

Time as an Emergent Property in Quantum Mechanics: A Connection Between Relativity, Fine-Structure Constant, and Quantum Dynamics

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1 Introduction

In modern physics, time and space are treated differently. While spatial coordinates in quantum mechanics are represented by operators, time primarily appears as a parameter. This asymmetric treatment raises fundamental questions about the nature of time. This work explores the extent to which time can be understood as an emergent property, linked to fundamental constants and the mass of the system under consideration.

This investigation is part of a broader conceptual framework, discussed in detail in the companion paper *Complementary Extensions of Physics: Absolute Time and Intrinsic Time* [1] (March 24, 2025). There, the intrinsic time introduced here is connected with a complementary model of absolute time (the *T0 Model* [5]), resulting in a *time-mass duality* [7] conceptually similar to the well-known wave-particle duality.

2 Time in Special Relativity

Einstein's famous formula $E = mc^2$ connects energy and mass via the speed of light. To establish a connection to time, we introduce:

$$E = mc^2 \tag{1}$$

$$E = h\nu = \frac{h}{T} \tag{2}$$

where h is the Planck constant, ν is the frequency, and T is the period. Equating these yields:

$$mc^2 = \frac{h}{T} \tag{3}$$

$$T = \frac{h}{mc^2} \tag{4}$$

This time T can be interpreted as a characteristic or intrinsic timescale linked to the mass m .

3 Connection to the Fine-Structure Constant

The fine-structure constant α_{EM} is a dimensionless physical constant that describes the strength of electromagnetic interaction:

$$\alpha_{\text{EM}} = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137.035999} \tag{5}$$

3.1 Derivation via Electromagnetic Constants

The Planck constant can be expressed in terms of electromagnetic vacuum constants:

$$h = \frac{1}{2\pi\sqrt{\mu_0\epsilon_0}} \tag{6}$$

Thus, the intrinsic time T can be rewritten as:

$$T = \frac{h}{mc^2} \tag{7}$$

$$= \frac{1}{2\pi\sqrt{\mu_0\epsilon_0}} \cdot \frac{1}{mc^2} \tag{8}$$

Since $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$, we obtain:

$$T = \frac{1}{2\pi\sqrt{\mu_0 \varepsilon_0}} \cdot \frac{1}{m \cdot \frac{1}{\mu_0 \varepsilon_0}} \quad (9)$$

$$= \frac{\mu_0 \varepsilon_0}{2\pi m c} \quad (10)$$

4 Time in Quantum Mechanics

4.1 Standard Treatment of Time

In conventional quantum mechanics, time appears as a parameter in the Schrödinger equation:

$$i\hbar \frac{\partial}{\partial t} \Psi(x, t) = \hat{H} \Psi(x, t) \quad (11)$$

Unlike spatial or momentum coordinates, there is no time operator. Time is treated as a continuous parameter along which quantum states evolve.

4.2 A New Perspective: Intrinsic Time

Consider the characteristic time $T(x) = \frac{\hbar}{\max(mc^2, \omega)}$ as the intrinsic time of a quantum object, encompassing both massive particles and photons. This time depends on the object's mass or energy and could be interpreted as the minimal timescale on which the object undergoes quantum mechanical changes. The Schrödinger equation is modified to:

$$i\hbar T(x) \frac{\partial}{\partial t} \Psi + i\hbar \Psi \frac{\partial T(x)}{\partial t} = \hat{H} \Psi \quad (12)$$

This implies that time evolution is no longer uniform for all objects but depends on their properties.

5 Extended Relationships Between Time, Mass, and Fundamental Constants

5.1 A Unified Relation to the Fine-Structure Constant

Using $T = \frac{\hbar}{mc^2}$ for massive particles and extending:

$$T = \frac{\hbar}{mc^2} \cdot \frac{4\pi\varepsilon_0 \hbar c}{e^2} \cdot \alpha_{\text{EM}} \quad (13)$$

This reveals a deep connection between time evolution and electromagnetic interactions.

5.2 Modified Dispersion Relation

In standard quantum mechanics:

$$\omega = \frac{\hbar k^2}{2m} \quad (14)$$

With $T(x) = \frac{\hbar}{\max(mc^2, \omega)}$, for massive particles:

$$\omega_{\text{eff}} = \frac{\hbar^2 k^2}{2m^2 c^2} \quad (15)$$

This differs from the standard $\omega \propto \frac{1}{m}$.

5.3 Treatment of Multi-Particle Systems

For two particles (m_1, m_2):

$$i(m_1 + m_2)c^2 \frac{\partial}{\partial t} \Psi(x_1, x_2, t) = \hat{H} \Psi(x_1, x_2, t) \quad (16)$$

For entangled states:

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}}(|0(t/T_1)\rangle_{m_1} \otimes |1(t/T_2)\rangle_{m_2} + |1(t/T_1)\rangle_{m_1} \otimes |0(t/T_2)\rangle_{m_2}) \quad (17)$$

where $T_1 = \frac{\hbar}{m_1 c^2}$, $T_2 = \frac{\hbar}{m_2 c^2}$.

5.4 Mass-Dependent Coherence Times and Instantaneity

Decoherence rate:

$$\Gamma_{\text{dec}} = \Gamma_0 \cdot \frac{mc^2}{\hbar} \quad (18)$$

Energy-time uncertainty:

$$\Delta t \gtrsim \frac{\hbar}{mc^2} \quad (19)$$

6 Lagrangian Formulation

$$\mathcal{L}_{\text{Total}} = \mathcal{L}_{\text{Boson}} + \mathcal{L}_{\text{Fermion}} + \mathcal{L}_{\text{Higgs-T}} + \mathcal{L}_{\text{intrinsic}}, \quad \mathcal{L}_{\text{intrinsic}} = \frac{1}{2} \partial_\mu T(x) \partial^\mu T(x) - V(T(x)) \quad (20)$$

7 Implications for Physics

7.1 A New Perspective on Time

Time is not derived as fundamental but considered an emergent property.

7.2 Connection to Time Dilation

The T0 model reflects relativistic effects through mass variation.

7.3 Emergent Gravity

In the T0 model, gravity emerges as a force from the gradients of the intrinsic time field $T(x)$, defined by $m = \frac{1}{T(x)}$ in a unified unit system ($\hbar = c = G = \alpha_{\text{EM}} = \beta_{\text{T}} = 1$). The gravitational potential arises as:

$$\Phi(r) = -\ln\left(\frac{T(x)(r)}{T_0}\right) \approx \frac{M}{r}, \quad (21)$$

where $T(x)(r) = T_0 \left(1 - \frac{M}{r}\right)$ for a point mass M . The resulting force is:

$$\vec{F} = -\nabla\Phi \approx -\frac{M}{r^2} \hat{r}, \quad (22)$$

reproducing Newtonian gravity. On larger scales, an additional term κr may appear, explaining flat rotation curves. A detailed derivation is provided in [8, 10].

8 Cosmological Implications in SI Units

- **Redshift:** In the T0 model, cosmic redshift z is determined by the variation of the intrinsic time field $T(x)$, with the relation $1 + z = \frac{T(x)_0}{T(x)}$, where $T(x)_0$ is the local value of the time field. In SI units, this becomes $1 + z = e^{\alpha d}$, with $\alpha \approx 2.3 \times 10^{-28} \text{ m}^{-1}$, where $\alpha = H_0/c$ describes the spatial variation rate of $T(x)$ [9, 8].
- **Gravitational Potential:** The emergent gravitational potential in the T0 model is $\Phi(r) = -\frac{GM}{r} + \kappa r$, with $\kappa = \frac{yv}{r_g}$ [8].
- **Wavelength Dependence:** Redshift exhibits a wavelength-dependent component, described by $z(\lambda) = z_0 \left(1 + \beta_T^{\text{SI}} \ln \left(\frac{\lambda}{\lambda_0}\right)\right)$, with $\beta_T^{\text{SI}} \approx 0.008$. In natural units with $\beta_T^{\text{nat}} = 1$, it becomes $z(\lambda) = z_0 \left(1 + \ln \left(\frac{\lambda}{\lambda_0}\right)\right)$ [?, 10].

9 Role of β_T

The parameter $\beta_T^{\text{SI}} \approx 0.008$ in SI units serves as a factor in the natural derivation of the wavelength-dependent redshift $z(\lambda) = z_0 \left(1 + \beta_T^{\text{SI}} \ln \left(\frac{\lambda}{\lambda_0}\right)\right)$ in the T0 model [10]. In a unified unit system, $\beta_T^{\text{nat}} = 1$ is set, defining the characteristic length scale $r_0 \approx 1.33 \times 10^{-4} \cdot l_P$ and supporting consistency with $\alpha_{\text{EM}} = 1$.

10 Experimental Verification Possibilities

- **Differences in Coherence Times:** Measurement of temporal deviations in interferometric experiments.
- **Mass-Dependent Phase Shifts:** Investigation of phase differences depending on particle masses.
- **Spectroscopy Signatures:** Detection of wavelength-dependent redshift with high-precision spectroscopy.
- **Test of Modified Dispersion Relation:** $\omega_{\text{eff}} \propto \frac{1}{m^2}$, verifiable through light propagation experiments.

11 Effects on Instantaneous Coherence in Quantum Mechanics

11.1 Problem of Instantaneous Coherence

Quantum correlations appear instantaneous, challenging causality within standard physics [12].

11.2 Mass-Dependent Coherence Times

Heavier particles decohere faster in lab time due to mass variation $m = \frac{\hbar}{Tc^2}$ in the T0 model [9].

11.3 Mathematical Formulation for Multi-Particle Systems

Dynamics are described by coupling to $T(x)$ (see detailed equations in [7]).

11.4 Effects on Entangled States

Mass differences influence the coherence of entangled states through the intrinsic time $T(x)$.

11.5 New Interpretation for EPR and Bell

Nonlocality could reflect mass-dependent timescales, testable through modified Bell experiments with variable masses [12].

12 Conclusions and Outlook

The T0 model views time as emergent and provides a unified, experimentally verifiable framework that connects relativity, quantum mechanics, and the fine-structure constant, with β_T playing a central role in deriving cosmological and quantum mechanical effects [9, 10].

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