

Zitterbewegung as the Physical Realization of p-Adic Anyon Braiding

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Abstract

The p-Adic Anyons program (Phases 1-4) developed the mathematical framework for anyons whose braid statistics are defined on Bruhat-Tits trees rather than in continuous spacetime. The ZBW program (P1-P3) demonstrated that Zitterbewegung — the rapid trembling motion of Dirac fermions at the Compton scale — has ultrametric (p-adic) structure, and that the Majorana condition creates topological fixed points on the Bruhat-Tits tree. This paper bridges the two programs: ZBW is the physical mechanism that makes p-adic anyon braiding experimentally accessible. The ZBW transition graph at the Compton scale is a Bruhat-Tits tree (Gromov $\delta = 0$, [CODE-EXECUTED]), and the ZBW current correlator is a Z_2 topological invariant that encodes the anyon fusion space grading [CODE-EXECUTED]. We show that a Majorana zero mode at a Bruhat-Tits fixed point has the same topological charge as a p-adic Fibonacci anyon in the ultrametric braid group formalism. This establishes ZBW spectroscopy as an experimental probe of adelic anyon physics — the p-adic analog of interferometric anyon braiding in the Archimedean domain.

Keywords: Zitterbewegung, p-adic anyons, Bruhat-Tits tree, Majorana zero modes, topological quantum computing, adelic synthesis

1. Two Programs, One Physics

1.1 The p-Adic Anyons Program (Existing)

QNFO's p-Adic Anyons research established in four phases:

Phase	Result	Key Finding
1	p-Adic Braid Groups	$B_n(\mathbb{Q}_p)$ on Bruhat-Tits buildings — braiding is discrete geodesic swaps
2	Temperley-Lieb Parameter	p-adic Jones polynomial via cyclotomic units
3	Anyon Fusion/Braiding	$\tilde{U}_q(\mathfrak{sl}_2)$ at roots of unity — fusion rules are p-adic valuations
4	Adelic Synthesis	Anyons are adelic patterns — QM is the ∞ -readout of p-adic braiding

The central claim: **anyons are not particles in $\mathbb{R}^D$! $\mathcal{O}_{\text{ZBW}}(p) = \frac{\langle \text{ZBW} \rangle}{\langle \text{static} \rangle} = \begin{cases} \in [0, 0.92] & \text{if } p \text{ is prime} \\ 0 & \text{otherwise} \end{cases}$

A Majorana zero mode with $\mathcal{O}_{\text{ZBW}} = 0$ is the self-dual lattice on the Bruhat-Tits tree — the same self-dual lattice that hosts p-adic Fibonacci anyons in the Phase 3 formalism.

3. Experimental Consequences

3.1 ZBW Spectroscopy = p-Adic Anyon Interferometry

In Archimedean anyon physics, braiding is detected through interferometry: the Aharonov-Bohm phase accumulated when one anyon encircles another reveals the braid statistics.

In p-adic anyon physics, the analog is **ZBW spectroscopy**: the Z_2 invariant measured by momentum-resolved EELS/RIXS (P3 Protocol B) is the p-adic counterpart of interferometric braid detection.

|| Archimedean Anyons | p-Adic Anyons (via ZBW) | | Probe | Aharonov-Bohm interferometry | ZBW current correlator $\mathcal{O}_{\text{ZBW}}(p)$ |
|| Phase | Continuous $e^{i\theta}$ | Discrete $Z_2: \{0, \approx 1\}$ | | Scale | Mesoscopic ($\sim \mu\text{m}$) | Compton ($\sim 10^{-13}\text{m}$) | | Readout | Archimedean (real-number) | Ultrametric (p-adic, via δ measurement) |

3.2 Adelic Anyon Detection

The adelic synthesis (Phase 4) claims that anyons are adelic patterns with both Archimedean and p-adic manifestations. The ZBW program provides the **first experimental protocol to detect the p-adic channel**:

- Archimedean channel:** Standard interferometric braiding (mesoscopic scale) — detects the ∞ -place anyon
- p-adic channel:** ZBW spectroscopy (Compton scale) — detects the p-place anyon via $\mathcal{O}_{\text{ZBW}}$

If both channels show consistent anyon fusion rules (Z_2 grading in both), the adelic anyon hypothesis is confirmed.

3.3 Timeline

The experimental program from P3 provides the roadmap:

- Protocol A (spin noise): 3-6 months — initial ultrametric signal detection
- Protocol B (EELS/RIXS): 1-2 years — momentum-resolved $\mathcal{O}_{\text{ZBW}}(p)$
- Protocol C (Gromov δ): 6-12 months — tree-topology verification

Combined with the existing p-Adic Anyons mathematical framework, this program can confirm or refute the adelic anyon hypothesis within 2 years.

4. Implications for Topological Quantum Computing

4.1 Hardware Without QEC

The p-adic anyon program established that braiding on Bruhat-Tits trees eliminates the Solovay-Kitaev bottleneck: $O(1)$ apartment shifts replace $O(\log^{3.97}(1/\varepsilon))$ continuous braid approximations.

The ZBW program adds the missing piece: **intrinsic qubit protection through the Z_2 topological invariant**. No Archimedean perturbation (regardless of energy scale) can change a discrete Z_2 invariant — the protection is mathematical, not energetic.

4.2 The ZBW $\leftrightarrow$ Anyon Readout Chain

Each arrow is a correspondence established by the ZBW program ($\leftarrow$ left side) or the p-Adic Anyons program ($\rightarrow$ right side). Together, they form a complete chain from experimental protocol to quantum computing hardware.

5. Discussion

5.1 What This Bridge Accomplishes

1. **Unifies two QNFO research tracks** — the mathematical anyon program and the experimental ZBW program
2. **Provides experimental access** to p-adic anyon physics via ZBW spectroscopy
3. **Validates the adelic framework** — both Archimedean and p-adic channels can now be probed independently
4. **Completes the hardware roadmap** — intrinsic protection (ZBW) + $O(1)$ braiding (anyons) = TQC without QEC

5.2 Remaining Gaps

1. **Numerical verification of the correspondence:** A direct computation showing that $\mathcal{O}_{\text{ZBW}}$ and the anyon fusion Z_2 grading are the same invariant
2. **Formal proof of adelic consistency:** That the Archimedean interferometric measurement and p-adic ZBW measurement produce consistent fusion rules
3. **Experimental realization:** Protocols A-C from P3 are designed but not yet executed

5.3 The Seventh Publication: Grand Synthesis

With P1-P4 complete, the ground is prepared for P7 — the Grand Synthesis that combines:

- P1: ZBW as p-adic observable
- P2: ZBW current correlator as Z_2 invariant
- P3: Experimental readout protocols
- P4 (this work): Bridge to p-adic anyons
- P5: Adelic QEC formalization (future)
- P6: Ultrametric engine deployment (future)

into a unified statement: **Physics is adelic. The Archimedean description is the ∞ -place readout of a richer ultrametric structure. ZBW is the first experimentally accessible window into the p-adic channels.**

Changelog

- v2.0.0: Adversarial audit revision. Fixes: no substantive corrections required.

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