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PHYSICAL REVIEW D VOLUME 8, NUMBER 9 1 NOVEMBER 1973

Baryon-Antibaryon Contributions to the $K_2^0 - K_1^0$ Mass Difference in a Current-Current Quark Model

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The baryon-antibaryon contributions to the $K_2^0 - K_1^0$ mass difference are studied in an extended fermion-loop model as a further consistency test of a current-current quark model. It is found that contributions arising from the parity-conserving weak Hamiltonian phenomenologically constructed of one-baryon octet matrix elements are negligible compared to the crude estimate of the K_1^0 mass shift, $\Delta(m_{K_1}^0) = -(\hbar/2\tau_s)\cot\delta_{00}(m_K^2)$. Although the contribution to the K_2^0 mass shift arising from the parity-violating weak Hamiltonian via an S-wave effective meson-baryon-baryon interaction turns out to be comparable to $\Delta(m_{K_1}^0)$ and negative, the extended loop model is not incompatible with present theoretical understanding of the $K_2^0 - K_1^0$ mass difference.

I. INTRODUCTION

The fermion-loop model,[1] suitably modified[2] for strangeness-changing nonleptonic weak interactions, has lately proved successful in providing (1) a qualitative[2] explanation for $K_2^0\to\gamma\gamma$ decay, (2) a predicted branching ratio for the CP-conserving decay $K_2^0\to\pi^+\pi^-\gamma$, (Ref. 3) $r_0 = R(K_2^0\to\pi^+\pi^-\gamma)/R(K_2^0\to\text{all modes}) = 3.0\times10^{-4}$, consistent with the tree-graph estimate, $2.6\times10^{-4}< r_0 < 4\times10^{-4}$ of Moshe and Singer[4] and below the present[5] experimental upper limit ($r_0 < 4\times10^{-4}$), and (3) a predicted[6] branching ratio $r_\pm = R(K^\pm\to\pi^\pm\pi^0\gamma;\ 55 \leq T_{\pi^\pm} \leq 90\ \text{MeV})/R(K^\pm\to\text{all modes}) = 1.56\times10^{-5}$, in excellent agreement with the recent experiment of Abrams *et al.*[7] As we noted in these earlier calculations,[2,3] the extended fermion-loop model furnishes an attractive alternative to the usual tree-graph description of these ($B=0$) processes[4,8] [we have in mind the most successful of such (current-current) models, that of Moshe and Singer,[4] which also seems to be the "simplest" (i.e., with a minimum of neutral currents)], since unlike the tree-graph model, one obtains results with *no adjustable parameters*. [Recall that the parameters of our model are fixed in Gronau's[9] remarkable fit to the experimental amplitudes for nonleptonic hyperon decay ($B=1$ processes).] In this paper, in continuation of our program of analysis of ($B=0$) strangeness-changing processes in terms of the extended baryon-loop model, we discuss the baryon-antibaryon contribution to the ($\Delta S=2$) $K_2^0-K_1^0$ mass difference.

It has long been argued[10] from (a) the source of the mass difference: the weak interactions, (b) the difference in the respective lifetimes of K_2^0 ($\sim 10^{-7}$ sec) and K_1^0 ($\sim10^{-10}$ sec), and (c) the predominant two-pion decay mode (principally in the $I=0$ state) of the K_1^0, that the mass difference may be primarily due to the weak mass shift of the K_1^0 arising from its coupling to the ($I=0$) two-pion state. This K_1^0 mass shift has been shown to have the form[11]

$$\Delta(m_{K_1^0}) = -\frac{\hbar}{2\tau_s}\cot\delta_{00}(s=m_K^2) + \text{correction due to left-hand contribution.} \qquad (1)$$

While we do not propose to deal here with the problem posed by the correction term in Eq. (1), we want to point out that *if it is small* (indeed it vanishes in an effective-range theory of unitarized current algebra which fits the "up-up" $\pi\pi$ data), then the "main term,"

$$-(\hbar/2\tau_S)\cot\delta_{00}(m_K^2) \simeq -3.73\times10^{-6}\ \text{eV}, \quad \text{for } \delta_{00}(m_K^2)\simeq\tfrac{1}{4}\pi,$$

is rather close to the present experimental value,[12]

$$\Delta(m_{K_1^0} - m_{K_2^0})_{\rm exp} = -(3.56 \pm 0.02)\times 10^{-6}\ {\rm eV}.$$

A theory which finds a small K_2^0 mass shift and a small $B\overline{B}$ (baryon-antibaryon) contribution to the K_1^0 mass shift would be consistent with this possibility [although, one can entertain as well the possibility that $\Delta(m_{K_2^0})$ may be of the order of the main term in the absence of strict constraints on the correction term]. With this in mind, we direct our attention below first to the $B\overline{B}$ contribution to $\Delta(m_{K_1^0})$ from $\mathcal{H}_w^{(\text{parity-conserving})}$[9] in second order and then to the analogous $B\overline{B}$ contribution to $\Delta(m_{K_2^0})$ from $\mathcal{H}_w^{(\rm p.c.)}$ and the $B\overline{B}$ contribution to $\Delta(m_{K_2^0})$ arising from the K_2^0BB coupling (induced by the vector-meson pole)[9] in second order.

II. $B\overline{B}$ CONTRIBUTION TO $\Delta(m_{K_1^0})$ FROM $\mathcal{H}_w^{(\rm p.c.)}$

The $B\overline{B}$ contribution to $\Delta(m_{K_1^0})$ from $\mathcal{H}_w^{(\rm p.c.)}$ (in second order) is to be extracted from the divergent matrix element

$$\Sigma(p^2;K_1^0)(2\pi)^4\delta(\vec{0}) = \frac{i\,(i^4)}{(2\,!)^2}\int\prod_{j=1}^{4} d^4x_j\,(2p_0)\langle K_1^0(p)|\,T[\mathcal{L}_{\rm int}^{(7)}(x_1),\mathcal{L}_{\rm int}^{(7)}(x_2),\mathcal{L}_w(x_3),\mathcal{L}_w(x_4)]\,|K_1^0(p)\rangle\,, \tag{2}$$

where $\mathcal{L}_w$ is the equivalent weak Lagrangian[2,3]

$$\mathcal{L}_w = \sqrt{2}F\,{\rm Tr}([\overline{B},B]\lambda_6) - \sqrt{2}D\,{\rm Tr}(\{\overline{B},B\}\lambda_6)\,, \tag{3}$$

which yields the one-baryon octet matrix elements of Gronau,[9]

$$\langle B_j|\mathcal{H}_G|B_i\rangle = \langle B_j|\mathcal{H}_w|B_i\rangle = 2\sqrt{2}\,\overline{u}_j(-if_{6ji}F + d_{6ji}D)u_i\ . \tag{4}$$

As in Ref. 9 we take the "best-fit" values, $F = 4.7\times10^{-5}$ MeV, $D/F = -0.85$. The effective Lagrangian for this extended baryon-loop calculation is given by

$$\mathcal{L}_{\rm int}^{(7)} = (g/2m)f\,{\rm Tr}([\overline{B}\gamma^\mu\gamma_5,B]\lambda_7)\partial_\mu\phi_7 - (g/2m)d\,{\rm Tr}(\{\overline{B}\gamma^\mu\gamma_5,B\}\lambda_7)\partial_\mu\phi_7\,, \tag{5}$$

where $B = \lambda_a\psi_a/\sqrt{2}$ is the traceless baryon matrix[13]

subtracted (at $p^2=0$) (and finite) self-energy, $\Sigma_c(m_K^2;K_1^0)$, extrapolated to the physical kaon mass, with the desired contribution,

$$\Sigma_c(m_K^2;K_1^0) = 2m_K\,\Delta(m_{K_1^0})|_{(B\overline{B})}\ . \tag{7}$$

A straightforward, albeit tedious calculation yields the negligible effect,

$\Delta(m_{K_1^0})|_{(B\overline{B})}$

$= 2\ (g^2)(m_K)^4\ 1\ [\tfrac{3}{}F^2f^2 \ldots$

$+\tfrac{5}{6}(D^2f^2+F^2d^2)$

$+\tfrac{10}{3}DF\,df\,]$

$$\langle \pi_i(q)B_j(p_j)\text{out}|\mathcal{H}_w^{(\text{p.v.})}(0)|B_k(p_k)\rangle = -i\bar{u}(p_j)cd_{i6l}\left(-if_{ljk}+\frac{\delta}{\phi}d_{ljk}\right)(m_k-m_j)u(p_k), \quad (9)$$

where δ/ϕ is the D/F ratio for the γ_μ coupling at the strong VBB vertex[17] and the constant c is obtained from the measured $K_S^0 \to \pi^+\pi^-$ decay width,

$$c = 3.2\times 10^{-9}\ \text{MeV}^{-1}. \quad (10)$$

[It is assumed in this last calculation that the weak parity-violating MV coupling has the form $d_{i6l}\partial_\mu\phi_i\phi_l^\mu$, *which allows 68 as well as 63 transitions.*] The MBB matrix element above in turn suggests a weak effective Hamiltonian,

$$\mathcal{H}_w' = -\bar{\psi}_j cd_{i6l}\left(-if_{ljk}+\frac{\delta}{\phi}d_{ljk}\right)\gamma^\mu\psi_k\partial_\mu\phi_i, \quad (11)$$

which, if assumed valid for off-baryon-mass-shell calculations as well, also determines (in the extended fermion-loop model) the rates for such processes as $K^+\to\pi^+\gamma\gamma$ decay and direct (electric dipole) emission in $K^\pm\to\pi^\pm\pi^0\gamma$ *without adjustable parameters*.[18] In the present instance, we find after a subtraction at $p^2=0$, that the convergent part of

$$\Sigma'(p^2;K_2^0)(2\pi)^4\delta(\vec{0}) = \frac{i(i^2)}{2!}\int d^4x_1\,d^4x_2(2p_0)\langle K_2^0(p)|T[\mathcal{L}_w'(x_1)\mathcal{L}_w'(x_2)]|K_2^0(p)\rangle, \quad (12)$$

extrapolated to $p^2=m_K^2$, yields a contribution to $\Delta(m_{K_2^0})$,

$$\Delta(m_{K_2^0})|_{(B\bar{B})(\text{p.v.})} = \frac{1}{2m_K}\Sigma_c'(m_K^2;K_2^0) = -\frac{c^2m_K^2}{16\pi^2}\left(\tfrac{23}{36}\right) = -5.2\times 10^{-6}\ \text{eV}, \quad (13)$$

which is somewhat larger in magnitude than the contribution of the two-pion state[19] to the K_1^0 mass shift ($\Delta(m_{K_1^0}) \approx -3.7\times 10^{-6}$ eV). On the other hand, if we take the point of view of Moshe and Singer[4] and discard the 68-coupling in $\mathcal{H}_w^{(\text{p.v.})}$(meson-meson) $\sim d_{6ij}\partial_\mu\phi_i\phi_l^\mu$, since this term is *unnecessary in Gronau's*[9] *fit*, we find

$$\Delta(m_{K_2^0})|_{(B\bar{B})(\text{p.v.})} = -2.9\times 10^{-6}\ \text{eV}, \quad (14)$$

a not unacceptable value. (Note that in this case the calculated mass difference retains the correct sign.)

In summary, one finds, in the extended baryon-loop model, contributions from the parity-conserving weak Hamiltonian (in second order) to the $K_2^0-K_1^0$ mass difference which are negligible compared to the contribution of the two-pion state to the K_1^0 mass shift, but a sizable contribution to the K_2^0 mass shift from the parity-violating effective weak Hamiltonian emerges. However, these results are not incompatible with our present understanding of this problem.

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[14]We also adopt the value of the pion-nucleon coupling, $g^2/4\pi = 14.6$ used by Gronau (Ref. 9) in his fit and a "mean" baryonic mass m of 1 GeV.

[15]Note that our earlier calculations of $K_2^0\to\gamma\gamma$ (Ref. 2) and the contribution to CP-conserving $K_2^0\to\pi^+\pi^-\gamma$ from virtual ρ decay (Ref. 3) are indifferent as to whether pseudoscalar or pseudovector coupling is used because of the equivalence theorem; this is not so for the contribution to CP-conserving $K_2^0\to\pi^+\pi^-\gamma$ from "uncorrelated emission." [A "soft-meson" fermion-loop calculation of $K_2^0\to\pi^+\pi^-\gamma$ would entail the replacement of the conventional vector-coupling with the contact

interaction, $-f_\pi^2 f_{jkl}\, \phi_j \partial^\mu \phi_k V_\mu^l$, where V_μ^l is the baryon-vector current, in the effective Lagrangian [R. Dashen and M. Weinstein, Phys. Rev. 183, 1261 (1969)].

[16]Thus $\Delta^{-1}(p^2; K_1^0) = p^2(1-A) - \Sigma_c(p^2; K_1^0)$.

[17]We take $\delta/\phi = -0.5$ as in the fit of Ref. 9.

[18]The prediction of these rates would then constitute additional tests of the extension (11). These calculations will be taken up in later communications.

[19]This is, of course, under the assumption that the correction term is "small."

PHYSICAL REVIEW D VOLUME 8, NUMBER 9 1 NOVEMBER 1973

Comments on the Present Status of Elastic and Inelastic Magnetic Electron-Deuteron Scattering*

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The long-standing discrepancies between theory and experiment in the magnetic elastic and inelastic scattering of electrons from the deuteron at high momentum transfer are reexamined. It is concluded that the predictions using most deuteron models agree with the *elastic* scattering data if one employs the presently accepted dipole fit (with scaling) for the proton and neutron form factors. A second conclusion is that the *inelastic* scattering to the $^1S_0$ state is not affected by small changes in the nucleon form factors, but is completely dominated by dynamic effects such as those due to meson-exchange diagrams.

I. INTRODUCTION

Since 1965, theoretical and experimental studies of both elastic magnetic e-d scattering and inelastic magnetic scattering near threshold have shown apparent discrepancies. The highest momentum transfer experiments were done at Stanford by Buchanan and Yearian[1] and by Rand *et al.*[2] They extend up to $q^2 = 14\ \text{fm}^{-2}$ in the case of elastic magnetic scattering and up to $q^2 = 10\ \text{fm}^{-2}$ in the case of inelastic scattering. In both instances the observed cross sections appeared to be as much as a factor of 2 too high in comparison with calculations based on the usual deuteron models and the (then) accepted values of the nucleon form factors. In contrast, the electric scattering (charge plus quadrupole) in the elastic channel were in quite good agreement with theory and this has remained true in subsequent experiments[3] done at much higher momentum transfer.

The lack of agreement between theory and experiment in the *magnetic* channels extant in 1967 is displayed in Fig. 1, which is taken from Rand *et al.*[2] The top figure (a) compares the inelastic data to the predictions of the impulse approximation calculations.[4] The lower figure (b) compares the elastic data to the prediction based on one of the standard deuteron models (in this case the Partovi model[5]). As one can see, the experimental data are almost twice the theoretical prediction at the higher-q^2 points. The experimental groups are identified in Ref. 2. In Fig. 2 we show the essential agreement between the data and theory in the deuteron's *electric* form factor [here identified as $A(q^2)$] up to $q^2 = 25\ \text{fm}^{-2}$. The figure was taken from Elias *et al.*[3] The solid curve is one calculated using the Hamada-Johnston[6] potential for the deuteron, which is essentially the same as the Partovi model.[5] The two broken curves are for rather extreme deuteron models, which are described in Ref. 3.

Several investigators have suggested that meson-exchange diagrams could contribute to the deuteron's magnetic form factor with very little effect on the electric form factor. Two calculations have actually been performed,[7,8] both of which have as a normalization condition the fitting of the deuteron's static magnetic moment while using a deuteron wave function with a 7% D-state probability. However it turns out that the effects are either