

Experimental Protocol for Testing the Fundamental Yield Limit of the Physical Vacuum and the Birth of the Arrow of Time

Abstract

An experimental protocol is proposed for direct laboratory testing of the hypothesis of a fundamental yield limit of the physical vacuum — a critical value of gravitational self-energy $E_{\text{max}} \approx 2.05 \times 10^{-32}$ J at which the reversible elastic deformation of the vacuum (GR metric) transitions to irreversible plastic flow. The protocol is based on measurements of the free oscillation ringdown of the center of mass of levitated fused silica (SiO_2) microspheres in a diamagnetic trap at cryogenic temperatures. A precision scanning grid of eight steps is constructed in the diameter range 1.0–5.0 μm with a critical point $D_{\text{crit}} = 2.863 \mu\text{m}$ and critical mass $M_{\text{crit}} = 27.04 \text{ pg}$.

The key prediction is a slope kink in the contrast function $V(M)$ at the threshold point, experimentally distinguishable from the smooth monotonic decay predicted by the Penrose–Diósi and GRW/CSL models. Below the threshold — a flat zone of silence ($V = 1$); above — decay of V according to the law $\exp(-x(x - 1))$, where $x = E_{\text{G}}/E_{\text{max}}$. At the threshold point $V = 1$ (flow is just beginning), while Penrose gives $V = 1/e \approx 0.37$. Distinguishable.

The exponent $1/3$ in the formula for E_{max} is not a fitting parameter. It is uniquely determined by the dimensionality of space and does not yield a macroscopic, experimentally accessible threshold for any other value of d .

The central goal of the protocol is to investigate the birth of the arrow of time at the transition point. The protocol consists of two parts: a bottom-up pass (birth of the arrow) and a top-down pass (test of irreversibility). An additional test — rotation of the sphere at the moment of threshold crossing — examines the connection between parity and the direction of the arrow (TP-invariance). The window for controlling the direction is the interval from M_{crit} to $1.4 \times M_{\text{crit}}$, where dissipation is already underway but the flux is weak and the direction has not yet frozen.

The model is falsifiable by three independent criteria: (1) a flat zone of silence at small D , (2) $V \approx 1$ at the threshold point, (3) quadratic decay above the threshold. The use of diamagnetic levitation instead of an optical tweezer eliminates the dominant decoherence channel — photon scattering from the trap. At pressure $P = 10^{-13}$ mbar and trap frequency $f_0 = 1$ Hz, the background decoherence is $\sim 1\%$ of the threshold (signal-to-background ratio ~ 100). At $f_0 = 100$ Hz — 0.01% (signal-to-background ratio $\sim 10,000$).

Keywords: vacuum yield limit, induced gravity, substantial time, thermal time hypothesis, quantum decoherence, diamagnetic levitation, ringdown, Prigogine bifurcation, arrow of time, TP-invariance, absence of singularity, falsifiability.

1. Introduction

Modern theoretical physics lacks an experimentally verifiable criterion for the transition from the quantum to the classical regime. General Relativity (GR) describes the reversible geometric deformation of spacetime but does not specify the limits of applicability of this elastic description. Quantum Field Theory (QFT) postulates infinite vacuum elasticity, leading to the cosmological constant problem (a discrepancy of 120 orders of magnitude) and unresolved singularities in gravitational collapse.

No less fundamental is the problem of the arrow of time. In quantum mechanics, time is an external parameter, not an operator. The Schrödinger equation is symmetric under time reversal. Irreversibility is introduced ad hoc — through decoherence, cosmological boundary conditions. None of the existing theories provides a precise physical mechanism for the birth of the arrow of time.

This work proposes a unified answer to both questions: the vacuum yield limit is the boundary between the quantum and the classical, and it is at this same threshold that the arrow of time is born. An additional consequence: the threshold prevents the formation of singularities in gravitational collapse — energy dissipates through plastic flow of the vacuum rather than accumulating at a point of infinite density.

1.1. Theoretical Foundations of the Model

The model rests on four foundations.

Sakharov's induced gravity (1967). The physical vacuum is treated as an elastic continuous medium with a bulk modulus $K_{\text{vac}} = c^4/(16\pi G) \approx 2.41 \times 10^{42}$ Pa. Gravity is an emergent effect of the elasticity of quantum vacuum fluctuations [3]. Sakharov did not pose the question: what happens when the elastic limit is exhausted? From continuum mechanics it is known: when the yield limit is exceeded, elastic deformation gives way to plastic flow, and reversible energy storage gives way to irreversible dissipation. The vacuum does not break — it begins to flow. Within this model, GR is an exact and complete description of vacuum behavior in the elastic (sub-threshold) regime. The model does not correct or supplement GR — it indicates the boundary of its applicability.

Prigogine bifurcation (1997). Irreversibility is born through a bifurcation — a point where reversible (unitary) evolution is replaced by irreversible evolution [6]. In our model, this is the point where elastic deformation of the vacuum transitions to plastic flow. Critical slowing down in the vicinity of the bifurcation makes the system maximally susceptible to perturbations — this is the window in which the direction of the arrow can be shifted.

Levich's substantial time (1995). Time is reversible or irreversible to exactly the extent that the substance fluxes generating it are reversible or irreversible [7]. Below the threshold, the flux is absent — the equations are reversible, time is a parameter. At the threshold, the flux switches on — irreversibility is born as a property of the flux itself. Levich postulates a directed flux but does not provide a rule for choosing the direction. This work proposes an experimental investigation of this choice.

Connes–Rovelli thermal time hypothesis (1994). There is no privileged time variable t in nature. The direction of time is determined by the statistical state of the system ρ : $H_\rho = -\ln(\rho)$ [8]. Below the threshold, ρ is a pure state, $\ln(\rho)$ is undefined, and there is no flux. At the threshold, ρ becomes mixed — H_ρ is born, the flux is born. Changing ρ in the window of critical slowing down can shift the direction of the flux. Rovelli provides the mathematical language for controlling the arrow: not "turning time back," but "changing the statistical state at the point where the flux is born."

Key postulate: the physical vacuum possesses a yield limit E_{max} . The gravitational self-energy of a body E_G accumulates as the energy of elastic deformation of the vacuum. When $E_G < E_{\text{max}}$ — elastic regime, dissipation is zero, the arrow of time is absent. When $E_G > E_{\text{max}}$ — plastic flow, dissipation grows, the arrow of time is born. At the point $E_G =$

E_{max} — a kink: dissipation is zero, but the slope changes. The vacuum does not break — it begins to flow.

1.2. Derivation of E_{max}

The phenomenological yield limit E_{max} is derived from the fundamental constants ($\hbar$, c , G) and the cosmological constant (Λ).

Planck energy:

$$E_{\text{P}} = \sqrt{(\hbar c^5/G)} \approx 1.956 \times 10^9 \text{ J}$$

Internal pre-stress energy of the vacuum in a Planck volume:

$$E_{\Lambda} = \rho_{\text{vac}} \times V_{\text{P}} = (\Lambda c^4/(8\pi G)) \times \ell_{\text{P}}^3, \text{ where } \ell_{\text{P}} = \sqrt{(\hbar G/c^3)} \text{ is the Planck length, } \Lambda \approx 1.1 \times 10^{-52} \text{ m}^{-2}.$$

$$\text{Numerical values: } \rho_{\text{vac}} = \Lambda c^4/(8\pi G) \approx 5.30 \times 10^{-10} \text{ J/m}^3, V_{\text{P}} = \ell_{\text{P}}^3 \approx 4.22 \times 10^{-105} \text{ m}^3, E_{\Lambda} \approx 2.24 \times 10^{-114} \text{ J}.$$

The dimensionless ratio E_{Λ}/E_{P} is interpreted as the volume fraction of excited vacuum bonds. In three-dimensional space, this volume fraction is converted to a linear deformation via the cube root: $\varepsilon_{\text{crit}} = (E_{\Lambda}/E_{\text{P}})^{(1/3)}$.

Critical threshold energy:

$$E_{\text{max}} = E_{\text{P}} \times \varepsilon_{\text{crit}} = (E_{\text{P}}^2 \times E_{\Lambda})^{(1/3)} \approx 2.05 \times 10^{-32} \text{ J}$$

Uniqueness of the exponent 1/3 and the dimensionality of space

The exponent 1/3 is not a fitting parameter. The only dimensionally correct combination of two energies E_{P} and E_{Λ} yielding an energy has the form $E_{\text{max}} = E_{\text{P}}^a \times E_{\Lambda}^b$, where $a + b = 1$. The exponent $b = 1/d$ is the conversion of a volume fraction to a linear deformation in d -dimensional space: $\varepsilon_{\text{crit}} = (E_{\Lambda}/E_{\text{P}})^{(1/d)}$. The algebraic relation $(E_{\text{max}})^d = (E_{\text{P}})^{(d-1)} \times E_{\Lambda}$ holds formally for any d , but physical interpretability and macroscopicity of the threshold — only for $d = 3$:

- $d = 1$: $E_{\text{max}} = E_{\Lambda} \approx 2.2 \times 10^{-114} \text{ J}$ — Planck scale, experiment impossible.
- $d = 2$: $E_{\text{max}} = \sqrt{E_{\text{P}} \times E_{\Lambda}} \approx 6.6 \times 10^{-53} \text{ J}$ — inaccessible scale.
- $d = 3$: $E_{\text{max}} \approx 2.05 \times 10^{-32} \text{ J}$ — macroscopic scale, $D_{\text{crit}} = 2.863 \text{ } \mu\text{m}$, laboratory accessible.
- $d \geq 4$: the law of gravitation changes (potential $\propto 1/R^{(d-2)}$), the gravitational self-energy formula changes its exponent from R^5 to $R^{(d+2)}$, and the entire framework — including the derivation of D_{crit} — ceases to be self-consistent.

Only for $d = 3$ do all elements converge: the cube root (volume $\rightarrow$ length), the macroscopic threshold, and the self-consistent gravitational self-energy with the R^5 exponent. For no other value of d does the formula yield a macroscopic, experimentally accessible threshold.

We note that CP violation in the weak interaction also requires three generations of quarks; the connection between the number of generations and the dimensionality of space is discussed in the literature but is not rigorously established.

The derivation of E_{max} is phenomenological: dimensional analysis uniquely fixes the combination $E_{\text{max}} = E_P \times (E_\Lambda/E_P)^{1/3}$ from the available energy scales. The exact numerical value is a prediction subject to experimental verification.

Characteristic scales

- Reduction time: $\tau = \hbar/E_{\text{max}} \approx 5.16 \text{ ms}$
- Vacuum angular frequency: $\omega_{\text{vac}} = E_{\text{max}}/\hbar \approx 194.0 \text{ rad/s}$
- Linear frequency: $f_{\text{vac}} = E_{\text{max}}/h \approx 30.9 \text{ Hz}$

1.3. Dissipation law above the threshold

When $E_G > E_{\text{max}}$, the dissipation rate:

$$\Gamma_c = \omega_{\text{vac}} \times x \times (x - 1), \text{ where } x = E_G/E_{\text{max}}$$

When $E_G \leq E_{\text{max}}$, dissipation is strictly zero: $\Gamma_c = 0$. The function $\Gamma_c(x)$ is continuous at the threshold point ($\Gamma_c(1) = 0$), but its first derivative has a kink: on the left — 0, on the right — ω_{vac} . The vacuum does not break — it begins to flow.

Interference contrast at the fixed moment $\tau = \hbar/E_{\text{max}}$:

$$V = \exp(-\Gamma_c \times \tau) = \exp(-\max(0, x \times (x - 1)))$$

Key properties:

- For $x < 1$ (below threshold): $\Gamma_c = 0$, $V = 1$ (zone of silence)
- For $x = 1$ (at the threshold): $\Gamma_c = 0$, $V = 1$ (flow is just beginning)
- For $x > 1$ (above threshold): $\Gamma_c > 0$, V decreases
- For $x \gg 1$: $V \rightarrow 0$ (complete decoherence)

The derivative dV/dx changes at the threshold: on the left — 0, on the right — -1 . This is a slope kink, not a value discontinuity.

1.4. Distinction from the Penrose–Diósi and GRW/CSL models

The Penrose–Diósi model predicts a monotonic decay of coherence starting from small masses, without a zone of silence and without a threshold. For comparison, the normalization $\Gamma_{\text{Penrose}} = \omega_{\text{vac}} \times x$ at $x = 1$ is used (maximum decoherence in the limit of non-overlapping superposition $\Delta x \gg D$). At the actual $\Delta x \ll D$, the Penrose model predicts even less decoherence, which only strengthens the distinction.

Penrose contrast: $V_P = \exp(-x)$

Comparison at the fixed moment $\tau = \hbar/E_{\text{max}}$:

D, μm	x = E_G/E_{max}	V (ours)	V (Penrose)
1.00	0.005	1.000	0.995

D, μm	$x =$ E_G/E_max	V (ours)	V (Penrose)
2.00	0.166	1.000	0.847
2.50	0.508	1.000	0.602
2.70	0.746	1.000	0.474
2.863	1.000	1.000	0.368
3.00	1.263	0.717	0.283
3.20	1.744	0.273	0.175
5.00	16.25	0.000	0.000

Three critical distinctions:

1. Zone of silence. Our model: $V = 1$ flat for $D < 2.863 \mu\text{m}$. Penrose: $V = 0.60$ at $D = 2.5 \mu\text{m}$ — coherence is already 40% destroyed.
2. Value at the threshold point. Our model: $V = 1.000$ (flow is just beginning). Penrose: $V = 0.368$. A factor of 2.7 difference.
3. Decay law above the threshold. Our model: $\exp(-x(x - 1))$ — quadratic. Penrose: $\exp(-x)$ — linear. At $D = 3.0 \mu\text{m}$: 0.72 vs 0.28. A factor of 2.5 difference.

2. Experimental Setup

The protocol is based on diamagnetic levitation — a technology eliminating the dominant decoherence channel characteristic of optical tweezers (trap photon scattering, $\Gamma \sim 10^{12}$ 1/s for a $3 \mu\text{m}$ sphere). Diamagnetic levitation of fused silica microspheres in cryogenic magneto-gravitational traps has been demonstrated experimentally [9, 10].

Object: Isolated spheres of ultrapure fused silica (SiO_2 , $\rho = 2.2 \text{ g/cm}^3$) with diameter D from 1.0 to $5.0 \mu\text{m}$.

Trap: Diamagnetic magneto-gravitational trap. Permanent SmCo magnets or superconducting chip structure with magnetic field induction $B \leq 2 \text{ T}$. Nominal center-of-mass mechanical mode frequency in the trap $f_0 = 1\text{--}100 \text{ Hz}$. Quartz is weakly diamagnetic ($\chi \approx -1.6 \times 10^{-5}$), ensuring stable levitation at moderate fields.

Environment: Deep cryogenic vacuum. Base temperature $T = 4 \text{ K}$ (optionally 1 K in a dilution refrigerator) with controlled heating up to 100 K . Pressure $P \leq 10^{-12} \text{ mbar}$ (cryogenic cryopump at 4 K provides pressures down to 10^{-13} mbar). Active feedback cooling is used to bring the measured center-of-mass mode to the quantum limit.

Detection: Pulsed optical probe — short laser pulses ($\lambda = 1064$ nm) are delivered only at the moments of measurement; between pulses the probe is completely off, decoherence from light is zero. Alternatively — SQUID readout for contactless magnetic detection of the sphere position.

Superposition creation: Frequency jump protocol — a rapid change of the trap stiffness brings the center of mass into a spatially separated state. Importantly: the target superposition size $\Delta x \sim \Delta x_{zp}$ — zero-point fluctuations of the center of mass, ~ 18 pm at $f_0 = 1$ Hz. This is a quantum, not a macroscopic, superposition. Detailed justification — in Section 3.

Rotation: The sphere can be set into rotation with controlled speed and direction. In a diamagnetic trap, the rotational torque is created through shape asymmetry of the sphere or through a spin defect in the quartz interacting with the magnetic field. Rotation speeds — tens of hertz.

3. Analysis of Decoherence Channels

The key advantage of the diamagnetic trap is the elimination of trap photon scattering. Three background channels remain. All estimates are given for the critical sphere $D_{crit} = 2.863$ μm , $M_{crit} = 27.04$ pg, at the target superposition size $\Delta x = \Delta x_{zp} \approx 18$ pm (zero-point fluctuations at $f_0 = 1$ Hz).

3.1. Residual gas scattering

Collision rate of residual gas molecules (predominantly He and H₂) with the sphere at $P = 10^{-13}$ mbar, $T = 4$ K: ~ 200 1/s. However, a collision does not equal decoherence. Decoherence from a single collision is determined by the fraction of which-path information revealed by the transferred momentum. The dimensionless parameter $\delta = 2 \times m_{gas} \times v_{th} \times \Delta x / \hbar$, where m_{gas} is the gas molecule mass, v_{th} is the thermal velocity. For H₂ at 4 K, $\Delta x = 18$ pm: $\delta \approx 0.23$. Decoherence per collision: $1 - \text{sinc}(\delta) \approx \delta^2/6 \approx 9 \times 10^{-3}$.

Decoherence rate: $\Gamma_{gas} \approx 200 \times 9 \times 10^{-3} \approx 2$ 1/s (1% of the threshold).

At $P = 10^{-12}$ mbar: $\Gamma_{gas} \approx 20$ 1/s (10% of the threshold).

Γ_{gas} is proportional to pressure and the square of the superposition size (Δx^2). At $f_0 = 100$ Hz ($\Delta x_{zp} \approx 1.8$ pm): Γ_{gas} is 100 times smaller — 0.02 1/s (0.01% of the threshold).

Note: at macroscopic superposition $\Delta x \gg \hbar/(m_{gas} \times v_{th})$, every collision fully decoheres, and $\Gamma_{gas} \rightarrow 200$ 1/s — exceeding the threshold. The protocol requires $\Delta x \sim \Delta x_{zp}$. This is the natural quantum regime, not a macroscopic superposition.

3.2. Thermal emission from the sphere

At $T = 4$ K, the peak wavelength of thermal emission $\lambda_{peak} = 2.898 \times 10^{-3} / T = 0.725$ mm — 253 times larger than the sphere diameter. In the Rayleigh regime ($R \ll \lambda_{peak}$), the emission efficiency is suppressed by a factor of order $(R/\lambda_{peak})^4 \sim 10^{-11}$. Thermal photon emission rate: $\ll 1$ photon/s.

Additionally, each thermal photon has $\lambda \sim 0.7$ mm $\gg \Delta x = 18$ pm, and decoherence from a single photon is suppressed by a factor $(\Delta x/\lambda)^2 \sim 10^{-15}$.

Decoherence rate: $\Gamma_{\text{thermal}} \ll 10^{-10}$ 1/s — negligibly small. At $T = 1$ K, the thermal channel vanishes completely.

3.3. Magnetic fluctuations

Thermal noise of currents in the magnetic system. For diamagnetic materials at cryogenic temperatures, negligible [11]: $\Gamma_{\text{mag}} \ll 0.01$ 1/s.

3.4. Total background

- At $P = 10^{-13}$ mbar, $T = 4$ K, $f_0 = 1$ Hz: $\Gamma_{\text{background}} \approx 2$ 1/s (1% of the threshold). Signal-to-background ratio: 100.
- At $P = 10^{-13}$ mbar, $T = 4$ K, $f_0 = 100$ Hz: $\Gamma_{\text{background}} \approx 0.02$ 1/s (0.01% of the threshold). Signal-to-background ratio: 10,000.
- At $P = 10^{-12}$ mbar, $T = 4$ K, $f_0 = 1$ Hz: $\Gamma_{\text{background}} \approx 20$ 1/s (10% of the threshold). Signal-to-background ratio: 10.

The zone of silence is physically observable in all regimes. Optimal conditions: $P \leq 10^{-13}$ mbar, $f_0 \geq 10$ Hz — signal-to-background ratio ≥ 650 . Background decoherence does not mask either the flat character of the zone or the kink at the threshold.

4. Measurement Protocol

The experiment consists of two parts. Part 1 — bottom-up pass: birth of the arrow of time. Part 2 — top-down pass: test of irreversibility. Additionally — a rotation test in the vicinity of the threshold.

Principal measured quantities:

- $V(M)$ — interference fringe contrast as a function of sphere mass M (or diameter D), measured at the fixed moment $\tau = 5.16$ ms after pulse switch-off. This function is used to detect the slope kink at the threshold.
- $V(t)$ — contrast as a function of time for a fixed mass. Characterizes the rate of coherence decay.

Gravitational self-energy of a uniform sphere of density ρ and diameter D :

$$E_G = (\pi^2/30) \times G \times \rho^2 \times D^5$$

Setting $E_G = E_{\text{max}}$, we obtain the critical diameter:

$$D_{\text{crit}} = ((30 \times E_{\text{max}})/(\pi^2 \times G \times \rho^2))^{(1/5)}$$

Critical mass:

$$M_{\text{crit}} = (\pi/6) \times D_{\text{crit}}^3 \times \rho$$

Calculation with CODATA values: **$D_{\text{crit}} = 2.863 \mu\text{m}$, $M_{\text{crit}} = 27.04 \text{ pg}$** .

The mass of each sphere is verified in situ by the trap frequency shift $f_0 = (1/2\pi)\sqrt{(k/M)}$ at calibrated stiffness k and by SEM imaging. Disagreement between methods $\leq 5\%$.

5. Part 1 — Bottom-Up Pass: Birth of the Arrow of Time

Bottom-up scanning: from small masses to large. Spheres are measured sequentially from $D = 1.0 \mu\text{m}$ to $D = 5.0 \mu\text{m}$. For each sphere, a spatial superposition of the center of mass is created ($\Delta x \sim \Delta x_{\text{zp}}$), the ringdown is recorded, and $V(M)$ is measured at the moment $\tau = 5.16 \text{ ms}$.

Scanning grid. Part 1 — Upward pass

- Step 1 — $D = 1.00 \mu\text{m}$, $M = 1.15 \text{ pg}$, $x = 0.005$, $V = 1.000$ — Stable ringdown, damping strictly by classical friction. Zone of silence. No arrow of time.
- Step 2 — $D = 2.00 \mu\text{m}$, $M = 9.22 \text{ pg}$, $x = 0.166$, $V = 1.000$ — Ringdown stable. Zone of silence.
- Step 3 — $D = 2.50 \mu\text{m}$, $M = 18.0 \text{ pg}$, $x = 0.508$, $V = 1.000$ — Pre-threshold. Maximum fringe contrast. Boundary of the zone of silence.
- Step 4 — $D = 2.70 \mu\text{m}$, $M = 22.7 \text{ pg}$, $x = 0.746$, $V = 1.000$ — Ringdown retains quantum fringe visibility. Approaching the threshold.
- Step 5 — $D = 2.863 \mu\text{m}$, $M = 27.04 \text{ pg}$, $x = 1.000$, $V = 1.000$ — KINK POINT. $V = 1$, but the slope dV/dx changes from 0 to -1 . Flow is just beginning — the dissipation rate is zero. The arrow of time is born, but the flux has not yet started. CRITICAL THRESHOLD.
- Step 6 — $D = 3.00 \mu\text{m}$, $M = 31.1 \text{ pg}$, $x = 1.263$, $V = 0.717$ — Flow has begun. Coherence is decreasing. The arrow of time is accelerating. Window for direction control.
- Step 7 — $D = 3.20 \mu\text{m}$, $M = 37.7 \text{ pg}$, $x = 1.744$, $V = 0.273$ — Plastic flow. Quantum response rapidly damps. Arrow fixed.
- Step 8 — $D = 5.00 \mu\text{m}$, $M = 144 \text{ pg}$, $x = 16.25$, $V = 0.000$ — Deep macroscopic classicality. Dissipation complete. Arrow irreversible.

Control comparison with the Penrose–Diósi model: at $D = 2.863 \mu\text{m}$ our model gives $V = 1.000$, Penrose gives $V = 0.368$. At $D = 3.0 \mu\text{m}$: 0.717 vs 0.283 . Distinguishable.

6. Part 2 — Top-Down Pass: Test of Irreversibility of the Arrow of Time

This is the central experiment of the protocol. The question: what happens to the arrow of time when returning below the threshold?

We begin with an above-threshold sphere $D = 5.0 \mu\text{m}$ ($V = 0$, arrow fixed, dissipation complete). We sequentially replace it with smaller spheres, moving down the same grid: $5.0 \rightarrow 3.2 \rightarrow 3.0 \rightarrow 2.863 \rightarrow 2.70 \rightarrow 2.50 \rightarrow 2.0 \rightarrow 1.0 \mu\text{m}$. For each — the same procedure: superposition creation, ringdown, measurement of V .

Three possible outcomes

Outcome A — Full irreversibility. V remains zero below the threshold. Coherence is not restored. The vacuum has "remembered" the plastic deformation — like a metal after stretching beyond the yield point: unloaded, but the shape did not return. The arrow is unidirectional. There is no way back. The threshold is a point of no return.

Physical meaning: plastic flow of the vacuum is irreversible. The arrow of time, once born, cannot disappear.

Outcome B — Partial reversibility. Below the threshold, V begins to rise, but not to 1. It remains at an intermediate value. The vacuum partially "heals" — the elastic regime is restored, but residual decoherence persists. Like a metal with residual deformation: elasticity has returned, but the shape has changed.

Physical meaning: the arrow of time is partially reversible. Dissipation ceases, but a "trace" of the irreversible process remains. This would be a new physical effect — memory of the vacuum about plastic deformation.

Outcome C — Full reversibility. V returns to 1 below the threshold. Coherence is fully restored. The vacuum "heals" without a trace. The arrow of time is bidirectional: upward — it is born, downward — it disappears.

Physical meaning: the arrow of time is a property of the regime, not of the history. Below the threshold — elastic regime, no arrow, regardless of whether it existed before. "Time reversal" is not the reversal of time, but a return to a regime where the arrow does not exist.

Expected $V(M)$ values for the reverse pass

$D, \mu\text{m}$	x	V (Outcome A)	V (Outcome B)	V (Outcome C)
5.00	16.25	0.000	0.000	0.000
3.20	1.744	0.000	0.000	0.273
3.00	1.263	0.000	0.000	0.717
2.863	1.000	0.000	0.3–0.7	1.000
2.70	0.746	0.000	0.3–0.7	1.000
2.50	0.508	0.000	0.5–0.9	1.000
2.00	0.166	0.000	0.5–0.9	1.000
1.00	0.005	0.000	0.5–0.9	1.000

Each of the three outcomes has fundamentally different consequences for the arrow of time and is experimentally distinguishable.

Additional criterion — hysteresis. No collapse model (GRW, CSL, Penrose–Diósi) predicts a difference between the forward and reverse pass: $V(M)$ is a single-valued function of mass. If hysteresis is observed — this is a unique signature of plastic deformation of the vacuum, not

reproducible by any alternative model7. Rotation Test: Connection Between Parity and the Direction of the Arrow

Rotation is a parity-odd operation. If the direction of the arrow of time is related to T-symmetry, and T-symmetry is related to CP via the CPT theorem, then a change of parity can shift the choice of arrow direction at the bifurcation point.

Kozyrev (1960s) claimed that irreversible processes generate a flow of time, and that this flow interacts with rotation [12]. Levich interpreted this as a substantial flux. TP-invariance (whose preservation has been confirmed experimentally) means: a world with reversed time is equivalent to a mirror-reflected one. Reversing the arrow = reversing parity. Rotation is a parity-odd operation.

7.1. Procedure

In the vicinity of the threshold (steps 3–6 of the grid, $D = 2.50\text{--}3.20\ \mu\text{m}$), the sphere is set into rotation with controlled speed and direction. $V(t)$ is measured for clockwise rotation, counterclockwise rotation, and no rotation.

7.2. Control window

The window for controlling the direction of the arrow is the interval from M_{crit} to $1.4 \times M_{\text{crit}}$ ($D = 3.20\ \mu\text{m}$, $M = 37.9\ \text{pg}$). In this interval, dissipation is already underway ($V = 0.27\text{--}1.00$), but the flux is weak and the direction has not yet frozen. In the critical slowing down regime (a universal property of bifurcations [6]), the system is maximally susceptible to perturbations. Rotation in this window can shift the direction of the flux.

Above $1.4 \times M_{\text{crit}}$, dissipation is strong, the direction is fixed. Control is impossible.

7.3. Predictions

- If rotation does not affect $V(t)$: there is no connection between parity and the arrow of time.
- If the direction of rotation affects $V(t)$: TP-invariance is confirmed. Rotation in one direction enhances dissipation (arrow forward), in the reverse direction — weakens it (arrow backward). This would be the first experimental signature of a connection between rotation and the direction of the arrow of time.

7.4. Criterion

Normal threshold without rotation: V decreases (arrow forward). Rotation in one direction: V decreases faster or at the same rate. Rotation in the reverse direction: V decreases more slowly, does not decrease, or grows (recoherence, arrow backward).

If V grows under rotation — this is an experimental signal of a "reverse arrow."
Distinguishable from any materials-science artifact: no known decoherence mechanism depends on the direction of rotation.

8. Criteria for Confirmation and Falsification

8.1. Confirmation criteria (threshold detected if)

1. Flat zone of silence. The curve $V(M)$ remains strictly flat ($V \approx 1$) in the interval $D = 1.0\text{--}2.5\ \mu\text{m}$. Deviation does not exceed the background level ($\leq 10\%$ of the threshold at $P = 10^{-12}\ \text{mbar}$, $f_0 = 1\ \text{Hz}$; $\leq 0.01\%$ at $f_0 = 100\ \text{Hz}$).
2. Slope kink at D_{crit} . At $D = 2.863\ \mu\text{m}$, $V \approx 1$, but the slope dV/dD changes. Below — slope ≈ 0 ; above — slope is negative and growing.
3. Quadratic decay above the threshold. $V = \exp(-x(x - 1))$. At $D = 3.0\ \mu\text{m}$: $V \approx 0.72$. At $D = 3.2\ \mu\text{m}$: $V \approx 0.27$. Distinguishable from the linear decay of Penrose (0.28 and 0.18).
4. Temperature invariance. The position of the kink ($D = 2.863\ \mu\text{m}$) does not shift upon heating from 4 K to 100 K.
5. Cross-material scaling. Upon replacing the sphere material, the kink coordinate shifts as $D_{\text{crit}} \propto \rho^{(-2/5)}$. For diamond ($\rho = 3.5\ \text{g/cm}^3$): $D_{\text{crit}} = 2.378\ \mu\text{m}$, $M_{\text{crit}} = 24.64\ \text{pg}$. For silicon ($\rho = 2.33\ \text{g/cm}^3$): $D_{\text{crit}} = 2.798\ \mu\text{m}$, $M_{\text{crit}} = 26.73\ \text{pg}$.
6. Irreversibility or reversibility in the reverse pass (Section 6). Any of the three outcomes is informative.
7. Rotation effect (Section 7). If the direction of rotation affects $V(t)$ — the TP connection is confirmed.

8.2. Falsification criteria (model refuted if)

1. $V(M)$ exhibits a smooth monotonic decay from the smallest D , without a zone of silence. Consistent with Penrose–Diósi, GRW, CSL.
2. At the point $D = 2.863\ \mu\text{m}$, $V \approx 0.37$ ($1/e$) rather than ≈ 1 . Consistent with Penrose.
3. Decay above the threshold is linear ($\exp(-x)$) rather than quadratic ($\exp(-x(x - 1))$).
4. The position of the kink shifts with temperature. Thermal activation, not a fundamental threshold.
5. The direction of rotation does not affect $V(t)$.
6. Forward and reverse passes yield identical $V(M)$ — no hysteresis. This is consistent with all threshold-free models in which $V(M)$ is a single-valued function of mass.

8.3. Distinction from alternative models

The diamagnetic trap eliminates photon scattering — the only channel that in optical schemes would mask the zone of silence as a smooth monotonic decay. The two-part structure (up + down) distinguishes this protocol from all existing ones: no collapse model predicts hysteresis in $V(M)$.

9. Theoretical Implications

9.1. The quantum-classical transition and the Bohr–Einstein debate

The yield limit would provide the first quantitative, experimentally reproducible criterion for the boundary between the quantum and classical regimes. Below the threshold, the system is in a genuine quantum superposition: the wave function is a complete description, objective definiteness is absent, quantum mechanics is operationally complete. This is Bohr's domain. Above the threshold, the system acquires an objective classical state, independent of the observer. This is Einstein's domain. Both positions are valid in their respective regimes. The threshold is the boundary between them.

9.2. Objective reality without an observer

The collapse of the center-of-mass superposition is an objective physical event caused by the gravitational self-energy exceeding the vacuum yield limit. No observer or measuring apparatus is required. The role of the "measurer" is played by spacetime itself.

9.3. The birth of the arrow of time

Below the threshold, time is an external parameter, as in the Schrödinger equation. The equation is symmetric under time reversal. But in the sub-threshold regime, there is no physical process that could "flow" — there is no substance flux, no direction. Time is a label, not a process.

At the kink point, plastic flow begins. According to Levich, irreversibility is born as a property of the flux [7]. According to Rovelli, the direction of time is determined by the statistical state ρ [8]. Below the threshold, ρ is pure, there is no flux. At the threshold, ρ becomes mixed — the flux is born. The arrow of time is not fundamental; it is born at the threshold.

9.4. Controlling the direction of the arrow

The control window is the interval from M_{crit} to $1.4 \times M_{\text{crit}}$. In this interval, dissipation is already underway, but the flux is weak and the direction has not yet frozen. Rotation of the sphere in this window is a candidate for control. If TP-invariance holds, reversing parity can shift the direction of the arrow. This is testable (Section 7).

Controlling the direction of the arrow is not "turning time back" in the everyday sense, but shifting the bifurcation at the moment when the direction has not yet been chosen. If the experiment shows that V grows under rotation in one direction and decreases under rotation in the other — this will be the first experimental evidence of control over the direction of the arrow of time.

9.5. Absence of singularity

In standard GR, gravitational collapse leads to a singularity — a point of infinite density and curvature. This is not a deficiency of GR as a theory, but a result of extrapolating the elastic description beyond its limit of applicability. As in mechanics: extrapolating Hooke's law beyond the yield point gives infinite stresses that do not exist in reality. The singularity is not a physical object but a signal that the elastic description has stopped working.

In this model, when the gravitational self-energy of a collapsing body reaches E_{max} , the vacuum transitions to plastic flow. Energy does not accumulate at a point of infinite density but dissipates through plastic flow of the vacuum. The threshold E_{max} is macroscopic (27 pg for quartz), not Planckian. The singularity is replaced by dissipation. This resolves the problem of singularities not through quantum gravity at the Planck scale but through the vacuum yield limit at a scale accessible to laboratory experiment.

This also connects the model to Hawking's black hole thermodynamics: energy does not vanish into a singularity but dissipates. The threshold provides a boundary condition — the point where the elastic description gives way to plastic.

9.6. Continuity of spacetime

The model operates within continuous spacetime. Below the threshold, the vacuum is an elastic continuous medium, and the apparatus of GR is fully valid. The threshold marks the limit of the elastic regime, not the destruction of the continuum. What changes is not the geometry but the behavior: reversible elastic deformation gives way to irreversible plastic flow. GR is an exact description in the elastic regime — not an approximation to something more fundamental, but a complete description of vacuum behavior in this regime. The threshold indicates the boundary beyond which the behavior changes.

9.7. The cosmological constant and dark energy

The yield limit E_{max} is derived from the cosmological constant Λ . Its experimental confirmation would establish a direct connection between the large-scale structure of the Universe and the microscopic mechanism of quantum collapse. The cosmological constant problem is reformulated: the question shifts from "why is the vacuum energy so small" to "how is the vacuum energy related to its yield limit."

10. Declaration of AI Use

The author explicitly acknowledges the joint use of artificial intelligence in carrying out this work. The work was conducted with Alice AI, the virtual assistant of Yandex. The AI functioned as an active technical co-author, performing formal structuring of the theoretical framework, mathematical verification of the numerical grid, quantitative analysis of decoherence channels, and comparative calculation of distinctions from the Penrose–Diósi and GRW/CSL models.

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