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The Unruh Effect and the Cosmological Constant Problem

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Abstract: In this work, I show that the vacuum energy arising from zero-point fluctuations and symmetry breakings vanishes when the acceleration exceeds the critical value as observed by an accelerating observer taking into account the Unruh effect. By requiring that the cosmological constant is a small constant independent of the observer, it would however probably be a mistake to construct the vacuum stress-energy tensor using vacuum energy derived from quantum fluctuations and symmetry breakings. The fact that the zero-point energy density of the vacuum is proportional to the fourth power of the particle mass implies that only the covariant part of the self-energy of particles contributes to the cosmological constant, resulting in a significantly reduced theoretical value. It turns out that a correct calculation of the cosmological constant may rely on a hypothetical covariant theory of quantum gravity.

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1. Introduction

The cosmological constant problem stands as one of the most profound puzzles in modern theoretical physics, bridging cosmology and quantum field theory (for a review see [1–5]). The cosmological constant Λ is typically understood to represent the energy density of the vacuum. Observations of the universe's accelerated expansion confirmed by supernovae data suggest a small positive value for Λ. However, the predictions of quantum field theory exhibit significant discrepancies with observational data. A proper statement of the cosmological constant problem includes: Why is the cosmological constant not Planckian? Why is it so small? Why is it not zero?

There are at least two sources for the vacuum energy. In the cosmological context, spontaneous symmetry breakings in the early universe may have induced phase transitions, potentially contributing to the vacuum energy density associated with the cosmological constant. Although one can always adjust the vacuum energy today to zero by tuning the parameter of the potential, it is not a very satisfactory method because the vacuum energy cannot be zero before and after the phase transition. In addition, in quantum field theory the vacuum is filled with quantum fluctuations contributing to a zero-point energy (ZPE). However, the theoretical prediction of the cosmological constant from quantum field theory contrasts with its observed value, giving rise to a discrepancy that spans over 120 orders of magnitude. One promising avenue for addressing the cosmological constant problem is supersymmetry (SUSY), a theoretical framework that posits a symmetry between fermions and bosons [6]. But experimental searches at the Large Hadron Collider have yet to detect supersymmetric particles. Furthermore, the precise mechanism by which SUSY could resolve the cosmological constant problem remains elusive, as the required cancellations demand an extraordinary degree of fine-tuning in the SUSY-breaking sector.

On the other hand, it is well known that all inertial observers in a de Sitter universe see a thermal spectrum with a Gibbons–Hawking temperature $T_\Lambda = H_0/2\pi$ due to the cosmological horizon [7]. Note that the cosmological constant Λ is related to the Hubble constant H_0 through $\Lambda = 3H_0^2$. A Planckian cosmological constant would result in a Planckian Gibbons–Hawking temperature. Such a high temperature would give rise to numerous nontrivial phenomena, such as phase transitions, thereby affecting the vacuum energy. This strongly suggests a connection between the cosmological constant and UV/IR mixing [8]. UV/IR mixing is a fascinating and counterintuitive phenomenon in quantum field theory where high-energy (UV) and low-energy (IR) physics become interdependent. It arises naturally in non-local theories and holographic dualities like AdS/CFT, where the UV physics of the boundary theory is mapped to the IR physics of the bulk geometry, and vice versa. This mixing challenges traditional notions of locality and renormalization group (RG) flow, offering deep insights into quantum gravity. The connection between vacuum energy and Gibbons–Hawking radiation on cosmological scales may also provide insights into the nature of the cosmological constant.

In this work, I will calculate the vacuum energy arising from zero-point fluctuations and symmetry breakings. In Ref. [9], it has been shown that the electroweak phase transition (EWPT) occurs and the electroweak gauge symmetry can be restored when the acceleration exceeds the critical value as seen from the point of view of an accelerating observer (for other related studies see Ref. [10,11]). Therefore, the true vacuum stress-energy tensor will be significantly different from the usual vacuum stress-energy tensor as observed by an accelerating observer taking into account the Unruh effect which predicts that an accelerating observer in a vacuum will detect a thermal bath at a temperature proportional to its proper acceleration [12]. The analysis is based on the conservative assumption of maximal validity of quantum field theory and general relativity. For convenience, I use natural units with $c = \hbar = k = 1$.

2. Vacuum Energy for Accelerated Observers

For an accelerating observer the electroweak $SU(2) \times U(1)$ gauge symmetry in the Standard Model is restored for acceleration larger than a critical value. The acceleration-dependent vacuum expectation value (VEV) is given by [9]

$$v(a) = v_0\sqrt{1 - \frac{a^2}{a_{\rm EW}^2}}. \tag{1}$$

where v_0 is the VEV for the inertial observer, a is the proper acceleration and $a_{\rm EW}$ is the critical proper acceleration of the EWPT. The second-order phase transition of the restoration of electroweak symmetry occurs at $a_{\rm EW}$ and for $a > a_{\rm EW}$, we have $v = 0$. The masses of all elementary particles (gauge bosons, quarks, leptons and the Higgs boson itself) must be corrected by an acceleration-dependent factor because in the Standard Model all of them gain masses controlled by the Higgs VEV. The elementary particles therefore acquire a acceleration-dependent mass which is

$$m(a) = m_0\sqrt{1 - \frac{a^2}{a_{\rm EW}^2}}, \tag{2}$$

where m_0 is the mass of the elementary particle for the inertial observer. By introducing the Unruh-like temperature:

$$T_{\rm EW} = \frac{a_{\rm EW}}{2\pi} \tag{3}$$

and

$$T(a) = \frac{a}{2\pi}, \tag{4}$$

Equation (2) can be also written as

$$m(T) = m_0\sqrt{1 - \frac{T^2}{T_{\rm EW}^2}}, \tag{5}$$

where $T_{\rm EW} \sim 10^2$ Gev is the critical temperature of the EWPT. It turns out that all massive particles of Standard Model become massless for the local accelerating observer when the acceleration exceeds the critical value.

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The vacuum energy receives contributions from both zero-point fluctuations and symmetry breakings. The ZPE density of a real free scalar field is given by

$$\rho_Z = \frac{1}{(2\pi)^3}\frac{1}{2}\int d^3\boldsymbol{k}\,\omega(k) \tag{6}$$

with

$$\omega(\boldsymbol{k}) = \sqrt{|\boldsymbol{k}|^2 + m_0^2}, \tag{7}$$

where $(\omega, \boldsymbol{k})$ is the four-dimensional momentum and m_0 is the mass of the scalar field. Obviously, the integral is divergent in the ultraviolet region. The common method is to introduce an ultraviolet cut-off Λ_{UV} at the Planck scale, then one obtains $\rho_Z \sim 10^{76}$ GeV^4, which is larger than the observed value of vacuum energy density by a factor of 10^{120}. But a straightforward but lengthy calculation leads to

$$\rho_Z = \frac{\Lambda_{\mathrm{UV}}^4}{16\pi^2} + \frac{m_0^2\Lambda_{\mathrm{UV}}^2}{16\pi^2} + \frac{m_0^4}{64\pi^2}\ln\left(\frac{m_0^2 e^{\frac{1}{2}}}{4\Lambda_{\mathrm{UV}}^2}\right) + \cdots, \tag{8}$$

$$p = \frac{\Lambda_{\mathrm{UV}}^4}{48\pi^2} - \frac{m_0^2\Lambda_{\mathrm{UV}}^2}{48\pi^2} - \frac{m_0^4}{64\pi^2}\ln\left(\frac{m_0^2 e^{\frac{7}{6}}}{4\Lambda_{\mathrm{UV}}^2}\right) + \cdots, \tag{9}$$

where p is the pressure. The Lorentz symmetry of the vacuum requires that the energy density and pressure satisfy the equation of state $p = -\rho_Z$. Notice that the first two terms of Equations (8) and (9) break Lorentz invariance and can be removed by local counterterms. Therefore, upon using a regularization scheme that preserves Lorentz symmetry of the vacuum, for any quantum field one arrives at the following expression for the ZPE density [13]

$$\rho_Z = \pm\frac{s m_0^4}{64\pi^2}\ln\left(\frac{m_0^2}{\mu^2}\right), \tag{10}$$

where μ is the renormalization scale, s represents the number of polarization states and the signs $\pm$ are associated with bosons and fermions respectively. The result can be generalized to any other interacting fields by simply replacing m_0 with the renormalized mass m_R. We see that the expression is proportional to the mass of the particle to the power four and the massless particles do not contribute to the ZPE. This result is very different from the result obtained by imposing a Planck cut-off.

Another contribution to the cosmological constant comes from the symmetry breakings. Let us now calculate the vacuum energy produced by the EWPT at the classical level. We should also consider the QCD symmetry breaking ($\sim 10^{-1}$ Gev) and other symmetry breakings at higher energy scales (e.g., the grand unification scale at 10^{14} Gev and the Planck scale at 10^{19} Gev). However, all these expressions take a similar form and the analysis parallels the electroweak case. The Higgs field consists of two complex scalar fields arranged into a doublet. After the EWPT, the field acquires a VEV and the corresponding vacuum energy density is $\rho_{\mathrm{EW}} = \lambda v^4 \sim 10^8$ Gev^4 with λ being the coupling constant describing the self-interaction of Higgs fields. In addition to being inconsistent with observational data, such a large vacuum energy density corresponding to a large cosmological constant would also produce a high Gibbons–Hawking temperature due to the cosmological horizon, thereby triggering a phase transition. The Gibbons–Hawking temperature produced by the huge vacuum energy density ρ_s of symmetry breakings is

$$T_h = \frac{1}{2\pi}(8\pi G\rho_s/3)^{1/2}. \tag{11}$$

When the vacuum energy density exceeds $\rho_s \sim T_{\mathrm{EW}}^2/G \sim 10^{42}$ GeV^4, the broken electroweak symmetry is restored and ρ_{EW} vanishes. Therefore, the cosmological constant cannot be Planckian because a Planckian cosmological constant corresponding to the Planckian Gibbons–Hawking temperature

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would restore the broken symmetries at all energy scales. As a result, the vacuum energy would be driven back to zero, providing a possible connection to the UV/IR mixing.

On the other hand, the usual vacuum stress-energy tensor $T_{\mu\nu}$ takes the form

$$T_{\mu\nu} = -\rho_{\text{vac}} g_{\mu\nu}, \tag{12}$$

where ρ_{vac} is the total vacuum energy density and $g_{\mu\nu}$ is the metric tensor. If we assume that the cosmological constant's effect is entirely due to the vacuum energy-momentum tensor, we have $\rho_{\text{vac}} = \Lambda/8\pi G$. The vacuum energy vanishes when the acceleration exceeds the critical value as seen from the point of view of an accelerating observer. This means that the vacuum stress-energy tensor can be reduced to zero through coordinate transformations. Thus, the usual vacuum stress-energy tensor fails to satisfy the transformation properties of a tensor. The key theoretical insight of the Unruh effect is that the very existence of the vacuum state is observer-dependent rather than fundamental. Since Λ is a constant independent of the observer, it would however probably be a mistake to construct the vacuum stress-energy tensor using vacuum energy derived from quantum fluctuations and symmetry breaking. Although the mass arising from the interaction between the particle and the Higgs field depends on the acceleration and vanishes for enough accelerated observers, we may extract the covariant part of the mass arising from other interactions, such as electromagnetic interactions (electromagnetic mass). From Equation (10), we can infer that only the self-energy of elementary particles contributes to the vacuum energy density. Therefore, for a hypothetical covariant theory of quantum gravity, we may be able to compute and construct the true vacuum stress-energy tensor that is invariant for all observers based on self-energy.

3. Conclusions

In this work, I investigate the vacuum energy based on quantum field theory. The vacuum energy becomes zero for enough accelerated observers. Here, I calculate the vacuum energy density arising from symmetry breaking at the tree level. If quantum corrections are considered, one only needs to replace it with the Coleman-Weinberg effective potential [14]. However, the result is the same because quantum corrections also depend on acceleration. It turns out that only the self-energy of elementary particles contributes to the vacuum energy density and the theoretical value of the cosmological constant gets significantly reduced. Although this still does not resolve the cosmological constant problem, as we cannot directly calculate the finite self-energy of all elementary particles and determine whether it matches the observed cosmological constant value. According to Pauli's conjecture, the ultraviolet divergences of quantum field theory might be removed in a theory in which gravity is quantized [15]. Thus, a correct calculation of the cosmological constant may rely on a theory of quantum gravity. Furthermore, we cannot determine whether neutrinos contribute to the ZPE since the origin of neutrino masses likely involves new physics beyond the Standard Model Higgs mechanism.

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