Particle Physics Meets Cosmology

Matter-Antimatter asymmetry and
the origin of the visible universe

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Cosmology – The Big Questions

Where did the Universe come from?

What is the structure of the Universe now?

How will the Universe evolve in the future?
Symmetries and Conservation Laws
Matter and Antimatter
Big Bang Cosmology and Concordance Model
Composition of Universe
Sakharov Conditions
Standard Model of Particle Physics
The SLAC B-Factory and BaBar
CP Violation in $B$ Mesons
Open Questions
Symmetries in Physics

Physics works from simple rules and broad generalizations

**Conservation laws** and **Symmetry Relations** limit what “could” happen, and describe what “does” happen

**Symmetries**

Physical laws are equivalent when parameters are systematically changed: left $\leftrightarrow$ right, $+ \leftrightarrow -$ $t \leftrightarrow -t$

**Conservation laws**

Some quantities cannot change as a result of interactions: total energy, momentum, rotation, electric charge
Symmetries in Physics

Position and Time \((x \rightarrow x + x_0)\): Physics does not depend on specific location in space or time

Science is reproducible and predictable

Parity \((P)\): Physics looks the same in a mirror \((x \rightarrow -x)\)

Charge Conjugation \((C)\): Physics depends on relative electric charges, not absolute positive or negative

Time Reversal \((T)\): Local interactions look the same running forward or backward \((t \rightarrow -t)\)

Complex systems need not be T-symmetric (entropy)

Matter-Antimatter: Neutrinos not P symmetric, but neutrinos/antineutrinos equivalent under CP combined
Conservation Laws

Energy: You can’t get something for nothing

Momentum: Rockets can’t be pushed faster than their exhaust; things don’t “just stop”

Electric charge: Electrons don’t appear or disappear*

Baryon number: Quarks don’t appear or disappear*

* Individuals can transform; total of system remains constant

Friction may appear to violate energy/momentum conservation: “missing” energy turns into heat, motion of atoms or of Earth

Emmy Noether (1918) showed that conservation laws can be derived from symmetry relations
Particles and antiparticles have opposite electric charge, other properties (mass, spin, forces) equal.

**Charge-conjugation Symmetry**: physics would look just the same on an antimatter planet!
Over past ten years, observational data has converged on one explanation for how the Universe began and evolved, the *Concordance Model*

- Spacetime singularity (infinite energy density)
- $10^{-43}$ seconds: Quantum fluctuations “inflating” billions of times to macroscopic size
- Energy density (temperature) drops as Universe expands
- $10^{-10}$ seconds: Particles “freeze out” as temperature drops below each mass scale
- **Cold dark matter** (massive, slow neutral particles) clumps in high density regions
• 200 seconds: Unstable particles decay, leaving electrons, protons, neutrons, neutrinos, ...

• High temperature (photons) keeps electrons and nuclei from combining into atoms: cosmic plasma

• 372,000 years: temperature low enough for neutral atoms, simple molecules ($H_2$), to form

• Atoms pulled into dark-matter clumps by gravity

• Stars, galaxies, etc. form; expansion slows over time

• 10–12 billion years: expansion starts accelerating due to “cosmological constant” $\Lambda$

• 13.7 billion years: we evolve to figure all that out
Composition of Universe

**Cosmic Pie**

- Chemical Elements: (other than H & He) 0.03%
- Neutrinos: 0.47%
- Stars: 0.5%
- Free H & He: 4%
- Dark Matter: 25%
- Dark Energy: 70%
- *Nothing matters!*

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Composition of Visible Universe

What we see through telescopes is “baryonic” matter, made up of quarks (protons and neutrons), with electrons to balance charge.

Only 4.5% of total content of Universe, but most familiar:

- Stars, planets, nebulae, galaxies
- Molecular clouds, dust, gas
- Interstellar & intergalactic medium

Elemental composition from spectral lines: emission or absorption intensity gives relative amounts.

Observed H, D, He, $^7$Li abundances match predictions.
Astronomy: Matter or Antimatter?

Same spectral lines from atoms or anti-atoms

Energy levels same whether nucleus positive or negative

Attractive force between nucleus and electrons needs opposite charges. Doesn't care which is which

Experiments underway to make anti-H and verify!

Gravity depends only on mass, not electric charge

Orbits of binaries, galaxies, etc. same for “antistars”

Tested with “fountains” of antiprotons, antineutrons

Astronomers could not tell if stars or galaxies are made of matter or of antimatter!
What if there were antimatter stars or galaxies?

When particles and antiparticles meet, they *annihilate*

Pure energy $\Rightarrow$ gamma rays

Contact between regions of matter and antimatter?

Broad, continuous gamma sources, with lines at specific energies (511 keV $e^+e^-$, 140 MeV $\pi^0$’s from $p\bar{p}$)
Matter, Matter, Everywhere

Earth and Moon
Apollo didn’t explode into gamma rays

Rest of solar system
Meteorites, comet tails, planetary probes

Local galactic region
Solar system passes through ISM gas, dust

Milky Way Galaxy
Stars move through ISM
gas, dust clouds touch each other

Local Group of galaxies
IGM surrounding Milky Way
Magellanic clouds, Andromeda, etc. in IGM
“Direct” limit $< 10^{-7}$ antimatter in local 20 Mpc

Non-observation of large continuous gamma sources

Cosmological value $6 \times 10^{-10}$ \[ \frac{(n_B - n_{\overline{B}})}{n_{\gamma}} \lesssim \frac{n_B}{n_{\gamma}} \]

Cosmic microwave background data from WMAP

Measurement of Hubble expansion

Big Bang nucleosynthesis and isotopic abundances
Charge conservation and CP Symmetry

Particles and antiparticles must be created in pairs.

If CP symmetry valid, why isn’t Universe half antimatter?

If matter and antimatter all mixed together in Big Bang, why is anything left to see?

Andrei Sakharov outlined requirements in 1967

1. Universe must have been out of thermal equilibrium
2. Baryon number conservation must be violated
3. CP symmetry must be violated
**Testing Sakharov’s Conditions**

**Thermal equilibrium:**
Cooling from expansion passes through “phase transition” (freezing), non-equilibrium process.

**Baryon number violation:**
Proton decay predicted, not observed. Current limit on proton lifetime $> 2.9 \times 10^{33}$ years

**C, CP violation:**
Particles and antiparticles might have different lifetimes, or decay inequivalently.

CP violation observed in neutral $K$ mesons (1964).
General property or special case?
Sufficient to explain cosmological asymmetry?
Ordinary matter made of $u, d$ quarks [protons, neutrons] and electrons

Other “generations” existed in first $10^{-10}$ seconds.

Now created from energy in particle accelerators.

Hundreds of short-lived particles are made of (anti)quarks

Many places to search for CP violation or other unexpected physics
Weak interaction ($W^\pm$ and $Z^0$ force-carrying particles) allows quarks to transform one to another ("mix").

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Probabilities described by $3 \times 3$ "CKM Matrix" (Cabibbo, 1963; Kobayashi & Maskawa, 1973)

Matrix can have complex (imaginary number) terms ("phases"). Non-zero phase $\delta$ indicates CP violation.
The \( B \)-Factory

Proposed in early 1990’s, running 1999 – 2008

Another \( B \)-Factory running at KEKB (Tsukuba) in Japan
Two particle beams circulate in opposite directions in rings, cross through each other at center of detector.

“Beams” are actually series of bunches, $5 \times 160$ $\mu$m cross-section, 6 cm long, spaced 1.2 m (4 ns) apart.

About $7 \times 10^{15}$ electrons or positrons in each bunch.

**Electrons** 9 GeV, “boiled” off heated filament.

**Positrons** 3.1 GeV, $e^-$ on tungsten target.

Energy in target produces $e^+e^-$ pairs.

Collect and store $e^+$ coming out back.

Both accelerated in linac before “injection” into rings.
The BaBar Detector

Completed in 1999
1000 metric tons
5 separate detectors
234,000 readout channels

250M beam crossings
3000 triggers
300 events to disk
... per second
Bunches cross paths inside detector 250 million times per second

99.99% of bunch crossings just pass through each other

Once each 10,000 crossings, $e^-$ and $e^+$ “scatter” (deflect) each other

Most scattering events ignored by detector readout system
Every .5 ms or so, something “interesting” happens; detector “triggered” to read out data for further study

10% of triggers recorded to disk

1% of recorded events are $B\bar{B}$

Nearly 400 million $B\bar{B}$ events recorded for analysis, 40 billion others $\Rightarrow$ 600 terabyte database!
Select events where B and anti-B were produced in collision

$B^0$ and $\bar{B}^0$ mix and oscillate in time, just like $K$ mesons
Average lifetime about $10^{-12}$ seconds

One particle might decay (10% probability) into stuff which includes an electron or muon

$B^0$ will produce $e^+$ or $\mu^+$

$\bar{B}^0$ will produce $e^-$ or $\mu^-$

High-energy physics jargon: “flavor tagging”

Other particle keeps oscillating until it decays

Watch for other decay to a CP “eigenstate” (like $\pi^+\pi^-$)
CP Violation in $B^0 - \overline{B}^0$

Count events vs. decay time for each of $B^0$ and $\overline{B}^0$.

Look for differences between flavors, oscillations.

Asymmetry is difference between $B^0$ and $\overline{B}^0$.

Height measures CP violation:

$$\sin 2\beta = 0.687 \pm 0.032$$

T-symmetry: events with tag after CP decay ($\Delta t < 0$) also count!
Big bang needs CP violation to leave Universe with matter

Standard Model of particle physics predicts CP violation “naturally,” through mixing of quark generations

Quark masses, $\sin 2\beta$, $m_Z$, suggest $n_B/n_{\gamma} \sim 10^{-20}$

Cosmological value is $6 \times 10^{-10}$ (WMAP)

What does this mean? New physics required

Neutrinos have mass; could they mix with CP violation? Supersymmetry? String theory models? Something we haven’t thought of yet?
Temperature needed for cosmological CP violation corresponds to mass of force carriers

Mass of $W$, $Z$ about 100 GeV

CP violation only occurs if all quarks have different masses.

Baryogenesis depends on mass differences, mixing elements, phase

$$\frac{n_B}{n_\gamma} \sim \left( m_s - m_d \right) \left( m_b - m_s \right) \left( m_b - m_d \right) \left( m_c - m_u \right) \times \frac{m^4}{m^4_Z} \times V_{us} V_{ub} V_{td} \delta$$

(Neglecting small numerical factors like $\pi$, 2, etc.)
Observing CP Violation

Particles may have either of two “eigenvalues”, +1 or −1

Particle decays should conserve CP eigenvalue.

Compute CP of final state, match to CP of decaying particle:

\[ K_S \rightarrow \pi^+ \pi^- \text{ has } CP = (-1)(-1) = +1 \]
\[ K_L \rightarrow \pi^+ \pi^- \pi^0 \text{ has } CP = (-1)(-1)(-1) = -1 \]

Produced state mix of CP: \( K^0 = K_S + K_L \)

CP state at decay depends on time: \( K_S \rightarrow K_L \rightarrow K_S \rightarrow K_L \cdots \)

Observe “indirect” CP violation through this mixing

Particle decays could also “directly” violate CP:

\( 2 \times 10^{-3} \text{ decays } K_L \rightarrow \pi^+ \pi^- \text{ has } CP = +1, \text{ wrong!} \)
Observing CP Violation

(a) Kaon Mixing

(b) Indirect CP Violation

(c) Polarized Light Analogy

(d) Direct CP Violation
Turning Time Into Space

Beams have different energies (9 GeV on 3.1 GeV), so collision is moving relative to detector.

Relativity: speed of B’s stretches lifetime ($\Delta z = \beta \gamma c \tau$)

B’s decay at different times (few picoseconds apart) separated in space: $\Delta z \approx 0.25$ mm