of natural radioactivity, known as α - β - and γ -decay, respectively.

An α -particle consists of two protons and two neutrons. (This is a helium nucleus.) α -decay proceeds via the mechanism described in Item (6).

A β -particle is a high-energy electron. In some barely-bound nuclei, a second, much weaker nuclear force known as the weak force can compete with the strong force and cause a neutron to decay even though it is in the presence of protons. As noted in Item (4), the decaying neutron gives off an electron, and this is the β -particle.

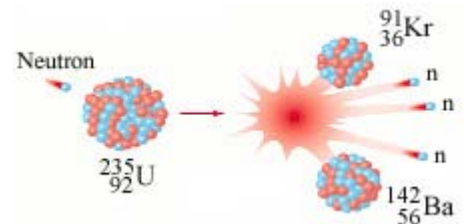
A γ -particle is a high-energy photon, also called a γ -ray. γ -rays are exactly the nuclear equivalent of spectral lines in atoms: if the protons and neutrons shift between energy levels within the nucleus, they must either give up or absorb a photon. But, since the strong force between protons and neutrons is much stronger than the electromagnetic force between a proton and an electron, nuclear energy levels are much further apart, and thus the photons given off are very energetic. As a rule, γ -emitters are excited nuclei that have been created in the aftermath of either α -decay or β -decay.

8) The three forms of radioactivity have very different abilities to penetrate matter. α -particles are very easy to stop (a sheet of cardboard will do it); β -particles are harder to stop (you need a sheet of aluminum); and γ -rays are the most difficult to stop (they can penetrate over an inch of lead). If you consider microscopically what is happening, this is easy to understand. Matter consists of charged particles: positively charged nuclei and negatively charged electrons. α -particles are heavy, thus relatively slow-moving, and have two electric charges. So they are pummeled by attractive and repulsive forces as they move through matter, and quickly lose their energy. β -particles travel much faster and have only one charge, thus they can penetrate matter more easily. γ -rays have no charge at all and are moving at the speed of light, thus they are very penetrating. They more-or-less have to hit a nucleus head-on to be stopped.

9) Since the chemical properties of an element (i.e., its position in the periodic table) are determined solely by the number of protons in its nucleus, α - and β -decay change the chemical identity of the decaying nucleus. α -decay subtracts two protons, so the element moves down two notches in the periodic table. β -decay changes a neutron into a proton, so the element moves up one notch in the table.

10) Radioactivity is characterized by the half-life of the nucleus. Definition: if I have x atoms of any radioactive element at some time, then one half-life later I will have $\frac{1}{2}x$ of those atoms remaining. And one half-life later I have a half of the half, or one-quarter, of the original atoms left. And so forth. The half-life is a statistical concept. It is completely impossible to determine whether any given atom will decay one microsecond from now or in a billion years. You can only say that it has a 50-50 chance of doing so in the time of one half-life.

11) If a large nucleus, such as that of uranium, is hit by an incoming particle (usually a neutron), then it will split into two smaller nuclei. This is called nuclear fission. If the total mass of the “after” products is smaller than that of the “before” products, the missing mass is turned into energy via $E = mc^2$. In the case of certain isotopes of uranium and plutonium, three neutrons are also thrown off when they fission. If the isotopes are pure enough, thereby concentrating the fissionable nuclei close enough together, then it is possible for one decay to send out three neutrons which in turn fission three more nuclei, which in turn fission 9 more nuclei, which in turn fission 27 more nuclei, and etc. This is called a chain reaction, and is the mechanism behind the A-bombs dropped on Hiroshima and Nagasaki.



12) If two small nuclei (such as hydrogen, which consists of only a single proton) can be brought close enough together, they can be fused into a single nucleus. This is called nuclear fusion. Fusion is very difficult to achieve, because the protons strongly repel each other. Only gases heated to tremendous temperatures – millions of degrees K° – have atoms moving fast enough that they can approach each other close enough to achieve fusion. A hydrogen bomb works by using the heat of a uranium fission bomb to trigger the hydrogen fusion.

The Sun is powered by hydrogen fusion, but its mechanism is very different than that of an H-bomb, and it works at far lower temperatures. In the case of the Sun, its mass is so great, and the pressure at its center so high, that it relies on a certain number of protons achieving the necessary fusion velocity just by statistical accident.

As you no doubt recall from our discussion of heat earlier in the course, the temperature of anything is an average measure of the kinetic energy of its atoms. Some will be going faster, and others slower, than the average. Theoretically, there is no upper limit on what top speed an atom might attain. In the Sun, an incredibly small percentage of the hydrogen atoms (like, 10^{-18}) are moving so much faster than the average that they actually acquire enough energy to ignite nuclear fusion! Such “fusion by statistical accident” can only work if you have a truly vast amount of material with which to overwhelm the low probability of fusion. The Sun does. The ratio of the mass of the Sun to the maximum mass we could hope to contain in a fusion generator on Earth is about a factor of 10^{30} . So whereas an “efficiency” of 10^{-18} could not possibly produce any profits for ConEd, in the Sun it means that about 1.5 trillion tons of hydrogen are fused into helium every second.