A State-Dependent Formulation of Energy with an Effective Mass Parameter

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Abstract: ***This study proposes a state-dependent reformulation of mass–energy equivalence expressed as $E = Sc^2$, where $S = m_0\,\alpha$. Here, m_0 represents invariant rest mass and α is a dimensionless state function describing interaction-dependent coupling between a system and its environment. The formulation preserves dimensional consistency and reduces to the classical relation when $\alpha = 1$. In the limiting case $\alpha \to 0$, the effective mass contribution (S) to energy vanishes without eliminating other energy forms. The framework is phenomenological and maintains relativistic invariance while providing a conceptual bridge to effective mass interpretations in quantum and cosmological contexts. The results suggest that energetic mass contribution may emerge as a state-dependent property rather than a strictly intrinsic quantity.***

Keywords: Mass–energy equivalence, state-dependent mass (S), effective mass, dimensional consistency, quantum interpretation, theoretical physics, Lorentz invariance, phenomenological modeling, effective field theory.

1. Introduction

The mass–energy relationship is fundamentally described by Einstein's relativistic equation:

$$E = mc^2$$

where the rest mass is treated as an invariant scalar quantity **(Einstein, 1905)**. This formulation has been extensively validated experimentally and remains central to modern physics. However, developments in quantum theory, effective field descriptions, and cosmology suggest that the energetic role of mass may depend on interaction conditions rather than intrinsic properties alone **(Roche, 2005)**.

In this context, a generalized formulation is considered:

$$E = Sc^2$$

Where **S** represents an effective mass parameter that remains dimensionally equivalent to mass but may vary with system state. This work proposes consistent decomposition:

$$S = m_0\,\alpha$$

where m_0 is an invariant mass scale and α is a dimensionless state function. Building on previous explorations of mass behavior in extreme states **(Perinjelil, 2024a)**, the purpose of this formulation is to provide a phenomenological framework for describing regimes in which the effective mass contribution (**S**) to energy emerges or vanishes due to interaction-dependent conditions.

2. Dimensional Consistency of the Parameter S

For dimensional consistency within the SI system:

- Energy (E): joule (J) = $kg.\ m^2.s^{-2}$
- Speed of light (c): $m.s^{-1}$
- Therefore (c^2): $m^2.s^{-2}$

It follows directly that:

$$S = [E] / [C^2] = kg$$

Thus, parameter **S** must retain the physical dimension of mass. This aligns with the requirements for maintaining the integrity of the stress-energy tensor in relativistic contexts **(Jacobson, 1995)**. To introduce state dependence without violating dimensional integrity, **S** is defined as:

$\mathbf{S = m_0}\ \alpha$

where m_0 is the invariant rest mass (kg) and α is a dimensionless state function. This construction ensures that the generalized formulation remains fully consistent with classical dimensional analysis.

3. Dual-state Interpretation of Parameter S

The term **Dual-state** refers to the energetic contribution of mass under differing interaction conditions and should not be interpreted as implying multiple intrinsic mass values. The invariant mass m_0 remains unchanged throughout this framework; only the effective energetic contribution encoded by **S** varies through the state function α.

3.1 Coupled Interaction Regime

When the system is fully coupled to its interaction or observational environment, $\alpha = 1$. The generalized formulation reduces to the classical expression: $E = m_0c^2$. This corresponds to the standard relativistic regime **(Einstein, 1905)**.

3.2 Interaction-decoupled Regime

In a weakly interacting or effectively decoupled regime, $\alpha \to 0$. Consequently, the mass-associated contribution to energy vanishes:

$$\lim_{\alpha \to 0} \mathbf{E} = (\mathbf{m_0} \cdot 0)\mathbf{c}^2$$

This limit does not imply the absence of other energy components such as field energy, momentum, or vacuum contributions, but describes the effective mass suppression in specific interaction regimes **(Perinjelil, 2025a)**.

3.3 Consistence with Relativistic Invariance

The present formulation preserves Lorentz invariance by maintaining the invariant rest mass $\mathbf{m_0}$ and introducing state dependence only through the effective parameter **S**. No modification to relativistic dispersion relations or conservation laws is implied. The state function α serves as a phenomenological modulation of energy attribution rather than a dynamical field.

4. State Function Formalism

The dimensionless function α may be expressed generically as:

$$\alpha = \mathbf{f}\,(\mathbf{C}, \mathbf{g}, \boldsymbol{\Omega})$$

where **C** represents system configuration, **g** denotes interaction or coupling strength, and **Ω** corresponds to quantum state conditions. For physical consistency, α is assumed to satisfy the constraint $0 \leq \alpha \leq 1$. This interpretation allows mass (**S**)to be treated as an emergent energetic property dependent on interaction conditions rather than a strictly intrinsic attribute.

5. Relations to Massless and Effective-Mass Behavior

Massless behavior in this framework corresponds to the limiting case $\alpha \to 0$. Key implications include:

- The dimensional unit of **S** remains kilograms at all times.
- **Effective massless behavior** ($\alpha \to 0$) represents a vanishing effective mass contribution rather than the absence of mass as a physical concept.
- The formulation is conceptually analogous to effective mass descriptions in condensed matter physics, where particles moving through a potential lattice exhibit a modified mass response **(Kittel, 2004)**.

6. Illustrative Mathematical Example

As a phenomenological illustration, α may be defined in terms of interaction strength:

$$\alpha = \frac{(\Omega \mid \mathbf{H_{int}} \mid \Omega)}{N}$$

Where $\mathbf{H_{int}}$ represents an interaction Hamiltonian, Ω is the system state, and **N** is a normalization constant ensuring $0 \leq \alpha \leq 1$ quantum mechanical framework without altering foundational postulates.

7. Discussion

The proposed reformulation preserves Einstein's mass–energy equivalence as a limiting case while extending its interpretation into a state-dependent regime. The introduction of the **S** parameter offers consistent dual-state interpretation and preserves dimensional integrity. This framework provides a structured basis for exploring emergent mass behavior in quantum and cosmological contexts **(Perinjelil, 2026)** without losing their identity as massive particles.

8. Conclusion

This work introduces a state-dependent formulation of mass–energy equivalence given by $\mathbf{E} = \mathbf{S}\mathbf{c}^2$ where $\mathbf{S} = \mathbf{m_0}\,\alpha$. The framework preserves dimensional consistency and relativistic invariance while allowing structured variability in the effective mass contribution to energy through a dimensionless state function. in the limit $\alpha = 1$, the classical relation is recovered, while $\alpha \to 0$ describes an interaction-decoupled regime with vanishing effective mass contribution. Although phenomenological, the model provides a basis for exploring emergent mass behavior in quantum and cosmological systems.

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