

Zitterbewegung as Archimedean–2-adic Channel Mixing: A Conjectural Adelic Framework and Its Testable Consequences

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Abstract

Zitterbewegung (ZBW) — the trembling motion of Dirac wave packets at the Compton scale, first identified by Breit and Schrödinger — is conventionally explained as interference between positive- and negative-energy branches on the real line. We develop a conjecture, motivated by the adelic physics program, that ZBW is instead (or additionally) the observable signature of mixing between the Archimedean completion $\mathbb{Q}_\infty = \mathbb{R}$ and the 2-adic completion $\mathbb{Q}_2$ of the rational base field: a packet localized at the real place x_∞ necessarily contains Fourier components delocalized at the 2-adic place x_2 , and the observed oscillation at angular frequency $\omega_{\text{ZBW}} = 2E/\hbar$ is interpreted as the beat between these sectors. The Majorana reality condition realizes the identification of the two places, and topological protection arises from Ostrowski incommensurability of $\mathbb{R}$ and $\mathbb{Q}_2$. We formulate a two-channel effective Hamiltonian, compute the product-formula identity for the prime 2 explicitly, derive the electron-scale numbers with full arithmetic ($\omega_{\text{ZBW}} = 1.5521 \times 10^{21} \text{ s}^{-1}$, $T_{\text{ZBW}} = 4.0483 \times 10^{-21} \text{ s}$), and show that the predicted frequency is representation-independent under the Foldy–Wouthuysen transformation. We state falsifiable tests on emulation platforms and enumerate the framework's failure modes; the framework remains conjectural, and its empirical content currently hinges on an undetermined mixing amplitude Δ .

1. Introduction

The velocity operator of the Dirac equation has eigenvalues $\pm c$, and a localized Dirac wave packet does not move uniformly: its position oscillates rapidly at the Compton scale. This is Zitterbewegung (ZBW), named by Schrödinger following the work of Breit [1]. The standard account treats ZBW as an interference effect between positive- and negative-frequency components of a packet on the real line [2]. On that account, ZBW is a kinematic artifact: a suitable change of representation (Foldy–Wouthuysen, FW) diagonalizes the Hamiltonian and the trembling disappears from the position operator.

Yet ZBW is not merely an artifact of one representation. It survives, reappears, or can be externally driven across radically different physical systems: it can be converted into directed center-of-mass motion by resonant modulation of a Dirac-like equation [3]; it appears as an internal-state oscillation in discrete-time quantum walks implemented in fiber loops [5]; it can be controlled in cold atoms by mirror oscillation driving an effective spin-orbit interaction [6]; it is modified by Zeeman fields and harmonic traps in spin-orbit-coupled spin-1 ultracold atoms [7]; and it produces measurable charge oscillations in a three-terminal junction whose period can be tuned by spin-orbit strength or magnetic field [8]. This robustness across implementations and representations motivates treating ZBW as ontological rather than coordinate-dependent.

This paper advances a specific ontological hypothesis, taken from the adelic physics program [9]: the physically accessible base field is $\mathbb{Q}$, not $\mathbb{R}$, and by Ostrowski's theorem all completions of $\mathbb{Q}$ — the real place $\mathbb{R}$ and the p -adic places $\mathbb{Q}_p$ — are physically meaningful. We conjecture that ZBW is the Archimedean shadow of mixing between the ∞ -place and the 2-place: a channel-mixing phenomenon analogous in structure to flavor mixing in quantum field theory, where flavor and mass Fock spaces are unitarily inequivalent [4]. The choice of the prime $p = 2$ is motivated by the companion program's identification of ZBW as a $\mathbb{Z}_2$ -valued topological observable

distinguishing Dirac from Majorana fermions [11], [12], and by the structural underdetermination of the position operator, which manifests at the Archimedean place as ZBW (the Newton–Wigner no-go) and at p -adic places as a discrete Bruhat–Tits observable [10].

Our contributions are deliberately modest and explicit. We do not claim a complete adelic Dirac theory. We: (i) state the Archimedean–2-adic channel-mixing conjecture precisely; (ii) construct a two-channel effective Hamiltonian in which the standard ZBW frequency is recovered as a beat frequency; (iii) compute the predicted rest-frame frequency and the adelic product-formula identities with fully shown arithmetic; (iv) give a representation-independence argument under FW transformation; and (v) specify a falsification plan grounded in existing emulation platforms [3], [5], [6], [7], [8]. All quantitative claims are either computed here with shown arithmetic or explicitly labeled projections with stated assumptions.

2. Background and Related Work

Historical core. Breit and Schrödinger showed around 1930 that the eigenvalues of the velocity of a particle described by wave-packet solutions of the Dirac equation are simply $\pm c$, the speed of light; Schrödinger coined the term Zitterbewegung ("trembling motion") for the resulting back-and-forth zig-zag of fermions at the speed of light [1]. The statistical-mechanical treatment of the problem of motion in [1] frames ZBW as the central puzzle of the Dirac position operator; the supplied summary is truncated before its later results, so we use it only for this historical framing. Our conjecture accepts this puzzle as real rather than representational.

Interference and chirality. The immediate description of chiral oscillations in terms of the trembling motion of the velocity (Dirac) operator α arises when the complete set of Dirac-equation solutions is taken, so that a free propagating Dirac wave packet is composed of positive and negative frequency components [2]. This is precisely the interference picture our conjecture reinterprets: the positive/negative frequency split on $\mathbb{R}$ is proposed to be the Archimedean projection of a two-channel adelic structure, and [2] supplies the mathematical template (complete-solution packets, cross-frequency beats) that Section 3 formalizes.

Flavor-mixing analogy. In the quantum-field-theoretic treatment of neutrino mixing, the Fock space of flavor states is unitarily inequivalent to that of mass states (the inequivalent-vacua model), and a paradox emerges when these weak states are used to compute the amplitude of W boson decay, with the branching ratio of $W^+ \rightarrow e^+ + \nu_\mu$ relative to $W^+ \rightarrow e^+ + \nu_e$ appearing approximately suppressed [4]. The supplied summary does not give the exact numerical value of that suppression, so we use the structural lesson only: mixing between inequivalent sector constructions produces oscillation phenomena and apparent paradoxes in amplitudes. Our $\infty \leftrightarrow 2$ channel mixing is modeled on exactly this pattern, with "flavor" replaced by "place," and any adelic mixing amplitude must be checked against such consistency conditions.

Emulation and control platforms. ZBW can be converted to directed center-of-mass motion by a modulation of the Dirac-like equation when the modulation is on resonance with the ZB frequency; tailored modulation may also stop or re-launch the motion [3]. This matters for us because it demonstrates that the ZB frequency is an experimentally addressable channel carrier: if ZBW were an adelic cross-place beat, resonance modulation [3] would be the natural knob for driving population between the ∞ and 2 channels. In a discrete-time quantum walk in coupled fiber loops, ballistic spreading and an oscillation between two internal quantum states similar to Zitterbewegung were experimentally observed, and a position-dependent phase gradient produces localization and Bloch oscillations [5]; this shows that ZBW-like two-state beating is realizable and measurable in synthetic systems, the platform class our simulation protocol targets. Mirror oscillation in a "tripod-scheme" laser–atom system can drive an effective spin-orbit interaction and thereby control the amplitude, frequency, and damping of cold-atom ZBW, as shown both analytically and numerically [6] — establishing that the parameters our model predicts to be

place-mixing dependent are externally tunable. In spin-orbit-coupled spin-1 cold atoms, the Zeeman field and harmonic trap significantly affect ZBW: the external Zeeman field can suppress or enhance the ZBW amplitude and change the oscillation frequencies, with a much slower oscillation also appearing [7]; this sensitivity is consistent with a mixing picture in which external fields renormalize the effective channel coupling. Finally, ZBW charge oscillations can be detected through a charge conductance measurement in a three-terminal junction; tuning the spin-orbit interaction strength or an external magnetic field modulates the ZBW period, translating into complementary conductance oscillations in the two outgoing leads [8]. The two-lead complementary-signal structure of [8] is structurally analogous to our two-channel ($\infty/2$) readout. These platforms [3], [5], [6], [7], [8] define the experimental landscape in which an adelic channel-mixing signature would have to be sought or bounded.

The adelic program. The QNFO Adelic Physics Program proposes that the physically accessible base field of physics is $\mathbb{Q}$, not $\mathbb{R}$, and that Ostrowski's theorem demands all p -adic completions of $\mathbb{Q}$ be physically meaningful; it supplies the epistemological and pedagogical infrastructure for this claim [9]. Within that program, the structural underdetermination of the position operator in relativistic quantum mechanics is diagnosed as having a single representation-theoretic origin, manifesting at the Archimedean place as ZBW (the Newton–Wigner no-go) and at p -adic places as a discrete Bruhat–Tits observable [10]; this is the closest existing statement to our thesis, and our model can be read as a concrete two-place instantiation of it. The ZBW–Majorana hypothesis establishes that ZBW — the rapid trembling motion of Dirac fermions at the Compton scale — is a $\mathbb{Z}_2$ topological observable distinguishing Dirac from Majorana fermions at the hardware level, developed across companion papers [11]; in our channel language, the Majorana condition is the self-conjugacy that identifies the ∞ and 2 places, killing the beat. And ZBW has been formulated as a p -adic topological observable: the ZBW current J_{ZBW}^μ carries a $\mathbb{Z}_2$ invariant encoding the Dirac/Majorana distinction, with ultrametric readout protocols proposed via Bruhat–Tits buildings [12]; this supplies the candidate readout geometry for the x_2 channel. Our paper is the concrete, computationally explicit realization of the $\infty \leftrightarrow 2$ link asserted in [9], [10], [12].

3. Methods

3.1 Adelic kinematics

Let $\mathbb{A}_{\mathbb{Q}}$ denote the adèle ring of $\mathbb{Q}$, the restricted product $\mathbb{A}_{\mathbb{Q}} = \mathbb{R} \times \prod'_p \mathbb{Q}_p$, where the prime restricts almost all factors to $\mathbb{Z}_p$. A one-particle position is an adelic point $x = (x_\infty, x_2, x_3, \dots)$ with $x_v \in \mathbb{Q}_v$. The conjecture of this paper restricts attention to the two places $v \in \{\infty, 2\}$; all other places are assumed to factor out of the ZBW dynamics (an assumption we flag as a limitation in Section 6).

The free Dirac Hamiltonian on the real sector is

$$H_\infty = c \boldsymbol{\alpha} \cdot \mathbf{p}_\infty + \beta mc^2, \quad H_\infty^2 = c^2 p_\infty^2 + m^2 c^4,$$

with spectrum $\pm E_\infty$, $E_\infty = \sqrt{c^2 p_\infty^2 + m^2 c^4}$. On the 2-adic sector we postulate the analogous quadratic form

$$H_2^2 = c^2 |p_2|_2^2 + m^2 c^4,$$

where $|\cdot|_2$ is the 2-adic norm, normalized so that $|2|_2 = 2^{-1}$ and $|q|_2 = 2^{-v_2(q)}$ for $q \in \mathbb{Q}$, with $v_2(q)$ the 2-adic valuation. The key structural fact is Ostrowski incommensurability: the norms $|\cdot|_\infty$ and $|\cdot|_2$ satisfy no nontrivial relation, so a state sharply localized in x_∞ (a delta-like packet, broad in real momentum) is delocalized in x_2 , and vice versa. Localization at one place forces delocalization at the other; this is the channel-mixing kinematics.

3.2 Channel-mixing ansatz

We write a two-level effective Hamiltonian in the place basis $\{|\infty\rangle, |2\rangle\}$:

$$H_{\text{mix}} = \begin{pmatrix} E_\infty & \Delta \\ \Delta^* & E_2 \end{pmatrix},$$

where $E_2 = \sqrt{c^2|p_2|_2^2 + m^2c^4}$ and Δ is the $\infty \leftrightarrow 2$ transition amplitude, assumed real and proportional to the overlap of the packet's Fourier support at both places. The eigenfrequencies of H_{mix} are

$$\Omega_\pm = \frac{E_\infty + E_2}{2} \pm \sqrt{\left(\frac{E_\infty - E_2}{2}\right)^2 + |\Delta|^2},$$

and the channel populations oscillate at the beat frequency

$$\omega_{\text{beat}} = \Omega_+ - \Omega_- = \frac{2}{\hbar} \sqrt{\left(\frac{E_\infty - E_2}{2}\right)^2 + |\Delta|^2}.$$

In the standard interference picture the observed ZBW frequency is $\omega_{\text{ZBW}} = 2E/\hbar$ (the gap between $+E$ and $-E$ branches). The conjecture identifies the two: the $\pm E$ branches on $\mathbb{R}$ are the projections of the two mixed adelic eigenmodes, so that in the resonant regime $E_\infty \approx E_2 \equiv E$ and small $|\Delta|$,

$$\omega_{\text{beat}} \approx \frac{2|\Delta|}{\hbar} \longrightarrow \omega_{\text{ZBW}} = \frac{2E}{\hbar} \text{ when } |\Delta| \sim E.$$

We do not derive $|\Delta| \sim E$ from first principles here; we state it as the conjecture's calibration condition and note that it is what makes the hypothesis empirically equivalent to the standard picture at the frequency level while differing in ontology.

3.3 Majorana condition and topological protection

The Majorana condition identifies particle and antiparticle; in the adelic language of this conjecture it realizes the identification of the ∞ and 2 places, since the $\mathbb{Z}_2$ grading of the ZBW observable [11], [12] has exactly two sectors. When the identification is exact, the cross-channel beat term cancels and the ZBW signal vanishes — the $\mathbb{Z}_2$ Dirac/Majorana distinction. Topological protection then follows from Ostrowski incommensurability: no continuous deformation of the packet can tune the ratio $|p|_\infty/|p|_2$ through zero, because the two norms are multiplicatively independent, so the channel gap cannot be closed by a smooth Archimedean perturbation — the $\mathbb{Z}_2$ invariant is stable.

3.4 Simulation protocol

Following the demonstrated controllability of ZBW in synthetic systems [5], [6], [7] and its electrical detectability [8], we propose a simulation in which a discrete dynamics emulating a p -adic (ultrametric) position space is coupled to a continuous real-space sector, with a tunable coupling Δ . The predicted signatures are: (i) an oscillation at $\omega_{\text{ZBW}} = 2E/\hbar$ (in scaled simulator units, $2\tilde{E}/\hbar_{\text{eff}}$) that survives diagonalization of the real-sector Hamiltonian; (ii) complementary oscillations in two readout channels attached to the two places, in analogy with the two-lead conductance signals of [8]; (iii) suppression of the oscillation when the Majorana identification constraint is imposed.

4. Analysis

All input numbers below are standard physical constants stated here explicitly as inputs; all arithmetic is shown step by step.

Inputs. Electron mass $m_e = 9.109 \times 10^{-31}$ kg; speed of light $c = 2.998 \times 10^8$ m s⁻¹; reduced Planck constant $\hbar = 1.055 \times 10^{-34}$ J s.

Derivation 1: rest-frame ZBW angular frequency. At rest, $p_\infty = 0$, so $E = m_e c^2$. Compute the rest energy:

$$E_0 = m_e c^2 = (9.109 \times 10^{-31}) \times (2.998 \times 10^8)^2 \text{ J}.$$

First, $c^2 = (2.998 \times 10^8)^2 = 8.988 \times 10^{16}$ m² s⁻². Then

$$E_0 = 9.109 \times 10^{-31} \times 8.988 \times 10^{16} = 81.87 \times 10^{-15} \text{ J} = 8.187 \times 10^{-14} \text{ J}.$$

The conjectured and standard ZBW angular frequency is

$$\omega_{\text{ZBW}} = \frac{2E_0}{\hbar} = \frac{2 \times 8.187 \times 10^{-14}}{1.055 \times 10^{-34}} \text{ s}^{-1}.$$

Numerator: $2 \times 8.187 \times 10^{-14} = 1.6374 \times 10^{-13}$ J. Dividing:

$$\omega_{\text{ZBW}} = \frac{1.6374 \times 10^{-13}}{1.055 \times 10^{-34}} = 1.552 \times 10^{21} \text{ s}^{-1}.$$

The corresponding ordinary frequency is

$$\nu_{\text{ZBW}} = \frac{\omega_{\text{ZBW}}}{2\pi} = \frac{1.552 \times 10^{21}}{6.2832} = 2.470 \times 10^{20} \text{ Hz}.$$

The ZBW period is

$$T_{\text{ZBW}} = \frac{2\pi}{\omega_{\text{ZBW}}} = \frac{6.2832}{1.552 \times 10^{21}} \text{ s} = 4.048 \times 10^{-21} \text{ s},$$

since $6.2832/1.552 = 4.048$. The Compton angular frequency is $\omega_C = E_0/\hbar = 8.187 \times 10^{-14}/1.055 \times 10^{-34} = 7.7604 \times 10^{20} \text{ s}^{-1}$, exactly half of ω_{ZBW} , so the ZBW oscillation runs at twice the Compton frequency, as the conjecture's beat structure predicts.

Derivation 2: the adelic product formula for $q = 2$. For any nonzero rational q , the product formula states $\prod_v |q|_v = 1$ over all places v . For $q = 2$ only the ∞ and 2 places contribute nontrivially (for every odd prime p , $v_p(2) = 0$ so $|2|_p = 1$). Compute:

$$|2|_\infty = 2, \quad |2|_2 = 2^{-v_2(2)} = 2^{-1} = \frac{1}{2}, \quad |2|_p = 1 \quad (p \text{ odd}).$$

Therefore

$$\prod_v |2|_v = 2 \times \frac{1}{2} \times 1 = 1.$$

For a composite check, $q = 12 = 2^2 \cdot 3$: $|12|_\infty = 12$, $|12|_2 = 2^{-2} = 1/4$, $|12|_3 = 3^{-1} = 1/3$, and all other places give 1; hence

$$|12|_\infty |12|_2 |12|_3 = 12 \times \frac{1}{4} \times \frac{1}{3} = \frac{12}{12} = 1.$$

This exact identity is the algebraic seed of the conjecture: the real and 2-adic norms of the prime 2 are reciprocal, so the ∞ and 2 channels are balanced in a way that, in the conjecture, enforces the bookkeeping between Archimedean localization and 2-adic delocalization. For comparison, $|3|_\infty \times |3|_3 = 3 \times \frac{1}{3} = 1$ as well — the product formula holds for every prime — but the conjecture singles out $p = 2$ because the ZBW observable is $\mathbb{Z}_2$ -valued [11], not because the product formula is special to 2.

Derivation 3: Ostrowski incommensurability, explicit. For $n = 10$: $|2^{10}|_\infty = |1024|_\infty = 1024$, while

$$|2^{10}|_2 = 2^{-10} = \frac{1}{1024} = 9.765625 \times 10^{-4}.$$

The product is again $1024 \times 9.765625 \times 10^{-4} = 1$. As $n \rightarrow \infty$, $|2^n|_\infty \rightarrow \infty$ while $|2^n|_2 \rightarrow 0$: the two norms are monotone opposites on the same sequence, which is the precise sense in which no Archimedean perturbation can be relabeled as a 2-adic one.

Derivation 4: mixed-channel beat frequency (projection). Take a relativistic packet with $p_\infty c = 3E_0$. Then

$$E_\infty = \sqrt{(3E_0)^2 + E_0^2} = E_0 \sqrt{10}.$$

With $E_0 = 8.187 \times 10^{-14}$ J and $\sqrt{10} = 3.1623$:

$$E_\infty = 3.1623 \times 8.187 \times 10^{-14} = 2.5890 \times 10^{-13} \text{ J}.$$

Assume the calibration $|\Delta| = 0.1 E_\infty$ and $E_2 = E_\infty$ (the 2-adic sector tuned to the same energy shell — a stated assumption, not a derivation). Then

$$\omega_{\text{beat}} = \frac{2|\Delta|}{\hbar} = \frac{2 \times 0.1 \times 2.589 \times 10^{-13}}{1.055 \times 10^{-34}} = \frac{5.178 \times 10^{-14}}{1.055 \times 10^{-34}} = 4.908 \times 10^{20} \text{ s}^{-1}.$$

This is a *projection* conditional on the calibration assumptions; its uncertainty is unbounded in practice, since $|\Delta|$ is not independently determined and could range over orders of magnitude. The purpose of this derivation is to exhibit the functional dependence $\omega_{\text{beat}} \propto |\Delta|/\hbar$, not to claim a measured value. Equivalently, in the weak-mixing limit the population of the partner channel obeys the projected structure $P_2(t) \propto (|\Delta|/2E)^2 \sin^2(2Et/\hbar)$; since Δ is undetermined, no numerical modulation depth is claimed.

Derivation 5: representation independence under Foldy–Wouthuysen. The FW transformation U_{FW} diagonalizes H_∞ into βE_∞ , removing the odd operator α from the position dynamics. However, U_{FW} acts only on the Archimedean factor of the adelic Hilbert space $\mathcal{H} = \mathcal{H}_\infty \otimes \mathcal{H}_2$; it is a real-place unitary and cannot touch the $\infty \leftrightarrow 2$ mixing matrix element Δ , which couples different places. Hence the beat frequency

$$\omega_{\text{beat}} = \frac{2}{\hbar} \sqrt{\left(\frac{E_\infty - E_2}{2}\right)^2 + |\Delta|^2}$$

is invariant under FW: the mixing is not a coordinate effect of the real representation. Equivalently, $\omega_{\text{ZBW}} = 2E/\hbar$ is a difference of eigenvalues of H_∞ , and no unitary changes a spectrum; for the electron this is the value of Derivation 1, $1.552 \times 10^{21} \text{ s}^{-1}$, in every frame including the FW frame. This is the precise sense in which the conjecture explains the persistence of ZBW under representation change, in contrast to the interference picture, in which a representation change that diagonalizes the Hamiltonian removes the trembling from the transformed position operator.

5. Results

We report only quantities computed in Section 4, plus clearly labeled projections; no empirical or simulated data are reported.

1. **Rest-frame ZBW angular frequency (computed).** $\omega_{\text{ZBW}} = 2m_e c^2 / \hbar = 1.5521 \times 10^{21} \text{ s}^{-1}$, from inputs $m_e = 9.109 \times 10^{-31} \text{ kg}$, $c = 2.998 \times 10^8 \text{ m s}^{-1}$, $\hbar = 1.055 \times 10^{-34} \text{ J s}$ (Derivation 1).
2. **Rest-frame ZBW ordinary frequency (computed).** $\nu_{\text{ZBW}} = \omega_{\text{ZBW}} / 2\pi = 2.4702 \times 10^{20} \text{ Hz}$ (Derivation 1).
3. **ZBW period (computed).** $T_{\text{ZBW}} = 2\pi / \omega_{\text{ZBW}} = 4.0483 \times 10^{-21} \text{ s}$ (Derivation 1).
4. **Compton angular frequency (computed).** $\omega_C = E_0 / \hbar = 7.7604 \times 10^{20} \text{ s}^{-1} = \omega_{\text{ZBW}} / 2$ (Derivation 1).
5. **Adelic product identities (computed, exact).** $\prod_v |2|_v = 2 \times \frac{1}{2} = 1$; $|12|_\infty |12|_2 |12|_3 = 12 \times \frac{1}{4} \times \frac{1}{3} = 1$; $|2^{10}|_\infty \times |2^{10}|_2 = 1024 \times 9.765625 \times 10^{-4} = 1$ (Derivations 2 and 3).
6. **Mixed-channel beat frequency (projection).** Under the stated calibration assumptions $E_2 = E_\infty$ and $|\Delta| = 0.1 E_\infty$ with $p_\infty c = 3E_0$, $\omega_{\text{beat}} = 4.908 \times 10^{20} \text{ s}^{-1}$ (Derivation 4). This is a projection, not a measurement: $|\Delta|$ is undetermined and could range over orders of magnitude, so the uncertainty on this number is unbounded in practice. The robust content is the functional dependence $\omega_{\text{beat}} \propto |\Delta| / \hbar$ and the projected population structure $P_2(t) \propto (|\Delta| / 2E)^2 \sin^2(2Et / \hbar)$, for which no numerical modulation depth is claimed.
7. **Representation independence (structural result).** The beat frequency ω_{beat} is invariant under the Foldy–Wouthuysen transformation because U_{FW} acts only on the Archimedean factor $\mathcal{H}_\infty$ of $\mathcal{H} = \mathcal{H}_\infty \otimes \mathcal{H}_2$ and cannot alter the cross-place matrix element Δ (Derivation 5). No numerical content beyond item 1 is asserted here.

6. Discussion

Status of the conjecture. The framework is conjectural. Its empirical content at the frequency level is currently identical to the standard interference picture: both predict $\omega_{\text{ZBW}} = 2E / \hbar$, and the identification of the $\pm E$ branches with mixed adelic eigenmodes requires the calibration condition $|\Delta| \sim E$, which we have not derived from first principles. What the conjecture adds is ontological interpretation and two structural predictions: (i) persistence of the oscillation under representation change, formalized in Derivation 5; and (ii) suppression of the oscillation under the Majorana identification of the ∞ and 2 places, which is the operational content of the $\mathbb{Z}_2$ Dirac/Majorana distinction of [11], [12].

Limitations and failure modes. (a) The restriction to two places $v \in \{\infty, 2\}$ is an assumption; nothing in the product formula (Derivation 2) singles out $p = 2$ algebraically, since $\prod_v |q|_v = 1$ holds for every rational q and every prime. The justification offered is structural — the $\mathbb{Z}_2$ -valued ZBW observable of [11], [12] has exactly two sectors — but a critic could equally argue that the two sectors are the positive/negative energy branches of the ordinary theory, in which case the adelic layer is decoration. (b) The 2-adic Hamiltonian $H_2^2 = c^2 |p_2|_2^2 + m^2 c^4$ is postulated by analogy; no dynamics on $\mathbb{Q}_2$ is derived, and the notion of a wave packet delocalized at x_2 is used heuristically without a constructed 2-adic Fourier theory in this paper. (c) The mixing amplitude Δ is a free parameter; until an independent determination or bound exists, every mixed-channel number is a projection with unbounded uncertainty, as stated in Results item 6. (d) The claim that FW transformations cannot act on $\mathcal{H}_2$ rests on the tensor-product factorization $\mathcal{H} = \mathcal{H}_\infty \otimes \mathcal{H}_2$, which is itself part of the conjecture; if the adelic Hilbert space does not factor, Derivation 5 fails.

What would falsify the claims. The conjecture is falsified if: (i) a ZBW-like oscillation is observed in a system prepared in a Majorana-like self-conjugate configuration, contradicting the suppression prediction of Section 3.3; (ii) the oscillation frequency is found to shift under a representation change in an emulation platform in a way not attributable to the driving protocol, contradicting the invariance argument; or (iii) the emulation protocol of Section 3.4, run with Δ tuned to zero, still shows the two-channel complementary readout signals predicted by analogy with the two-lead conductance oscillations of [8], indicating that the two-channel structure is an artifact of the readout rather than of the mixing. Conversely, observation of the predicted complementary two-channel signals with a tunable coupling behaving as $\omega_{\text{beat}} \propto |\Delta|/\hbar$ would be the first positive, if still circumstantial, evidence.

Open questions. Can $|\Delta| \sim E$ be derived from a consistency condition analogous to the amplitude-consistency requirements that arise in the inequivalent-vacua treatment of flavor mixing [4]? Do the other primes $p \neq 2$ support analogous beats, and if so why are they not observed at the Compton scale? Does the Bruhat–Tits readout geometry proposed in [12] admit a concrete emulator implementation? These questions are open and are stated as questions, not results.

7. Conclusion

We have stated a conjectural adelic reinterpretation of Zitterbewegung as mixing between the Archimedean and 2-adic completions of $\mathbb{Q}$, built a two-channel effective Hamiltonian whose beat frequency reduces to the standard $\omega_{\text{ZBW}} = 2E/\hbar$ under an explicit calibration condition, computed the electron-scale numbers with fully shown arithmetic ($\omega_{\text{ZBW}} = 1.5521 \times 10^{21} \text{ s}^{-1}$, $\nu_{\text{ZBW}} = 2.4702 \times 10^{20} \text{ Hz}$, $T_{\text{ZBW}} = 4.0483 \times 10^{-21} \text{ s}$, $\omega_C = 7.7604 \times 10^{20} \text{ s}^{-1}$), verified the adelic product formula for $q = 2$ and $q = 12$ exactly, exhibited Ostrowski incommensurability on the sequence 2^n , and argued that the beat frequency is invariant under Foldy–Wouthuysen transformation. The framework's distinctive predictions — Majorana suppression and two-channel complementary readout — are falsifiable on existing emulation platforms of the type demonstrated in [3], [5], [6], [7], [8]. All quantitative claims are either computed here with shown arithmetic or explicitly labeled projections with stated assumptions; the conjecture itself remains unproven, and its empirical distinctiveness currently hinges on the undetermined mixing amplitude Δ .

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Appendix A. Divergence report

The independent drafts converged on all substantive claims: the channel-mixing conjecture, the two-channel Hamiltonian, the calibration condition $|\Delta| \sim E$, the computed electron-scale numbers of Derivation 1, the product-formula identities of Derivations 2–3, the projection of Derivation 4 with its stated assumptions, and the FW invariance argument of Derivation 5. No conflicting conventions or conflicting numerical values were reported between drafts, so no divergence required adjudication; this appendix is retained for completeness. The only structural defect found in reconciliation was truncation of the Results section in one draft, which has been completed here from the convergent derivations of Section 4.

Appendix B. Claim attribution

Claim	Substance	Source drafts	Status
C1	ZBW is conventionally interference of $\pm E$ branches; conjecture reinterprets it as $\infty \leftrightarrow 2$ adelic channel mixing	A, B, C	CONVERGENT
C2	Two-channel Hamiltonian H_{mix} with beat $\omega_{\text{beat}} = \frac{2}{\hbar} \sqrt{\left(\frac{E_{\infty} - E_2}{2}\right)^2 + \Delta ^2}$	A, B, C	CONVERGENT
C3	Calibration condition $ \Delta \sim E$ stated, not derived	A, B, C	CONVERGENT
C4	$\omega_{\text{ZBW}} = 1.5521 \times 10^{21} \text{ s}^{-1}$, $\nu_{\text{ZBW}} = 2.4702 \times 10^{20} \text{ Hz}$, $T_{\text{ZBW}} = 4.0483 \times 10^{-21} \text{ s}$, $\omega_C = 7.7604 \times 10^{20} \text{ s}^{-1}$	A, B, C	CONVERGENT
C5	Product formula for $q = 2$ and $q = 12$; Ostrowski incommensurability on 2^n	A, B, C	CONVERGENT
C6	Beat-frequency projection $4.908 \times 10^{20} \text{ s}^{-1}$ under $ \Delta = 0.1 E_{\infty}$, $E_2 = E_{\infty}$, $p_{\infty} c = 3E_0$	A, B	CONVERGENT (C omitted the projection; retained with explicit labeling)
C7	FW invariance of ω_{beat} via tensor-factorization argument	A, B, C	CONVERGENT
C8	Majorana identification suppresses the beat; $\mathbb{Z}_2$ topological protection via Ostrowski incommensurability	A, B, C	CONVERGENT
C9	Falsification plan on emulation platforms [3], [5], [6], [7], [8]	A, B, C	CONVERGENT