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$Q_1(1290)$ AND $Q_2(1400)$ DECAY RATES AND THEIR SU(3) IMPLICATIONS*

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ABSTRACT

We summarize and combine the known information on the decay rates of the strangeness-one axial vector mesons, Q_1 and Q_2. From this information and the rate for $B \to \omega\pi$, we determine the Q_A-Q_B mixing angle and the S-wave, symmetric and antisymmetric octet couplings for vector-pseudoscalar decays of axial vector mesons. If we assume the D(1285) and the E(1420) belong to the $J^{PC} = 1^{++}$ nonet, we find the A_1 to have a mass of ~ 1.47 GeV and a large ($> .3$ GeV) width.

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Of the four ℓ=1, $q\bar{q}$ nonets expected from the three-quark model [1], only the A_2 nonet† is well established [2,3], while the δ nonet at least has sufficient candidates [3,4]. In contrast, even good candidates for the two axial vector nonets have been elusive. Only the namesake of the B nonet is clearly established [5,3], while the D(1285) and, possibly,†† the E(1420) may be identified with the A_1 nonet. The lack of experimental confirmation of the axial vector nonet states remains a nagging problem for quark model phenomenology.

Recently, however, evidence for two strangeness-one, axial vector mesons was obtained from partial wave analyses [7,8] of diffractively produced $K^{\pm}\pi^{+}\pi^{-}$ systems. Subsequently, fits to the partial wave mass spectra of ref. [7] were made in two studies [9,10] using rather different models for the partial wave amplitudes.††† These fits yield information on the masses, total widths, and $K^*\pi$, ρK couplings of $Q_1(1290)$ and $Q_2(1400)$. We combine that information with other branching ratios to ωK [12,13] and $\kappa\pi$, ϵK [14] to obtain two complete sets of Q_1 and Q_2 partial widths. With the model-dependent uncertainties of refs. [9] and [10] in mind, we obtain from these two sets of partial widths a conservative estimate of the decay rates for Q mesons. From this estimate and the rate for $B \to \omega\pi$, we determine the S-wave, octet couplings g_A (antisymmetric) and g_B (symmetric) for vector-pseudoscalar (V-PS) decays of axial vector mesons as well as the Q_A-Q_B mixing [15] angle, θ_Q. Identifying the D

†We refer to each nonet by its isovector member: δ ($J^{PC} = 0^{++}$), A_1 ($J^{PC} = 1^{++}$), A_2 ($J^{PC} = 2^{++}$), B ($J^{PC} = 1^{+-}$).

††Both $J^{PC} = 0^{-+}$ and 1^{++} remain possibilities for the E; see ref. [3]. The pseudoscalar assignment is attractive from the four quark point of view; see ref. [6].

†††In addition to ourselves, Bowler (ref. [10]) and Basdevant and Berger (ref. [11]) have considered models with only one Q resonance present. From the results of these studies, we conclude at the present time that a one-resonance model cannot provide a quantitative description of the measurements.

and E with the A_1 nonet isosinglets, we can then compute the mass and $\rho\pi$ width of the A_1.

To combine the diverse information on Q decays, we use the fact that the total width is the sum of all (known) partial widths. From refs. [9] and [10], we fix the total width and $K^*\pi/\rho K$ branching ratio. For $\kappa\pi$ and ϵK decays, we use our observed cross section ratios [14]: $\Gamma(Q_1 \to \kappa\pi)/\Gamma(Q_1 \to \rho K) = 0.35 \pm .08$, $\Gamma(Q_1 \to \epsilon K)/\Gamma(Q_1 \to \rho K) = 0.3 \pm .1$, and $\Gamma(Q_2 \to \epsilon K)/\Gamma(Q_2 \to K^*\pi) = 0.2 \pm .1$. For $Q_1 \to \epsilon K$ we have assumed a 10% background (tail of Q_2), and for $Q_2 \to \epsilon K$ we have inflated the error to accommodate a possibly large background in the $K^*\pi$ mode. The branching ratio $Q_1 \to \omega K/Q_1 \to \rho K$ is more difficult to estimate. Because of the narrow ω width, the ratio of ωK to ρK phase space exhibits [13] a roughly step-function behavior at ~ 1.28 GeV. Thus this branching ratio is extremely sensitive to the precise value of the Q_1 mass. Consequently we choose to use the upper limit [13,12] $\Gamma(Q_1 \to \omega K)/\Gamma(Q_1 \to \rho K) \leq 0.32 \pm .03$.

Combining the above information, we obtain columns two and three of table I, corresponding to the input of refs. [9] and [10] respectively. We have used from ref. [10] the results of the "original model" fit in which the SU(3), Q_A - Q_B mixing constraints were not imposed. We comment on several important features. First, although the $Q_1 \to \rho K$ width is the principal contribution, it corresponds to, at best, only half the total width of Q_1. Secondly, both models indicate that Q_1 decouples from $K^*\pi$ while Q_2 decouples from ρK. This coupling pattern was central to the qualitative interpretation of the $1^+ K^*\pi$ - ρK relative phase motion in terms of two Q mesons as discussed in ref. [7]. Thirdly, there is a substantial difference in the magnitudes of the widths from the two models. Basically this reflects the uncertainty in the amount of coherent background under Q_2 in the $K^*\pi$ channel. Quantitatively, it corresponds to the very different parametrizations employed in the fits of refs. [9] and [10]. As an attempt to reflect such systematic uncertainties, we offer in the fourth column of table I a conservative estimate of the partial widths for Q_1 and Q_2, corresponding to the mean and standard deviation of the values and errors in the preceding columns. For comparison, the last column of table I corresponds to the SU(3) constrained fit of ref. [10]. We note that this fit provides a mildly worse [10] description of the partial wave data and that the ratio $\Gamma(Q_1 \to \rho K)/\Gamma(Q_2 \to K^*\pi)$ is roughly 1/3 that in the unconstrained fit. All the V-PS widths in table I are for S-wave decay, as the D-wave coupling is known to be small or nonexistent [7,8].

We now turn to the extraction of SU(3) parameters from the information of table I. For V-PS decays of the axial vector (A) mesons, we define the reduced couplings $\gamma(A \to V\text{-}PS)$ by the formula

$$\Gamma(A \to V\text{-}PS) = \frac{\langle q_V \rangle}{M_A^2} \gamma^2(A \to V\text{-}PS) , \tag{1}$$

where $\langle q_V \rangle$ is the vector meson momentum averaged over its line shape [13]. These couplings are presented in the upper half of table II. They follow from the corresponding widths of table I, with the exception of $Q_1 \to \omega K$. In this case we use $\gamma^2(Q_1 \to \omega K) = (.22 \pm .07)\gamma^2(Q_1 \to \rho K)$, which is independent of the precise mass of Q_1 [13]. We will also need the S-wave coupling† for $B \to \omega\pi$, $|\gamma(B \to \omega\pi)| = .72 \pm .03$ GeV, assuming nominal values [3,5] for the mass, total width, and D/S ratio.

In the usual spirit of SU(3) phenomenology [2], we assume that symmetry breaking effects are accounted for by using observed masses in the phase space

†By S- and D-wave we mean those amplitudes such that $\Gamma = q(|S|^2 + |D|^2)/M^2$.

of eq. (1), while the reduced couplings are related by exact SU(3), modified by vector meson singlet-octet mixing. In addition we assume that the physical Q meson states are mixtures [15], characterized by an angle θ_Q, of the Q_A and Q_B states. We may now relate the observed couplings for Q_1 and Q_2 V-PS decays to g_A, g_B, θ_Q, and the symmetric singlet coupling, g_1. These relations are given in table III. As our final assumption, we set $\gamma(B \to \phi\pi) = 0$ on experimental grounds [3]. This relates g_1 to g_B through

$$g_1 = -g_B \cot \theta_V/\sqrt{5} , \tag{2}$$

where we take [2] $\theta_V = -31^{\circ} \pm 3^{\circ}$.

Qualitatively the observed pattern of the V-PS couplings for Q_1 and Q_2 can be readily understood by careful inspection of table III. Thus, if we simply set $g_A/g_B = -6/\sqrt{20}$ and $\theta_Q = 45^{\circ}$, we find $\gamma(Q_1 \to K^*\pi) = 0$ and $\gamma(Q_2 \to \rho K) = 0$; that is, we predict that Q_1 decouples from $K^*\pi$ and Q_2, from ρK. In addition, for magically mixed [16] ω-ϕ, we have $\gamma(\omega K)/\gamma(\rho K) = -1/\sqrt{3}$ for both Q's. This is in rough accord with the observed ratio for Q_1 (table II); since Q_2 decouples from ρK, we would also expect it to decouple from ωK (table I). Of course a set of relations similar to those of table III may be written for scalar-pseudoscalar (S-PS) Q meson decays. For $\theta_Q = 45^{\circ}$, a ratio of h_A to h_B (the S-PS analogues of g_A and g_B) may be chosen to have Q_2 decouple from $\kappa\pi$ (table I). Such a ratio would predict comparable couplings of Q_1 and Q_2 to $\kappa\eta$, the phase space being similar to that for the ϵK mode. However, the ϵK decays involve not only h_A, h_B, and θ_Q but also h_1 and the complications of ϵ, S^* mixing [4], as well as their relative contributions to the Q rates [7,8]. While such complications presently preclude an SU(3) analysis of S-PS decays, there appears to be sufficient flexibility to accommodate the observations of table I.

To determine g_A, g_B, and θ_Q, we have made least squares fits of the formulas in table III to the couplings of table II and $\gamma(B \to \omega\pi)$. The results of these fits and their χ^2's are summarized in the lower half of table II. We note that g_B and θ_Q are rather independent of which input data we use. This reflects the facts that g_B is principally determined by the B width and that $\theta_Q \approx 45^\circ$ corresponds to Q_1 decoupling from $K^*\pi$ and Q_2, from ρK. The spread in values for g_A stems from the differences in magnitudes of the partial widths from refs. [9] and [10]. With model uncertainties in mind, we take

$$g_A = +1.67 \pm .18 \text{ GeV}, \quad g_B = -.83 \pm .03 \text{ GeV}, \quad \theta_Q = 41^\circ \pm 4^\circ \tag{3}$$

as conservative estimates for these SU(3) parameters. They are consistent with the parameters† which follow from the SU(3) constrained results of ref. [10].

Restricting our attention to the parameters of eq. (3), we may graphically assess the SU(3) consistency of V-PS decays. For a given value of θ_Q (and θ_V), the reduced couplings are linearly related to g_A and g_B. Thus, in a plot of g_A vs g_B, the observed couplings and their errors determine straight bands which must intersect at a common point (g_A, g_B) for a consistent SU(3) description. From fig. 1 we see that the V-PS decays are in good agreement with SU(3) expectations, the only mild inconsistency possibly being in the coupling for $Q_1 \to \rho K$. For $\theta_Q \approx 45^\circ$ we expect (table III) the ratio $\Gamma(Q_1 \to \rho K)/\Gamma(Q_2 \to K^*\pi)$ to equal that of the phase spaces for these decays ($\sim .37$). Note that this is essentially the ratio found (table I) from the fit of ref. [10] constrained by Q_A-Q_B mixing. Within the uncertainties of the models [9, 10, 11] used, we conclude that the decay rates for Q_1 and Q_2 lie within the conservative limits of table I and that they are consistent with SU(3).

† $g_A = 1.76 \pm .05$, $g_B = -.87 \pm .03$, $\theta_Q = 42^\circ \pm 1^\circ$, and $\chi^2 = 9.1$.

Having established a range of possible values for g_A, g_B, and θ_Q, we now discuss what inferences may be made regarding the A_1. For $1.0 < M(A_1) < 1.6$ GeV, we find the A_1 width to $\rho\pi$ ($\Gamma = \frac{2}{3}\langle q_\rho\rangle g_A^2/M^2(A_1)$) to be large (> .3 GeV). To determine the A_1 mass, we need an additional assumption. For the A_1 nonet, the SU(3) mass formula (with particle names for masses) is

$$A_1^2 = 4Q_A^2 - 3(E^2\cos^2\theta_A + D^2\sin^2\theta_A) , \tag{4}$$

where we denote the A_1 nonet isosinglets by D, E and their mixing angle by θ_A. From the Q_A-Q_B mixing mass formula

$$Q_{A,B}^2 = \frac{1}{2}\left(Q_1^2 + Q_2^2 \pm (Q_1^2 - Q_2^2)\cos 2\theta_Q\right), \tag{5}$$

we find $Q_A \sim 1.34$ GeV, roughly independent of which value of θ_Q in table II we use. We now assume that the E and D are indeed in the A_1 nonet. Using the only measurement [17,3] of the rate for $E \to K^*\bar{K}$ ($\Gamma = \langle q_{K^*}\rangle g_A^2\cos^2\theta_A/M_E^2$), we may estimate the E-D mixing angle, θ_A. We find $72^\circ < |\theta_A| < 77^\circ$, the spread reflecting the range in values for g_A. From eq. (4) we thus compute $A_1 \sim 1.47$ GeV with a broad $\rho\pi$ width as summarized in table II. We note that three recent partial wave analyses [18,19,20] of nondiffractively produced 3π systems find a broad bump in the $J^P = 1^+$, $I = 1$ wave at ~ 1.5 GeV. The values of the corresponding cross sections are consistent with the expectations of production mechanisms [21] for a broad A_1.

We have summarized and combined the known information on Q decays to obtain a complete set of partial widths for $Q_1(1290)$ and $Q_2(1400)$. In addition we have given a conservative estimate of these rates and their errors to reflect the model-dependent assumptions [9,10] needed to determine the total widths of Q_1 and Q_2. From this information we determined the range of SU(3) parameters which characterize the V-PS decays of axial vector mesons. These parameters and the assumption that the D and E mesons have $J^{PC} = 1^{++}$ lead to the prediction that the elusive A_1 has a broad $\rho\pi$ width and a mass of ~ 1.47 GeV. As such a mass yields a curious inverted level structure for the A_1 nonet $(M(A_1) > M(Q_A))$, it is clear that the spin of the E and the 3π bumps [18, 19, 20] at ~ 1.5 GeV deserve further study. The A_1 issue aside, we conclude that the observed $Q_1(1290)$ and $Q_2(1400)$ decay rates can be reasonably described within the context of SU(3).

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Figure Caption

1. g_A vs g_B plot for $\theta_Q = 41^\circ$ of known vector-pseudoscalar decays of axial vector mesons. A best estimate gives $g_A = 1.67 \pm .18$ GeV, $g_B = -.83 \pm .03$ GeV, and $\theta_Q = 41^\circ \pm 4^\circ$.

TABLE I. Partial decay widths (MeV) for $Q_1(1290)$ and $Q_2(1400)$. The vector-pseudoscalar widths are for S-wave decay only. Note that Refs. 9 and 10 find only the total widths and the $\rho K/K^*\pi$ amplitude ratios. We have combined that information with other Q branching ratios to obtain the tabulated values.

Mode[a]	Ref. 9	Ref. 10[b] No SU(3)	Mean	Ref. 10[b] SU(3)
$Q_1 \rightarrow K^*\pi$	2 ± 2	21 ± 2	12 ± 13	13 ± 1
$\rightarrow \rho K$	75 ± 6	125 ± 8	100 ± 35	83 ± 6
$\rightarrow \omega K$[c]	24 ± 3	40 ± 5	32 ± 11	27 ± 3
$\rightarrow \kappa\pi$	26 ± 6	44 ± 10	35 ± 13	29 ± 7
$\rightarrow \epsilon K$	22 ± 5	36 ± 8	29 ± 10	24 ± 5
$Q_2 \rightarrow K^*\pi$	117 ± 10	191 ± 19	154 ± 52	239 ± 23
$\rightarrow \rho K$	2 ± 1	2 ± 1	2 ± 1	1 ± 1
$\rightarrow \omega K$	~ 0	~ 0	~ 0	~ 0
$\rightarrow \kappa\pi$	~ 0	~ 0	~ 0	~ 0
$\rightarrow \epsilon K$	23 ± 12	38 ± 19	31 ± 11	48 ± 24

(a) Possible $\kappa\eta$ mode neglected; it could be as large as ϵK and would reduce all numbers by a few percent.
(b) SU(3) refers only to the assumption that Q_A and Q_B mix; the errors are our estimates.
(c) Maximum ωK width; see text.

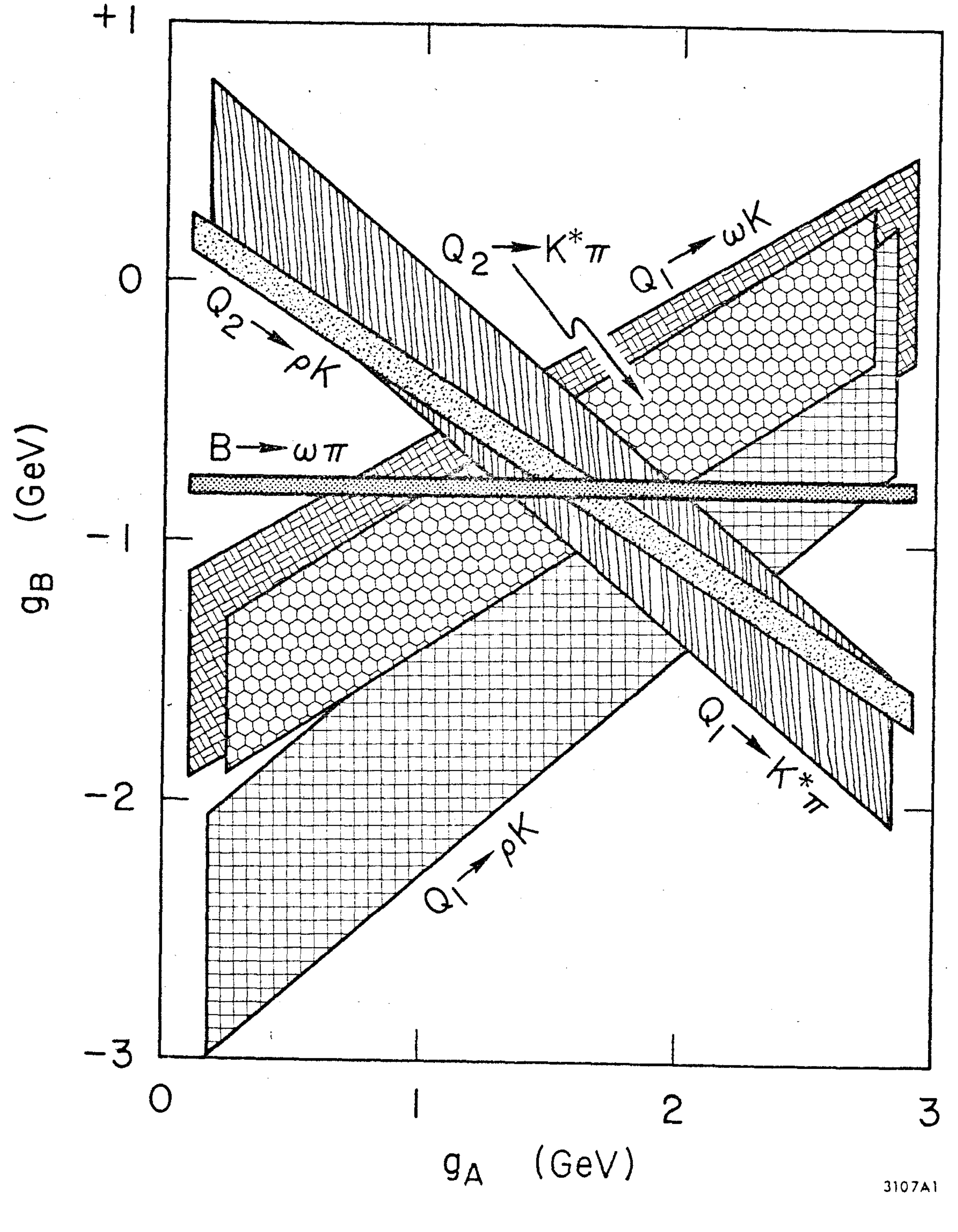
TABLE II. S-wave couplings (GeV) for vector-pseudoscalar decays of Q_1, Q_2 and resulting SU(3) parameters.

	Ref. 9	Ref. 10 No SU(3)	Mean[(a)]
$\gamma(Q_1 \rightarrow K^*\pi)$	$.11 \pm .05$	$.34 \pm .02$	$.26 \pm .14$
$\gamma(Q_1 \rightarrow \rho K)$	$1.02 \pm .04$	$1.32 \pm .04$	$1.18 \pm .21$
$\gamma(Q_1 \rightarrow \omega K)$[(b)]	$-.47 \pm .08$	$-.61 \pm .11$	$-.54 \pm .13$
$\gamma(Q_2 \rightarrow K^*\pi)$	$-.78 \pm .03$	$-.99 \pm .05$	$-.89 \pm .15$
$\gamma(Q_2 \rightarrow \rho K)$	$-.13 \pm .03$	$-.13 \pm .03$	$-.13 \pm .03$
g_A (GeV)	$1.40 \pm .06$	$1.95 \pm .04$	$1.67 \pm .18$
g_B (GeV)	$-.80 \pm .03$	$-.90 \pm .02$	$-.83 \pm .03$
θ_Q	$45^\circ \pm 2^\circ$	$40^\circ \pm 1^\circ$	$41^\circ \pm 4^\circ$
χ^2	25.1	32.0	1.3
M_{A_1} (GeV)[(c)]	1.47	1.46	1.47
$\Gamma_{A_1 \rightarrow \rho\pi}$ (GeV)	.32	.60	.45

(a) Values correspond to mean widths and errors in Table I.
(b) With $\gamma^2(Q_1 \rightarrow \omega K) = (.22 \pm .07)\gamma^2(Q_1 \rightarrow \rho K)$.
(c) Assumes both the D <u>and</u> E have $J^{PC} = 1^{++}$.

TABLE III. Relation of the couplings $\gamma(Q \rightarrow V\text{-}PS)$ to the S-wave, SU(3) V-PS couplings (g_A, g_B, g_1), the Q_A-Q_B mixing angle (θ_Q), and the ω-ϕ mixing angle (θ_V).

Mode	Q_1	Q_2
$K^*\pi$	$\frac{1}{2}g_A \cos\theta_Q + \frac{3}{\sqrt{20}} g_B \sin\theta_Q$	$-\frac{1}{2}g_A \sin\theta_Q + \frac{3}{\sqrt{20}} g_B \cos\theta_Q$
ρK	$\frac{1}{2}g_A \cos\theta_Q - \frac{3}{\sqrt{20}} g_B \sin\theta_Q$	$-\frac{1}{2}g_A \sin\theta_Q - \frac{3}{\sqrt{20}} g_B \cos\theta_Q$
ωK	$\frac{1}{2}g_A \cos\theta_Q \sin\theta_V + \left(\frac{1}{\sqrt{20}} g_B \sin\theta_V + g_1 \cos\theta_V\right) \sin\theta_Q$	$-\frac{1}{2}g_A \sin\theta_Q \sin\theta_V + \left(\frac{1}{\sqrt{20}} g_B \sin\theta_V + g_1 \cos\theta_V\right) \cos\theta_Q$



+1
0
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g_B (GeV)
g_A (GeV)
$Q_2 \to K^*\pi$
$Q_1 \to \omega K$
$Q_2 \to \rho K$
$B \to \omega\pi$
$Q_1 \to K^*\pi$
$Q_1 \to \rho K$
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Fig. 1

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$\gamma(Q_1 \to \rho K)$	1.02 ± .04	1.32 ± .04	1.18 ± .21
$\gamma(Q_1 \to \omega K)$[b]	-.47 ± .08	-.61 ± .11	-.54 ± .13
$\gamma(Q_2 \to K^*\pi)$	-.78 ± .03	-.99 ± .05	-.89 ± .15
$\gamma(Q_2 \to \rho K)$	-.13 ± .03	-.13 ± .03	-.13 ± .03
g_A (GeV)	1.40 ± .06	1.95 ± .04	1.67 ± .18
g_B (GeV)	-.80 ± .03	-.90 ± .02	-.83 ± .03
θ_Q	$45^\circ \pm 2^\circ$	$40^\circ \pm 1^\circ$	$41^\circ \pm 4^\circ$
χ^2	25.1	32.0	1.3
M_{A_1} (GeV)[c]	1.47	1.46	1.47
$\Gamma_{A_1 \to \rho\pi}$ (GeV)	.32	.60	.45

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Mode	Q_1	Q_2
$K^*\pi$	$\frac{1}{2}g_A\cos\theta_Q + \frac{3}{\sqrt{20}}g_B\sin\theta_Q$	$-\frac{1}{2}g_A\sin\theta_Q + \frac{3}{\sqrt{20}}g_B\cos\theta_Q$
ρK	$\frac{1}{2}g_A\cos\theta_Q - \frac{3}{\sqrt{20}}g_B\sin\theta_Q$	$-\frac{1}{2}g_A\sin\theta_Q - \frac{3}{\sqrt{20}}g_B\cos\theta_Q$
ωK	$\frac{1}{2}g_A\cos\theta_Q\sin\theta_V + \left(\frac{1}{\sqrt{20}}g_B\sin\theta_V + g_1\cos\theta_V\right)\sin\theta_Q$	$-\frac{1}{2}g_A\sin\theta_Q\sin\theta_V + \left(\frac{1}{\sqrt{20}}g_B\sin\theta_V + g_1\cos\theta_V\right)\cos\theta_Q$