CP Violation in the Neutral K System†
(A brief review of the theory)

SUK KOO YUN‡
Department of Physics, Syracuse University,
Syracuse, New York 13210

Received: 2 March 1970

Abstract

The theoretical aspect of CP-violation is reviewed. The $K_S$ and $K_L$ states, the unitarity relation, parametrization and analysis, the electric dipole moment of the neutron, $\eta$ asymmetry and $C$ noninvariance in $\eta_{3\pi}$ are all discussed. Then five theoretical models concerning neutral $K \to 2\pi$ are dealt with.

1. Introduction

Although the possibility of CP violations was previously discussed theoretically, the discovery of the $K_L \to 2\pi$ decay (i.e. $K_L \to \pi^+ \pi^-$) by Christensen et al. (1964) started the discussions of the topic in earnest.

Experimentally (Barash-Schmidt et al., 1969) we observe the following nonleptonic weak decays of the neutral $K$ system:

$$
\begin{align*}
\pi^+ \pi^- \ (68.1 \pm 1.1)\% & \quad \tau_S = 0.874 \times 10^{-10} \text{ sec} \\
\pi^0 \pi^0 \ (31.6 \pm 1.1)\% & \quad \tau_L = 5.30 \times 10^{-8} \text{ sec}
\end{align*}
$$

The neutral $K$ system $\to \left\{ \begin{array}{l} 
\pi^+ \pi^- \ (68.1 \pm 1.1)\% \\
\pi^0 \pi^0 \ (31.6 \pm 1.1)\% \\
\pi^+ \pi^- \ (28.1 \pm 0.8)\% \\
\pi^+ \pi^- \ (0.157 \pm 0.001)\% \\
\pi^0 \pi^0 \ (uncertain)
\end{array} \right\}$

Here we notice the two definitely distinct mean lives $\tau_S$ and $\tau_L$ for the neutral $K$ system.

According to the CPT theorem (or Lüder’s theorem), 'If a theory of interacting fields obeys the Wightman postulates and is invariant under the restricted Lorentz group (i.e. without any discrete element like $P$ or $T$) then it will be invariant under CPT'. If we assume CPT invariance (which we shall do throughout this review), a consequence of the theorem

† Work supported in part by the United States Atomic Energy Commission.
‡ Present address: Department of Physics, Saginaw Valley College, University Center, Michigan 48710.
is that the observable mass and lifetime of a particle are always exactly the same as those of the corresponding antiparticle.

Thus the parent states of the two different lifetimes $\tau_S$ and $\tau_L$ cannot be $K^0$ or $\bar{K}^0$. Note that since the system is neutral its decay is indirectly observed. We measure the energy-momentum of the decay product and measure the quantum numbers of the products system instead of the neutral $K$ system. Therefore, we name the short-lived and long-lived parent states as $K_S$ and $K_L$, respectively, and have

$$
\begin{align*}
K_S &\rightarrow \begin{cases} 
\pi^+ \pi^- & , +1 \\
\pi^0 \pi^0 & , +1 \\
\pi^0 \pi^0 & , -1 \\
\pi^+ \pi^- & , -1 
\end{cases} \\
K_L &\rightarrow \begin{cases} 
\pi^+ \pi^- & , +1 \\
\pi^0 \pi^0 & , +1 
\end{cases}
\end{align*}
(1.2)
$$

Here we have used the following conventions:

$$
\begin{align*}
CP |K^0\rangle &= |\bar{K}^0\rangle \\
CP |K^0\rangle &= -|\bar{K}^0\rangle \\
CP |\pi^0\rangle &= -|\pi^0\rangle \\
CP |\pi^+ \pi^-\rangle &= +|\pi^+ \pi^-\rangle \text{ in the center-of-mass system.}
\end{align*}
(1.3)
$$

In the decay modes shown in (1.2), if $K_L \rightarrow 2\pi$ then the $K_S$ and $K_L$ states may be assigned $CP = +1$ and $-1$, respectively, and $CP$ conservation holds. But the $K_L$ decays show a clear $CP$ violation.

2. $K_S$ and $K_L$ States

Now we can ask the following question: What are the $K_S$ and $K_L$ states?‡ In strong interactions ($H_S$), the hypercharge $Y$ is conserved, i.e. $\Delta Y = 0$, and $|K^0\rangle$ and $|\bar{K}^0\rangle$ are eigenstates of $H_S$. Therefore, transitions $K^0 \leftrightarrow \bar{K}^0$ are not allowed. Thus the two particles $K^0$ and $\bar{K}^0$ are quite distinct, and we can tell definitely which of the two particles is produced. Since weak interactions ($H_w$) do not conserve hypercharge, as soon as the weak interaction is turned on, the hypercharge is no longer a good quantum number (i.e. $\Delta Y \neq 0$). Thus the following is possible:

$$
K^0 \rightarrow \pi^+ \pi^- \rightarrow \bar{K}^0
$$

and $K^0$ and $\bar{K}^0$ become degenerate. $|K^0\rangle$ and $|\bar{K}^0\rangle$ are no longer different states, but the combinations of the two states may be the eigenstates of the mass operator.

‡ For the discussions of $K_S$ and $K_L$ states, see, for example, Gasiorowicz, S. (1966). *Elementary Particle Physics*. John Wiley, New York,