Mathematical Formulation of the Higgs Mechanism in Time-Mass Duality

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Abstract

This work develops a precise mathematical formulation of the Higgs mechanism within the framework of a novel time-mass duality theory. Assuming that time and mass are complementary aspects of the same fundamental reality, we show how the Higgs mechanism serves as a mediator between two equivalent descriptions: the conventional picture with time dilation and constant rest mass on the one hand, and an alternative picture with absolute time and variable mass on the other. The formulation not only leads to an elegant mathematical structure but also yields concrete, experimentally verifiable predictions that deviate from the Standard Model of particle physics.

Introduction

Modern theoretical physics is based on two fundamental, yet not completely reconcilable theories: relativity theory and quantum mechanics. While relativity theory describes time and space as dynamic quantities dependent on the observer, quantum mechanics treats time as an external parameter. This conceptual tension possibly indicates a deeper structure that could unite both perspectives.

In this paper, we examine an alternative theoretical foundation based on the idea of a fundamental dualism between time and mass. Similar to the wave-particle duality in quantum mechanics, we postulate that time and mass represent two complementary descriptions of the same physical reality. While conventional relativity theory considers time as relative (time dilation) and rest mass as constant, we propose an alternative, mathematically equivalent picture in which time is absolute and mass varies instead.

The Higgs mechanism plays a special role in this context, as it is responsible for generating particle masses in the Standard Model. In our dual formulation, the Higgs field becomes the central mediator between both perspectives and defines both the rest mass and the intrinsic time scale of all particles. Particularly noteworthy is that the unique position of the Higgs boson in the particle zoo—as the only particle without a clear "mirror image"—finds a natural explanation in this framework.

In the following, we develop a mathematically precise formalism for this time-mass duality, reformulate the basic field equations, and derive concrete experimental consequences. This theory does not represent a break with established physics, but rather extends its interpretative framework and potentially reveals deeper connections between seemingly independent phenomena such as quantum coherence, Higgs interactions, and cosmological observations.

1 Starting Point: Higgs Mechanism in the Standard Model

In the Standard Model, the Higgs field is introduced as a complex scalar doublet:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \tag{1}$$

The Lagrangian density for the Higgs field is:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \tag{2}$$

with the Higgs potential:

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \tag{3}$$

The Yukawa coupling that describes the coupling of the Higgs field to fermions:

$$\mathcal{L}_{\text{Yukawa}} = -y_f\bar{\psi}_L\Phi\psi_R + \text{h.c.} \tag{4}$$

After spontaneous symmetry breaking, the Higgs field acquires a vacuum expectation value (VEV):

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix} \tag{5}$$

The fermion masses then result as:

$$m_f = \frac{y_f v}{\sqrt{2}} \tag{6}$$

2 Reformulation in the Time-Mass Duality Framework

2.1 Time Dilation Picture (Standard Relativity Theory)

In this picture, the rest mass of particles is constant, while time is relative (time dilation). The mass-energy relation is:

$$E = \gamma m_0 c^2 \tag{7}$$

where $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ is the Lorentz factor.

Time dilation is described by:

$$t' = \gamma t \tag{8}$$

The Yukawa coupling in this picture leads directly to a constant rest mass:

$$m_0 = \frac{y_f v}{\sqrt{2}} \tag{9}$$

2.2 Mass Variation Picture (Time-Mass Duality)

In this alternative picture, time T_0 is absolute (constant), while mass is variable. The intrinsic time is defined as:

$$T = \frac{\hbar}{mc^2} \tag{10}$$

The transformation relation to the standard picture is:

$$m = \gamma m_0 \tag{11}$$

and

$$T = \frac{T_0}{\gamma} \tag{12}$$

where $T_0 = \frac{\hbar}{m_0 c^2}$ is the intrinsic time in the rest state.

3 The Higgs Field as Mediator of Time-Mass Duality

3.1 Modified Higgs Lagrangian Density

In the time-mass duality framework, we modify the Higgs Lagrangian density:

$$\mathcal{L}_{\text{Higgs-T}} = (D_{T\mu}\Phi_T)^\dagger(D_T^\mu\Phi_T) - V_T(\Phi_T) \tag{13}$$

where the index T denotes the dependence on intrinsic time. The covariant derivative is modified to:

$$D_{T\mu} = \partial_{t/T,\mathbf{x}} + ig\mathbf{A}_\mu \tag{14}$$

This means that the time derivative is with respect to the intrinsic time T:

$$\partial_{t/T} = \frac{\partial}{\partial(t/T)} = T\frac{\partial}{\partial t} \tag{15}$$

3.2 Modified Yukawa Coupling

The Yukawa coupling in the mass variation picture is reinterpreted:

$$\mathcal{L}_{\text{Yukawa-T}} = -y_f\bar{\psi}_L\Phi_T\psi_R \cdot \mathcal{T}(\gamma) + \text{h.c.} \tag{16}$$

where $\mathcal{T}(\gamma)$ is a function that mediates the transformation between the two pictures:

$$\mathcal{T}(\gamma) = \gamma \tag{17}$$

This modified Yukawa coupling leads to a velocity-dependent mass:

$$m(v) = \gamma \cdot \frac{y_f v}{\sqrt{2}} = \gamma m_0 \tag{18}$$

while the intrinsic time scales accordingly:

$$T(v) = \frac{\hbar}{m(v)c^2} = \frac{\hbar}{\gamma m_0 c^2} = \frac{T_0}{\gamma} \tag{19}$$

3.3 Higgs Field as a Connection Between the Pictures

In the new framework, the Higgs field plays a dual role:

1. It generates the rest mass m_0 through its VEV in the standard picture
2. It defines the intrinsic time scale $T_0 = \frac{\hbar}{m_0 c^2}$ in the duality picture

The fundamental connection is expressed by:

$$T_0 \cdot m_0 c^2 = \hbar \tag{20}$$

This relationship is preserved in both pictures, since:

$$T \cdot mc^2 = \frac{T_0}{\gamma} \cdot \gamma m_0 c^2 = T_0 \cdot m_0 c^2 = \hbar \tag{21}$$

4 Field Equations in Dual Formulation

4.1 Klein-Gordon Equation

The standard Klein-Gordon equation for the Higgs boson is:

$$(\Box + m_H^2)h(x) = 0 \tag{22}$$

In the time-mass duality picture, it becomes:

$$\left(\frac{\partial^2}{\partial(t/T)^2} - \nabla^2 + m_H^2\right) h_T(x) = 0 \tag{23}$$

This leads to a modified dispersion relation:

$$\omega_T^2 = \mathbf{k}^2 + \frac{m_H^2 c^4}{\hbar^2} \cdot T^2 \tag{24}$$

4.2 Dirac Equation

The Dirac equation for fermions in the Standard Model:

$$(i\gamma^\mu \partial_\mu - m_f)\psi(x) = 0 \tag{25}$$

becomes in the time-mass duality picture:

$$\left(i\gamma^0 \frac{\partial}{\partial(t/T)} + i\gamma^i \partial_i - m_f\right) \psi_T(x) = 0 \tag{26}$$

4.3 Field Equations for Gauge Bosons

The Yang-Mills equations for gauge bosons are similarly modified, with the time derivative replaced by $\partial_{t/T}$.

5 Higgs as a Universal Medium

The Higgs field can be considered a universal medium that not only mediates mass but also determines the intrinsic time scale of all particles. Since the Higgs field is present everywhere in space, it defines, in a sense, a preferred reference frame—not for spacetime coordinates, but for the time-mass duality.

The intrinsic time of a particle is determined by its coupling to the Higgs field:

$$T_0 = \frac{\hbar}{m_0 c^2} = \frac{\hbar\sqrt{2}}{y_f v c^2} \tag{27}$$

This shows that the intrinsic time scale is inversely proportional to the Yukawa coupling constant.

6 Symmetry Considerations

6.1 Conserved Quantities

In the standard picture, the energy $E = mc^2$ is a conserved quantity. In the time-mass duality picture, the product $T \cdot mc^2 = \hbar$ is constant, corresponding to a new conserved quantity.

6.2 Symmetry Transformations

The Lorentz transformation is reinterpreted:

$$t \to t' = \gamma t \qquad \text{(standard picture)} \tag{28}$$

$$m \to m' = \gamma m_0 \qquad \text{(duality picture)} \tag{29}$$

The global phase in quantum mechanics $\psi \to e^{i\theta}\psi$ could acquire a deeper meaning in this context, possibly as a rotation in "time-mass space."

7 Philosophical and Epistemological Implications

The time-mass duality theory, beyond its physical consequences, also raises profound scientific-philosophical questions:

7.1 Decidability Between Mathematically Equivalent Theories

It is particularly fascinating that our theory raises a central scientific-philosophical question: To what extent can we decide between mathematically equivalent but conceptually different theories? In the standard picture with time dilation and in the alternative picture with mass variation, we initially obtain the same computational results for known phenomena such as GPS corrections or the extended lifetime of moving muons.

The answer may lie in subtle experimental effects that appear "natural" in only one of the two pictures. The predicted nonlinearities in Higgs couplings or mass-dependent coherence times could represent such distinguishing criteria. This is reminiscent of the debate between the geocentric and heliocentric worldviews, where both models could mathematically describe the movement of planets, but the heliocentric model led to a simpler and more elegant explanation.

7.2 Emergent Properties of Fundamental Quantities

The interpretation of time as an emergent property derived from mass and fundamental constants (such as $\hbar$ and c) fundamentally challenges our conception of basic quantities. As extensively elaborated in previous works [1, 2], the relationship $T = \frac{\hbar}{mc^2}$ suggests that time might not be a fundamental property but rather a derived one.

This conception could have far-reaching implications, as it suggests that other seemingly fundamental parameters of physics may also be emergent properties of deeper underlying structures. The mass-dependent time scale could indicate that we need to reconsider the hierarchy of fundamental physical quantities, as further discussed in [3].

7.3 The Vacuum Energy Paradox in a New Light

The so-called "Cosmological Constant Problem" - the enormous discrepancy between the theoretically calculated and the observed vacuum energy - could find a fundamentally new interpretation in our framework. The formulation of vacuum energy as

$$E_{\text{Vacuum}} = \sum_i \frac{\hbar}{2T_i} = \sum_i \frac{m_i c^2}{2} \tag{30}$$

directly links vacuum energy to the intrinsic time of quantum fluctuations. The apparent discrepancy could result from the fact that the standard model sums the "wrong" degrees of freedom.

This new interpretation could explain why the observed vacuum energy (dark energy) is about 10^{-120} times smaller than the naive calculation of the zero-point energy of all quantum fields. In our model, the Higgs field would provide a natural upper limit for the summation that would be consistent with the observed cosmological constant.

7.3.1 Detailed Examination of the Vacuum Energy Problem

In conventional quantum field theory, vacuum energy is calculated as the sum of the zero-point energies of all field modes:

$$E_{\text{Vacuum, conv.}} = \sum_{\text{modes}} \frac{\hbar\omega_k}{2} \tag{31}$$

This sum diverges unless an arbitrary cutoff is introduced at high energies. Even with a Planck scale cutoff ($\Lambda_{\text{Planck}} \sim 10^{19}$ GeV), the resulting energy density is about 10^{120} times larger than the observed value of the cosmological constant – one of the largest discrepancies between theory and observation in physics.

In our time-mass duality model, a fundamentally different approach emerges. The zero-point energy of a quantum field is directly linked to the intrinsic time T_i of the particles involved:

$$E_i = \frac{\hbar}{2T_i} = \frac{m_i c^2}{2} \tag{32}$$

This leads to several crucial consequences:

- **Natural Weighting:** The contribution of each quantum fluctuation to vacuum energy is proportional to the mass of the corresponding particle, not to the third power of its energy scale as in the standard model.
- **Intrinsic Regularization:** Massless particles with $T \to \infty$ provide no contribution, while very massive particles with small T automatically provide a finite contribution – a natural regularization without arbitrary cutoffs.
- **Higgs Mechanism as Regulator:** Since masses are generated by the Higgs field, the sum of vacuum energy is directly regulated and stabilized by the Higgs field.

The total vacuum energy in our model is:

$$E_{\text{Vacuum}} = \sum_i n_i \frac{m_i c^2}{2} \tag{33}$$

where n_i represents the number of effective degrees of freedom for each type of particle.

This formulation provides several natural mechanisms that could explain why the observed vacuum energy is much smaller than the naive expectation:

- **Partial Cancellation:** Contributions from fermions and bosons could partially cancel each other, where the cancellation does not require perfect supersymmetry but follows from the intrinsic time structure.

- **Dynamic Equilibrium:** The vacuum energy could be in a dynamic equilibrium with the Higgs field, leading to a natural "self-adjustment."
- **Alternative to Cosmological Expansion:** The intrinsic time T provides an alternative explanatory framework for phenomena typically attributed to cosmic expansion. In our model, the universe does not expand, but the observed effects result from the energy decrease of photons over large distances according to $E(r) = E_0 e^{-\alpha r}$.

The resulting value of vacuum energy in this model would not be an arbitrarily fine-tuned quantity, but the result of the fundamental structure of the particle-time relationship in the universe.

7.4 Realism versus Instrumentalism

The time-mass duality also sheds new light on the scientific-philosophical debate between realism and instrumentalism. Is one of the two descriptions (time dilation or mass variation) "more real" than the other, or are they merely mathematically equivalent descriptions without ontological difference?

Our approach suggests that both pictures might describe different aspects of the same underlying reality, similar to the wave-particle duality in quantum mechanics. This would argue for a "perspectivistic realism" where the choice of picture depends on the context and the specific phenomena being investigated.

8 Experimental Signatures and New Predictions

The dual formulation of the Higgs mechanism leads to several experimentally verifiable predictions that deviate from the Standard Model. These are particularly important as they offer a concrete possibility to distinguish between the time-mass duality theory and the conventional interpretation:

8.1 Mass-Dependent Quantum Coherence

In the time-mass duality theory, differently massive particles have different intrinsic time scales ($T = \frac{\hbar}{mc^2}$). This leads to the following testable predictions:

- **Coherence Time Ratio:** For quantum systems of different mass, the coherence times τ_1 and τ_2 of two otherwise identical quantum systems with masses m_1 and m_2 should follow the ratio:
$$\frac{\tau_1}{\tau_2} = \frac{m_2}{m_1} \tag{34}$$
This could be tested in precision experiments with molecules of different isotopes or Bose-Einstein condensates of different atom species.
- **Mass-Dependent Interference Patterns:** In double-slit experiments with particles of different mass (at the same velocity), subtle differences in the interference patterns should occur that go beyond the de Broglie wavelength differences.

8.2 Modified Higgs Couplings

The time-mass duality should cause deviations in the Higgs couplings:

- **Nonlinearity in the Mass Hierarchy:** The Standard Model predicts that Higgs couplings are strictly proportional to particle mass. In the time-mass duality theory, this relationship could exhibit slight nonlinearities:

$$g_H \propto m \left(1 + \delta \cdot \ln\left(\frac{m}{m_0}\right)\right) \tag{35}$$

  where δ is a small correction and m_0 is a reference mass.

- **Dynamic Higgs Couplings:** At very high energies, the Higgs couplings could show slight deviations from relativistic predictions, which could be detectable with precision measurements at the LHC or future accelerators.

8.3 Entanglement Effects with Unequal Masses

The time-mass duality makes unique predictions for entangled quantum systems with different masses:

- **Mass-Dependent Entanglement Correlations:** In Bell tests with entangled particles of different mass, the measured correlations should show a subtle mass dependence.
- **Delayed Correlations:** The intrinsic time scale $T = \frac{\hbar}{mc^2}$ could lead to measurable delays in quantum correlations, proportional to the mass ratio of the entangled particles.

8.4 Modified Energy-Momentum Relation

The time-mass duality leads to a modified energy-momentum relation:

$$E^2 = (pc)^2 + (mc^2)^2 + \alpha\frac{\hbar c}{T} \tag{36}$$

where α is a small dimensionless constant and T is the intrinsic time of the particle. This effect would be visible in very precise measurements of the energy-momentum relation, especially for light particles with large intrinsic time scales.

8.5 Cosmological Tests

- **Energy Transfer Coefficient:** The absorption coefficient $\alpha = \frac{H_0}{c} \approx 2.3\times10^{-28}\ \mathrm{m}^{-1}$ should be experimentally detectable in precise measurements of cosmic redshift and could provide an alternative explanation for the observed cosmic acceleration.
- **Modified Gravitational Potential:** In galactic rotation curves, the parameter $\kappa \approx 4.8 \times 10^{-7}\ \mathrm{GeV/cm \cdot s^{-2}}$ should be measurable and could explain the observed deviations without dark matter:

$$\Phi(r) = -\frac{GM}{r} + \kappa r \tag{37}$$

8.6 New Interpretation of Vacuum Energy

The time-mass duality leads to a new interpretation of vacuum energy:

$$E_{\text{Vacuum}} = \sum_i \frac{\hbar}{2T_i} = \sum_i \frac{m_i c^2}{2} \tag{38}$$

This formulation links vacuum energy directly to the intrinsic time of quantum fluctuations and could lead to measurable deviations in the Casimir force or other vacuum effects.

8.7 Photon Energy Loss

According to the theory, photons should experience a slight energy decrease according to $E(r) = E_0 e^{-\alpha r}$, where $\alpha = \frac{H_0}{c}$ is the absorption coefficient. This could alternatively explain cosmic redshift and be verified through precision spectroscopy of distant quasars.

8.8 Practical Experimental Feasibility

The most promising experiments to verify these predictions would be:

1. High-precision atomic clock comparisons with different elements
2. Quantum interference experiments with particles of different mass
3. Precision measurements of Higgs couplings at the LHC or future accelerators
4. Bell tests with entangled particles of different mass
5. Detailed analyses of cosmic redshift over large distances

References

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