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The Mystery of CP Violation

The study of CP violation addresses a very fundamental question: are the laws of physics the same for matter and anti-matter, or are matter and anti-matter intrinsically different? The answer to this question may hold the key to solving the mystery of the matter-dominated Universe.

ACCORDING TO THE BIG BANG THEORY, equal amounts of matter and anti-matter were initially created. When matter and anti-matter come into contact, they annihilate into pure energy, producing photons and nothing else. The relic of this primordial annihilation is the Cosmic Microwave Background, the 2.7 Kelvin radiation that fills the entire Universe. But not all of the matter annihilated into photons: about one out of every billion quarks survived and originated the Universe as we know it today. How could some matter survive the primordial annihilation? Where did the corresponding anti-matter go? Why did matter survive instead of anti-matter?

In 1967, the Russian physicist Andrei Sakharov proposed a solution to this puzzle.[1] Sakharov's explanation required the violation of what was considered a fundamental symmetry of nature: the CP SYMMETRY.

Is Nature CP Symmetric?

CP is a discrete symmetry of nature given by the product of two components: charge conjugation (C) and parity (P). Charge conjugation transforms a particle into the corresponding anti-particle, *e.g.*, if we apply C to an electron, we will obtain a positron. In other words, charge conjugation maps matter into anti-matter. Parity is the transformation that inverts the space coordinates. If we apply P to an electron moving with a velocity $\vec{v}$ from left to right, the electron will flip direction and end up moving with a velocity $-\vec{v}$, from right to left. Parity produces the mirror image of reality.

Therefore, when we apply a CP transformation to an electron moving with a velocity $\vec{v}$ we will obtain a positron moving with a velocity $-\vec{v}$. This means that applying CP on matter gives us the mirror image of the corresponding anti-matter. Let's imagine having a "CP-mirror," a device that returns the mirror image of the anti-matter *(Figure 1)*. Intuitively, we expect that our "anti-self" will wave back at us in the CP-mirror. That is, we expect CP to be a good symmetry of Nature. But is this actually the case?

Both electromagnetic and strong interactions are symmetric under C and P, therefore they must also be symmetric under the product CP. This is not necessarily the case for the weak force, which violates both C and P symmetries, as demonstrated by Chien-Shiung Wu in 1957 in the study of β decays of Cobalt-60.[2] Until 1964, however, CP symmetry was naively assumed to hold in weak interactions as well. One reason for this assumption was the CPT theorem, which states that all quantum field theories must be symmetric under a combined transformation of C, P and T (time reversal). CP violation therefore implies violation of the time-reversal symmetry, which at the time was beyond imagination.

The discovery of CP violation was therefore completely unexpected when, in 1964, Val Fitch, Jim Cronin, and collaborators observed this phenomenon for the first time[3] in the study of the decays of neutral kaons, particles formed by a *strange*

FIGURE 1

When we look at our image in a standard mirror, we are looking at a parity transformation of ourselves. *The figure above is an artist's illustration of what we would see in a "CP-mirror": will our anti-self wave back to us? Not necessarily, if CP is violated. . .*

quark and a *down* anti-quark. The observed effect was small, one part in a thousand, but was extremely important because it proved that matter and anti-matter are intrinsically different. For this discovery Fitch and Cronin were awarded the Nobel Prize in 1980.

It took us almost ten years to explain this phenomenon in the context of the Standard Model of particle physics. In 1973, two Japanese physicists, Makoto Kobayashi and Toshihide Maskawa, successfully explained CP violation[4] by postulating the existence of a third family of quarks, for which there was no experimental evidence at the time.

CP Violation in the Standard Model and Beyond

The Kobayashi-Maskawa mechanism provides an elegant and simple explanation of CP violation. The model has only one free parameter that governs CP violation, and yet it manages to explain all the CP-violation measurements obtained in particle physics experiments to date. Unfortunately, despite its many successes, this theory is still unable to provide an explanation for our original question. The amount of baryons in the Universe predicted using the Kobayashi-Maskawa mechanism falls several orders of magnitude short of what is observed by astronomers.

The implication of this shortcoming is profound: the Standard Model is incomplete and other sources of CP violation must exist because…we exist! Many extensions of the Standard Model have been proposed, and most of them contain additional sources of CP violation. If any one of these theories is correct, the first glimpse of physics beyond the Standard Model may come from studies of CP violation. The task given to experimentalists, therefore, is to very precisely measure CP violation in processes that can be reliably predicted by the Standard Model, and look for any disagreement.

Measurements of CP violation in the kaon system have been performed for over 40 years. Despite the high precisions of the experimental results, the constraints on the theory from such measurements are not very stringent. As it turns out, kaons are very difficult objects to model in the theory, due to the nature of the strong force that holds them together.

Since theoretical calculations become easier with heavier quarks such as the *beauty* quark, *B* mesons (bound states of one *beauty* and one anti-*down* quark) provide the ideal environment for measurements of CP violation. The parameters of the Kobayashi-Maskawa mechanism are constrained in the form of a triangle, known as the Unitarity Triangle, whose height measures the amount of CP violation in the theory. The sides and angles of this triangle can be precisely determined in the study of *B* decays.

While in the Standard Model these measurements should all be self-consistent with their interpretation in terms of sides and angles of a triangle, in the presence of New Physics some measurements may be inconsistent: the angles may not add up correctly; sides may be too short or too long; two measurements of the same angle may disagree. Each measurement is a piece of a puzzle, and all pieces must fit together if the Standard Model is correct.

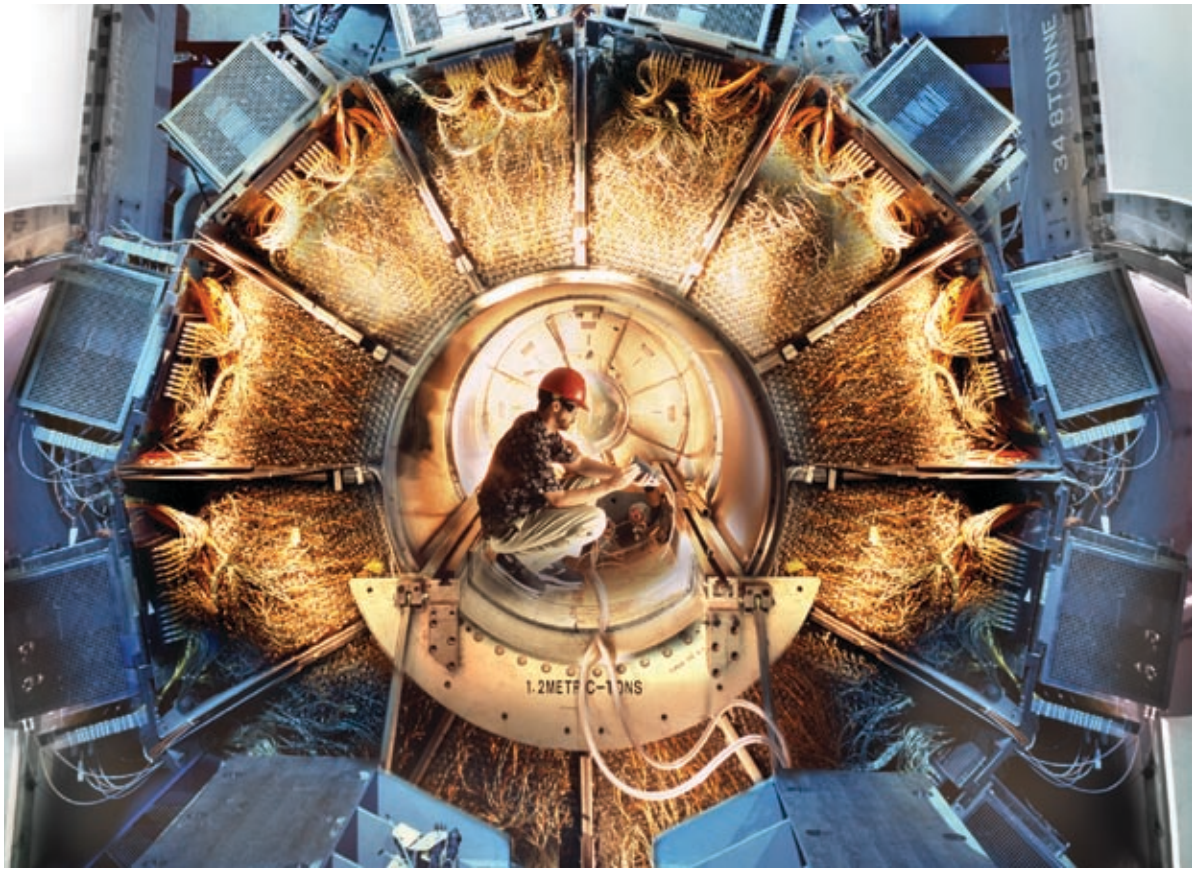

FIGURE 2

The BaBar detector at Stanford Linear Accelerator Center

A key ingredient to this program is determining accurately the angles of the Unitarity Triangle based on the study of CP violation in B decays. Specifically, the angles are related to the amplitude of the so-called time-dependent CP asymmetry, defined as the asymmetry between the decay rates of the neutral *B* and anti-*B* meson to the same final state.

The Asymmetric B Factories

The measurement of CP violation in *B* decays poses daunting experimental challenges. First of all, it requires very large samples (hundreds of millions) of *B* mesons, because only rare final states can be used in the measurement. Second, the environment has to be very clean to be able to precisely reconstruct even exotic decays—ideally, we want to be able to identify and understand the origin of all the particles present in an event. In addition, we need the *B* mesons moving in the laboratory with known velocities, so that their time of decay can be established by measuring where they decayed in space.

The first two requirements can be achieved by colliding electrons and positrons with the center-of-mass energy of about 10 GeV. To satisfy the third requirement, the two beams must have asymmetric momenta. These characteristics define a new kind of accelerator known as an "asymmetric B factory."

When Pier Oddone of the Lawrence Berkeley National Laboratory first proposed the concept of an asymmetric B factory in 1987, the idea was received with some skepticism. Nobody had ever built an asymmetric collider before, and the luminosity required to carry out the measurement was orders of magnitude higher than any existing collider. But the payoff of such measurements was high, and proposals for B factories sprang up all over the world. Two such machines were eventually built: one at the Stanford Linear Accelerator Center (SLAC) in California, and one at KEK laboratory, in Tsukuba, Japan. The two B factories began data-taking in 1999 and were both spectacularly successful in reaching luminosities well above their design values. Today, each B factory can collect over one million *B* mesons per day of operation. The hundreds of millions of *B* decays that each experiment accumulated over the years opened the road to a quantitative understanding of the phenomenon of CP violation in nature.

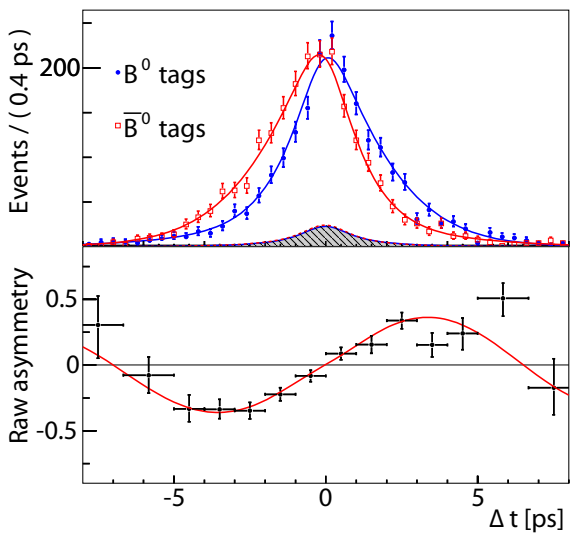

FIGURE 3

Measurement of CP violation in $B^0 \rightarrow J/\psi\ K^0$ decays from the BaBar Collaboration. *The* top plot *shows the decay time distribution for B^0 mesons (in red) and anti-B^0 mesons (in blue): a difference between the two distributions is clearly visible, proving that matter and anti-matter are intrinsically different. The* bottom plot *shows the time dependent CP asymmetry $A_{CP}(t)$, where the amplitude of the oscillation measures directly the parameter β. If CP were conserved in nature, this distribution would be completely flat.*

Large Detectors for Little Particles

At the interaction point of each collider, state-of-the-art detectors are ready to capture the traces left by the sub-atomic particles originated by the decay of the *B* mesons and their anti-particles. While the particles are small, the detectors that observe them must be very large to precisely measure their properties.

The SLAC experiment, named BaBar after the elephant in Laurent de Brunhoff's children's books, is a roughly cylindrical device measuring 6 meters in length, 6 meters in diameter and weights over 1,200 tons. Building and operating this elephantine machine required a collaboration of over 500 physicists and engineers from 73 institutions all over the world.

At its core, BaBar has a silicon detector, able to measure the passage of charged particles with a precision of a few tens of microns, which is required to measure the ~250-micron separation between the decay vertices of the two *B* mesons. The vertex detector is surrounded by a drift chamber, a gaseous detector that determines the momentum of charged particles from the curvature of the traces they leave in the 1.5-T magnetic field.

Encircling the drift chamber, a Cherenkov detector identifies the various particle species: as a charged particle penetrates the quartz bars that constitute this device, it emits Cherenkov radiation at an angle that depends on its velocity. Combining the measurement of this velocity with that of the momentum from the drift chamber allows us to determine the mass of the particle, and hence the particle type. At still larger radii, photons and electrons are captured and their energies recorded by a calorimeter, which consists of blocks of cesium iodide crystals. Finally, muons are identified by muon chambers immersed in the return yoke of the solenoid.

The Japanese counterpart of BaBar, an experiment named Belle, is very similar in design and performance.

Unveiling the CP Sector of the Standard Model

CP violation in B decays was observed for the first time in 2001, when the B factories announced the first measurement of the time-dependent CP asymmetry[5,6] in the decay of $B^0 \rightarrow J/\psi\, K^0$, where J/ψ is a particle made of one *charm* and one *anti-charm* quark and K^0 is a neutral kaon *(Figure 4)*. Such final states measure one of the angles (β) of the Unitarity Triangle with negligibly small theoretical uncertainty.

To date, experimental measurements have achieved remarkable precisions: the angle β is now known within 1.2 degrees, and is the best-measured quantity in the Unitarity Triangle. *Figure 3* shows the latest results published by the BaBar Collaboration.[7] The top plot shows the decay time distribution for B^0 mesons (in red) and anti-B^0 mesons (in blue). A difference between the two distributions is clearly visible, proving that matter and anti-matter are intrinsically different.

This difference is even more striking when we look at the distribution of the time dependent CP asymmetry $A_{CP}(t)$ (bottom plot), where the amplitude of the oscillation measures directly the angle β. If CP were conserved in nature, this distribution would be completely flat.

A precise measurement of the angle β provided the first quantitative test of the CP sector of the Standard Model. By comparing the measurement of this angle with the allowed region for the apex of the Unitarity Triangle as defined by its sides, we proved that the Kobayashi-Maskawa mechanism is indeed responsible for the CP violation as observed in our experiment—another triumph for the Standard Model.

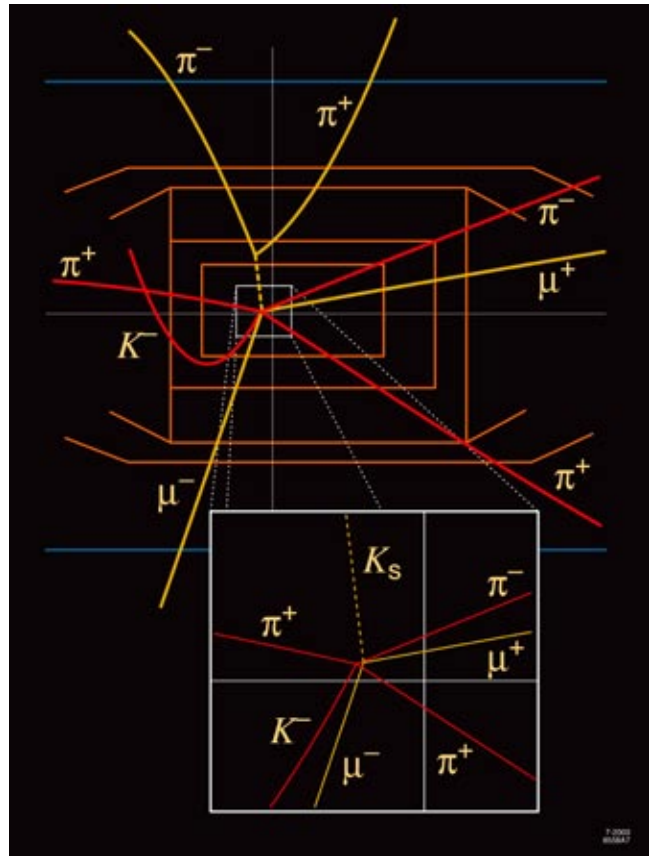

FIGURE 4

Reconstruction of a "gold plated" event in the BaBar detector. *The decay products of $B \rightarrow J/\psi\, K_S$ are shown in yellow: the two muons come from the J/ψ decay, while the two pions originate from the decay of the K_S. The other four particles (in red) originated from the decay of the other B meson in the event.*

Hunting for New Physics

The study of the decay $B^0 \rightarrow J/\psi\, K_S$ is not the only way of measuring the angle β with small theoretical uncertainty. In the Standard Model, other modes such as $B^0 \rightarrow \phi\, K_S$ measure the same angle with comparable theoretical precision. The difference between these two decays is due to the fact that they are mediated by different short-distance physics. In particular, the decay $B^0 \rightarrow \phi\, K_S$ is mediated by rare loop diagrams known as "penguin diagrams," potentially very sensitive to New Physics. Measuring different values of the angle β in these two different modes would unambiguously signal the existence of New Physics.

While theoretically clean, the measurement of CP violation in "penguin" modes is experimentally very challenging, due to the extremely low rates of the final states of interest and the difficulty in separating these decays from various sources of background. The high luminosity and the clean environment provided by the B factories are essential to perform these measurements.

The data collected at the two B factories in the past five years show that the angle β in "penguin" modes differs by about 2.7 standard deviations compared to the measurement of the same angle in the standard mode. Is this the first sign of Physics Beyond the Standard Model? The analysis of the data collected by the two B factories in the next two years will be crucial to answer this important question.

The Future of CP Violation

In the past five years, the unprecedented luminosities reached by the B factories together with the precise theoretical understanding of B decays allowed us to finally gain a quantitative understanding of CP violation in the Standard Model. This phenomenon has been measured so precisely that it has become one of the most sensitive probes of New Physics. While physics beyond the Standard Model affects only some rare decays, its signature is expected to be very clean, and an unambiguous evidence for New Physics may be within reach by the end of 2008, when the B factory program will come to an end.

In this article, I only discuss CP violation in the quark sector for which we have precise measurements, thanks to the wealth of experimental data. Yet the same phenomenon is expected to exist in the neutrino sector as well, although it has never been experimentally observed. According to Leptogenesis, one of the most popular theories attempting to explain the matter-dominated Universe, it is CP violation in the neutrino sector that is responsible for the observed matter-antimatter asymmetry. Experiments to carry out this experimental program have been proposed both in Japan and in the United States, opening a whole new chapter for the study of CP violation.

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