A One-Way Relativistic Decay-Clock Test of Kinetic Preferred-Frame Time Dilation

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May 30, 2026

Abstract

A recently proposed kinetic route to the Lorentz transform models an elementary particle as a closed lightlike intrinsic motion whose internal cycle is reallocated, under bodily translation, between intrinsic circulation and spatial advance. The construction recovers the usual time-dilation law and the Lorentz boost as a hyperbolic state map, while allowing a physical "special" frame in which the intrinsic tick count and the external time parameter coincide. In such a framework, ordinary closed-path clock tests are not necessarily the most sensitive probes of the special frame, because the leading directional term proportional to $\mathbf{U} \cdot \mathbf{v}$ cancels when the transported clock returns to its starting point. This paper develops a sharper null test: a one-way lifetime anisotropy measurement using unstable relativistic particles as intrinsic clocks. If a laboratory has special-frame velocity $\mathbf{U}$ and an unstable particle beam of speed $u = \beta c$ is sent along direction $\hat{\mathbf{n}}$, the strong preferred-frame reading of the kinetic model predicts, to leading order,

$$\tau_{\mathrm{lab}}(\hat{\mathbf{n}}) \simeq \gamma_u \tau_0 \left(1 + \beta \frac{\mathbf{U} \cdot \hat{\mathbf{n}}}{c}\right),$$

whereas standard special relativity predicts $\tau_{\mathrm{lab}} = \gamma_u \tau_0$ independent of absolute orientation. Antiparallel one-way beams would therefore exhibit a fractional lifetime asymmetry

$$\frac{\tau_+ - \tau_-}{(\tau_+ + \tau_-)/2} \simeq 2\beta \frac{\mathbf{U} \cdot \hat{\mathbf{n}}}{c}.$$

For a candidate $|\mathbf{U}| \sim 369\,\mathrm{km\,s^{-1}}$, as suggested by the CMB dipole scale, the maximal signal for relativistic beams is of order 2.5×10^{-3}, far larger than the fourth-order residuals expected in closed transport tests. The decisive experimental signature is an antiparallel lifetime or decay-length asymmetry with sidereal modulation as the Earth rotates the beam axis relative to the putative preferred-frame vector. The proposal is framed as a falsifiable extension of the kinetic model: a null result would strongly constrain the strong preferred-frame interpretation rather than merely refine an existing relativistic clock test.

1 Motivation

The Lorentz transform is normally presented as a spacetime symmetry: inertial frames in uniform relative motion are physically equivalent, and the invariant interval fixes the transformation between their coordinates. The kinetic programme developed in Ref. [1] begins from a different physical picture. It models the elementary substrate as a closed intrinsic motion whose instantaneous speed is c. Bodily translation cannot be added Galilei-wise to the intrinsic wavefront velocity, because the wavefront speed is already pinned to c. Instead, the intrinsic cycle and the translational advance form a coupled two-channel motion.

The central cycle relation is

$$T^2 = \tau^2 + \left(\frac{x}{c}\right)^2, \tag{1}$$

where τ is the closed-cycle period at true rest, T is the prolonged cycle period under bodily motion, and x is the spatial headway accumulated over the same intrinsic cycle. With $v = x/T$, Eq. (1) gives

$$T = \gamma_v \tau, \qquad \gamma_v = \frac{1}{\sqrt{1 - v^2/c^2}}. \tag{2}$$

Differentiating Eq. (1) and defining a symmetric exchange rate $k(t)$ gives

$$\dot{T} = k\frac{x}{c}, \qquad \dot{x} = kcT. \tag{3}$$

In one spatial dimension this integrates to the hyperbolic state map

$$\begin{bmatrix} x/c \\ T \end{bmatrix}_{t_1} = \begin{bmatrix} \cosh\phi & \sinh\phi \\ \sinh\phi & \cosh\phi \end{bmatrix} \begin{bmatrix} x/c \\ T \end{bmatrix}_{t_0}, \qquad \phi = \int_{t_0}^{t_1} k(t)\,\mathrm{d}t, \tag{4}$$

with $v/c = \tanh\phi$. The standard Lorentz form therefore appears, but as a finite kinetic reallocation between intrinsic cycling and bodily headway, not primarily as a postulated equivalence of frames. The three-dimensional version is not a merely cosmetic extension. With the state vector

$$\mathbf{z} = \begin{bmatrix} T & x/c & y/c & z/c \end{bmatrix}^T, \tag{5}$$

and directional exchange rates k_x, k_y, k_z, the kinetic equation takes the form

$$\dot{\mathbf{z}} = K\mathbf{z}, \qquad K = \begin{bmatrix} 0 & k_x & k_y & k_z \\ k_x & 0 & 0 & 0 \\ k_y & 0 & 0 & 0 \\ k_z & 0 & 0 & 0 \end{bmatrix}. \tag{6}$$

Since $K^3 = \chi^2 K$, with $\chi = (k_x^2 + k_y^2 + k_z^2)^{1/2}$, the exponential closes in a Rodrigues-type form,

$$\exp(\Delta t K) = I_4 + \sinh(\chi\Delta t)\widehat{K} + \big(\cosh(\chi\Delta t) - 1\big)\widehat{K}^2, \qquad \widehat{K} = K/\chi. \tag{7}$$

This is important for the present paper because the kinetic picture is genuinely directional in three-space, even though the final clock-rate expression is a scalar. Appendix C records this 3D generator explicitly and explains the Rodrigues-type closure.

This distinction motivates a direct experimental question. If the intrinsic cycle has a real frame in which it is closed without bodily advance, then a laboratory moving with velocity $\mathbf{U}$ relative to that frame may not be equivalent, at the microscopic bookkeeping level, to a laboratory at true rest. Ordinary Lorentz covariance may still emerge for many measurements, especially closed-path measurements. The important question is whether any observable avoids the cancellations that make the special frame operationally invisible.

2 Why closed clock transport is a poor leading-order probe

Let the laboratory have special-frame velocity $\mathbf{U}$, and let a transported clock have additional laboratory velocity $\mathbf{v}(t)$. In the simplest strong preferred-frame reading, the clock rate is governed by the absolute speed $|\mathbf{U}+\mathbf{v}|$. Comparing the transported clock to an identical ground clock gives the instantaneous rate ratio

$$R(\mathbf{v}) = \frac{\sqrt{1-|\mathbf{U}+\mathbf{v}|^2/c^2}}{\sqrt{1-U^2/c^2}}. \tag{8}$$

For $U/c \ll 1$ and $v/c \ll 1$, writing $q = \mathbf{U}\cdot\mathbf{v}$ and $s = v^2$, expansion gives

$$R(\mathbf{v}) - 1 = -\frac{q}{c^2} - \frac{s}{2c^2} - \frac{1}{c^4}\left(U^2 q + \frac{U^2 s}{2} + \frac{q^2}{2} + \frac{qs}{2} + \frac{s^2}{8}\right) + \mathcal{O}(c^{-6}). \tag{9}$$

The first term,

$$-\frac{\mathbf{U}\cdot\mathbf{v}}{c^2}, \tag{10}$$

is the desired preferred-frame directional term. But for a clock transported around a closed path,

$$\int \mathbf{U}\cdot\mathbf{v}\,\mathrm{d}t = \mathbf{U}\cdot\int \mathrm{d}\mathbf{x} = 0, \tag{11}$$

provided $\mathbf{U}$ is effectively constant over the journey. This is the mathematical reason why Hafele–Keating-like round trips are unlikely to expose the leading term. They are intrinsically closed-clock experiments.

The second term in Eq. (9),

$$-\frac{s}{2c^2} = -\frac{v^2}{2c^2}, \tag{12}$$

behaves differently. It does not vanish for a closed trip. Its time integral is negative whenever the clock is moving relative to the laboratory,

$$\int -\frac{v^2}{2c^2}\,\mathrm{d}t < 0, \tag{13}$$

and is just the familiar second-order kinematic time-dilation contribution. For an aircraft with speed $u = 250\,\mathrm{m\,s^{-1}}$, this fractional rate is approximately $u^2/(2c^2) \simeq 3.5\times10^{-13}$, corresponding to roughly 30 ns over one day. Thus it is not too small in the Hafele–Keating context. Rather, it is not a preferred-frame directional signature. If two eastward and westward flights have equal speed profiles relative to the ground, then $s_E = s_W = u^2$, and the $s/(2c^2)$ contribution is the same in both arms. It therefore cancels in the east-minus-west comparison even though it contributes to each individual flying clock. The distinction is summarized in Appendix A: the $\mathbf{U}\cdot\mathbf{v}$ term vanishes for a closed path by displacement cancellation, whereas the v^2 term survives for each path but cancels only in a matched directional difference.

For eastward and westward aircraft at equal speed u relative to the ground, the local instantaneous difference contains the leading contribution

$$\big(R_E - R_W\big)_{c^{-2}} = -\frac{2u}{c^2}\,\mathbf{U}\cdot\hat{\mathbf{e}}, \tag{14}$$

where $\hat{\mathbf{e}}$ is the local eastward unit vector. Around a complete latitude circle the part due to a fixed cosmic $\mathbf{U}$ integrates away. What remains at leading order is the familiar east–west effect due to the Earth's rotation, not a clean exposure of the cosmic preferred frame. Thus the kinetic model itself suggests that the correct experiment should be one-way, not closed.

3 The one-way decay clock

An unstable particle is a natural clock. Its decay law is governed by an intrinsic proper-time scale τ_0. Unlike an aircraft clock, an unstable particle need not be returned. It is born, propagates one way, and decays. The path is open by construction, so Eq. (11) does not apply.

Consider a laboratory moving with special-frame velocity $\mathbf{U}$. A beam of unstable particles moves through the laboratory with speed $u = \beta c$ along unit direction $\hat{\mathbf{n}}$. The standard prediction is

$$\tau_{\rm lab}^{\rm SR} = \gamma_u \tau_0, \qquad \gamma_u = \frac{1}{\sqrt{1-\beta^2}}, \tag{15}$$

with no dependence on the absolute orientation of the beam.

The strong preferred-frame kinetic hypothesis instead assigns the intrinsic decay rate to the particle's boost relative to the special kinetic frame, and compares it with the boost of the laboratory clock relative to the same frame. For small U/c, and retaining the direction-sensitive term, the laboratory lifetime becomes

$$\boxed{\tau_{\rm lab}(\hat{\mathbf{n}}) \simeq \gamma_u \tau_0 \left(1 + \beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c}\right).} \tag{16}$$

The opposite beam direction gives

$$\tau_{\rm lab}(-\hat{\mathbf{n}}) \simeq \gamma_u \tau_0 \left(1 - \beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c}\right). \tag{17}$$

Therefore an antiparallel pair of one-way beams should exhibit the asymmetry

$$\boxed{A_\tau(\hat{\mathbf{n}}) := \frac{\tau_+ - \tau_-}{(\tau_+ + \tau_-)/2} \simeq 2\beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c}.} \tag{18}$$

This is the central observable of the proposal.

3.1 Equivalent decay-length form

A lifetime anisotropy may also be measured as a decay-length anisotropy. In standard SR, the mean decay length in a straight beamline is

$$L_{\rm SR} = \beta \gamma_u c \tau_0. \tag{19}$$

The kinetic preferred-frame version predicts

$$L_\pm \simeq \beta \gamma_u c \tau_0 \left(1 \pm \beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c}\right), \tag{20}$$

so that

$$\boxed{A_L(\hat{\mathbf{n}}) := \frac{L_+ - L_-}{(L_+ + L_-)/2} \simeq 2\beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c}.} \tag{21}$$

The decay-length form is experimentally attractive because it can be obtained from vertex or decay-position distributions, reducing reliance on distant clock synchronization.

4 Derivation from boost composition

The leading factor in Eq. (16) can be obtained compactly from rapidity composition. Let the laboratory have boost velocity $\mathbf{U}$ relative to the special frame, and let the beam have laboratory velocity $\mathbf{u} = u\hat{\mathbf{n}}$. To first order in U/c, the gamma factor of the particle relative to the special frame obeys

$$\gamma_{\rm abs} = \gamma_U \gamma_u \left(1 + \frac{\mathbf{U}\cdot\mathbf{u}}{c^2}\right) + \mathcal{O}(U^2/c^2). \tag{22}$$

The laboratory clock has special-frame gamma γ_U. If the particle's intrinsic decay is dilated by $\gamma_{\rm abs}$ relative to special-frame time, while the laboratory clock is dilated by γ_U, the lifetime inferred against laboratory ticking is

$$\tau_{\rm lab} = \tau_0 \frac{\gamma_{\rm abs}}{\gamma_U} = \gamma_u \tau_0 \left(1 + \frac{\mathbf{U}\cdot\mathbf{u}}{c^2}\right) + \mathcal{O}(U^2/c^2), \tag{23}$$

which is Eq. (16). A compact derivation for the antiparallel observable is given in Appendix B.

Equation (23) is also the point at which the proposed experiment departs sharply from orthodox special relativity. In standard SR, the laboratory is an inertial frame in which the beam lifetime is simply $\gamma_u\tau_0$; there is no observable $\mathbf{U}$. In the kinetic preferred-frame reading, $\mathbf{U}$ is not merely a coordinate convention but a physical velocity relative to the intrinsic-cycle baseline. The proposed test asks whether this physical velocity leaks into one-way decay-clock measurements.

5 Sidereal signature

A fixed apparatus asymmetry could mimic a constant difference between two beamlines. The discriminating signature is therefore not merely a nonzero A_τ, but modulation with the orientation of the Earth relative to the preferred-frame vector.

Let $\hat{\mathbf{n}}(t)$ be the beam direction expressed in the special-frame basis. Because the Earth rotates,

$$\mathbf{U}\cdot\hat{\mathbf{n}}(t) \tag{24}$$

contains a sidereal component. Thus

$$A_\tau(t) \simeq 2\beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}(t)}{c}. \tag{25}$$

A robust search should fit not only a constant antiparallel asymmetry but also the coefficients of the sidereal sinusoid determined by the laboratory latitude, beam azimuth, and the unknown or hypothesised direction of $\mathbf{U}$. If the CMB dipole direction is adopted as a candidate, the phase is specified a priori; otherwise the experiment can report bounds on the vector components of $\mathbf{U}$ in a celestial frame.

6 Expected scale

The CMB dipole is commonly associated, under the usual kinematic interpretation, with a solar-system velocity of approximately $369\,\mathrm{km\,s^{-1}}$ relative to the CMB rest frame [5, 6]. The present proposal does not require the special kinetic frame to be the CMB frame, but this value supplies a useful benchmark:

$$\frac{U}{c} \approx 1.23\times 10^{-3}. \tag{26}$$

For $\beta \simeq 1$ and favourable alignment,

$$|A_\tau|_{\max} \simeq 2\frac{U}{c} \approx 2.46 \times 10^{-3}. \tag{27}$$

This is a fractional effect of about 0.25%.

For muons, the rest lifetime is about

$$\tau_\mu \simeq 2.197\,\mu\text{s}, \tag{28}$$

with a rest decay length

$$c\tau_\mu \simeq 658.7\,\text{m}. \tag{29}$$

At $\gamma_u = 30$, the standard mean decay time is

$$\gamma_u \tau_\mu \simeq 65.9\,\mu\text{s}, \tag{30}$$

while the maximal antiparallel split predicted by Eq. (18) is approximately

$$\Delta\tau_{+-} \sim 2.46 \times 10^{-3} \times 65.9\,\mu\text{s} \simeq 0.16\,\mu\text{s}. \tag{31}$$

Equivalently, the decay-length split is of order

$$\Delta L_{+-} \sim 2.46 \times 10^{-3} \times \gamma_u c\tau_\mu \simeq 49\,\text{m} \qquad (\gamma_u = 30). \tag{32}$$

The absolute distance is large because the relativistic muon decay length is large. Lower-γ beams reduce facility length at the cost of shorter absolute displacement, but the fractional asymmetry remains of order $2\beta U/c$.

Table 1: Benchmark signal sizes for a candidate $U = 369\,\text{km}\,\text{s}^{-1}$ and favourable beam alignment. The fractional asymmetry is $A \simeq 2\beta U/c$. Muon rest values use $\tau_\mu \simeq 2.197\,\mu\text{s}$.

γ_u	β	$A_{\max}$	Mean muon decay length
3	0.943	2.32×10^{-3}	1.86 km
10	0.995	2.45×10^{-3}	6.55 km
30	0.999	2.46×10^{-3}	19.8 km

The large scale is both an opportunity and a danger for the model. If the strong preferred-frame interpretation is correct at the level expressed in Eq. (16), existing or modestly modified relativistic decay experiments should be capable of seeing the effect. Conversely, a targeted null search would impose a severe bound on the model's preferred-frame leakage.

7 Experimental design

The cleanest arrangement is a simultaneous antiparallel beam experiment.

1. Produce unstable particles in a central source or in two matched sources.
2. Momentum-select two beams of equal speed u into directions $+\hat{\mathbf{n}}$ and $-\hat{\mathbf{n}}$.
3. Measure decay curves or decay-position distributions in the two arms.

4. Reverse magnetic polarities, interchange detector modules, and periodically reverse which physical arm is called "positive" in the analysis.

5. Fit the asymmetry
$$A(t) = \frac{\tau_+(t) - \tau_-(t)}{(\tau_+(t) + \tau_-(t))/2} \tag{33}$$
or the corresponding decay-length asymmetry.

6. Search for a sidereal component of the form
$$A(t) = A_0 + A_c \cos(\omega_\oplus t) + A_s \sin(\omega_\oplus t) + \cdots , \tag{34}$$
where $\omega_\oplus$ is the Earth's sidereal rotation frequency.

The experiment should be designed as a null test. Standard SR predicts no dependence on a cosmic velocity vector after ordinary beam-energy, magnetic, detector, and gravitational effects are modelled. The kinetic preferred-frame model predicts that the coefficient vector extracted from (A_c, A_s) points toward the projection of $\mathbf{U}$ onto the rotating beam basis.

7.1 Systematic controls

The main systematics are mundane but manageable in principle:

- unequal beam momentum distributions, since γ_u directly controls the mean lifetime and decay length;
- charge-dependent detector efficiencies if μ^+ and μ^- or other charge-conjugate beams are compared;
- magnetic-field asymmetries and acceptance differences between the two arms;
- matter interactions, energy loss, and beam scraping along the decay channel;
- clock, trigger, and RF phase offsets if a timing rather than vertex-distribution method is used;
- ordinary environmental drifts that may create day-night but not sidereal signatures.

The strongest mitigation is simultaneous antiparallel operation, frequent reversal of beamline fields, and extraction of the sidereal rather than merely static component. A false static asymmetry can be produced by imperfect apparatus; a sky-locked sidereal vector is much harder to generate accidentally.

8 Relation to existing tests

The Hafele–Keating experiment transported cesium clocks around the world eastward and westward and found results consistent with the combined special- and general-relativistic predictions [3, 4]. Its geometry, however, is a closed or nearly closed clock-transport geometry, precisely the case in which the leading $\mathbf{U} \cdot \mathbf{v}$ term integrates to zero in the preferred-frame expansion.

High-precision optical clocks now reach fractional uncertainties at or below the 10^{-18} scale in clock comparisons [8, 9]. Such clocks are ideal for closed-loop fourth-order anisotropy searches. However, the present proposal is complementary. It avoids the closed-path cancellation by replacing transported material clocks with one-way unstable-particle clocks. In the strong preferred-frame hypothesis, this raises the signal from a suppressed fourth-order residual to a leading first-order anisotropy in U/c.

Existing particle lifetime measurements, especially those using relativistic beams, likely already constrain such an effect indirectly. The point of the present proposal is that a dedicated antiparallel and sidereal analysis would be cleaner than retrospective comparison of unrelated beam experiments. A null result at fractional precision ϵ would bound the projected special-frame speed by

$$|\mathbf{U} \cdot \hat{\mathbf{n}}| \lesssim \frac{\epsilon c}{2\beta}. \tag{35}$$

For example, a null antiparallel asymmetry at 10^{-5} with $\beta \simeq 1$ would imply

$$|\mathbf{U} \cdot \hat{\mathbf{n}}| \lesssim 1.5\,\mathrm{km\,s^{-1}}, \tag{36}$$

for the component sampled by the beam orientation.

9 Interpretation of possible outcomes

There are three qualitatively different outcomes.

Positive sidereal signal. A reproducible antiparallel lifetime or decay-length asymmetry with sidereal phase and amplitude consistent across particle species and beam energies would be a serious challenge to the usual frame-equivalence interpretation of special relativity. It would support the kinetic view that Lorentz dilation is a real reallocation between intrinsic cycling and bodily motion relative to a special physical baseline.

Null result at the 10^{-3} level. A null result well below 10^{-3} would rule out the most direct identification of the preferred kinetic frame with a CMB-scale velocity vector in Eq. (16). This would not automatically refute the entire kinetic construction, because the Lorentz transform may emerge exactly enough to hide $\mathbf{U}$ from this observable. But it would remove the strongest and simplest empirical lever.

High-precision null result. A null result at 10^{-5} or better would force a substantial revision of the strong preferred-frame reading. The model would then need either an exact cancellation mechanism for one-way decay clocks, a different operational definition of laboratory time, or a special frame whose velocity relative to the laboratory is far smaller than CMB-scale expectations.

10 Conclusion

The kinetic route to the Lorentz transform suggests a subtle tension. Time dilation is scalar in its final form, but the kinetic exchange that produces bodily motion is directional. In closed clock transport, the leading directional term $\mathbf{U} \cdot \mathbf{v}$ cancels because the clock returns to its starting point. This explains why aircraft-clock experiments and closed velocity loops are not the sharpest tests of a kinetic preferred frame.

One-way unstable-particle decay avoids the cancellation. The particle is created, travels, and decays; its intrinsic clock is not brought home. Under the strong preferred-frame interpretation, antiparallel relativistic beams should show a fractional lifetime or decay-length asymmetry

$$A \simeq 2\beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c},$$

with sidereal modulation as the Earth turns. For a CMB-scale candidate velocity, the maximal relativistic signal is of order 10^{-3}, much larger than the residuals expected in closed-loop clock tests.

The proposal is deliberately severe. It offers the kinetic model a chance to make a clean, directional, falsifiable prediction. If the signal is found, the frame-symmetric interpretation of special relativity would require deep reconsideration. If the signal is absent, the strong preferred-frame leakage hypothesis is sharply constrained, and the kinetic model must either collapse back to exact Lorentz equivalence or identify a more subtle mechanism by which the special frame remains hidden.

Appendix A Expansion of the transported-clock rate ratio

Starting from

$$R(\mathbf{v}) = \frac{\sqrt{1-|\mathbf{U}+\mathbf{v}|^2/c^2}}{\sqrt{1-U^2/c^2}}, \tag{37}$$

write $q = \mathbf{U}\cdot\mathbf{v}$ and $s = v^2$. Then

$$|\mathbf{U}+\mathbf{v}|^2 = U^2 + 2q + s. \tag{38}$$

Use

$$\sqrt{1-a} = 1 - \frac{a}{2} - \frac{a^2}{8} + \mathcal{O}(a^3), \qquad \frac{1}{\sqrt{1-b}} = 1 + \frac{b}{2} + \frac{3b^2}{8} + \mathcal{O}(b^3). \tag{39}$$

With $a = (U^2+2q+s)/c^2$ and $b = U^2/c^2$, multiplication and cancellation of the pure ground-clock terms gives

$$R(\mathbf{v}) - 1 = -\frac{q}{c^2} - \frac{s}{2c^2} - \frac{1}{c^4}\left(U^2 q + \frac{U^2 s}{2} + \frac{q^2}{2} + \frac{qs}{2} + \frac{s^2}{8}\right) + \mathcal{O}(c^{-6}). \tag{40}$$

For a closed path with constant $\mathbf{U}$, the time integral of the first term is zero:

$$\int -\frac{\mathbf{U}\cdot\mathbf{v}}{c^2}\,\mathrm{d}t = -\frac{\mathbf{U}}{c^2}\cdot\int \mathrm{d}\mathbf{x} = 0. \tag{41}$$

The second term is different:

$$\int -\frac{s}{2c^2}\,\mathrm{d}t = -\frac{1}{2c^2}\int v^2\,\mathrm{d}t, \tag{42}$$

which is not zero for a moving transported clock. It is eliminated only when one forms a matched east-minus-west or plus-minus comparison with identical speed profiles, because v^2 is even under $\mathbf{v} \mapsto -\mathbf{v}$. In contrast, the $\mathbf{U}\cdot\mathbf{v}$ term is odd under reversal but becomes unobservable in a closed route because it is an exact displacement integral.

Appendix B Antiparallel one-way beam derivation

Let $\mathbf{u} = u\hat{\mathbf{n}}$. To first order in U/c, the absolute gamma factor under boost composition is

$$\gamma_{\rm abs} = \gamma_U \gamma_u \left(1 + \frac{\mathbf{U}\cdot\mathbf{u}}{c^2}\right) + \mathcal{O}(U^2/c^2). \tag{43}$$

Dividing by the laboratory clock factor γ_U gives

$$\tau_{\rm lab}(\hat{\mathbf{n}}) = \tau_0 \frac{\gamma_{\rm abs}}{\gamma_U} = \gamma_u \tau_0 \left(1 + \beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c}\right). \tag{44}$$

The result for $-\hat{\mathbf{n}}$ follows by changing the sign of the dot product. Therefore

$$\frac{\tau(\hat{\mathbf{n}}) - \tau(-\hat{\mathbf{n}})}{[\tau(\hat{\mathbf{n}}) + \tau(-\hat{\mathbf{n}})]/2} = 2\beta \frac{\mathbf{U}\cdot\hat{\mathbf{n}}}{c} + \mathcal{O}(U^2/c^2). \tag{45}$$

Appendix C Three-dimensional kinetic generator and Rodrigues-type closure

The 1D kinetic exchange equations are sufficient to recover the usual longitudinal Lorentz boost, but the proposed substrate model is intrinsically three-dimensional. Over a closed intrinsic cycle, let the accumulated bodily displacement be the vector (x, y, z). The cycle relation becomes

$$c^2T^2 = c^2\tau^2 + x^2 + y^2 + z^2. \tag{46}$$

Differentiation gives

$$T\dot{T} = \frac{x\dot{x} + y\dot{y} + z\dot{z}}{c^2}. \tag{47}$$

Introducing directional exchange rates

$$k_x = \frac{\dot{x}}{cT}, \qquad k_y = \frac{\dot{y}}{cT}, \qquad k_z = \frac{\dot{z}}{cT}, \tag{48}$$

one obtains

$$\dot{T} = \frac{k_x x + k_y y + k_z z}{c}, \qquad \dot{x} = k_x cT, \qquad \dot{y} = k_y cT, \qquad \dot{z} = k_z cT. \tag{49}$$

With

$$\mathbf{z} = \begin{bmatrix} T & x/c & y/c & z/c \end{bmatrix}^T, \tag{50}$$

this is

$$\dot{\mathbf{z}} = K\mathbf{z}, \qquad K = \begin{bmatrix} 0 & k_x & k_y & k_z \\ k_x & 0 & 0 & 0 \\ k_y & 0 & 0 & 0 \\ k_z & 0 & 0 & 0 \end{bmatrix}. \tag{51}$$

The generator has the minimal-polynomial closure

$$K^3 = \chi^2 K, \qquad \chi = (k_x^2 + k_y^2 + k_z^2)^{1/2}. \tag{52}$$

For constant rates over a short interval, or for a sliced approximation to time-dependent rates, the exponential therefore evaluates exactly as

$$\exp(\Delta t K) = I_4 + \sinh(\chi\Delta t)\widehat{K} + \big(\cosh(\chi\Delta t) - 1\big)\widehat{K}^2, \qquad \widehat{K} = K/\chi. \tag{53}$$

This is Rodrigues-like in the same algebraic sense that the ordinary rotation formula follows from a cubic closure of a skew-symmetric generator. The difference is that the present generator is symmetric in the time-displacement channels and therefore produces hyperbolic rather than circular functions. This appendix is included to emphasize the conceptual tension exploited in the proposed experiment: the kinetic generator is directional, while the scalar clock-rate formula tends to hide that directionality unless an open, one-way clock process is used.

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