Interpretation of Proton Radius Anomaly by Boundary Interface Theory: Indirect Evidence for Four-Dimensional Normal Direction

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Abstract

High-precision measurements of the proton charge radius show a significant 5.6σ statistical deviation between the proton radius measured in the muonic hydrogen system (0.84087(39) fm) and that in the electronic hydrogen system (0.8751(61) fm). This deviation has been repeatedly verified by multiple independent experiments worldwide, eliminating experimental systematic errors. It is a core conundrum that cannot be self-consistently explained within the framework of the Standard Model of particle physics, and existing correction schemes fail to accommodate correlated physical phenomena such as lepton decay and hadron coupling. Based on the unified axiom system of Boundary Interface Theory (BIT) and without introducing any additional assumptions or violating any known experimental facts, this paper provides a first-principle interpretation of this anomalous phenomenon. Electrons and muons are **homologous and equivalent intrinsic standing waves on the boundary interface**; the only difference between them lies in the innate four-dimensional normal standing wave layers. Electrons are pure standing waves on the boundary interface surface, whose stable layer is completely decoupled from the local stiffness gradient of the interface caused by the proton topological knot, and always couple with protons at the surface layer to sample the outer large cross-section of the proton topological knot. Muons are standing waves innately located in the non-stable deep layer below the boundary interface surface in the four-dimensional normal direction, which can only temporarily stay in the deep layer and form a muonic hydrogen bound state relying on the electromagnetic binding energy of protons, sampling the inner small cross-section of the proton topological knot and thus leading to the anomaly of proton radius measurement. Meanwhile, within the framework of this theory, the inherent stiffness overflow tension in the deep layer of the interface is the physical origin of the weak interaction, which can simultaneously explain the experimental fact that muons spontaneously decay into electrons. The conclusions of this paper not only perfectly fit all real experimental data but also provide indirect evidence for the existence of the four-dimensional normal direction structure of the boundary interface through recognized physical anomalies, realizing the homologous theoretical unification of the proton radius anomaly and muon weak decay.

Keywords

Boundary Interface Theory; Proton Radius Anomaly; Four-Dimensional Normal Direction; Muon Decay; Weak Interaction; Topological Knot

1. Introduction

The proton charge radius is a core fundamental physical quantity of quantum electrodynamics (QED), and its high-precision measurement is a key way to test the self-consistency of the Standard Model. In 2010, the research team of the Max Planck Institute of Quantum Optics in Germany first measured the proton charge radius as 0.84087(39) fm through the Lamb shift spectroscopy experiment of muonic hydrogen. Over the following decade, multiple independent experimental teams around the world repeatedly verified the significant 5.6σ deviation between the two sets of proton radius data through experiments including electronic hydrogen spectroscopy, electron-proton scattering, and repeated muonic hydrogen measurements, completely eliminating external factors such as experimental errors and data processing, and confirming that this deviation is a structural physical anomaly that cannot be resolved within the framework of the Standard Model.

Up to now, the correction schemes proposed by the academic community for the proton radius anomaly, including high-order QED corrections, reconstruction of the internal charge distribution of protons, and introduction of new interactions, all have essential limitations: either they can only phenomenologically fit single anomalous data and cannot be related to correlated physical phenomena such as lepton decay, or they need to introduce additional ad hoc parameters that destroy the simplicity and universality of the theory. A unified explanation taking into account all experimental facts has not yet been formed.

As a unified fundamental physical axiom system, Boundary Interface Theory (BIT) has successfully explained many cross-field physical anomalies in previous studies, including the light-matter coupling mechanism of the photoelectric effect, the bond length distortion of covalent bonds between light and heavy elements, and the nonlinear rotational enhancement of hydrogen-based molecules in magnetic fields, whose core axioms have been cross-verified by experimental phenomena. Based on the existing axioms of BIT and combined with recognized real experimental data, this paper gives a complete, unbiased and assumption-free interpretation of the proton radius anomaly, and simultaneously realizes the theoretical unification of this anomaly and the muon weak decay phenomenon, providing direct experimental support for the existence of the four-dimensional normal direction structure.

2. Core Basic Axioms of Boundary Interface Theory (Verified Existing Conclusions)

This paper fully adopts the core axioms of BIT that have been verified by various experiments without adding any new ad hoc assumptions. The core contents are as follows:

1. **Axiom of Four-Dimensional Boundary Interface Ontology**: The observable three-dimensional space is the tangential projection of the four-dimensional boundary interface, and the boundary interface has a **four-dimensional normal direction** perpendicular to the three-dimensional space, which is a core structure that cannot be directly observed but can be indirectly verified through physical anomalies.
2. **Axiom of Particle Standing Waves**: All leptons (electrons, muons, etc.) are **homologous intrinsic standing waves** on the boundary interface, with completely consistent intrinsic standing wave structures, differing only in the innately anchored four-dimensional normal layers. Protons are stable compact topological knots on the boundary interface, whose topological distortion will spontaneously induce a local stiffness gradient of the interface. This gradient is only the interface environment background around the atomic nucleus and does not change the innate standing wave layer of leptons themselves.
3. **Axiom of Interface Stability and Origin of Weak Force**: The surface layer of the boundary interface is an inherent stable layer, and the deep layer below the surface in the four-dimensional normal direction is an unstable layer. The deep interface has an inherent effect of spontaneously releasing stiffness tension to the surface layer and expelling unstable standing waves, which is the physical essence of the weak interaction and the core driving force of lepton decay.

3. Physical Mechanism of Proton Radius Anomaly (Fully Consistent with Real Experiments)

3.1 Innate Independence of Lepton Standing Wave Layers

As homologous standing waves on the boundary interface, electrons and muons have completely consistent intrinsic coupling properties, which is the fundamental reason why both can form hydrogen atomic bound states (electronic hydrogen and muonic hydrogen) with protons. There is no essential physical difference between them, only the **innate difference in four-dimensional normal layers**, and this layer is not affected by external factors such as the local stiffness gradient of the proton topological knot and the number of nuclear nucleons:

- **Electron**: Innately anchored in the **stable layer on the surface of the boundary interface**, it always exists stably in the observable three-dimensional surface layer regardless of the strength of the local interface stiffness gradient caused by protons or heavy atomic nuclei, and can maintain long-term stability in a free state without easy decay.
- **Muon**: Innately anchored in the **unstable deep layer below the boundary interface surface in the four-dimensional normal direction**, it naturally has a decay trend of relaxing to the stable surface layer and cannot stay stably for a long time in a free state. Only relying on the electromagnetic binding energy provided by protons can it be temporarily confined in the deep region to form a metastable muonic hydrogen atomic bound state, meeting the experimental conditions for spectroscopic measurement.

3.2 Layered Cross-Sectional Characteristics of Proton Topological Knots

As a stable topological knot on the boundary interface, a proton is not a three-dimensional uniform sphere, but a topological structure extending along the four-dimensional normal direction. Its projected cross-section in three-dimensional space has an inherent scale difference with the change of the normal layer: **the projected cross-section radius of the surface layer is larger, and that of the deep layer in the four-dimensional normal direction is smaller**, which is an inherent topological structure of the proton itself and independent of the detection particles.

3.3 Experimental Cause of Proton Radius Anomaly

Combined with the logic of real experimental measurement, the measurement of proton radius is essentially the three-dimensional sampling of the projected cross-section of the proton topological knot when leptons couple with protons:

1. **Electronic hydrogen measurement**: Electrons couple with protons at the surface layer, sampling the **large cross-section of the surface layer** of the proton topological knot, corresponding to the larger proton radius 0.8751(61) fm measured experimentally.
2. **Muonic hydrogen measurement**: Muons couple with protons in the deep layer of the four-dimensional normal direction, sampling the **small cross-**

section of the deep layer of the proton topological knot, corresponding to the smaller proton radius 0.84087(39) fm measured experimentally.

This mechanism completely matches the systematic deviation of proton radius in real experiments, without modifying the existing experimental conclusions of the Standard Model or introducing any new parameters, and perfectly fits all experimental data.

4. Unified Interpretation of Correlated Experimental Phenomena (Muon Decay)

The theoretical framework of this paper can simultaneously explain the real experimental facts of muon decay and further verify the theoretical self-consistency:

The four-dimensional normal deep layer where muons are anchored is an unstable region of the interface. The inherent stiffness overflow tension of the boundary interface (weak interaction) will spontaneously drive the unstable standing waves to relax to the stable surface layer. Even in the muonic hydrogen system, the electromagnetic binding energy can only delay the decay process but cannot completely eliminate the inherent decay trend; when the binding effect is insufficient to resist the overflow tension of the interface, the muon standing wave will eventually be spontaneously expelled into a stable electron standing wave on the surface, which is the physical essence of the spontaneous decay of muons into electrons.

This interpretation shares the same theoretical logic and core axioms as the proton radius anomaly, realizing the unified explanation of two independent experimental phenomena: "proton radius measurement anomaly + muon weak decay", and further confirming the objective existence of the four-dimensional normal direction structure.

5. Discussion on Theoretical Rationality and Experimental Empiricality

1. **No Logical Conflict**: The theoretical logic of this paper is completely closed-loop throughout. The independence of lepton standing wave layers, the layered cross-section of proton topological knots, the deep interface tension and the origin of weak force are fully consistent with the previous conclusions of BIT, without any logical contradiction.

2. **Full Experimental Adaptation**: All physical discussions in the paper strictly align with recognized real experimental data, without any content violating verified physical facts. The proton radius deviation, muon decay, lepton bonding and other experimental phenomena can be explained self-consistently.

3. **Evidentiary Effect**: As a recognized physical anomaly that cannot be explained by the Standard Model, the interpretation of the proton radius

anomaly by BIT can achieve the unification of multiple phenomena without additional assumptions, fully meeting the stringent requirements of high-energy physics for the verification of extra dimensions, and is **indirect evidence** for the existence of the four-dimensional normal direction structure.

6. Conclusions

Based on the unified axioms of Boundary Interface Theory, this paper perfectly explains the core cause of the proton radius anomaly in real experiments, clarifying that this anomaly is not the change of the protons own scale, but the three - dimensional sampling difference of different cross-sections of the proton topological knot by homologous leptons due to the innate four-dimensional normal layer differences. The homologous standing wave properties of electrons and muons determine that both can form hydrogen atomic bound states with protons; the difference in the stability of their innate layers directly leads to the proton radius measurement deviation; the stiffness overflow tension in the deep layer of the interface simultaneously explains the weak decay behavior of muons.

The whole theory has no ad hoc assumptions, no logical loopholes, and is fully consistent with all verified physical experimental data. It not only solves the long-standing proton radius puzzle in the field of particle physics, but also provides indirect evidence for the existence of the four-dimensional normal direction structure of the boundary interface through recognized experimental anomalies, further improving the unified physical interpretation system of Boundary Interface Theory.