A Brief History of Quantum Mechanics

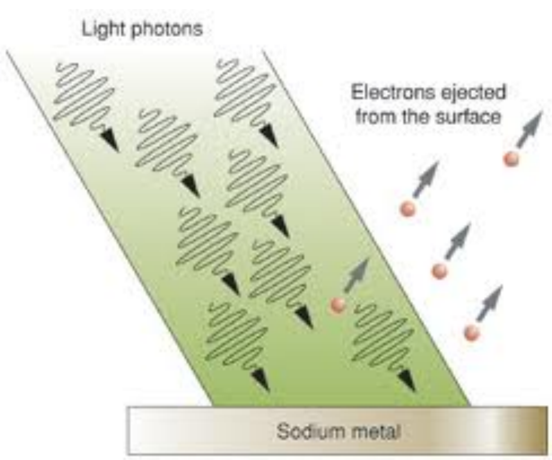
Photoelectric Effect:

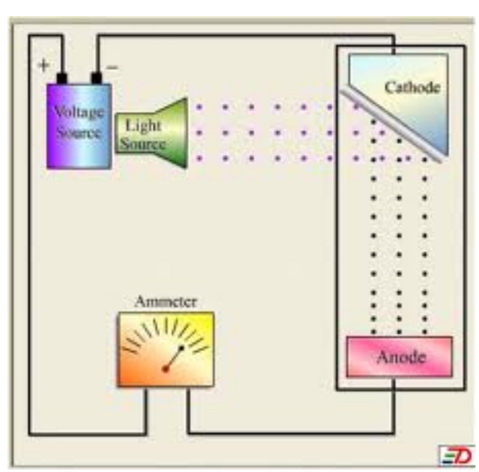
Classical idea:

• Even as recent as the **1850s** nobody had any idea about the structure/nature of matter. However, much had been found about the behavior of gas (relation between temperature, volume and pressure), light propagation and some behaviors (reflection, reflection and refraction), electricity (static and electrolysis) and magnetism (force and production). It was a very exciting time-----

• It had also come to believed that if one illuminates a metal with a light source, or heats metal, it would (slowly) accumulate energy, and eventually (free) electrons would be ejected from the surface. The speed and energy of the emissions would be dependent on the ***intensity*** of illuminated light and/or temperature.

• In **1887**, Heinrich Hertz discovered that electrodes illuminated with ultraviolet light create electric sparks more easily (photo-electric effect). Nobody had a good explanation for this effect-----





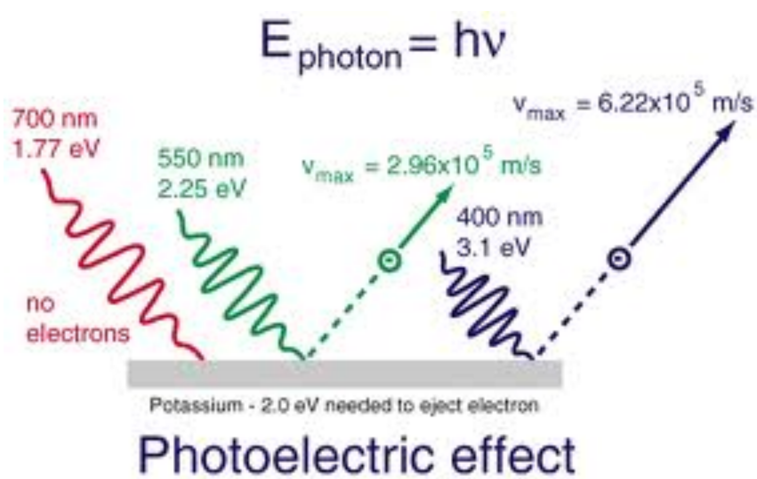
Photoelectric Effect:

After Einstein:

• However, in **1905** Albert Einstein published a paper that explained the experimental data from the photo-electric effect experiments in an absolutely new way: that it exhibits the result of light energy being carried in discrete quantized packets (now called **photons, quanta of energy**). Thus, one of the earliest clues to the **quantum nature** of our universe occurred with an experiment on the behavior of electrons in metals. Einstein proposed that the experimental results could be explained by:

1) assuming that light acts as ***both** a wave and a particle* (named "photon"), depending on the circumstances, and

2) that the energy of a photon is *proportional to its frequency*, or inversely to its wavelength.



• The "h" in the equation is called Plank's constant, a number derived by Max Plank in **1900** regarding Blackbody curves and "quanta" of energy.

$$6.62606957 \times 10^{-34}\ m^2\ kg\ /\ s$$

• This idea by Plank and Einstein was a beginning of Quantum Mechanics. An individual photon interacts with an individual electron, and causes it to be ejected.

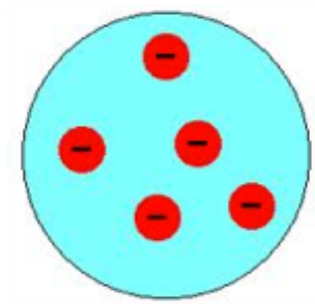
“Plumb Pudding” model of matter:

• By the 20th century electrons (1897; J. J. Thompson) had been unveiled through experiments. The electron has a negative opposite charge.

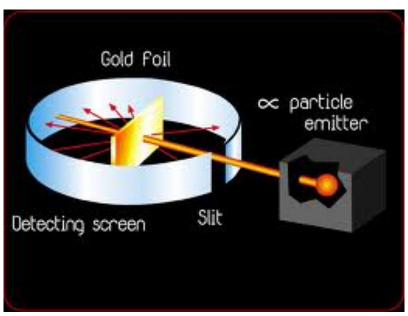
J. J. Thompson further postulated a “plumb pudding” model in 1904 to explain all matter: Electrons were said to have motions around a “soup, or cloud of positive charge”. The various structures/motions would represent the different elements.

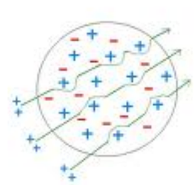
• Here the blue color is the proton “soup”

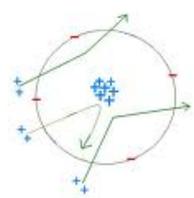
• Red are electron “plums”



Rutherford Experiment and Model of an Atom:





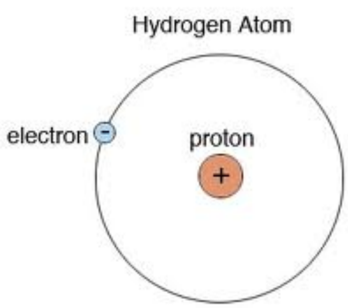


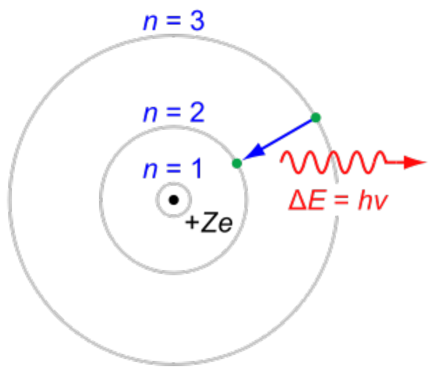
• The 1904 Thomson model was disproved in 1909 by an experiment conducted by Hans Geiger and Ernst Marsden. They bombarded a thin foil of gold by alpha particles. It was speculated that the alpha particles would zoom directly through the gold foil, thought to be a plumb pudding of electrons and protons.

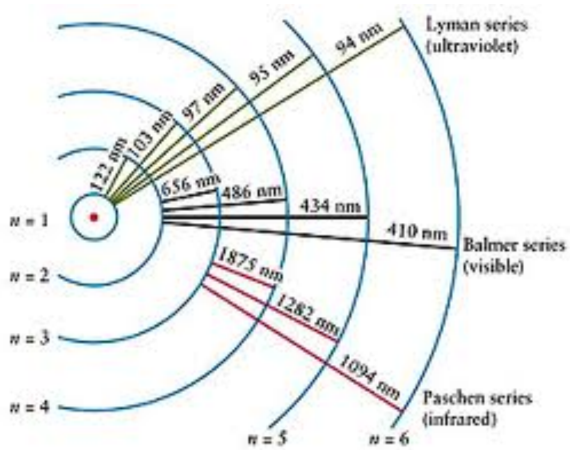
The results were completely unexpected. Though most of the alpha particles did move directly through the foil, as expected, some were radically scattered, even directly backwards. This was interpreted by Ernest Rutherford Ernest in **1911** to imply a very small nucleus of the atom containing a high positive charge (in the case of gold, enough to balance about 100 electrons), thus leading to the ”Rutherford model” of the atom. Although gold has an atomic number of 79, immediately after Rutherford's paper appeared in **1911** an intuitive suggestion was made that the atomic number is the nuclear charge. In **1920** Rutherford named the nucleus as a “proton” after finding the Hydrogen nucleus from radioactive decay.

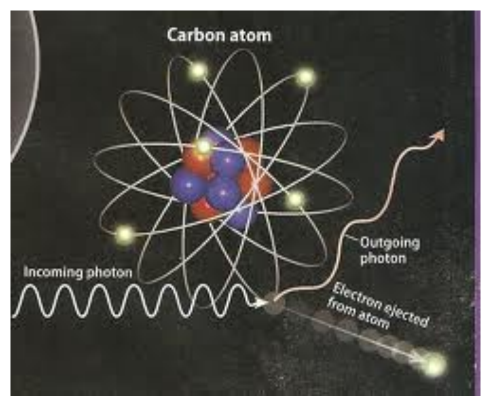
Bohr Model of a Hydrogen Atom:

• In **1910** Rutherford did a scattering experiment of alpha particles on gold foil and made a surprising discovery, which led to a model of atoms. Then, in **1913** Danish physicist Niels Bohr proposed a bold model of the hydrogen atom. In this model negative electrons are in circular orbits around a positive nucleus in discrete orbits. They cannot exist between these very definite orbits, based on the discrete – quantum – concept of Plank & Einstein.









Problems with the Bohr model & fixing them:

1) Radiation: Conventional classical thinking predicted that such an atom is impossible, since the circular motion of the electron is acceleration (change of direction) and therefore the electron should continuously radiate and spiral into the nucleus.

2) Discrete orbits: In classical physics matter can have continuous orbits or velocities or locations. But in this model the orbits are discrete.

3) Theoretical predictions and experiments: In spite of these problems, the predicted energy absorption and emission agreed fairly well with the experimental evidence, but not perfectly.

Improving the model:

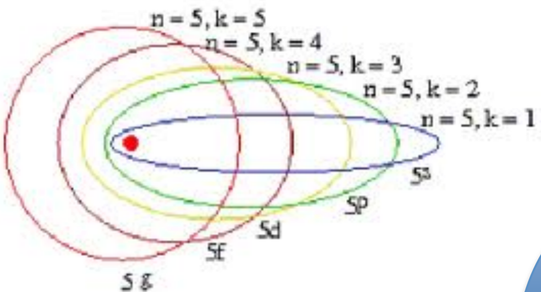
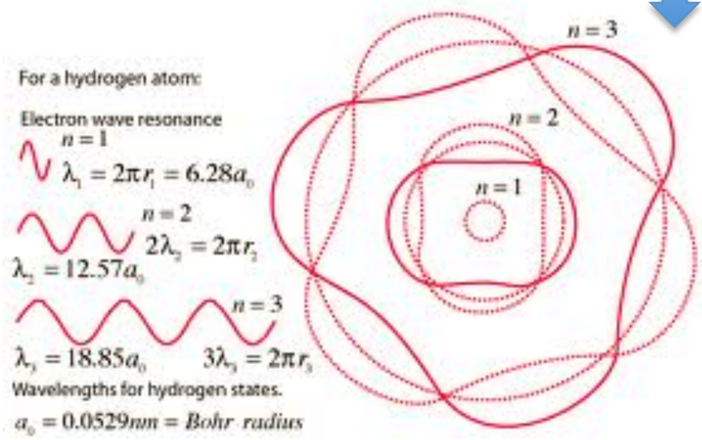
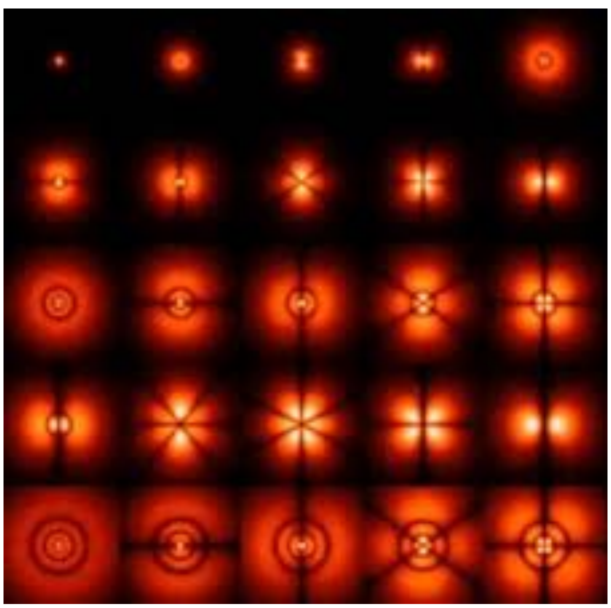


Fig.6 Sommerfeld's elliptical orbits.

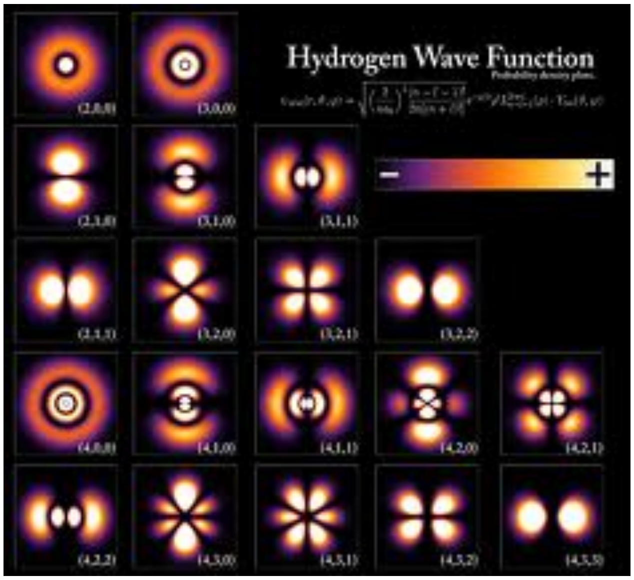
- Model improved by making elliptical orbits rather than circular.
- Since waves can act like particles (**1924**; de Broglie), supposed that particles could act like waves.
- So proposed that electrons not in orbits, standing waves filling orbits.



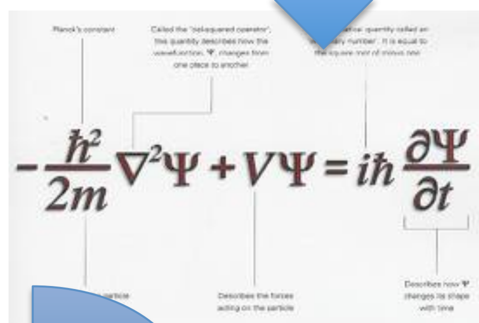


- This picture eventually changed to the view that the wave is a PROBABILITY function

The wave equation and function:

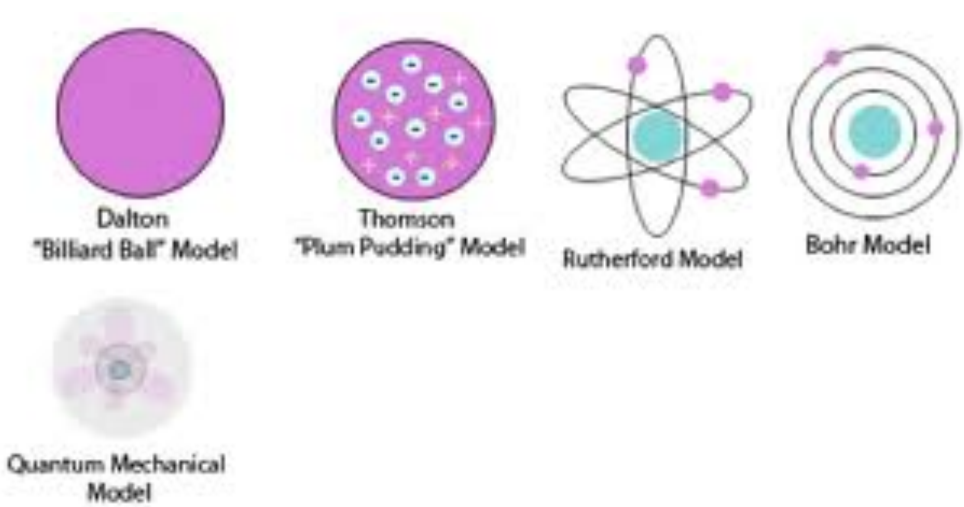


- The Schrodinger wave equation was derived (**1925**), the solution of which could describe the details of a particle or system, like an atom



$$\Psi$$

The Wave Function



Uncertainty Principle:

In quantum mechanics, the **uncertainty principle** is any of a variety of mathematical inequalities asserting a fundamental limit to the precision with which certain pairs of physical properties of a particle known as complementary variables, such as position, *x*, and momentum, *p*, can be known simultaneously. For instance, the more precisely the position of some particle is determined, the less precisely its momentum can be known, and vice versa. The formal inequality relating the standard deviation of position, σ_x and the standard deviation of momentum, σ_p , was derived by Hesse, Kennard, and Weyl in **1928**,

$$\sigma_x \sigma_p \geq \frac{\hbar}{2},$$

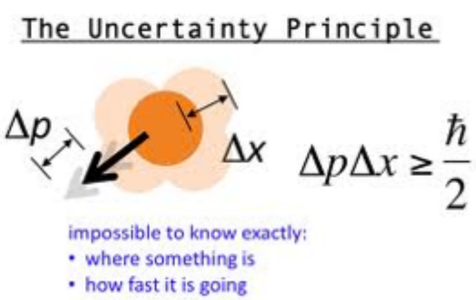
where $\hbar$ is the reduced Plank constant.

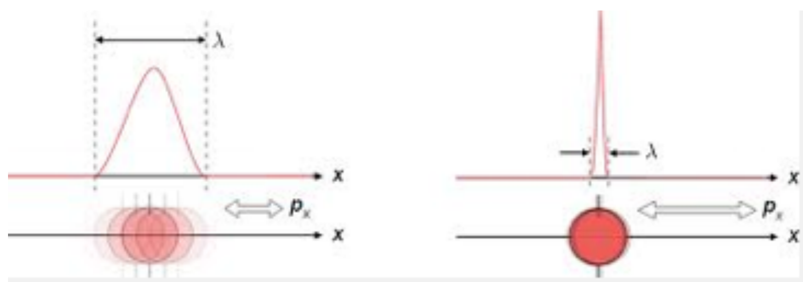
The original heuristic argument that such a limit should exist was given by Wener Heisenberg in **1927**, after whom it is sometimes named the **Heisenberg principle**. This ascribes the uncertainty in the measurable quantities to the jolt-like disturbance triggered by the act of observation. Though widely repeated in textbooks, this physical argument is now known to be fundamentally misleading. While the act of measurement does lead to uncertainty, the loss of precision is less than that predicted by Heisenberg's argument; the formal mathematical result remains valid, however.

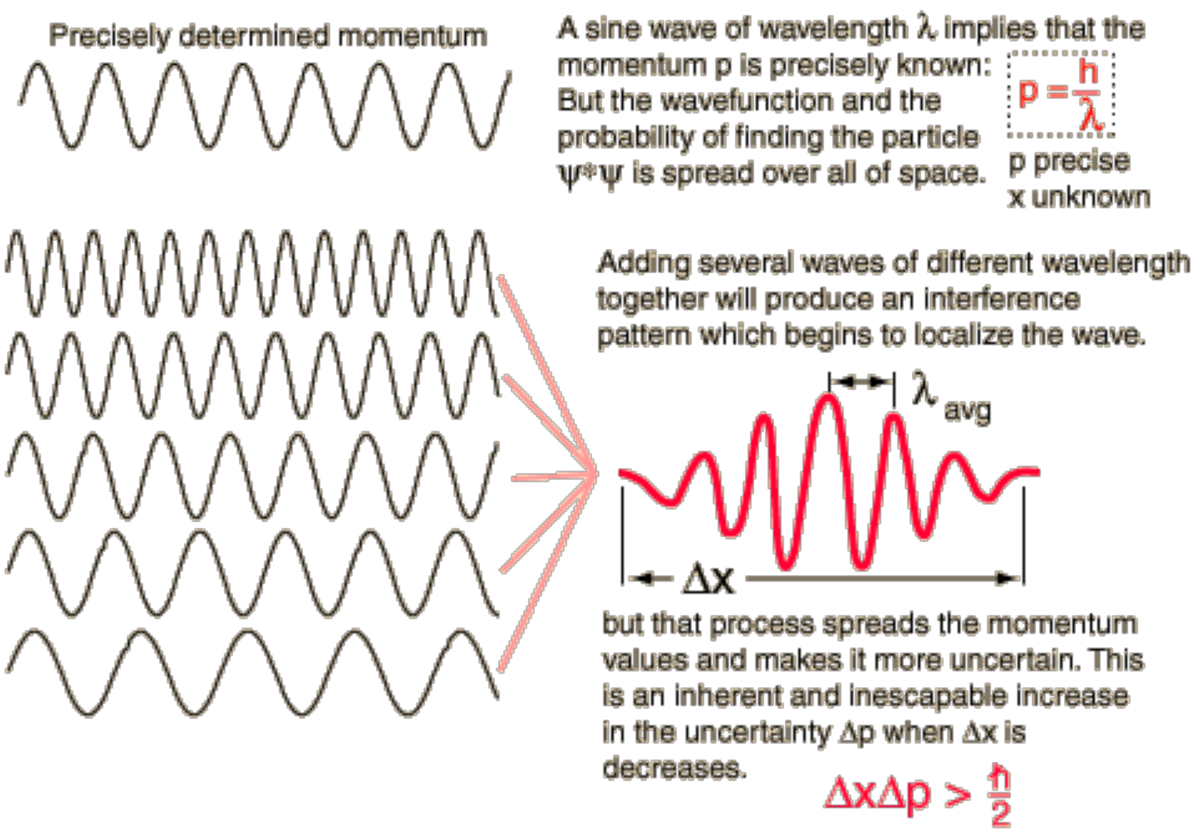
Historically, the uncertainty principle has been confused with a somewhat similar effect in physics, called the observer effect, which notes that measurements of certain systems cannot be made without affecting the systems. Heisenberg offered such an observer effect at the quantum level as a physical "explanation" of quantum uncertainty. It has since become clear, however, that the uncertainty principle is inherent in the properties of all wave-like systems, and that it arises in quantum mechanics simply due to the matter-wave nature of all quantum objects. Thus, *the uncertainty principle actually states a fundamental property of quantum systems, and is not a statement about the observational success of current technology*. It must be emphasized that *measurement* does not mean only a process in which a physicist-observer takes part, but rather any interaction between classical and quantum objects regardless of any observer.

Illustrating the Uncertainty Principle:

• By making a measurement of a particle or atom, like the position, this very act will change the velocity, and thus momentum. ***If you know <u>position exactly</u>, can no nothing about momentum.***

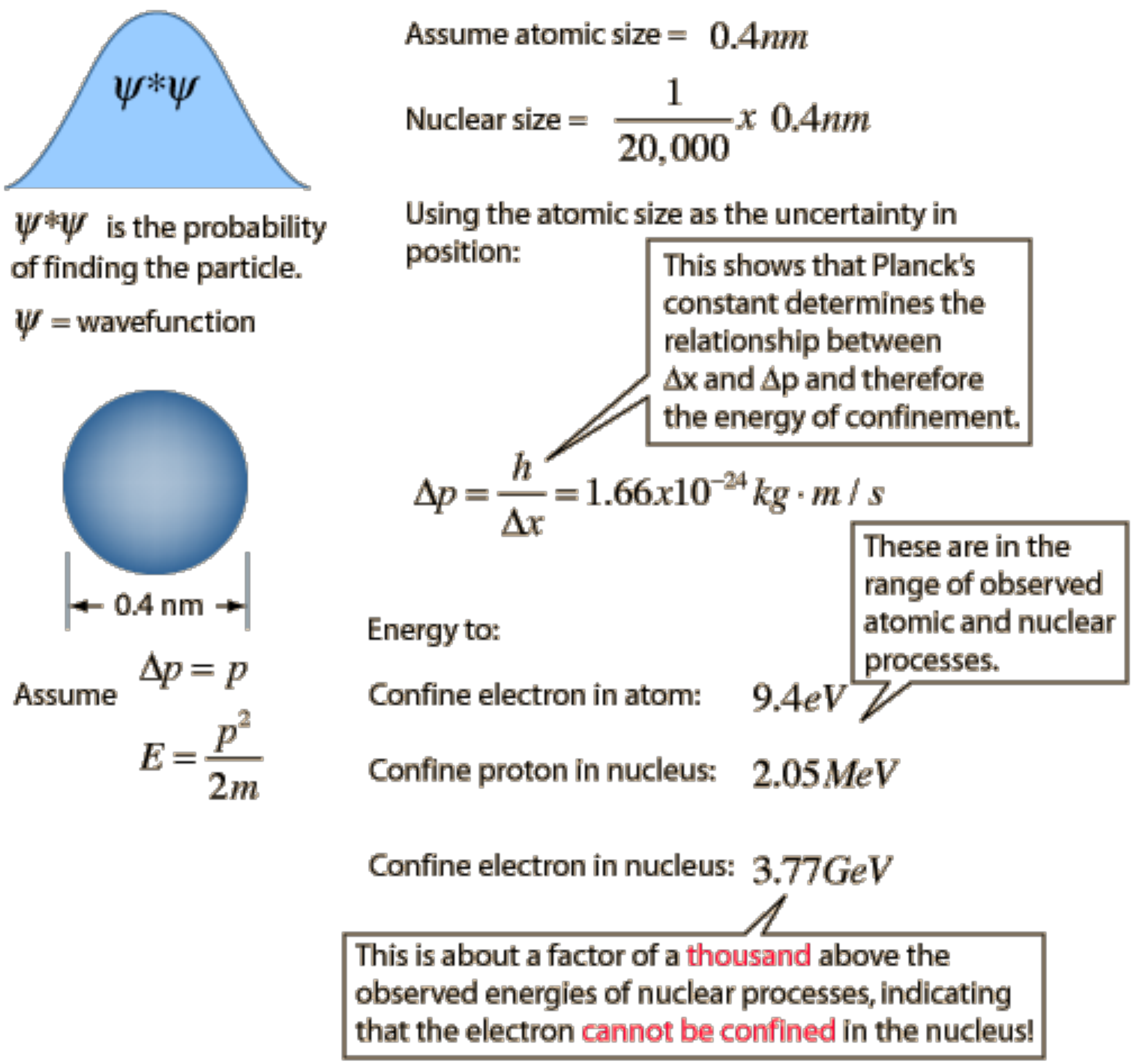






Particle Confinement

The uncertainty principle contains implications about the energy that would be required to contain a particle within a given volume. The energy required to contain particles comes from the fundamental forces. In particular, the electromagnetic force provides the attraction necessary to contain electrons within the atom, and the strong nuclear force provides the attraction necessary to contain particles within the nucleus. But Plank’s constant, appearing in the uncertainty principle, determines the size of the confinement that can be produced by these forces. Another way of saying it is that the strengths of the nuclear and electromagnetic forces along with the constraint embodied in the value of Planck's constant determine the scales of the atom and the nucleus.



Degeneracy force of a star, and formation of black holes:

• When we talked about stars, an important concept is that the outward thermal force is balanced by the inward gravitational force. But there is also a repulsive "**degeneracy force**" that helps to keep the core from being crushed: a force based on the quantum rule that these particles can not get ever closer together. There is a limit. BUT for very massive stars at the end of their life, even this force is overcome and the core of the star collapses into a neutron star or black hole.

Big-Bang creation of a universe from nothing:

• Another very important aspect of the uncertainty principle involves Time and Energy. Even I the emptiness (vacuum) of space, the uncertainty relation between time and energy allows energy to be created (borrowed) out of nothing for a shot period of time, owing to "uncertainty".

$$\Delta x \Delta p > \frac{\hbar}{2}$$

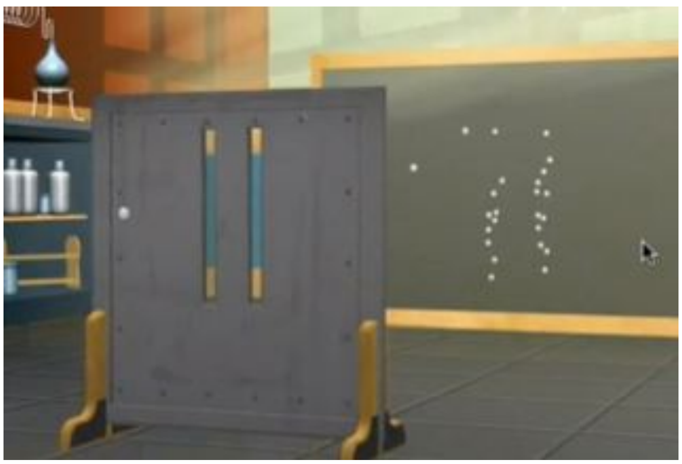
$$\Delta E \Delta t > \frac{\hbar}{2}$$

$$\Delta E \Delta t > \frac{\hbar}{2}$$

• When events transpire at shorter time intervals, there is a greater uncertainty in the energy of these events. Therefore it is not that the conservation of energy is *violated* when quantum field theory uses temporary electron-positron pairs in its calculations, but that the energy of quantum systems is not known with enough precision to limit their behavior to a single, simple history.

$$\Psi$$

Double Slit Experiment:



Observation Effects Outcome

- Now know that observing something affects results.
- If shoot large bullets through double slit get lines. Bullets are macroscopic articles.
- If shoot light get interference pattern, since light sometimes has wave characteristics.
- If shoot one photon at a time, still get interference pattern????
- If measure which slit photon passes through, get macroscopic bullet effect.
- This OBSERVATION-CONSCOUSNESS changes everything.

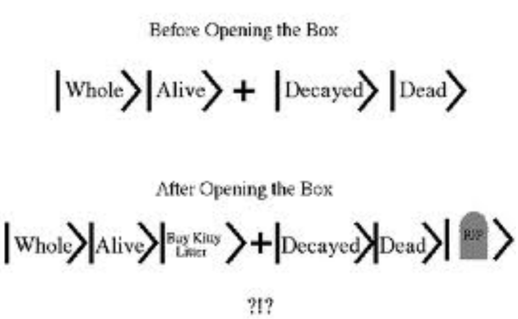
- Because of this type of thinking:

Schrodinger's Cat:

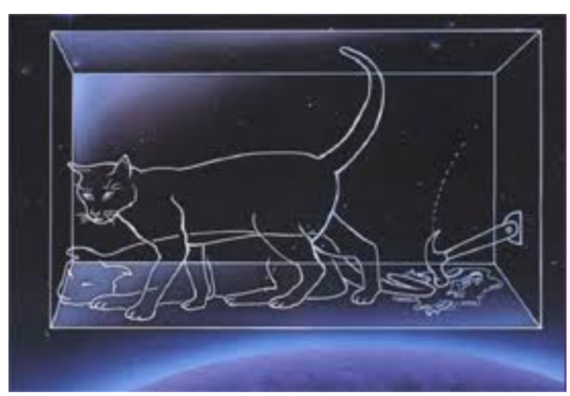
- When Niels Bohr and Einstein were arguing about QM, Bohr proposed a mind experiment:
- A cat is placed in a box with a radiation device that will trigger a hammer that can fall on a bottle of poison and kill the cat.
- When box is closed the wave function is combination of alive and dead.
- When consciousness makes and observation this COLLAPSES the wave function to one or the other.

?

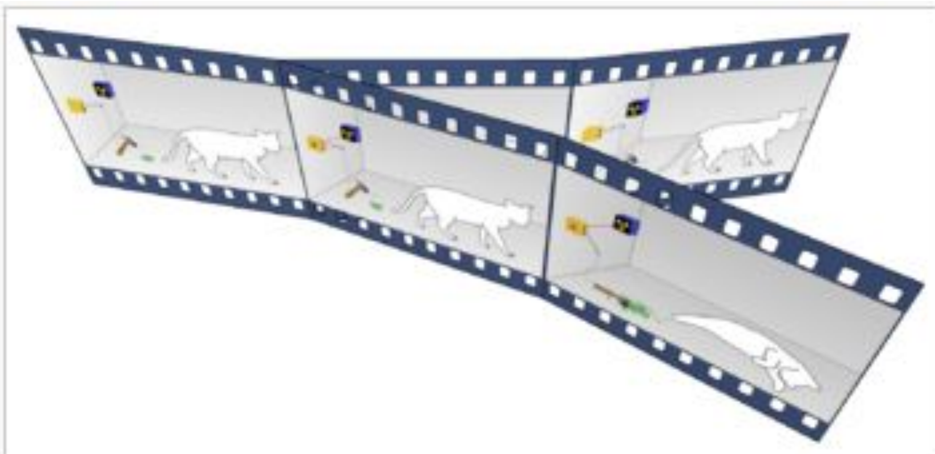
Ψ



[Copenhagen Interpretation of QM]

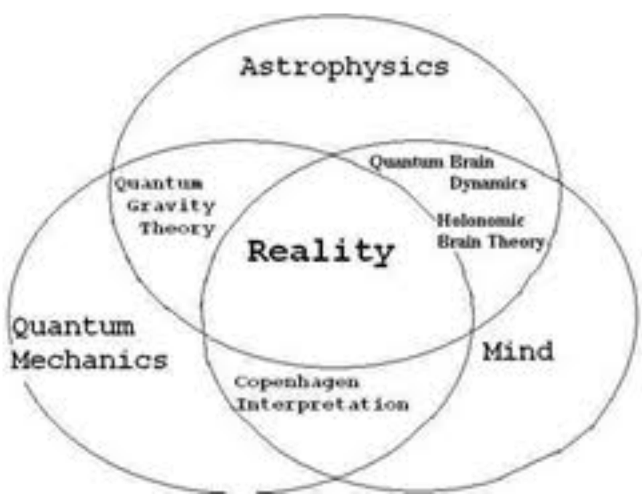


Many-Worlds Interpretation of QM:



The quantum-mechanical "Schrödinger's cat" paradox according to the many-worlds interpretation. In this interpretation, every event is a branch point. The cat is both alive and dead—regardless of whether the box is opened—but the "alive" and "dead" cats are in different branches of the universe that are equally real but cannot interact with each other.

?



Why we might doubt such stuff: Environmental Decoherence

In quantum mechanics, **quantum Decoherence** is the loss of coherence, or ordering of the phase angles between the components of a system in a quantum superposition. One consequence of this dephasing is classical or probabilistically additive behavior. Quantum decoherence gives the *appearance* of wave function collapse (the reduction of the physical possibilities into a single possibility as seen by an observer) and justifies the framework and intuition of classical physics as an acceptable approximation: decoherence is the mechanism by which the classical limit emerges from a quantum starting point and it determines the location of the quantum-classical boundary. Decoherence occurs when a system interacts with its environment in a thermodynamically irreversible way. This prevents different elements in the quantum superposition of the total scene's wavefunction from interfering with each other. Decoherence has been a subject of active research since the 1980s.

Decoherence can be viewed as the loss of information from a system into the environment (often modeled as a heat bath, since every system is loosely coupled with the energetic state of its surroundings. Viewed in isolation, the system's dynamics are non-unitary (although the combined system plus environment evolves in a unitary fashion. Thus the dynamics of the system alone are irreversible. As with any coupling, entanglements are generated between the system and environment. These have the effect of sharing quantum information with—or transferring it to—the surroundings.

Decoherence does not generate *actual* wave function collapse. It only provides an explanation for the *observance* of wave function collapse, as the quantum nature of the system "leaks" into the environment. That is, components of the wave function are decoupled from a coherent system, and acquire phases from their immediate surroundings. A total superposition of the global or universal wavefunction still exists (and remains coherent at the global level), but its ultimate fate remains an interpretational problem. Specifically, decoherence does not attempt to explain the measurement problem. Rather, decoherence provides an explanation for the transition of the system to a mixture of states that seem to correspond to those states observers perceive. Moreover, our observation tells us that this mixture looks like a proper quantum ensemble in a measurement situation, as we observe that measurements lead to the "realization" of precisely one state in the "ensemble".

Decoherence represents a challenge for the practical realization of quantum computers, since such machines are expected to rely heavily on the undisturbed evolution of quantum coherences. Simply put, they require that coherent states be preserved and that decoherence is managed, in order to actually perform quantum computation.

Dirac equation and antimatter:

Paul Dirac, a great physicist and mathematician, tried to formulate a wave equation that combined quantum mechanics and special relativity

The result was the Dirac Equation:

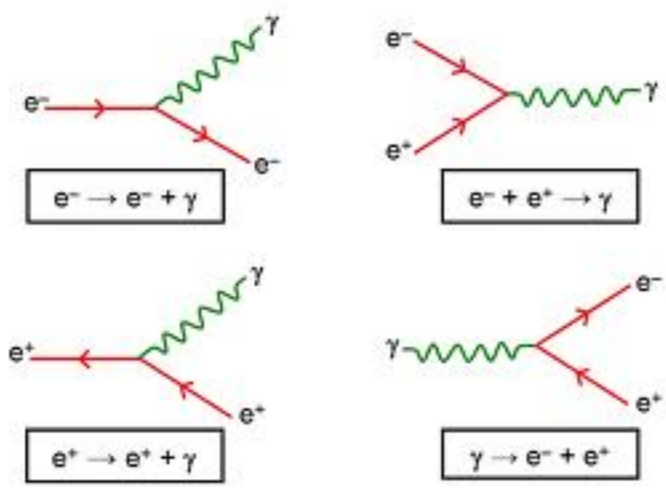
$$(i\gamma^{\mu}\partial_{\mu} - m)\psi = 0$$

$$\begin{pmatrix} 0 & i\bar{\partial} \\ i\partial & 0 \end{pmatrix} \begin{pmatrix} \bar{\Psi}^{\dagger} P_3 \\ \Psi P_3 \end{pmatrix} = m \begin{pmatrix} \bar{\Psi}^{\dagger} P_3 \\ \Psi P_3 \end{pmatrix}$$

• Not only was this equation successful, but it also predicted “anti-particles”:

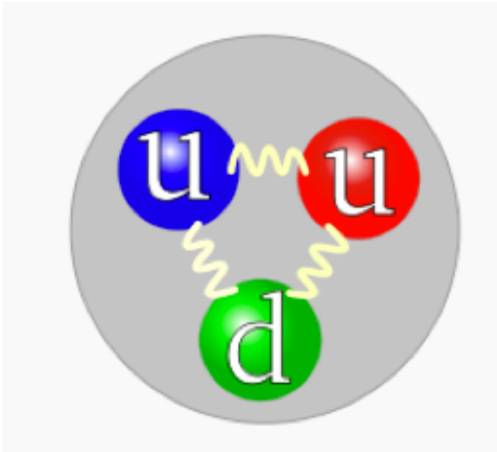
• Electrons would have an anti-electron, “positron, which would have the same mass, but opposite charge and spin.

• When an electron and anti-electron meet they would interact and annihilate each other while creating a gamma ray.



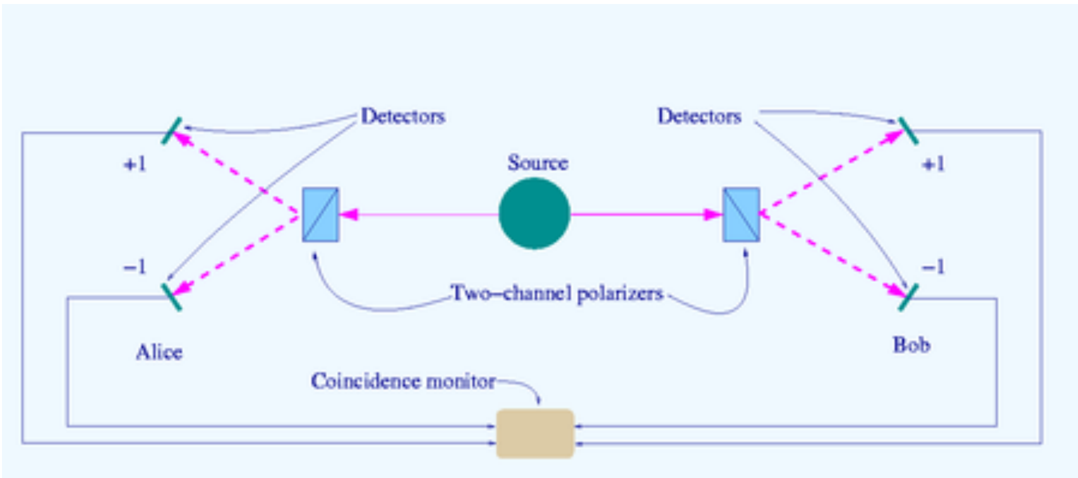
Antimatter produced in the atmosphere.

Quarks and strings:



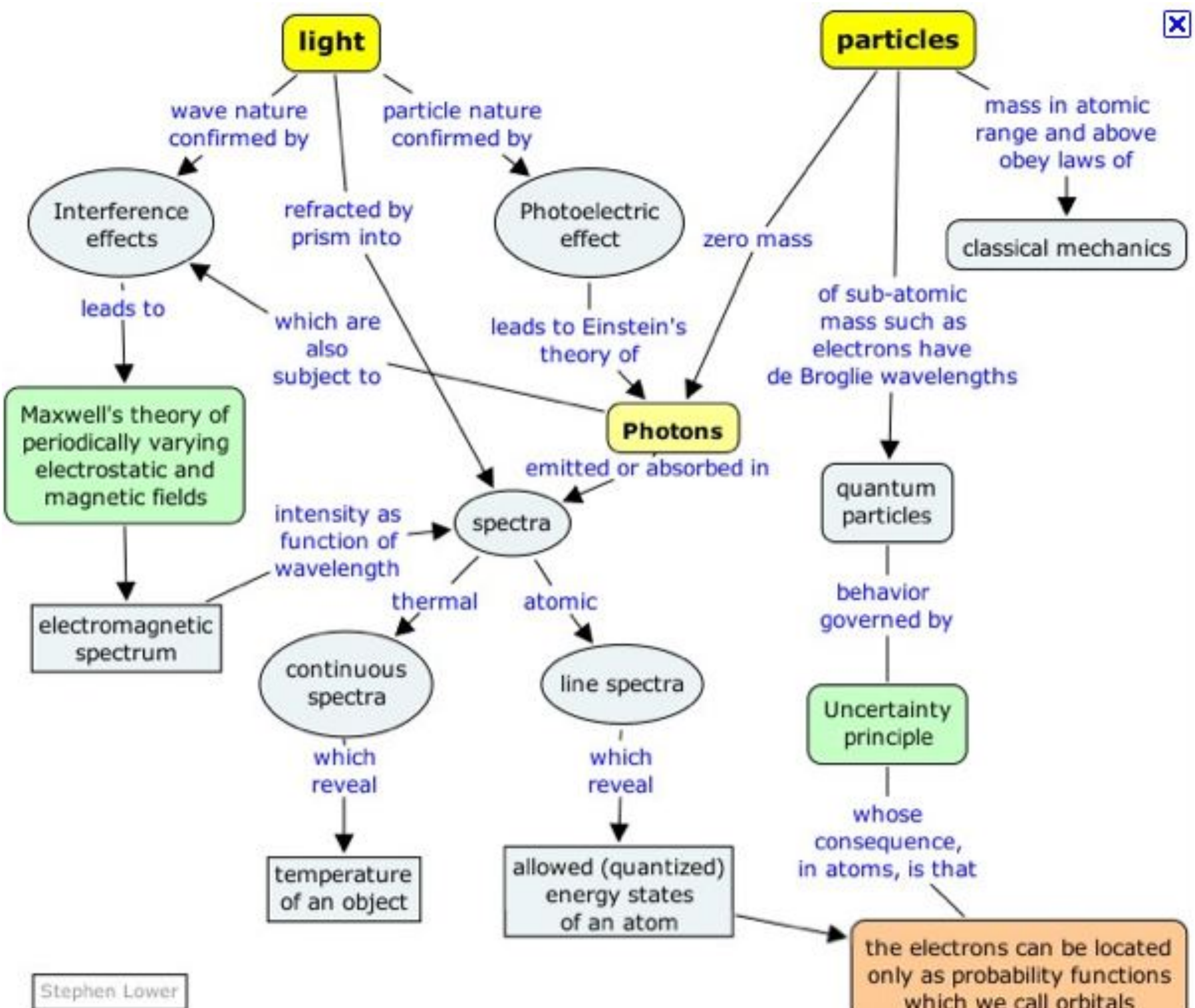
Bell's Theorem & Entanglement

Paul Dirac, a great physicist and mathematician, tried to formulate a wave equation that combined quantum mechanics and special relativity



Relation about the particle/wave nature of light

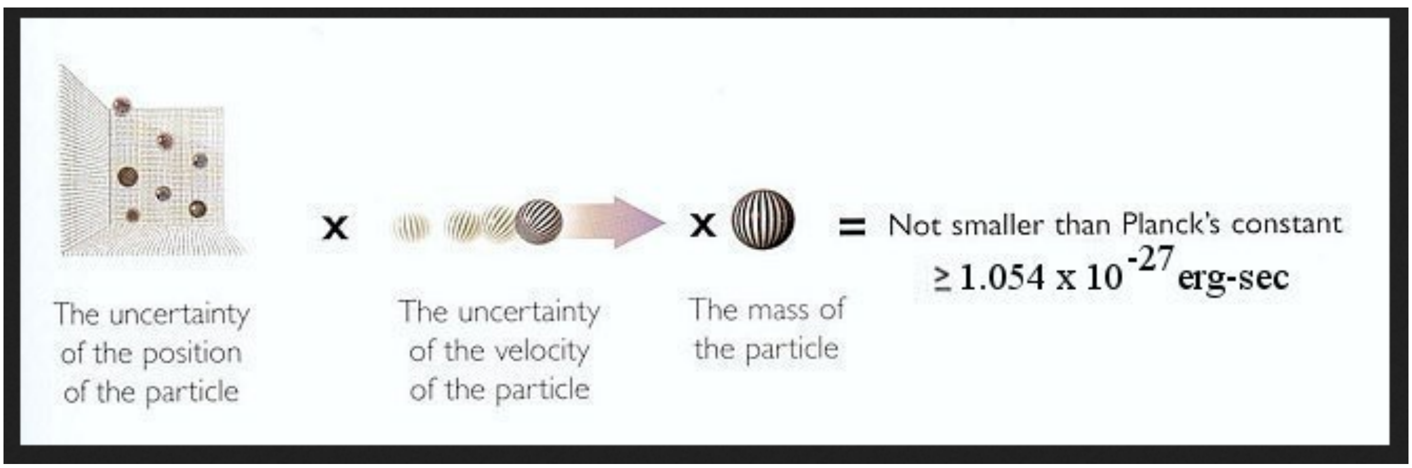
Diagram of wave-particle duality:



Quantum Fluctuation

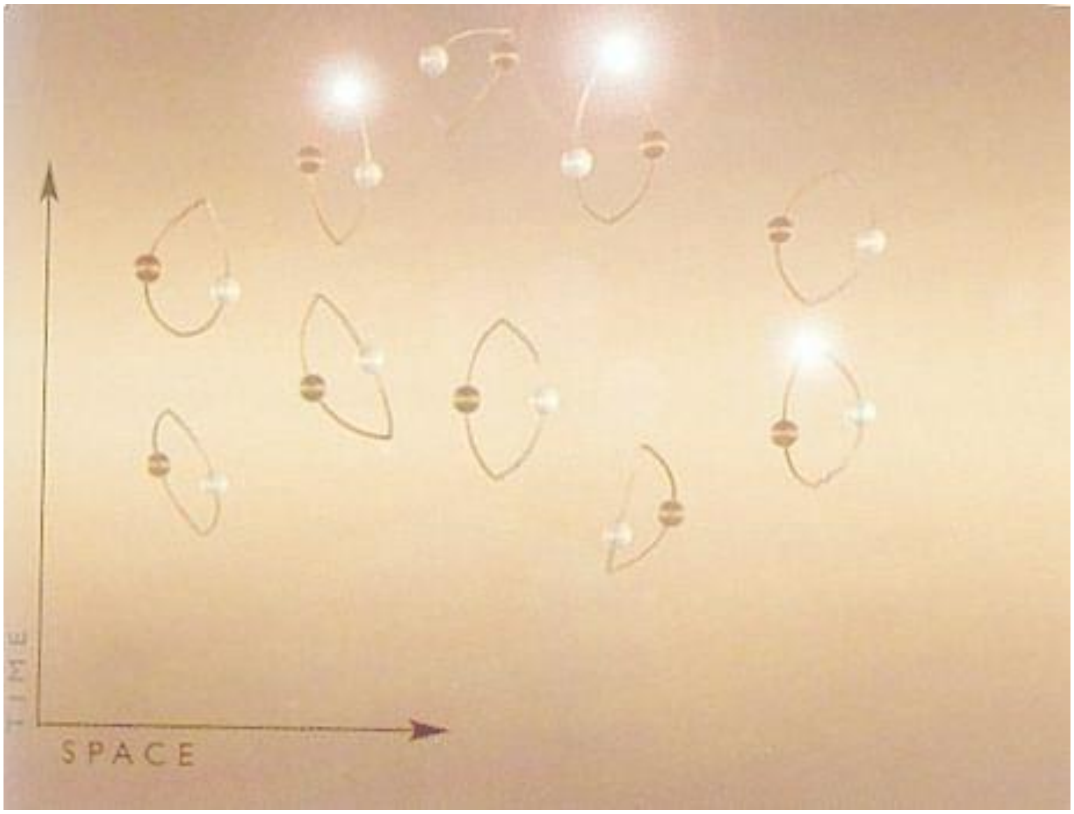
Quantum fluctuation is the temporary appearance of energetic particles out of nothing, as allowed by the Uncertainty Principle. It is synonymous with vacuum fluctuation.

The Uncertainty Principle states that for a pair of conjugate variables such as position/momentum and energy/time, it is impossible to have a precisely determined value of each member of the pair at the same time. For example, a particle pair can pop out of the vacuum during a very short time interval.



The uncertainty principle is illustrated with a schematic representation on the left. An extension is applicable to the "uncertainty in time" and "uncertainty in energy" (including the rest mass energy mc^2). When the mass is very large (such as a macroscopic object), the uncertainties and thus the quantum effect become very small, classical physics is applicable once more.

In classical physics (applicable to macroscopic phenomena), empty space-time is called the vacuum. The classical vacuum is utterly featureless. However, in quantum mechanics (applicable to microscopic phenomena), the vacuum is a much more complex entity. It is far from featureless and far from empty. The quantum vacuum is just one particular state of a quantum field (corresponding to some particles). It is the quantum mechanical state in which no field quanta are excited, that is, no particles are present. Hence, it is the "ground state" of the quantum field, the state of minimum energy. The picture on the left illustrates the kind of activities going on in a quantum vacuum. It shows particle pairs appear, lead a brief existence, and then annihilate one another in accordance with the Uncertainty Principle.



Frontiers of Elementary Particles & Cosmology

Particle physics:

- Quantum gravity; Space-time foam?; Plank length, 10^{-35} m
- Higgs Boson; that which gave mass to particles after the time of particles of no mass and trailing at C
- Strings;
- Dark energy & dark matter
- banes and higher dimensions