Why Antimatter Lost and Matter Won

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The universe should have destroyed itself before it made anything worth destroying. This is not a philosophical position. It follows directly from the most precisely tested theory in the history of science, applied to the conditions that existed in the first microsecond after the Big Bang. Matter and antimatter should have been produced in equal quantities. Equal quantities annihilate completely. What remains is radiation. A cold, expanding sea of light with no surfaces, no atoms, no time for anything to accumulate into structure. The equations are unambiguous. And yet here we are, made of atoms, asking why the equations were wrong.

They were not wrong. Something broke the symmetry. Something in the first fraction of a second produced slightly more matter than antimatter, one extra particle per ten billion pairs, and that surplus is the reason everything exists. The question of what that something was is one of the genuinely open problems in physics. Not open in the way that some problems are open, where the answer is suspected and the confirmation is pending. Open the way a room is open when you do not know what is inside it.

Dirac's Unwanted Prediction

Antimatter was not discovered. It was derived. In 1928, Paul Dirac wrote down an equation reconciling quantum mechanics with special relativity. The equation described the electron with extraordinary precision, predicting its spin, its energy levels, its behavior at relativistic speeds. It also had four solutions. Two described the electron. Two described something else: a particle with identical mass and opposite charge. A mirror electron that nobody had ever seen.

Physicists tried to explain this away. Dirac himself initially suggested the extra solutions might correspond to protons, which were known to exist. The mathematics did not support this. Protons are nearly two thousand times heavier than electrons, and the equation was describing something with exactly the electron's mass. The positive solutions were pointing at something genuinely new, and the physics community spent several years hoping the problem would resolve itself.

It did not resolve itself. In 1932, Carl Anderson at Caltech was studying cosmic ray tracks in a cloud chamber when a particle left a trail that curved the wrong way under the applied magnetic field. Positive charge. Electron mass. He spent nearly a year cross-checking before publishing. The paper used the phrase "with due reserve in interpretation." He named the particle a positron.

The theoretical prediction and the experimental discovery arrived from completely different directions and met at the same object. Every known particle, it followed, has an antiparticle of equal mass and opposite charge. For the photon, the particle and antiparticle are identical. For everything else, two versions exist. And when they meet, both disappear.

The positron was not found. It was derived from an equation, and then confirmed by a photograph of a curved line in a cloud chamber. Theory and experiment arriving at the same doorstep from opposite directions.

The Arithmetic of the Surplus

The matter surplus left after the Big Bang annihilation is quantified by the baryon-to-photon ratio, written as η. Its measured value is:

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Six baryons for every ten billion photons. One surviving matter particle for every billion matter-antimatter pairs that annihilated. The photons are the record of the destruction. Each one carries the energy of particles that ceased to exist in the first second. Those photons, expanded and cooled across nearly fourteen billion years of cosmic expansion, are the cosmic microwave background, the faint thermal radiation that fills the sky in every direction at 2.725 degrees above absolute zero.

What makes η particularly significant is that it has been measured by two completely independent methods, using different physics from different epochs in cosmic history.

The first measurement comes from Big Bang Nucleosynthesis. Between roughly one second and twenty minutes after the Big Bang, the universe was hot and dense enough for protons and neutrons to bind into light nuclei. The rates of those reactions, and the resulting abundances of hydrogen, helium, deuterium, and lithium, depend sensitively on how many baryons were present per photon. Measuring the primordial abundances of these elements in the oldest, least-processed regions of the universe pins down η independently of anything else.[1]

The second measurement comes from the cosmic microwave background. Sound waves propagated through the photon-baryon plasma for 380,000 years before recombination froze them in place. The pattern of acoustic peaks in the CMB power spectrum encodes the baryon density at that epoch. More baryons produce a specific asymmetry between compression and rarefaction peaks. Reading that asymmetry gives an independent value of η.

Both methods return the same number. The agreement is not guaranteed by the model. It is a confirmation that the model is internally consistent across 380,000 years of cosmic history.

Sakharov's Three Conditions

In 1967, Andrei Sakharov published a three-page paper in a Soviet physics journal identifying the necessary conditions for any physical mechanism that could generate the baryon asymmetry from a symmetric beginning. He named three requirements, all of which must be satisfied simultaneously.[2]

The first is baryon number violation. If every physical process conserves the total count of baryons minus antibaryons, a universe beginning with zero net baryon number will always have zero net baryon number. There must exist interactions capable of changing this count.

The second is C and CP symmetry violation. Charge conjugation symmetry (C) relates a particle to its antiparticle. CP symmetry combines charge conjugation with spatial reflection. If both are exact symmetries, every process favoring matter has an equally probable mirror process favoring antimatter. The net result is always zero. The laws of physics must genuinely distinguish between matter and antimatter.

The third is departure from thermal equilibrium. In perfect thermal equilibrium, forward and reverse reactions proceed at the same rate. Any asymmetry produced by a forward process is immediately erased by its reverse. A window of disequilibrium is required for the asymmetry to build and persist.

Sakharov identified these conditions before grand unified theories existed, before the sphaleron was understood, before CP violation had been measured in anything other than neutral kaons. He was writing down what any explanation must include, not what the explanation was. More than fifty years later, the conditions are established. The mechanism is not.

Why the Standard Model Cannot Be the Answer

The Standard Model of particle physics satisfies all three Sakharov conditions in principle. Baryon number is violated by electroweak sphaleron processes. CP violation exists in the Cabibbo-Kobayashi-Maskawa (CKM) matrix through a complex phase. The early universe provided out-of-equilibrium conditions during phase transitions. The checklist clears.

The problem is quantitative. The CP violation in the CKM matrix is suppressed by a factor of approximately 10^{-19} relative to what is required to generate the observed η.[3] The suppression factor arises from the structure of the CKM matrix itself:

$$\epsilon_{\rm CP} \sim \frac{1}{T_c^{12}} \prod_{i>j,\, u,c,t}(m_i^2 - m_j^2) \prod_{i>j,\, d,s,b}(m_i^2 - m_j^2) \cdot J_{\rm CP} \sim 10^{-19}$$

where $J_{\rm CP}$ is the Jarlskog invariant encoding the CP-violating phase and T_c is the critical temperature of the electroweak phase transition. The result is nineteen orders of magnitude below the required asymmetry. This is not a rounding error or an uncertain parameter. It is a structural feature of the Standard Model that cannot be adjusted within the existing framework.

The electroweak phase transition presents a second problem. Electroweak baryogenesis requires a strongly first-order phase transition to provide the sharp departure from equilibrium that Sakharov's third condition demands. With a Higgs boson mass of 125 GeV, confirmed at the LHC in 2012, the electroweak transition is a smooth crossover. Not first-order. The dynamics are insufficient.

The Standard Model can describe the shape of the solution. It cannot provide the solution.

The Sphaleron: A Topological Engine

The electroweak sphaleron is not a particle. It is a field configuration, an extended arrangement of the electroweak gauge fields that sits at the saddle point of an energy barrier between topologically distinct vacuum states of the theory.

The vacuum states of the electroweak field are not all equivalent. They form a discrete sequence of topological classes, labeled by the Chern-Simons number $N_{\rm CS}$. Transitions between adjacent classes change $N_{\rm CS}$ by one unit and, through the chiral anomaly, change baryon number by exactly three:[4]

$$\Delta B = \Delta L = N_f \cdot \Delta N_{\rm CS} = 3$$

where $N_f = 3$ is the number of fermion generations. The sphaleron is the field configuration at the top of the barrier between adjacent vacua. Its energy is approximately 8 to 10 TeV.

At low temperatures, crossing this barrier requires quantum tunneling, which is exponentially suppressed. Baryon number is effectively conserved today. At temperatures above roughly 100 GeV, thermal fluctuations are energetic enough to drive the field over the barrier classically. Sphaleron transitions were active continuously in the early universe, changing baryon number at a rate:

$$\Gamma_{\rm sph} \propto \alpha_W^5 T^4$$

where α_W is the weak coupling constant and T is temperature. They are the physical pathway through which any lepton asymmetry can be converted into baryon number, and any baryon asymmetry generated in a CP-asymmetric environment can be frozen into the broken-symmetry phase.

Three Proposed Mechanisms

Electroweak Baryogenesis

As the universe cooled through the electroweak phase transition, bubbles of broken electroweak symmetry nucleated and expanded through the plasma. At the bubble wall, CP-violating interactions caused quarks and antiquarks to scatter differently, generating a slight excess of left-handed fermions in the symmetric phase ahead of the wall. Sphalerons, active in the symmetric phase, converted this chiral asymmetry into a net baryon excess. The asymmetry was swept into the bubble and frozen as the wall advanced.

The mechanism is testable at collider energies and makes specific predictions about the Higgs sector and CP-violating operators. The LHC has been searching for the required new physics for fifteen years. It has not found it. The parameter space in which the mechanism works is considerably narrower than it was in 2010.

Leptogenesis

Heavy right-handed Majorana neutrinos, with masses M_1 potentially between 10^9 and 10^{16} GeV, decayed out of thermal equilibrium in the very early universe. The decays were CP-asymmetric, producing slightly more leptons than antileptons. The CP asymmetry in the decay of the lightest heavy neutrino N_1 is:[5]

$$\epsilon_1 = -\frac{3}{8\pi} \sum_{i \neq 1} \frac{{\rm Im}\left[(Y_\nu Y_\nu^\dagger)_{1i}^2\right]}{(Y_\nu Y_\nu^\dagger)_{11}} \frac{M_1}{M_i}$$

where Y_ν is the neutrino Yukawa coupling matrix. Sphaleron processes then converted the lepton asymmetry into the baryon asymmetry, with the conversion fraction given by $a_{\rm sph} = 28/79$.

Leptogenesis connects naturally to the seesaw mechanism for neutrino masses. The same right-handed neutrinos responsible for the matter asymmetry suppress ordinary neutrino masses through:

$$m_\nu \simeq \frac{(Y_\nu v)^2}{M_1}$$

where $v \approx 246$ GeV is the Higgs vacuum expectation value. One mechanism. Two consequences. The matter surplus and the lightness of neutrinos, both following from the same particles.

Leptogenesis does two things simultaneously: it explains why matter exists, and it explains why neutrino masses are so extraordinarily small. The same particles are responsible for both.

The Affleck-Dine Mechanism

In supersymmetric theories, scalar fields can occupy flat directions in the potential where the energy does not change with field value. These flat directions can carry baryon or lepton number. After inflation, CP-violating terms in the scalar potential cause the condensate to rotate in field space, accumulating a net charge. When the condensate decays, the asymmetry transfers to ordinary particles.

The mechanism requires supersymmetry, which has not been confirmed experimentally. Superpartner searches at the LHC have returned null results across the most accessible parameter space. The Affleck-Dine mechanism remains viable but contingent on a framework whose existence is unestablished.

Recent Experimental Signals

CP Violation in Baryons: LHCb 2025

In March 2025, the LHCb collaboration published the first observation of CP violation in baryon decays. The Lambda-b baryon (Λ_b^0, quark content udb) was found to decay into its final state at a rate measurably different from its antimatter counterpart:[6]

$$A_{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$$

The result differs from zero by 5.2 standard deviations. CP violation had previously been established only in meson systems. This result extends it into three-quark baryons, directly relevant to the matter sector responsible for the asymmetry. The measured value is consistent with Standard Model predictions from the CKM mechanism and does not close the gap between observed CP violation and the required amount. It confirms the machinery works as expected in a new regime.

Neutrino CP Violation: T2K and NOvA 2025

In October 2025, the T2K and NOvA collaborations published their first joint neutrino oscillation analysis. The combined dataset, using baselines of 295 km and 810 km respectively, reduced uncertainty in the neutrino mass squared differences to below two percent.

The CP-violating phase δ_{CP} in the lepton mixing matrix governs the asymmetry between neutrino and antineutrino oscillation probabilities. The joint analysis found that if the neutrino mass ordering is inverted, the data provide evidence for nonzero δ_{CP}, consistent with leptonic CP violation.[7]

This result does not confirm leptogenesis. The CP violation relevant to leptogenesis operates at energy scales many orders of magnitude above what oscillation experiments probe. But a nonzero δ_{CP} would establish that the lepton sector is CP-asymmetric at all, which is the qualitative prerequisite leptogenesis requires.

The Sky Has No Seams

If antimatter domains existed anywhere in the observable universe, their boundaries with matter regions would produce continuous gamma-ray emission at 511 keV from electron-positron annihilation, with additional higher-energy components from proton-antiproton annihilation. The signal would be unmistakable and persistent.

ESA's INTEGRAL satellite has surveyed the gamma-ray sky since 2002 with specific sensitivity to the 511 keV line. The Fermi Gamma-ray Space Telescope has mapped the sky from 20 MeV to above 300 GeV. Neither has found boundary emission consistent with matter-antimatter domain interfaces. The diffuse extragalactic gamma-ray background is consistent with known astrophysical source populations with no statistically significant excess attributable to annihilation at domain boundaries.

The constraints from these observations place lower limits on the scale of any surviving antimatter domains well above several megaparsecs. For practical purposes, the observable universe is uniformly matter-dominated. The baryogenesis mechanism, whatever it was, operated uniformly across the entire observable cosmos.

INTEGRAL did detect a 511 keV signal from the galactic center, diffuse and persistent, implying positron production at approximately 2×10^{43} per second. The source of these positrons remains unidentified. Candidate explanations include low-mass X-ray binaries, millisecond pulsars, radioactive isotope decay, and dark matter annihilation or decay. None has been confirmed as the dominant source. The morphology of the emission, smooth and centrally concentrated, does not match well with the known spatial distribution of any proposed source population.

What the Lab Says About the Mirror

CERN's ALPHA experiment produces antihydrogen, a positron orbiting an antiproton, and holds it in magnetic traps for precision spectroscopy. The 1S-2S transition frequency in antihydrogen has been measured and found to agree with hydrogen to within parts per trillion, testing CPT symmetry in the leptonic and hadronic sectors simultaneously.

In 2023, ALPHA-g measured the gravitational acceleration of antihydrogen directly. Antimatter falls downward. The weak equivalence principle holds for antimatter at approximately twenty percent precision, with improvements ongoing. In 2026, the hyperfine splitting of antihydrogen was measured at one hundred times better precision than the previous best result, finding agreement with hydrogen within experimental uncertainty.

Every laboratory measurement confirms the mirror. The more precisely the symmetry between matter and antimatter is established in the lab, the stranger the cosmological asymmetry becomes. If the fundamental laws treat matter and antimatter as reflections of each other to parts-per-trillion precision, the mechanism that broke the symmetry in the first second must be subtle, high-energy, and possibly beyond any framework currently written down.

What We Actually Know

The baryon asymmetry of the universe is real, measured, and precisely quantified. $\eta \approx 6 \times 10^{-10}$, confirmed independently by nucleosynthesis and the CMB. The asymmetry is uniform across the observable universe, with no antimatter domains detected at any scale. The Standard Model satisfies Sakharov's conditions in form but not in magnitude, falling short by nineteen orders of magnitude in CP violation and producing the wrong type of electroweak phase transition.

Three mechanisms are theoretically viable. Electroweak baryogenesis is testable and increasingly constrained by LHC results. Leptogenesis is well-motivated and connects naturally to neutrino mass physics but operates at energies beyond any planned experiment. The Affleck-Dine mechanism requires supersymmetry, which remains unconfirmed. All three require physics beyond the Standard Model. None has been established as the correct explanation.

Recent experimental results have added information without resolving the question. LHCb confirmed CP violation in baryons at 5.2 sigma in 2025, consistent with Standard Model predictions and insufficient to explain the asymmetry. T2K and NOvA found evidence for leptonic CP violation in 2025, suggestive of the qualitative conditions leptogenesis requires, not yet conclusive. ALPHA has confirmed CPT symmetry in antihydrogen to extraordinary precision, tightening rather than loosening the constraints on any proposed symmetry-breaking mechanism.

The answer is specific. It left a specific measurable trace. It is a physics question with a physics answer that the universe arrived at once, in conditions that lasted less than a second and will not recur. Whether that answer is accessible to instruments we can build, or whether it operated at scales permanently beyond experimental reach, is itself not yet known.

One part in ten billion survived the annihilation. The question of why is still open. But the edges of the question are known, and the edges are informative. Whatever the answer turns out to be, it must fit inside them exactly.

[1] The standard reference for Big Bang Nucleosynthesis constraints on the baryon-to-

photon ratio is the Particle Data Group review: Iocco et al., "Primordial Nucleosynthesis: from precision cosmology to fundamental physics," Physics Reports 472 (2009) 1-76. The concordance value $\eta_{10} = 6.1 \pm 0.4$ is consistent across independent light-element abundance measurements.

[2] Sakharov, A.D., "Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe," JETP Letters 5 (1967) 24-27. The paper is three pages. Its implications took decades to fully absorb.

[3] The suppression of CP violation in the Standard Model relative to the required baryogenesis level is derived in Berkooz, Nir, and Volansky, "Baryogenesis from the Kobayashi-Maskawa Phase," arXiv:hep-ph/0401012. The factor $\epsilon_{\rm CP} \sim 10^{-19}$ follows from the product of quark mass differences divided by the critical temperature to the twelfth power.

[4] The sphaleron energy and topological baryon number violation are reviewed in Klinkhamer and Manton, "A saddle-point solution in the Weinberg-Salam theory," Physical Review D 30 (1984) 2212. The baryon number change per sphaleron transition, $\Delta B = N_f = 3$, follows from the structure of the chiral anomaly in the electroweak theory.

[5] The Davidson-Ibarra bound on the CP asymmetry in leptogenesis, and the derivation of ϵ_1, are given in Davidson and Ibarra, "A Lower Bound on the Right-Handed Neutrino Mass from Leptogenesis," Physics Letters B 535 (2002) 25-32.

[6] LHCb Collaboration, "Observation of CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decays," Nature 633 (2025). The result represents the first observation of CP violation in a decay involving three quarks of the same generation structure as the proton.

[7] T2K and NOvA Collaborations, "Joint constraints on neutrino oscillation parameters," Nature (October 2025). The combined analysis used 0.43 ab^{-1} from Belle II, full NOvA exposure through 2024, and T2K data through 2023. The mass ordering preference depends on the assumed hierarchy and is not yet definitive.