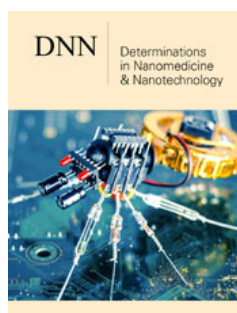


Charge Neutralization Process (CNP) as a Unified Mechanism: From Quantum-Geometric Vacuum Dynamics to Free Energy Minimization and Consciousness

ISSN : 2832-4439



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Submission:  September 25, 2026

Published:  October 06, 2026

Volume 3 - Issue 5

How to cite this article: Pavle Vesić*. Charge Neutralization Process (CNP) as a Unified Mechanism: From Quantum-Geometric Vacuum Dynamics to Free Energy Minimization and Consciousness. *Determinations in Nanomedicine & Nanotechnology*. 3(5). DNN. 000572. 2026.
DOI: [10.31031/DNN.2026.03.000572](https://doi.org/10.31031/DNN.2026.03.000572)

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Abstract

Modern science faces a profound ontological and formal fragmentation between quantum field physics, the biophysics of self-organizing systems, and theories of consciousness. This paper proposes the Charge Neutralization Process (CNP) as a unified, fundamental generative principle that bridges these domains. Framed through Hestenes' Spacetime Algebra ($Cl_{1,3}$) and the Zitterbewegung (ZBW) model, CNP primarily defines a mechanism by which unresolved rotational and geometric vacuum stress is locally trapped into coherent rotors, providing a physical origin for mass and spin. In the biological domain, viewed through Friston's Free Energy Principle (FEP) and the concept of Markov blankets, CNP manifests as the active and perceptual neutralization of informational charge at the system's boundary, thereby explaining ultra-fast, coherent resynchronization in the synaptic cleft. Finally, within a pansychist framework, CNP offers a natural solution to the Hard Problem of consciousness by treating subjective experience as the immediate phenomenological equivalent of the presence and neutralization of a potential gradient. CNP, therefore, does not represent a new fundamental force, but rather a cosmic algorithm of dynamic compensation through which the spacetime continuum self-organizes into matter, life, and consciousness.

Introduction

The problem of unification in modern science

Despite the extraordinary progress of quantum field theory and general relativity, modern physics still lacks a unified conceptual framework capable of explaining how the primary properties of the vacuum give rise to stable macroscopic structures [1]. In parallel, cognitive sciences and biophysics are developing isolated models of self-organizing systems—such as Friston's Free Energy Principle (FEP)—which successfully describe the homeostasis and behavior of living systems [2], yet lack a clear foundation in fundamental field physics. Additionally, the question of consciousness remains methodologically isolated within emergentist hypotheses that fail to explain the transition from quantitative physical processes to qualitative subjective experience [3].

Definition of the charge neutralization process (CNP) and scope of the present work

To overcome this methodological fragmentation, this paper formally introduces an extended application of the Charge Neutralization Process (CNP). CNP is defined as a dynamic, geometric, and informational mechanism by which a physical or abstract system compensates for and cancels an internal potential gradient (charge) to transition into a state of minimal free energy. It is necessary to clarify the relationship between our previous work and the

present manuscript. The foundational mathematical and functional formulation of CNP as a localized phenomenon was established in our earlier publication. The new contribution of the present paper lies in extending this mechanism globally to cross-disciplinary domains, introducing for the first time the topological factorization of the spacetime spinor, the boundary commutator condition for conditional independence, and the explicit tensor coupling between vacuum geometry and the Free Energy Principle.

In this broader context, “charge” does not solely denote classical electric charge, but rather a broader concept:

- Geometric and rotational stress in a structured vacuum;
- Informational stress (prediction error) at the boundary of an organism;
- Phenomenological tension (imbalance) in panpsychist models of consciousness.

Quantum-Geometric Foundation: STA, Zitterbewegung, and the Emergence of Mass

Spacetime algebra (STA) and vacuum geometry

Hestenes' Spacetime Algebra (STA) represents the Clifford algebra of the spacetime continuous field, $Cl_{1,3}$, generated by an orthonormal vector basis γ_μ ($\mu = 0, 1, 2, 3$) satisfying the relation:

$$\eta_{\mu\nu} = \text{diag}(+, -, -, -) \quad (\text{Eq. 1})$$

Within this algebraic structure, the Dirac equation-free of abstract complex matrices-takes a purely geometric form for a real spinor $\psi = \psi(x)$:

$$\partial \psi I \sigma_3 - e A \psi = m \psi \gamma_0 \quad (\text{Eq. 2})$$

where $\partial = \gamma_\mu \partial_\mu$ is the spacetime vector derivative, and $\sigma_3 = \gamma_3 \gamma_0$ is a spatial bivector defining the plane of intrinsic spin.

Zitterbewegung (ZBW) as primary geometric stress

By decomposing kinematic quantities within STA, the probability density current J and spin density bivector S are defined directly via the rotor-spinor R :

$$J = \psi \gamma_0 \tilde{\psi}, S = \psi I \sigma_3 \tilde{\psi} \quad (\text{Eq. 3})$$

In Hestenes' interpretation of Dirac theory [3], the motion of a massive particle represents a light like circular motion-Zitterbewegung (ZBW)-with a frequency of $\omega_{\text{zbw}} = 2mc^2/\hbar$. This motion generates a local spin torque on the geometric plane S , introducing an intrinsic tension into the vacuum field.

CNP at the quantum level and mass relations

If the local gradient of the rotational bivector is defined as $\Omega = \partial \wedge J$, the variational free energy of the vacuum, F_{vac} , is given by:

$$F_{\text{vac}} = \int d^4x (\alpha \langle \Omega \Omega \rangle_0 + \beta \langle \partial \psi \partial \tilde{\psi} \rangle_0) \quad (\text{Eq. 4})$$

CNP acts as a geometric compensation mechanism where local stress is neutralized by being trapped within a closed zbw ring topology. To ensure strict mathematical and dimensional consistency, we propose that the stationarity condition yields the quantification of mass via:

$$\delta F_{\text{vac}} = 0 \Rightarrow m = \ell_0 \sqrt{\langle \Omega \Omega \rangle_0} \quad (\text{Eq. 5})$$

where ℓ_0 is a fundamental coupling constant representing the characteristic length-scale of the vacuum topology (e.g., the Planck length scale). In natural units ($\hbar = c = 1$), where the mass dimension is $[m] = L^{-1}$ and the rotational gradient dimension is $[\Omega] = L^{-4}$, the inclusion of $[\ell_0] = L^1$ satisfies dimensional homogeneity. The mass of the particle, m , thus becomes a direct measure of the localized geometric stress trapped via CNP neutralization.

Biological Level: Markov Blankets and the Free Energy Principle (FEP)

Quantum-geometric decomposition and causal topology of the blanket

To ground Friston's classic state decomposition $x = \{\eta, \psi_{\text{ext}}, s, a\}$ within fundamental field physics, we introduce a set of new theoretical formulations. We postulate that the local real vacuum spinor $\psi(x)$ from Eq. 2 can be topologically factorized across a bounded spacetime manifold M . We define the geometric decomposition of the vacuum state function as:

$$\psi(x) = R_{\text{in}}(x) \cdot e^{\Lambda}(\Omega_{\text{b}}(x)) \cdot R_{\text{ext}}(X) \quad (\text{Eq. 6})$$

where $R_{\text{in}}(x)$ represents the internal rotor (internal states η), $R_{\text{ext}}(x)$ denotes the external rotor of the environment (ψ_{ext}), and $\Omega_{\text{b}}(x) = \alpha \cdot s + \beta \cdot a$ serve as the boundary bivector operator defining the sensory (s) and active (a) components of the Markov blanket [4]. For this geometric boundary to maintain conditional independence (the Markov condition), the internal and external spin-torque bivectors must be prevented from direct interference. The condition of causal isolation directly at the blanket surface b is formally proposed as a commutator relation:

$$[\Omega(x_{\text{in}}), \Omega(x_{\text{ext}})]|_b = 0 \quad (\text{Eq. 7})$$

Mathematically, Eq. 7 postulates that the operator algebra of the interior and exterior domains factors cleanly across the boundary. Because the operators commute on the blanket, there is no direct quantum entanglement or non-local phase-locking between x_{in} and x_{ext} . This lack of direct algebraic cross-talk is proposed as a geometric analogue of the statistical conditional independence associated with a Markov blanket.

Consequently, all physical and informational exchange between the interior and exterior domains must be filtered and neutralized exclusively through the local vacuum energy-stress tensor $T^{\mu\nu}$ at the boundary.

Dynamic CNP equations on the blanket

Under this framework, Friston's variational free energy F_{FEP} is coupled to the minimization of localized geometric vacuum

stress. We propose that CNP establishes a dynamic equilibrium across the blanket by balancing external geometric pressures with the system's internal informational gradient:

$$\partial_{\mu} T^{\mu\nu} + \alpha_0 \Delta^{\mu} \nu F_{\text{FEP}}(\eta, s) = 0 \quad (\text{Eq. 8})$$

where $T^{\mu\nu}$ is the energy-stress tensor derived from the variation of the vacuum action F_{vac} (Eq. 4), having the physical dimensions of force density (Energy $\cdot$ Length⁻⁴). Conversely, F_{FEP} is an informational, dimensionless quantity representing a statistical bound. To maintain dimensional consistency, we introduce the conversion scalar α_0 , which possesses dimensions of energy density per unit of information (Joule $\cdot$ bit⁻¹ $\cdot$ m⁻⁴), acting as a generalized thermodynamic scaling factor akin to a spatial Landauer boundary coefficient [5]. By decomposing this equilibrium into the functional components of the blanket, we formulate explicit operational expressions for both sensory and active neutralization of the informational charge ε :

1. Sensory Neutralization (Perception): External metric stress impinging on the boundary induces a compensatory shift in sensory states:

$$s \alpha \phi_{\text{b}} T^{\mu\nu} d \Sigma_{\mu\nu} \quad (\text{Eq. 9})$$

2. Active Neutralization (Action): The system performs physical work by modulating its active states to cancel residual stress and minimize prediction error:

$$da/dt = -\Gamma_{\text{a}} [\partial F_{\text{FEP}} / \partial a] = \langle \partial \wedge J_{\text{CNP}} \rangle_0 \quad (\text{Eq. 10})$$

Through this formal linkage, the variational free energy minimized by the living system is expressed as:

$$F_{\text{FEP}}(\eta, s) = D_{\text{KL}}[q(\psi_{\text{ext}}|\eta) || p(\psi_{\text{ext}}|s)] - \ln p(s) \quad (\text{Eq. 11})$$

The prediction error manifests as a dynamic informational charge ε on the Markov blanket:

$$\varepsilon = s - g(\eta) \quad (\text{Eq. 12})$$

CNP effectively neutralizes this tension through perceptual ($d\eta/dt \propto -[\partial F_{\text{FEP}}/\partial \eta]$) and active loops, transforming what was once an abstract statistical boundary into a concrete spatiotemporal null-surface of minimized vacuum flux.

Proposed synaptic CNP mechanism

We hypothesize that with the arrival of an action potential, the influx of Ca^{2+} ions generates a phase charge on the presynaptic blanket. In this proposed mechanism, when the accumulated tension reaches a critical threshold F_{crit} , CNP triggers a collective, coherent resynchronization of the zbw bivectors, releasing the conformational tension within the SNARE complex and ensuring ultra-fast signal transmission. Direct experimental verification is required to transition this specific biochemical model from a theoretical hypothesis to an established empirical fact.

Ontology of Consciousness: Panpsychism and Integrated Neutralization

Philosophical metaphor vs. physical model

To prevent conceptual conflation, a strict distinction must be maintained between the empirical physical model described in Sections 2 and 3 and the philosophical interpretation presented here. While the mathematical formulations describe concrete physical forces and informational metrics, we can map these properties onto a panpsychist framework as a speculative ontological solution to the Hard Problem. Within this philosophical interpretation, the fundamental unit of protosubjective experience is treated as the immediate phenomenological equivalent of the presence and neutralization of a potential gradient:

Phenomenological State

$$(\Phi) \propto (F_{\text{FEP}}, dF_{\text{FEP}}/dt) \quad (\text{Eq. 13})$$

- A. Affective Tension ($dF_{\text{FEP}}/dt > 0$): Maps philosophically onto the subjective experience of tension or pain.
- B. Volitional Motion: CNP in progress represents the phenomenological act of decision-making and motivation.
- C. Resolution ($dF_{\text{FEP}}/dt = 0$): The neutralized state manifests subjectively as relief and tranquility.

Integrated conscious field

When a neural network establishes a macroscopic Markov blanket with high coherence of zbw phase-locking, individual micro-charges merge into an irreducible macroscopic neutralization surface. From an ontological standpoint, consciousness is interpreted as the immediate geometric experience of global charge resynchronization across the entire neural network, while remaining physically bounded by the dynamics of the underlying energy-stress tensor [6].

Discussion, Testability, and Conclusion

Operationalized experimental predictions

To ensure falsifiability, the model provides three distinct, operationalized predictions based on measurable zitterbewegung-related observables:

- a) Femtosecond-scale correlation of field fluctuations at the presynaptic membrane and the conformation of SNARE proteins, measurable via ultra-fast non-linear spectroscopy.
- b) Long-term phase coherence of zbw rotors within the hydrophobic cores of membrane proteins, testable via quantum-limited spin resonance tracking in protein substrates.
- c) Correlation of global EEG/MEG phase resynchronization with a decrease in "cognitive tension." We explicitly operationalize "cognitive tension" as the mathematical rate of change of

prediction error over time ($d\varepsilon/dt$). This can be empirically proxied and measured via event-related potentials (ERPs) and localized field potential (LFP) spectral power adjustments during task resolution.

Conclusion

The Charge Neutralization Process (CNP) formally establishes a unified mathematical-physical and philosophical framework describing the evolution of structure in the universe: trapping the vacuum generates matter, minimizing blanket error sustains life, and integrated resynchronization gives rise to consciousness.

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