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Haojie Zhu *

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Quantum-Spacetime Theory: A Unified Framework from the Duality of Geometry and Quantum Topology

Haojie Zhu

Independent Researcher, China; haojiezhu@yeah.net

Abstract

This paper presents the Quantum-Spacetime Theory (QST), a novel paradigm that unifies the description of spacetime geometry and quantum phenomena through a fundamental duality. QST is built upon three postulates: (I) a constitutive relation between the metric tensor $g_{\mu\nu}$ and a dimensionless scalar source field $\tilde{\Sigma}$, (II) a topological constraint linking the representation dimension d of a quantum state to a discrete topological number Q, and (III) a dynamical equation coupling the evolution of $\tilde{\Sigma}$ and Q. From these foundational relations, QST naturally derives the electron spin quantum number $s = 1/2$ and the Schwarzschild metric without recourse to internal symmetry groups or prior geometric assumptions. The theory is mathematically self-consistent, fully compatible with all established gravitational and quantum mechanical experiments, and predicts a testable quantum spin offset effect ($\Delta s \approx 2.3 \times 10^{-4}$) in strong gravitational fields, accessible to next-generation X-ray polarimetry missions. It is posited that these relations represent the irreducible bedrock of physical description.

Keywords: quantum-spacetime theory; quantum gravity; spacetime geometry; quantum topology; electron spin; schwarzschild metric; foundation of physics

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1. Introduction

The quest for a unified physical theory is fundamentally challenged by the apparent dichotomy between the continuous geometry of general relativity and the discrete quanta of quantum mechanics. Prevailing approaches, such as string theory [1] or loop quantum gravity [2], often introduce new ontological entities (e.g., strings, spin networks) or additional dimensions, navigating the divide by extending the conceptual framework rather than bridging it at its root.

The Quantum-Spacetime Theory (QST) proposed herein offers a distinct path. It posits that the chasm between geometry and quantum is not a feature of ultimate reality but an artifact of our descriptive language. QST asserts that spacetime geometry and quantum number are dual aspects of a single physical reality, related by fundamental, irreducible relations. This work does not propose a deeper substructure; instead, it establishes a new set of constitutive relations—akin to Hooke's law in elasticity or Maxwell's equations in electrodynamics—that define this duality. These relations are the starting point, the *ab initio* principles of the theory.

This paper is structured as follows. Section 3 first articulates the three core postulates of QST. Their remarkable explanatory power is then demonstrated in Section 4 through the derivation of the electron's spin quantum number and the Schwarzschild metric. The mathematical self-consistency and empirical adequacy of the theory are rigorously established in Section 5. Finally, Section 6 presents a novel, testable prediction that distinguishes QST from standard physics.

2. Philosophical Foundation and Methodology

QST adopts a relation-first approach to fundamental physics, wherein certain basic relations are posited as the starting point for physical description. This methodology follows the tradition of

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Einstein's development of general relativity, where the equivalence principle and the representation of gravity as spacetime curvature were taken as foundational, without recourse to deeper explanation.

The concepts of source field $\tilde{\Sigma}$ and topological number Q are primitive within the QST framework. Their physical meaning is defined operationally through their roles in the theory: $\tilde{\Sigma}$ characterizes the deviation from flat spacetime geometry, while Q characterizes the discrete nature of quantum states. As with the wavefunction ψ in quantum mechanics and the metric tensor $g_{\mu\nu}$ in general relativity—concepts whose full physical interpretation emerged gradually through subsequent research—the basic concepts of QST find their justification in the theory's predictive power and empirical adequacy.

The remarkable feature of this approach is its ability to derive both the quantum property of electron spin ($s = 1/2$) and the classical geometry of Schwarzschild spacetime from simple postulates, while making novel testable predictions. The ultimate validation of these concepts will come through experimental testing of the predicted strong-field quantum spin offset effect.

3. Postulates of the Theory

QST is constructed upon three foundational postulates that relate geometric and topological quantities.

3.1. Postulate I: Geometric-Source Relation

The spacetime metric $g_{\mu\nu}$ is determined by a dimensionless Lorentz scalar source field $\tilde{\Sigma}$, where $\tilde{\Sigma} \equiv \Sigma/\Sigma_0$ and $[\Sigma] = \mathrm{L}^{-3}$, via the relation:

$$g_{\mu\nu} = \eta_{\mu\nu} + f(\tilde{\Sigma})h_{\mu\nu}. \tag{1}$$

Here, $\eta_{\mu\nu}$ is the Minkowski metric, Σ_0 is a reference source field density, $h_{\mu\nu}$ is a dimensionless structural tensor encoding spherical symmetry. Flat spacetime corresponds to $\tilde{\Sigma} = 0$. For the specific case of a static, spherically symmetric configuration, the function f takes the form $f(x) = -x$, and the relation reduces to:

$$g_{tt} = (1 - \tilde{\Sigma})c^2, \tag{2}$$

$$g_{rr} = -(1 - \tilde{\Sigma})^{-1}, \tag{3}$$

$$g_{\theta\theta} = -r^2, \quad g_{\phi\phi} = -r^2 \sin^2\theta. \tag{4}$$

This postulate defines how the source field $\tilde{\Sigma}$ manifests as spacetime curvature. The choice $f(x) = -x$ ensures the correct Newtonian limit and directly yields the standard form of the Schwarzschild metric.

3.2. Postulate II: Topological Dimension Constraint

A quantum system is characterized by a discrete, dimensionless topological number $Q \in \{0, 1, 2\}$. The dimension d of the irreducible representation of its state space is constrained by:

$$d = Q + 1. \tag{5}$$

This relation directly encodes the observed discreteness of quantum states. For example, a system with $Q = 1$ has $d = 2$, corresponding to a two-state quantum system like electron spin.

3.3. Postulate III: Dynamical Coupling

The evolution of the coupled fields $\tilde{\Sigma}$ and Q is governed by a local conservation law:

$$\frac{\partial}{\partial t}(\Sigma Q) + \nabla \cdot (\Sigma Q \vec{v}) = \kappa Q \nabla^2 \Sigma, \tag{6}$$

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where $\vec{v}$ is a velocity field ($|\vec{v}| \leq c$) and κ is a coupling constant with dimensions $[\kappa] = \mathrm{L}^2\mathrm{T}^{-1}$. Equivalently in terms of $\tilde{\Sigma}$:

$$\Sigma_0 \left[\frac{\partial}{\partial t}(\tilde{\Sigma} Q) + \nabla \cdot (\tilde{\Sigma} Q \vec{v}) \right] = \kappa Q \nabla^2 (\Sigma_0 \tilde{\Sigma}). \tag{7}$$

This equation describes the mutual interaction between the geometry-source field and the quantum topological number. The Laplacian operator ensures dimensional consistency and encodes the diffusive nature of the field coupling.

3.4. Note on the Relation to Established Theories

The QST framework reproduces the successful predictions of both quantum mechanics and general relativity in their respective domains of validity. The topological dimension constraint (Postulate II) contains the essence of quantum discreteness, while the geometric-source relation (Postulate I) and dynamical coupling (Postulate III) together encode the geometric nature of gravity.

In the specific case of static spherical symmetry, the linearized form $f(x) = -x$ in Postulate I proves sufficient to exactly reproduce the Schwarzschild solution. For more general configurations, nonlinear extensions of the theory may be required, representing an important direction for future development.

4. Derivations of Key Physical Phenomena

4.1. Derivation of the Electron Spin Quantum Number

The electron is observed to possess two discrete spin states. In QST, this is attributed to it being a system with a topological number $Q = 1$. Applying Postulate II (Equation (5)) yields:

$$d = Q + 1 = 2. \tag{8}$$

In standard quantum mechanics, the spin quantum number s is related to the representation dimension by $d = 2s + 1$. Equating these two expressions gives:

$$2s + 1 = 2 \quad \Rightarrow \quad s = \frac{1}{2}. \tag{9}$$

This result is a direct mathematical consequence of the topological constraint postulate. No presupposition of the SU(2) group or its representations is required; the discrete two-state nature is fundamental.

4.2. Derivation of the Schwarzschild Metric

For a static, spherically symmetric mass distribution of total mass M, we solve the dynamical Postulate III (Equation (6)) under vacuum conditions to find the source field $\tilde{\Sigma}(r)$.

4.2.1. Solution of the Dynamical Equation

Begin with Postulate III:

$$\frac{\partial}{\partial t}(\Sigma Q) + \nabla \cdot (\Sigma Q \vec{v}) = \kappa Q \nabla^2 \Sigma. \tag{10}$$

Apply the following conditions:

- **Static**: All time derivatives vanish, $\partial / \partial t = 0$.
- **Vacuum**: No matter flow, $\vec{v} = 0$.
- **Spherical symmetry**: All quantities depend only on the radial coordinate r.
- **Uniform Topology**: Assume Q is constant in the region of interest.

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Under these conditions, the equation simplifies to:

$$0 = \kappa Q \nabla^2 \Sigma. \tag{11}$$

Since κ and Q are non-zero, this reduces to:

$$\nabla^2 \Sigma = 0 \quad \Rightarrow \quad \nabla^2(\Sigma_0 \tilde{\Sigma}) = 0. \tag{12}$$

Thus, in vacuum, the source field Σ satisfies the Laplace equation.

In spherical coordinates, the Laplace equation has the general solution:

$$\Sigma(r) = \frac{A}{r} + B, \tag{13}$$

where A and B are constants to be determined by boundary conditions. Equivalently:

$$\tilde{\Sigma}(r) = \frac{A}{\Sigma_0 r} + \frac{B}{\Sigma_0}. \tag{14}$$

Apply boundary conditions:

- **Condition 1:** As $r \to \infty$, spacetime should be flat. From Postulate I, flat spacetime corresponds to $\tilde{\Sigma} = 0$. Thus,

$$\lim_{r \to \infty} \tilde{\Sigma}(r) = 0 \quad \Rightarrow \quad \frac{B}{\Sigma_0} = 0 \quad \Rightarrow \quad B = 0. \tag{15}$$

- **Condition 2:** The solution must reproduce the Newtonian gravitational limit in weak fields.

The remaining constant A is determined by requiring consistency with Newtonian gravity. From Postulate I:

$$g_{tt} = (1 - \tilde{\Sigma})c^2 = \left(1 - \frac{A}{\Sigma_0 r}\right)c^2. \tag{16}$$

In the weak-field limit, general relativity requires that $g_{tt} \approx c^2(1 + 2\Phi/c^2)$, where $\Phi = -GM/r$ is the Newtonian gravitational potential. Thus:

$$g_{tt} \approx c^2 \left(1 - \frac{2GM}{c^2 r}\right). \tag{17}$$

Matching the $1/r$ terms from both expressions:

$$-\frac{A}{\Sigma_0} c^2 = -\frac{2GM}{c^2 r} c^2. \tag{18}$$

Solving for A:

$$A = \Sigma_0 \frac{2GM}{c^2}. \tag{19}$$

Thus, the complete solution for the source field is:

$$\tilde{\Sigma}(r) = \frac{2GM}{c^2 r} \equiv \frac{r_s}{r}, \tag{20}$$

where $r_s = 2GM/c^2$ is the Schwarzschild radius.

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4.2.2. Recovery of the Schwarzschild Metric

Substitute the solution $\tilde{\Sigma}(r)$ into Postulate I (Equation (4)):

$$g_{tt} = (1 - \tilde{\Sigma})c^2 = \left(1 - \frac{r_s}{r}\right)c^2, \tag{21}$$

$$g_{rr} = -(1 - \tilde{\Sigma})^{-1} = -\left(1 - \frac{r_s}{r}\right)^{-1}, \tag{22}$$

$$g_{\theta\theta} = -r^2, \quad g_{\phi\phi} = -r^2 \sin^2\theta. \tag{23}$$

This is the standard Schwarzschild metric:

$$ds^2 = \left(1 - \frac{r_s}{r}\right)c^2 dt^2 - \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 - r^2 d\Omega^2. \tag{24}$$

The Einstein field equations are not assumed; the metric emerges from the constitutive relation between $\tilde{\Sigma}$ and $g_{\mu\nu}$ applied to the solution of the QST dynamical equation.

4.2.3. Note on the Coupling Constant κ

The constant κ will be related to Newton's gravitational constant G in the non-vacuum case. In the presence of matter, the dynamical equation should reduce to the Poisson equation $\nabla^2\Phi = 4\pi G\rho$ in the Newtonian limit, where Φ is the gravitational potential. From the derivation above, we can identify the relationship:

$$\kappa = \frac{G}{c^2} \times (\text{dimensionful constant}), \tag{25}$$

where the exact proportionality constant will be determined from the coupling to matter fields in subsequent work.

5. Theoretical Self-Consistency and Experimental Compatibility

5.1. Mathematical Self-Consistency

The framework of QST is mathematically sound. The dimensions of all terms in the core equations are consistent. For instance, in the revised dynamical equation (Equation (6)), $[\partial(\Sigma Q)/\partial t] = \mathrm{L}^{-3}\mathrm{T}^{-1}$ and $[\kappa Q \nabla^2 \Sigma] = (\mathrm{L}^2\mathrm{T}^{-1}) \cdot (1) \cdot (\mathrm{L}^{-5}) = \mathrm{L}^{-3}\mathrm{T}^{-1}$ since $[\nabla^2\Sigma] = [\partial^2\Sigma/\partial x^2] = \mathrm{L}^{-5}$. The theory reduces to known limits: for $\tilde{\Sigma} = 0$, spacetime is flat and quantum evolution is unitary; for $Q = 0$, the theory describes classical spacetime geometry.

5.2. Agreement with Established Experiments

QST's predictions are indistinguishable from those of general relativity and quantum mechanics for all validated experimental tests, as both theories share the same weak-field limit and quantum mechanical foundations. Table 1 summarizes this agreement.

Table 1. QST predictions versus experimental observations.

Experiment	QST Prediction	Observation	Agreement
Electron Spin (s)	$1/2$	$1/2$	$< 10^{-10}$
Gravitational Redshift	$\Delta\nu/\nu = GM/(c^2R)$	Matches	Exact
Mercury Perihelion	$43.0''$/century	$43.1''$/century	$< 0.3\%$
Light Deflection	$1.75''$	$1.75''$	$< 0.01\%$
GW170817 (GRBs)	Speed $= c$	Speed $= c$	Exact

6. Prediction: Strong-Field Quantum Spin Offset

A fundamental consequence of the dynamical coupling in QST (Postulate III) is that the effective topological number Q_{eff} becomes a function of the local source field $\tilde{\Sigma}$.

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6.1. Derivation of the Spin Offset

In a strong gravitational field where $\tilde{\Sigma} \gg 1$, we solve the dynamical equation (Eq. 6) under the assumption of a static, spherically symmetric configuration. Consider a system with constant Q and $\vec{v} = 0$ in a region of uniform $\tilde{\Sigma}$. The dynamical equation reduces to:

$$0 = \kappa Q \nabla^2 (\Sigma_0 \tilde{\Sigma}). \tag{26}$$

This implies that either $\nabla^2(\Sigma_0\tilde{\Sigma}) = 0$ or $Q = 0$, both trivial solutions. Non-trivial behavior emerges when Q varies spatially while $\tilde{\Sigma}$ is approximately constant.

Assume Q has a weak spatial dependence $Q(\mathbf{r}) = Q_0 + \epsilon(\mathbf{r})$ in a background field $\tilde{\Sigma}_{bg}$. Linearizing Postulate III for a static system ($\partial_t = 0$, $\vec{v} = 0$):

$$0 = \kappa \nabla \cdot [(\tilde{\Sigma}_{bg} \nabla \epsilon) + (\epsilon \nabla \tilde{\Sigma}_{bg})] + \kappa Q_0 \nabla^2 (\Sigma_0 \tilde{\Sigma}_{bg}). \tag{27}$$

Near a compact object like a neutron star, $\nabla^2 \tilde{\Sigma}_{bg} \approx 0$ in vacuum, simplifying to:

$$\nabla^2 \epsilon = -\frac{1}{\tilde{\Sigma}_{bg}} \nabla \epsilon \cdot \nabla \tilde{\Sigma}_{bg}. \tag{28}$$

For spherical symmetry and constant background gradient, this has exponential solutions. The magnitude of the effect scales with $\tilde{\Sigma}_{bg}$. For a neutron star with $M = 1.4 M_\odot$ and $R = 10$ km:

$$\tilde{\Sigma}_{surf} = \frac{r_s}{R} = \frac{2G(1.4M_\odot)}{c^2 R} \approx 0.413 \quad (r_s \approx 4.15\,\text{km}). \tag{29}$$

6.2. Calculation of the Spin Offset Constant

The dimensionless constant $C \approx 2.7 \times 10^{-3}$ is determined by numerical solution of the linearized perturbation equation under neutron star conditions. Solving the equation $\nabla^2 \epsilon = -(1/\tilde{\Sigma}_{bg}) \nabla \epsilon \cdot \nabla \tilde{\Sigma}_{bg}$ with appropriate boundary conditions yields a topological number suppression:

$$Q_{eff} \approx 1 - C \tilde{\Sigma}_{surf}^2, \tag{30}$$

where C is a dimensionless constant. For $\tilde{\Sigma}_{surf} \approx 0.413$, we find:

$$Q_{eff} \approx 0.99954 \quad (C \approx 2.7 \times 10^{-3}). \tag{31}$$

This corresponds to a measurable offset in the observed spin quantum number for $Q = 1$:

$$\Delta s = \frac{1 - Q_{eff}}{2} \approx 2.3 \times 10^{-4}. \tag{32}$$

6.3. Observational Implications

This quantum spin offset effect would manifest as a characteristic energy-dependent shift in the polarization angle of X-rays emitted from the surfaces of neutron stars. The predicted polarization shift is on the order of 10^{-3} arcseconds. Upcoming observatories like the enhanced Insight-HXMT [3] and Athena [4] are designed with the polarimetric sensitivity ($\sim 10^{-3}$ arcsec) required to detect this signature. A confirmed detection would provide direct empirical evidence for the QST framework.

7. Conclusions

The Quantum-Spacetime Theory (QST) presents a coherent and unified description of physics by positing a fundamental duality between spacetime geometry and quantum topology. Its core postulates are simple yet powerful, directly yielding two cornerstones of modern physics—the electron's spin value and the Schwarzschild metric—without relying on the conceptual apparatus of prior theories.

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QST is not merely a reformulation but a novel paradigm that treats the geometry-quantum duality as an irreducible principle. It is empirically adequate, passing all classical tests, and falsifiable through its unique prediction of a spin offset in strong gravity. This theory provides a new foundation for exploring the universe's deepest laws, inviting both theoretical refinement and experimental scrutiny.

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