The Cosmological Matter-Antimatter Asymmetry, CP Violation, and New Physics

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The Question:

Why is there more matter than antimatter in the universe?

-or-

Why is there anything in the universe at all?

Let's hope the answer resides in a *comprehensible property of particles and forces.* So: first we will review the **properties of particles and forces**

This is called **"The Standard Model"**

Postulate an explanation for the asymmetry: **Baryon Number Violation** + **CP Violation** + **Thermal Non-equilibrium**

Review the status of our knowledge of those 3 ingredients, to understand what experiments need to be done next.

2

Develop the question: **Why is there Something rather than Nothing?**

In laboratories and in theories, particles and antiparticles always come in pairs. So why does the universe appear to contain unequal amounts of them, so that they have not completely annihilated?

"The Cosmological Matter/Antimatter Asymmetry"

FROM THEORY:
In relativistic quantum mechanics, the relativistic version of the Schroedinger Equation

(called **the Dirac Equation**):

Its solution naturally requires particle-antiparticle pairs.

FROM EXPERIMENT:
Collisions at particle colliders always produce equal amounts of particles and antiparticles

The universe appears to be almost 100% matter.

How do we know this?

(1) Sampling data from *within the Milky Way* - cosmic rays arriving from all regions are matter.

(2) Sampling data from *beyond the Milky Way* - collisions between matter and antimatter regions would emit gamma rays. No known gamma ray sources have the right characteristics.

(3) *What if there are matter galaxies and antimatter galaxies, but separated by large voids?* How the universe might evolve into such a state from a pointlike Big Bang presents a NEW BIG QUESTION...

so FOR NOW, let's assume that the universe IS mostly matter, and ask WHY?

Did the universe begin with an asymmetry? *Why would initial conditions be so special?*

Or did the universe begin with equal amounts of matter and antimatter, and then develop the asymmetry later? **This option seems more appealing.**

Let's assume that the answer is due to some feature of elementary particles and forces.

As a foundation for developing the answer, *review the theory* of elementary fields: **The Standard Model.**

Four types of interactions:
Gravity
Electromagnetism
Weak – leads to radioactive decay
Strong – holds the protons together in the nucleus

These affect *fundamental particles* including:
the 6 quarks (up, down charm, strange, top, and bottom), 6 antiquarks, and non-quarks like the electron, the photon....

How the electromagnetic (EM) interaction works:

(1) two particles interact electromagnetically only if both have a quantum number called electric charge.

(2) the electromagnetic attraction or repulsion is conveyed by a particle that they exchange between them - a "gauge boson" -   which for EM is the photon (particle of light)

An example EM interaction between 2 electrons:
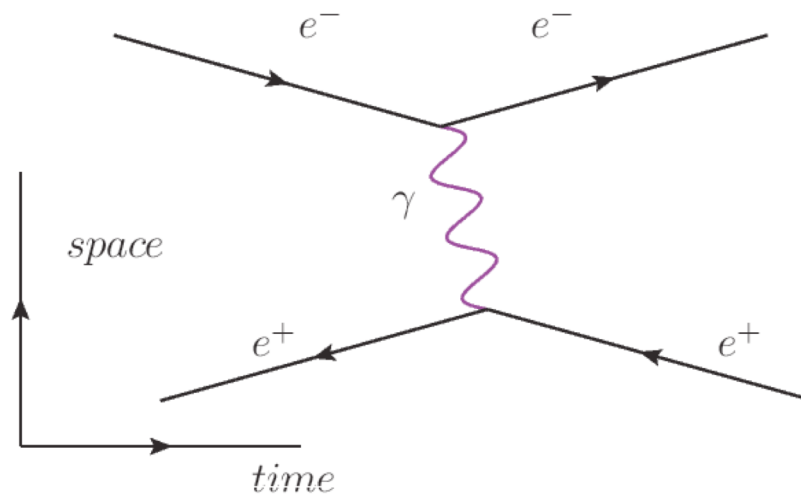
The success of the EM description led people to try to describe the strong and weak forces analogously.

How the WEAK force works:

- interacting particles have a "weak charge" that is different from the EM charge

- the interaction is also carried by gauge bosons, but whereas EM has only 1 kind of boson (the photon), the weak force has 3 kinds (W^+, W^-, Z^0)

BIG DIFFERENCE between the weak force and all the other forces:

- the other forces *never change the fundamental type ("flavor") of the quarks.* Thus: an "up"-type quark remains "up"-type throughout a strong or EM interaction.

- **the weak force can change the quark flavor** (for example turn up-type into down-type)

So these can happen:
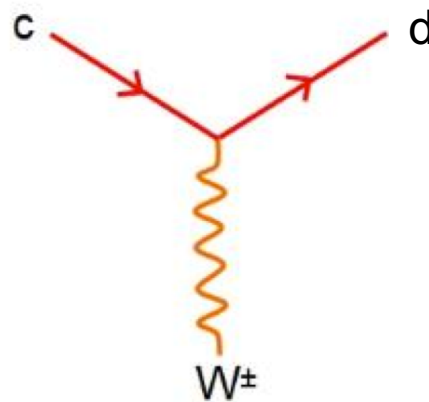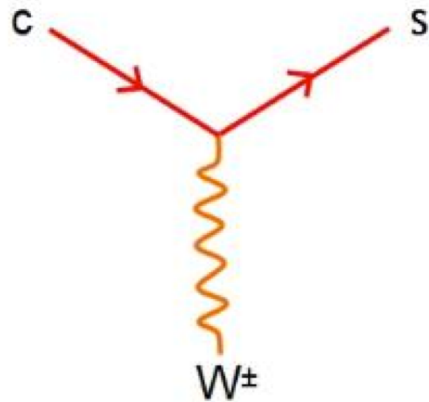
but $c \rightarrow u$ does not happen.

How we describe this mathematically...using a matrix:

...first (to simplify) suppose that there are only 4 quark types, not 6

u, d, c, s

(i.e., ignore t and b just temporarily).

Recall 2 things from quantum mechanics:

(1) We can describe **agents in nature that cause change** by mathematical operators.

(such as forces)

In particular, there are operators for the EM, strong, and weak forces.

Example: Act with the EM operator O_{EM} on an up quark $|u\rangle$:

$$O_{EM}|u\rangle = ?$$

(2) If an operator does not change the nature of the state, but just scales it by a coefficient, we say the state is an **eigenstate of the oper**ator

so in particular: $O_{EM}|q\rangle = |q\rangle$

and $O_{strong}|q\rangle = |q\rangle$

but this can happen: $O_{weak}|q\rangle = |q'\rangle$ where $|q\rangle \neq |q'\rangle$

Physical quarks are not eigenstates of O_{weak}.

To construct the eigenstates of O_{weak}, suppose they come in pairs:

<div style="color:green">Pair #1   Pair #2   [Later, Pair #3 will be:]</div>

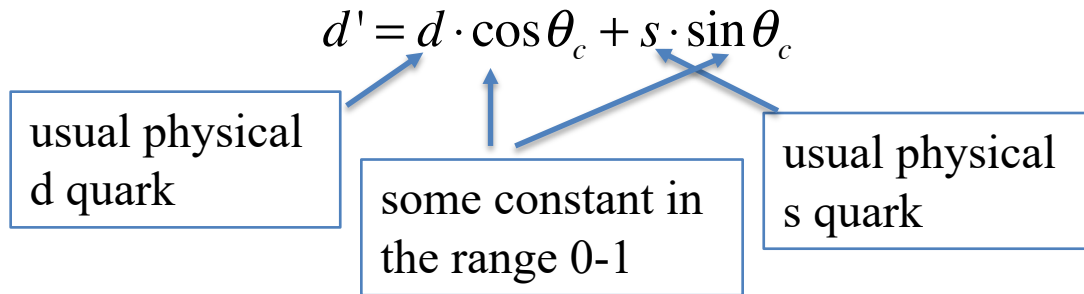$$\begin{pmatrix} u \\ d' \end{pmatrix} \qquad \begin{pmatrix} c \\ s' \end{pmatrix} \qquad \begin{pmatrix} t \\ b' \end{pmatrix}$$

Guess that the rules are:

(1) O_{weak} can only convert quark types back and forth within a pair
(e.g., $u \leftrightarrow d'$ or c $\leftrightarrow$ s')

(2) u is the wavefunction of the normal physical up quark. But
d′ is NOT the same as d, the physical down quark. Instead,

$$d' = d \cdot \cos\theta_c + s \cdot \sin\theta_c$$

usual physical
d quark

some constant in
the range 0-1

usual physical
s quark

(3) Similarly, c is the normal physical charm quark's
wavefunction, while

$$s' = -d \cdot \sin\theta_c + s \cdot \cos\theta_c$$

Put this info in matrix form:

The weak eigenstates are related to the physical ones by:

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}}_{\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix}} \begin{pmatrix} d \\ s \end{pmatrix}$$

Notice V_{ud} is the **amplitude for transition** u↔d

Note this is √ (the probability that it happens)

Now recall that there are really 6 quarks, so the matrix of quark couplings is actually 3x3:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

"The Cabibbo-Kobayashi-Maskawa (CKM) Matrix"

In a 3x3 matrix, one variable (θ_c) is no longer enough to describe all possible quark transitions: *we need 4 variables.* Call them θ_{12}, θ_{23}, θ_{13}, and δ_{13}.

To compress the notation, define: $cos\ \theta_{ij} = c_{ij}$
$$sin\ \theta_{ij} = s_{ij}$$

It turns out that one cannot avoid having this complex phase $e^{-i\delta_{13}}$ in some of the entries.

Then the CKM matrix is:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{-i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{-i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{-i\delta_{13}} & -c_{12}c_{23}-s_{12}c_{23}s_{13}e^{-i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

Optional slide on the necessary number of real and imaginary parameters:

- Consider first a 4-quark world, requiring a 2x2 "CKM" matrix (actually then called just the Cabibbo matrix):
  - The number of independent real parameters in a general 2x2 matrix: 3
  - We are free to change the phase of every quark's wavefunction arbitrarily. But changing the phase of all 4 quarks by the same amount has no effect, so we really have (4-1) = 3 free parameters.
  - So we can choose the transformation matrix to be all real, for a 4-quark system.

- Consider now a 6-quark world, requiring the actual 3x3 CKM matrix:
  - The number of independent real parameters in a general 3x3 unitary matrix: 6
  - (We need it to be unitary to preserve quantum mechanical probability.)
  - The number of arbitrary phases for 6 quarks: (6-1) = 5 free parameters
  - So we cannot make the CKM matrix all real; we must permit at least 1 complex phase.

Note: the CKM matrix is a MODEL of the relationships between quark states – so it requires experimental validation. *To check it, we must measure the rate of every type of transition.*

-end of Standard Model review -

In 1967, Andrei Sakharov proposed[*] that a combination of **3 ingredients can produce a matter/antimatter asymmetry:**

1) A natural process that does not conserve "matter-ness" (baryon number **B**). This process converts quarks into non-quarks (electrons, photons, neutrinos, etc.) This process leads to Baryon Number Violation...to be explained.

2) CP Violation......to be explained.

3) A period in the history of the universe when processes are out of thermal equilibrium....also to be explained.

Andrei Sakharov won the Nobel Peace Prize in 1975

[*]JETP Lett. 5, 25 (1967).

Explaining the 3 ingredients:

1) Baryon Number (**B**) Violation

An example of a process that violates **B** (and other quantum numbers too) is:

$$q \rightarrow e^- e^-$$

The same process, for antiquarks, would be

$$\overline{q} \rightarrow e^+ e^+$$

*No process that produces measurable B violation appears to be active in nature today. **But there is a class of models called Grand Unified Theories (GUTs) that attempt to unify the fundamental forces** – describe them all as different aspects of a single force. And GUTs naturally include **B** violation.
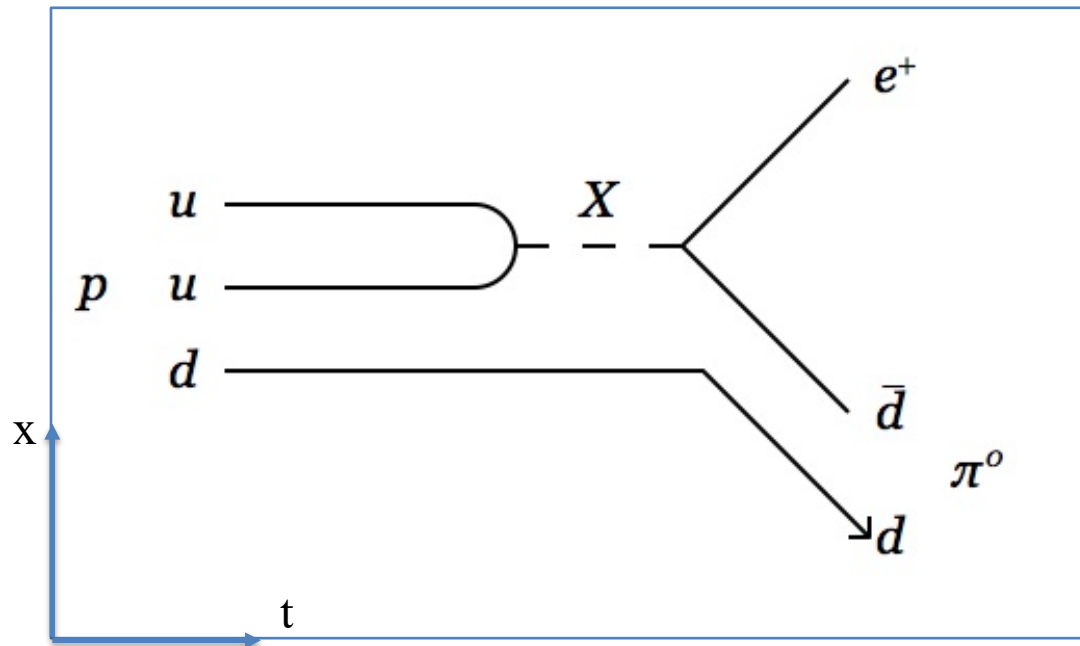
GUT's say:

The early universe had the same total energy as now, but was smaller

so it had higher energy density (energy/volume)

Very massive particles could be created in collisions then, via $E = mc^2$

Let's call those particles, X's and Y's, the "leptoquarks"

They could mediate **B** violation, for example through:

While that looks promising, *it's not enough*, because

B violation alone cannot create a matter/antimatter asymmetry. If CP is conserved, the rate of <u>matter loss</u> will always balance the <u>rate of antimatter loss</u>.
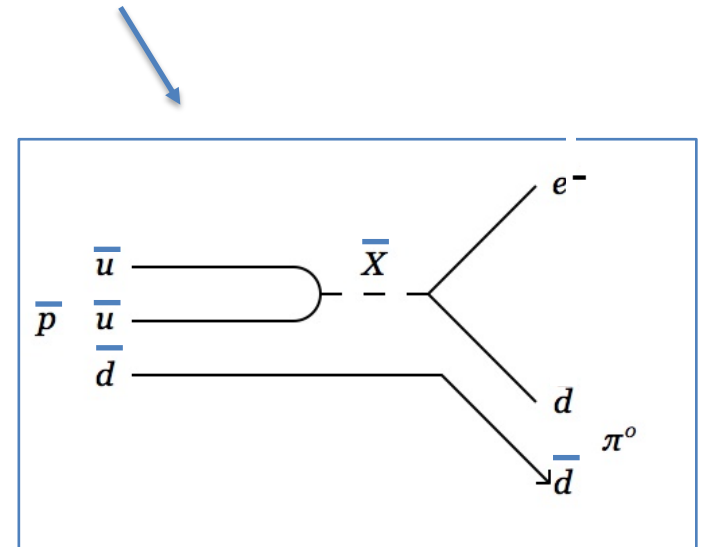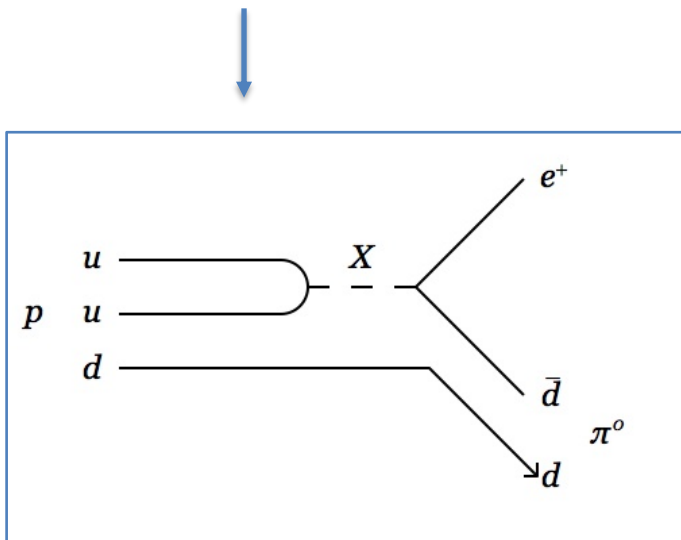
So in addition to **B**-violation, we need a process that treats matter and antimatter differently...

Ingredient #2: CP violation

Consider the decay of an elementary particle H:

$$H \rightarrow J + K$$

All of these particles have both momentum p and spin s.

The Parity operator **P** acts on the wavefunction of a particle by reflecting each vector through the origin. We can think of this as sort of like viewing that particle in a mirror.

Momentum: a vector, so its direction is reversed by a mirror.

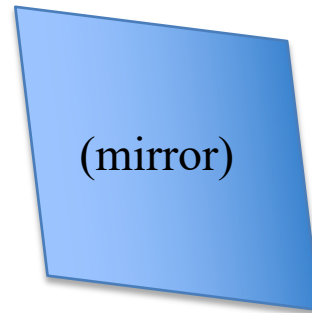Spin, a pseudovector, so its direction is NOT reversed by a mirror.

Decay before application of P	**Operate on all the particles' wavefunctions with P**	*Decay after application of P*

$$K \leftarrow H \rightarrow [J \Rightarrow \rightarrow]$$

$$\text{s} \quad \text{p}$$

(mirror)

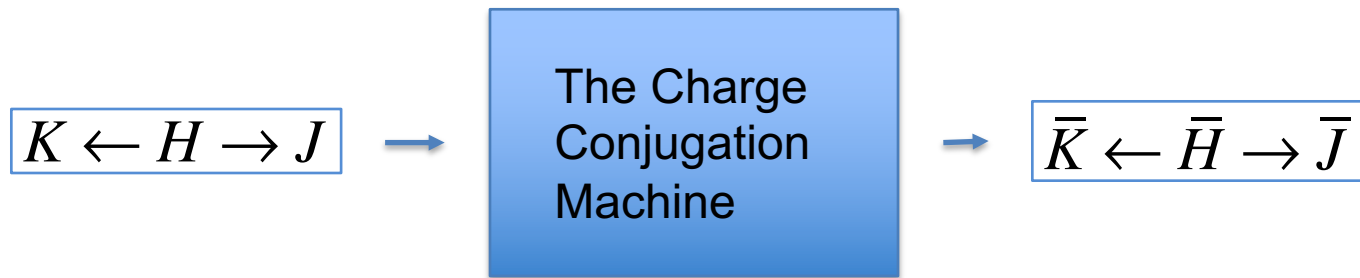$$[\leftarrow J \Rightarrow] \leftarrow H \rightarrow K$$

$$\text{p} \quad \text{s}$$
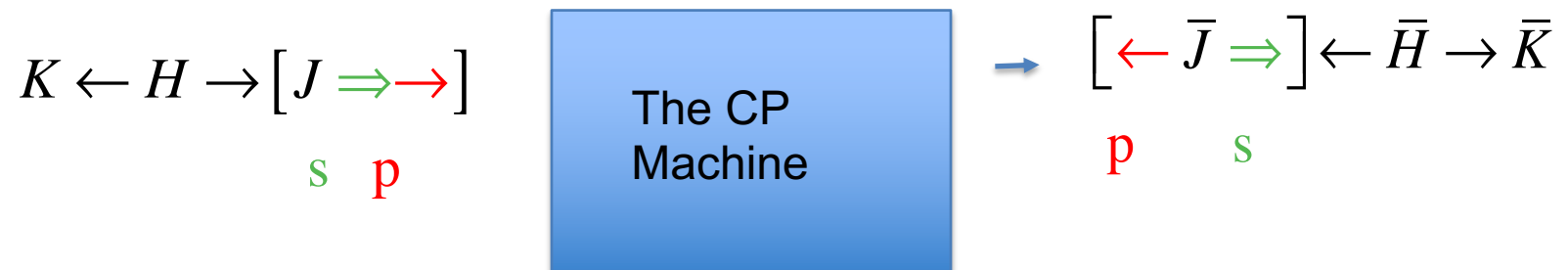
This particle J is "right-handed"

This particle J is "left-handed"

If **P** were conserved during weak decays, we should see left-handed and right-handed decay products with equal probability. We don't: *the weak force does not conserve parity **P***.

Charge conjugation C is an operator that acts on a particle's wavefunction to transform it into the antiparticle. *(Remember: an antiparticle is exactly like its corresponding particle in terms of mass, but with opposite physical charges, such as electric charge.)*

$$K \leftarrow H \rightarrow J$$ ⟶ The Charge Conjugation Machine ⟶ $$\bar{K} \leftarrow \bar{H} \rightarrow \bar{J}$$

Applying both **C** and **P** produces:

$$K \leftarrow H \rightarrow \left[J \Rightarrow \rightarrow \right]$$
s p

The CP Machine

⟶ $$\left[\leftarrow \bar{J} \Rightarrow \right] \leftarrow \bar{H} \rightarrow \bar{K}$$
p   s

Thus if CP is conserved by the weak force, 2 facts should always be true:

Formulation #1 of CP Conservation:
Rate (H $\rightarrow$ righthanded J) = Rate ($\overline{\text{H}}$ $\rightarrow$ lefthanded $\overline{\text{J}}$)

Formulation #2 of CP Conservation:
If H has a definite product of quantum numbers (C $\times$ P = -1 or +1), then the daughters J and K must have quantum numbers C and P which combine to produce the same value.

An experiment was carried out...and it showed that **CP is not conserved.** Here is how it was done....

Val Fitch and Jim Cronin won the Nobel Prize in 1980 for the discovery of CP Violation.
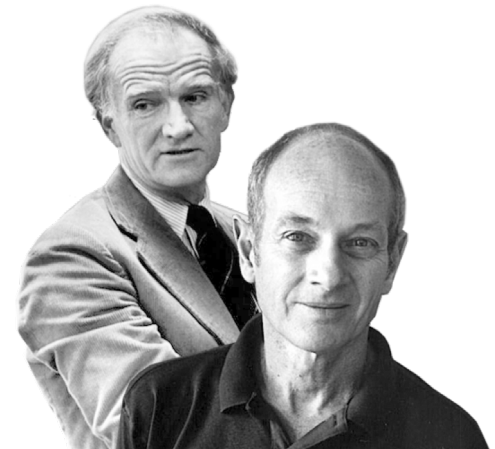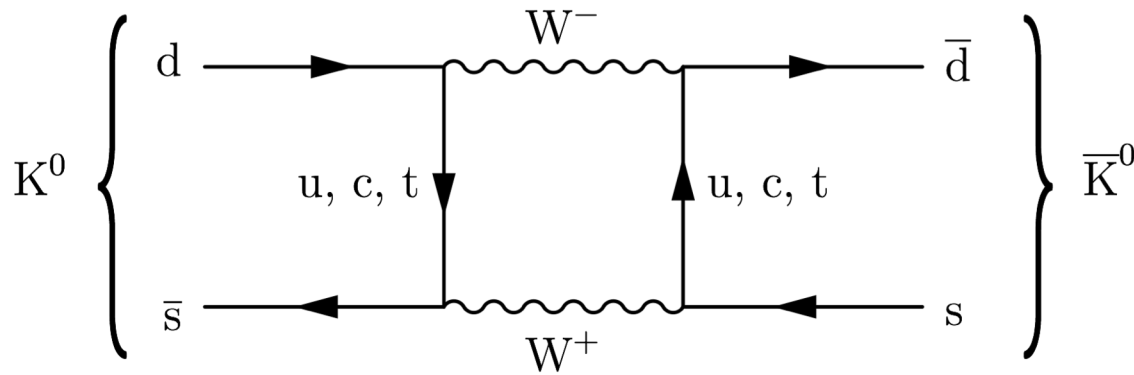
Consider some particles called K mesons ("kaons"). They are bound states of down quarks and strange quarks:

$$K^0 = d\ \bar{s} \qquad\qquad \bar{K}^0 = \bar{d}\ s$$

An interesting property of kaons:
the weak force causes K^0's and $\bar{K}^0$'s to turn into each other ("kaon mixing") as time passes, for example:

$$K^0 \left\{ \begin{array}{c} d \xrightarrow{} W^- \xrightarrow{} \bar{d} \\ u, c, t \qquad u, c, t \\ \bar{s} \xleftarrow{} W^+ \xleftarrow{} s \end{array} \right\} \bar{K}^0$$

So it is impossible to have a stable state of pure K^0 or pure $\bar{K}^0$. At any moment, there is always a mixture.

Define 2 linear combinations of the wavefunctions of these kaons:

$$|K_1\rangle \equiv \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \quad \text{and} \quad |K_2\rangle \equiv \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)$$

It turns out that

$$CP|K_1\rangle = +|K_1\rangle \quad \text{and} \quad CP|K_2\rangle = -|K_2\rangle$$

So K_1 is "CP even" and K_2 is "CP odd".

*Although we can't get a state of pure K^0's or K^0's, it IS experimentally possible to create a state of pure K_2.

What do kaons decay into? Pions, "π's" – mesons that are bound states of d and u quarks.

A state of 2π's is CP even.
A state of 3π's is CP odd.

So if CP is conserved in kaon decays, the pure K_2 state should decay only into 3 pions, never just two.

The experiment by Fitch and Cronin discovered that sometimes, $K_2 \rightarrow 2\pi$.
This means, *sometimes CP is not conserved by the weak force. Nature does treat matter and antimatter differently.*

So the combination of B violation + CP violation looks promising as a means to explain the matter/antimatter asymmetry. But! **a third ingredient is essential**. Here is why:

Suppose that in the early universe,

- There are X's converting $q's \rightarrow \overline{q}'s$
- There are $\overline{X}'s$ converting $\overline{q} \rightarrow q$
- There is CP violation enhancing the $q \rightarrow \overline{q}$ rate.

*...we STILL won't get the asymmetry if the universe is in **thermal equilibrium**.*

In thermal equilibrium, every process AND ITS REVERSE PROCESS have the SAME RATE, so the processes that create X's and $\overline{X}'s$ will operate as fast as the processes that decay them.

In a system at thermal equilibrium, an enhanced rate of $\bar{q} \rightarrow q$ will just make extra q's

make extra X's

make extra $\bar{q}\,'s$

cancel any enhancement.

The way to "lock in" a matter/antimatter asymmetry is for the universe to reach a state of coolness beyond which no more X's and $\bar{X}\,'s$ can be produced. That is: we need **a stage at which the temperature is too low** to get $2 \cdot m_X$ from $E = mc^2$.

*THEN the remaining X's and $\bar{X}\,'s$ decay away, and if a quantum mechanical fluctuation happens to have produced just a few more of one or the other right before the cooling process onset, those few will not be annihilated, and **there will remain a residual matter/antimatter asymmetry.***

This moment in the history of the universe when X and $\bar{X}$ could decay but no longer be created is the:

Ingredient #3: thermal non-equilibrium.

This is a beautiful idea, and no one has found a logical error in it. But **how do we know if it is the correct explanation** for the situation in our universe? We need to find out:

1). *whether B violation can be explained by the Standard Model – or does it require New Physics?*

2). *whether CP violation can be explained by the Standard Model, and does it happen often enough to account for the size of the observed asymmetry?*

3). *What mechanism would provide the thermal non-equilibrium and be consistent with present known facts of cosmology?*

The status of answering Question 1: the Baryon Number Violation

- The Standard Model includes a class of processes – "anomalies" - that naturally violate baryon number.[*] The rate for this is highly suppressed at temperatures corresponding to most of the history of the universe, but could proceed unsuppressed[**] during the era when the ambient temperature was 100 GeV - that's 10^{15} Kelvin degrees, about 10^{-11} seconds after the Big Bang. Still the average rate of B violation will be zero unless there is a process that favors fluctuations.[***]. *So New Physics is probably required.*

- B violation is a natural part of Grand Unified Theories, as these include the leptoquarks that convert quarks to non-quarks. To test whether GUT's apply to our actual universe: *look, experimentally, for proton decay.*

[*]G. 't Hooft, PRL 37, 8 (1976).
[**] V.A. Kuzmin et al., Phys Lett. B 155, 36 (1985).
[***]A.G. Cohen, et al., Annu. Rev. Nucl. Part. Sci. 43, 27 (1993), including references.

About Question 3 – the mechanism for thermal non-equilibrium.

▪ It turns out that *just waiting for the universe to expand and cool does not produce the asymmetry*[*] (the "baryogenesis") that is observed.

▪ *There needs to be an instant of "supercooling"* during the history of the universe. *The weak phase transition (when particle mass became possible, at temperature 159 GeV) might have provided this.*[**]

[*]E.W. Kolb and M.S. Turner, The Early Universe, Addison-Wesley (1990).
[**] V.A. Kuzmin et al., Phys Lett. B 155, 36 (1985); A. G. Cohen et al., Phys. Lett. 245 B, 561 (1990); N. Turok et al., PRL 65, 2331 (1990); L. McLerran et al., Phys. Lett. 256 B, 451 (1991).

About Question 2: Does CP Violation arise naturally in the Standard Model?
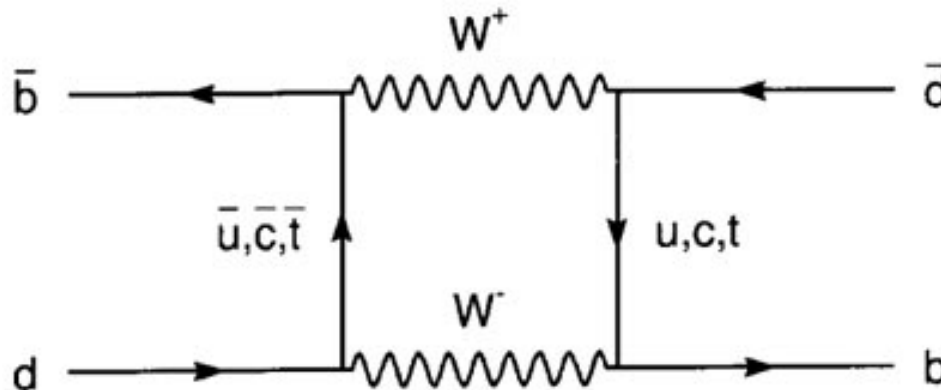
Consider these particles:

$B^0 = \bar{b}d$

$\bar{B}^0 = b\bar{d}$

$\psi = \bar{c}c$

K_s^0 : sort of like a K_2, can mix to become either K^0 or $\bar{K}^0$.

Note: B^0 and $\bar{B}^0$ mix, as the kaons do:

Consider 2 CP-conjugate decays[*]:

$$B^0 \to \psi K_s^0 \qquad \text{and} \qquad \overline{B}^0 \to \psi K_s^0$$

Plan:

- Use Standard Model rules to *predict both rates*.
- Recall that rate = |total amplitude|^2.
- *Each process has more that one amplitude* to be summed to produce the total.
- **If unequal rates are predicted, then CP Violation is a natural consequence of the Standard Model.**

[*]This example was motivated by I. Bigi and A. Sanda, PRD 29, no. 7, 1393 (1984).
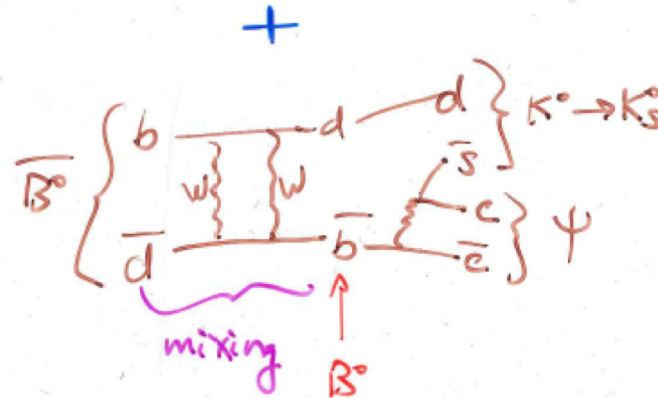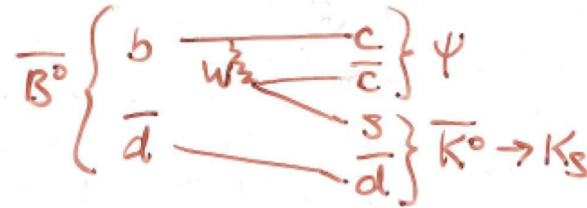
Total amplitude for
$B^0 \to \psi K_s^0$
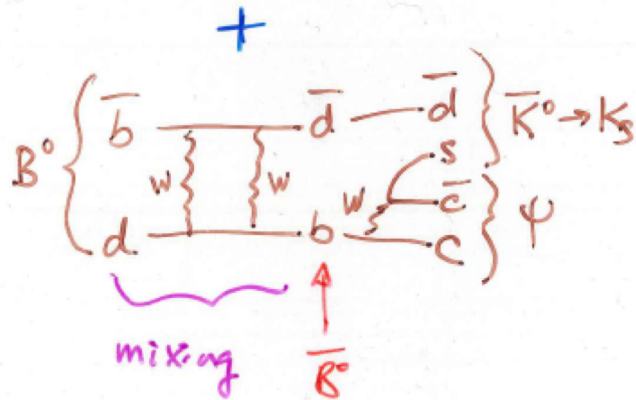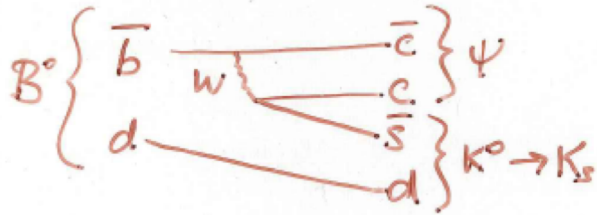
Total amplitude for
$\bar{B}^0 \to \psi K_s^0$

This TOTAL amplitude
$\propto V_{bc}^* V_{cs} + A_{mix} V_{bc} V_{cs}^*$

This TOTAL amplitude
$\propto V_{bc} V_{cs}^* + A_{mix} V_{bc}^* V_{cs}$

These are NOT EQUAL, because
$V_{cs} = c_{12} c_{23} - s_{12} s_{23} s_{13} e^{-i\delta_3}$, and $\text{Im}(e^{-i\delta_3}) \neq 0$

So the presence of the complex phase in the CKM matrix makes CP violation in B-meson decays *a natural part of the Standard Model.* CP-violation in B mesons was experimentally observed[*] in 2001, by combining studies of this decay mode with others.

Only very recently, CP violation was observed in decays of charm quarks.[**]

The problem is: *when we add up all of this CP-violation, it does not produce a large enough baryon asymmetry to account for what is observed in our universe.* It occurs at a rate that is a factor of 10^{-10} too low!

So New Physics is needed, in addition.

[*]K. Abe et al. (Belle Collaboration), PRL 87, 091802 (2001); B. Aubert et al. (Babar Collaboration), PRL 87, 091801 (2001).
[**]R. Aaij et al. (LHCb Collaboration), PRL 122, 211803 (2019).

Places to look for more CP violation:

(1). In leptons. The lepton families have their own mixing matrix, like the CKM – it's called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, and it too indicates a mechanism for mixing that could lead to CP violation. *In April 2020, the T2K Experiment in Japan reported* the first possible experimental observation of CP violation in leptons*, using 9 years of data.
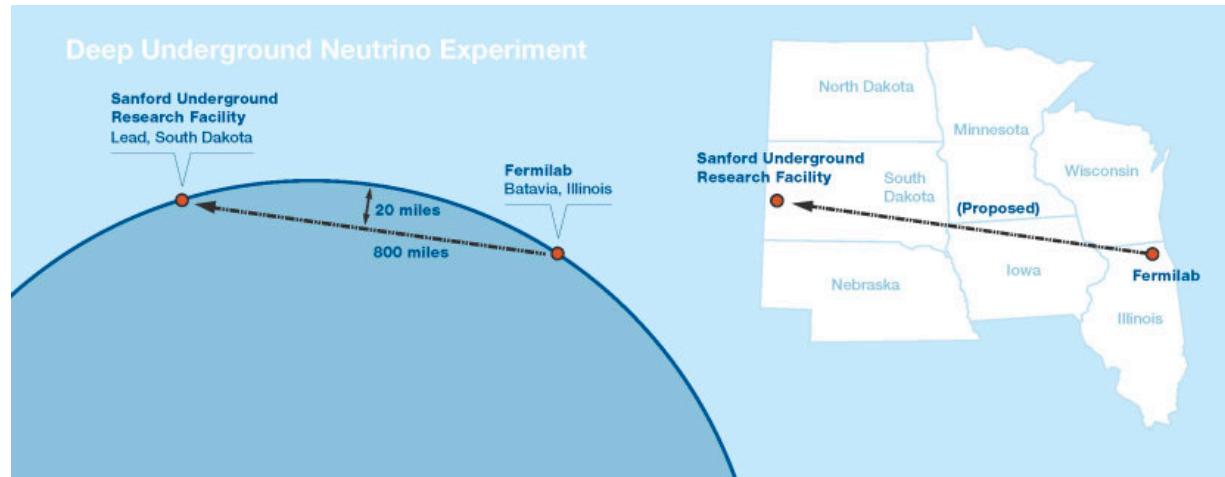
Confirmation of this could come from the planned T2HK and in-construction DUNE experiments.

*K. Abe et al., Nature 580 (7803) 339-344; arXiv:1910.03887 (16 April 2020).

Leptons might manifest CP-violation in 3 different ways. And if that is still not enough to make the Sakharov mechanism work – what other sources are there?

(2). Could there be CP-violation produced in strong interactions, as it is in the weak? Not observed yet – but it's not clear why not. This is called **the Strong CP Problem.**

(3). And if none of these are enough – we need completely new physics to obtain enough CP violation to apply the Sakharov model to our universe – new particles and forces would have to be added to the Standard Model, and observed.

Summary

- There is astronomical evidence for the matter-antimatter asymmetry, universally.
- Andrei Sakharov proposed a combination of 3 effects that could explain it – Baryon Number Violation + CP Violation + Thermal non-equilibrium.
- To understand these effects, we've reviewed some features of the Standard Model.
- The Baryon Number Violation requires New Physics, and this motivates searches for proton decay.
- The thermal non-equilibrium is not sufficiently achieved with the observed universal expansion – but might have been accomplished by the electroweak phase transition – when Higgs particles were born and mass became possible.
- CP violation arises naturally in the quark sector of the Standard Model. It's been observed in K, D, and B mesons. But that's not enough. It may now also have been observed in leptons. This needs further study – planned by the T2HK and DUNE experiments.
- **And if they don't observe enough CP violation to explain the matter/antimatter asymmetry – we need new physics.**