RADIATIVE π^+ AND K^+ DECAYS AND THE EFFECTIVE $q\bar{q}$ POTENTIAL NEAR THE ORIGIN

H.C. LEE
Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

and

Q. HO-KIM
Department of Physics, Laval University, Sainte Foy, Quebec, Canada G1K 7P4

Received 11 November 1981
Revised manuscript received 18 June 1982

The pion and kaon are considered to be $q\bar{q}$ bound states and it is shown that the ratio of axial vector to vector form factors in their radiative decays is determined by $(\nabla^2\psi)/\psi$ averaged over a small region around the origin, where ψ is the relative $q\bar{q}$ wavefunction. This quantity is proportional to the average of $\langle V-E\rangle$ at $r \approx 0$, where V is the effective $q\bar{q}$ potential. Existing data on the decays suggest that $\langle V-E\rangle$ is either large and negative ($\ll -1$ GeV) or small and positive ($\sim$0.5 GeV), but consistent with zero, near the origin. A typical confining $q\bar{q}$ potential with an attractive core gives a small, negative value

Some time ago Van Royen and Weisskopf [1] showed that the amplitude for the annihilation of a bound quark–antiquark pair ($q\bar{q}$) by a current is proportional to the relative $q\bar{q}$ wavefunction at the origin, $\psi(0)$. Such an amplitude appears, for example, in the semileptonic decays of pseudoscalar mesons, $P \to \ell\nu$, and the lepton-pair annihilation of vector mesons, $V \to \ell^+\ell^-$. For some mesons $|\psi(0)|$ is then a quantity that is directly measurable and becomes an experimental datum that must be accounted for whenever an understanding of the structure of the meson is attempted. Unfortunately, precisely because $\psi(0)$ specifies the wavefunction in a very confined region, it does not impose a strong constraint on the overall picture of the structure of the meson. In a potential description of the meson, $\psi(0)$ can be made to vary over a wide range of values by fine tuning the potential only near the origin, without changing the energy and other properties of the meson. In principle the behavior of the $q\bar{q}$ pair at very short separating distances can be studied by a probe of very short wavelength. Generally, however, under such a probe the description of the meson as a composite of $q\bar{q}$ breaks down, and the potential at $r \approx 0$ becomes meaningless. Rather, what is needed is a relatively low energy probe that can give us information on the $q\bar{q}$ system in addition to the value of $\psi(0)$.

In this paper we shall show that the structure-dependent radiative decay, $P \to \gamma e\nu$, of π^+ and K^+ provides precisely this kind of information. The decay is the annihilation of a $q\bar{q}$ pair into two currents, the product of which has two terms with respectively the structure of VV and VA, where V (A) is the vector (axial-vector) current. The annihilation amplitude through the VV term is similar to that in the two-photon decay of pseudoscalars, $P \to 2\gamma$. Isgur [2] [‡1] has shown that for light as well as heavy quarkonia (where q and $\bar{q}$ have identical flavor) the amplitude for $P \to 2\gamma$ is proportional to $\psi(0)$ times a factor that depends on the average magnitude of the relative momentum $\boldsymbol{p}$ of the $q\bar{q}$ system. We extend Isgur's formula for the VV-amplitude to K^+, where the constituent quarks have different masses. More importantly, we show that the VA-amplitude is essentially proportional to the laplacian of ψ *near* the origin, a quantity which in the potential model is simply related to the $q\bar{q}$ potential near the origin.

‡1 For a calculation of $\pi^+ \to \gamma e\nu$ based on the quark model, see ref. [3].

Our premise is that the $P \to \gamma e\nu$ decays should be understandable in terms of the underlying $q\bar{q}$ structure of the mesons without recourse to current-algebra and vector-dominance [4] [‡2]. In particular we adopt the view that weak currents can be expressed in terms of fields of quarks and leptons, so that the existence of a second-class current [6] in the decay process is not permitted. We shall also assume that the theory of quarks and leptons is free [7] of triangle anomalies [8] so that a calculation of $P \to \gamma e\nu$ based on the lowest order Feynman diagrams is justified.

The decay amplitude for $P \to \gamma e\nu$ has two parts, a structure-independent part commonly referred to as inner bremsstrahlung (IB) [4,5,9] that is helicity suppressed (proportional to m_e/M_P) and infrared divergent, and a structure-dependent (SD) part that is not suppressed and is infrared finite. We shall be concerned only with the SD amplitude. It suffices to say that the relative magnitude of the partial width due to the interference of the two parts is of $O(m_e/M_P)$ and can be ignored, and that the contribution from the VV and VA components of the SD amplitude can be separated by measuring the spectra of emitted electrons and photons [10].

For our notation, P and M are the momentum and mass of the decaying meson, p is the $q\bar{q}$ relative momentum, $k(\epsilon)$ is the photon momentum (polarization), J^μ is the leptonic current and we shall use the subscripts 1 and 2 to denote the quark and antiquark, respectively.

The SD amplitude is

$$\mathscr{A}_{SD} = -4\int d^3p\, F(p)\,\epsilon^\lambda J^\mu [\tfrac{1}{2}MP - (m_1 - m_2)p]^\alpha$$
$$\times \{[i(e_1/D_1 + e_2/D_2)k^\beta \epsilon_{\alpha\beta\lambda\mu}]_V$$
$$+ [(e_1/D_1)(k^\beta s_{\alpha\beta\lambda\mu} + (\tfrac{1}{2}P + p)_\lambda g_{\alpha\mu})$$
$$- (e_2/D_2)(k^\beta s_{\alpha\mu\lambda\beta} + (\tfrac{1}{2}P - p)_\lambda g_{\alpha\mu})]_A\} \qquad (1)$$

where

$$D_i = (p_i - k)^2 - m_i^2, \quad p_1 = P/2 + p, \quad p_2 = P/2 - p,$$
$$s_{\alpha\beta\lambda\mu} = g_{\alpha\beta}g_{\lambda\mu} + g_{\alpha\mu}g_{\beta\lambda} - g_{\alpha\lambda}g_{\beta\mu},$$

and the normalization of the relative wavefunction $F(p)$ in momentum space is such that

$$\int d^3p\, \exp(i\boldsymbol{p}\cdot\boldsymbol{r})\, F(p) = M^{-3/2}\psi(r),$$
$$\psi(0) \equiv M^{1/2} f_P/2, \qquad (2)$$

where f_P is the decay constant. The $[\quad]_V$ term in (1) arises from the vector coupling and leads to the familiar amplitude

$$\mathscr{A}_V = i(v/M)\epsilon^\lambda P^\alpha k^\beta J^\mu \epsilon_{\alpha\beta\lambda\mu}, \qquad (3)$$

where

$$v = -2M^2 \int d^3p\, F(p)(e_1/D_1 + e_2/D_2) \qquad (4)$$

is the vector form factor. Later it will become clearer why the term linear in p does not contribute to $\mathscr{A}_V$. The $[\quad]_A$ term in (1) arises from the axial vector coupling. The portion that is proportional to M is the meson-pole term and must be combined with the lepton-pole term to make the IB amplitude gauge invariant [9]. The portion that is proportional to $m_1 - m_2$ gives the SD contribution:

$$\mathscr{A}_A = -4(m_2 - m_1)\int d^3p\, F(p)\,\epsilon^\lambda J^\mu$$
$$\times [(e_1/D_1 + e_2/D_2)2p_\lambda p_\mu$$
$$+ (e_1/D_1 - e_2/D_2)(P_\lambda p_\mu - p_\lambda k_\mu + p\cdot k g_{\lambda\mu})]. \qquad (5)$$

This expression is not manifestly gauge invariant. We obtain a gauge invariant expression by making use of the expressions

$$e_1/D_1 \pm e_2/D_2 = (-1/D_1D_2)$$
$$\times [(e_1 \pm e_2)P\cdot k - 2(e_1 \mp e_2)p\cdot k], \qquad (6)$$

and by noting that the integral vanishes when the integrand is linear in p_μ if $F(p)$ is assumed to be spherically symmetric (hereafter $p \equiv |\boldsymbol{p}|$). We thus have the manifestly gauge invariant

$$\mathscr{A}_A = (a/M)\epsilon^\lambda J^\mu (P\cdot k g_{\lambda\mu} - P_\lambda k_\mu), \qquad (7)$$

$$a = 8M(m_2 - m_1)(e_1 + e_2)\int d^3p F(p)\, p_\mu p^\mu / D_1 D_2. \qquad (8)$$

[‡2] See also the review article on $\pi \to e\nu$ and $\pi \to e\nu\gamma$ in ref. [5].

Eqs. (4) and (8) are the general expressions for the vector and axial-vector form factors and our task is to evaluate the two integrals there. The form factors depend explicitly on the structure of the meson so now we must not consider the two constituent quarks as being on-shell. For quarks of unequal masses we write

$$p_\mu = (p_0, \boldsymbol{p}), \quad p_0 = (m_1^2 - m_2^2)/2M. \tag{9}$$

Using $k \approx M/2$ we find [‡3]

$$D_i \approx -[(p \mp k)^2 - p_0^2 + m_i^2].$$

When p is much less than all masses, $M \approx m_1 + m_2$ and $D_i = -Mm_i + \mathrm{O}(p^2)$ which is the familiar result of the static quark model. For light mesons where the condition $|p| < M/2$ in particular may not be satisfied, the effect of p in D_i becomes important. Thus, as would be expected, the static model does not work at all for the pion and the kaon. For light mesons Isgur [2] pointed out a very useful method to evaluate (4) approximately. The integration over the $\boldsymbol{p}$ orientations can be carried out independently of $F(p)$,

$$1/\langle D_i\rangle \equiv \int \frac{\mathrm{d}\Omega}{4\pi} \frac{1}{D_i}$$

$$\approx -\frac{1}{4pk} \log\left(\frac{(p + M/2)^2 + m_i^2 - p_0^2}{(p - M/2)^2 + m_i^2 - p_0^2}\right)$$

$$\equiv -L_i(p)/2Mp. \tag{10}$$

Unlike $1/D_i(p)$, $L_i(p)/p$ is a smooth function of p. Therefore for moderate values of p we may write

$$\int \mathrm{d}^3p\, F(p)\, \frac{1}{D_i}$$

$$\approx (1/\langle D_i\rangle) \int \mathrm{d}^3p\, F(p) = (1/\langle D_i\rangle) M^{-3/2} \psi(0), \tag{11}$$

where the momentum p in L_i is replaced by the average value $\langle p\rangle$. From (2), (4) and (11)

$$v \approx (1/M^{1/2}\langle p\rangle)(e_1 L_1 + e_2 L_2)\psi(0)$$

$$= (f_\mathrm{P}/2\langle p\rangle)(e_1 L_1 + e_2 L_2), \tag{12}$$

‡3 The average energy of each of the photons in $\mathrm{P} \to 2\gamma$ is $M/2$, but the average energy of the photon in $\mathrm{P} \to \gamma e\nu$ is $M/3$. In the latter case the term p_0^2 in the expression for D_i should be replaced by $p_0^2 \pm Mp_0/3 + M^2/36$. Since this replacement affects our result by less than 2% we shall use the simpler expression for D_i.

with L_i being a function of $\langle p\rangle$. This result extends the validity of the Van Royen–Weisskopf formula [1] for the decay of a bound state into one current to the decay into two currents, one of which must be a vector current. The decay amplitudes in both cases are proportional to $\psi(0)$, but in our present case the coefficient is not a constant but depends on $\langle p\rangle$. The approximation (12) works very well for the two-photon (i.e. two vector currents) decays of light as well as heavy quarkonia [2,3].

To compute the axial vector form factor, we first note the identity

$$(1/4\pi) \int \mathrm{d}\Omega\, \frac{1}{D_1 D_2}$$

$$= -(1/\langle D_1\rangle + 1/\langle D_2\rangle)(b^2 + 2p^2)^{-1}, \tag{13}$$

where

$$b^2 = -(D_1 + D_2 + 2p^2) = M^2/2 + m_1^2 + m_2^2 - 2p_0^2.$$

Note for π^+ and K^+, p_0^2 is either zero or very small so $b^2 > 0$. If we replace p^2 in the denominator in (13) by $\langle p\rangle^2$ then from (8), (12) and (13) we obtain our main result

$$\gamma = a/v \approx 4M^{-1}(m_2 - m_1)\, \frac{(e_1 + e_2)(L_1 + L_2)}{(e_1 L_1 + e_2 L_2)}$$

$$\times (b^2 + 2\langle p\rangle^2)^{-1} [(p_0^2 + \nabla^2)\psi]_{r\approx 0}/\psi(0). \tag{14}$$

The approximation of replacing p^2 by $\langle p\rangle^2$ would be a very good one if $b^2 \gg \langle p\rangle^2$. For the present case however, as we shall see later, $b^2 \gtrsim 2\langle p\rangle^2$ for the pion and $b \gtrsim 4\langle p\rangle^2$ for the kaon. The equality given in (14) is therefore rather qualitative than rigorously quantitative. This understanding is indicated by the suffix $r \approx 0$ attached to the quantity $(p_0^2 + \nabla_0^2)\psi(r)$, which should be interpreted as avaraged over a region around the origin with a radius of $\mathrm{O}(b^{-1})$. A more accurate relation than (14) could be justified if, for example, more about the dynamics of the $\mathrm{q\bar{q}}$ system were known. Later we shall give such a relation for the case when $\mathrm{q\bar{q}}$ potential is explicitly given.

For the following discussion, we shall assume that neither ψ nor $\nabla^2\psi$ oscillates in the vicinity of the origin. We expect this to be true for the ground state, since oscillations in the wavefunction and its derivatives would increase the kinetic energy. In this case it is meaningful to talk about the quantity $(\nabla^2\psi)/\psi$ near the origin, for which we shall use the symbol $\langle\nabla^2\rangle_0$. For both π^+ and K^+, $m_2 - m_1 > 0$, so the sign of γ is given by the sign of $p_0^2 + \langle\nabla^2\rangle_0$, or essentially by $\langle\nabla^2\rangle_0$, since $(p_0)_\pi \approx 0$ and $(p_0)_K$ is small. In a potential model,

$$\langle\nabla^2\rangle_0 = 2\mu[V(r) - E]_{r\approx 0}, \tag{15}$$

where μ is the $(q\bar{q})$ reduced mass, E $(= M - m_1 - m_2)$ is the binding energy and V is the effective potential. Eqs. (15) and (14) show that *the ratio γ is proportional to the averaged $V-E$ near the origin.* If $\gamma < 0$, then the potential has an attractive core, $V(r \approx 0) < E$, in which case it would be appropriate to approximate $\langle\nabla^2\rangle_0$ by $-\langle p\rangle^2$. Conversely, if $\gamma > 0$, then the potential has a "repulsive" core, $V(r\approx 0) > E$, in which the replacement of $\langle\nabla^2\rangle_0$ by $-\langle p\rangle^2$ would lead to gross errors.

The SD radiative decay width is [10] $\Gamma(P \to \gamma\ell\nu)_{SD} = \Gamma_+ + \Gamma_-$,

$$\Gamma_\pm = (\alpha G^2 M^5/3840\pi^2)v^2(1\pm\gamma)^2[1 + O(y_\ell)], \tag{16}$$

where $y_\ell = (m_\ell/M)^2$ and the + and − signs refer respectively to the antiparallel and parallel photon–lepton final states. A ratio that we shall use to compare with experimental data is $\Delta \equiv \Gamma(P\to\gamma e\nu)_{SD}/\Gamma(P\to e\nu) = \Delta_+ + \Delta_-$,

$$\Delta_\pm = (\alpha/480\pi)(M^4/m_e^2 f_P^2)v^2(1\pm\gamma)^2. \tag{17}$$

In the numerical calculation, we shall use the constituent quark masses [2] $m_u = 0.34$ and $m_s = 0.48$ GeV. The evidence is quite strong [11], particularly from the analysis of electromagnetic mass differences of the hadronic SU(2)-multiplets, that $m_d - m_u = (3 \pm 1)$ MeV. For the decay constants we use the experimental values [12] $f_\pi = 134$ MeV and $f_K = 165$ MeV. The average momentum is expected to be $\langle p\rangle \approx 1/R \approx 0.2$ GeV where $R \sim O(1$ fm) is the size of the meson. In practice we use $\langle p\rangle = (0.25 \pm 0.10)$ GeV, as determined by Isgur [2].

Experimentally measured values of limits [13–16] ‡4 of v, γ and Δ for π^+ and K^+ are given in the second column of table 1. The value for v_π is actually derived from the measured width of $\pi^0 \to 2\gamma$ and the hypothesis of conserved-vector-current,

$$v_{\pi^+} = v_{\pi^0}/\sqrt{2} = [2\Gamma(\pi^0\to 2\gamma)/\pi\alpha^2 M_\pi]^{1/2}, \tag{18}$$

which is expected to hold true to $O((m_d - m_u)/M_\pi)$ [17] ‡5. The upper limit for Δ_π is derived from the theoretical expression [9]

$$R_\pi \equiv \Gamma(\pi\to e\nu, \gamma e\nu)/\Gamma(\pi\to\mu\nu, \gamma\mu\nu)$$

$$= (1.239 + 1.28\,\Delta_{SD}) \times 10^{-4} \tag{19}$$

and the recent TRIUMF measurement [13] $R_\pi = (1.229 \pm 0.014) \times 10^{-4}$.

We now discuss results of our calculation, presented in column 3, table 1. Here we have used the simple prescription whereby $\langle\nabla^2\rangle_0$ is replaced by

‡4 A later analysis of the experiment reported in ref. [14] yielded $(1+\gamma_\pi)^2 = 1.40 \pm 0.12$, see ref. [15].

‡5 Note that the equality of (18) may be broken without violating CVC, because the energies of the photons in the two-photon and radiative weak decays are different. However, this happens not to be the case; see ref. [9].

Table 1

Decay		$\langle V - E_0\rangle_0$ (GeV)	v	γ	Δ_+	Δ_-
π^+	experiment		0.026 a)	−2.17 ± 0.11 b) or 0.15 ± 0.11	< 3.1 c)	
	calculation e)	−(0.21 ± 0.14)	0.035 ∓ 0.011	−(0.023 ± 0.013)	1.1 ∓ 0.6 d)	
K^+	experiment			< −1.86 f) or > −0.54	1.0 ± 0.2 f)	< 10 f)
	calculation e)	−(0.21 ± 0.14)	0.018 ∓ 0.04	−(0.10 ± 0.08)	1.3 ∓ 0.8	1.5 ∓ 0.4

a) Eq. (18) and ref. [17]. b) Refs. [14,15]. c) Ref. [13], $\Delta \times 10^3$ shown. d) $\Delta \times 10^3$ shown.
e) $\langle\nabla^2\rangle_0 = -\langle p\rangle^2$, calculated with $\langle p\rangle = 0.25 \pm 0.10$ GeV. f) Ref. [16].

$-\langle p\rangle^2$. For π^+ the measured vector form factor $v = 0.026$ [17] is consistent with our prediction $v = 0.035 \mp 0.011$, while the experimental measurement $(1+\gamma_\pi)^2 = 1.32 \pm 0.27$ agrees with our calculation $(1+\gamma_\pi)^2 = 0.95 \pm 0.03$ to within a little more than a standard deviation. As for K^+, the data are more tenuous but there is evidence, based on $\Delta_\pm$, that they are consistent with our results. We emphasize that all the parameters used in this calculation are fixed by independent considerations. We now use (14) and (15) to express the empirical solutions of γ_π in terms of $\langle V-E\rangle_0$, which can be loosely interpreted as an average of $V-E$ over a region near the origin. We find that the solution $\gamma_\pi \sim -2.17$ can be rejected because it implies an unreasonably large $\langle V-E\rangle_0 \sim -14$ GeV. The other solution, $\gamma_\pi = 0.15 \pm 0.11$, implies $\langle V-E\rangle_0 = 0.97 \pm 0.80$, which is reasonable. Taking into account the relatively large uncertainty in the empirical value of $(1+\gamma_\pi)^2$, we infer that γ_π must be small, but with an indefinite sign. In the following, we discuss the significance of the sign of γ.

In order to illustrate the kind of results one might expect from a realistic $q\bar{q}$ potential that is used to compute meson properties, we consider the QCD-inspired Coulomb plus linear potential [18]

$$V(r) = -\tfrac{4}{3}\alpha_s r^{-1} + kr, \tag{20}$$

where $k \approx 0.14\sqrt{2\mu}$ (GeV^2), and $\alpha_s \approx 0.5$ is the strong coupling constant. This potential is not necessarily better than others in the literature but it is more amenable to the following analysis. No spin–spin interaction term, which usually serves to break the ρ–π and K^*–K mass degeneracies, is included in this calculation because we do not attempt any comparison between the pseudoscalar and vector mesons. If the variation of ψ over the region $r < 1/b$ is ignored, then from (8) and (13) the quantity $(\nabla^2\psi)/(b^2 + 2\langle p\rangle^2)\psi$ in (14) should be replaced by $2\mu\langle V-E\rangle_0/b^2$, where

$$\langle V-E\rangle_0 = \frac{b^2}{2}\int_0^R \mathrm{d}r\, r \exp(-br/\sqrt{2})[V(r)-E], \tag{21}$$

The cut-off radius R is used to simulate the finite extension of the wavefunction. Using $R \sim 1$ fm and the parameters of [18] one obtains $\langle V-E\rangle_0 \approx -0.042$ GeV for π^+ and -0.12 GeV for K^+, corresponding to $\gamma_\pi \approx -0.038$ and $\gamma_K \approx -0.13$, respectively. These results are not sensitive to R. We can expect similar results from potentials that, like (20), have a moderately attractive core. On the other hand, a positive value for γ_π can be obtained only if V_π has a repulsive core, or $\langle V_\pi - E\rangle_0 > 0$. Similarly, a positive value for γ_K results only if $\langle V_K - E\rangle_0 > 35$ MeV.

One of the serious alternatives to the potential description of the bound $q\bar{q}$ system is the MIT bag model [19]. In this model, since the quark and antiquark move as free particles inside the bag, with wave number K, p^2 is a positive constant and is equal to $K^2/2$. It follows that in the bag model γ_π and γ_K will be small and negative. Specifically, boundary conditions at the bag surface requires that $K = 2.04/R$, where $R \approx O(1$ fm) is the radius of the bag. Thus $p \approx 0.3$ GeV, $\gamma_\pi \approx -0.03$ and $\gamma_K \approx -0.2$. The important point is that in the MIT bag model γ cannot be positive. This situation will not be qualitatively different in modified bag models [20], so long as quarks are essentially free particles in the interior of the bag.

In this work we have asked ourselves the following question: what are the specific details of the mesonic structure the radiative decay form factors v and a can tell us? We have shown that whereas the vector form factor v depends on the relative $q\bar{q}$ wavefunction at the origin, as does the decay constant f, the axial form factor a carries a new and more sensitive information on the wave function, $\gamma \propto (\nabla^2\psi)/\psi$, and on some aspects of the effective $q\bar{q}$ potential itself. We have shown that of the two possible experimental values for γ_π, $\gamma_\pi = -2.17$ leads to a large and negative $(-14 \pm 3$ GeV) value for $\langle V-E\rangle_0$ and must be rejected. The other possible experimental value is small and implies the magnitude of $\langle V-E\rangle_0$ should be $\sim$1 GeV. A typical confining $q\bar{q}$ potential with an attractive core will yield a small and negative value for $\langle V-E\rangle_0$ and for γ. Similarly, bag models yield a small and negative γ. Only a $q\bar{q}$ potential with a repulsive core can give a positive $\langle V-E\rangle_0$ or γ. This implies that if the experimentally measured value for γ is positive, then it can be taken as strong evidence that the corresponding $q\bar{q}$ potential possesses a repulsive core. At the moment the experimental situation is inconclusive.

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