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APPARENT CP VIOLATION IN K_2^o DECAY DUE TO A NEUTRAL VECTOR BOSON*

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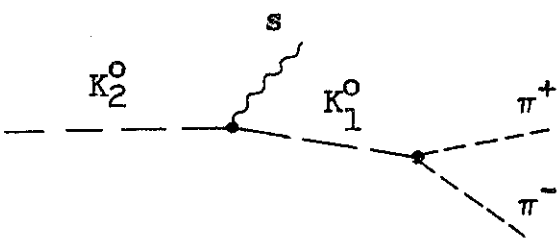
The decay of K_2^o in two pions has recently been reported [1] and it has been suggested that this implies a violation of CP invariance in weak interactions [1,2]. However, the CP violation can be avoided if we introduce an isoscalar neutral vector boson s of very small mass, say of the order of the mass difference of K_2^o and K_1^o, with strangeness zero. This boson is weakly coupled to strangeness currents only and the interaction conserves the strong selection rules [3]. We calculate here the process

$K_2^o \longrightarrow \pi^+ + \pi^- + s$



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The interaction of the K^o current with the vector boson can be written

$$(-if_s)\left[\bar{K}(\partial_\mu K) - (\partial_\mu \bar{K})K\right]S_\mu$$
$$= f_s\left[(\partial_\mu K_2^o)K_1^o - K_2^o(\partial_\mu K_1^o)\right]S_\mu + \dots$$

while for the $K_1^o\pi^+\pi^-$ interaction, we take

$$\left(g_{k_1^o\pi^+\pi^-}\ m_{k_1^o}\right)K_1^o\ \pi^+\pi^-$$

where

$$\frac{g^2_{k_1^o\pi^+\pi^-}}{4\pi} = 5.03 \times 10^{-14}$$

The decay rate for $K_2^o \longrightarrow S + \pi^+ + \pi^-$ is calculated* to be $(\hbar = c = 1)$

$$\Gamma \simeq f_s^2 \times \left(\frac{g^2_{k_1}}{4\pi}\right) \times 0.7 \times 10^{46}\ \sec^{-1}$$

Here we take** $m_s \simeq \left(m_{k_2^o} - m_{k_1^o}\right)$. A comparison with the experimental decay rate [1] $\Gamma_{exp.} \sim 2 \times 10^{-3}$. Γ(all charged modes of K_2^o) leads us to

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* See appendix.

** Even if we suppose the bare rest mass of the vector boson to be zero, the non-conservation of the strangness in weak interactions will lead to small finite mass m_s. The production of the real s particle in the $K_2^o \longrightarrow K_1^o + s$ transition is possible if $m_s < (m_{K_2^o} - m_{K_1^o})$, in which case the propagator of K_1^o has a delta function term corresponding to the real production of K_1^o and its subsequent decay.

$$f_s^2 \simeq 1.02 \times 10^{-28}$$

or
$$f_s \simeq 1.01 \times 10^{-14}$$

which is comparable with the square of the weak coupling constant ($\sim 10^{-14}$).

Thus the introduction of a weakly coupled boson to strangeness currents may allow us to retain the CP invariance for the weak interactions in the K_2^o decay. That the coupling $K_2^o K_1^o s$ turns out to be of the order of the square of the weak coupling constant suggests us to speculate on the possible process $K_2^o \rightarrow \nu + \bar{\nu} + \pi^+ + \pi^-$. The work along this line is in progress.

* * *

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1. J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, Phys. Rev. Letters 13, 138 (1964).
2. R. G. Sachs, Phys. Rev. Letters 13, 286 (1964); N. Cabibbo, CERN preprint, 1964; S. B. Treiman, Report on Weak Interactions, Dubna Conference on High Energy Physics, 1964.
3. A similar suggestion has been made by M. Levy and M. Nauenberg, CERN preprint, 1964, received by us after the conclusion of this paper. The estimation of the ($K_2^o K_1^o s$) coupling constant in our case is, however, much smaller.

APPENDIX

The matrix element for the decay $K_2^o \longrightarrow \pi^+ + \pi^- + s$ is:

$$S = \frac{1}{\left[(2\pi)^{3/2}\right]^3} \frac{1}{\sqrt{16\ P_o\ K_o\ q_{10}\ q_{20}}} (2\pi)^4\ \delta^4(P - k - q_1 - q_2)\,\mathbb{M}$$

where

$$\mathbb{M} = (-i)^2\ f_s\ m_{k_1^o}\ g_{k_1^o \pi\pi}\ \frac{\epsilon\cdot(2P - k)}{\left[(P-k)^2 + (m_{k_1^o} - i\frac{\Gamma}{2} - i\epsilon)^2\right]}$$

where P_1 k, q_1, q_2 are the four momenta of K_2^o, vector meson s, and the two charged pions respectively. $\varepsilon_\mu(k)$ is the linear four-polarization vector of the vector meson and Γ the decay width of the K_1^o-meson. Using $\epsilon\cdot k = 0$ and the result

$$\sum_{\text{polarization}} \varepsilon_\mu(k)\ \varepsilon_\nu(k) = \delta_{\mu\nu} + \frac{k_\mu k_\nu}{k^2}$$

the squared matrix element summed over the polarization states of the vector meson is given by

$$\sum_{\text{polarization}} |\mathbb{M}|^2 = f_s^2\ g_{k_1^o\pi\pi}\ m^2_{k_1^o}\ \frac{4\left(P^2 - \frac{(k\cdot P)^2}{k^2}\right)}{\left|(P-k)^2 + (m_{k_1^o} - i\frac{\Gamma}{2} - i\epsilon)^2\right|^2}$$

The decay rate is then given by

$$\Gamma = \int \frac{\sum_{\text{pol.}} |S|^2}{TV}\ d^3_{q_1}\ d^3_{q_2}\ d^3k$$

$$= \frac{1}{(2\pi)^9 (2\ P_o)} \int \left(\sum_{\text{pol.}} |M|^2 \right) (2\pi)^4\ \delta^4(P - k - q_1 - q_2)\ \frac{d^3q_1}{2q_{10}}\ \frac{d^3q_2}{2q_{20}}\ \frac{d^3k}{2\ k_o}$$

$$= \frac{1}{(2\pi)^5\ 4\ P_o} \int \sum_{\text{pol.}} |M|^2\ \frac{d^3k}{k_o} \iint \delta^4(P - k - q_1 - q_2)\ \frac{d^3q_1}{2q_{10}}\ \frac{d^3q_2}{2q_{20}}\ .$$

Now, the Lorentz invariant integral,

$$\iint \delta^4(P - k - q_1 - q_2)\ \frac{d^3q_1}{2q_{10}}\ \frac{d^2q_2}{2q_{20}} = I$$

can be easily calculated, say in the C.M. frame of K_{20}, as follows.
Put

$$P' = P - k, \quad Q = q_1 + q_2, \quad R = q_1 - q_2$$

$$I = \iint \delta^4(P' - Q)\ \delta(Q\ R)\ \delta(Q^2 + R^2 + 4m^2)\ d^4Q\ d^4R$$

$$= \int \delta^4(P' - Q)\ \ 2\pi \sqrt{\frac{Q^2 + 4m^2}{-Q^2}}\ d^4Q$$

$$= 2\pi \sqrt{\frac{P'^2 + 4m^2}{-P'^2}} = 2\pi \sqrt{-1 + \frac{4m^2}{P'^2}}$$

C.M. of K_2^o: $\quad \vec{P}' = -\vec{k}, \quad P_o' = \left(m_{K_2^o} - E \right)$

$$P'^2 = k^2 - \left(m_{K_2^o} - E \right)^2$$

$$= \left(m_s^2 - m_{K_2^o}^2 \right) + 2\ m_{K_2^o}\ E$$

Then, for the integral we may write:

$$I = 2\pi \sqrt{\frac{(E_o - E)}{\left(\frac{m_{k_2^o}}{2} - E\right)}}, \qquad E_o = \frac{m_{k_2^o} - 4m_\pi^2}{2m_{k_2^o}}$$

Therefore, the decay rate is

$$\omega = \frac{f_s^2\, g_{k_1}^2}{(2\pi)^5} \left(\frac{m_{k_1^o}^2}{4m_{k_2^o}}\right) 2 \left(\frac{m_{k_2^o}}{m_s}\right)^2 \frac{2\pi}{m_{k_2}^2} \int_{m_s}^{E_o} \frac{(E^2 - m_s^2)\,dE_s}{|E - (a \mp ib)|^2} \left(\sqrt{\frac{E_o - E}{\frac{m_{k_2^o}}{2} - E}}\right)$$

$$\simeq \frac{f_s^2\, g_{k_1}^2}{(2\pi)^4} \left(\frac{m_{k_1^o}}{m_s}\right)^2 \left(\frac{1}{8m_{k_2^o}}\right) \left(\sqrt{\frac{E_o - E}{\frac{m_{k_2^o}}{2} - E}}\right) \int_{m_s}^{E_o} \frac{E^2 - m_s^2}{(E-a)^2 + b^2}\, dE$$

where

$$a = \frac{m_{k_2^o}^2 + m_s^2 - m_{k_1^o}^2 - \Gamma^2/\Delta - \epsilon^2}{2m_{k_2^o}}; \qquad b = \frac{m_{k_1}(\Gamma - 2\epsilon)}{2\, m_{k_1}}$$

Now, in the limit when $\epsilon \longrightarrow 0$,

$$a \simeq \frac{2\Delta}{2} = \Delta$$

$$b \simeq \frac{\Gamma}{2} = \frac{\Delta}{2}$$

where

$$\Gamma = \Delta = \left(m_{k_2^o} - m_{k_1^o}\right);$$

The integral I' for $a \simeq \Delta$, $b \simeq \frac{\Delta}{2}$ gives:

$$I' = \int_{m_s}^{E_o} \frac{E^2 - m_s^2}{(E-a)^2 + b^2}\, dE = (E_o - m_s) + \Delta \ln \left[\frac{(E_o - \Delta)^2 + \frac{\Delta^2}{4}}{(m_s - \Delta)^2 + \frac{\Delta^2}{4}} \right] +$$

$$+ 2\Delta\left(\frac{3}{4} - \frac{m_s^2}{2}\right) \tan^{-1} \left\{ \frac{\left(\frac{E_o - m_s}{\Delta}\right)}{2\left[1 + 4\left(\frac{E_o - \Delta}{\Delta}\right)\left(\frac{m_s - \Delta}{\Delta}\right)\right]} \right\} .$$

For real production, $m_s \lesssim \Delta$, this integral, as $E_o \gg \Delta$, gives E_o; therefore, the rate of decay is:

$$\Gamma = \left(\frac{f_s^2}{4\pi}\right)\left(\frac{g_{k_1}^2}{4\pi}\right) \times 8.76 \times 10^{46} \text{ sec.}^{-1}$$

Now, since

$$\Gamma_{exp} = 2 \times 10^{-3}\ \Gamma_{k_2^o} = 3.56 \times 10^4 \text{ sec}^{-1}$$

the coupling constant will be

$$f_s^2 \simeq 1.02 \times 10^{-28} .$$