Committee I
The Limits of Science?

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COMMENTS ON SPACE, TIME, AND ENERGY LIMITS

by

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to **George Marx's**

SPACE, TIME AND ENERGY LIMITS

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SPACE, TIME AND ENERGY LIMITS

Comments by Marcelo Alonso
on the paper by George Marx

In his paper George Marx examines three of the more exciting concerns of contemporary physics, that fall in the cathegory of "physical" limits of science: How small in space ($r \to 0$), how far back in time ($t \to 0$), and how high in energy ($E \to \infty$) can we reach in exploring the universe. It is hard to add something meaningful to the ideas that he has expressed so clearly and precisely. Thus I will restrict my comments to a few points emphasizing the conceptual rather than the physical limits.

Going deeper into smaller regions of space is important because our intense curiosity to decipher the ultimate structure of matter. Going back in time is important because our desire to relate the universe as we know it today with its origin about 15 billion years ago, presumably in a Big Bang. And pushing for higher energies is important because it reveals an underlying dynamic phenomenology of creation and destruction of particles that is not apparent in our sensorial perception of the universe, but that played a key role in its evolution. Also the higher we push the particles energies the closer we get to the early conditions of the universe.

There are severe "technical" limits to reaching those three goals because they require elaborate and complex experimental, observational and measuring methods, such as huge particle accelerators and detectors that are sophisticated and costly. But perhaps more serious are the "*conceptual*" limits imposed by our inherent difficulty in visualizing what is so far removed from our direct sensorial experience. We want to reach distances smaller than 10^-15 m, time intervals shorter than 10^-32 s, and energies larger than 10^18 eV, when in our daily life we deal with distances of the order of a few meters, time intervals in general larger than a few seconds, and energies of a few eV at the most.

We are used to call a "*particle*" something that is very small, such as grain of sand or a speck of dust. But, as Marx mentions in his paper, for over two centuries the notion of "particle" has been used in classical physics as a convenient idealization, stemming from "materializing" the notion of geometric point, without posing any conceptual problem. The "*classical particle*" was invented to describe the motion of bodies when their shapes, dimensions and internal structure could be ignored, and therefore it does not imply an intrinsically small body. Thus, in a first approximation, the Earth can be treated as a "particle" in its motion around the Sun, and the Sun in turn can be considered as a "particle" in its motion around the Galaxy. A highly successful formalism, called *classical mechanics*, was developed during the 18th and 19th centuries by Newton, Lagrange, Hamilton and many others, who introduced useful concepts such as mass, momentum, angular momentum and energy to analyze the motion of "particles".

A different situation occurs when dealing with entities that are localized in very small regions, say smaller than 10^-10 m, designated "fundamental particles", such as electrons, mesons, nucleons, even photons. We still can attach to the "fundamental particles" the same attributes (mass, charge, momentum, energy, etc.) used in classical mechanics to describe the motion of the classical macroscopic "particles". (This is due in part because those attributes are related to symmetries in space-time that are above the sensorial picture of "particle"). Even more, we still can apply the methods of classical mechanics to describe the behavior of "fundamental particles" when they are in an environment much larger than their "sizes", and treat them as classical "particles". That applies for example to electrons in a TV tube or protons in an accelerator. However the classical notion of "particle" collapses when we want to describe the behavior of a "fundamental particle" in a small environment, such as an electron inside an atom or moving through a crystal lattice, or a fast proton hitting a target. This collapse of the classical picture of "particle" when applied to a "fundamental particle" has forced physicists to introduce new ideas for the description of the motion of "fundamental particles".

The most radical conceptual revolution, initiated in 1924 by L. de Broglie and elaborated in more detail since 1926 by E. Schrödinger and others, has been to recognize that "fundamental particles" must be described by a field, a "matter field", unfortunately called the wave function, dependent on space and time and designated $\psi(\underset{\sim}{r},t)$. This amounts to renounce to the notion of localization in the sense of that of a classical "particle". The formalism to describe this new situation is called quantum theory, which so far has proved to be highly successful. At low energies the matter field of a "fundamental particle" associated with a particular physical situation is obtained by solving the time-dependent Schrodinger equation

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V(\underset{\sim}{r})\;\psi = i\hbar\frac{\partial\psi}{\partial t}.$$

The physical environment is given by the potential energy function $V(\underset{\sim}{r})$. This equation is different, in several respects, from the standard wave equation

$$\nabla^2 f = \frac{1}{c^2}\frac{\partial^2 f}{\partial t^2},$$

satisfied by electromagnetic and elastic waves. One is the presence of the potential energy $V(\underset{\sim}{r})$, that amounts to a dispersive medium. Another is that it is of first order in time (which is also the case of transport equations, such as heat transfer). And the third is the presence of the imaginary factor "i" multiplying $\partial\psi/\partial t$ (which is not the case of transport equations). The immediate conclusion is that the matter field is essentially different from an electromagnetic or an elastic wave. Another consequence is that the matter field is necessarily a complex function of time of the form $\exp - i\omega t$, where $\omega = 2\pi\nu$ is related to the energy of the "particle" by the well known relation $E = \hbar\omega$, as mentioned by Marx. In addition the matter field $\psi(\underset{\sim}{r},t)$ itself is not a physical observable; the observable quantity is $|\psi(r,t)|^2$, which is a real quantity. However $\psi(\underset{\sim}{r},t)$ can be used to obtain information about the physical properties of the system, according to the rules of quantum mechanics.

In the case of a "free" particle, with $V(\underset{\sim}{r}) \equiv 0$, which is the simplest physical situation, the matter field is given by $\exp -i(\omega t \pm kx)$, where k is related to the momentum by $p = \hbar k$ (see also Marx). This represents a field propagating with constant amplitude and phase velocity $v = \omega/k$, and therefore no localization. This is where any similarity between the matter field and electromagnetic or elastic waves ends.

In the presence of a potential energy $V(\underset{\sim}{r})$ the time-dependent part of the matter field is still given by $\exp - iEt/\hbar$, but the space part is different from that of a free particle and depends on the form of $V(\underset{\sim}{r})$. In this case we may have a <u>stationary</u> field or a <u>travelling</u> field. A stationary field is the appropriate form for describing the state of a "fundamental particle" constrained to move within a limited region of space, such as an electron in an atom or a nucleon in a nucleus. A travelling field must be used to describe the state of an unbound "fundamental particle", such as an unbound electron or proton accelerated by an electric field or subject to a magnetic field. A new situation occurs in this case.

First the traveling matter field is affected by the potential energy in the region through which it propagates, as it happens in scattering experiments. This gives rise to interference-like and diffraction-like situations, such as when electrons or neutrons move through a crystal lattice or when electrons hit a screen with one or several slits of the proper dimensions. There is nothing mysterious about these phenomena because the matter field by its own nature is extended in space and the screen with slits is equivalent to a singular potential energy. Consequently situations such as the much discussed double slit experiment do not have the "metaphysical" implications that some ascribe to them.

Second to have a traveling matter field localized in space, which is what is called a pulse in the case of electromagnetic and elastic waves, it is necessary to use the mathematical procedure of combining matter fields of various frequencies and amplitudes. This is equivalent to say that a localized "fundamental particle" has neither well defined energy nor momentum. Therefore localization at the level of "fundamental particles" can be achieved only at the expense of losing information about some dynamical variables. This is a basic law of nature, expressed quantitatively by Heisenberg's uncertainty principle.

The conclusion is that neither the classical geometric concept of "particle" nor our macroscopic perception of "waves" are applicable to describe a "fundamental particle", as Marx correctly points out. By the same token a "fundamental particle" is not a misterious combination of "particle" and "wave" natures, that manifests one way or the other depending on how we push it in our laboratory. This is not philosophy, as Marx seems to imply. The problem is that unfortunately philosophers (including many good scientists) have confused the issue by talking about the particle-wave "duality". This I consider total nonsense consequence of not recognizing our mental "limitations" for describing situations beyond our direct sensorial perceptions. In this respect Marx statement that an "electron propagates like a wave and hits like a bullet" is very descriptive but for my taste goes too far because its dualistic implication.

The proper scientific position is that "fundamental particles" are entities beyond our direct sensorial experience (even if we are all made of such particles), characterized by certain parameters (mass, charge, spin, etc.) and described "always and in all circumstances" by a matter field which is determined by the physical environment. Whether we can assimilate the behavior of a matter field "pulse" to that of a macroscopic "particle" depends on the size of the region in which we observe it and the type of measurements we perform.

A grain of sand or a speck of dust are [illegible] actually composed of a large number of "fundamental particles", each described by its own matter field. But when they are all put together and their fields properly combined the microscopic finesse of the matter field is lost and the system is truly a "particle" in the macroscopic sense. In the case of an atom, which we normally consider as a macroscopic "particle", albeit composed of a few "fundamental particles" (electrons and nucleus) the aggregate matter field of the electrons has to be taken into account if the atom is confined to a small region, as experiments have shown.

Had this situation been understood correctly from the very beginning of quantum theory, we would have been spared a lot of futile philosophical misinterpretations and discussions. Thus it is good that Marx has brought out this question in his paper. But I repeat this is not a philosophical question; it is a "conceptual limit" of science.

The elaborations in the third and fourth sections of Marx's paper are a direct consequence of the relation between the energy and momentum of a "fundamental particle" and the properties of the matter field ($E = \hbar\omega$, $p = \hbar k$, $\omega = 2\pi\nu$, $k = 2\pi/\lambda$). Exploring the finer structure of matter involves extremely small regions of space, smaller than 10^-15 m., that requires "localized" matter fields with wavelengths of the same order of magnitude or energies much higher than 10^12 eV.

Next I will refer briefly to the problem of time, that Marx considers in the second half of his paper. What is time has been the subject of innumerable scientific and philosophical discussions, and several "kinds" of time have been recognized. The time we perceive or biological time is a sensorial experience completely independent of the notion of space. By extension scientists have used time as an ordering parameter to describe the evolution of a system, independently of the observers and the surroundings of the system. The theory of relativity has changed that assumption by recognizing that time and space are not independent quantities, with their coupling determined by the energy or mass distribution around the observer. This is an assumption in conflict with our sensorial experience but that can be handled in precise mathematical form and verified by delicate measurements.

A more severe extrapolation occurs when we think of "fundamental particles" such as excited hadrons or resonaces, with half lives shorter than 10^-20 s, or wish to look at the events that occurred in very early stages of the universe, at times shorter than 10^-30 s, according to current astrophysical cosmologies. Are we talking about the same time we use presently or just a convenient parameter that appears in expressions such as t·E^2∼ 2.5 x 10^11 s.eV^2, that relates cosmological time with the average energy of the particles in the universe? Does it make sense to talk about t = 0 or t < 0 in connection with the evolution of the universe? The notion of t = 0 makes sense only if the universe had a beginning. Current thinking is that the Big Bang was the origin of time and that it is meaningless to talk about t< 0. This, incidentally, would be a modern version of St. Augustine's statement quoted by Marx (p. 6). And, as S. Hawkins has suggested, if St. Augustine had been asked what could mean t<0 he could have replied that that was the time when God was preparing Hell for those who asked such questions.

Many interesting considerations have been put forward to explain the origin of time. One mentioned by Marx is that the cosmological origin of time (t = 0) is a mathematical singularity "introduced only for computational comfort, and that there could be a quantum mechanical leakage (of cosmical stuff) through the Big Bang". We may think of parallel universes, of leakage through black holes and other exciting ideas which I love to think about but those will remain metaphysical considerations, beyond our present observational and experimental possibilities. The same applies to extremely large periods of time, such of the half life of the proton, about 10^31 yr, or future events that will occur in the further evolution of the universe such as collapse of planetary systems in about 10^15 yr, intergalactic encounters after 10^19 yr, radiative collapse of black holes at about 10^64 yr, and so on, as F. Dyson has suggested. These are times that are beyond our conceptual possibilities, even if we can manage them mathematically. Therefore pushing the notion of time to the extremes of the very small and the very large is another "conceptual limitation" of science.

From the above considerations one can see that Marx is absolutely correct when he says that "space, time and energy limits are just one single limit", even if that statement is hard to understand in simple terms. What is extraordinary is that the human mind has been able to explore in a meaningful though abstract way the extreme limits of the very small and the very large that are way beyond our direct sensorial experience. This to me is one of the most astonishing and unique capabilities of the human intellect. There are no reasons to believe that the human intellect has reached the limit of its evolutionary process, and it is possible that future generations will have a better understanding of such extreme physical limits. However, is society currently prepared to support such intellectual, costly and seemingly esotheric excursions beyond our present limits of perception? This is one aspect of the confrontational issue of "Big Science" vs. "Societal Needs" that is explored in other papers of this Committee. It can be resolved only through a better and more serious and meaningful science education at all levels. This will make all people more aware of the scientific and technical issues faced by modern societies in the context of the overall societal needs and will help to make the right decisions.

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