EVOLUTION OF ELEMENTARY PARTICLE PHYSICS IN THE 20TH CENTURY

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Summary

The history of physics from the middle of the 19th century until 2000 is presented. The dominant drive for the development is related to the creation of Quantum Mechanics in the first half of the 20th century. New concepts like the particle-wave duality and the definition of an elementary particle are discussed. The explosion of the number of particles, due to new accelerators, led to the theory of particles as we know it today. Future possible developments are indicated.

1. Introduction

Quantum mechanics became one hundred years old at the end of the twentieth century. We will soon celebrate the one hundredth anniversary of the special theory of relativity in 2005. Together with the general theory of relativity, these three are the fundamental pillars of 20th Century Physics and have changed our views of Nature in a most profound way.

In the early 20th century, X rays were so mysterious that they accordingly earned their name; the radiation of hot bodies was not understood; light emission by chemical elements presented a major quest, and the existence of the atom itself was not well established. Physics relied on Newtonian mechanics, Maxwell's electromagnetism and Boltzmann's statistical physics, all of them forming the basis of what is now called classical physics. But classical physics was unable to cope with the issues mentioned above.

In what follows we shall recount some of the highlights of the story of physics in the 20th century. We shall describe a set of discoveries that opened the way to our understanding of the microscopic world, from atoms to superstrings. We hope that this brief account of the history and evolution of elementary particles physics in the last hundred years serves the purpose of providing enthusiasm to the general reader, so that he gets interested in looking for a more profound level of understanding of today's physical theories and experiments.

2. Atoms, Nuclei and Radioactivity

When the first international scientific congress met in Karlsruhe in 1860, the difference between an atom and a molecule, which is a collection of atoms, became clear. The ideas of Dalton, capable of explaining Proust law and leading to the Atomic Table of Elements as proposed by Mendeleyev, put forward the XIX century chemist's idea of an atom -an indivisible particle, heir of the Democritus creature in the fifth century B.C.-. With the spectroscope, invented by the German scientists Bunsen and Kirchhoff, it was shown that the atoms corresponding to different chemical elements emit light with a set of characteristic frequencies. This set of frequencies was called the spectrum of the atom that serves as its optical footprint. Understanding this atomic spectrum is one of the many aims of modern atomic theory.

With these ideas in mind, scientists reached the end of the 19th century. Then, in 1895, Roentgen discovered a mysterious and penetrating radiation he called X-ray. He produced these rays by manipulating a cathode ray tube, called Crookes tube at that time. J.J. Thomson, with the same apparatus, established that cathode rays are in fact negatively charged particles, thereby discovering the first elementary particle known to mankind: the electron. This discovery suggested that the atom was not indivisible, and that it was not an elementary particle, so Thomson thought the atom to be a sphere of homogeneously distributed positive charge in which the electrons were located, as the raisins in a pudding cake. As a by-product, this discovery also provided the explanation for the origin of X-rays in the cathode ray tube which is produced when the electrons are suddenly decelerated by colliding with the tube screen.

Around the same period, Henri Becquerel and Pierre and Marie Curie, working in Paris, discovered another mysterious type of radiation. Ernest Rutherford, a great experimenter born in New Zealand, classified the newly arrived radiations in three categories: α, β and γ. He showed that the first class consists of particles similar to helium, that β radiation is made of electrons and that γ rays have the same nature as X rays, being in fact electromagnetic radiation but with a higher penetrating power and larger energy.

In the same way as Birchhoff and Bunsen, who used light to perform chemical analysis with their spectroscope, Rutherford used α-particles to analyze the atom. When these particles were thrown against thin gold sheets, it was surprisingly found that some of the particles bounced, as if they had collided with a very massive, positively charged particle located in a small region within the atom. This led to the discovery of the atomic nucleus in 1911 and to a model for the atom that resembles a miniature solar system: the nucleus plays the role of the Sun, and the electrons revolving around it play the role of the planets. Instead of the gravitational force that links the planets to the Sun, the attraction between nucleus and electrons was provided by the electric Coulomb force.

3. Ultraviolet and Atomic Catastrophes

Meanwhile, theoreticians were also working hard. The great German theoretical physicist Max Planck made a seminal contribution in 1900. To explain the black body radiation, with its ultraviolet catastrophe, he had to assume that the energy of electromagnetic waves comes in packets, which he called quanta. Five years later, Einstein explained the photoelectric effect using the same idea. Light is formed by photons, whose energy is linked to the frequency v of the electromagnetic wave through Planck's constant h:

$$E=hv. \quad (1)$$

The value of h, necessary to explain the experimental data in both cases is extremely small when units appropriate to deal with ordinary life phenomena are used. In fact, in the units of the International Unit System,

$$h= 6.625 \times 10^{-34}\ \mathrm{kg{\cdot}m^2/s^2} \quad (2)$$

That h be so small explains many facts, in particular why Newtonian mechanics is a correct description of the motion of macroscopic bodies and why a new physics is indispensable when very light particles, such as the electron, are dealt with.

After the discovery of the nucleus by Rutherford and his proposal of a planetary model for the atom, another catastrophe was left unexplained. According to classical physics, when an electric charge is accelerated it emits electromagnetic radiation, thereby loosing energy. Therefore, so do electrons when circling around the nucleus. This will mean that eventually electrons loose their energy and tend to fall into the nucleus, which will lead us to think that the atom is not stable, a prediction which is obviously unsustainable. Furthermore, according to classical ideas, the frequency of the emitted radiation would change continuously, so in Rutherford's model the observed atomic spectrum, formed by a set of discrete frequencies, is not predicted.

4. Quantum Mechanics

A young Danish physicist, Niels Bohr, was the first to propose in 1913 an *ad hoc* explanation to solve these mysteries. Among all possible orbits of the electron around the nucleus, some have a peculiar property. These orbits are stationary and the electron remains there if it is not perturbed. The atom emits light only when the electron passes from one stationary orbit to another which is also stationary. The emitted light frequency *v* is again linked to Planck constant *h: hv* is given by the energy difference between the stationary orbits. With this simple hypothesis, Bohr could explain the spectrum of the hydrogen atom. In any case, *h* appears again, now in connection with atomic physics.

Bohr's ideas were important, but by themselves they did not constitute a theory for the atomic world. This theory started getting in a good shape when added to another far reaching idea, this time from the French nobleman Louis de Broglie, who proposed in 1924 that to each particle moving with momentum *p*, a wave with wavelength equal to $\lambda=h/p$ should be associated. This gave rise to the wave-particle duality, a question which seemed to be solved on and off along the whole twentieth century.

The associated De Broglie wave was assumed only for a free particle. Two years later, the Austrian physicist Erwin Schrödinger extended this assumption to electrons within the atom. Bohr's stationary orbits would correspond to those orbits for which an integer number of the electron's wavelength λ could accommodate in the perimeter of the orbit. This is possible only for certain values of λ, therefore of the momentum and, of course, of the energy. Discrete values of the energy appeared naturally so we now had a deeper understanding of the atomic spectrum.

Wave-particle duality is not easy to swallow. Indeed, to define a particle, which is a material point such as an electron, a set of operations that are definitely opposed to those operations necessary to define a wave are required. The most important step to solve this paradox was taken by a young German physicist, Werner Heisenberg, when he postulated the uncertainty principle in 1924. According to this principle it is impossible to define simultaneously and with unlimited precision the position and momentum of a particle. Heisenberg's uncertainty principle asserts that the momentum indeterminacy multiplied by the position uncertainty is of the order of *h*, Planck's constant again. When *h* is negligible with respect to typical values of the system, as occurs when dealing with macroscopic objects, Heisenberg's principle has no influence. As a consequence, classical mechanics is recovered in the limit $h \to 0$ and so does the idea of a classical orbit. But when the relevant physical quantities are of the same order of magnitude as *h*, as happens with an electron, due to its very small mass equal to 9×10^{-31} kg, the uncertainty principle comes into action and the classical notions loose validity. In particular, it is not possible any more to define an electron's trajectory.

If in a given theory an element is eliminated, a different one should replace it. If the classical trajectories do not exist but are replaced by De Broglie or Schrödinger waves, how is it that these take the place of the old concept of orbit? The answer to this crucial question was given by Max Born, Heisenberg's teacher, who postulated that the wave function ψ associated to a particle provides us with the probability of finding it. In those regions of space where the wave is null, it is impossible to find a particle. In other regions where the amplitude of the wave is different from zero, it is possible that we can locate a particle, although never with absolute certainty. The new mechanics, quantum mechanics, is therefore a probabilistic theory.

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Biographical Sketch

Jorge Flores, obtained Ph,D. in Physics at the National University of Mexico (UNAM) in 1965 and was then a research associate at Princeton University. Since then he has been a professor of physics at the Institute of Physics of UNAM which he directed from 1974 to 1982. He acted as Undersecretary of Higher Education and Scientific Research from 1982 to 1985. In 1988 he was appointed director of Universum, the science museum of UNAM. He is now director of the Centro de Ciencias Fisicas of UNAM. For his work in theoretical physics, mainly on group theoretical methods and random matrices, he was awarded the prize of the Mexican Academy of Science in 1972, the Premio Universidad Nacional in 1988 and the Mexican National Science Prize in 1994. He also received in 1992 the Kalinga Prize for the Popularization of Science awarded by UNESCO.