CPLEAR data on semileptonic decay of K^0 , $\bar{K}^0$ and the mass difference of K_L^0 and K_S^0 mesons

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It is demonstrated that for a determination of the mass difference of the K_L^0 and K_S^0 mesons an explicit theoretical formula to be derived by an assumption of the CP-conservation has been used by CPLEAR Collaboration in a fitting of the time-dependent CPLEAR data on ASYMMETRY.

So, in such procedure the mass difference $m_2 - m_1$ of the K_2^0 and K_1^0 mesons has been found and in no case $m_L - m_S$ one as in this case the CP-violation has to be considered.

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1. Introduction

The neutral K -mesons $K^0, \bar{K}^0$, produced in strong and electromagnetic (EM) interactions, appear with charged $K^\pm$ -mesons as the iso-doublets (K^+, K^0) and ($K^-, \bar{K}^0$) in the nonet of pseudoscalar mesons - $\pi^+, \pi^0, \pi^-, K^+, K^0, \bar{K}^0, K^-, \eta, \eta'$ - characterized by the quantum numbers $I(J^P) = 1/2(0^-)$ and the “strangeness” $S = +1$ and $S = -1$, respectively.

The single K^0 mesons can be produced e.g. in the process $\pi^- p \rightarrow K^0 \Lambda^0$.

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However, “concurrently” K^0 and $\bar{K}^0$ are produced by the $\bar{p}$ annihilation at rest in a hydrogen target $\bar{p}p \rightarrow K^-\pi^+K^0$ or $K^+\pi^-\bar{K}^0$ (CPLEAR at CERN) each having the branching ratio 2.10^{-3} .

Then the “strangeness” S of neutral K -mesons can be “tagged” by measuring the charge sign of the accompanying $K^\pm$ — therefore it is known “event by event”.

Another possibility to “tag” strangeness S of produced K^0 and $\bar{K}^0$ is an investigation of their subsequent semi-leptonic decays $K \rightarrow l\pi\nu$ ($l = e, \mu$) by the charge-sign of e.g. “positron” and “electron” in final state, as $K_0 \rightarrow e^+\pi^-\nu$ $\bar{K}_0 \rightarrow e^-\pi^+\bar{\nu}$.

The quantum number “strangeness” S is conserved in strong and EM interactions.

The violation of the strangeness S in weak interaction is responsible not only for decays of K^0 and $\bar{K}^0$ mesons, but also gives rise to the so-called “oscillations” of neutral K -mesons $K^0 \leftrightarrow \bar{K}^0$ in time.

Both K^0 and $\bar{K}^0$ can decay into two pions $\pi^0\pi^0$, $\pi^+\pi^-$ and also into three pions $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$, whereby the pion system possess well defined “CP-parity”, $+1$ and -1 , respectively.

However, neither K^0 nor $\bar{K}^0$ are eigenstates of CP operator, as

$$CP|K^0\rangle = -|\bar{K}^0\rangle$$

$$CP|\bar{K}^0\rangle = -|K^0\rangle.$$

On account of this reason new particles K_1^0 and K_2^0 have been defined to exist as a superposition of K^0 and $\bar{K}^0$

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$

with definite CP parity values

$$CP|K_1^0\rangle = +|K_1^0\rangle$$

$$CP|K_2^0\rangle = -|K_2^0\rangle.$$

As a consequence of the latter K_1^0 can decay into two pions and K_2^0 can decay into three pions.

But in 1964 the decay of $K_2^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$ with some small probability have been revealed¹ violating CP -invariance. As a consequence another two neutral K -mesons, K_S^0 and K_L^0 to be a linear combinations of K_1^0 and K_2^0 , have been introduced to exist

$$|K_S^0\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(|K_1^0\rangle + \varepsilon|K_2^0\rangle)$$

$$|K_L^0\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(\varepsilon|K_1^0\rangle + |K_2^0\rangle)$$

where ε is a complex CP -violation parameter, whereby $|\varepsilon| = 2,3 \cdot 10^{-3}$ and the CP -violation phase $\Phi = 43,5^\circ$.

Next $K^0 \leftrightarrow \bar{K}^0$ “oscillations” in vacuum are investigated.

First, oscillations through K_1^0 and K_2^0 mesons, when CP -invariance is considered. Then, oscillations through K_S^0 and K_L^0 mesons, considering the CP -violation, are discussed. However, according to our knowledge there are no experimental results on direct measurements of the $K^0 \leftrightarrow \bar{K}^0$ “oscillations” in vacuum.

Only measurements of the semi-leptonic decays of neutral K -mesons

$$\begin{aligned} K^0 &\rightarrow \pi^- e^+ \nu \\ \bar{K}^0 &\rightarrow \pi^+ e^- \bar{\nu} \end{aligned} \quad (4)$$

are carried out and the data on the so-called ASYMMETRY (see Fig. 1)

$$A_{\text{exp}}(\tau) = \frac{[R_+(\tau) + \bar{R}_-(\tau)] - [\bar{R}_+(\tau) + R_-(\tau)]}{[R_+(\tau) + \bar{R}_-(\tau)] + [\bar{R}_+(\tau) + R_-(\tau)]}, \quad (5)$$

extracting four decay rates R

$$\begin{aligned} R_+(\tau) &= R(K_{t=0}^0 \rightarrow \pi^- e^+ \nu_{t=\tau}) \\ \bar{R}_-(\tau) &= R(\bar{K}_{t=0}^0 \rightarrow \pi^+ e^- \bar{\nu}_{t=\tau}) \\ R_-(\tau) &= R(K_{t=0}^0 \rightarrow \pi^+ e^- \bar{\nu}_{t=\tau}) \\ \bar{R}_+(\tau) &= R(\bar{K}_{t=0}^0 \rightarrow \pi^- e^+ \nu_{t=\tau}) \end{aligned} \quad (6)$$

as a function of the decay eigentime τ of the lighter neutral K_S meson have been obtained from CPLEAR at CERN.

Therefore, we have first to evaluate theoretical formulas for probabilities of all possible transitions between neutral K mesons, $P(K^0(0) \rightarrow \bar{K}^0(t))$, $P(\bar{K}^0(0) \rightarrow K^0(t))$, $P(K^0(0) \rightarrow K^0(t))$, $P(\bar{K}^0(0) \rightarrow \bar{K}^0(t))$, and then substitution of the latter into (5) leads to an explicit theoretical formula for the ASYMMETRY mentioned above.

Fig. 1. The data on ASYMMETRY to be obtained by CPLEAR Coll.

But, before the latter, a relation between the mass difference of K_1^0 and K_2^0 , $(m_2 - m_1)$ and the mass difference of K_S^0 and K_L^0 , $(m_L - m_S)$ is derived in order to demonstrate that they are not identical.

2. Relation Between Mass Differences $(m_L - m_S)$ and $(m_2 - m_1)$

The complex masses of the K_1^0 and K_2^0 mesons can be defined as matrix elements of the weak Hamiltonian between K_1^0 and K_2^0 meson state vectors.

If one substitutes instead of the latter expressions to be expressed through $|K^0\rangle$ and $|\bar{K}^0\rangle$, one gets relations

$$m_1 - i\frac{\Gamma_1}{2} = \langle K_1^0 | H^w | K_1^0 \rangle = \frac{1}{2} [\langle K^0 | H^w | K^0 \rangle - \langle \bar{K}^0 | H^w | K^0 \rangle - \langle K^0 | H^w | \bar{K}^0 \rangle + \langle \bar{K}^0 | H^w | \bar{K}^0 \rangle]; \quad (7)$$

$$m_2 - i\frac{\Gamma_2}{2} = \langle K_2^0 | H^w | K_2^0 \rangle = \frac{1}{2} [\langle K^0 | H^w | K^0 \rangle + \langle \bar{K}^0 | H^w | K^0 \rangle + \langle K^0 | H^w | \bar{K}^0 \rangle + \langle \bar{K}^0 | H^w | \bar{K}^0 \rangle], \quad (8)$$

from where for the mass difference of K_2^0 and K_1^0 mesons one obtains

$$(m_2 - m_1) = \text{Re}\langle \bar{K}^0 | H^w | K^0 \rangle + \text{Re}\langle K^0 | H^w | \bar{K}^0 \rangle. \quad (9)$$

Now, similarly

$$\begin{aligned} m_S - i\frac{\Gamma_S}{2} &= \langle K_S^0 | H^w | K_S^0 \rangle \\ &= \frac{1}{2(1 + |\varepsilon|^2)} \times [(1 + \varepsilon^*)(1 + \varepsilon)\langle K^0 | H^w | K^0 \rangle \\ &\quad - (1 - \varepsilon^*)(1 + \varepsilon)\langle \bar{K}^0 | H^w | K^0 \rangle - (1 + \varepsilon^*)(1 - \varepsilon)\langle K^0 | H^w | \bar{K}^0 \rangle \\ &\quad + (1 - \varepsilon^*)(1 - \varepsilon)\langle \bar{K}^0 | H^w | \bar{K}^0 \rangle] \end{aligned} \quad (10)$$

$$\begin{aligned} m_L - i\frac{\Gamma_L}{2} &= \langle K_L^0 | H^w | K_L^0 \rangle \\ &= \frac{1}{2(1 + |\varepsilon|^2)} \times [(1 + \varepsilon^*)(1 + \varepsilon)\langle K^0 | H^w | K^0 \rangle \\ &\quad + (1 - \varepsilon^*)(1 + \varepsilon)\langle \bar{K}^0 | H^w | K^0 \rangle + (1 + \varepsilon^*)(1 - \varepsilon)\langle K^0 | H^w | \bar{K}^0 \rangle \\ &\quad + (1 - \varepsilon^*)(1 - \varepsilon)\langle \bar{K}^0 | H^w | \bar{K}^0 \rangle] \end{aligned} \quad (11)$$

and for the mass difference of K_L^0 and K_S^0 mesons one obtains the relation

$$\begin{aligned} (m_L - m_S) &= \frac{(1 - |\varepsilon|)^2}{(1 + |\varepsilon|)^2} (m_2 - m_1) \\ &\quad + \frac{2 \text{Im} \varepsilon}{(1 + |\varepsilon|^2)} [\text{Im}\langle K^0 | H^w | \bar{K}^0 \rangle - \text{Im}\langle \bar{K}^0 | H^w | K^0 \rangle] \end{aligned} \quad (12)$$

from where one can see immediately that both mass differences are not identical.

3. Oscillations of Neutral K Mesons Through K_1^0 and K_2^0

Now one can write relations

$$|K^0\rangle = \frac{1}{\sqrt{2}}(|K_1^0\rangle + |K_2^0\rangle), \quad |\bar{K}^0\rangle = \frac{1}{\sqrt{2}}(-|K_1^0\rangle + |K_2^0\rangle), \quad (13)$$

which are just the inverse transformations to those by means of which the existence of $|K_1^0\rangle$ and $|K_2^0\rangle$ has been introduced previously.

The time evolution of state vectors of K_1^0, K_2^0 is

$$|K_1^0(t)\rangle = e^{-im_1t - \Gamma_1/2t} |K_1^0(0)\rangle, \quad |K_2^0(t)\rangle = e^{-im_2t - \Gamma_2/2t} |K_2^0(0)\rangle \quad (14)$$

with m_1, m_2 and Γ_1, Γ_2 the masses and widths of K_1^0, K_2^0 , respectively.

Then, for the state vectors $|K^0(t)\rangle$ and $|\bar{K}^0(t)\rangle$ one can write expressions

$$\begin{aligned} |K^0(t)\rangle &= \frac{1}{2}[e^{-im_1t - \Gamma_1/2t} + e^{-im_2t - \Gamma_2/2t}] \cdot |K^0(0)\rangle \\ &\quad + \frac{1}{2}[e^{-im_2t - \Gamma_2/2t} - e^{-im_1t - \Gamma_1/2t}] |\bar{K}^0(0)\rangle \\ |\bar{K}^0(t)\rangle &= \frac{1}{2}[e^{-im_2t - \Gamma_2/2t} - e^{-im_1t - \Gamma_1/2t}] \cdot |K^0(0)\rangle \\ &\quad + \frac{1}{2}[e^{-im_1t - \Gamma_1/2t} + e^{-im_2t - \Gamma_2/2t}] \cdot |\bar{K}^0(0)\rangle \end{aligned} \quad (15)$$

to be ready for calculations of the $K^0 \leftrightarrow \bar{K}^0$ oscillations.

In order to find an explicit form of the theoretical ASYMMETRY $A_{th}(\tau)$ one has to calculate probabilities of the following transitions: $P(K^0(0) \rightarrow \bar{K}^0(t))$, $P(\bar{K}^0(0) \rightarrow K^0(t))$, $P(K^0(0) \rightarrow K^0(t))$ and $P(\bar{K}^0(0) \rightarrow \bar{K}^0(t))$.

The probability that the K^0 meson produced at the moment $t = 0$ will be at the moment $t \neq 0$ in the state of $\bar{K}^0$ meson, is given by the absolute value squared of the product $\langle \bar{K}^0(0) | \bar{K}^0(t) \rangle$. Similarly the reversed probability, whereby the orthogonality of $K^0(0)$ and $\bar{K}^0(0)$ states is exploited.

The result is an equality of $P(K^0(0) \rightarrow \bar{K}^0(t))$ and $P(\bar{K}^0(0) \rightarrow K^0(t))$

$$\begin{aligned} P(K^0(0) \rightarrow \bar{K}^0(t)) &\equiv P(\bar{K}^0(0) \rightarrow K^0(t)) \\ &= \frac{1}{4}[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2 \cos[(m_2 - m_1)t] e^{-\frac{(\Gamma_1 + \Gamma_2)}{2} t}] \end{aligned} \quad (16)$$

as we consider the CP -invariance which creates T -invariance because of the CPT conservation.

One has to calculate also $P(K^0(0) \rightarrow K^0(t))$ and $P(\bar{K}^0(0) \rightarrow \bar{K}^0(t))$ transitions in a similar way, which are taking the following forms

$$P(K^0(0) \rightarrow K^0(t)) \equiv P(\bar{K}^0(0) \rightarrow \bar{K}^0(t)) \quad (17)$$

$$= \frac{1}{4}[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + 2 \cos[(m_2 - m_1)t] e^{-\frac{(\Gamma_1 + \Gamma_2)}{2} t}]. \quad (18)$$

Substituting all these probabilities of the corresponding transitions into the theoretical ASYMMETRY (see (5))

$$A_{th}(t) = \frac{[P_{K^0(0) \rightarrow K^0(t)} + P_{\bar{K}^0(0) \rightarrow \bar{K}^0(t)}] - [P_{\bar{K}^0(0) \rightarrow K^0(t)} + P_{K^0(0) \rightarrow \bar{K}^0(t)}]}{[P_{K^0(0) \rightarrow K^0(t)} + P_{\bar{K}^0(0) \rightarrow \bar{K}^0(t)}] + [P_{\bar{K}^0(0) \rightarrow K^0(t)} + P_{K^0(0) \rightarrow \bar{K}^0(t)}]} \quad (19)$$

finally, the following three-parametric expression

$$A_{th}(t) = \frac{2 \cdot \cos[(m_2 - m_1)t] e^{-\frac{(\Gamma_1 + \Gamma_2)}{2}t}}{e^{-\Gamma_1 t} + e^{-\Gamma_2 t}} \quad (20)$$

is found, in which, however, the time t has to be redefined $t' = \frac{t}{\tau_1} \cdot \tau_1$.

4. Oscillations of Neutral K Mesons Through K_S^0 and K_L^0

The neutral K_S^0 and K_L^0 mesons have been introduced by the relations

$$\begin{aligned} |K_S^0\rangle &= \frac{1}{\sqrt{1 + |\varepsilon|^2}} (|K_1^0\rangle + \varepsilon |K_2^0\rangle) \\ |K_L^0\rangle &= \frac{1}{\sqrt{1 + |\varepsilon|^2}} (\varepsilon |K_1^0\rangle + |K_2^0\rangle), \end{aligned} \quad (21)$$

where ε is a complex CP -violation parameter, whereby $|\varepsilon| = 2,3 \cdot 10^{-3}$ and the CP -violation phase $\Phi = 43,5^\circ$.

If for K_1^0 and K_2^0 the previous relations

$$\begin{aligned} |K_1^0\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle - |\bar{K}^0\rangle) \\ |K_2^0\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle + |\bar{K}^0\rangle) \end{aligned} \quad (22)$$

are substituted, then one obtains K_S^0 , K_L^0 to be expressed through K^0 and $\bar{K}^0$ as follows

$$\begin{aligned} |K_S^0\rangle &= \frac{1}{\sqrt{2}\sqrt{1 + |\varepsilon|^2}} [(1 + \varepsilon)|K^0\rangle - (1 - \varepsilon)|\bar{K}^0\rangle] \\ |K_L^0\rangle &= \frac{1}{\sqrt{2}\sqrt{1 + |\varepsilon|^2}} [(1 + \varepsilon)|K^0\rangle + (1 - \varepsilon)|\bar{K}^0\rangle] \end{aligned} \quad (23)$$

and the inverse relations to them are

$$\begin{aligned} |K^0\rangle &= \frac{\sqrt{1 + |\varepsilon|^2}}{\sqrt{2}(1 + \varepsilon)} [|K_S^0\rangle + |K_L^0\rangle] \\ |\bar{K}^0\rangle &= \frac{\sqrt{1 + |\varepsilon|^2}}{\sqrt{2}(1 - \varepsilon)} [-|K_S^0\rangle + |K_L^0\rangle]. \end{aligned} \quad (24)$$

The time evolution of state vectors $|K_S^0\rangle$ and $|K_L^0\rangle$ is given by the expressions

$$|K_S^0(t)\rangle = e^{-im_S t - \Gamma_S/2t} |K_S^0(0)\rangle, \quad |K_L^0(t)\rangle = e^{-im_L t - \Gamma_L/2t} |K_L^0(0)\rangle, \quad (25)$$

with m_S, m_L and Γ_S, Γ_L the masses and widths of K_S^0, K_L^0 , respectively, and finally for $|K^0(t)\rangle$ and $|\bar{K}^0(t)\rangle$ one can then write

$$|K^0(t)\rangle = \frac{1}{2} \left[(e^{-im_S t - \Gamma_S/2t} + e^{-im_L t - \Gamma_L/2t}) |K^0(0)\rangle + \frac{(1 - \varepsilon)}{(1 + \varepsilon)} (-e^{-im_S t - \Gamma_S/2t} + e^{-im_L t - \Gamma_L/2t}) |\bar{K}^0(0)\rangle \right] \quad (26)$$

$$|\bar{K}^0(t)\rangle = \frac{1}{2} \left[\frac{(1 + \varepsilon)}{(1 - \varepsilon)} (-e^{-im_S t - \Gamma_S/2t} + e^{-im_L t - \Gamma_L/2t}) |K^0(0)\rangle + (e^{-im_S t - \Gamma_S/2t} + e^{-im_L t - \Gamma_L/2t}) |\bar{K}^0(0)\rangle \right]. \quad (27)$$

The probability that the K^0 meson produced at the moment $t = 0$ will be at the moment $t \neq 0$ in the state of $\bar{K}^0$ meson, is given by the absolute value squared of the product $\langle K^0(0) | \bar{K}^0(t) \rangle$, i.e.

$$\begin{aligned} P(K^0(0) \rightarrow \bar{K}^0(t)) &= \frac{1}{4} \frac{(1 + |\varepsilon|^2 + 2 \operatorname{Re} \varepsilon)}{(1 + |\varepsilon|^2 - 2 \operatorname{Re} \varepsilon)} [e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2 \cos[(m_L - m_S)t] e^{-\frac{(\Gamma_S + \Gamma_L)}{2} t}], \end{aligned} \quad (28)$$

whereby the orthogonality of $|K^0(0)\rangle$ and $|\bar{K}^0(0)\rangle$ states is again exploited. Similarly the probability of inverse transition

$$\begin{aligned} P(\bar{K}^0(0) \rightarrow K^0(t)) &= \frac{1}{4} \frac{(1 + |\varepsilon|^2 - 2 \operatorname{Re} \varepsilon)}{(1 + |\varepsilon|^2 + 2 \operatorname{Re} \varepsilon)} [e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2 \cos[(m_L - m_S)t] e^{-\frac{(\Gamma_S + \Gamma_L)}{2} t}]. \end{aligned} \quad (29)$$

One can see immediately that

$$P(K^0(0) \rightarrow \bar{K}^0(t)) \neq P(\bar{K}^0(0) \rightarrow K^0(t))$$

as we consider now CP -violation which creates T -noninvariance because of the CPT conservation.

In order to calculate the theoretical ASYMMETRY one has to calculate also $P(K^0(0) \rightarrow K^0(t))$ and $P(\bar{K}^0(0) \rightarrow \bar{K}^0(t))$ in a similar way.

They are

$$\begin{aligned} P(K^0(0) \rightarrow K^0(t)) &\equiv P(\bar{K}^0(0) \rightarrow \bar{K}^0(t)) \\ &= \frac{1}{4} [e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2 \cos[(m_L - m_S)t] e^{-\frac{(\Gamma_S + \Gamma_L)}{2} t}]. \end{aligned} \quad (30)$$

Substituting all these probabilities of the corresponding transitions into the theoretical ASYMMETRY (5) now the following five parametric expression is found

$$A_{th}(t) = \frac{2 \cos[(m_L - m_S)t] e^{-\frac{(\Gamma_S + \Gamma_L)}{2}t} - \frac{4 \operatorname{Re}^2 \varepsilon}{(1 + |\varepsilon|^2)^2} (e^{-\Gamma_S t} + e^{-\Gamma_L t})}{(e^{-\Gamma_S t} + e^{-\Gamma_L t}) - \frac{4 \operatorname{Re}^2 \varepsilon}{(1 + |\varepsilon|^2)^2} 2 \cos[(m_L - m_S)t] e^{-\frac{(\Gamma_S + \Gamma_L)}{2}t}}, \quad (31)$$

however, different from the previous relation with characteristics of K_1^0 , K_2^0 .

Since experimentally the ASYMMETRY is measured in the mean life time τ of K_S^0 , the time t is again redefined

$$t' = \frac{t}{\tau_S} \cdot \tau_S.$$

5. Conclusions

Despite of differences in theoretical ASYMMETRIES $A_{th}(t)$ given by (20) and (31), the authors of the CPLEAR Coll. paper² for a determination of mass differences $K_L - K_S$ have used the $A_{th}(t)$ formula (20) to be derived by considerations of $K^0 \leftrightarrow \bar{K}^0$ “oscillations” through K_1^0 , K_2^0 , i.e. by consideration of the CP-invariance.

In such a way they have measured actually the mass difference of $K_2 - K_1$ mesons and in no case $K_L - K_S$ one as they are declaring, because for a determination of mass difference $K_L - K_S$ the formula (31) has to be exploited to be derived under the assumption of the CP-violation.

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