Computational Analysis of Early-Universe CPT Violation Viability: Temperature-Dependent Effects on Big Bang Nucleosynthesis

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ABSTRACT

We investigate whether CPT symmetry could have been violated at high temperatures in the early universe while remaining unobservable today. Using a computational framework modeling temperature-dependent CPT-violating electron–positron mass splitting via $b_0(T) = \alpha T^2$, we simulate Big Bang Nucleosynthesis (BBN) across 101 values of the coupling parameter $\alpha \in [-0.5, 0.5]$. Our results show that primordial helium-4 mass fraction Y_p varies from 0.0935 to 0.0994 across this range, with standard BBN yielding $Y_p = 0.0948$. The present-day mass splitting is suppressed by a factor of $\sim 3 \times 10^{-39}$ due to the T^4 temperature dependence, yielding splittings of order 10^{-20} eV—well below the Penning trap bound of 8×10^{-9} eV. Bayesian model comparison yields a Bayes factor of 1.0, indicating current data cannot distinguish between CPT-violating and standard scenarios. Sensitivity analysis identifies the neutron–proton mass difference (δm_{np}) as the dominant parameter affecting Y_p with relative sensitivity 4.04, while neutron lifetime contributes 0.28.

1 INTRODUCTION

CPT symmetry—the combined symmetry under charge conjugation (C), parity (P), and time reversal (T)—is a cornerstone of local quantum field theory [4]. Present-day tests using Penning traps constrain electron–positron mass differences to below 8×10^{-9} eV [5], while neutral meson experiments provide complementary bounds [6]. However, these constraints apply at effectively zero temperature, leaving open the question of whether CPT could have been violated at the high temperatures of the early universe.

Barenboim et al. [1] proposed a scenario where a CPT-violating background field $b_0(T) = \alpha T^2$ generates temperature-dependent electron–positron mass asymmetries during BBN ($T \sim 1$ MeV) while naturally vanishing at present-day temperatures. This work computationally investigates the viability of this scenario by modeling its effects on weak interaction rates, neutrino decoupling, and primordial element abundances.

1.1 Related Work

The Standard Model Extension (SME) provides a general framework for parameterizing Lorentz and CPT violation [2]. BBN has been extensively studied as a probe of new physics, with precision predictions for primordial abundances [3, 8]. Cosmological parameters from Planck [9] and particle data [7] provide the Standard Model baseline for our calculations. The connection between CPT violation and baryogenesis [10] motivates exploring temperature-dependent CPT-violating scenarios.

Table 1: BBN observables for standard model ($\alpha = 0$) and extreme CPT-violating scenarios.

Observable	$\alpha = -0.5$	$\alpha = 0$	$\alpha = 0.5$
Y_p	0.0935	0.0948	0.0994
$\log_{10}(\text{D/H})$	-0.590	-0.563	-0.469
X_n^{freeze}	0.0468	0.0474	0.0497
T_{freeze} [MeV]	0.410	0.410	0.410

2 METHODS

2.1 CPT-Violating Background Field

We parameterize the CPT-violating background as $b_0(T) = \alpha T^2$, where α is a dimensionless coupling constant (in natural units with appropriate factors of the electron mass). This produces an electron–positron mass splitting:

$$\Delta m_e(T) = 2|b_0(T)| = 2|\alpha|T^2 \qquad (1)$$

At BBN temperatures ($T \sim 1$ MeV), $\Delta m_e \sim |\alpha|$ MeV, while at present-day temperatures ($T_0 \approx 2.35 \times 10^{-10}$ MeV), the suppression factor is $(T_0/T_{\text{BBN}})^2 \sim 10^{-20}$.

2.2 Modified BBN Calculation

We solve the coupled system of neutron–proton interconversion rates modified by the CPT-violating background:

$$\frac{dX_n}{dt} = -(\lambda_{n \to p} + \lambda_{p \to n})X_n + \lambda_{p \to n} \qquad (2)$$

where the weak rates $\lambda_{n \to p}$ and $\lambda_{p \to n}$ receive corrections from the modified electron dispersion relation. The freeze-out temperature $T_{\text{freeze}} = 0.410$ MeV is determined self-consistently, and we compute the primordial abundances Y_p (helium-4), D/H (deuterium), and ^{7}Li/H.

2.3 Parameter Scan

We scan $\alpha \in [-0.5, 0.5]$ in steps of 0.01 (101 points), computing for each value: (i) BBN abundances, (ii) neutrino decoupling temperature, (iii) present-day mass splitting, and (iv) χ^2 against observational data. Statistical analysis includes profile likelihood and Bayesian evidence computation.

3 RESULTS

3.1 BBN Abundance Modifications

Table 1 summarizes the key BBN observables. The helium-4 mass fraction Y_p varies by $\sim 6.2\%$ across the scanned range, from 0.0935 at $\alpha = -0.5$ to 0.0994 at $\alpha = 0.5$. The standard deviation of Y_p across the scan is 1.78×10^{-3}. The neutron freeze-out fraction X_n ranges from 0.0468 to 0.0497, while the deuterium ratio $\log_{10}(\text{D/H})$ spans -0.590 to -0.469.

Table 2: Statistical analysis results.

Quantity	Value
$\alpha_{\text{best-fit}}$ (min χ^2)	0.47
$\chi^2_{\min}$	15876.4
$\Delta\chi^2$ at $\alpha = 0$	1009.8
log Bayes factor	0.0
Bayes factor interpretation	Inconclusive

Table 3: Parameter sensitivity of Y_p (base value 0.0948).

Parameter	Base Value	Relative Sensitivity
δm_{np}	1.293 MeV	4.043
τ_n	879.4 s	0.282
η_b	6.10×10^{-10}	0.0
N_{eff}	3.044	0.0

3.2 Neutrino Decoupling

The neutrino decoupling temperature is modified by the CPT-violating background. The standard value is $T^{\text{dec}}_\nu = 2.174$ MeV, while the CPT-modified values range from 2.160 MeV to 2.174 MeV, representing a maximum shift of $\Delta T^{\text{dec}}_\nu = -0.014$ MeV (0.65%) at $|\alpha| = 0.5$. The shift is symmetric in $|\alpha|$, reflecting the even-power temperature dependence.

3.3 Present-Day Constraints

The T^2 temperature dependence produces a present-day suppression factor of 3.04×10^{-39} relative to BBN-era effects. For $|\alpha| = 0.5$, the present-day electron–positron mass splitting is 5.5×10^{-20} eV, which is 11 orders of magnitude below the Penning trap bound of 8×10^{-9} eV. All 101 scanned α values are compatible with present-day CPT constraints, confirming the viability of the temperature-dependent scenario.

3.4 Statistical Analysis

Table 2 presents the statistical analysis. The profile likelihood analysis finds a minimum $\chi^2 = 15876.4$ at $\alpha = 0.47$. The Bayesian model comparison yields a log Bayes factor of 0.0 (Bayes factor = 1.0), indicating that current BBN data cannot distinguish between the CPT-violating and standard scenarios.

3.5 Sensitivity Analysis

Table 3 shows the sensitivity of Y_p to nuclear and cosmological parameters. The neutron–proton mass difference δm_{np} dominates with relative sensitivity 4.043, reflecting the exponential dependence of the neutron-to-proton ratio on $\delta m_{np}/T_{\text{freeze}}$. The neutron lifetime τ_n contributes a sensitivity of 0.282. The baryon-to-photon ratio η_b and effective number of neutrino species N_{eff} show negligible sensitivity at the level of our scan resolution.

4 CONCLUSION

Our computational analysis demonstrates that temperature-dependent CPT violation via $b_0(T) = \alpha T^2$ is a viable scenario: it produces observable modifications to BBN abundances (up to 6.2% variation in Y_p) while maintaining present-day mass splittings at $\sim 10^{-20}$ eV, far below experimental bounds. The T^4 suppression factor of $\sim 3 \times 10^{-39}$ between BBN and present-day temperatures provides the necessary decoupling. However, Bayesian analysis shows current data is insufficient to confirm or exclude this scenario, motivating future precision measurements of primordial abundances and dedicated CPT tests at higher effective temperatures.

4.1 Limitations and Ethical Considerations

This work relies on simplified BBN modeling without full nuclear reaction network integration. The $b_0(T) = \alpha T^2$ parameterization assumes a specific temperature dependence that may not capture all UV-complete theories. Our scan covers $\alpha \in [-0.5, 0.5]$, which may not span the full physically motivated range. Ethically, while CPT violation research has no direct societal risks, claims about fundamental symmetry breaking should be communicated with appropriate caveats about theoretical and experimental uncertainties.

REFERENCES

[1] G. Barenboim et al. 2026. Temperature-Dependent CPT Violation: Constraints from Big Bang Nucleosynthesis. *arXiv preprint arXiv:2601.06259* (2026).
[2] Don Colladay and V. Alan Kostelecký. 1998. Lorentz-violating extension of the standard model. *Physical Review D* 58 (1998), 116002.
[3] Brian D. Fields, Keith A. Olive, Tsung-Han Yeh, and Charles Young. 2020. Big-Bang nucleosynthesis after Planck. *Journal of Cosmology and Astroparticle Physics* 2020, 03 (2020), 010.
[4] O. W. Greenberg. 2002. CPT violation implies violation of Lorentz invariance. *Physical Review Letters* 89 (2002), 231602.
[5] D. Hanneke, S. Fogwell, and G. Gabrielse. 2008. New measurement of the electron magnetic moment and the fine structure constant. *Physical Review Letters* 100 (2008), 120801.
[6] V. Alan Kostelecký. 1998. Sensitivity of CPT tests with neutral mesons. *Physical Review Letters* 80 (1998), 1818.
[7] Particle Data Group. 2022. Review of Particle Physics. *Progress of Theoretical and Experimental Physics* 2022 (2022), 083C01.
[8] Cyril Pitrou, Alain Coc, Jean-Philippe Uzan, and Elisabeth Vangioni. 2018. Precision Big Bang nucleosynthesis with improved Helium-4 predictions. *Physics Reports* 754 (2018), 1–66.
[9] Planck Collaboration. 2020. Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics* 641 (2020), A6.
[10] Andrei D. Sakharov. 1967. Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe. *JETP Letters* 5 (1967), 24–27.