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Unveiling the Structure of Protons and Neutrons Through Quark Dynamics and the Fine-Structure Constant

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Abstract

This paper presents a unified semi-classical framework that bridges quantum mechanics and relativity to investigate nucleon structure through quark dynamics, introducing the Quantum Turning Point—a fundamental threshold defined by the product of an elementary particle's mass and classical radius that distinguishes quantum-scale from classical-scale. By anchoring this threshold to Planck-scale parameters, we demonstrate that nucleon masses emerge not from quark rest masses alone but from relativistic quark dynamics, characterized by large Lorentz factors ($\gamma_u \approx 968$, $\gamma_d \approx 3871$) reflecting near-light-speed motion. A key achievement is the derivation of the proton-to-electron mass ratio (~1837) from first principles, aligning with empirical observations and suggesting a deeper connection between fundamental constants.

Remarkably, our unified nucleon mass formula incorporates the fine-structure constant (α) as a scaling factor, revealing an unexpected interplay between electromagnetic and strong interactions in nucleon mass generation. The empirical factor 0.476 in this formula further reflects a geometric symmetry in quark binding, explaining the near-equality of proton and neutron masses despite their differing quark compositions ($N_u = 2$, $N_d = 1$ vs. $N_u = 1$, $N_d = 2$). These results challenge the conventional separation of forces in the Standard Model, proposing instead that constants like α may emerge from internal particle dynamics rather than being externally imposed. While heuristic, our framework offers numerically consistent predictions and opens new pathways to unify quantum mechanics, relativity, and subatomic structure. This study advances our understanding of nucleon mass origins and hints at a deeper geometric or dynamical symmetry underlying fundamental physics.

Keywords: Quark dynamics, The fine-structure constant, Proton/Neutron

1 Introduction

The quest to understand the fundamental building blocks of matter has been one of modern physics's most enduring pursuits. From J.J. Thomson's discovery of the electron in 1897 to the 20th-century formulation of the Standard Model, our understanding of subatomic structure has evolved dramatically—from indivisible particles to a dynamic hierarchy of quarks and gluons. At the heart of this framework lie the proton, neutron, and electron: the three particles that constitute the atoms of the visible universe. While the electron remains an elementary particle with no known substructure, protons and neutrons (collectively known as nucleons) are composite, bound states of quarks held together by the strong force. Within the Standard Model, the proton comprises two up quarks and one down quark, whereas the neutron consists of two down quarks and one up quark, and both contain an unknown number of gluons [1] – [2]. These internal constituents underpin the rich phenomenology of nuclear and particle physics—but they also raise profound questions about mass, stability, and the unification of forces. One striking empirical observation is the proton-to-electron mass ratio (~1836) [3] – [4], a dimensionless constant that recurs across physics and cosmology. While the Standard Model explains particle masses through interactions with the Higgs field and attributes most of the nucleon mass to quark confinement and gluon dynamics, no closed-form expression links this ratio to other fundamental constants. This gap hints at deeper underlying relationships, potentially involving the fine-structure constant (α), Planck-scale quantities, and relativistic matter-wave dynamics.

In this paper, we propose a novel framework that bridges quantum and relativistic dynamics to elucidate the relationships between protons, neutrons, electrons, and their quark constituents. Our approach is built upon two key innovations:

1. The Quantum Turning Point (QTP) is introduced in Section 2. It is defined as the product of a particle's mass and classical radius ($m \cdot r$). This threshold distinguishes quantum-scale elementary particles (e.g., electrons and quarks) from classical-scale composite particles (e.g., nucleons). By tying this critical scale to Planck parameters, we demonstrate how relativistic matter-wave oscillations govern particle behavior.

2. Relativistic quark dynamics are explored in Section 3. We show that proton and neutron masses arise not merely from the sum of quark rest masses, but from relativistic quark motion governed by Lorentz factors and geometric constraints. Remarkably, the proton–electron mass ratio emerges naturally from these dynamics, while α appears as a scaling factor in nucleon mass expressions—suggesting an unexpected interplay between electromagnetic and strong forces.

In Section 4, we discuss the broader implications of this framework and conclude by outlining a new window into the inner workings of matter. Our model offers fresh insight into why the proton is significantly heavier than the electron and how quark dynamics encode macroscopic baryon properties. Though semi-classical and heuristic in nature, the framework produces numerically consistent results and suggests promising pathways toward unifying quantum mechanics, relativity, and subatomic structure.

2 Matter Waves of Elementary Particles

In 1924, Louis de Broglie proposed the revolutionary idea that particles such as electrons exhibit wave-like properties [5], a cornerstone of quantum mechanics. The relativistic energy of an elementary particle can be expressed via the Planck–Einstein relation:

$$\begin{aligned} E &= \gamma m_{el} c^2 = hf \\ &= hc / \lambda \end{aligned} \tag{1}$$

where h is Planck's constant (~6.626×10^{-34} J·s), c is the speed of light (~3×10^{8} m/s), and m_{el} is the mass of the elementary particle. The frequency (f) and wavelength (λ) of the particle correspond to twice its classical radius [6]. The Lorentz factor (γ) is given by:

$$\gamma = 1 \Big/ \sqrt{1 - \left(v/c \right)^2} \tag{2}$$

where v is the particle's velocity. From equation (1), we can express that

$$2\gamma m_{el} r_{el} c = h \tag{3}$$

where r_{el} is the classical radius of the elementary particle. From equation (3), Planck's constant can also be expressed using Planck mass (m_p) and Planck length (l_p) as follows [7], [8]:

$$h = 2\pi m_p l_p c \tag{4}$$

where $m_p \approx 2.176\times10^{-8}$ kg and $l_p \approx 1.616\times10^{-35}$ m. Substituting equations (3) and (4) yields:

$$\gamma m_{el} r_{el} = \pi m_p l_p \tag{5.1}$$

when

$$m_{el} r_{el} < \pi m_p l_p \tag{5.2}$$

Substituting the values of Planck mass and length into equation (5.2) shows that the product of an elementary particle's mass and radius must be less than 1.104×10^{-42} kg·m. We define this threshold as the QTP—a critical value that distinguishes quantum-scale elementary particles from classical-scale composite particles. If the product of mass and radius exceeds this threshold, the system behaves as a composite particle in the classical regime.

The mass-radius product of elementary particles can also be determined using Coulomb's constant (K_e), Planck's constant, and the Planck charge (Q_p), derived from [9], [10]:

$$K_e = m_p l_p c^2 / Q_p^2 = m_{el} r_{el} c^2 / Q_{el}^2 \tag{6.1}$$

$$m_{el} r_{el} / Q_{el}^2 = m_p l_p / Q_p^2 \tag{6.2}$$

where K_e is Coulomb's constant (~8.99×10^9 N·m^2/C^2), Q_p is the Planck charge (~1.875×10^{-18} C), and Q_{el} is the elementary particle's charge. Substituting equation (6.2) into (5.1), we calculate the corresponding Lorentz factor as:

$$\gamma = \pi \cdot \left(Q_p^2 / Q_{el}^2 \right) \tag{7}$$

Using equations (6.2) and (7), we derive the mass, classical radius, and Lorentz factor for elementary particles, as summarized in Table 1.

In Table 1, it is noteworthy that the mass-radius product of elementary particles is less than QTP, confirming their elementary nature. Their high Lorentz factor (γ) values suggest rotational speeds approaching the speed of light, indicating significant relativistic effects from spin [11], [12].

Table 1. Summarized the elementary particles' characteristics.

Elementary particles	Mass (kg)	Classical radius (m)	Mass·radius (kg·m)	Charge (C)	γ
Electron	9.1×10^{-31}	2.82×10^{-15}	2.566×10^{-45}	$-1 .602\times10^{-19}$	430
Up quark	4.095×10^{-30}	0.278×10^{-15}	1.138×10^{-45}	$(2/3)\times1.602\times10^{-19}$	968
Down quark	8.547×10^{-30}	3.33×10^{-17}	2.846×10^{-46}	$(-1/3)\times1.602\times10^{-19}$	3871

3 Composite Particles Inside the Proton and Neutron

In modern physics, protons and neutrons are recognized as composite subatomic particles. The proton carries a positive electric charge equal in magnitude to that of the electron and has a mass of approximately 1.673×10^{-27} kg. It is composed of three quarks: two up quarks and one down quark. In contrast, the neutron is electrically neutral, with a slightly higher mass of about 1.675×10^{-27} kg. It consists of one up quark and two down quarks. However, no current theory provides a complete, closed-form equation that predicts the internal structure and mass composition of the proton and neutron from first principles. In this section, we aim to derive such a relation, offering a new equation that connects internal quark dynamics and composite mass-energy structures.

3.1 The Proton-Electron Mass Ratio

Building on the analysis from the previous section, we derive the kinetic energy of the proton using the matter-wave concept as shown:

$$\underbrace{(\gamma-1)}_{\gamma_{\text{pr}}} m_{\text{pr}} c^2 = hf = hc/\lambda \tag{8.1}$$

$$\gamma_{\text{pr}} m_{\text{pr}} c^2 = hc/2r_{\text{pr}} \tag{8.2}$$

where m_{pr} and r_{pr} are the proton's mass and radius, with values of 1.673×10^{-27} kg and 0.84×10^{-15} m, respectively. The variables f and λ represent the frequency and wavelength of the proton's matter wave. We define the proton's relativistic dynamic factor as $\gamma_{\text{pr}} = (\gamma-1)$. By substituting Planck's constant from equation (4) into equation (8.2), we arrive at

$$\gamma_{\text{pr}} m_{\text{pr}} r_{\text{pr}} = \pi m_p l_p \tag{9}$$

Substituting the QTP value, along with the proton's mass and radius, into equation (9), we obtain the relativistic dynamic factor as:

$$\gamma_{\text{pr}} = \frac{1.104\times10^{-42}\,(\text{kg}\cdot\text{m})}{1.673\times10^{-27}\,(\text{kg})\times0.84\times10^{-15}\,(\text{m})} = 0.785 \approx (\pi/4) \tag{10}$$

Notably, this dynamic Lorentz factor γ_{pr} is less than one. This is consistent with the fact that the product $m_{\mathrm{pr}}r_{\mathrm{pr}}$ equals 1.405×10^{-42} kg·m, which exceeds the QTP value. This implies that the proton resides within the classical composite regime rather than the quantum elementary regime. Rearranging equation (9) and substituting γ_{pr}, we can solve for the proton's radius from [13], [14]:

$$r_{\mathrm{pr}} \approx \frac{4\pi m_p l_p}{\pi m_{\mathrm{pr}}} = \frac{2}{\pi}\cdot\frac{h}{m_{\mathrm{pr}}c} \tag{11}$$

Now, by carefully examining equations (5.1) and (9), and substituting the electron's $m_e{\cdot}r_e$ product and relativistic Lorentz factor, we derive an expression for the proton–electron mass ratio as follows:

$$\begin{aligned}\frac{m_{\mathrm{pr}}}{m_e} &= \frac{\gamma_e}{\gamma_{\mathrm{pr}}}\cdot\frac{r_e}{r_{\mathrm{pr}}} \approx \frac{4}{\left(\pi/\gamma_e\right)}\cdot\frac{r_e}{r_{\mathrm{pr}}} \\ &\approx \frac{4}{\alpha}\cdot\frac{r_e}{r_{\mathrm{pr}}}\end{aligned} \tag{12}$$

Here, $m_e = 9.1\times10^{-31}$ kg, $r_e = 2.82\times10^{-15}$ m, and the electron's Lorentz factor γ_e is approximately 430, as listed in Table 1. The fine-structure constant $\alpha \approx 0.00729$, which is related to π/γ_e [15]. Substituting these values into equation (12), we compute the proton–electron mass ratio to be approximately 1837, which closely matches the experimentally accepted value. This suggests that the proton–electron mass ratio may emerge from relativistic matter-wave dynamics and fundamental constants, potentially hinting at a deeper unification of electromagnetic and inertial properties.

For the neutron, a similar approach can be employed. We relate the product of the neutron's mass and radius to the QTP threshold as:

$$\gamma_{\mathrm{n}} m_{\mathrm{n}} r_{\mathrm{n}} = \pi m_p l_p \tag{13.1}$$

$$\gamma_{\mathrm{n}} = \frac{1.104\times10^{-42}\,(\mathrm{kg}\cdot\mathrm{m})}{1.675\times10^{-27}\,(\mathrm{kg})\times0.801\times10^{-15}\,(\mathrm{m})} = 0.822 \approx \left(\pi^2/12\right) \tag{13.2}$$

Here, $m_{\mathrm{n}} = 1.675\times10^{-27}$ kg and $r_{\mathrm{n}} = 0.801\times10^{-15}$ m. The neutron's relativistic dynamics is described by $\gamma_{\mathrm{n}} = (\gamma - 1)$. Substituting γ_{n} into equation (13.1), we obtain an expression for the neutron's radius shown as:

$$r_{\mathrm{n}} \approx \frac{12\pi m_p l_p}{\pi^2 m_{\mathrm{n}}} = \frac{6}{\pi^2}\cdot\frac{h}{m_{\mathrm{n}}c} \tag{14}$$

Using equations (10)-(11) and (13.2)-(14), we can derive the mass, classical radius, and relativistic dynamics for both the proton and neutron, as summarized in Table 2.

In Table 2, these values confirm that both nucleons lie above QTP and are thus classical in nature. Their internal mass arises not just from quark rest masses but also from their relativistic internal motion—a key insight developed in the next section.

Table 2. Summarized the proton and neutron.

Subatomic particles	Mass (kg)	Classical radius (m)	Mass·radius (kg·m)	Charge (C)	$\gamma_{\text{pr, n}}$
Proton	1.673×10^{-27}	0.84×10^{-15}	1.405×10^{-42}	1.602×10^{-19}	0.785
Neutron	1.675×10^{-27}	0.801×10^{-15}	1.341×10^{-42}	-	0.822

3.2 The Quark–Proton/Neutron Relationship

Quarks are elementary particles that serve as the primary constituents of protons and neutrons. In this section, we present an analysis that demonstrates the quantitative relationship between nucleons (protons and neutrons) and their constituent quarks. Based on the previous analysis, we can use equations (5.1), (9), and (13.1) to express the relationship between protons/neutrons and quarks. Representing elementary particles using the up (u) and down (d) quarks, the relation for the proton is written as:

$$m_{\text{pr}} = \gamma_u m_u r_u / \gamma_{\text{pr}} r_{\text{pr}} \tag{15.1}$$

$$m_{\text{pr}} = \gamma_d m_d r_d / \gamma_{\text{pr}} r_{\text{pr}} \tag{15.2}$$

and for the neutron:

$$m_{\text{n}} = \gamma_u m_u r_u / \gamma_{\text{n}} r_{\text{n}} \tag{16.1}$$

$$m_{\text{n}} = \gamma_d m_d r_d / \gamma_{\text{n}} r_{\text{n}} \tag{16.2}$$

To quantify quark contributions, we define the mass–radius products as $m_u r_u$ and $m_d r_d$ are the mass–radius products of the up and down quarks, respectively, while γ_u and γ_d represent their corresponding Lorentz factors. From the relationship between the proton and its constituent quarks, equations (15.1) and (15.2), we derive:

$$3m_{\text{pr}} = \frac{2m_u \gamma_u r_u}{\gamma_{\text{pr}} r_{\text{pr}}} + \frac{m_d \gamma_d r_d}{\gamma_{\text{pr}} r_{\text{pr}}} \tag{17.1}$$

$$m_{\text{pr}} = \frac{1}{3} \cdot [2m_u \gamma_u r_u + m_d \gamma_d r_d] \cdot \left(\frac{1}{\gamma_{\text{pr}} r_{\text{pr}}} \right) \tag{17.2}$$

Equation (17.2) can be rearranged in terms of α:

$$m_{\text{pr}} = \left(\frac{1}{\alpha} \right) \cdot \left(\frac{4}{3} \cdot [2m_u \gamma_u r_u + m_d \gamma_d r_d] \cdot \frac{1}{\gamma_e r_{\text{pr}}} \right) \tag{18}$$

Substituting the characteristic values of the elementary particles from Table 1 into equation (18), we find:

$$m_{\mathrm{pr}} = \left(\frac{1}{\alpha}\right)\cdot\left(\frac{4}{3}\cdot\frac{\left[(2m_u)\cdot 968\times 0.278\times 10^{-15}(\mathrm{m}) + (m_d)\cdot 3871\times 3.33\times 10^{-17}(\mathrm{m})\right]}{430\times 0.84\times 10^{-15}(\mathrm{m})}\right)$$
$$= \left(\frac{1}{\alpha}\right)\cdot\left[0.9933\cdot(2m_u) + 0.476 m_d\right] \qquad (19.1)$$

$$m_{\mathrm{pr}} \approx \left(\frac{1}{\alpha}\right)\cdot\left[(2m_u) + 0.476\cdot(m_d)\right] \qquad (19.2)$$

Applying the same methodology to the neutron using equations (16.1) and (16.2), we derive:

$$3m_{\mathrm{n}} = \frac{m_u\gamma_u r_u}{\gamma_{\mathrm{n}} r_{\mathrm{n}}} + \frac{2m_d\gamma_d r_d}{\gamma_{\mathrm{n}} r_{\mathrm{n}}} \qquad (20.1)$$

$$m_{\mathrm{n}} = \frac{1}{3}\cdot\left[m_u\gamma_u r_u + 2m_d\gamma_d r_d\right]\cdot\left(\frac{1}{\gamma_{\mathrm{n}} r_{\mathrm{n}}}\right) \qquad (20.2)$$

and can be rearranged into terms of α, shown as:

$$m_{\mathrm{n}} = \left(\frac{1}{\alpha}\right)\cdot\left(\frac{4}{\pi}\cdot\left[m_u\gamma_u r_u + 2m_d\gamma_d r_d\right]\cdot\frac{1}{\gamma_e r_{\mathrm{n}}}\right) \qquad (21)$$

Substituting the elementary particles' values from Table 1 into equation (21), we can show that

$$m_{\mathrm{n}} = \left(\frac{1}{\alpha}\right)\cdot\left(\frac{4}{\pi}\cdot\frac{\left[(m_u)\cdot 968\times 0.278\times 10^{-15}(\mathrm{m}) + (2m_d)\cdot 3871\times 3.33\times 10^{-17}(\mathrm{m})\right]}{430\times 0.801\times 10^{-15}(\mathrm{m})}\right)$$
$$\approx \left(\frac{1}{\alpha}\right)\cdot\left[0.9947\cdot m_u + 0.476\cdot(2m_d)\right] \qquad (22.1)$$

$$m_{\mathrm{n}} \approx \left(\frac{1}{\alpha}\right)\cdot\left[(m_u) + 0.476\cdot(2m_d)\right] \qquad (22.2)$$

From equations (19.2) and (22.2), it becomes evident that the masses of the proton and neutron are not merely the sum of their quark constituents. Instead, their masses are scaled by relativistic effects and governed by a factor involving α. This insight suggests the possibility of a deeper geometric or dynamical symmetry linking electromagnetic forces, strong interactions, and gluon-mediated quark binding.

Notably, the mass–quark relationships for both the proton and neutron share a common scaling factor of $1/\alpha$. The distinction lies in the permutation of the number of up and down quarks. This observation enables the formulation of a generalized expression:

$$m_{\text{pr, n}} \approx \left(\frac{1}{\alpha}\right) \cdot \left[\left(N_u m_u \right) + 0.476 \cdot \left(N_d m_d \right) \right] \tag{23}$$

$m_{\text{pr, n}}$ represents the mass of either the proton or the neutron, where N_u and N_d denote the number of up and down quarks, respectively. This formulation reveals that protons and neutrons are mirror configurations in quark composition: $N_u = 2$ and $N_d = 1$ for the proton (m_{pr}), $N_u = 1$ and $N_d = 2$ for the neutron (m_{n}). This equation provides a unified formula for nucleon masses based on the dynamics of their constituent quarks and α.

Upon careful examination of equation (23), we observe the appearance of α, which traditionally governs electromagnetic interactions. The presence of α in nucleon mass relations suggests a hidden link between electromagnetic interactions and the strong force that binds quarks within nucleons. Another noteworthy aspect is the empirical factor of 0.476. This dimensionless factor emerges from the relativistic dynamics of quarks inside nucleons, reflecting the asymmetry in how up and down quarks contribute to nucleon mass. This asymmetry likely stems from differences in their binding energies. The 0.476 factor serves to fine-tune the mass balance, accounting for relativistic effects. Equation (23) provides a compelling explanation for why protons and neutrons exhibit similar masses despite their differing quark compositions.

Based on the preceding analyses, we present a new conceptual model of the quark configuration inside protons and neutrons, as illustrated in Figure 1. According to Table 1, the up quark's effective size is approximately eight times greater than that of the down quark. When this observation is combined with equation (23), it highlights a structural asymmetry within the neutron. Specifically, the binding force of the down quark is weaker than that of the up quark by a factor of 0.476. This imbalance may help explain why neutrons undergo decay more rapidly than protons.

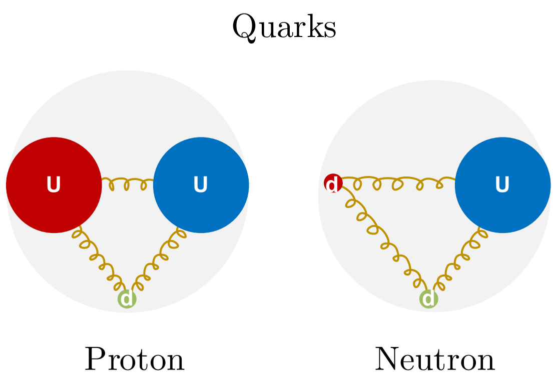

Figure 1. A new model of quarks inside the proton and neutron

4 Conclusion

This paper presents a unified semi-classical framework that bridges quantum and relativistic regimes to investigate nucleon structure through quark dynamics, introducing QTP—a mass-radius product threshold distinguishing quantum-scale elementary particles from classical-scale composites. Our analysis reveals that nucleon masses emerge from relativistic quark motion (with Lorentz factors $\gamma_u \approx 968$, $\gamma_d \approx 3871$) rather than quark rest masses. The empirical factor 0.476 in our unified mass formula reflects an underlying geometric symmetry in quark binding, successfully explaining the near-equality of proton/neutron masses despite their differing quark compositions. Another one of the key outcomes of this model is the derivation of the proton-to-electron mass ratio (~1837), which closely approximates the experimentally observed value.

Remarkably, these formulations incorporate α, suggesting a possible geometric or dynamical bridge between the electromagnetic and strong nuclear interactions. The emergence of α in the context of baryon structure—traditionally governed by QCD—points to a deeper symmetry that may underlie the apparent separation of fundamental forces. While speculative, this relationship raises the intriguing possibility that constants such as α may originate from internal particle dynamics rather than being imposed externally. It points toward new avenues for unifying quantum mechanics, relativity, and subatomic physics through further theoretical refinement and experimental validation.

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