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K.C. Chou[a] and Y.L. Wu[b1]
[1]Institut für Physik
Johannes Gutenberg-Universität
Staudingerweg 7, Postfach 3980,
D-6500 Mainz, Germany

[2]Institute of Theoretical Physics
Academia Sinica, Beijing, CHINA

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A GENERAL SCALING LAW FOR ALL PSEUDOSCALAR MESON DECAY CONSTANTS

K.C. Chou[a] and Y.L. Wu[b1]
a, Institute of Theoretical Physics, Academia Sinica, Beijing China.
b, Institut für Physik Johannes-Gutenberg-Universität Mainz
D-6500 Mainz, Germany

ABSTRACT

A general scaling law (GSL) of the pseudoscalar decay constants is presented from both a relativistic quark model analysis and a 'soft-hard -compensating' method. The 'modified meson mass' is found to play an essential role for GSL. It is also shown that the ground state wave functions of the pseudoscalar mesons might be universal in the limit of $SU_F(3)$ flavor symmetry and the binding energy of heavy mesons in the order of QCD scale. Normalizing to the measured value $f_K = 162$Mev, we find from GSL that $f_B = 113 \pm 14$ Mev, $f_{B_s} = 139 \pm 17$ Mev, $f_D = 165 \pm 23$ Mev, $f_{D_s} = 203 \pm 28$ Mev.

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The leptonic decay constants for the heavy flavor systems are not experimentally determined, but are of considerable importance in the hadronic physics of the near future, they also enter crucially into many calculations in the heavy flavor sector of the standard model. Examples are the mass and lifetime difference in $B^0 - \bar{B}^0$ mixing and estimates of CP-violating phase and top quark mass [1,2], Many theoretical efforts in determining these decay constants have been made in the past thirty years, however, the range of the predictions is still quite large and spread between 50 $\sim$ 300 Mev for B meson and 90 $\sim$ 350 Mev for D meson [3].

Recently an effective theory [4-10] based on the expansion in terms of inverse powers of the heavy quark mass, i.e. $1/m_Q$ shows that the decay constant of a heavy pseudo-scalar meson (made up of a heavy quark Q and a light anti-quark $\bar{q}$) satisfies a scaling relation in the limit $m_Q \to \infty$ [4,6]

$$\frac{f_P}{f_{P'}} = [\frac{\alpha_s(m_Q)}{\alpha_s(m_{Q'})}]^{-6/(33-2n_f)} \sqrt{\frac{m_{Q'}}{m_Q}} \tag{1}$$

To apply eq.(1) to the physical systems, some extropolations are needed which could be extracted from the lattice simulations of QCD [5].

As $m_P \sim m_Q$ in the heavy quark limit $m_Q \to \infty$, it is interesting to note that eq.(1) reduces, up to logarithmic corrections, to the early quark model calculation [11]

$$f_P = \sqrt{\frac{12}{m_P}} |\psi(0)| \tag{2}$$

and

$$\frac{f_P}{f_{P'}} = \sqrt{\frac{m_{P'}}{m_P}} \tag{3}$$

It was known in the early 60's that eq.(3) gave too small a ratio for $f_K/f_\pi \sim (m_\pi/m_K)^{1/2} = 0.53$, compared with the current experimental value of 1.23 [12]. Since then one of the most challenging problems is to correct the eq.(3) for the ratio f_K/f_π in the standard quark model. Unfortunately, up to now little progress has been made.

Encouraged by the results obtained in the heavy quark sector we succeed in finding a general scaling law for the decay constants including both heavy and light quarks. A brief account of our analysis will be reported in this note.

In the covariant quark model, the quark-antiquark structure of a meson state $|M(p)>$ with momentum p is described by a gauge invariant tensor wave function

$$\Phi_M^{\alpha\beta}(x_1, x_2, \mu) =< 0|T(\bar{\psi}_2^{\beta}(x_2)Pe^{\int_{x_2}^{x_1} dz.A(z)}\psi_1^{\alpha}(x_1))(\mu)|M(p) > \tag{4}$$

where μ refers to the quark-antiquark operator normalized at the point of order of the binding energy of the corresponing meson, i.e. $\mu \sim R^{-1}$, R refers to the 'size' of the meson. In the absence of external fields, by translational invariance

$$\Phi_M^{\alpha\beta}(x_1, x_2, \mu) = e^{-ip.X}\Phi_M^{\alpha\beta}(x, p, \mu) \tag{5}$$

where

$$x = x_1 - x_2, \qquad X = \eta_1 x_2 + \eta_2 x_1 \tag{6}$$

with $\eta_1 + \eta_2 = 1$ governing the centre-of-mass prescription. The corresponding tensor wave function in momentum space is defined by its Fourier transformation

$$\Phi_M^{\alpha\beta}(x, p, \mu) = \int_k e^{-ik.x}\Phi_M^{\alpha\beta}(k, p, \mu) \tag{7}$$

where the momentum k governs the relative motion between quark and antiquark.

In this note only the ground state pseudo-scalar mesons will be considered . Lorentz invariance and parity conservation imply that

$$\Phi_P(k, p, \mu) = -N_P i\gamma_5\phi_P(k, p, \mu) - N_P i\gamma_\nu\gamma_5\phi_P^\nu(k, p, \mu) \tag{8}$$

In terms of the divergence condition between the current $j_{5\nu} = \bar{\psi}_2\gamma_\nu\gamma_5\psi_1$ and density $j_5 = \bar{\psi}_2\gamma_5\psi_1$, which is also valid in the presence of strong interactions [13]

$$< 0|j_{5\nu}(\mu)|P(p) >= - < 0|j_5(\mu)|P(p) > p_\nu/\bar{m}_P \tag{9}$$

where

$$\begin{aligned} \bar{m}_P &= m_P z_P, \qquad 1/z_P = (m_1+m_2)/m_P = 1 - \Delta m_P/m_P \\ \Delta m_P &= m_P - (m_1+m_2) \end{aligned} \tag{10}$$

m_1 and m_2 are the bare quark masses. We may call $\bar{m}_P$ a 'modified meson mass' which will be seen to play a crucial role. Applying above constraint to the tensor wave function, one arrives at the condition

$$\int_k \phi_P^\nu(k,p,\mu) = \frac{1}{\bar{m}_P}\int_k \phi_P(k,p,\mu)p^\nu \tag{11}$$

with this constraint and Lorentz invarance, the Eq.(8) can be rewritten

$$\Phi_P(k,p) = -\frac{i}{2\sqrt{\bar{m}_P}}\{(\not{p}+\bar{m}_P)\gamma_5\phi_P(k^2) + (\not{k} - \not{p}\frac{p.k}{p^2})\gamma_5\phi_1(k,p) + \not{k}\phi_2(k^2)\} \tag{12}$$

where the normalization constant N_P in the Eq.(8) have been choosen so that $\int_k Tr(\overline{\Phi_P}\gamma_\mu\Phi_p)/\int_k \phi_P^\dagger\phi_P = 2p_\mu$ (with $\overline{\Phi_P} = \gamma^0\Phi_P^\dagger\gamma^0$).

As a first simple application, we now consider the matrix element of the axial current $j_{5\nu} = \bar{\psi}_2\gamma_\nu\gamma_5\psi_1$ between the ground state pseudo-scalar meson P and the vacuum, which is known to be parametrized by the decay constant

$$< 0|j_{5\nu}|P(p) >= if_P p_\nu \tag{13}$$

In this definition the current operator $j_{5\nu}$ refers to the normalization point $\mu = max[m_1, m_2, R^{-1}]$. Therefore for the current operator $j_{5\nu}$ containing both heavy quark, $\psi_1 \equiv Q$ with mass $m_Q \gg R^{-1}$ and light quark, $\psi_2 \equiv q$ with mass $m_q \ll R^{-1}$, fields, it is necessary to take account of the evolution of the operator $j_{5\nu}$ from $\mu \sim m_Q$ to $\mu \sim R^{-1}$, or the exchange of hard gluons with virtuality $R^{-2} \ll p^2 \ll m_Q^2$ before applying the covariant quark model estimate [4,6]. The relation of the matrix element between the two scales is

$$< 0|j_{5\nu}(m_Q)|P(p) >= C(\mu) < 0|j_{5\nu}(\mu)|P(p) > \tag{14}$$

In leading logarithmic approximation, it is given by [4,6]

$$C(\mu) = [\frac{\alpha_s(m_Q)}{\alpha_s(\mu)}]^{-\gamma/b} \tag{15}$$

where $b = 11 - 2n_f/3$, and n_f is the number of "unfrozen" quark flavors. γ is the so-called "hybrid" anomalous dimension with the concrete value $\gamma = 2$.

In general, one may write

$$< 0|j_{5\nu}(m_Q)|P(p) >= C(\mu_P/\mu) < 0|j_{5\nu}(\mu)|P(p) > \tag{16}$$

here $\mu_P = max[m_P, \mu]$. With these analyses and definitions of decay constant in Eq.(13) and wave function in Eq.(4), it is not difficult to establish the relation between the decay constant and the wave function

$$f_P = -iC(\frac{\mu_P}{\mu})\frac{p^\nu}{p^2}Tr\gamma_\nu\gamma_5\Phi_P(x=0,p,\mu) \equiv C(\frac{\mu_P}{\mu})\frac{i}{\bar{m}_P}Tr\gamma_5\Phi_P(0,p,\mu) \tag{17}$$

Substituting Eq.(12) into above equation and performing the simple trace calculations, we find that the decay constant is given by a new scaling in terms of the 'modified meson mass' $\bar{m}_P$ rather than the meson mass m_P in Eq.(2)

$$f_P = C(\frac{\mu_P}{\mu})\frac{2}{\sqrt{\bar{m}_P}}\int_k \phi_P \tag{18}$$

which modifies the early quark model results [11] (see eqs.(2) and (3)) by formally modifying a renormalization constant $C(\mu_P/\mu)$ as first observed by Shifman and Voloshin [4] and replacing the meson mass m_P by the 'modified meson mass' $\bar{m}_P$. The latter modification is substantial important for the light mesons which can be see explicitly from the numerical values, $\bar{m}_\pi \sim (10 \sim 14)m_\pi$ and $\bar{m}_K \sim (3 \sim 4)m_K$.

Note that introduce of $\bar{m}_P$ is acturally natural when one defines the pseudo-scalar meson decay constant by considering the matrix element of the pseudo-scalar meson into the corresponding pseudoscalar current. Based on this new scaling the wave functions of both heavy mesons containing a single heavy quark Q and light mesons are then described mainly by the components of the pure light degrees of freedom (i.e. light quarks and soft gluons). For heavy mesons it can be understood from the heavy quark effective theory where the heavy quark acts, in its meson's rest frame, like a spatially static source of

color field. In the heavy quark limit ($\bar{m}_P \sim m_P \sim m_Q \gg \Lambda_{QCD}$), the heavy quark's couplings to the gluon degrees of freedom are independent of its mass and spin [4-10]. For light mesons it could be shown from PCAC and soft pion limit that only scaling out the scaling factor in terms of $\bar{m}_P$ by the SU(3) chiral symmetry rather than m_P one could then express the light meson wave functions in terms of the fields of the pure light degrees of freedom (for explicit results see below Eqs.(27-28)).

From flavor independence of the QCD strong interactions the confining force , and thus the wave function $\int_k \phi_P$ at $\mu \sim R^{-1}$, is not expected to be much different for the various ground state pseudo-scalar mesons. Even though at least the radius of the π-meson differs somewhat from the radius of the other ground state pseudo-scalar mesons, we take for granted $\int_k \phi_P$ to be universal for all pseudo-scalar mesons and will estimate the deviation from $SU_F(3)$ flavor symmetry in latter discussions. The consequence of this ansatz leads to the following general scaling law (GSL) for the decay constants of pseudo-scalar mesons

$$\frac{f_P}{f_{P'}} = [\frac{\alpha_s(\mu_P)}{\alpha_s(\mu_{P'})}]^{-6/(33-2n_f)} \sqrt{\frac{\bar{m}_{P'}}{\bar{m}_P}} \tag{19}$$

For further understandings of this general scaling law, we now make an alternative derivation. As well known that for light mesons PCAC [14] and soft-pion limit [15] provide a powerful approach for realistic calculations. Numerous remarkable results have been derived. A well-known result relevant to our present discussions is the well known CTMOP relation [16], showing that the ratio between π- meson decay constant f_π and any other pseudoscalar meson decay constant f_P is related to their transition form factors as

$$\frac{f_P}{f_\pi} = f_+(m_P^2) + f_-(m_P^2) \tag{20}$$

on the other hand, if pseudoscalar meson P is a heavy one containing one heavy quark, Q, and one light quark, q, it was shown that the heavy quark pole dominance (for brevity's sake we shall refer to this as HQPD) hypothesis in the heavy quark limit leads to another similar 'compensated' relation [17]

$$\frac{f_\pi}{f_P}\frac{\bar{m}_\pi}{m_P}[\frac{\alpha_s(m_Q)}{\alpha_s(\mu)}]^{-2\gamma/b} = f_+(m_P^2) + f_-(m_P^2), \qquad m_P \gg m_\pi \tag{21}$$

Comparing eq.(20) with eq.(23), one reads off

$$\frac{f_P}{f_\pi} = [\frac{\alpha_s(m_Q)}{\alpha_s(\mu)}]^{-\gamma/b}\sqrt{\frac{\bar{m}_\pi}{m_P}}, \qquad m_P \gg m_\pi \tag{22}$$

Note that in the heavy quark limit $m_Q \to \infty$, one has

$$z_P \to 1, \qquad \bar{m}_P \sim m_P \sim m_Q \tag{23}$$

One obtains again eq.(19) applying to the special case of K-meson.

In fact, for both heavy mesons, P and P', with $m_P > m_{P'}$ and the same spectator quarks, one can also directly applying HQPD in twice to P and P' and obtain two similar 'compensated' relations [17]

$$\frac{f_{P'}}{f_P}\frac{\bar{m}_{P'}}{m_P}[\frac{\alpha_s(m_Q)}{\alpha_s(m_{Q'})}]^{-2\gamma/b} = f_+(q^2_{max}) + f_-(q^2_{max}) \tag{24}$$

and

$$\frac{f_P}{f_{P'}} = f_+(q^2_{max}) + f_-(q^2_{max}) \tag{25}$$

with $q^2_{max} = (m_P - m_{P'})^2$. Equating these two relations, one arrives at

$$\frac{f_P}{f_{P'}} = [\frac{\alpha_s(m_Q)}{\alpha_s(m_{Q'})}]^{-\gamma/b}\sqrt{\frac{\bar{m}_{P'}}{\bar{m}_P}} \tag{26}$$

which coinsides with the well known scaling relation of the heavy mesons in the limit $m_Q \to \infty$ i.e. $z_P \to 1$ and $\bar{m}_P \sim m_P \sim m_Q$ (see eq. (1))

We hope that this alternative method (for brevity's sake we may refer to it as a 'soft-hard-compensating' method) has further illuminated the reliability of the genaral scaling law (GSL) of eq.(19). It implies that the introduction of the "modified meson mass" might be essential and the ansatz of the universality of the wave functions at the origin is an approximation valid up to $SU(N)_f$ breaking. For more explicit, it may be helpful to represent another well-known result [18] obtained from PCAC, i.e.

$$f_\pi = \frac{1}{\sqrt{\bar{m}_\pi}}(- < \bar{u}u + \bar{d}d >)^{1/2} \tag{27}$$

and

$$f_K = \frac{1}{\sqrt{\bar{m}_K}}(- < \bar{u}u + \bar{s}s >)^{1/2} \tag{28}$$

where $< \bar{q}q >$ (q=u,d,s) is the vacuum-to-vacuum matrix element, i.e. the so called quark condensates, and has been known for a long time [19]. Its nonvanishing is the simplest manifestation of spontaneous chiral symmetry breaking. Comparing with eq.(18), this explicit result might implies that the universal wave function is relevant to the quark condensates and given in the order

$$\int_k \phi_P(k,p,\mu) \sim \frac{1}{\sqrt{2}}(- < \bar{q}q >)^{1/2} \tag{29}$$

If $SU(3)_F$ flavor symmetry is assumed then

$$< \bar{u}u >=< \bar{d}d >=< \bar{s}s > \tag{30}$$

which leads to

$$\frac{f_K}{f_\pi} = \sqrt{\frac{\bar{m}_\pi}{\bar{m}_K}} \tag{31}$$

and again back to the GSL of eq.(19).

Apply the general scaling law (GSL) to the physical meson states: π-, K-, D-, B-, D_s- and B_s- meson, it is possible to calculate the unknown decay constants from the measured ones.

Taking $m_\pi = 0.140$Gev, $m_K = 0.498$Gev, $m_D = 1.87$Gev, $m_B = 5.27$Gev $m_{D_s} = 1.97$Gev, $m_{B_s} = 5.38$Gev and $m_u + m_d = 10$Mev, $m_s = 125$Mev, $m_c = 1.46$Gev, $m_B = 4.8$Gev and $\Lambda_{QCD} = 100$Mev, $R^{-1} \sim 0.5$Gev, we obtain from eq.(19)

$$\frac{f_B}{f_K} = 0.70, \qquad \frac{f_D}{f_K} = 1.02 \tag{32}$$

and

$$\frac{f_{B_s}}{f_B} = 1.0, \qquad \frac{f_{D_s}}{f_D} = 0.99, \qquad \frac{f_K}{f_\pi} = 1.0 \tag{33}$$

Here all decay constants are scaled to the experimentally known one f_K . In addition these ratios could be determined by lattice calculation using the "f_P/f_K" method [20], which is considered to be fairly reliable. One may notice that although our prediction of f_K/f_π from GSL has improved significantly compared with the one obtained from the early quark model ($f_K/f_\pi = 0.53$), it is, however, still smaller than the current data by about 20%. The deviation might be understood by $SU_F(3)$ symmetry breaking, i.e. $\int_k \phi_K / \int_k \phi_\pi \sim 1.23$ rather than 1. Similar considerations suggest that the symmetry breaking effect is also about 20% in the case of heavy mesons. For convenient we take

$$\frac{f_{B_s}}{f_B} \simeq \frac{f_{D_s}}{f_D} \simeq \frac{f_K}{f_\pi} \tag{34}$$

With these considerations and taking into acount of the errors from the ratios of the quark masses, we then get, by inputting the measured value $f_K = 162$ Mev, for our final answers

$$\begin{aligned} f_B &= 113 \pm 14 Mev, \qquad f_{B_s} = 139 \pm 17 Mev \\ f_D &= 165 \pm 23 Mev, \qquad f_{D_s} = 203 \pm 28 Mev \end{aligned} \tag{35}$$

where the errors mainly come from the strange quark mass [21], we choose here $m_s = (125 \pm 25)$ Mev.

For comparison we list below the results obtained by other methods, namely

$$\begin{aligned} f_B &= 105 \pm 17 \pm 30 Mev, \qquad f_{B_s} = 155 \pm 31 \pm 48 Mev \\ f_D &= 174 \pm 26 \pm 46 Mev, \qquad f_{D_s} = 234 \pm 46 \pm 55 Mev \end{aligned} \tag{36}$$

$$\begin{aligned} f_B &\simeq 120 Mev, \qquad f_{B_s} \simeq 150 Mev \\ f_D &= 194 \pm 15 Mev, \qquad f_{D_s} = 215 \pm 17 Mev \end{aligned} \tag{37}$$

by lattice calculation [20,22] and

$$f_B = 130 \pm 20Mev, \qquad f_D = 170 \pm 10Mev \tag{38}$$

By QCD Green function approach [23] and QCD sum rule [24]

We would like to point out that bigger values of f_B have been presented from the recent lattice computations [25, 26, 27] in the static approximation. While a detail calculation [28] from QCD Green function approach based on sum rule shows that the predicted values of f_B are very sensitive to the binding energy (meson and quark mass differences). For example, for m_b = 4.9Gev,then f_B = 121Mev and for m_b = 4.5Gev, f_B = 200Mev, the corresponding values of f_B in static approximation are f_B = 129Mev and f_B = 242Mev, the latter is consistent with the lattice computations where a big binding energy has already been taken in fact. We then conclude that for a precise prediction for it one would need accurate values of the b-quark mass as input. This problem is under investigation.

To summarize, We have presented a general scaling law (GSL) of the pseudoscalar decay constants by using two approaches: relativistic quark model analysis and 'soft-hard-compensating' method. It has shown that GSL provides the most simple and available way to extract the unknown decay constants from the measured ones. The numerical results obtained in this way are consistent with those found by other methods. The 'modified meson mass' $\bar{m}_P$ has been found to play an essential role for GSL. It has also been guessed that the ground state wave functions of the pseudoscalar mesons at the origin might be universal in the limit of the $SU_F(3)$ symmetry and heavy quark symmetries. These observations might be useful in the treatment of other related problems.

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