How to Measure a Triangle: Probing the Matter/Antimatter Asymmetry in the Universe

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Brookhaven National Laboratory

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Overview

- A little background
  - A brief history and the Standard Model
  - The Big Bang, and a Big Question
  - Matter and antimatter
  - Symmetries
  - Parity and CP violation

- The triangle and the elephant
  - CP violation in the Standard Model
  - Why B’s are better than K’s
  - The BaBar experiment
  - Discovery of CP violation in B decays

- A final thought from my favorite politician…
A Brief History of the 20th Century…

- 1900-1950:
  - Relativity and quantum mechanics emerge as the pillars of 20th century physics
  - Antimatter predicted (1928) and positron discovered (1933)
  - Quantum Electrodynamics sets the template for particle theories

- 1950-1983: If you build it, they will come
  - 100’s of new particles and “resonances” are discovered in new accelerators at Berkely, Brookhaven, and elsewhere
  - Quark model (1964) brings order from chaos
  - Electroweak theory postulated by Glashow, Weinberg, and Salam
    - Dramatically confirmed with the discovery of the W and Z bosons (1983)

- 1983-present:
  - The Standard Model is established as the most likely theory of particle interactions. But there are still some loose ends…
The Standard Model of Particle Physics

- The modern theory of particle physics is called the “Standard Model”
- The underlying principle is that Nature can be described in the context of forces acting on particles
  - Quantum Field Theory is the official language
- The Fundamental Forces:
  - Electromagnetism (light, atomic and molecular binding)
  - Weak (beta, and other, decays)
  - Strong (binds quarks inside protons, neutrons, etc…)
  - Unification of all forces (including gravity)? Not in this talk!
- The Fundamental Particles:
  - Quarks (nuclear building blocks)
  - Leptons (the “light” particles: electrons, neutrinos, etc…)
The Particle Rubik’s Cube
Big Bang: From Particles to People…

- Pre-heat oven to $10^{32}$ degrees, add quarks/leptons/forces
- Reduce temperature and stuff “hadrons” with quarks using a strong glue
  - **Mesons** – quark/antiquark pairs
    - $K^0$ meson = down + antistrange
    - $B^0$ meson = down + antibottom
  - **Baryons** – three quarks or three antiquarks
    - Proton = up + up + down
    - Neutron = up + down + down
- Continue reducing temperature, electrons will bind to the protons → atoms (watch out for clumping galaxies)
- Slowly cool atoms to form molecules, proteins, cells, and, after 15 billion years in the kitchen, people!
Big Question: Where is the Antimatter?

Added equal amounts matter and antimatter...

In fact, all matter should have annihilated; lucky for us it didn’t!
Mom: “So what is antimatter anyway?”

- The marriage of relativity and quantum mechanics embodied in the Dirac equation predicts that for every particle there is an antiparticle with opposite charge and magnetic moment
  - All other attributes are identical: mass, lifetime, etc…
  - Neutral (fundamental) particles are their own antiparticles

- The discovery of the positron in 1933 confirmed the prediction, but does *every* particle have an antiparticle?
  - Antiproton and antineutron were discovered in 1955-6

- The laws of physics at that time treated particle and antiparticle equally, so how could an imbalance arise in the early universe?
Symmetry and Conservation Laws

- Symmetry is a deep and fundamental concept in physics.
- Nöether’s theorem states that for every symmetry in Nature there is a conserved quantity.
  - Conservation laws separate the theory wheat from the chafe by requiring the fundamental interactions to obey the corresponding symmetries.
- Some well-known examples:
  - Lorentz invariance → conservation of energy-momentum
  - Rotational invariance → conservation of angular momentum (spin)
- These dynamical symmetries refer to the fundamental structure of space-time itself. What about discrete symmetries related to sub-atomic particles?
Three very important discrete symmetries:

- **Charge conjugation (C):** particle $\leftrightarrow$ antiparticle
- **Parity (P):** $x \rightarrow -x$, $y \rightarrow -y$, $z \rightarrow -z$
  - The mirror image of any physical process should be possible
- **Time reversal (T):** $t \rightarrow -t$

Before 1956, all interactions were assumed to obey all three symmetries independently.

In practical terms, it means that we cannot tell particle from antiparticle, left-handed from right-handed, or the direction in time; they are relative, not absolute concepts.

To distinguish these characteristics you need to break the symmetry! So what happened in 1956?
T. D. Lee (Columbia)

C.N. Yang (IAS)
Is Parity Conserved in Weak Interactions?

T. D. Lee (Columbia)  C.N. Yang (IAS)
Is Parity Conserved in Weak Interactions?

NO!

All electrons spin left-handed about their direction of motion.

The mirror image does not exist!
C and P Bad, CP Good?

- Wu and others found that left-handed positrons do not exist either, so C and P are maximally violated!
- However, the combined operation (CP) of swapping particle/antiparticle and left-handed/right-handed restores the symmetry:
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However, the combined operation (CP) of swapping particle/antiparticle and left-handed/right-handed restores the symmetry:

\[
\begin{array}{c}
\text{Left-handed Particle} \\
\text{e}^- \\
\rightarrow \text{CP} \\
\text{Right-Handed Antiparticle} \\
\text{e}^+ \\
\end{array}
\]
CP Violation

In 1964, Princeton researchers (Cronin and Fitch) working at the Brookhaven AGS observed the CP-violating decay $K_L \rightarrow \pi^+ \pi^-$.

- **Completely unexpected!**
- Unlike parity violation, CP violation did not fit into existing models.
- Fundamentally altered our understanding of the weak force.
A Nobel Prize, and a Cartoon!

(Hank Martin, New Yorker)

Jim Cronin
Val Fitch

Then
Now

from A. J. Smith
So What?

CP violation is one of the necessary ingredients to produce a matter/antimatter asymmetry in the early universe!

Matter and antimatter will cancel like these hands folded over. Need some misalignment - CP violation
A Cosmological Fight to the Death…

For every billion ordinary particles annihilating with antimatter in the early Universe, one extra was left “standing.”

-- The Smithsonian
Intermission

- Calculations showed that the level of CP violation observed in the Cronin-Fitch experiment failed, by billions, to explain the matter/antimatter asymmetry in the universe. Hmmm.....

- Meanwhile, a mechanism to describe CP violation in the Standard Model was developed by Kobayashi and Maskawa (1973), with inspiration from Cabibbo (1963).

- Despite tireless efforts by experimentalist, for 37 years the question of whether the CKM mechanism was the source of CP violation in the K-meson system remained unanswered...
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Enter the B Factories!
Beauty is Better than Strangeness

- B mesons have several advantages over K mesons when it comes to studying CP violation:
  - CP-violating observables are much larger (0.5 vs 0.002)
  - Many more decays modes → can cross-check measurements in several decay modes to look for (in)consistencies
  - Less theoretical uncertainty → tighter constraints on theory
- The B’s allow for direct confrontation of the Standard Model with experiment, and the possibility to distinguish between competing models of CP violation
- In 1999, two dedicated CP violation experiments using B mesons began taking data: BaBar at Stanford, and Belle at Tsukuba, Japan
Finally, the Triangles!

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- The strength of the interaction is proportional to one of the elements of the “CKM matrix”.

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]
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  - Leads to “triangles” in the complex plane.

*CP violation is proportional to the area!*
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\[K\text{ mesons: } V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0\]

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  - \textit{CP violation is proportional to the area!}

\textbf{K mesons:} \[ V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0 \]

\textbf{B mesons:} \[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]
It’s easy, and not so easy…

- The angles of the Unitarity Triangle are observable as CP-violating asymmetries in the time spectra of $B^0$ and anti-$B^0$ decays to well-defined states of CP symmetry
  - CP violation demonstrated if any angle is different from 0 or 180!
- Task of the B Factories is to measure the angles and sides of the Unitarity Triangle with unprecedented precision
- But, the relevant decays are rare (1 in 10,000), and the B meson lives for only 1.5 *trillionths* of a second
  - Need lots of B’s → B Factories!!!
  - Even at B Factories, the B flies on average only .25 millimeters before decay → precision detectors needed to “see” the B decay
BaBar Detector: Peel the Onion

- **DIRC (PID)**: 144 quartz bars, 11000 PMs
- **1.5T solenoid**
- **EMC**: 6580 CsI(Tl) crystals
- **Drift Chamber**: 40 stereo layers
- **Silicon Vertex Tracker**: 5 layers, double sided strips
- **Instrumented Flux Return**: iron / RPCs (muon / neutral hadrons)

*Beam:* $e^-$ (9 GeV) → $e^+$ (3.1 GeV)
BaBar Detector: Peel the Onion

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- e^+ (3.1 GeV)
- e^- (9 GeV)

Me!
- 6’3”, xxx lbs

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How many physicists does it take to herd an elephant?
How many physicists does it take to herd an elephant?

~600!
It’s Really a B Factory!

90 million B/anti-B pairs produced!

All previous B data recorded since the Big Bang
Electron and positron collide producing an Upsilon meson boosted in the lab frame.
Electron and positron collide producing an Upsilon meson boosted in the lab frame. Upsilon decays to B/anti-B pair in coherent angular momentum state
Start the clock when one B (call it $B_{\text{tag}}$) decays, “tag” its flavor.

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Electron and positron collide producing an Upsilon meson boosted in the lab frame. Upsilon decays to B/anti-B pair in coherent angular momentum state. After a time $\Delta t$, the second B (call it $B_{\text{CP}}$) decays into a CP eigenstate that is fully reconstructed.
A Real Event: \( B^0 \rightarrow J/\psi K^0_S (\pi^+ \pi^-) \)
What Do We Expect?

With a perfect detector

\[ B_{CP} = B^0 \]

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Decay Time Difference (ps)

Smeared by finite detector resolution

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Decay Time Difference (ps)
What Do We Expect?

With a perfect detector

\[ B_{CP} = B^0 \]

Smeared by finite detector resolution

\[ B_{CP} = B^0 \]

\[ \sin 2\beta \]

Matter/Antimatter Asymmetry

\[ \Delta t \text{ (ps)} \]

July 18, 2002

J. Olsen
Observation of CP Violation in B Decays

- Matter/antimatter asymmetry visible to the naked eye!
- First observation July 2001
- Latest measurement (yesterday!):

$$\sin^2 \beta = 0.741 \pm 0.067 \text{ (stat)} \pm 0.033 \text{ (syst)}$$

(hep-ex/0207042)

So $\beta = 24$ degrees $\neq 0$ or 180!
What is the Predicted Value?

A triumph for the Standard Model!
So What Does it All Mean?

- The observation of CP violation in B decays, and the extraordinary agreement with the Standard Model prediction, leave little doubt that the CKM paradigm is the common source of CP violation in B and K mesons.

- But this still leaves us billions of times short of describing the cosmological CP violation that led to our matter-dominated Universe!
  - Is it “New Physics”, or something less exotic?

- We are now in a new phase of the experiments, looking at different, and rarer decay modes.

- The B Factories continue taking data at ever-higher rates in order to squeeze the Triangle until it cracks!
A Final Thought…

“This is not the end. It is not even the beginning of the end. It is, perhaps, the end of the beginning…”

-- Winston Churchill