Foundations of Physics, Vol. 34, No. 12, December 2004 (© 2004)
DOI: 10.1007/s10701-004-1630-5

The Vacuum as Ether in the Last Century

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Received September 7, 2004

In this paper we review the evolution of the concept of "vacuum" according to different theories formulated in the last century, like Quantum Mechanics, Quantum Electrodynamics, Quantum Chromodynamics in Particle Physics and Cosmology. In all these theories a metastable vacuum state is considered which transforms from one state to another according to the energy taken into consideration. It is a "fluid" made up by matter and radiation present in the whole Universe, which may be identified with a modern definition of ether.

KEY WORDS: ether; QM; QED; QCD; cosmology.

1. INTRODUCTION

In the theory of Lorentz, which appeared a year before Einstein's 1905 special relativity publication, it is recognized that a "luminiferous ether" is a "preferred" reference system to which all laws of physics should be referred and the Lorentz transformations allow the description of physical phenomena from one inertial system to another. The need of such an ether was eliminated by Einstein with the postulate that all inertial systems are equivalent. After 1916 and till his death, Einstein reintroduced the concepts of ether which he intended as physical space or field. Nowadays the concept of a relativistic ether which can be identified with a vacuum state is being used by an increasing number of researchers.

2. THE VACUUM IN PARTICLE PHYSICS

In the first quantization, the Heisenberg's uncertainty principle is stating that energy can be uncertain to within a ΔE for a time Δt such that:

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$\Delta E^* \Delta t$ is greater than or equal to $h/4\pi$ and the same is true for $\Delta x^* \Delta p$ for a given particle. If this principle is applied to the Electromagnetic field of vacuum, it turns out that it is impossible for the electrical and the magnetic field be zero at same time; therefore the vacuum is subject to fluctuations, the so called vacuum fluctuations and because of this fact it cannot be considered a static and empty entity as in classical physics, but it is a complex and dynamic one.

In Modern Quantum Mechanics all physical entities are described by fields: the photon is a manifestation of the electromagnetic field, the electron is the manifestation of the electron field and so on. The second quantization in fact is the representation of a field as a summation over its quanta with coefficients specifying the probability of the creation and destruction of its quanta. A quantum field is equivalent to an infinite collection of harmonic oscillators, which can be represented as a series of springs with masses attached: when one oscillator of this field is excited, it vibrates at a particular frequency and leads to the manifestation of the particle. After the second World War Feymann, picking up the previous work initiated by Fermi, developed Quantum Electrodynamics which was advanced further by Schwinger and Tomonaga. In this theory it was postulated that the quantum vacuum is a particular state of the quantum field. It is the state in which no field quanta are excited, no particles are present and it was defined as the zero Energy level or Ground State. Only small perturbations of this state are admitted. It is very difficult to observe such perturbation or fluctuation because there is no state of lower energy with which the vacuum can be compared. However in 1948, Hendrik Casimir predicted that two clean, neutral, parallel flat metal plates attract each other by a very weak force that varies inversely as the forth power of the distance between them. The so called "Casimir Effect" was experimentally verified in 1958. Its interpretation is that the zero-point energy filling the vacuum exerts pressure on everything. In general this pressure is not detected because is acting in all directions and the total effect is zero; however, between the two metal plates the vacuum has different properties because some of the zero-point vibrations of the quantum field are suppressed, namely those with wavelengths greater than the distance between the plates and therefore the external pressure on the plates is greater and the plates attract each other. In case that the distance between the plates is less than 10^{-5} m, the Casimir force is stronger than gravitation, and therefore it is not negligible from the engineering point of view and should be taken into account in nano-technology applications. Recently Alexander Feige of Rockefeller University has predicted that a dielectric body placed in crossed electric and magnetic fields will extract linear momentum from the vacuum and start moving. Unlike the Casimir effect, which is insensitive to the ultra violet cut-off needed to make summations and integrals converge, this new effect depends upon high frequency vacuum modes. The effect is calculated to be about $50\,\mathrm{nm\,s^{-1}}$ for a $17\,\mathrm{T}$ magnetic field and an electric field of $100.000\,\mathrm{V\,m^{-1}}$ and it might be just observable.

Quantum Electrodynamics (QED) is the relativistic quantum field describing the interaction of electrically charged particles via photons; the Feyman diagrams describe with good approximation the effect of such interactions. As an example let us consider Figure 1.

Notice that this figure does not have a time ordering but just a start and stop. It depicts the electron and positron annihilation in the "vacuum" state energy, identified with a virtual photon materialized in a new electron and positron. We should stress that this photon is virtual because when it is created the simultaneous cancellations of energy (E) and momentum (p) are not allowed by the Heisenberg Uncertaineity Principle. Briefly, the virtual photon does not satisfy the relation

$$\mathrm{E}^2 = \mathrm{p}^2\mathrm{c}^2 + \mathrm{m}^2\mathrm{c}^4.$$

In spite of this fact, the QED has led to a spectacular agreement between theoretical calculations and experimental results. The g-factor of an electron is

$$\mathrm{g}/2 = 1.00115965238 \pm 0.00000000026$$

according to theoretical calculations and

$$1.00115965241 \pm 0.00000000202$$

according to experiments.

The g factors measured for the muons are also in an excellent agreement. The QED theory contains various sub-processes described by first,

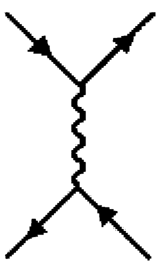

Fig. 1.

second, third and higher order diagrams corresponding to a perturbation theory. The Perturbative Ground State of QED has been adopted as basis of Quantum ChromoDynamics (QCD) formulated to describe strong interactions. QCD is a field theory equivalent to QED applied to quarks and gluons instead of electrons and photons. These new particles are believed to be the building blocks of matter although quarks and gluons have not been observed as free particles because they are confined in protons and hadrons. The quarks are characterized by their colour and in their interactions they exchange gluons in the same way charged particles exchange photons in QED. While the last one is based on only one kind of photon, QCD allows eight types of colours. The absorption or the emission of a gluon can modify the colour of a quark and the gluon, acting as mediator, has also colour and anticolour.

In QED the photon is a neutral particle while in QCD the gluons are charged and this fact gives an explanation of the different behaviour of the electromagnetic and strong interactions over distance. The masses of all particles are generated by the action of empty space (vacuum) on each single particle; this is possible if a field, named the Higgs field, pervades all space and affects the way a particle moves. Particles, influenced by this field would acquire mass. Certain particles would be influenced by this field more than others, hence a variety in particle masses. The Higgs Boson, should be a zero-spin boson that would give mass to particles everywhere. But, at low temperature it seems that it does not work. This boson can be created only at energies above 1 T eV. An analogy of how this works, is a balloon filled with steam; there is perfect symmetry throughout. If you let it cool, you will get a liquid at the bottom with possible ice floating in it. Symmetry is broken just by the simple act of cooling. A hunting of this particle is under way, using the largest particle accelerators in the world: LEP, Tevatron and LHC. The expected mass is more than 109 G eV, somewhat less than the atom of silver. In QCD the vacuum can be considered like the surface of a calm lake where waves can be produced and each wave corresponds to a new particle. Theory needs the Higgs Boson to explain the variety of the masses of particles existing in Nature.

2.1. Vacuum Polarization

From the previous section it follows that vacuum can be conceived as a complex medium and the properties of ordinary matter can serve as analogue to help us understand the properties of vacuum. Insulating materials polarized by an electrical field behave like dielectrics, namely when an external charge is introduced in the material, the electrons in the molecules move a little bit relative to the atomic nuclei tending to shield this charge. This causes polarization of the material. Each substance has its own dielectric constant ϵ which is always greater than 1. In case of magnetic substances, the molecules are acting as tiny permanent magnets oriented at random (ferromagnetic materials like, iron excepted), so the total magnetization is zero, but if we apply a magnetic field they tend to orient themselves along this field as in the case of the electric field. In this case too, we define a magnetic polarization μ, always greater than 1. Such materials like aluminium are called paramagnets, they pull the magnetic field in them and they are attracted towards region of stronger field. If the individual molecules have no permanent magnetization it is possible to have μ less than 1, the material is called diamagnetic (bismuth), the field is expelled and the material is repelled by a stronger magnetic field. Paramagnetic is analogous to dielectric, while diamagnetic is the opposite. Diamagnetism is connected with the flow of electric charges in a magnetic field and there is not analogy with the electric fields because there are no isolated magnetic poles. The description given above is valid only over scales which are large compared to intermolecular distances. Very near to the point charge (electron) there is no shielding effect and ϵ depends on distance. In fact ϵ in this region depends on the distance from the point charge. The polarization effect reduces the efficacy of the electron charge, increasing with distance. Only at very short distances, at submolecular level and beyond the screening of the positive charges attracted by the electron, it is possible to see its bare charge. In QED the analogy is good and in fact for very short time intervals, there is a possibility to find pairs of opposite charges in the vacuum. These virtual charges can be polarized as the molecules in a gas or in a liquid. In an analogue way vacuum can be polarized. The QED predicts that in the vacuum the electric charge is shielded and its effect is weakened at large distances (Figure 2).

In Figure 2 the electron (big circle) is surrounded by virtual positrons, which are shielding partially its charge. In analogy to the case of a dielectric material, we can define an ϵ which depends on the distance. By definition ϵ approaches 1 for large distances and is less than 1 for very small ones, but this analogy breaks down when we consider that the speed of light in a medium is given by $c/(\varepsilon\mu)^{1/2}$ and that special relativity says that in vacuum the speed is c and therefore the vacuum must have $\varepsilon\mu = 1$. This means that if vacuum is dielectric (ϵ increasing with distance), then it is diamagnetic (μ decreasing with distance). This conclusion is true if the virtual particles in vacuum have no spin, but in QED we deal with e^+ and e^- which have spin and are magnetic. Therefore, we expect vacuum to be paramagnetic in contrast to what we said before. In QCD too,

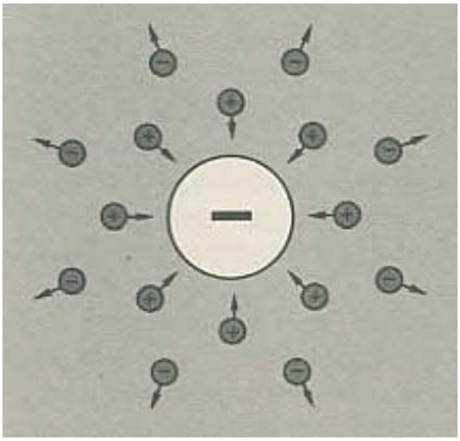

Fig. 2.

since the vacuum is filled with pairs of quarks and antiquarks, each time that a quark is introduced in the vacuum state it interacts with the virtual particles carrying charged colour of opposite sign. The particles with the same charge will be repelled and the colour of the quark will be hidden by the cloud of different colours generating a reduction of the efficacy of the quark charge at larger distances. Vacuum is polarized. The only difference with QED is that in strong interactions it is stronger at large distances; only at a distance of the order of 10^{-13} cm, which is the proton diameter, it becomes weaker. To probe this distance one needs to go to energies higher than those of QED. This effect is called asymptotic freedom because at very short distances (or equivalently at asymptotically large transfer momenta, because of the uncertainty principle), the quarks become almost free. An example of this occurs when a beam of electrons collides with a beam of positrons at a high transfer momentum, we have events of electron–positron annihilation, where their total energy reappears in a quark–antiquark pair which when produced are close together and so almost free. Free quarks and free gluons have never been detected. Their evidence is always indirect: we have quarks bound into hadrons (like pions) and quarks with gluons living a very short time appearing as jets. The QCD prohibits colour charge to be free. This property is called confinement. In QCD the vacuum has ε decreasing with the interaction distance while μ increases with it. Vacuum is paramagnetic. In order to explain the asymptotic freedom and the confinement some researchers suggest that the vacuum of QCD is analogous to a superconductive state. There is state in which is zero and the state in which it is not zero (less than 1). The second one would occur at distances of order of 10^{-15} m. The transition between the two states of the vacuum should not be sharp.

3. VACUUM IN COSMOLOGY

3.1. The Cosmic Background Radiation (CBR)

In 1965 Penzias and Wilson using a horn reflector antenna built for radio-astronomical observations, discovered a background radiation corresponding to a temperature of 3.5 ± 1 K at 7.3 cm wavelength. Since it was almost isotropic and homogeneous it has been interpreted as a relic of the Hot Big Bang. On the largest scale, for theta $= 360°$, a dipole component has been detected at a level of DI/I $= 10^{-3}$, justified by the motion of the Earth at a velocity of 350 km s^{-1} relative to an isotropic frame of reference. Note that I is the radiation intensity. More recent measurements of the kinematics of elliptical and spiral galaxies relative to distant galaxies at a distance of 100 Mps have been made and a velocity of about 600 km s^{-1} has been found for the elliptical galaxies relative to a frame of reference in which the CBR would be isotropic. These measurements were not in the direction of maximum intensity of CBR. As far as our Galaxy is concerned, its motion with respect to a frame of reference in which the CBR is 100% isotropic, is the vector sum of the Earth's motion about the Sun, the Sun's motion in the Galaxy (about 220 km s^{-1}), the Galaxy's motion in the Local Group of Galaxies (about 200 km s^{-1}), the Local Group motion with respect to the Local supercluster motion measured with respect to the frame of reference in which the CBR is 100% isotropic. The value of this vector sum should be compared to the most modern experiment made in 1964 to measure the absolute motion of the Earth which was found to be about 200 km s^{-1}. Therefore CBR can be considered a good candidate to ether.

3.2. Dark Energy and Dark Matter

The prevailing picture of the Universe according to the most recent data from the Wilkinson Microwave Anisotropy Probe (WMAP) and other observatory measurements, is the following:

It is 13.7 billion years old with only 1% margin of error.

The first stars ignited about 200 million years after the big bang.

The WMAP portrait shows the light from 380.000 years after the big bang.

> The Universe is made: 4% of ordinary matter, 23% cold matter and 73% cold energy.

The Hubble constant, measuring the expansion rate of the universe is $Ho=71\,km\,s^{-1}\,Mps^{-1}$ with only 5% margin of error. Dark matter is believed to be the matter existing in the Galaxies, which however is transparent to radiation and its existence is only indirectly deduced by the rotational motion of the spiral galaxies. Dark Energy has an antigravity effect and is responsible for the acceleration of the expansion of the Universe. The dark matter is supposed to be made up of neutrinos or other exotic, weakly interacting particles. Todate, we have no firm evidence that dark energy is made of particles at all. One candidate is the vacuum energy, the energy of empty space. Einstein introduced this possibility in 1917 in his attempt to apply his new theory of gravity to cosmology. In fact Einstein was convinced that the universe was static and therefore he introduced the so called cosmological constant known as Lambda. By carefully choosing the amount of matter and the value of the cosmological constant, he could balance the gravitational forces to obtain a static universe. Some years later, when Hubble concluded from his astronomical data that the universe was expanding, he acknowledged that the cosmological constant was his "greatest blunder". Today, cosmologists find Lambda to be just as objectionable for a different reason. All quantum fields possess a finite amount of "zero-point" vacuum energy because of the uncertainty principle. An estimation of the zero-point energy predicts a vacuum energy density, which is 120 orders of magnitude greater than the energy density of all matter in the universe. If the vacuum energy is so big, it would cause an exponential expansion of the universe that would rip apart all electrostatic and nuclear bonds that hold the atoms and the molecules together. The galaxies, the stars and the life could not be possible. So, a mechanism to nullify the vacuum energy should be found and for this matter the unified theories of gravity have resurrected "Einsten's error" as a possible solution of the dark-energy problem. Instead of making Lambda exactly zero, the mechanism cancels to 120 decimal places after zero. Then the vacuum energy comprises the missing two-thirds of the critical density; In other words, the vacuum energy density remained constant as the universe was expanding, but the total vacuum energy increased as the volume of space increased.

3.3. The Quintessence

It would seem more natural for dark energy to start with an energy density, similar to the density of matter and radiation in the early universe.

However, if the dark energy density has been changing, it cannot consist of vacuum energy. Therefore the concept of quintessence was introduced.

Quintessence is a dynamic, time-evolving and spatially dependent form of energy with negative pressure to drive the accelerating expansion of the universe. According to Paul Steinhard of Princeton University (New Jersey), the quintessence should not consist of baryons, leptons, photons or exotic particles, but of a fifth kind of matter. The scalar fields are the best candidates for it. The quintessence, contrary to the dynamic aspect of quantum mechanical vacuum, should be subject to the laws of classical physics and should evolve with time. The quest for it is made in several ways: the acceleration effect of the dark energy component depends on the ratio w of its pressure to its energy density: more negative values of this ratio lead to greater acceleration. Quintessence and vacuum energy have different values of w and therefore, more precise measurements of supernovae over a longer span of distance, would enable the separation of these two possibilities. Quintessence should have an effect on the cosmic microwave background radiation because, differences in the acceleration rate will produce small differences in the angular size of the hot and cold spots. In addition CBR is not spatially homogeneous. Small variations in the amount of quintessence across the sky should be seen as ripples in the microwaves background temperature. In conclusion quintessence too can be considered a new form of ether.

ACKNOWLEDGEMENTS

This paper has been written for the celebration of the 70th birthday of Prof. Franco Selleri, of whom the author has been a student and friend. Many thanks are due to Prof. A.K. Theophilou for fruitful discussions.

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