ELEMENTARY AND FUNDAMENTAL PARTICLES

C.A. Garcia Canal
Laboratorio de Física Teórica, Departamento de Física, Universidad Nacional de La Plata, Argentina.

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Summary

After a brief account of the evolution of the concept of elementariness, the basic ideas of contemporary particle physics are discussed combined with a historical overview. Symmetries as dominant features of the present comprehension of the fundamental interactions of Nature are presented. Future lines of development are sketched.

1. Introduction

ELEMENTARY a. Rudimentary, introductory, simple; (Chem.) not decomposable; ~ y particle, (Phys.) one of several subatomic particles not known to be composed of simpler particles.

ELEMENTARY (adjective) 1. Of, relating to, or constituting the basic, essential, or fundamental part. 2. Of, relating to, or involving the fundamental or simplest aspects of a subject.

ELEMENTAL: Fundamental, primordial, fácil de entender, evidente.

Even if dictionary definitions are in general quite imprecise in physics language, the above entries of the Oxford Dictionary, the American Heritage Dictionary and the Diccionario de la Real Academia Española de la Lengua, respectively, give as a primer, a just impression of what we mean for elementariness in our scientific description of Nature.

The Physics of Elementary and Fundamental Particles has, as its only objective, the description of the basic structure of matter and the elucidation of the ultimate laws of nature. For this reason we can say that in some way or another it underlies all natural sciences. It deals with the relationships among the basic elements that provide the constituent structure of all matter.

This property of the discipline makes it intrinsically different from other areas of knowledge as Mathematics, Chemistry, Biology or History... because what they all have in front of them is, on the contrary, a countless number of problems. This difference should not be understood as a hierarchical order; on the contrary, it proposes a clear challenge.

In front of this conceptualization it is evident that the history of Physics of Particles and Fields is the history of progress, at least we hope it has been, towards a precise and unique objective. The road Physics has followed is that of the elimination of prejudices. As P.A.M. Dirac, one of the fathers of Quantum Mechanics, used to say, big jumps in knowledge and the process of leaving aside prejudices are intimately related.

Matter appears under different qualities, shapes, sizes... otherwise our daily world would be really too monotonous. However, if we start making a more detailed analysis of the material world around us, we rapidly find recurrent qualities. When we want to characterize those qualities we immediately perceive that they are strongly dependent on how deep our observation is, up to what minimum dimensions we have succeeded in exploring the interior of matter. This is the origin of the concept - or *idea* in the Platonic sense - of "elementary particle”. From what we have already said, it is then clear that this is an idea in continuous evolution and therefore we would not get to the final concept of elementary particle.

Each time we manage to explore smaller dimensions inside matter we evolve in our road to elementariness. In this way we hope to obtain an easier and better comprehension of the primordial structure of everything including the living creatures. Let us trace back the “idea” of elementary particle.

2. Historical, Semantic and Formal Aspects

We have to go back as far as Leucipus (VI B.C.) and Democritus (V B.C.) and their idea of non dividable atoms constituting the final recurrent quality of matter. By the way, it is worth mentioning that they were the first physicists frankly materialist in the sense that they exclude the intervention of gods in explaining the Universe. According to this atomistic view, the principles of everything are the vacuum and the atoms, eternal and non divisible whose properties are size, shape and movement. In an alternative position one finds Anaxagoras (V B.C.) who thought that materials were ultimately formed by seeds infinitely divisible into other seeds. For his part, Epicurus (III B.C.) spoke of minimum parts permanently *confined*. Strangely enough, this is a contemporary terminology since confinement is nowadays a characteristic property of some elementary particles.

We also remember Anaximander (VI B.C.), Pythagoras (VI B.C.) and Plato (IV B.C.)

whose preoccupation was to express everything that underlies matter in terms of numbers and symmetries. We are here again in close contact with contemporaneity since our present understanding of the interactions among elementary particles is based on the symmetry considerations which give origin to gauge theories.

We should also mention Isaac Newton (1642-1727) who referred to the idea of elementariness in terms of incomparable toughness, possibly to indicate the impossibility of an eventual following division to go further inside matter.

In any case, this concern about the final constitution of matter is still present. It is necessary to say that all along History and more insistently in recent years, there has appeared an arrogant prejudice, fortunately not a long lasting one, which claims that the search for the basic bricks of nature will be completed in a short time. We think this prejudice should be eliminated so that the interest in the Physics of Elementary Particles will be maintained.

From a formal point of view, we can ask ourselves what we imagine when we speak about particles. If we refer to the classical notion, a particle is an entity whose dimensions are neglected in comparison to the rest of the dimensions in the problem. It is an object, physically point-like, which may be characterized giving its position and its velocity simultaneously. This information allows us to predict, via classical mechanics, its position and velocity at a following instant. In fact, this is the content of the Newton law of Mechanics, namely

$$\vec{F} = m\,\vec{a} = \frac{d\vec{p}}{dt} \qquad (1)$$

This equation, a differential equation, relates the force $\vec{F}$ acting on the particle with the acceleration $\vec{a}$ it acquires, through its mass m; or, using the second equality, with the temporal change of the momentum $\vec{p} = m\vec{v}$. The equation has a unique solution giving the position and velocity of the particle at any time, provided one gives the necessary initial conditions, namely the position and velocity of the particle at the initial instant. The classical particle can then be individualized and followed in its space-time trajectory. This is the image imposed by our everyday prejudices in front of the notion particle. It is, in a sense, the classical prejudice.

When we reach the quantum world, the world of atoms and molecules, the scale of the Angstrom ($1\text{Å} = 10^{-8}\,\text{cm}$), we come across the dilemma of defining, with our macroscopically designed language, what are the basic quantum objects. W. Heisenberg (1925) uncertainty principle tells us that the position and the velocity of a quantum object cannot be known exactly in a simultaneous way. More precisely, the corresponding uncertainties in the position, Δx, and in momentum, Δp, obey the inequality

$$\Delta x\,\Delta p \geq h \qquad (2)$$

with the Planck constant h defining the scale at which the uncertainties are dominant.

The dynamical description of quantum objects, those which behave constrained by the uncertainty principle, is done in terms of the wave theory of E. Schrödinger (1926). Here all the information about the quantum object is contained in the solution, $\psi(x, y, z, t)$ of the Schrödinger equation. This equation, written for simplicity in only one spatial dimension, x, is as follows:

$$-\frac{h^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x,t) + V(x)\psi(x,t) = \imath h\frac{\partial}{\partial t}\psi(x,t). \tag{3}$$

Here $V(x)$ is a potential energy representing the field of forces where the quantum particle is immersed, as for example a Coulomb potential due to the nucleus in the case of an atom. The solution of this wave equation, a partial differential equation, provides information about the position of the particle. In fact, $|\psi(x)|^2$ is the probability density for finding the particle around the position x at the time t. As soon as we have a wave description for a quantum particle, the wave-particle duality concept shows up.

In a sense, this concept only expresses our uneasiness, clearly conditioned by a prejudice: are those quantum objects waves or particles? The answer is: they are neither waves nor particles. If we eliminate the prejudice we can introduce a new term: the “partwave” or “wavepart”.... but, besides being a cacophony, these words do not enhance our comprehension of the phenomenon. In spite of our consciousness of the intrinsic semantic difficulty of the word ‘particle’, at a quantum scale, our conceptualization of things leads us to maintain this word to name the basic quantum objects, even though we realize they are not particles strictly speaking. So we stole the word particle from classical physics aware of the inaccuracy of its quantum meaning. The quantum particle described by the Schrödinger equations lacks a trajectory due to the uncertainty principle.

Between 1924 and 1926 there was an eclosion of the atomic theory, once it was coherently structured in terms of quantum mechanics. It was able to account for the matter stability and the atom identity of a given chemical element. In fact, the atomic theory correctly describes from macroscopic matter to molecules, atoms and its parts: nucleus and electrons, together with the atomic spectra. Moreover, based on the atom mechanics we now understand the subtleties of the condensed matter, the interactions between matter and energy, the superconductivity, the magnetism of matter and even the following step in elementariness, namely the elementary particles.

In any case, we have kept the name “particle” to refer not only to atoms but also to parts of atoms: electrons and nucleons. We have gone even further and maintained the idea of *particle* to refer to components of atomic nuclei: protons and neutrons. We have to perceive that not only we “evolve” with the idea of “elementary particle” when we go from the classical world to the quantum world but that in the latter environment we go into smaller and smaller distances, being already at the level of elementariness of electrons and nucleons (nuclear particles).

At this point, we must remember the connection between Relativity Theory and Quantum Mechanics, because the outcome of this union is the concept of antiparticle.

We have here again an abuse of the language.

In fact, the well known equation

$$E = mc^2, \qquad (4)$$

should be read saying that energy is equal to matter plus antimatter. In effect, there appears the energy, E, that has no labels, for example electric charge or any other, while matter is characterized by those charges. The simultaneous requirements of relativity and quantum mechanics impose the presence in nature of new entities entirely similar to particles with almost all of their features identical, except for a few labels (quantum numbers in the physics jargon) such as the electrical charge, the baryon number or the lepton number. Associated to the electron, there is the antielectron or positron, which is almost identical to the electron, with exactly the same mass, but with a positive electric charge and an opposite lepton number. In relation with the proton, there is the antiproton with a negative charge and opposite baryon number. Therefore, in front of each "particle" we have an antiparticle, the exceptions being the cases in which particle and antiparticle coincide as is the case with the neutral pion, and the photon. In the 1960's the "elementary particle", comprised three main categories: leptons which were the electron, the electron neutrino and the family constituted by the muon and the muon neutrino; hadrons, which experience strong nuclear interactions, subdivided in baryons (of large weight) such as the neutron, the proton and the delta, and mesons (of medium weight) such as pion, kaon, rho, omega, etc.; and finally the photon mediator of the electromagnetic interaction. With the above mentioned "particle" it is possible to build the whole matter that surrounds us daily, including ourselves.

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Biographical Sketch

Carlos Garcia Canal, obtained Licentiate in Physics and Doctor in Physics respectively in 1965 and 1967 both from National University of La Plata. He is presently a Professor in the Department of Physics, National University of La Plata, Argentina and Member of the National Research Council of Argentina as a Superior Researcher.He won many awards which include the First Prize "University Promotion" awarded by the Secretary of Culture, Buenos Aires Province, 1968 jointly with Huner Fanchiotti; First Prize "Coca Cola in the Arts and the Sciences" Physics 1981-1982. jointly with R. Baragiola, G. Dussel and A. Kreiner; - Houssay Prize1987 Category A, awarded by the National Research Council of Argentina; John S. Guggenheim Memorial Foundation Fellowship. 3/1989 - 2/1990; - "National Academy of Exact, Physical and Natural Sciences, Teófilo Isnardi" Prize 1992; “Prize Houssay of the Science and Technology Secretary of Argentina 2003" Trajectory in Physics First Edition. and Antorchas Fellowship, 1992.He was "E. A. de Moshinsky" Professor, Instituto de Física, Univ.Nacional Autónoma de México, 1992. He is an Associate Member of the Third World Academy of Sciences, Centro Brasileiro de Pesquisas Físicas, Brazil; Member of the Brazilian Academy of Sciences from 11/1997and Associate Member of the International Centre for Theoretical Physics, Trieste, Italy, 1984/89.