New Developments in the K_S Decay Parameters and the
CP Violation Parameters in the K_L System[†]

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New measurements of the K_S lifetime and the CP violating decay $K_L \rightarrow \pi^+ \pi^-$ done since 1970 have differed significantly from previous values. The purpose of this review is to present what has happened and to reanalyze the state of the various parameters that describe the K_S and K_L decays.

Let me begin by discussing the history of the K_S lifetime. This is shown in Table 1 and in Figure 1. As can be seen there is a discrepancy between the measurements around 1967 and those in 1972. The change between these 2 sets is around 3.5% compared with an error assigned to each of the earlier experiments of about 1%. I will discuss this in more detail later on when I discuss the problems with the measurement of the CP violating decay $K_L \rightarrow \pi^+ \pi^-$ (η_{+-}). Let me just add that the measurement of this lifetime is very insensitive to η_{+-} . The two values of measurement #11 indicate that if the phase angle of η_{+-} changes sign, the lifetime changes by $\sim .8\%$.

The measurements of the K_S branching ratio is shown in Table 2 and here things are pretty consistent. It would be nice if we could reduce the errors but measuring the $K_S \rightarrow 2\pi^0$ mode is very hard. I don't expect much of an improvement in this measurement over the next few years. Measurements are insensitive to the value of the K_S lifetime. Only measurement #3 depends on it with the two entries showing what happens to the value due to the 3.5% change in the lifetime.

We can now combine these measurements with the $K^+ \rightarrow \pi^+ \pi^0$ decay rate and the $\pi \pi$ scattering phase shifts to get a feeling for how much $\Delta I = 5/2$ and $\Delta I = 3/2$ amplitude there exist in these decays. This state of affairs is shown in the next few pages and also in Figure 2. As can be seen there is a 3% $\Delta I = 3/2$ transition and there is no clear evidence for $\Delta I = 5/2$. Fig. 2 is a fit to the data showing that $(\Delta I = 5/2)/(\Delta I = 3/2) \sim 1/10$. This situation

will not improve until we reduce the errors in the $\pi\pi$ phase shifts and we can calculate much more accurately the electromagnetic corrections in the $K_S \rightarrow$ branching ratio. Neither one of these is expected to improve in the next year or so.

$$K^+, K_S \rightarrow 2\pi \quad \Delta I = 3/2, 5/2 \text{ Amplitudes}$$

From $\pi\pi$ scattering we have δ_J^I (phase shifts)

$$\delta_0^0 = (36 \pm 6)^\circ \quad (\text{varies between 30 and 42})$$

$$\delta_0^2 = (-7.5 \pm 2.5)^\circ \quad (\text{varies between 5 and 10})$$

$$\delta_0^2 - \delta_0^0 = (-43.5 \pm 6.5)^\circ \quad \cos(\delta_0^2 - \delta_0^0) = .725 \pm .078$$

Let $A_{0,2}$ = amplitude for 2π in $I = 0, 2$ state. The $I = 2$ state can be reached by $\Delta I = 3/2$ or $5/2$ transitions which we label a_3, a_5 .

$$\begin{aligned} \text{From } \frac{K^+ \rightarrow \pi^+ \pi^0}{K_S \rightarrow 2\pi} &= \frac{|\sqrt{3/2} a_3 - \sqrt{1/3} a_5|^2}{|A_0|^2} \frac{\rho_f(K^+ \rightarrow 2\pi)}{\rho_f(K_S \rightarrow 2\pi)} \\ &= \frac{(.8865 \pm .0068) \times 10^{-10}}{(1.2371 \pm .0026) \times 10^{-8}} \times .2106 \pm .0018 = (15.09 \pm .18) \times 10^{-4} \end{aligned}$$

$$\therefore \frac{|\sqrt{3/2} a_3 - \sqrt{1/3} a_5|}{|A_0|} = (3.904 \pm .023) \times 10^{-2}$$

From the K_S Branching Ratio

$$B.R. = 2.207 \pm .027 = .986 \left\{ 2 + 6\sqrt{2} \frac{\text{Re} A_2}{A_0} \cos(\delta_2 - \delta_0) \right\} + \text{e.c.}$$

where e.c. = $.006 \pm .04$ = electromagnetic corrections

$$\text{From } \left| \frac{K_L \rightarrow 2\pi^0}{K_S \rightarrow 2\pi^0} \right|^{1/2} \approx \left| \frac{K_L \rightarrow \pi^+ \pi^-}{K_S \rightarrow \pi^+ \pi^-} \right|^{1/2} \approx 2 \times 10^{-3} \left\} \rightarrow \frac{\text{Im} A_2}{A_0} \ll \frac{\text{Re} A_2}{A_0} = \frac{|A_2|}{A_0}$$

Since $A_2 = a_3 + a_5$ we can solve

$$\frac{\text{Re} A_2}{A_0} = \left\{ \frac{(2.207 - .006) \pm .05}{.986} - 2 \right\} \frac{1}{6\sqrt{2} \cos(\delta_2 - \delta_0)}$$

$$\text{or } \frac{|a_3 + a_5|}{A_0} = (3.77 \pm .90) \times 10^{-2}$$

Assuming T invariance we can consider a_3 and a_5 real and we get

$$\frac{a_3}{A_0} = (3.36 \pm .52) \times 10^{-2}$$

$$\frac{a_5}{A_0} = (.40 \pm .60) \times 10^{-2}$$

TABLE 1

Measurements of the K_S Lifetime(Includes only Measurements with $\Delta\tau \leq 0.05$) τ_{K_S} ($\times 10^{10}$ Sec)

- (1) $(0.94 \pm .05)$
- (2) $(0.94 \pm .05)$
- (3) $(0.885 \pm .025)$
- (4) $(0.90 \pm .05)$
- (5) $(0.87 \pm .05)$
- (6) $(0.86 \pm .04)$
- (7) $(0.8658 \pm .015)$
- (8) $(0.92 \pm .04)$
- (9) $(0.843 \pm .013)$
- (10) $(0.90 \pm .05)$
- (11) $(0.865 \pm .009) \rightarrow (0.872 \pm .009)$
- (12) $(0.856 \pm .008)$
- (13) $(0.8958 \pm .0045)$
- (14) $(0.899 \pm .005)$

$$\tau_{K_S} = (.8865 \pm 0.0027) \times 10^{-10} \text{ Sec}$$

$$\tau_{K_S} \text{ (not including last 2 measurements)} = (.8644 \pm .0048) \times 10^{-10} \text{ Sec}$$

TABLE 2

Measurements of B.R. = $(K_S \rightarrow \pi^+ \pi^-) / (K_S \rightarrow 2\pi^0)$

(Includes only Measurements with $\Delta(\text{B.R.}) \leq .11$)

- 1) $2.285 \pm .055$
 $2.282 \pm .043$ (appears in Bulletin APS later)
- 2) $2.10 \pm .06$
- 3) $0.345 \pm .005^{(a)} \rightarrow 2.22 \pm .095^{(b)} \rightarrow 2.18 \pm .095$
- 4) $2.22 \pm .08$
- 5) $0.345 \pm .005^{(a)} \rightarrow 2.22 \pm .10$
- 6) 2.10 ± 0.11
- 7) $0.342 \pm 0.004^{(a)} \rightarrow 2.16 \pm .08$

$$\text{B.R.} = 2.207 \pm .027$$

a) Really measures $(K_S \rightarrow \pi^+ \pi^-) / \text{all } K^0 \equiv R$

$$\text{B.R.} = \frac{K_S \rightarrow \pi^+ \pi^-}{K_S \rightarrow 2\pi^0} \approx \frac{2R}{1-2R} \pm \frac{2}{(1-2R)^2} \Delta R$$

where we assume the CPT prediction $K_S \approx 1/2(\text{all } K^0, \bar{K}^0)$.

b) Change in the value due to dependence on τ_S .

Now we want to discuss how the measurement of the mass difference $M_{K_L} - M_{K_S} = \Delta m$ and of the phase of $\eta_{+-} = \varphi_{+-}$ depends on the K_S lifetime. The present values of φ_{+-} and Δm are

$$\varphi_{+-} = 42.0 \pm 3.0$$

$$\Delta m = (.5402 \pm .0035) \times 10^{10} \text{ h sec}^{-1}$$

Using the gap regeneration method invented by Fitch we get the best measurements of the mass difference and then

$$\frac{\Delta m}{m} \approx \frac{1}{2} \frac{\Delta \tau_S}{\tau_S}$$

Using the free decay distribution to measure φ_{+-} the dependence for experiment 4 is

$$\frac{\Delta \varphi_{+-}}{m} = 295.0 \frac{\Delta m}{m} \approx 147.5 \frac{\Delta \tau_S}{\tau_S}$$

while others like experiment 3 are insensitive to changes in Δm .

If we assume that τ_S changes from $(.864 \rightarrow .897) \times 10^{-10}$ sec, a change of 3.4% we find in the worst case new values for Δm and φ_{+-} namely

$$\Delta m = (.549 \pm .004) \times 10^{10} \text{ h sec}^{-1}$$

$$\varphi_{+-} \approx 47.0 \pm 3.0$$

We must remember that the predictions of the "superweak theory" for φ_{+-} also change, namely

TABLE 3

$$\text{Measurements of } \eta_{+-} = \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} .$$

$$\eta_{+-} \times 10^3$$

- 1) $1.94 \pm .20$
- 2) $2.02 \pm .17$
- 3) $1.86 \pm .20$
- 4) $1.935 \pm .040$
- 5) $1.91 \pm .06$
- 6) $2.37 \pm .10$
- 7) $2.23 \pm .05 \rightarrow 2.25 \pm .05$
- 8) $2.38 \pm .15$

previously $\varphi_{+-} = \tan^{-1} \frac{2\Delta m \tau_S}{h} = \tan^{-1} 1.080 \times .864 = \tan^{-1} .933 = 43^\circ$

The new value $= \tan^{-1} 1.098 \times .897 = \tan^{-1} .985 = 44.5^\circ$

Hence the comparison of experiment and theory of this type will not be disrupted by the small changes in Δm and φ_{+-} .

Finally I would like to discuss what has happened with the measurement of $\eta_{+-} = |(K_L \rightarrow \pi^+ \pi^-) / (K_S \rightarrow \pi^+ \pi^-)|^{1/2}$. The state of affairs is shown in Table 3 and in Figure 3. Again we notice that the value of η_{+-} changed after 1970. There are now 3 measurements with the high value of η_{+-} . I would like to discuss this in relation to the new value of the K_S lifetime. There are 2 ways to measure η_{+-} :

1) Measure the branching ratio $K_L \rightarrow \pi^+ \pi^- / K_L \rightarrow \text{all charged or}$

$K_L \rightarrow \pi^+ \pi^- / K_L \rightarrow \text{any other decay mode } (K\pi_3, K\mu_3, Ke_3 \dots)$.

From these measurements one can get η_{+-} by the following

$$|\eta_{+-}|^2 = \frac{R(K_L \rightarrow \pi^+ \pi^-)}{R(K_S \rightarrow \pi^+ \pi^-)} = \frac{R(K_L \rightarrow \pi^+ \pi^-)}{R(K_L \rightarrow \text{all charged})} \times$$

$$\frac{R(K_L \rightarrow \text{all charged})}{R(K_L \rightarrow \text{all})} \times \frac{R(K_S \rightarrow \text{all})}{R(K_S \rightarrow \pi^+ \pi^-)} \times \frac{\tau_S}{\tau_L}$$

Hence in this case η_{+-} is only weakly dependent on the value of the K_S lifetime. η_{+-} increases by 1.7% due to the 3.5% change in τ_S .

This method of measuring η_{+-} was used by all the experiments in Table 3.

- 2) By measuring the shape of the free decay distribution of an initial K^0 or $\bar{K}^0$ beam into a $\pi^+\pi^-$ final state. The time distribution is given by

$$N_{+-} = N_0 \left(e^{-t/\tau_S} + |\eta_{+-}|^2 e^{-t/\tau_L} + 2 |\eta_{+-}| \cos(\Delta m t - \phi_{+-}) e^{-\frac{1}{2}(t/\tau_S + t/\tau_L)} \right)$$

Both experiments 6 and 8 in Table 3 use this method also to measure η_{+-} . Because of the experimental difficulties of measuring decays very near the target they only measure this distribution after a time $t \approx 7 \tau_S$. The fit to this distribution is very sensitive to τ_S . The value of η_{+-} obtained depends sensitively on the value of τ_S but not vice versa. Experiment 6 cannot get a good fit to the data with the old value of τ_S . Nevertheless both in experiment 6 and 8 they get $|\eta_{+-}| \approx 2 \times 10^{-3}$ with the old K_S lifetime and $|\eta_{+-}| \approx 2.35 \times 10^{-3}$ with the new lifetime. Hence both the changes in $|\eta_{+-}|$ and τ_S were of such magnitude and sign as to make the results from methods 1 and 2 compatible. That implies that if you assume the new values of η_{+-} are correct then one must conclude that the new values of τ_S are also correct if the expression for the free decay of K^0 describes the system properly.

HISTORY OF THE K_S LIFETIME

FIG 1

FIGURE 2-(a)

HISTORY OF η_{+-}

FIG 3

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