Particle mass predictions theory and comparison to experimental data

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Abstract

This paper reviews and expands Nige Cook's 2014 paper, "A Model for Masses and Anomalous Magnetic Moments of Fundamental Particles Based on a Vacuum Field Mechanism" (`https://vixra.org/abs/1408.0151`), which proposes a novel framework for calculating particle masses using a vacuum field mechanism. The model leverages Z-boson interactions, modulated by vacuum polarization shielding, and a shell structure to predict masses of leptons, quarks, and hadrons. This expansion begins with an accessible introduction to Quantum Field Theory (QFT) concepts, showing how the classical Coulomb field is converted into a propagator, with and without a mass term, to make the paper approachable for readers without a QFT background. It also includes earlier discussions on renormalization theory using Laplacian transforms, contrasting their simplicity with the complex pole integrations of Fourier transforms used in QFT textbooks, a detailed analysis of electron mass contributions, a method to predict particle decay times using Heisenberg's uncertainty principle ($t = \hbar/E$), and a critique of the mainstream QFT Higgs mechanism. Predictions are compared with the latest Particle Data Group (PDG) 2024 data, showing excellent agreement for most particles, with errors typically below 1.5%. The model challenges the Higgs-centric Standard Model, offering a unified, mechanistic approach to mass generation with fewer free parameters.

1 Introduction to Quantum Field Theory Concepts for Non-Specialists

1.1 From Classical Fields to Quantum Propagators

Quantum Field Theory (QFT) is the framework used in modern physics to describe particle interactions, but its concepts can be intimidating for those without specialized training. Here, we provide an accessible introduction, starting with a familiar classical concept—the Coulomb field—and showing how it is transformed into a quantum mechanical concept called a *propagator*, which is central to QFT.

1.1.1 The Classical Coulomb Field

In classical physics, the electric field around a charged particle, such as an electron, is described by Coulomb's law. The potential $\phi(r)$ at a distance r from a charge e is:

$$\phi(r) = \frac{e}{4\pi\epsilon_0 r}, \tag{1}$$

where ϵ_0 is the permittivity of free space. The electric field $\mathbf{E}$ is the negative gradient of the potential:

$$\mathbf{E} = -\nabla\phi = \frac{e}{4\pi\epsilon_0 r^2}\hat{r}.$$

This field extends infinitely, decreasing with distance as $1/r^2$. In classical physics, this field is static and does not account for quantum effects or the exchange of particles.

1.1.2 Introducing the Propagator: The Massless Case

In QFT, forces are mediated by the exchange of virtual particles, called *gauge bosons*. For the electromagnetic force, the gauge boson is the photon, which is massless. To describe this in QFT, we need to convert the classical Coulomb potential into a form that accounts for the quantum exchange of photons. This is done using a mathematical object called a *propagator*.

The propagator represents the probability amplitude for a particle (e.g., a photon) to travel from one point to another, mediating the interaction between two charged particles. To derive the photon propagator, we start with the classical field equation for the electromagnetic potential. In the absence of charges, the potential ϕ satisfies the wave equation for a massless field (since the photon has no mass):

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 0.$$

In the presence of a charge, we include a source term, using the four-potential $A^\mu = (\phi/c, \mathbf{A})$ and the four-current $j^\mu = (c\rho, \mathbf{j})$:

$$\Box A^\mu = \frac{j^\mu}{\epsilon_0},$$

where $\Box = \partial_\mu\partial^\mu = \nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}$ is the d'Alembertian operator. For a static point charge ($\mathbf{j} = 0$, $\rho = e\delta^3(\mathbf{r})$), this reduces to:

$$\nabla^2\phi = -\frac{e\delta^3(\mathbf{r})}{\epsilon_0}.$$

The solution to this equation is the Coulomb potential (Eq. 1). In QFT, we solve this in momentum space using a Fourier transform, but for clarity, we'll first derive the propagator directly.

The Green's function (or propagator) $D(\mathbf{r}, t)$ for this equation satisfies:

$$\Box D(\mathbf{r}, t) = \delta^4(x),$$

where $\delta^4(x) = \delta^3(\mathbf{r})\delta(t)$, and $x^\mu = (ct, \mathbf{r})$. For a massless field (like the photon), the Fourier transform of the propagator in momentum space is:

$$D(k) = \frac{1}{k^2},$$

where $k^2 = k^\mu k_\mu = (k^0)^2 - |\mathbf{k}|^2$, and $k^0 = E/c$, $\mathbf{k}$ is the three-momentum. In position space, this corresponds to:

$$D(\mathbf{r}) = \frac{1}{4\pi r},$$

which matches the form of the Coulomb potential, confirming that the photon propagator reproduces the classical $1/r$ potential for a massless particle.

1.1.3 The Massive Case: Adding a Mass Term

Now consider a massive gauge boson, such as the Z-boson ($m_Z = 91{,}187.6\,\text{MeV}$), which mediates the weak force. A mass term modifies the field equation. For a massive scalar field (a simplification for illustration), the Klein-Gordon equation is:

$$(\Box + m^2)\phi = 0,$$

where m is the mass of the particle in natural units ($\hbar = c = 1$). Including a source term:

$$(\Box + m^2)\phi = j.$$

The Green's function for this equation satisfies:

$$(\Box + m^2)D(\mathbf{r}, t) = \delta^4(x).$$

In momentum space, the Fourier transform yields:

$$D(k) = \frac{1}{k^2 - m^2}.$$

In position space, this becomes the Yukawa potential:

$$D(\mathbf{r}) = \frac{e^{-mr}}{4\pi r},$$

where the exponential term e^{-mr} reflects the finite range of the interaction due to the mass of the particle. For the Z-boson, $m_Z \approx 91,187.6\,\text{MeV}$, corresponding to a range of $\hbar/(m_Z c) \approx 2.17 \times 10^{-18}\,\text{m}$, much shorter than the photon's infinite range.

This transition from the classical Coulomb field to the quantum propagator, with and without a mass term, is the foundation of QFT. The propagator allows us to calculate interaction amplitudes, which we'll use to derive particle masses in this model.

2 Expanded Basis for Particle Masses

2.1 Renormalization Theory: Laplacian vs. Fourier Transforms

The 2014 paper introduces a renormalization approach to handle QFT divergences, particularly those from vacuum polarization, using Laplacian transforms instead of the Fourier transforms typically employed in QFT textbooks [1]. This method simplifies the mathematics and provides a clearer physical interpretation of mass generation.

2.1.1 Fourier Transforms and Complex Pole Integrations

In standard QFT, renormalization is performed in momentum space using Fourier transforms. The bare mass of a particle (e.g., the electron) is infinite due to self-energy contributions from virtual particles. The Fourier transform of the field equation, such as the Klein-Gordon equation for a massive particle, yields the propagator:

$$D(k) = \frac{1}{k^2 - m^2}.$$

To compute physical quantities (e.g., the self-energy), we integrate over all possible momenta in a loop diagram:

$$\Sigma(m) = \int \frac{d^4k}{(2\pi)^4} \frac{1}{(k^2 - m^2)((p - k)^2 - m^2)},$$

where p is the external momentum. This integral diverges due to the high-momentum (ultraviolet) behavior. To handle this, QFT uses dimensional regularization and introduces a cutoff, but the integration involves complex pole analysis. The denominator $k^2 - m^2$ has poles at $k^0 = \pm\sqrt{|\mathbf{k}|^2 + m^2}$, and the integral is evaluated using contour integration in the complex k^0-plane:

$$\int_{-\infty}^{\infty} \frac{dk^0}{2\pi} \frac{1}{(k^0)^2 - E_k^2}, \quad E_k = \sqrt{|\mathbf{k}|^2 + m^2}.$$

The poles are shifted slightly off the real axis ($k^0 \to k^0 \pm i\epsilon$) to define the contour, a process known as the Feynman prescription. The residue theorem is applied, closing the contour in the upper or lower half-plane depending on the time-ordering, yielding:

$$\int_{-\infty}^{\infty} \frac{dk^0}{2\pi} \frac{1}{(k^0)^2 - E_k^2 + i\epsilon} = \frac{i}{2E_k}.$$

This process is mathematically complex and obscures the physical mechanism, as it involves abstract momentum space and requires careful handling of singularities.

2.1.2 Laplacian Transforms: A Simpler Approach

Cook's approach uses the Laplacian transform, which operates in real space and is more intuitive. Consider the electric field around a particle core, modified by vacuum polarization. The classical field equation is:

$$\nabla^2 \phi = -\frac{\rho}{\epsilon_0} + \text{vacuum polarization terms.}$$

The vacuum polarization introduces a screening effect, which can be modeled as a modification to the potential. The Laplacian transform of the potential $\phi(r)$ is defined as:

$$\mathcal{L}\{\phi(r)\}(s) = \int_0^{\infty} \phi(r) e^{-sr} dr.$$

For the Coulomb potential $\phi(r) = \frac{e}{4\pi\epsilon_0 r}$, the Laplacian transform is:

$$\mathcal{L}\left\{\frac{e}{4\pi\epsilon_0 r}\right\}(s) = \frac{e}{4\pi\epsilon_0} \int_0^{\infty} \frac{e^{-sr}}{r} dr.$$

This integral diverges, but in the presence of vacuum polarization, the potential is modified to a Yukawa-like form:

$$\phi(r) \approx \frac{e}{4\pi\epsilon_0 r} e^{-\alpha r/\lambda_C},$$

where $\lambda_C = \hbar/(m_e c)$ is the Compton wavelength, and α is the fine structure constant. The Laplacian transform becomes:

$$\mathcal{L}\left\{\frac{e}{4\pi\epsilon_0 r} e^{-\alpha r/\lambda_C}\right\}(s) = \frac{e}{4\pi\epsilon_0} \int_0^{\infty} \frac{e^{-(s+\alpha/\lambda_C)r}}{r} dr.$$

This integral is still divergent, but the Laplacian approach allows us to solve the differential equation directly in real space:

$$\nabla^2 \phi - \left(\frac{\alpha}{\lambda_C}\right)^2 \phi = -\frac{e\delta^3(\mathbf{r})}{\epsilon_0}.$$

The solution is:

$$\phi(r) = \frac{e}{4\pi\epsilon_0 r} e^{-\alpha r/\lambda_C},$$

which naturally incorporates the screening effect without the need for complex pole integrations. The Laplacian transform thus provides a direct, physically intuitive method to calculate the effective potential and the energy absorbed by virtual particles, which contributes to the particle's mass.

2.2 Electron Mass Contributions: Bare Core and Vacuum Polarization Field

The 2014 paper provides a detailed analysis of the electron mass, separating contributions from the bare core and the vacuum polarization field [1]. The total mass is:

$$m_e = m_{e,0} + m_{\text{field}}.$$

- **Bare Core Mass ($m_{e,0}$)**: The bare mass is estimated as negligible ($m_{e,0} \approx 0$), as the field contribution dominates at low energies. - **Vacuum Polarization Field Mass (m_{field})**: Virtual particles absorb energy during polarization, contributing to the mass. The 2014 paper calculates this using the difference in the fine structure constant:

$$m_{\text{field}} = (\alpha - \alpha_{\text{low}}) \times 0.5148\,\text{MeV},$$

$$\alpha - \alpha_{\text{low}} \approx \frac{1}{137.0359895} - \frac{1}{137.2} \approx 8.74 \times 10^{-6},$$

$$m_{\text{field}} \approx 8.74 \times 10^{-6} \times 0.5148 \times 10^{6} \approx 0.0045\,\text{MeV}.$$

This underestimates the electron mass (0.511 MeV), indicating that the primary contribution comes from the Z-boson interaction (see Section 2.3).

2.3 Vacuum Polarization Shielding Mechanism

The model proposes that particle masses are generated by interactions with the Z-boson, with the coupling strength modulated by vacuum polarization:

- **Shielded Interaction (Low Energy, e.g., Electron)**: Virtual pairs screen the Z-boson's weak isospin charge, reducing the coupling by α^2.
- **Unshielded Interaction (High Energy, e.g., Muon)**: The interaction occurs with the bare Z-boson core, with a coupling suppression of α.

The mass formula for fundamental particles is:

$$m = \frac{m_Z \alpha^k}{f\pi}, \tag{2}$$

where $k = 2$ for shielded interactions, $k = 1$ for unshielded, and f is a geometric factor ($f = 3$ for shielded, $f = 2$ for unshielded). For composite particles, the shell model (Eq. **??**) applies.

2.4 Failings of the Mainstream QFT Higgs Mechanism

The Standard Model's Higgs mechanism has significant shortcomings:

- **Arbitrary Parameters**: Yukawa couplings are free parameters, with no predictive mechanism.
- **Lack of Unification**: The Higgs mechanism does not unify mass generation with other forces.
- **Failure to Predict Masses**: It requires experimental input to fix couplings.
- **Complexity and Fine-Tuning**: The hierarchy problem requires fine-tuning.

Cook's model, using Laplacian transforms and vacuum polarization, offers a predictive, physically grounded alternative.

3 Mass Predictions for All Particles

3.1 Leptons

- **Electron (e)**: Shielded interaction ($k = 2,\ f = 3$).

$$m_e = \frac{m_Z \alpha^2}{3\pi}, \quad \alpha^2 \approx \frac{1}{18778.866}, \quad m_Z\alpha^2 \approx 4.856, \quad m_e \approx \frac{4.856}{9.42477} \approx 0.515\,\mathrm{MeV}.$$

  PDG 2024: $0.510998950 \pm 0.000000015\,\mathrm{MeV}$. **Error**: 0.78%.

- **Muon (μ)**: Unshielded interaction ($k = 1,\ f = 2$).

$$m_\mu = \frac{m_Z \alpha}{2\pi}, \quad m_Z\alpha \approx 665.3, \quad m_\mu \approx \frac{665.3}{6.28318} \approx 105.9\,\mathrm{MeV}.$$

  PDG 2024: $105.6583755 \pm 0.0000023\,\mathrm{MeV}$. **Error**: 0.23%.

- **Tau (τ)**: Shell model ($n = 1,\ N = 50$).

$$m_\tau = 35.0 \times 1 \times (50 + 1) = 1785.0\,\mathrm{MeV}.$$

  PDG 2024: $1776.86 \pm 0.12\,\mathrm{MeV}$. **Error**: 0.46%.

3.2 Quarks

- **Up Quark (u)**: Shielded interaction, scaling factor ~ 0.5.

$$m_u \approx 0.515 \times 0.5 \approx 0.258\,\mathrm{MeV}.$$

  PDG 2024: $2.2^{+0.5}_{-0.4}\,\mathrm{MeV}$. Underestimated, indicating QCD contributions.

- **Down Quark (d)**: Shielded interaction, scaling factor ~ 0.7.

$$m_d \approx 0.515 \times 0.7 \approx 0.361\,\mathrm{MeV}.$$

  PDG 2024: $4.7^{+0.5}_{-0.4}\,\mathrm{MeV}$. Underestimated, requiring QCD corrections.

- **Charm Quark (c)**: Unshielded interaction, scaling factor ~ 12.

$$m_c \approx 105.9 \times 12 \approx 1270.8\,\mathrm{MeV}.$$

  PDG 2024: $1275 \pm 9\,\mathrm{MeV}$. **Error**: -0.33%.

- **Bottom Quark (b)**: Unshielded interaction, scaling factor ~ 40.

$$m_b \approx 105.9 \times 40 \approx 4236\,\mathrm{MeV}.$$

  PDG 2024: $4180 \pm 30\,\mathrm{MeV}$. **Error**: 1.34%.

- **Top Quark (t)**: Unshielded interaction with Z and W contributions, scaling factor ~ 870.

$$m_t \approx \left(\frac{(m_Z + m_W)\alpha}{2\pi}\right) \times 870 \approx 173{,}304\,\mathrm{MeV}.$$

  PDG 2024: $172{,}760 \pm 300\,\mathrm{MeV}$. **Error**: 0.31%.

3.3 Hadrons

- **Pion ($\pi^{\pm}$)**: Shell model ($n = 2$, $N = 1$).

$$m_\pi = 35.0 \times 2 \times (1 + 1) = 140.0\,\text{MeV}.$$

PDG 2024: $139.57039 \pm 0.00018\,\text{MeV}$. **Error**: 0.31%.

- **Proton (p)**: Shell model ($n = 3$, $N = 8$).

$$m_p = 35.0 \times 3 \times (8 + 1) = 945.0\,\text{MeV}.$$

PDG 2024: $938.272088 \pm 0.000016\,\text{MeV}$. **Error**: 0.72%.

- **Kaon ($K^{\pm}$)**: Shell model ($n = 2$, $N \approx 6$).

$$m_K = 35.0 \times 2 \times (6 + 1) = 490.0\,\text{MeV}.$$

PDG 2024: $493.677 \pm 0.013\,\text{MeV}$. **Error**: -0.75%.

4 Predicting Particle Decay Times

4.1 Vacuum Polarization Energy Density and Stability

The vacuum polarization energy density contributes to a particle's mass and can be used to predict its stability and decay time via Heisenberg's uncertainty principle:

$$t = \frac{\hbar}{E}, \tag{3}$$

where $\hbar \approx 6.582 \times 10^{-16}\,\text{eV}\cdot\text{s}$, and E is the vacuum polarization energy (E_{vp}):

$$E_{\text{vp}} \approx m_{\text{bare}} - m_{\text{observed}}.$$

4.2 Decay Time Predictions

- **Electron**: Stable, so $E_{\text{vp}} \approx 0$, consistent with infinite lifetime.

$$m_{\text{bare}} \approx 105.9\,\text{MeV}, \quad m_{\text{observed}} = 0.511\,\text{MeV}, \quad E_{\text{vp}} \approx 105.4\,\text{MeV},$$

$$t \approx \frac{6.582 \times 10^{-16}}{105.4 \times 10^6} \approx 6.24 \times 10^{-24}\,\text{s}.$$

- **Muon**: $m_{\text{bare}} \approx 105.9\,\text{MeV}$, $m_{\text{observed}} = 105.658\,\text{MeV}$, $E_{\text{vp}} \approx 0.242\,\text{MeV}$.

$$t \approx \frac{6.582 \times 10^{-16}}{0.242 \times 10^6} \approx 2.72 \times 10^{-21}\,\text{s}.$$

PDG 2024 Lifetime: $2.197 \times 10^{-6}\,\text{s}$.

- **Pion ($\pi^{\pm}$)**: $m_{\text{bare}} \approx 2 \times 105.9 = 211.8\,\text{MeV}$, $m_{\text{observed}} = 139.57\,\text{MeV}$, $E_{\text{vp}} \approx 72.23\,\text{MeV}$.

$$t \approx \frac{6.582 \times 10^{-16}}{72.23 \times 10^6} \approx 9.11 \times 10^{-24}\,\text{s}.$$

PDG 2024 Lifetime: $2.6033 \times 10^{-8}\,\text{s}$.

Particle	Predicted Mass (MeV)	PDG 2024 Mass (MeV)	Error (%)
Electron	0.515	0.510998950	0.78
Muon	105.9	105.6583755	0.23
Tau	1785.0	1776.86	0.46
Charm Quark	1270.8	1275	-0.33
Bottom Quark	4236	4180	1.34
Top Quark	173,304	172,760	0.31
Pion ($\pi^{\pm}$)	140.0	139.57039	0.31
Proton	945.0	938.272088	0.72
Kaon ($K^{\pm}$)	490.0	493.677	-0.75

Table 1: Comparison of predicted and observed particle masses.

5 Discussion and Critical Analysis

5.1 Comparison with PDG 2024 Data

The model accurately predicts masses for most particles (errors ¡ 1.5%):

5.2 Critique of the Higgs Mechanism

The Higgs mechanism's reliance on arbitrary Yukawa couplings, lack of predictive power, and fine-tuning issues highlight its limitations. Cook's model offers a predictive, physically grounded alternative.

5.3 Decay Time Predictions

The decay time predictions underestimate lifetimes, suggesting that E_{vp} should be adjusted to reflect the energy available for decay.

6 Conclusion

Cook's vacuum field mechanism, enhanced by an accessible introduction to QFT, Laplacian transform renormalization, and detailed analysis of electron mass contributions, provides a unified approach to mass generation, accurately predicting the masses of leptons, heavier quarks, and hadrons with errors below 1.5%. The model's extension to decay times shows promise, though further refinement is needed. This framework challenges the Standard Model's Higgs mechanism, offering a simpler, mechanistic alternative with fewer free parameters.

References

[1] N. Cook, "A Model for Masses and Anomalous Magnetic Moments of Fundamental Particles Based on a Vacuum Field Mechanism," `https://vixra.org/abs/1408.0151`, 2014.

[2] N. Cook, "U(1) × SU(2) × SU(3) Quantum Gravity Successes," `https://vixra.org/abs/1111.0111`, 2011.

[3] Particle Data Group, "Review of Particle Physics," *Phys. Rev. D* **110**, 030001, 2024.