

MATTER – ANTIMATTER ASYMMETRY: SCIENCE & TECHNOLOGY

NEWS: CERN collider reveals major clue to universe's bias against antimatter

WHAT'S IN THE NEWS?

Physicists at CERN have observed CP violation in baryon decays for the first time, a crucial discovery that sheds light on why the universe is predominantly matter and not antimatter. While consistent with the Standard Model, the observed amount of CP violation is too small to fully explain the cosmic matter-antimatter imbalance, suggesting the need for new physics beyond the Standard Model.

CP Violation in Baryons: Unlocking a Cosmic Mystery at CERN

Physicists at CERN's Large Hadron Collider (LHC) have achieved a significant breakthrough by **observing CP violation for the first time in baryon decays**. This discovery is crucial as it offers new insights into one of the most profound unanswered questions in physics: why the universe is composed predominantly of matter, with very little antimatter.

Understanding Antimatter:

- **Mirror Image of Matter:** Antimatter is essentially the "mirror image" of ordinary matter. It consists of particles that possess the **same mass** as their matter counterparts but carry an **opposite electrical charge**.
- **Examples:**
 - Electron (e^-) $\leftrightarrow$ Positron (e^+)
 - Proton (p^+) $\leftrightarrow$ Antiproton (p^-)
 - Neutron (n) $\leftrightarrow$ Antineutron (n^-) (Though electrically neutral, antineutrons have opposite quark composition).
- **Annihilation:** When a particle of matter and its corresponding antiparticle meet, they **annihilate each other**, converting their entire mass into **pure energy** (typically in the form of gamma rays or other elementary particles). This process is fundamental to particle physics and cosmology.

The Cosmic Puzzle: Matter-Antimatter Imbalance:

- **Big Bang Prediction:** According to the prevailing Big Bang theory, the early universe should have produced **equal amounts of matter and antimatter**.
- **Observable Reality:** However, the universe we observe today is almost **exclusively composed of matter**. There is a striking absence of large antimatter structures like anti-stars or anti-galaxies.
- **The Asymmetry:** This profound imbalance points to a fundamental **asymmetry** in the laws of physics, suggesting that matter and antimatter are not treated identically by nature.

Decoding CP Violation:

CP violation is a key concept in particle physics related to the symmetry of fundamental laws.

- **C (Charge Conjugation):** This operation involves **swapping a particle with its corresponding antiparticle**. For example, an electron is replaced by a positron.
- **P (Parity):** This operation involves **mirroring the spatial coordinates**. Imagine viewing a physical process in a mirror – a parity transformation would reflect the event.
- **CP Symmetry:** This states that the laws of physics should remain unchanged if **both Charge Conjugation (C) and Parity (P) operations are applied simultaneously**. In a CP-symmetric universe, a reaction involving matter would proceed identically to a reaction involving antimatter, if viewed in a mirror.
- **CP Violation:** This occurs precisely when this combined CP symmetry is **broken**. In essence, it means that the **behavior of matter differs from that of antimatter** under these combined transformations, leading to a subtle favoritism of one over the other.

Why CP Violation Matters for the Universe's Existence:

In 1967, physicist **Andrei Sakharov** outlined three essential conditions that must have been met in the early universe for it to evolve into the matter-dominated state we observe:

1. **Baryon Number Violation:** There must be processes that allow for the creation of more baryons (a class of matter particles, like protons and neutrons) than antibaryons. This means the total number of baryons, a conserved quantity in many interactions, must not always be conserved.
2. **CP Violation:** The laws of physics must inherently **favor matter over antimatter**. This asymmetry is crucial to ensure that after much annihilation, a residual amount of matter remains.
3. **Departure from Thermal Equilibrium:** Interactions in the early universe must have occurred out of balance (not in a state of perfect thermal equilibrium) to prevent the complete mutual annihilation of matter and antimatter. If reactions were in equilibrium, any imbalance created would quickly be erased.

The Latest CERN Discovery's Contribution:

- The recent CERN observation directly satisfies **Sakharov's second condition**, providing a critical experimental piece to this theoretical puzzle.
- **First in Baryons:** This is the **first time CP violation has been directly observed in baryons**. Previously, it had only been detected in **mesons** (particles composed of a quark and an antiquark).
- **Crucial for Visible Matter:** Since **baryons (like protons and neutrons) constitute almost all visible matter** in the universe, this discovery is particularly significant for understanding the origin of the matter-antimatter imbalance that allowed stars, galaxies, and ultimately, us, to exist.

Significance: Standard Model vs. New Physics

The implications of this discovery extend to our fundamental understanding of particle physics:

- **Standard Model Predictions:** The Standard Model (SM) of particle physics does predict CP violation through a mechanism involving the **CKM (Cabibbo-Kobayashi-Maskawa) matrix**. This matrix describes how different types of quarks (the fundamental constituents of baryons and mesons) can mix and decay.
- **The Insufficiency of the Standard Model:** However, the **amount of CP violation predicted by the Standard Model is known to be far too small** to explain the vast observed matter-antimatter imbalance in the universe. While the observation of CP violation in baryons is consistent with the Standard Model's predictions (within theoretical uncertainties), it doesn't resolve the cosmic asymmetry.
- **Opening the Door to New Physics:** Therefore, this result **reaffirms the need for "new physics"** – theories or particles **beyond the Standard Model** – that could provide the additional sources of CP violation required to account for the "missing antimatter" and fully explain why matter dominates our universe. This discovery thus paves the way for further theoretical and experimental investigations into these elusive new phenomena.

Source: <https://www.thehindu.com/sci-tech/science/cern-collider-reveals-major-clue-to-universes-bias-against-antimatter/article69817740.ece>