Binary systems in QM and QFT: CPT.

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Quasi-degenerate neutral systems:

$(K, \bar{K})$, $(D, \bar{D})$, $(B, \bar{B})$

$\Downarrow$

Integrate other degrees of freedom

$\Downarrow$

Effective QM with

$$\boxed{H = M - i\frac{\Gamma}{2}}$$

$\Downarrow$

Most approaches to binary systems (and text books) do not go beyond QM level

QM of $K\bar{K}$

$$H = M - \frac{i}{2}\Gamma \quad ; \quad M^{+} = M, \quad \Gamma^{+} = \Gamma.$$

$$H = \begin{pmatrix} m_{11} - \frac{i}{2}\gamma_{11} & m_{12} - \frac{i}{2}\gamma_{12} \\ m_{21} - \frac{i}{2}\gamma_{21} & m_{22} - \frac{i}{2}\gamma_{22} \end{pmatrix}$$

$$|K_S\rangle = N_S \left[|K_1\rangle + \varepsilon_S |K_2\rangle \right]$$

$$|K_L\rangle = N_L \left[|K_2\rangle + \varepsilon_L |K_1\rangle \right]$$

CPT $\qquad H_{11} = H_{22}$

$$\Updownarrow$$

$$\boxed{\varepsilon_S = \varepsilon_L}$$

CP $\qquad H_{12} = e^{i\alpha} H_{21}$

$$\Updownarrow$$

$$\varepsilon = 0$$

Formalism of Mass Matrix seems never to be cast of doubt.

(Corrections to Wigner, Weisskopf)

Normality

$$[M, \Gamma] \neq 0 \iff [H, H^{+}] \neq 0$$

$$\Updownarrow$$

$$\{\langle out| \text{ space}\} \neq \{|in\rangle \text{ space}\}^{+}$$

$$H|K_{S,L}\rangle = \left(m_{S,L} - \frac{i\gamma_{S,L}}{2}\right)|K_{S,L}\rangle$$

$$\langle K_{S,L}|H = \left(m_{S,L} - i\frac{\gamma_{S,L}}{2}\right)\langle K_{S,L}|$$

$$\langle K_L|K_S\rangle = 0$$

$$\langle K_L| \neq |K_L\rangle^{+}$$

Effective QFT approach (motivated by ν-oscillations)

2x2 propagator

$$\hat{\Delta}(q^2) = \begin{pmatrix} \langle K|\hat{\Delta}|K\rangle & \langle K|\hat{\Delta}|\bar{K}\rangle \\ \langle \bar{K}|\hat{\Delta}|K\rangle & \langle \bar{K}|\hat{\Delta}|\bar{K}\rangle \end{pmatrix}$$

<u>Not-normal</u>

$$\hat{\Delta}(z)|R_\pm(z)\rangle = \lambda_\pm(z)\,|R_\pm(z)\rangle \quad , \quad z = q^2$$

$$\langle L_\pm(z)|\,\hat{\Delta}(z) = \lambda_\pm(z)\,\langle L_\pm(z)|\,;$$

<u>No-complex conjugation</u>

$$\langle R_+| \overset{\text{def}}{=} |R_+\rangle^+ \iff \langle R_+|R_-\rangle = 0$$

$$\langle K | \Delta(q^2) | K \rangle = \frac{Z_{KK}(q^2)}{q^2 - m_K^2 - \Pi_{KK}(q^2)}$$

Källen-Lehmann :

$$\hat{\Delta}(q^2) = \int_0^\infty \frac{ds}{s-q^2} \hat{\rho}(q^2)$$

<u>Analiticity</u>: $\hat{\Delta}(q^2) \Rightarrow \Delta(z)$

$z = q^2$

<u>Positivity</u>: $\hat{\Delta}(z) = [\hat{\Delta}(\bar{z})]^+$

Mass states $\Leftrightarrow$ poles of $\Delta(z)$

$$\boxed{\det\left(\Delta^{-1}(q^2)\right) = 0}$$

Two complex states

$z_1 = M_L^2$

$z_2 = M_S^2$

Introducing a mass matrix

QFT $\rightarrow$ QM

Near the pole $z \simeq z_i$:

$$\hat{\Delta}^{-1}(z) = \hat{A} z + \hat{B}$$

Positivity: $\hat{A}^{+} = \hat{A}$

$\Im m \hat{B} > 0$

Mass matrix

$$\Delta^{-1} \simeq \sqrt{A} \Big(z + \underbrace{\frac{1}{\sqrt{A}} B \frac{1}{\sqrt{A}}}_{M^{\{2\}} \equiv (M - \frac{i}{2}\Gamma)^2} \Big) \sqrt{A}$$

Near given pole z_i

we get <u>new</u> matrix M_i

$z_1 = M_L^2$

Physical states: $|R_+\rangle = |K_L\rangle_{in}$

$\langle L_+| = {}_{out}\langle K_L|$

Spurious states: $|R_-\rangle = |\widetilde{K}_L\rangle_{in}$

$\langle L_-| = {}_{out}\langle \widetilde{K}_L|$

Similar for $z_2 = M_S^2$

4 propagating states vs 4 spurious states.

CPT does not entail that CP parameter ϵ_L of K_L is <u>identical</u> to the one ϵ_S of K_S

$|K_L\rangle_{in} \sim \left(|K_2\rangle + \epsilon_L^{in} |K_1\rangle \right)$

$|K_S\rangle_{in} \sim \left(|K_1\rangle + \epsilon_S^{in} |K_2\rangle \right)$!!

"Applications".

Semi-Leptonic Asymmetries

$$\delta_{L,S} = \frac{|\langle \pi^- e^+ \nu | K_{L,S} \rangle|^2 - |\langle \pi^+ e^- \nu | K_{L,S} \rangle|^2}{|\langle \quad | \quad \rangle|^2 + |\langle \quad | \quad \rangle|^2};$$

$$A_{TCP} = \frac{|\langle \pi^+ e^- \nu | \bar{K} \rangle|^2 - |\langle \pi^- e^+ \nu | K \rangle|^2}{|\langle \quad | \quad \rangle|^2 + |\langle \quad | \quad \rangle|^2} \simeq$$

$$\overset{\Delta Q = \Delta S}{\simeq} \frac{|\langle \bar{K}(t_f) | \bar{K}(t_i) \rangle|^2 - |\langle K(t_f) | K(t_i) \rangle|^2}{|\langle \quad | \quad \rangle|^2 + |\langle \quad | \quad \rangle|^2};$$

PDG booklet

$$A_{TCP} = \delta_S - \delta_L \simeq 2\,\mathrm{Re}\,(\epsilon_S - \epsilon_L)$$

Explicit calculation

① $\left.\begin{aligned} \delta_L &\simeq 2\,\mathrm{Re}\,\epsilon_L^{in} \\ \delta_S &\simeq 2\,\mathrm{Re}\,\epsilon_S^{in} \end{aligned}\right\} \Rightarrow \begin{aligned} &\delta_L - \delta_S \sim 2\,\mathrm{Re}\,(\epsilon_L - \epsilon_S) \\ &\neq 0 \text{ for CPT!!} \end{aligned}$

② $A_{TCP} \sim \underset{|K\rangle}{\longrightarrow} \times \underset{|K_{S,L}\rangle}{\longrightarrow} \times \underset{|K\rangle}{\longrightarrow}$ +

$+ \underset{|K\rangle}{\longrightarrow} \times \underset{|K_{S,L}\rangle}{\longrightarrow} \times \underset{|K_{L,S}\rangle}{\longrightarrow} \times \underset{|K\rangle}{\longrightarrow}$ −

$- \underset{|\bar{K}\rangle}{\longrightarrow} \times \underset{|K_{S,L}\rangle}{\longrightarrow} \times \underset{|\bar{K}\rangle}{\longrightarrow}$ −

$- \underset{|\bar{K}\rangle}{\longrightarrow} \times \underset{|K_{S,L}\rangle}{\longrightarrow} \times \underset{|K_{L,S}\rangle}{\longrightarrow} \times \underset{|\bar{K}\rangle}{\longrightarrow}$

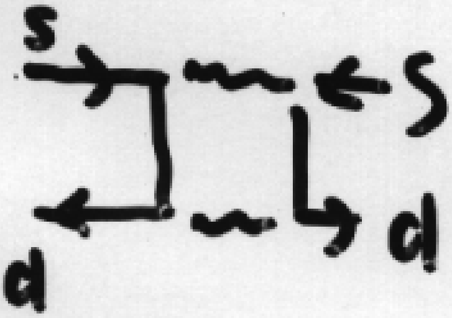
$\equiv 0 \qquad \sim \left(\langle K \to K \rangle \right|^{\ell}_{-} \langle \bar{K} \to$

$\Downarrow$

$A_{TCP} = 0 \neq \delta_S - \delta_L$!

A_{TCP} is a <u>good</u> test of TCP violation

Order of magnitude estimates of $\epsilon_S^{in} - \epsilon_L^{in}$



$$\Rightarrow \epsilon_S - \epsilon_L \sim \epsilon \frac{\Delta m_{L,S}}{m_W} \sim$$

$$\sim 10^{-18}$$

CPT violation

① Dolgov talk

② Non-local effects

$$\sim \frac{m_W}{m_{Pl}} \sim 10^{-17}$$

Conclusion

① There is substantial differences between QM and QFT in treatment of binary system

② QM is not appropriate framework for CPT violation if effects are small

(a) $\delta_L - \delta_S$ test the difference $\epsilon_S - \epsilon_L$

(b) A_{TCP} measures CPT violation

References

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