Quantum Physics

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Quantum Physics 1 [Concepts]

1. **Isotopes:** Atoms of the same element with the same number of protons but differing numbers of neutrons.

2. **Specific charge:** The charge to mass ratio of a particle.

3. **Fundamental (elementary) particles** have no substructure. They may be grouped into 'matter' particles [leptons (12) or quarks (12)] and 'force' particles [gauge bosons (4 fields)].

4. **Energy-Mass Equivalence:** $E = mc^2$. Total mass-energy (including rest energy) is always conserved. Increasing the total available energy produces particles that are more numerous, more massive and/or have a higher velocity.

$$\left(\Sigma E_{rest} + \Sigma E_{kinetic}\right)_{final} = \left(\Sigma E_{rest} + \Sigma E_{kinetic}\right)_{initial}$$

5. **Annihilation:** Particles and their corresponding antiparticles may annihilate, converting mass into energy (a pair of high energy gamma rays [moving in opposite directions to conserve momentum], which may then decay into further particles). Particles and their corresponding antiparticles have the same rest mass but opposite properties (such as charge and baryon/lepton number).

6. **Pair production:** The reverse of annihilation, involving energy converting into mass in the form of a particle-antiparticle pair (e.g. colliding protons, quark confinement, or high energy gamma rays interacting with matter).

7. **Decay and Interaction:** Particles may decay or interact by emitting and/or absorbing gauge bosons. Decay products have lower mass-energy than the original particle.

Quantum Physics 2 [Leptons]

1. **There are** six main 'flavours' of lepton: electron (e [or β], mass = m_e); muon (μ, mass ≈ $200m_e$); tau (τ, mass ≈ $3500m_e$); and their associated neutrinos. Antileptons take the total to twelve.

2. **Leptons (and antileptons) are** unaffected by the strong nuclear force. They may instead interact through the electromagnetic, weak nuclear, and gravitational forces.

3. **Leptons (and antileptons) exist** individually, rather than combining to form larger particles.

4. **Neutrinos were first proposed** to explain why β^- particles exhibit a range of energies which also seem to break energy and momentum conservation laws.

5. **Collisions between** leptons (or antileptons) of sufficient energy can produce hadrons.

6. **Leptons have** +ve lepton number. Antileptons have –ve lepton number.

7. **The only stable** leptons (or antileptons) are electrons and electron-neutrinos (tau and muons decay into electrons).

Quantum Physics 3 [Quarks]

1. **There are** six main 'flavours' of quark: up/down, charm/strange and top/bottom. Antiquarks take the total to twelve.

2. **Quarks (and antiquarks) are** affected by the strong nuclear force. They also may interact through the electromagnetic and gravitational forces, and decay through the weak nuclear force.

3. **Quarks (and antiquarks) cannot** exist individually, combining to form larger particles called baryons or mesons (known collectively as hadrons).

4. **Baryons comprise** three quarks (qqq), such as protons (uud) and neutrons (udd). Baryons have a baryon number of +1 and decay ultimately into protons. [Antibaryons comprise three antiquarks ($\bar{q}\bar{q}\bar{q}$) and have a baryon number of –1.)

5. **Mesons comprise** a quark–antiquark pair ($q\bar{q}$), such as pi-mesons (pions, π) and k-mesons (kaons, K). Mesons have a baryon number of 0 and do not decay into protons (e.g. kaons decay into pions).

6. **Strangeness:** Strange particles are created through strong interactions and decay through weak interactions. Kaons are strange ($S = \pm 1$) but pions are not ($S = 0$). The π^0 meson therefore comprises either $u\bar{u}$, $d\bar{d}$, or $s\bar{s}$, and is identical to its antiparticle (also π^0).

7. **The only stable** hadron is the proton.

Quantum Physics 4 [Gauge Bosons]

1. **Gauge bosons** ('exchange particles') transfer force, energy and momentum (and sometimes charge) in an interaction. They mediate the four fundamental forces (or 'interactions'): electromagnetism, gravity, weak nuclear, and strong nuclear.

2. **Electromagnetic force:** Affects particles with *charge* and is mediated by *virtual photons* (γ) [which are not observed and have zero rest mass]. Range is infinite, relative strength = 1.

3. **Gravitational force:** Affects particles with *mass* and is mediated by *gravitons* (G) [er . . . maybe]. Range is infinite, relative strength ≈ 10^{-38}.

4. **Weak nuclear force:** Affects *leptons* and *quarks* and is mediated by W^+, W^-, and Z^0 bosons [which appear to have rest mass]. Range ≈ 10^{-17} m, relative strength ≈ 10^{-5}.

5. **Strong nuclear force:** Affects *quarks* and is mediated by *gluons* (g) [which are carried within pi-mesons (π) and have rest mass]. Range ≈ 10^{-15} m (fm), relative strength ≈100.

6. **The strong nuclear force** stabilises nuclei, being attractive at ≈ 3 fm (which counters the electromagnetic repulsion of the protons) and repulsive at ≈ 0.5 fm (which prevents collapse to a singularity and fixes the density of all nuclei at a similar value).

7. **Conservation:** Mass-energy, momentum, charge, lepton number and baryon number are always conserved. Strangeness is conserved in strong interactions but not necessarily in weak interactions.

Quantum Physics 5 [Photoelectric Effect]

1. **Photoelectric effect:** The instantaneous emission of electrons from a metal surface when irradiated with electromagnetic radiation above a certain (threshold) frequency. (Classical wave theory suggested emission would be delayed and occur for all frequencies.)

2. **Photoelectric emission** is explained by assuming that light energy is quantised (i.e. discrete, rather than continuous), and that photons and electrons have particle like, one-to-one interactions.

3. **Planck's energy equation:** $E = hf$

4. **Work function (ϕ):** The minimum incident energy required to liberate an electron from a metal surface at zero potential ($\phi = hf_o$).

5. **Threshold frequency (f_o):** The minimum frequency of incident electromagnetic radiation required to liberate an electron from a metal surface at zero potential.

6. **Einstein's photoelectric equation:** $E_{k(max)} = hf - \phi$ $[= h\ (f - f_o)]$

7. **Emitted photolectrons have a range of energies** as some are liberated from deeper within the material and therefore lose more energy than the work function in reaching the surface. Although the photonic energy delivered may therefore be fixed (in the case of monochromatic light), the kinetic energy of liberated electrons will vary up to a maximum.

Quantum Physics 6 [Energy Levels]

1. **Quantum theory** predicts that electrons can only occupy discrete energy levels around a nucleus.

2. **Emission spectra** provide evidence for energy levels as emitted photon energies are equal to the energy lost from the atom when electrons transition down between two discrete levels ($E = hf$, where E is the difference in energy between levels).

3. **Ground state:** All electrons occupy the lowest possible energy level (i.e. the atom is not excited).

4. **Excitation:** Electrons transition from a lower to a higher energy level through the absorption of discrete quanta of energy, exciting the atom. Energy absorption is varied (e.g. light, electrical, thermal).

5. **Relaxation:** Excited states are unstable and electrons therefore quickly transition to a lower energy level by releasing discrete quanta energy, relaxing the atom. Energy release is always photonic (i.e. light) and its magnitude is equal to the difference in transitioned energy levels.

6. **Line spectra:** Discrete frequencies associated with specific photon energies, produced by isolated atoms. Spectrum is characteristic of the atom concerned.

7. **Fluorescent tubes:** Mercury atoms excited through collisions with current electrons relax by releasing ultraviolet photons. These photons are then absorbed by atoms in the fluorescent (phosphorus) coating, which relax by cascading, rather than through a single transition, releasing several photons of lower frequency in the visible spectrum.

Quantum Physics 7 [Duality]

1. **Wave-Particle duality** suggests that waves can exhibit particle-like characteristics and particles can exhibit wave-like characteristics.

2. **When transferring energy** as electromagnetic waves or small particles, wave theory explains where the energy goes and particle theory explains what happens when the energy arrives.

3. **Evidence of waves** behaving like particles is provided by the photoelectric effect and gamma radiation detection in a Geiger-Müller tube.

4. **Evidence of particles** behaving like waves is provided by electron diffraction and interference.

5. **Electrons behave** as both particles and waves during the electron diffraction 'rings' experiment: particles when accelerated by the electric field (charge) and exciting atoms in the screen (kinetic energy); waves when diffracting between atoms in foil and then interfering.

6. **De Broglie equation:** $$\lambda_{db} = \frac{h}{mv}$$

7. **Do not confuse** electromagnetic waves (Planck's equation) with matter waves (de Broglie's equation) when calculating values such as energy, frequency, and wavelength.