Quantum Vacuum Structure and Cosmology

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Introductory Remarks

Contemporary physics faces three great riddles that lie at the intersection of quantum theory, particle physics and cosmology. They are

1. The expansion of the universe is accelerating – an extra factor of two appears in the size.
2. Zero-point fluctuations do not gravitate – a matter of 120 orders of magnitude
3. The "True" quantum vacuum state does not gravitate.

The latter two are explicitly problems related to the interpretation and the physical role and relation of the quantum vacuum with and in general relativity. Their resolution may require a major advance in our formulation and understanding of a common unified approach to quantum physics and gravity. To achieve this goal we must develop an experimental basis and much of the discussion we present is devoted to this task.

In the following, we examine the observations and the theory contributing to the current framework comprising these riddles. We consider an interpretation of the first riddle within the context of the universe's quantum vacuum state, and propose an experimental concept to probe the vacuum state of the universe.

The Riddles

Riddle 1. Data indicate that the universe expansion is accelerating and comprehensive studies of cosmological and astrophysical observables determine the object driving the expansion to have an equation of state [1, 2]

$$w \equiv p/\rho = -0.94 \pm 0.1,$$

incompatible with normal matter which has $w \leq 1/3$ — hence the term dark energy, distinct from dark matter. Many works offer an explanation introducing new types of dynamical fields in order to provide the requisite behavior of the dark energy density (for review see [3]) or even both dark energy and dark matter at the same time [4]. However, theories entailing dynamics in the evolution of dark energy have been severely constrained [5]. Due to the homogeneity of its distribution in space and time, the dark energy is most consistent with a cosmological constant Λ which enters the Einstein equation (gravitational metric $-,+,+,+$, signs following convention of Weinberg [6])

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda = -8\pi G T_{\mu\nu}. \tag{1}$$

Considering the value

$$\lambda := \frac{\Lambda}{8\pi G} \simeq (2.6 \pm 0.6\,\mathrm{meV})^4 \simeq 3.4 \pm 0.4 \times 10^{-10}\,\mathrm{J/m}^3, \tag{2}$$

dark energy amounts to a strikingly small energy density $g^{00}\lambda$, corresponding to about 2 protons per m^3, or the energy content in the electric field of magnitude $8.3\,\mathrm{V/m}$, and yet, given the homogeneous distribution it is the dominant energy content in present day expansion diluted Universe. This dominance is a relatively recent phenomenon, for most of its history (on logarithmic time scale) the Universe has been dominated by matter, and earlier on, radiation, a negligible component today.

Moving on, general relativity and quantum field theory have not yet been made consistent, and the most striking symptoms of this situation are the two other riddles.

Riddle 2. The vacuum fluctuations of the known matter fields cannot gravitate: a simple summation of the zero-point energy of e.g. electron-positron Dirac field shows

$$\langle \epsilon \rangle_{\mathrm{matter}} = -2_s \cdot 2_p \cdot \int_0^{M_{\mathrm{Pl}}} dk \frac{4\pi k^2}{(2\pi)^3} \frac{1}{2}\sqrt{k^2+m^2} \simeq -\frac{M_{\mathrm{Pl}}^4}{16\pi^2}, \tag{3}$$

which using the Planck mass $M_{\mathrm{Pl}} = 1.2 \times 10^{19}\,\mathrm{GeV}$ gives

$$\langle \epsilon \rangle_{\mathrm{matter}} \simeq 10^{120}\lambda, \qquad -8\pi G \langle \epsilon \rangle_{\mathrm{matter}} = \frac{c}{\hbar}\frac{4}{8\pi G}\,.$$

No known framework, realistic formulations of super-symmetry included, cancels near to 120 orders of magnitude. Similarly, it is hard to imagine how to cancel a $1/G$ term in the curvature of the Universe. Consistency between the present day quantum field theory, and gravity, appears to be impossible.

Riddle 3. Thus for whatever reason the True Vacuum does not gravitate. The vacuum we observe in the universe—whether the True Vacuum or a False (quasi-stable) Vacuum—is highly structured by electric, weak and color charged interactions.

Recall that from electroweak (EW) theory and quantum chromodynamics (QCD) we derive many physical properties and structures this vacuum must have. Let us consider some examples:

1. In QCD, color confinement requires its vacuum state be defined by

$$\langle F^a_{\mu\nu}\rangle_V \equiv 0, \quad \text{i.e.} \ \langle \vec{E}^a\rangle_V \equiv 0 \ \text{ and } \ \langle \vec{B}^a\rangle_V \equiv 0. \tag{4}$$

   Yet evaluating the glue condensate, we have (color traces implied)

$$\langle \frac{\alpha_S}{\pi} G^2\rangle_V = [330(50)\,\mathrm{MeV}]^4\,, \tag{5}$$

   showing that the confining vacuum must be dominated by color-magnetic fluctuations

$$\langle B^2\rangle = \frac{1}{2}\langle G^2\rangle + \langle E^2\rangle. \tag{6}$$

2. The fluctuating color fields will induce a quark condensate and indeed one finds

$$\langle \overline{u}u + \overline{d}d\rangle_V = -2\,[225(25)\,\mathrm{MeV}]^3 \tag{7}$$

3. The spontaneous symmetry breaking structure of the EW vacuum implies an omni-present condensate

$$\langle H\rangle = (\sqrt{2}G_F)^{-1/2} \simeq 0.2462\,\mathrm{TeV}. \tag{8}$$

   We remark that the coupling of the Higgs to the top quark is almost unity: $g_t = 0.99$ so that $M_t = g_t\langle H\rangle/\sqrt{2} = 0.1724\,\mathrm{TeV}$ indicating a relationship between the QCD and EW vacuum structure, yet to be discovered.

4. Amidst the widely different energy scale the final puzzle piece is neutrino mass difference in the range $\Delta m_\nu = 10 - 100$ meV. How neutrinos acquire this mass is hotly debated. Since all other particle masses are properties of the vacuum structure, it is natural to assume that also neutrino masses are. This suggests existence of vacuum structure beyond the Standard Model with a scale corresponding to that of dark energy.

The True and The False Vacuum

A natural place in the present theoretical paradigm to 'find' a cosmological constant is in the quantum vacuum [7]. The dark energy in the form of Einstein's cosmological constant stands next to an energy momentum tensor $T_{\mu\nu}$, and should be inherent to the vacuum expectation values of the energy momentum tensor. Any energy momentum tensor which is not traceless, for which the energy density $T^{00} > 0$, and the pressure components $T^{ii} < 0, i = 1, 2, 3$ i.e. have wrong, non-matter-like sign, can be decomposed to make the inherent dark energy component visible. This is done by separating the energy-momentum trace

$$T_{\mu\nu} = \widetilde{T}_{\mu\nu} + g_{\mu\nu}\frac{T^\alpha_\alpha}{4}, \tag{9}$$

and the Einstein equation is presented in the form

$$\frac{1}{8\pi G}\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) = -\widetilde{T}_{\mu\nu} - g_{\mu\nu}\left(\lambda + \frac{T^\alpha_\alpha}{4}\right). \tag{10}$$

Such an effective dark energy term naturally arises in nonlinear electrodynamics [8].

The measurement of a finite value of dark energy tells us that the quantum ground state of the present Universe is **not** the true lowest energy state. We interpret the cosmological constant to be the difference in the energy density of the present state universe $|\Psi\rangle$ with regard to the True Vacuum $|\mathrm{TV}\rangle$:

$$\lambda = \langle\Psi|\mathcal{H}|\Psi\rangle - \langle\mathrm{TV}|\mathcal{H}|\mathrm{TV}\rangle. \tag{11}$$

The Hamiltonian $\mathcal{H}$ is that of the 'complete theory,' whose non-vanishing expectation value indicates that the universe is trapped by a large potential barrier in the (slightly) excited state $|\Psi\rangle$. This finding does not contradict our usual assumption that the vacuum energy is zero since up to the effect of gravity, the measurement of energy density of the vacuum is shift-invariant. That is, when we study properties of the vacuum and the laws of physics, we can assume that a quasi-stable quantum ground state has a vanishing energy density.

Recovering the True Vacuum

Under the hypothesis that the dark energy is a consequence of the universe being trapped in a false vacuum state, we must discuss the consequences of decaying to the True Vacuum. Such ideas have been widely discussed before [9, 10, 11, 12]. We note in analogy that the presence of an electric field in the vacuum renders it unstable to pair production at a rate that becomes extremely rapid as the Schwinger field $E_0 = m^2/e$ is approached.

Were we to succeed in inducing a transition to the True Vacuum in some finite volume element, it is likely in our present situation not to be catastrophic: the amount of energy released during local vacuum decay is too small to maintain combustion, because the apparent stability of the vacuum suggests that the rate of the decay is small and therefore the height (and the width of the barrier separating the false and the True vacuum states) can be much higher than the energy gained in the process,

$$\Delta V_{\mathrm{barrier}} \gg \lambda.$$

Thus to maintain combustion we need to keep the environment that catalyzes the decay. In other words we must arrange an experimental environment in which the dark energy can burn.

Frames of Reference and Mach's Principle

The question is posed, in what frame is the energy recovered which is freed should the false vacuum decay be observed? As remarked during the discussion session of this lecture by [13], the vacuum state in a Lorentz-covariant theory cannot be a preferred frame of reference. Therefore, we cannot detect motion of any apparatus with respect to the vacuum, and the concept of a relative observer-vacuum velocity is ill-defined, as is the production of energy in vacuum combustion.

The difficulty in conception here is encapsulated in Mach's Principle, which as formulated by Einstein is the statement that

$$\text{Mach's Principle}: \text{ Inertia is measured relative to the fixed stars.} \tag{12}$$

Contemporary cosmology assumes Mach's Principle in praxis, by *identifying* the frame of reference of the cosmic microwave background (CMB) as 'the frame of the universe.' This identification is defensible considering that the existence of a very high temperature (symmetry-restoring) heat bath early in the universe provides a preferred frame for the universe, which is the frame at rest with respect to the heat bath. The remnant photons in the CMB have with great likelihood preserved an observable link to this preferred frame.

While we cannot define a position in the sense of an absolute frame, we can not only measure our velocity with respect to cosmic frame but we can and indeed must presume that the global false vacuum state is defined with respect to this cosmological frame of reference. Dark energy is experimentally determined in this cosmological sense. Therefore, the dark energy, interpreted as energy of the false vacuum, would be released in this same frame, and the relative motion of the experiment with respect to the CMB is the correct relationship to consider.

Experimental observable

We imagine an experimental device that induces the transition to the True Vacuum and is crossing the universe. The energy of the false vacuum quench should in some part be converted to radiation. If we assume that all energy turns into radiation, we would have a temperature

$$\lambda = \frac{E}{V} = \frac{\pi^2}{30} 2_s T_{\rm eq}^4, \quad T_{\rm eq} = 0.9 \times 2.6 \text{ meV/k}_\text{B} = 23 \pm 6\,\text{K}, \tag{13}$$

well above that of the cosmic background radiation. Launched from Earth, the device travels at high speed $v \simeq 300$ km/s with respect to the cosmic microwave background. Inducing vacuum decay in the experimental volume, the device observes a heat flux:

$$J_Q = \lambda v = 10^{-4} \frac{\text{W}}{\text{m}^2} \tag{14}$$

Vacuum quench by QCD matter

Transition to the True Vacuum could be induced by providing energy in the form of an applied field, which deforms the effective potential and may reduce the barrier between states.

The large energy density of the QCD vacuum (recall Eq. (5)) suggests we study the volume transited by atomic nuclei to determine if it is converted to the True Vacuum. If so, a large material object could quench the false vacuum, in which case the experimental signature is that the object cannot drop to arbitrarily low temperature. A suitable environment for such an experiment is extraterrestrial space, so as to get out from under the 1000 g/cm^2 of air necessarily between any ground-based experiment and the false vacuum.

The dark side of the moon does not receive sunlight for 14 days at a time, and remote sensing could be setup to detect the appropriate temperature periodicity, which is a combination of the varying direction of the moon's motion with respect to cosmological frame and heating during solar days. The minimum moon temperature $T = 15 - 40$K in deep craters near the dark polar regions is notable in this regard.

A man-made experiment could involve the launching into space a long metal rod. The end of the rod oriented in the direction of motion relative to the cosmic frame of reference of the universe should experience a higher temperature, being the site of active vacuum combustion. Note that if successful such an experiment would resolve many cosmological questions.

Vacuum quench by Electro-Weak Interactions

The vacuum of quantum electrodynamics (QED) is not thought to have a rich structure. However the connection between QED and weak interactions is very complex and generates vacuum properties which have not yet been understood well even though they stand at the origin of the unification of QED and weak interactions into electro-weak theory. The similarity of the dark energy and neutrino mass scale, both beyond the standard model, inspires many to consider that the dark energy originates in the electro-weak sector.

A potential tool to probe neutrino related defects in the electro-weak vacuum structure could be an ultra intense pulsed laser. The natural wavelength of light is comparable to the Compton wavelength

$$l_\nu = 2\pi \frac{\hbar c}{m_\nu} = 1\ \mu\text{m} \quad \text{for} \quad m_\nu = 1.24\ \text{eV}. \tag{15}$$

Strong electromagnetic fields generated by extreme pulsed lasers with wavelengths at the micron appear to be natural tools capable to quench the false neutrino vacuum. However, even if this were happening today we are not quite able to detect the subtle effects. An exception to this arises should the weak interaction stability properties be modified. In fact, there have been sporadic and unconfirmed reports that strong laser fields can modify electro-weak decays and this subject warrants some attention.

In lieu of conclusions: Back to the æther

Over the past 50 years of continuous development of the standard model and improved understanding of the quantum vacuum structure we have in essence made a full circle: we are at the verge of recognizing that the Universe is in essence filled with an æther, which respects locally the Lorentz symmetry and thus can play a role only when we carve out a ponderable domain where modifications occur, or consider the entire Universe we can see.

It is not generally known how Einstein changed in his time his views: it is widely reported that he rejected æther as unobservable when formulating special relativity. Within 15 years, once the introduction of general relativity and cosmology was achieved, he writes in a 1920 letter to Lorentz [14]

> It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an æther velocity, instead of arguing the total non-existence of the æther, for... I can see that with the word æther we say nothing else than that *space has to be viewed as a carrier of physical qualities.*

[our emphasis] and again a few months later in his review prepared for presentation in front of Lorentz in Leiden, he discusses in depth the æther and he closes: [15]

> ...æther may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time. The idea of motion may not be applied to it.

Today we effectively accept these Einstein's views, and yet the last point, put forward within a fully classical framework, has turned out to be untenable once æther was identified implicitly as the quantum vacuum. Almost everybody argues that the ground state, the vacuum, can be viewed as a ponderable medium. We speak of melted vacuum, and formation of quark-gluon plasma. We modify the vacuum fluctuations and measure quasi-force named after Casimir, and we apply strong EM fields to induce vacuum decay. In these examples, the vacuum is locally defined, and only if this is true can we expect to to detect local vacuum changes. However, the presence of quantum physics discovered after Einstein's reintroduction of the æther and discussion of its properties are of substance because only in this way can we retain quasi-stability of local parts of the vacuum.

We hope that the present discussion will encourage work towards discovery of the false (dark energy) vacuum decay.

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