About the concept of particle: an introduction

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Abstract - ***In this paper we consider important aspects characterizing the physical concept of particle. Starting by a possible definition, we deal with classical and quantum aspects of particles, reality and dimensionality. We considering then theoretical developments related to the gravitational interaction about the notion of particle in quantum field theories (QFT) and how the concept of "point-like particle" changes in consideration to the recent theories of unification of forces in physics, in particular in relation to superstring theories and quantum gravity.***

Key Words: *Particle, Space, Time, Theoretical Physics, Quantum Field Theory, Superstring Theory, Quantum Gravity, Philosophy of Science.*

1. INTRODUCTION

If we search on a vocabulary the word "particle", we find explanations like "subatomic constituent of the matter, considered without own internal structure and therefore indivisible" [1] or "constituent of matter without further structure and indivisible" [2].
Also avoiding an etymological-semantic analysis of the word, it seems evident the problematic of such concept. In this paper some important aspects characterizing the concept of particle are presented. Starting from classical physics, we will do interesting consideration about the concept of "virtual particle", the problem of particle dimension, considerations related to superstring theories, quantum field theories (QFT) and quantm gravity.

2. STABILITY, MASS, EXCITED STATES

It could be called "particle" a single coherent object which has a defined identity and that can be localized in a limited region of space at a given instant. The particle is characterized by defined physical attributes and it is stable when alone in space [3].
Such a criterion, which seems at a first glance very good, reveals problems at a careful analysis; on fact not only stable nuclei, but even neutral atoms and ions in their ground states, as well as molecules and molecular ions, meet these criteria. On the contrary, it should to be excluded objects such as unstable nuclei with half lives of thousands years, then "almost" stable. The neutron should be excluded, since its average life, when it is free, is 1.01×10^{3} s. If we experimentally study a phenomenon in a time interval which is less than this value, the neutron behaves as a stable particle. The concept of "stability" of an elementary particle is therefore a not so clear concept.
The same can be said for the concept of "defined mass". If a particle has an finite average life τ, the rest energy of the particle is defined up to an uncertainty of order of $\hbar/\tau$. The uncertainty of its rest mass will be therefore of order of:

$$\Delta m \cong \frac{\hbar}{\tau c^2} \tag{1}$$

By calculating these Δm we note that they are small quantities, if compared to the rest mass of the particles, even for particles with a small average life. However, these quantities are different from zero.
Let's consider now the "excited states" of nuclei, atoms, molecules. The experimental determination of these states, i.e. the different energy levels from the ground states, manifests them as resonances in diffusion processes. The efficiency curves for a reaction represent the cross sections as a function of energy. The sharp peaks reveal the positions of the excited states. These peaks have a width which provides a measure of the energy indetermination of the corresponding excited

state. These excited states are considered "particles", according to the fact that a "close resonance" defines a particle. Also in this case, the general concept of "width" of a resonance becomes delicate.
Therefore it is not easy, nor perhaps beneficial, to try a precise definition of what we mean for "particle". In practice, it may be interesting to think to a hierarchy of "more and more elementary" particles. In every case the notion of "elementary constituent" is linked to the type of investigated physical phenomenon [4].

3. VIRTUAL PARTICLES

The concept of "virtual particle" is born with quantum field theory in the context of perturbation series [5]; there are indeed quantities that are calculated through the sum of an infinite series of mathematical terms. An example is given by the probability of a process of annichilation-creation of particles.
The physical meaning resides in the sum of the series. The individual terms of the series can contain infinities; "removing" these infinities, we get a theory called "renormalized". For a virtual particle it doesn't hold the relation:

$$E=\sqrt{p^2c^2+m^2c^4} \qquad (2)$$

with E the energy of the particle, p its moment and c the speed of light. This equation is one of the most important consequences of the theory of Einstein relativity. Every physical "real" object obeys that law. The existence of "virtual" particles, however, is expected by the theories which melt relativity with quantum mechanics. In technical terms, we say that these particles are not on their "mass shell". The Heisenberg uncertainty principle, one of the fundamental relations of quantum theory, states that it is not possible to simultaneously measure with arbitrary precision the position and the velocity of a particle; the same can be said for energy and time:

$$\Delta x \Delta p \geq \hbar/2 \qquad (3)$$

$$\Delta E \Delta t \geq \hbar/2 \qquad (4)$$

Relations (3) and (4) hold even using the best available devices, being independent from any particular equipment and any measurement procedure. These relations do not impose pratically restriction to a macroscopic body; at atomic and subatomic scale, however, the concept of classical particle must be left.
For the determination of motion of a classical particle, on which act known forces, we suppose that the initial conditions can be exactly determined and that the operation of measurement have a negligible effect on the motion. If this concept is applied to an electron or a photon, the situation loses such clarity.
Virtual particles, for a short time interval, violate the conservation of the energy. If a virtual particle interacts with another one, it can become real. If we consider the recent developments in theoretical physics, in particular quantum field theories, virtual particles are however important and significant [6].
An interaction between two charged particles, such as two electrons, occurs through the exchange of a virtual photon. In a similar way, weak interactions are mediated by the exchange of virtual bosons. Evaluating the energy involved in these processes, we note that there is not sufficient energy to produce such "real" particles, but only particles, which are far from their mass shell.

4. POINT-LIKE PARTICLES?

One of the fundamental problems of elementary particle physics concerns the apparent incompatibility between the two theories constituting the pillars of modern physics: Einstein's General Relativity and Quantum Mechanics [7].
Attempts to create the unification of forces led to theories that unify three of the four known forces of nature: the electromagnetic interaction, weak and strong forces. The major obstacle is always resulted the incompatibility of Einstein's theory of gravity with quantum mechanics.
The most serious difficulties arise on scales of minimum distance and point to a reformulation of the physical laws; this approach brought to a revision of the concepts of space and time as continuous sets of points [8].
Among the attempts to overcome the emerged problems, great importance had the so-called "string theories", or "superstring theories", in the version that considers a new symmetry, studied since 1974, and known as "supersymmetry".

These theories incorporate general relativity and overcome the problem of infinities at small range related to quantum field theories [7,9].
One of the big news of these theories concerns the fact that the coordinates of the material point are replaced with the coordinates of a one-dimensional structure, just called "string" or "superstring", in the case of a supersymmetric theory.
The characteristic size of a string is of order of the Planck length:

$$l_{Planck} = \sqrt{\frac{\hbar G_N}{c^3}} \cong 10^{-33} cm \quad (5)$$

i.e. 20 orders of magnitude smaller than the characteristic dimension of hadrons.
The space-time history of a string is described by functions $X^{\mu}(\sigma,\tau)$, which describe how the two-dimensional "world sheet" of the string, represented by the coordinates (σ,τ), is mapped into the space-time X^{μ}. Therefore in these (super)string theories the elementary particles differ from that of ordinary quantum field theories, since they are considered not more point-like. A string, having a length, can vibrate and the vibration modes are determined by its tension.
In quantum mechanics the same phenomenon has both a wave and a particle aspect, therefore each vibrational mode of a string corresponds to a particle. The vibration frequency determines the mass and the energy of the particle; the common elementary particles are interpreted as different vibrational modes of the string.
Avoiding with superstring theories the previously described problems in combining quantum mechanics with gravity, it is possible to treat the four fundamental forces as different aspects of the same fundamental principle. Neglecting on the contrary the gravity, it is possible to build unified theories of electromagnetic, strong and weak forces in a single field theory, with point-like quanta.
Superstring theories bring also new ideas concerning the geometry of the universe. They must approximate to the gravitation theory of Einstein in four-dimensional continuum "space-time". Gravity force determines the curvature of space-time; a particle moves along a path said "geodesic" [10]. A particle influences "geometrically" the space-time, perturbing the same geodesic along which it is moving.
In string theories the particles, being no longer considered point-like, move on a surface; these surfaces, in analogy to geodetics, are of minimal area. These theories are conceived in ten (eleven) dimensions; six (seven) extra-dimensions are not visible and "curled-up" in a structure of size of the Planck length, similar (but not equal) to an ipersphere, called "Calabi-Yau spaces" [11-13].

5. QUANTUM FIELD THEORIES AND QUANTUM GRAVITY

In quantum field theories the notion of particle has been debated in particular in relation to theoretical developments on the gravitational interaction. In general, on a curved space-time, uniquely-defined particle states don't exist. Still more generally, particle states are difficult to be defined in a background-independent quantum theory of gravity.
These problems suggested that quantum field theories would not be interpreted as theories of particle states, but better as eigenstates of local operators, i.e. eigenvectors associated with the operator of the observable in the Hilbert space. But it is not obvious how to reconcile this viewpoint with the empirical observed particle-like behaviour in experimental high-energy physics [14,15].
Already in flat space there exist two different notions of particles:

a) globally defined *n*-particle Fock-states: in quantum mechanics a "Fock-state" is a state of the Fock space with a defined number of particles in each state. If we limit for simplicity to a single mode, a Fock-state is defined as $|n\rangle$, with n integer number, i.e. there are n quanta of excitation in this mode. The Fock-states form the most convenient algebraic basis of the Fock space. They are defined so as to satisfy the particular relations in the algebra of bosons and fermions [16];

b) local particle states: this point of view describes the physical objects detected through finite-size particle detectors, considering eigenstates of local field operators. The particles, which are detected by experimental measuring equipments, are local objects, so they are best represented by states of quantum field theories, that are eigenstates of local operators, therefore local particle states. But usually in quantum field theories the observed particles in experimental detectors are represented as global particle states such as the *n*-particle Fock states. Global particle states well approximate local particle states; the distinction between global and local states can be neglected in real utilizations of quantum field theory. Understanding a particle as eigenstate of local operators, without correlation to global features, we have a notion of particle which is in general well defined.
It seems viable also the idea of considering a notion of particle for boundary formulations of quantum field theory, which are related to recent calculations of *n*-point functions in quantum gravity [17].

Particles described by the n-particle Fock states are idealizations that do not correspond to the real objects detected in the detectors. Therefore it is difficult to view them as the fundamental objects described by quantum field theories [18].
We have no reason for interpreting the Fock basis as "more physical" or "more close to reality" than any other basis in the state space of quantum field theories, also because the Fock number operator is not measured [19,20].

6. CONCLUSIONS

In this paper we considered interesting aspects which characterize the concept of particle for physics. Starting from the fact that already a possible definition of particle is not easy to give, classical and quantum aspects of particles bring to further difficulties. The concept of "point-like particle" has changed with the development of recent physics theories of unification, in particular superstring theories and quantum gravity.
The existence of a particle depends on what it is decided to measure; therefore there is no reason to select an observable as "more real" than the others. A Fock particle state can be replaced with a local particle state, which is more coherent with the basic rules of quantum mechanics. Following this way it is possible to extend methods of quantum field theories to more general contexts.
Global particle states, such as Fock particle states, are defined at theoretical level, but with experiments each finite size detector defines its own set of local particle states.

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BIOGRAPHY

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