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Beauty for Pedestrians
Toy Models for CP Violation and Baryon Asymmetry

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ABSTRACT

Why are particles different from antiparticles? C and P Violation - 1956; CP Violation - 1964. Why so little new experimental information in thirty years? Where has all the antimatter gone? Toy models are presented showing: 1. How CPT and $\Delta I = 1/2$ make life difficult in kaon physics by requiring equal $K^{\pm}$ total widths and also equal partial widths to many exclusive channels. 2. How to understand and get around CPT restrictions. 3. How CP asymmetries can occur in exclusive partial widths and still add up to equal total widths. 4. Sakharov's 1966 scenario for how CP Violation + proton decay can explain baryon asymmetry 5. How B physics can help.

1. A Toy model for understanding and beating CPT

CPT requires equal total widths for B^+ and B^- and also equal partial widths for all pairs of charge conjugate decays into exclusive channels described by the Fermi golden rule of first order perturbation theory [1]. Thus CP asymmetries can be observed only in decays violating the golden rule and these asymmetries in partial widths must somehow conspire to cancel in the total width. How this miracle can occur is seen in a simple B-decay toy model in which only $B \to K\pi$ decays occur. This model also illuminates a crucial ingredient in the search for CP violating charge asymmetries; namely the necessity for interference between two weak interaction diagrams with different weak phases and different strong phases. This requirement is much more general than the standard model and follows from a theorem[1] that charge asymmetry between decays of charge-conjugate hadrons $M^\pm$ to any pair $|f_i^\pm\rangle$ of charge conjugate eigenstates of the strong-interaction S matrix is forbidden by CPT to first order in the weak interaction and all orders in strong interactions.

In our toy model the isospin eigenstates $(K\pi)_I$ are exact strong-S eigenstates, the decay amplitudes for pairs $f^\pm$ of charge conjugate final states like $K^\pm\pi^o$ can be expressed by expanding these states into these isospin eigenstates, and CPT requires[1] equal magnitudes but not equal phases for the I=1/2 and 3/2 amplitudes.

$$A\{B^\pm \to f^\pm\} = \sum_{I=\frac{1}{2},\frac{3}{2}} C_I^f |A\{B^+ \to (K\pi)_I\}| \cdot e^{\pm iW_I} e^{iS_I} \tag{1a}$$

$$|A\{(B^+ \to (K\pi)_I\}| = |A\{B^- \to (\bar{K}\pi)_I\}| \tag{1b}$$

where C_I^f denote Clebsch-Gordan coefficients, S_I and W_I denote respectively a strong (CP-conserving) phase and a weak (CP-violating) phase which have respectively the same and opposite signs for charge-conjugare amplitudes. I=3/2 - 1/2 interference can produce charge asymmetry,

$$|A^+(K^+\pi^o)|^2 - |A^-(K^-\pi^o)|^2 = -4C_{\frac{1}{2}}^f C_{\frac{3}{2}}^f |A_{\frac{1}{2}} A_{\frac{3}{2}}| \sin(W_{\frac{1}{2}} - W_{\frac{3}{2}}) \sin(S_{\frac{1}{2}} - S_{\frac{3}{2}}) \tag{2a}$$

$$|A^+(K^o\pi^+)|^2 - |A^-(\bar{K}^o\pi^-)|^2 = 4C_{\frac{1}{2}}^f C_{\frac{3}{2}}^f |A_{\frac{1}{2}} A_{\frac{3}{2}}| \sin(W_{\frac{1}{2}} - W_{\frac{3}{2}}) \sin(S_{\frac{1}{2}} - S_{\frac{3}{2}}) \tag{2b}$$

The asymmetries are equal and opposite for the two charge states, cancel in the total rates as expected from CPT and vanish unless *both* $W_{\frac{1}{2}} \neq W_{\frac{3}{2}}$ *and* $S_{\frac{1}{2}} \neq S_{\frac{3}{2}}$. The condition for asymmetry is that at least two amplitudes arising from different strong eigenstates must contribute with both different strong phases and different weak phases.

The underlying physics can also be seen by describing the transition as a weak transition to a definite final state followed by final state rescattering.

$$\frac{W_{B^+\rightarrow K^+\pi^o}}{W_{B^-\rightarrow K^-\pi^o}} = \frac{|S_{el}M(K^+\pi^o) + S_{cex}M(K^o\pi^+)|^2}{|S_{el}M(K^-\pi^o) + S_{cex}M(\bar{K}^o\pi^-)|^2} \tag{3}$$

where the charge conjugate weak interaction matrix elements $M(K^{\pm}\pi)$ and $M(K\pi^{\pm})$ have equal magnitudes and possibly different phases, and the strong interaction S matrix elements S_{el} and S_{cex} for for elastic and charge exchange scattering are invariant under charge conjugation. Here we see that the condition for an asymmetry is two weak diagrams with different CP-violating phases and two different strong transitions for elastic and charge exchange scattering. This explains the perhaps puzzling result in the isospin description requiring different strong phases as well as weak phases. If the strong phases are equal for both isospins, the S-matrix is the unit matrix in isospin and there is no charge-exchange scattering.

In the standard model two diagrams, trees and penguins, depending upon different CKM matrix elements and therefore having different weak phases contribute to $B \rightarrow K\pi$ decays via two different strong eigenstates [2,3]. The tree diagram goes via the weak vertices, $b \rightarrow u$ and $u \rightarrow s$ and gives only $K^{\pm}\pi^o$, which is a linear combination of I=1/2 and I=3/2. The penguin diagram goes via the weak vertices, $b \rightarrow c$ and $c \rightarrow s$ and gives only the I=1/2 $K\pi$ final state. The CKM matrix elements for the penguin are seen to be much larger than those for the tree. Thus the penguin is expected to be strong enough to compete with the tree and produce tree-penguin interference and CP violation.

This model has no simple counterpart in the kaon system. Here both $K\pi$ isospin eigenstates $I = 1/2$ and $I = 3/2$ are $\Delta I = 1$ and equally allowed. In $K^{\pm} \rightarrow (\pi\pi)_I$ there is only a single allowed isospin and no possibility of interference. In $K^{\pm} \rightarrow (3\pi)_I$ two isospins are allowed, but $I = 3$ is $\Delta I = 5/2$ and expected to be strongly suppressed. This is one reason for the difficulty in finding CP violation in kaon physics.

2. The Sakharov scenario for baryon asymmetry in a simplified toy model

If the numbers of baryons and antibaryons are equal at the time of the Big Bang, the difference $(n_{\bar{N}} - n_N)$ must decrease with time: $\frac{d}{dt} \cdot (n_{\bar{N}} - n_N) < 0$. This violates baryon number conservation. The proton must decay, but slow enough to explain the failure to observe the decay.

Suppose the decay occurs via a very weak interaction through emission and absorption of a new superheavy boson,

$$p \rightarrow e^+ + K^- + \pi^+; \;\; \bar{p} \rightarrow e^- + K^+ + \pi^- \tag{4a}$$

CPT says $\tau(p) = \tau(\bar{p})$. So proton decay is not enough. The same weak interaction can give

$$K^+ + p \to e^+ + \pi^+; \quad K^- + \bar{p} \to e^- + \pi^- \tag{4b}$$

But CPT says these two transition rates are probably equal! Still no baryon asymmetry.

But if the K^- flux is bigger than K^+ flux, this can kill off $\bar{p}$ faster than p ! CP violation in B decay can produce charge asymmetry to get K^- flux bigger than K^+; e.g. via the charge asymmetry (2a) in B decays if $W_{B^+ \to K^+ \pi^o} < W_{B^- \to K^- \pi^o}$ Thus CPT can be satisfied, CP violated and a baryon asymmetry can arise if B^+ and B^- are produced equally, p and $\bar{p}$ are produced equally, B^- decays in mode that kills $\bar{p}$ and B^+ decays less in mode that kills p.

Thus baryon asymmetry is produced by CP violation if the following conditions first suggested by Sakharov[4] are met:

1. Baryon number violation $\Rightarrow$ proton decay
2. No thermal equilibrium (to prevent equalization of $K^{\pm}$ via statistical mechanics).
3. CP violation to produce charge asymmetry

3. Conclusion - Lessons from History

In 1956, after a 100% parity violation[5] was found in a difficult experiment, a much simpler experiment[6] showed that beta rays were polarized, proving parity violation. Anyone who had started our experiment[6] at the same time as Ambler et al[5] would have obtained results first and discovered parity violation. But the community had been brainwashed by the theorists who insisted that parity violation violated the "standard model" of that time. They only considered sensitive experiments where a negative result could shoot down this crazy theory, not a simple experiment that could only detect a 100% effect.

Moral for CP : Don't be brainwashed by the standard model. Keep it in mind but try to use a more general approach and look for clues in experimental data with insight looking beyond standard model folklore, the unitarity triangle and all that. There is still no experimental evidence for CP violation outside the neutral kaon system, nor for the CKM matrix as the source of CP violation. CP violation may rather arise from than new physics beyond the standard model.

Data inadequate for testing standard model CP predictions will be available long before adequate data. These preliminary data can supply information useful for planning subsequent experiments. There may also be unexpected large effects. Look for easy experiments that even Lipkin can do - even if theorists say no.

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