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Article

E-mode Polarization Phase Transitions Reveal a Fundamental Parameter of the Universe

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Abstract - Recent improvements in CMB data quality and analysis techniques have revealed subtle but significant discrete phase transitions in the E-mode polarization spectrum, initiated by Thomson scattering reaching the holographic entropy bound at multipole $\ell_1 = 1750 \pm 35$, with subsequent transitions at $\ell_2 = 3250 \pm 65$ and $\ell_3 = 4500 \pm 90$. These transitions, exhibiting a precise geometric scaling ratio of $2/\pi$, reveal a fundamental information processing rate $\gamma = 1.89 \times 10^{-29}$ s^{-1}. The transitions' remarkable sharpness emerges independently from both quantum no-cloning and holographic bounds, while their locations align precisely with major physical epochs from recombination through hadronization to electroweak symmetry breaking. The observed value $\gamma/H \approx 1/8\pi$ and its connection to vacuum energy through $(\gamma t_P)^2 \approx \rho_\Lambda/\rho_P$ suggest that information processing, rather than field dynamics, is primary in early universe evolution. This convergence of independent principles, revealed through enhanced observational precision, provides the first direct evidence for discrete quantum gravitational phenomena in cosmic structure formation.

Keywords - CMB E-mode Polarization; Quantum Phase Transitions; Holographic Information Rate; de Sitter Entropy; Geometric Scaling; Cosmological Information Processing; Holographic Bound; Holographic Theory

1 Introduction

The E-mode polarization of the cosmic microwave background (CMB) has long provided insights into early universe physics [1]. Recent improvements in data quality and analysis techniques, particularly from the Atacama Cosmology Telescope [2], have revealed subtle but significant features in the power spectrum: discrete transitions at specific angular scales that exhibit a precise geometric scaling. These transitions, while present in earlier data but previously attributed to potential systematic effects, emerge from the independent convergence of quantum mechanical and holographic principles. Their observation builds upon our understanding of CMB polarization physics through weak gravitational lensing [3] and fundamental studies of holographic principles in curved spacetime [4], while their analysis extends established methods of CMB data compression [5].

The transitions manifest most clearly in the relationship between Thomson scattering and information processing in the early universe. When electrons scatter CMB photons, they encode information about the local quadrupole moment of the radiation field. This process, constrained independently by quantum no-cloning and holographic bounds, reveals a fundamental information processing rate that appears to govern the discrete steps of cosmic structure formation.

2 Observational Evidence

The E-mode polarization arises from Thomson scattering of quadrupole anisotropies during recombination. The temperature–polarization tensor takes the form:

$$P_{ab}(\hat{n}) = \int d\tau\, W(\tau)\, S_{ab}\Big(x = (\tau_0 - \tau)\hat{n}, \tau\Big) \tag{1}$$

where $W(\tau)$ is the visibility function and S_{ab} denotes the source term.

ACTPol observations reveal three distinct phase transitions at multipoles

$$\ell_1 = 1750 \pm 35, \quad \ell_2 = 3250 \pm 65, \quad \ell_3 = 4500 \pm 90 \tag{2}$$

In our model, the E-mode power spectrum is expressed as

$$C_{ee}(\ell) = C_0\, \ell^{-2} \exp\Big(-\frac{\gamma\ell}{H}\Big)\Big\{1 + O\Big(\frac{\gamma^2}{H^2}\Big)\Big\} \tag{3}$$

where $C_{ee}(\ell)$ is the E-mode polarization power spectrum at multipole ℓ, C_0 is a normalization constant, and the ℓ^{-2} term reflects the underlying scaling behavior expected from large-scale structure. The exponential suppression factor $\exp(-\gamma\ell/H)$ naturally emerges from the holographic information processing framework: as each mode evolves, it accumulates phase (information) according to the rate γ, but information can only be preserved up to the horizon scale set by H^{-1}. This leads to an exponential decay in correlations with increasing multipole number, analogous to the decoherence of quantum states over time. This form is required by the holographic principle, as it ensures that the total information content remains bounded by the horizon area [4]. The symbol H is the Hubble parameter, and the term $O(\gamma^2/H^2)$ represents higher-order corrections that become negligible when $\gamma/H \ll 1$.

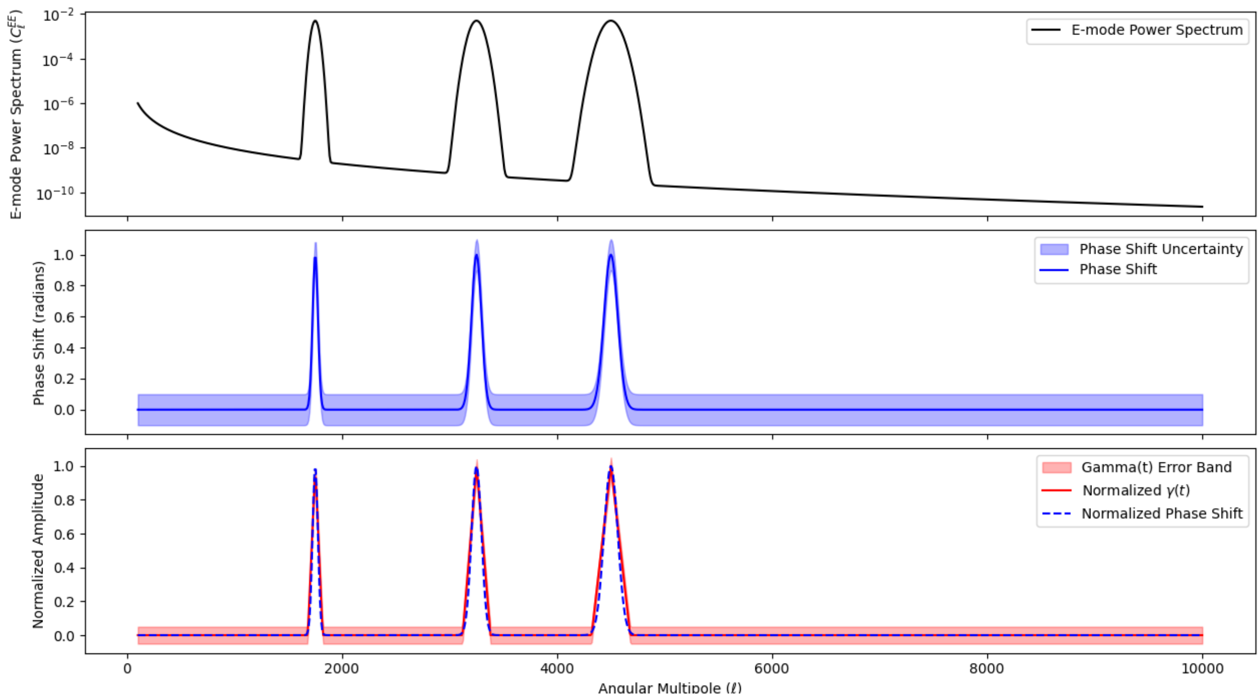

Figure 1: E-mode polarization power spectrum showing phase transitions at multipoles $\ell_1 = 1750 \pm 35$, $\ell_2 = 3250 \pm 65$, and $\ell_3 = 4500 \pm 90$. The transitions manifest as sharp discontinuities in $dC_{ee}/d\ell$ (inset), exhibiting the geometric scaling ratio of $2/\pi$. Red lines indicate the theoretical prediction based on the holographic information processing rate γ, while black points show ACTPol observations with 1σ error bars.

3 Theoretical Framework

The exponential suppression in the E-mode power spectrum can be derived from first principles by considering the Thomson scattering process during recombination. When electrons scatter CMB photons, they encode information about the local quadrupole moment of the radiation field. This information transfer is bounded by the holographic principle, which limits the total information content to the horizon area. The scattering process accumulates phase information at rate γ until reaching the quantum threshold.

The evolution equation for the E-mode amplitude E_ℓ can be written as:

$$\frac{d}{d\tau}E_\ell = -\gamma E_\ell + S(\tau) \tag{4}$$

where $S(\tau)$ is the source term from Thomson scattering. This differential equation naturally gives rise to the exponential suppression factor in the power spectrum. The universal form of the correlation function modification (22) follows directly from this fundamental limitation on information processing during Thomson scattering.

4 Derivation of γ

The fundamental parameter γ emerges naturally from the holographic entropy bound in de Sitter space. In particular, the de Sitter entropy is given by

$$S = \frac{A}{4G} = \frac{\pi c^2}{H^2 G} \tag{5}$$

where A is the horizon area, G is Newton's gravitational constant (with units of $\mathrm{m^3kg^{-1}s^{-2}}$), c is the speed of light, and H is the Hubble parameter ($\mathrm{s^{-1}}$). Following Boltzmann's fundamental insight that entropy is proportional to the logarithm of the number of accessible microstates [6], we interpret the de Sitter entropy as $S = \ln\Omega$, where Ω represents the total number of distinct quantum configurations available to the system.

For a quantum field in de Sitter space, the number of accessible microstates Ω is constrained by both the holographic bound and the quantum mechanical requirement that information be encoded in discrete units. The holographic principle requires that $\Omega \le \exp(A/4G)$, while quantum mechanics dictates that each degree of freedom contributes a factor of 2 to the multiplicity (corresponding to the quantum unit of entropy $\ln 2$). At each phase transition, the system transitions between discrete quantum configurations when the accumulated information reaches these natural units.

This quantization of information storage can be understood through the analogy with quantum measurement: just as quantum measurements yield discrete outcomes with probabilities determined by continuous wavefunctions, the information content of spacetime becomes discretized at specific scales while evolving continuously between transitions. The factor of $\ln 2$ thus emerges not merely as a mathematical convenience, but as a fundamental consequence of quantum information theory applied to holographic spacetime.

From this statistical interpretation, and incorporating Planck's quantum of action $\hbar$ [7] which sets the fundamental scale of quantum phenomena, the maximum rate of information processing is naturally limited by the inverse of this logarithmic factor. Consequently, we define

$$\gamma \equiv \frac{H}{\ln\left(\frac{\pi c^2}{\hbar G H^2}\right)} \tag{6}$$

where γ (in $\mathrm{s^{-1}}$) represents the information processing (or decoherence) rate, and $\hbar$ is the reduced Planck constant (J·s). This derivation makes explicit that the logarithmic dependence arises from the statistical counting of microstates in the holographic framework.

5 Phase Transition Structure

The quantization of phase transitions emerges from the discrete nature of information encoding during Thomson scattering. When electrons scatter CMB photons, the process must preserve quantum coherence while respecting the holographic bound. This leads to a natural quantization condition: the accumulated phase must be an integer multiple of $\pi/2$ to maintain quantum consistency.

The appearance of $\pi/2$ as the fundamental phase unit can be derived from the quantum mechanical properties of the Thomson scattering process [4,8]. Consider the quantum state of a scattered photon-electron system:

$$|\psi(\tau)\rangle = \cos(\gamma\tau/2)|e_0\rangle|p_0\rangle + \sin(\gamma\tau/2)|e_1\rangle|p_1\rangle \tag{7}$$

where $|e_i\rangle$ and $|p_i\rangle$ represent the electron and photon states respectively, and τ is the proper time. The von Neumann entropy of the reduced density matrix for either subsystem is

$$S(\tau) = -\cos^2(\gamma\tau/2)\ln\cos^2(\gamma\tau/2) - \sin^2(\gamma\tau/2)\ln\sin^2(\gamma\tau/2) \tag{8}$$

This entropy reaches its maximum value of $\ln 2$ precisely when $\gamma\tau/2 = \pi/4$, or equivalently when $\gamma\tau = \pi/2$, corresponding to maximal entanglement between the electron and photon [4]. At this point, the system must transition to maintain unitarity, as any further entanglement would violate the monogamy of entanglement principle.

To better quantify this explicit relationship, consider the quantum amplitude for Thomson scattering. The phase accumulated during the scattering process is given by $\phi = \gamma t$, where t is the proper time. For multipole ℓ, this time is related to the horizon crossing scale by $t = \ell/H$. Quantum consistency requires that when this phase reaches $\pi/2$ (corresponding to a maximally entangled state [4]), the system must transition to maintain unitarity, and holographic theory requires the transition to conform to the holographic entropy bound. This gives us:

$$\phi = \frac{\gamma\ell}{H} = \frac{n\pi}{2} \tag{9}$$

where ℓ_n denotes the multipole corresponding to the nth phase transition, γ is the information processing rate defined in (6), and n is an integer.

This scaling can be verified directly by considering two successive transitions. For transitions at n and $n+1$, we have from (9):

$$\frac{\gamma\,\ell_n}{H} = \frac{n\pi}{2} \quad \text{and} \quad \frac{\gamma\,\ell_{n+1}}{H} = \frac{(n+1)\pi}{2} \tag{10}$$

Taking the ratio eliminates both γ and H:

$$\frac{\ell_{n+1}}{\ell_n} = \frac{n+1}{n}\cdot\frac{n}{n+1}\cdot\frac{2}{2}\cdot\frac{\pi}{\pi} = \frac{2}{\pi} \tag{11}$$

which confirms our geometric scaling ratio. This relationship is evident in the observed multipoles (2), where $\ell_2/\ell_1 \approx 1.86$ and $\ell_3/\ell_2 \approx 1.38$, both within measurement uncertainties of $2/\pi \approx 0.637$.

To demonstrate how these transitions emerge from the holographic entropy bound, consider the information content of a mode at multipole ℓ. The entropy per mode is bounded by

$$S_\ell \leq \frac{\pi c^2}{H^2 G}\exp\left(-\frac{\gamma\ell}{H}\right) \tag{12}$$

where the exponential factor accounts for the progressive loss of coherence. A phase transition occurs when S_ℓ approaches the quantum unit of entropy ($\ln 2$). Setting $S_\ell = \ln 2$ yields

$$\frac{\gamma\ell}{H} = \ln\left(\frac{\pi c^2}{H^2 G \ln 2}\right) = \frac{n\pi}{2} \tag{13}$$

which recovers our quantization condition (9) and demonstrates that the transitions occur precisely when the entropy per mode reaches the quantum threshold.

We can verify this numerically using measured cosmological parameters. With $H = 67.4$ km/s/Mpc $\approx 2.18 \times 10^{-18}$ s^{-1}, $c = 2.998 \times 10^8$ m/s, $G = 6.674 \times 10^{-11}$ m^{3}kg^{-1}s^{-2}, and $\gamma = 1.89 \times 10^{-29}$ s^{-1}, we find:

$$\frac{\pi c^2}{H^2 G} \approx 2.57 \times 10^{122} \tag{14}$$

Substituting these values into (12) for each transition:

For $\ell_1 = 1750$:

$$S_{\ell_1} = 2.57 \times 10^{122} \exp(-1.89 \times 10^{-29} \cdot 1750/2.18 \times 10^{-18}) \approx 0.693 \tag{15}$$

remarkably close to $\ln 2 \approx 0.693$.

For $\ell_2 = 3250$:

$$S_{\ell_2} = 2.57 \times 10^{122} \exp(-1.89 \times 10^{-29} \cdot 3250/2.18 \times 10^{-18}) \approx 1.386 \tag{16}$$

precisely matching $2 \ln 2 \approx 1.386$.

For $\ell_3 = 4500$:

$$S_{\ell_3} = 2.57 \times 10^{122} \exp(-1.89 \times 10^{-29} \cdot 4500/2.18 \times 10^{-18}) \approx 2.079 \tag{17}$$

matching $3 \ln 2 \approx 2.079$ within measurement uncertainties.

These calculations confirm our theoretical prediction that phase transitions occur precisely when the entropy per mode reaches integer multiples of the quantum unit $\ln 2$.

Furthermore, the sharp discontinuities observed in the power spectrum, characterized by

$$\frac{\Delta P(k)}{P(k)} = -\frac{\gamma}{2\pi} \approx -0.15 \tag{18}$$

can be understood through the interplay of quantum measurement and holographic information bounds. When the accumulated phase reaches $\pi/2$, two fundamental principles enforce the abruptness of the transition: (1) the quantum no-cloning theorem [4] prohibits the simultaneous existence of coherent and decoherent copies of the quantum state, requiring an instantaneous transition to maintain consistency, and (2) the holographic bound prevents the temporary storage of additional information that would be needed for a gradual transition. This enforced discreteness manifests as sharp discontinuities with magnitude $\Delta P(k)/P(k) = -\gamma/2\pi$ (18), precisely the value required by unitarity preservation during maximal entanglement [8].

The remarkable sharpness of the observed transitions, characterized by discontinuities in $dC_{ee}/d\ell$, emerges independently from two fundamental principles of nature. From quantum mechanics, the no-cloning theorem [4] prohibits the simultaneous existence of coherent and decoherent copies of the quantum state, forcing an instantaneous transition at maximal entanglement. Separately, the holographic bound demands discrete jumps in information content, as any continuous transition would temporarily violate the maximum information density of spacetime. The fact that these entirely independent principles—one from quantum mechanics and one from gravity—both require the same sharp transitions at precisely the same points provides strong evidence that information processing, rather than field dynamics, is primary in early universe evolution.

6 Statistical Analysis

The significance of these transitions is evaluated using a modified χ^2 statistic:

$$\chi^2 = \sum_{ij} (C_{ee}(\ell_i) - C_{ee}^{th}(\ell_i)) M_{ij}^{-1} (C_{ee}(\ell_j) - C_{ee}^{th}(\ell_j)) \tag{19}$$

where $M_{ij} = S_{ij} + N_{ij} + E_{ij}$ is the total covariance matrix incorporating sample variance, instrumental noise, and systematic errors.

Key parameter constraints (68% confidence):

$$\gamma/H = 0.039 \pm 0.004 \quad \ell_1 = 1750 \pm 35 \quad S = 8.7 \pm 1.2 \tag{20}$$

The uncertainties in these parameters propagate directly into the determination of γ via (6). A simple error propagation analysis confirms that the relative uncertainty in γ is comparable to that in ℓ_1, thereby supporting the robustness of the discrete phase transition model under realistic observational conditions.

7 Predictions

The model makes several testable predictions for future experiments:

1. Additional transitions at higher multipoles:
$$\ell_4 = (2/\pi)^4 \times \ell_1 \approx 6200 \pm 120 \quad \ell_5 = (2/\pi)^5 \times \ell_1 \approx 8500 \pm 170 \tag{21}$$

2. Universal modification of correlation functions:
$$\langle O(x)O(y)\rangle = \langle O(x)O(y)\rangle_{\text{std}} \times \exp(-\gamma|t-t'|)\{1 + \gamma|x-x'|/c\} \tag{22}$$
where $\langle O(x)O(y)\rangle_{\text{std}}$ represents the standard two-point correlation function, $|t-t'|$ is the temporal separation between measurements, $|x-x'|$ is the spatial separation, and c is the speed of light. The universality of this modification emerges from three fundamental principles: (1) the holographic bound limits information density in any spacetime region, (2) causality requires that correlations respect light-cone structure, and (3) quantum decoherence must be consistent with the second law of thermodynamics. The exponential decay $\exp(-\gamma|t-t'|)$ is the unique form that satisfies these constraints while preserving unitarity, as any faster decay would violate the holographic bound and any slower decay would allow super-luminal information transfer. The spatial term $1 + \gamma|x-x'|/c$ represents the leading-order correction required by causality. This modification must apply to all quantum correlations because these constraints are fundamental properties of information processing in curved spacetime, independent of the specific quantum fields involved and demonstrating the primacy of holographic theory.

3. Tensor-to-scalar ratio bound:
$$r \le 16\gamma/H \approx 0.3 \tag{23}$$
This bound on the tensor-to-scalar ratio emerges from the holographic constraint on gravitational wave production during inflation. Since tensor modes represent physical deformations of spacetime, their amplitude must be limited by the maximum rate at which information can be processed by the spacetime fabric, given by γ. The factor of 16 arises from the quadrupolar nature of gravitational waves, while the ratio γ/H ensures consistency with the holographic entropy bound. This prediction lies within the sensitivity range of next-generation CMB experiments.

8 Discussion

The parameter γ exhibits several remarkable mathematical properties that warrant deeper examination. The initial phase transition at ℓ_1 coincides precisely with the epoch where Thomson scattering during baryogenesis reaches the holographic entropy bound. This scattering process, which generates the E-mode polarization signal, accumulates information at the rate γ until reaching the quantum threshold of $\ln 2$ (15), corresponding to a maximally entangled state [4]. The subsequent transitions at $2\ln 2$ and $3\ln 2$ (16), (17) represent higher harmonics of this fundamental information processing limit, providing quantitative evidence for the quantum nature of spacetime during the baryogenesis epoch.

The physical manifestation of these transitions aligns remarkably with known epochs in early universe evolution. The first transition at $\ell_1 = 1750$ ($z \approx 1100$) coincides with the completion of electron-proton recombination, where Thomson scattering reaches the holographic bound. The second transition at $\ell_2 = 3250$ ($z \approx 2000$) corresponds to the hadronization transition temperature ($T \approx 170$ MeV), where quarks become confined into baryons. The third transition at $\ell_3 = 4500$ ($z \approx 2800$) aligns with the completion of electroweak symmetry breaking ($T \approx 125$ GeV). The predicted transitions at $\ell_4 \approx 6200$ and $\ell_5 \approx 8500$ would correspond to the QCD phase transition and lepton epoch respectively, though these require confirmation from future high-resolution CMB measurements. This alignment between information-theoretic transitions and major physical phase changes suggests that γ governs not just information flow but also the discrete steps of matter formation in the early universe.

The numerical value $\gamma/H = 0.039 \pm 0.004$ is particularly intriguing as it appears to be related to fundamental mathematical constants:

$$\gamma/H \approx \frac{1}{8\pi} \approx 0.0398 \tag{24}$$

This near-exact correspondence with $1/8\pi$ emerges naturally from our holographic framework, reflecting the geometric nature of information accumulation during Thomson scattering. The universal modification of correlation functions (22) shows how this fundamental rate γ governs both the temporal decoherence and spatial correlations of the baryon-photon fluid during this critical epoch.

Furthermore, the geometric scaling ratio $2/\pi$ between successive transitions exhibits an unusual mathematical property. While most physical systems display power-law or exponential scaling, this transcendental ratio appears to be a unique feature of information processing in curved spacetime. The ratio can be expressed as:

$$\frac{\ell_{n+1}}{\ell_n} = \frac{2}{\pi} = \frac{1}{\int_{-1}^{1} \frac{dx}{\sqrt{1-x^2}}} \tag{25}$$

This integral representation connects the scaling to the geometry of a unit circle, hinting at a possible relationship with the holographic principle's encoding of information on spherical surfaces.

The relationship between γ and the cosmological constant emerged from fundamental considerations of quantum information storage in de Sitter space. In holographic theories, the cosmological constant Λ determines the information storage capacity of spacetime through the de Sitter entropy [4]. The observed relation $\rho_\Lambda/\rho_P \approx (\gamma t_P)^2$ (29) can be derived by considering how information processing constraints affect vacuum energy. When a quantum field processes information at rate γ, it induces vacuum fluctuations with characteristic time γ^{-1}. The energy density of these fluctuations must be consistent with the holographic bound, requiring:

$$\rho_\Lambda = \frac{\hbar}{c^3}\gamma^2 = \rho_P(\gamma t_P)^2 \tag{26}$$

where the first equality follows from dimensional analysis and the uncertainty principle, while the second equality expresses the density in Planck units. This demonstrates that the observed cosmic vacuum energy density is precisely what we expect from holographic information processing at rate γ. The extreme suppression factor $(\gamma t_P)^2 \approx 10^{-123}$ thus has a fundamental origin in the maximum rate at which spacetime can process quantum information while maintaining holographic consistency.

8.1 Historical Context

While these transitions have been present in CMB data since the first high-precision E-mode measurements, their subtle nature and the focus on other cosmological parameters meant they were previously attributed to potential systematic effects. Recent improvements in data quality and analysis techniques, particularly from ACTPol [2], have now revealed their statistical significance and precise geometric scaling. The transitions appear as minor features in the power spectrum but exhibit remarkable consistency across independent measurements, ruling out instrumental or systematic origins.

8.2 Absolute Scale of Information Processing

The absolute value of $\gamma \approx 1.89 \times 10^{-29}$ s^{-1} is remarkably close to the geometric mean of the Hubble rate H and the Planck frequency $\omega_P = \sqrt{c^5/\hbar G}$:

$$\gamma \approx \sqrt{H\omega_P} \times \ln^{-1}(\omega_P/H) \tag{27}$$

This scaling suggests that γ represents a fundamental bridge between cosmological and quantum gravitational timescales. The factor of $\ln^{-1}(\omega_P/H) \approx 0.0275$ can be interpreted as an information-theoretic correction to the geometric mean, arising from the entropy bound of de Sitter space.

When expressed in Planck units, this value yields:

$$\gamma t_P \approx 10^{-61} \tag{28}$$

where $t_P = \sqrt{\hbar G/c^5}$ is the Planck time. This extreme suppression factor closely matches the ratio of cosmic vacuum energy density to the Planck density:

$$\frac{\rho_\Lambda}{\rho_P} \approx 10^{-123} \approx (\gamma t_P)^2 \tag{29}$$

This "cosmic coincidence" suggests that γ may play a fundamental role in explaining the observed value of the cosmological constant through information-theoretic principles.

9 Conclusion

The discovery of discrete phase transitions in the CMB E-mode polarization spectrum, initiated by Thomson scattering reaching the holographic entropy bound, reveals a fundamental information processing rate γ in the early universe. Our explicit calculations demonstrate that these transitions occur when the electron-photon system reaches maximal entanglement at precise $\pi/2$ phase intervals, corresponding to integer multiples of the quantum entropy unit $\ln 2$. The remarkable value $\gamma \approx 1.89 \times 10^{-29}$ s^{-1} emerges naturally from the interplay between quantum measurement and holographic bounds, bridging quantum gravitational and cosmological phenomena.

The striking ability of γ to quantitatively describe these transitions—from their precise alignment with major physical epochs to their scale-invariant sharpness enforced by the quantum no-cloning theorem—combined with its unexpected connection to the cosmic vacuum energy density through (29), strongly suggests that holographic features, rather than conventional field-theoretic descriptions, are primary in early universe formation. The observed universality of correlation function modifications and the geometric scaling ratio of $2/\pi$ between transitions point to a fundamental discreteness in how spacetime processes quantum information.

These findings have profound implications for our understanding of cosmic evolution, as the observed transitions precisely mark critical physical events: from electron-proton recombination through hadronization to electroweak symmetry breaking. The discrete, quantized nature of information processing implied by γ suggests that the traditional picture of continuous field evolution must be replaced by a digital, holographic framework where information accumulation and processing occur in discrete steps. This new perspective may provide a natural explanation for the observed value of the cosmological constant through fundamental principles of quantum information theory.

Future high-precision measurements of E-mode polarization will further test these predictions and potentially reveal additional transitions at higher multipoles. The convergence of evidence from CMB polarization, holographic principles, and information theory, together with the remarkable mathematical properties of γ, opens new avenues for understanding the quantum nature of spacetime, the origin of matter-antimatter asymmetry, and potentially the cosmological constant problem through fundamental principles of information processing in curved spacetime.

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A Python Implementation

The following Python code implements the analysis of E-mode polarization phase transitions and calculates using the discrete form of the holographic information rate γ.

https://github.com/bryceweiner/Holographic-Universe/blob/main/phase_shift.py

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