CP Violation in the Hadronic Sector

Symmetry Principles and K^0- $\bar{K}^0$ System

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Introduction

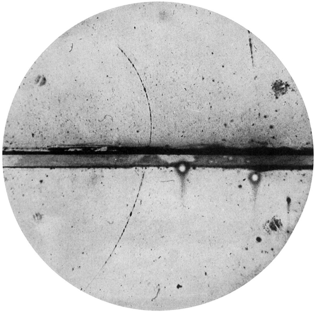

Figure 1: Discovery of the Positron [Anderson, C. (1932)]

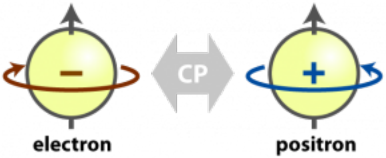

Figure 2: Ilustration of CP Symmetry

Parity ($\hat{P}$) and Charge Conjugation ($\hat{C}$)

The parity operation is equivalent to spatial inversion of a certain coordinate system such that $\mathbf{x} \to -\mathbf{x}$. Therefore,

$$\psi(\mathbf{x}, t) \to \psi'(\mathbf{x}, t) = \hat{P}\psi(\mathbf{x}, t) = \psi(-\mathbf{x}, t)$$

Applying the operator $\hat{P}$ once again, we recover the original wavefunction

$$\hat{P}\psi(-\mathbf{x}, t) = \psi(\mathbf{x}, t)$$

Hence, the parity operator is its own inverse. If the laws of physics are invariante under these transformations

$$\hat{P}^\dagger \hat{P} = I \quad \& \quad \hat{P}^\dagger = \hat{P}$$

Parity ($\hat{P}$) and Charge Conjugation ($\hat{C}$)

The effects of the charge conjugation are made by applying the operator $\hat{C}$ to the wavefunction/spinor such that

$$\psi \rightarrow \psi' = \hat{C}\psi$$

This operation replace particle wavefunction with the corresponding antiparticle wavefunction.

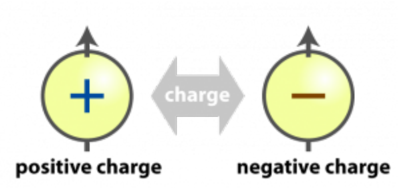

Figure 3: Ilustration of Charge Conjugation Symmetry

Parity ($\hat{P}$) and Charge Conjugation ($\hat{C}$)

Taking these results in the Dirac-Pauli representation, the operation of $\hat{P}$ and $\hat{C}$ can be written in function of the Dirac matrices as

$$\psi' = \hat{P}\psi = \gamma^0\psi \tag{1}$$

$$\psi' = \hat{C}\psi = i\gamma^2\psi^* \tag{2}$$

After applying these operators to the Dirac spinors, we found that parity is conserved in QED and QCD (apart from the colour factors).

Combination of $\hat{C}$ and $\hat{P}$ Operators

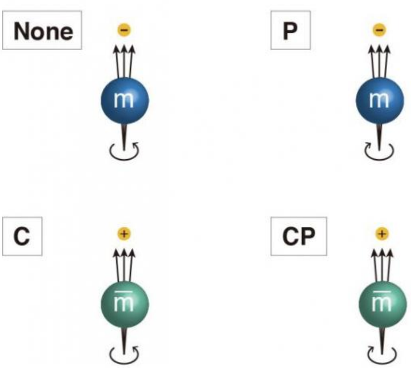

Figure 4: CP Symmetry scheme on mesons

Combination of $\hat{C}$ and $\hat{P}$ Operators

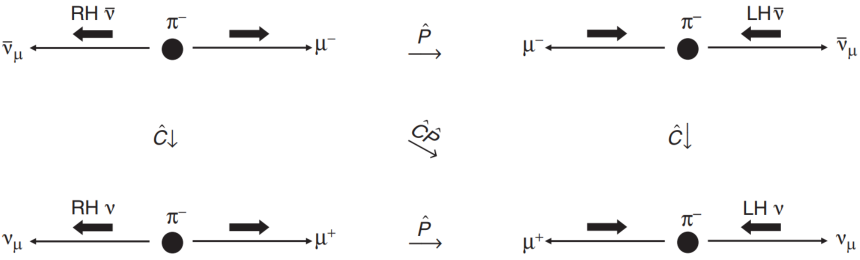

Figure 5: CP Symmetry in decay of the Pion system [Thomson, M. (2013)]

Direct CP Violation

Any observed difference between a decay rate $\Gamma(P \to f)$ and the CP conjugate $\Gamma(\bar{P} \to \bar{f})$ would indicate that CP is directly violated in the decay amplitude.

$$K_S^0 \to \pi^+ + \pi^- \qquad K_S^0 \to \pi^0 + \pi^0$$

$$K_L^0 \to \pi^+ + \pi^- + \pi^0 \qquad K_L^0 \to \pi^0 + \pi^0 + \pi^0$$

Figure 6: Neutral Kaon decay channels

$$m(K_S^0) \approx m(K_L^0) \approx 498 \text{ MeV}$$

$$\tau_{K_S^0} = 0.9 \times 10^{-10} \text{ s} \qquad \& \qquad \tau_{K_L^0} = 0.5 \times 10^{-7} \text{ s}$$

[Thomson, M. (2013)]

Indirect CP Violation

The Indirect CP violation arises from the mixing between particle and antiparticle states.

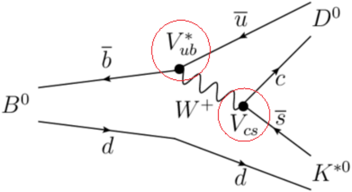

Figure 7: Decay of the B^0 meson [Aaij, R. *et al.* (2016)]

Indirect CP Violation

CP violation requires the presence of complex phases. The only part of the SM Lagrangian containing complex couplings is the Yukawa sector. Taking in consideration the quarks fields $U_{L,R}$ and $D_{L,R}$ [for up and down quarks]

$$U_{L,R} = \frac{1}{2}(1 \mp \gamma_5) \begin{bmatrix} u' \\ c' \\ t' \end{bmatrix} \quad \& \quad D_{L,R} = \frac{1}{2}(1 \mp \gamma_5) \begin{bmatrix} d' \\ s' \\ b' \end{bmatrix}$$

The Lagragian transforms as the charged-current couplings [Gamiz, E. (2004)]

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left\{ \bar{U}_L \gamma^\mu W_\mu^+ \mathbf{V} D_L + \bar{D}_L \gamma^\mu W_\mu^- \mathbf{V}^\dagger U_L \right\}$$

Where **V** is an unitary 3×3 matrix called the quark-mixing or Cabibbo-Kobayashi-Maskawa (CKM) matrix.

Indirect CP Violation - CKM Matrix

CKM matrix contains information on the strength of the flavour-changing weak interaction.

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

The SM Lagrangian remains invariant under the following transformation

$$U^i_{L,R} \longrightarrow e^{i\phi\left(u^i\right)} U^i_{L,R}, \quad D^j_{L,R} \longrightarrow e^{i\phi\left(d^j\right)} D^j_{L,R}, \quad V_{i,j} \longrightarrow e^{i\left(\phi\left(u^i\right)-\phi\left(d^j\right)\right)} V_{i,j}$$

In which, after proper parametrization, it results on complex phases that describe the mixing states of particles and anti-particles.

The Neutral Kaon System

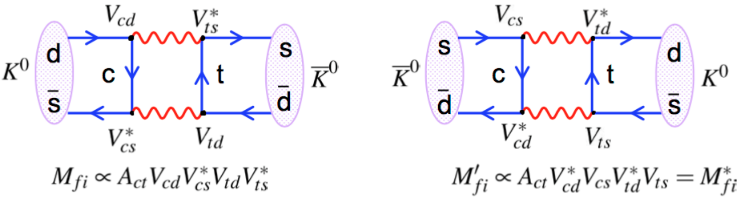

Figure 8: Neutral Kaon System decay

We already know there is a experimental diference in the decay rates of these system. Therefore

$$\Gamma(K^0 \to \bar{K}^0) - \Gamma(\bar{K}^0 \to K^0) \propto M_{fi} - M_{fi}^* = 2\Im\{M_{fi}\}$$

Hence, the decay rates can only be different if the CKM matrix has an imaginary component $\propto \Im\{M_{fi}\}$ [complex phases].

The Neutral Kaon System

Therefore the $K^0 - \bar{K^0}$ have a Direct and Indirect CP Violation.
So, the neutral kaons propagate as linear combinations of the K^0 and $\bar{K^0}$ such that the CP eigenstates can be described as

$$K_1 = \frac{1}{\sqrt{2}}(K^0 - \bar{K^0}) \quad \& \quad K_2 = \frac{1}{\sqrt{2}}(K^0 + \bar{K^0})$$

$$\hat{C}\hat{P}|K_{1(2)}\rangle = +(-)|\bar{K}_{1(2)}\rangle$$

As a consequence [Durt, T. *et al.* (2019)],

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left[|K_1\rangle + \epsilon\,|K_2\rangle\right]$$
$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left[\epsilon\,|K_1\rangle + |K_2\rangle\right]$$

Where ϵ is a complex CP-violation parameter.

The Neutral Kaon System

$$K_S^0 \to \pi^+ + \pi^- \qquad K_S^0 \to \pi^0 + \pi^0$$

$$K_L^0 \to \pi^+ + \pi^- + \pi^0 \quad K_L^0 \to \pi^0 + \pi^0 + \pi^0$$

Figure 9: Neutral Kaon decay channels

But, in 1969 it was observed the decay of K_L mesons into states of two pions, that were identified with K_2. This means that the physical K_L were not purely CP eigenstates but the result of a mixing between both CP odd K_2 [change of sign] and CP even K_1 [no change of sign], as the theory predicted.

In 2014, the measured $|\epsilon|$ was $(2.228 \pm 0.011) \cdot 10^{-3}$ [Durt, T. *et al.* (2019)].

The Neutral Kaon System

Moreover, in 1988 was made the first measurement of the ratio between the contribution of direct and indirect CP Violation in the K_L decay into two pions states, with their decay rates

$$\mathrm{Re}\left(\frac{\varepsilon'_{\mathrm{K}}}{\varepsilon_{\mathrm{K}}}\right) = \frac{1}{6}\left\{1 - \frac{\Gamma\left[\mathrm{K_L} \to \pi^+\pi^-\right]/\Gamma\left[\mathrm{K_S} \to \pi^+\pi^-\right]}{\Gamma\left[\mathrm{K_L} \to \pi^0\pi^0\right]/\Gamma\left[\mathrm{K_S} \to \pi^0\pi^0\right]}\right\}.$$

Where ϵ_K and ϵ'_K correspond to the indirect and direct CP Violation contributions, respectively.

Giving an experimental result of $\mathrm{Re}\left(\frac{\varepsilon'_{\mathrm{K}}}{\varepsilon_{\mathrm{K}}}\right) = (1.66 \pm 0.16) \cdot 10^{-3}$ [arXiv:hep-ex/9905060 (1999) & arXiv:hep-ex/0110019 (2001)].

Conclusion: This means that, in the neutral kaon decay, the contribution arises from mostly the indirect CP violation.

Current and Future Experiments

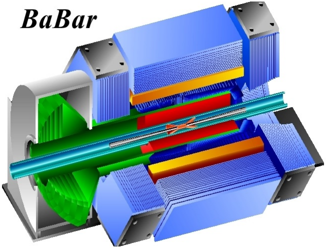

Figure 10: BaBar Experiment

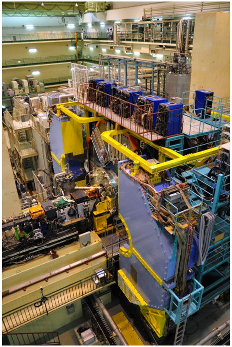

Figure 11: Belle Experiment

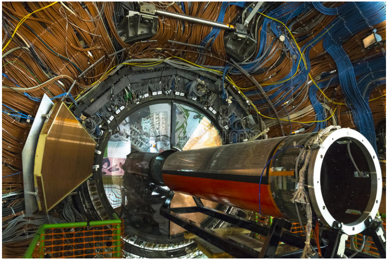

Figure 12: LHCb CERN

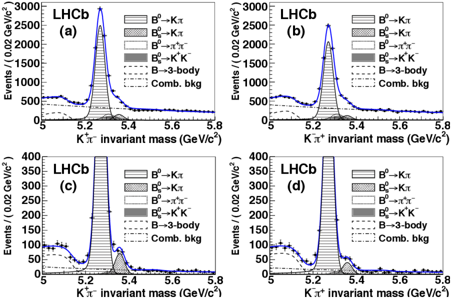

Figure 13: LHCb results for the B^0 decay [Karbach, T. (2012)]

Figure 14: T2K Experiment logo

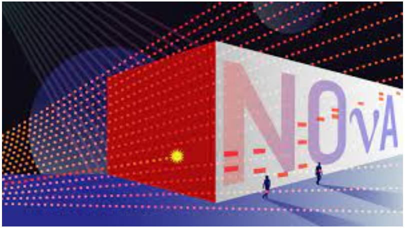

Figure 15: NOvA (Fermilab) Experiment logo

Conclusion

- CP Violation it's an essential topic when studying particle physics
- The existence of CP violation allows to explain the domination of matter over anti-matter in the Universe
- Helps us to exclude the different scenarios of particles creation in the early universe

References

[1] Carl D. Anderson. "The Positive Electron". In: *Phys. Rev.* 43 (6 1933), pp. 491–494. DOI: 10.1103/PhysRev.43.491. URL: https://link.aps.org/doi/10.1103/PhysRev.43.491.

[2] Mark Thomson. *Modern Particle Physics*. 2013.

[3] R. Aaij, Carlos Abellan Beteta, Bernardo Adeva, et al. "Model-independent measurement of the CKM angle γ using $B^0 \to DK^{*0}$ decays with $D \to K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$". In: (Apr. 2016).

[4] Elvira Gamiz. *Kaon Physics: CP Violation and Hadronic Matrix Elements*. 2004. arXiv: hep-ph/0401236 [hep-ph].

[5] Thomas Durt, Antonio Di Domenico, and Beatrix C. Hiesmayr. "Charge-conjugation-parity violation of neutral K-mesons in a temporal wave function model". In: *Eur.Phys.J.Plus* 134.3 (2019), p. 114. DOI: 10.1140/epjp/i2019-12468-6. URL: https://hal.science/hal-02101663.

[6] A. Alavi-Harati, I. F. Albuquerque, T. Alexopoulos, et al. In: *Physical Review Letters* 83.1 (1999), pp. 22–27. DOI: 10.1103/physrevlett.83.22. URL: https://doi.org/10.1103%2Fphysrevlett.83.22.

[7] A. Lai et al. and. In: *The European Physical Journal C* 22.2 (2001), pp. 231–254. DOI: 10.1007/s100520100822. URL: https://doi.org/10.1007%2Fs100520100822.

[8] Till Moritz Karbach and for the LHCb collaboration. "Results on direct CP violation in B decays in LHCb". In: *arXiv: High Energy Physics - Experiment* (2012).