IL NUOVO CIMENTO Vol. 32 C, N. 1 Gennaio-Febbraio 2009
DOI 10.1393/ncc/i2009-10335-6

Colloquia: GCM8

The physical vacuum of present particle physics and the Theory of Relativity

M. Consoli
INFN, Sezione di Catania - Via S. Sofia 64, 95123 Catania, Italy

(ricevuto il 3 Aprile 2009; pubblicato online il 20 Maggio 2009)

Summary. — The broken-symmetry vacuum of present particle physics is modeled as a Bose condensate of elementary quanta whose trivial empty vacuum state is not the true ground state of the theory. The symmetric phase will eventually be re-established above a critical temperature that, in the Standard Model of electroweak interactions, is so high that, even at ordinary temperatures, one can safely approximate the vacuum as a zero-temperature, superfluid medium where bodies can flow without any apparent friction consistently with the experimental results. In this sense, the basic quantum phenomenon of superfluidity, resolving the apparent contradiction existing in the notion of a "non-empty" vacuum state, seems to provide a key ingredient to reconcile the presently accepted view with the original foundations of Einstein's special relativity in 1905. Nevertheless, according to general theoretical arguments, this form of "quantum ether" characterizes the physically realized form of relativity and could play the role of preferred reference frame in a modern Lorentzian approach. By adopting a phenomenological two-fluid model of the vacuum, I explore the experimental implications of this scenario in connection with a new generation of dedicated ether-drift experiments.

PACS 11.30.Cp – Lorentz and Poincaré invariance.
PACS 11.30.Qc – Spontaneous and radiative symmetry breaking.
PACS 03.30.+p – Special relativity.

1. – Introduction

In present particle physics, fundamental phenomena, such as mass generation or quark confinement, are believed to be the consequence of a non-trivial structure of the vacuum state. This is not trivially empty but filled by particle condensates. In the physically relevant case of the Standard Model of electroweak interactions, the situation can be summarized by saying [1] that "What we experience as empty space is nothing but the configuration of the Higgs field that has the lowest possible energy. If we move from field jargon to particle jargon, this means that empty space is actually filled with Higgs particles. They have Bose condensed". The translation from field jargon to particle jargon can be obtained, for instance, along the lines of ref. [2] where the substantial equivalence between the effective potential of quantum field theory and the energy density of a dilute particle gas was established, see also ref. [3].

The symmetric phase will eventually be re-established above a critical temperature $T = T_c$. This in the Standard Model is so high that one can safely approximate the ordinary vacuum as a zero-temperature system (think of ^{4}He at a temperature 10^{-12} K). This observation provides the argument to represent the physical vacuum as a superfluid medium where bodies can flow without any apparent friction, consistently with the experimental results. In this sense, the basic quantum phenomenon of superfluidity, resolving the apparent contradiction existing in the notion of a "non-empty" vacuum state, seems to provide a key ingredient to reconcile the presently accepted view with the original foundations of Einstein's special relativity in 1905.

Still, in a picture based on the Bose condensation phenomenon, it becomes natural to ask [4] whether the spontaneous creation from the empty vacuum of elementary spinless quanta and their macroscopic occupation of the same quantum state, say $\mathbf{k} = 0$ in some reference frame Σ, might represent the operative construction of a "quantum ether". This would characterize the *physically realized* form of relativity and could play the role of preferred frame in a modern Lorentzian approach.

This possibility was considered in refs. [5,6] by also exploring those characteristic phenomenological signals that might be associated with the vacuum condensation process. Both aspects will be reviewed in the following. In sect. **2**, I will summarize the basic theoretical ingredients of the problem. In sects. **3-5**, I will discuss the main experimental implications. Finally, in sect. **6**, I will present a summary and the conclusions.

2. – Lorentz invariance and the energy of the vacuum

The idea of a preferred reference frame Σ dates back to the origin of the theory of relativity and to the basic differences between Einstein's special relativity and the Lorentzian point of view. No doubt, today, the former interpretation is widely accepted. However, the whole perspective on Lorentz symmetry has been recently re-considered on the basis of present quantum gravity models, see, *e.g.*, [7]. Moreover, in spite of the deep conceptual differences, it is not so obvious how to distinguish experimentally the two interpretations.

For a modern presentation of the Lorentzian approach one can, for instance, follow Bell [8,9]. Differently from the usual derivations within special relativity, one starts from physical modifications of matter (namely Larmor's time dilation and Lorentz-Fitzgerald length contraction) to deduce the basic Lorentz transformation between Σ and any moving frame S′. Due to the crucial underlying group property, two observers S′ and S″, individually connected to Σ by a Lorentz transformation, are then also mutually connected by a Lorentz transformation with relative velocity parameter fixed by the velocity composition rule. As a consequence, one deduces a substantial quantitative equivalence of the two formulations of relativity for most standard experimental tests. Thus, one is naturally driven back to the question: if the vacuum condensation process were really defining a preferred frame, could one observe the motion with respect to it?

To explore this possibility, one can start by considering different approaches to the vacuum state. In a first description, as in the axiomatic approach to quantum field theory [10], the vacuum could be described as an eigenstate of the total energy-momentum vector of the theory. In this framework, a natural assumption behind a non-trivial vacuum is that the physical vacuum state $|\Psi^{(0)}\rangle$ maintains both zero spatial momentum and zero angular momentum, but, at the same time, is characterized by a non-vanishing energy E_0. This vacuum energy might have very different explanations. Here, I shall limit myself to explore the physical implications of its existence by just observing that, in interacting quantum field theories, there is no known way to ensure consistently the condition $E_0 = 0$ without imposing an unbroken supersymmetry (which is not phenomenologically acceptable). Then, one can combine this idea with the algebra of the 10 generators P_α, $M_{\alpha,\beta}$ $(\alpha, \beta = 0, 1, 2, 3)$ of the Poincaré group. Here P_α are the 4 generators of the space-time translations and $M_{\alpha\beta} = -M_{\beta\alpha}$ are the 6 generators of the Lorentzian rotations. By imposing $(i, j = 1, 2, 3)$

$$\hat{P}_i|\Psi^{(0)}\rangle = \hat{M}_{ij}|\Psi^{(0)}\rangle = 0, \tag{1}$$

$$\hat{P}_0|\Psi^{(0)}\rangle = E_0|\Psi^{(0)}\rangle \neq 0 \tag{2}$$

and using the algebra among the boost generators M_{0i} and the energy-momentum operators, one deduces that the physical vacuum cannot be a Lorentz-invariant state. For instance, for a boost along the x-direction, by defining a boosted vacuum state $|\Psi'\rangle = \hat{U}'|\Psi^{(0)}\rangle$ with $\hat{U}' = e^{\lambda' \hat{M}_{01}}$ (recall that $\hat{M}_{01} = -i\hat{L}_1$ is an anti-Hermitian operator) one finds

$$\langle \hat{P}_1 \rangle_{\Psi'} = E_0 \sinh \lambda' \qquad \langle \hat{P}_0 \rangle_{\Psi'} = E_0 \cosh \lambda', \tag{3}$$

so that a boost produces a vacuum energy-momentum flow along the direction of motion with respect to Σ. Therefore, in the spirit of both classical and quantum field theory, where global quantities are obtained by integrating local densities over 3-space, for a moving observer S$'$ the physical vacuum looks like some kind of ethereal medium for which, in general, one can introduce a momentum density $\langle \hat{W}_{0i} \rangle_{\Psi'}$ through the relation

$$\langle \hat{P}_i \rangle_{\Psi'} = \int \mathrm{d}^3x \ \langle \hat{W}_{0i} \rangle_{\Psi'} \neq 0. \tag{4}$$

On the other hand, in an alternative picture where one assumes the following form of the vacuum energy-momentum tensor [11, 12]:

$$\langle \hat{W}_{\mu\nu} \rangle_{\Psi^{(0)}} = \rho_v \ \eta_{\mu\nu} \tag{5}$$

(ρ_v being a space-time–independent constant and $\eta_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$), one is driven to completely different conclusions. In fact, by introducing the Lorentz transformation matrices Λ^μ_ν to any moving frame S$'$, defining $\langle \hat{W}_{\mu\nu} \rangle_{\Psi'}$ through the relation

$$\langle \hat{W}_{\mu\nu} \rangle_{\Psi'} = \Lambda^\sigma{}_\mu \Lambda^\rho{}_\nu \ \langle \hat{W}_{\sigma\rho} \rangle_{\Psi^{(0)}} \tag{6}$$

and using eq. (5), the expectation value of $\hat{W}_{0i}$ in any boosted vacuum state $|\Psi'\rangle$ will vanish, just as it vanishes in $|\Psi^{(0)}\rangle$. Therefore, differently from eq. (4), one gets

$$\langle \hat{P}_i \rangle_{\Psi'} = \int \mathrm{d}^3x \ \langle \hat{W}_{0i} \rangle_{\Psi'} = 0. \tag{7}$$

To resolve the conflict, the author of ref. [11] advocates the point of view that the vacuum energy E_0 is likely infinite and represents a spurious concept. Thus one should definitely replace eqs. (1), (2) with eq. (5).

The issue is non-trivial and does not possess a simple solution. One can only observe that in an approach based solely on eq. (5) the properties of $|\Psi^{(0)}\rangle$ under a Lorentz transformation are not well defined. In fact, a transformed vacuum state $|\Psi'\rangle$ is obtained, for instance, by acting on $|\Psi^{(0)}\rangle$ with the global boost generator $\hat{M}_{01}$. Once $|\Psi^{(0)}\rangle$ is considered an eigenstate of the energy-momentum operator, one can definitely show that, for $E_0 \neq 0$, $|\Psi'\rangle$ and $|\Psi^{(0)}\rangle$ differ non-trivially. On the other hand, if $E_0 = 0$ there are only two alternatives: either $\hat{M}_{01}|\Psi^{(0)}\rangle = 0$, so that $|\Psi'\rangle = |\Psi^{(0)}\rangle$, or $\hat{M}_{01}|\Psi^{(0)}\rangle$ is a state vector proportional to $|\Psi^{(0)}\rangle$, so that $|\Psi'\rangle$ and $|\Psi^{(0)}\rangle$ differ by a phase factor.

Therefore, if the structure in eq. (5) were really equivalent to the exact Lorentz invariance of the vacuum, it should be possible to show similar results, for instance that such a $|\Psi^{(0)}\rangle$ state can remain invariant under a boost, *i.e.* be an eigenstate of

$$\hat{M}_{0i} = -i \int \mathrm{d}^3x \; (x_i \hat{W}_{00} - x_0 \hat{W}_{0i}) \tag{8}$$

with zero eigenvalue. As far as I can see, there is no way to obtain such a result by just starting from eq. (5) (that only amounts to the weaker condition $\langle \hat{M}_{0i} \rangle_{\Psi^{(0)}} = 0$). Thus, independently of the finiteness of E_0, it should not come as a surprise that one can run into contradictory statements once $|\Psi^{(0)}\rangle$ is instead characterized by means of eqs. (1), (2).

Alternatively, one might argue that a satisfactory solution of the vacuum-energy problem lies definitely beyond flat space. A non-zero ρ_v, in fact, will induce a cosmological term in Einstein's field equations and a non-vanishing space-time curvature which anyhow dynamically breaks global Lorentz symmetry.

Nevertheless, physical models of the vacuum in flat space can be useful to clarify a crucial point that, so far, remains obscure: the huge renormalization effect that is seen when comparing the typical vacuum-energy scales of modern particle physics with the experimental value of the cosmological term needed in Einstein's equations to fit the observations. For instance, the picture of the vacuum as a superfluid explains in a natural way why there might be no non-trivial macroscopic curvature in the equilibrium state where any liquid is self-sustaining [13]. In this framework, the condensation energy of the medium plays no observable role so that the relevant curvature effects may be orders of magnitude smaller than those expected by solving Einstein's equations with the full $\langle \hat{W}_{\mu\nu} \rangle_{\Psi^{(0)}}$ as a source term. In this perspective, "induced-gravity" [14] approaches, where gravity somehow arises from the excitations of the quantum vacuum itself, may become natural and, to find the appropriate form of the energy-momentum tensor in Einstein's equations, we are lead to sharpen our understanding of the vacuum structure and of its excitation mechanisms by starting from the physical picture of a superfluid medium. This provides a definite framework to exploit the possible phenomenological implications of eq. (4).

3. – The vacuum as a two-fluid medium

In ref. [5], to explore the possible effects of the energy-momentum flow expected from eq. (4), a phenomenological two-fluid model was adopted in which the quantum vacuum, in addition to the main zero-entropy superfluid component, contains a small fraction of "normal" fluid. This picture offers a simple mechanism to understand the physical origin of a non-zero $\langle \hat{W}_{0i} \rangle_{\Psi'}$ in any moving frame.

To estimate the possible observable consequences, one can adopt Eckart's thermodynamical treatment [15] of relativistic media. In the end, a non-zero energy-momentum flow should be equivalent to an effective thermal gradient

$$\frac{\partial T}{\partial x^i} \equiv -\frac{\langle \hat{W}_{0i} \rangle_{\Psi'}}{\kappa_0}, \tag{9}$$

κ_0 being an unknown parameter, introduced for dimensional reasons, that plays the role of vacuum thermal conductivity. Since its value is unknown, the effective thermal gradient is left as an entirely free quantity whose magnitude can be constrained by experiments.

In principle, this effective gradient could induce small convective currents in a loosely bound system as a gaseous medium (placed in a container at rest in the laboratory frame) and produce a slight anisotropy of the speed of light in the gas. In this sense, the frame where the (solid) container of the gas is at rest would not define a true rest frame.

On the other hand, for a strongly bound system, such as a solid or liquid transparent medium, the small energy flow generated by the motion with respect to the vacuum condensate should dissipate mainly by heat conduction with no appreciable particle flow and no light anisotropy in the rest frame of the medium, in agreement with the classical experiments in glass and water.

4. – The two-way speed of light in gaseous media

Rigorous treatments of light propagation in dielectric media are based on the extinction theory [16]. This was originally formulated for continuous media where the interparticle distance is smaller than the light wavelength. In the opposite case of an isotropic, dilute random medium [17], it is relatively easy to compute the scattered wave in the forward direction and obtain the refractive index. However, if there are convective currents, taking into account the motion of the molecules that make up the gas is a non-trivial problem. If solved, one expects an angular dependence of the refractive index and an anisotropy of the phase speed of the refracted light.

On a much simpler semi-quantitative basis, the problem can be addressed by introducing from scratch the refractive index $\mathcal{N}$ of the gas. By imposing that the anisotropy has to vanish if the gas were at rest in a preferred frame Σ, one can perform a double expansion in powers of the small parameter $(\mathcal{N}-1)$ and in powers of the velocity V of the laboratory with respect Σ. In this case, by using some simple symmetry properties [6] and working to $\mathcal{O}(V^2/c^2)$, one obtains the following expression for the two-way speed of light in the gas ($\beta = V/c$):

$$\bar{c}(\mathcal{N},\theta,\beta) \sim \frac{c}{\mathcal{N}} \left[1 - (\mathcal{N}-1)\ \beta^2 \sum_{n=1}^{\infty} \zeta_{2n} P_{2n}(\cos\theta) \right], \tag{10}$$

where θ is the angle between $\mathbf{V}$ and the direction of light propagation, $P_{2n}(\cos\theta)$ are even-order Legendre polynomials, and ζ_{2n} are $\mathcal{O}(1)$ coefficients that describe in full generality the possible types of convective motion.

This general structure can be compared with the corresponding result [21,22] obtained by using Lorentz transformations to connect S′ to the preferred frame

$$\bar{c}(\mathcal{N},\theta,\beta) \sim \frac{c}{\mathcal{N}}\ [1 - \beta^2\ (A + B\sin^2\theta)] \tag{11}$$

with

$$A \sim 2(\mathcal{N}-1), \qquad B \sim -3(\mathcal{N}-1) \tag{12}$$

that corresponds to set in eq. (10) $\zeta_2 = 2$ and all $\zeta_{2n} = 0$ for $n > 1$. Equations (11), (12), that represent a definite realization of the general structure in (10), provide a partial answer to the problems posed by our limited knowledge of the electromagnetic properties of gaseous systems and have been adopted in [6] as the basic model for the two-way speed of light. Notice also that, although originating from a different theoretical framework, eq. (11) is formally analogous to the expression of the two-way speed of light in the RMS formalism [18, 19] where A and B are taken as free parameters.

5. – Ether-drift experiments in gaseous media

An anisotropy of the speed of light could be experimentally detected in modern Michelson-Morley experiments by measuring the frequency shift of two orthogonal optical resonators, see, *e.g.*, [20]. In our case, the two orthogonal cavities should be filled with two gaseous media of refractive indices $\mathcal{N}_i$ $(i = 1, 2)$. Thus, by starting from the individual frequencies in each cavity

$$\nu_i(\theta_i) = \bar{c}_i(\mathcal{N}_i, \theta_i, \beta) k_i \tag{13}$$

one obtains the frequency shift

$$\Delta\nu = \nu_1(\theta_1) - \nu_2(\theta_2). \tag{14}$$

In the above relations I have introduced the parameters $k_i = m_i/(2L_i)$, where m_i are integers fixing the cavity modes and L_i are the cavity lengths. Finally, θ_i is the angle between the Earth's velocity $\mathbf{V}$ with respect to the hypothetical Σ and the axis of the i-th cavity while $\bar{c}_i(\mathcal{N}_i, \theta_i, \beta)$ are the two-way speeds of light (11) and (12).

Clearly, an effective vacuum thermal gradient might also induce pure thermal conduction effects in the solid parts of the apparatus with tiny differences of the cavity lengths (and thus of the cavity frequencies) upon active rotations of the apparatus or under the Earth's rotation. However, this effect does not depend on the gas that fills the cavity and can be preliminarily evaluated and subtracted out by first running the experiment in the vacuum mode, *i.e.* at the same room temperature but when no gas is present inside the cavities. The precise experimental limits of ref. [20] (obtained with vacuum cavities at room temperature) show that any such effect can be reduced to the level 10^{-15}–10^{-16} and thus would be irrelevant for our purpose where the typical signal should be larger by 4-5 orders of magnitude. For instance, for a symmetric experiment with $\mathcal{N}_1 = \mathcal{N}_2 = \mathcal{N}$, the magnitude of the relative frequency shift expected from eqs. (11) and (12) is

$$\frac{\Delta\nu}{\nu} \sim \frac{\Delta\bar{c}_\theta(\mathcal{N})}{c} \sim 3(\mathcal{N}-1)\,\frac{V^2}{c^2}\,. \tag{15}$$

Thus, if both cavities were filled with carbon dioxide (whose refractive index at atmospheric pressure is $\mathcal{N} \sim 1.00045$), by assuming the typical value $V^2/c^2 \sim 10^{-6}$ associated with most cosmic motions, one expects $\Delta\nu/\nu \sim 10^{-9}$. Analogously, for helium at atmospheric pressure (where $\mathcal{N} \sim 1.000035$) the effect should be $\Delta\nu/\nu \sim 10^{-10}$.

It must be emphasized that the trend in eq. (15) is in agreement with the pattern *observed* in some classical and modern ether-drift experiments, as illustrated in refs. [21, 22]. In fact, in the classical experiments performed in air at atmospheric pressure, where $\mathcal{N} \sim 1.000293$, the observed anisotropy was $\Delta\bar{c}_\theta/c \lesssim 10^{-9}$ thus providing a typical value $V/c \sim 10^{-3}$, as that associated with most cosmic motions. Analogously, in the classical experiments performed in helium at atmospheric pressure, where $\mathcal{N} \sim 1.000035$ (and in a modern experiment with He-Ne lasers where $\mathcal{N} \sim 1.00004$), the observed effect was $\Delta\bar{c}_\theta/c \lesssim 10^{-10}$ so that again $V/c \sim 10^{-3}$. This gives further support to the quest for a new generation of ether-drift experiments.

6. – Conclusions

Very general arguments related to a non-zero vacuum energy suggest that, in principle, the physical condensed vacuum of present particle physics might represent a preferred reference frame. Namely, in any moving frame, there might be a non-zero vacuum energy-momentum flow along the direction of motion. By treating the quantum vacuum as a relativistic two-fluid medium, that in addition to the main superfluid component contains a small fraction of "normal" fluid, this non-zero energy-momentum flow should behave as an effective thermal gradient and could induce small convective currents in a loosely bound system as a gas. In this sense, the frame where the (solid) container of the gas is at rest would not define a true rest frame and there might be a slight anisotropy of the speed of light.

One can thus consider a new class of ether-drift experiments in which optical resonators are filled by gaseous media. The existence of convective currents leads to the general structure of the two-way speed of light in eq. (10) that admits eqs. (11), (12) as a special case. In this particular limit, one gets definite predictions that can be compared with the experimental results. For the typical velocities involved in most cosmic motions, the expected relative frequency shift between the two resonators, governed by eq. (15), should be about 4–5 orders of magnitude larger than the limit 10^{-15}–10^{-16} placed by the present ether-drift experiments in vacuum.

As anticipated, see [21, 22], the trend in eq. (15) is consistent with the pattern observed in the classical ether-drift experiments (and in a modern experiment with He-Ne lasers). For this reason, to get a definitive test, one should perform this new generation of experiments and study the beat note of the two resonators, look for modulations of the signal that might be synchronous with the Earth's rotation and check the trend in eq. (15).

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I thank G. Giaquinta for many discussions on various aspects of superfluidity and for his kind invitation to the GCM8 Conference.

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