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Suppression factor in the decays of the ψ family

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From ordinary hadronic reactions one observes the empirical fact that large-momentum-transfer processes are generally suppressed. We abstract a prescription that any quark which undergoes a momentum transfer squared q^2 is suppressed by a factor $Q(q^2)$. We estimate that $Q(q^2)$ is given by the cube root of the proton form factor. Using such a prescription we are able to explain the leptonic decays of all ψ's and the known two-body hadronic decays of the ψ family. Furthermore we predict many reduced hadronic decay widths of the ψ family, which can be measured in the not-distant future. There exists a great range of values for the predicted decay widths, some of the order MeV and some of the order 10^{-4} MeV. The observation of such a great variation among the many decay modes of the ψ family will be crucial to the present scheme.

I. INTRODUCTION

The discovery of the extremely narrow resonances[1] J/ψ, ψ', ψ'', etc., has stimulated many theoretical developments. The Iizuka-Okubo-Zweig (IOZ) rule is generally used as a means of explaining the narrowness of the resonance width. Nevertheless, the origin of the IOZ rule requires an explanation. Furthermore, among the many decays of the J/ψ, ψ', there are still anomalies. For example, the coupling of $\psi' \to \psi\eta$ is 30 times larger than the coupling of $\psi' \to \rho\pi$. There are, at present, three general approaches to the problem of ψ decay:

(i) mixing method:[2] using various mixing schemes in SU(4), or the mixing of quarks, to explain the various decays of ψ;

(ii) group-theoretical method[3];

(iii) dual model.[4]

We wish to explore a fourth possibility: that the suppression of the ψ decay is due to some dynamical origin, for example, from some field-theoretical calculation in quantum chromodynamics. We adopt a phenomenological approach and ask, in Sec. II, first what regularity exists in ordinary hadron interactions, and then whether such a regularity can be extended to explain the narrowness of the ψ decays. Then we calculate the many other decay modes, and find great variety among them.

II. SUPPRESSION FACTOR DUE TO MOMENTUM TRANSFER IN KNOWN REACTIONS

The suppression due to momentum transfer in known reactions has been studied before.[5] We discuss the effect in two separate categories:

(A) ordinary hadrons,

(B) those involving J/ψ, and its family.

For category (A), it has long been recognized in two-body reactions $ab \to cd$ that the four-momentum transfer between two incident particles is extremely difficult, and that this produces a forward peak in multiparticle production. Chou and Yang[6] have proposed a minimal rule for asymptotic hadron scattering. It states that for processes $a+b \to a^+ + b^+$ the longitudinal momentum transfer Δp_L and energy transfer ΔE between a and a^+ (or b and b^+) approach zero as energy increases:

$$\begin{aligned} &\Delta P_L \to 0\,, \\ &\Delta E \to 0, \quad \text{as } s \to \infty\,. \end{aligned} \tag{2.1}$$

This rule has subsequently received solid experimental confirmation, both from pp and πp reactions.[7] The qualitative picture implied by this minimal rule is that the hadron resists changing its momentum in strong interaction. For the quark model, the picture suggests that the quark inside the hadron also resists changing its momentum in reaction processes. In other words, the quark line in a quark diagram resists the tendency to be bent or twisted. We shall call this assumption the stiff-quark-line hypothesis. This hypothesis has already been applied to obtain various selection rules.[8]

The resistance to momentum transfer can be understood qualitatively by an appeal to field theory: Four-pointlike-fermion interactions for $ab \to cd$ produce a flat differential cross section

$$\frac{d\sigma}{dt} \sim \text{const} \times e^t\,. \tag{2.2}$$

However, if between the two scattered fermions there is a particle exchange, the propagator of the exchanged particle will produce some suppression for finite momentum transfer. For instance, in electromagnetic interactions $e^-e^- \to e^-e^-$ scattering has a differential cross section

$$\frac{d\sigma}{dt} \propto \frac{1}{t^2}\,, \tag{2.3}$$

proportional to the photon propagator $(1/t)$

squared. In a strong interaction, for one-ρ exchange it should have a ρ-propagator squared, and for one-gluon exchange it should have a gluon-propagator squared. However, one-particle exchange is not a good approximation in strong interaction; it is not possible to calculate reliably the suppression factor due to four-momentum transfer.

In the following, we adopt a phenomenological approach, and present a semiquantitative prescription that can summarize the present experimental situation in an approximate way. The prescription is as follows: Whenever a hadron changes its four-momentum, it will be suppressed by a factor of

$$Q^m(q^2)\,, \tag{2.4}$$

where m is the number of quarks in the hadron.

We can check this suppression factor first in elastic hadron scattering. For pp elastic scattering, there are three quarks scattering off three quarks if the multiple-scattering terms are neglected. Then, according to our prescription, the differential cross section is

$$\frac{d\sigma}{dt}(pp) \propto [Q^6(q^2)]^2\,, \tag{2.5}$$

where $m=6$. For $\pi p \to \pi p$ it is

$$\frac{d\sigma}{dt}(\pi p) \propto [Q^5(q^2)]^2\,, \tag{2.6}$$

where $m=5$. The quark diagrams for these cross sections are shown in Fig. 1. The slope parameters b, defined by $d\sigma/dt = Ae^{bt}$ then approximately satisfy the following equality:

$$b(\pi p) = \tfrac{5}{6}b(pp)\,. \tag{2.7}$$

It is satisfied to within 2% accuracy. Similarly, in $ep \to ep$ scattering, three quark lines in the proton suffer a momentum transfer. According to our prescription, the proton form factor is given by

$$F_p(q^2) = Q^3(q^2)\,, \tag{2.8}$$

where $m=3$. Similarly, the pion form factor is

$$F_\pi(q^2) = Q^2(q^2)\,, \tag{2.9}$$

where $m=2$. The corresponding quark diagrams are shown in Fig. 2. From Eq. (2.8), the exact suppression factor is obtained:

$$Q(q^2) = F_p^{1/3}(q^2) = \left(\frac{1}{1+q^2/0.71}\right)^{2/3}. \tag{2.10}$$

The relation between the pion form factor and the proton form factor contained in (2.8) and (2.9) is

$$F_\pi(q^2) = F_p^{2/3}(q^2)\,. \tag{2.11}$$

This equality has been shown[5] to be consistent

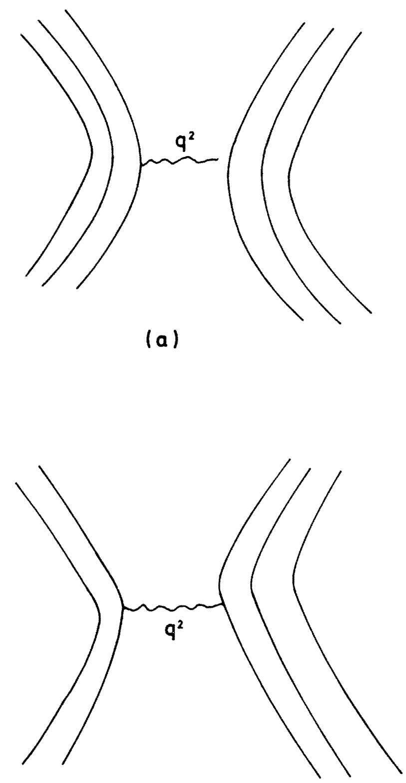

FIG. 1. Elastic pp scattering at small q^2 involves the bending of six quarks as shown in (a) with $m=6$, while πp scattering involves the bending of five quarks as shown in (b) with $m=5$.

with the present experimental data.

So far the momentum transfer q^2 is spacelike for elastic scatterings and form factors. To test whether it makes sense to use Eq. (2.10) for a timelike region, it is necessary to investigate the inelastic two-body scatterings

$$ab \to cd\,.$$

We draw, in Fig. 3, the quark diagram for

$$\begin{aligned} &\pi^- p \to \rho^0 n, \quad m=2 \\ &\bar{p}p \to \pi^-\pi^+, \quad m=3 \\ &K^- p \to pK^-, \quad \text{backward scattering}, m=5\,. \end{aligned} \tag{2.12}$$

Then the cross section will be suppressed by a factor as follows:

$$\sigma(s) \propto [Q^m(s)]^2 \sim F_p^{2m/3} \sim s^{-4m/3}\,. \tag{2.13}$$

[The proton form factor has not been measured in the timelike region. We just take the symmetric case for $Q(s) = (1+s/0.71)^{-3/2}$.] The power-law behavior in the energy squared s of the inelastic-scattering cross section has the same origin as the power-law behavior of the form factor in the

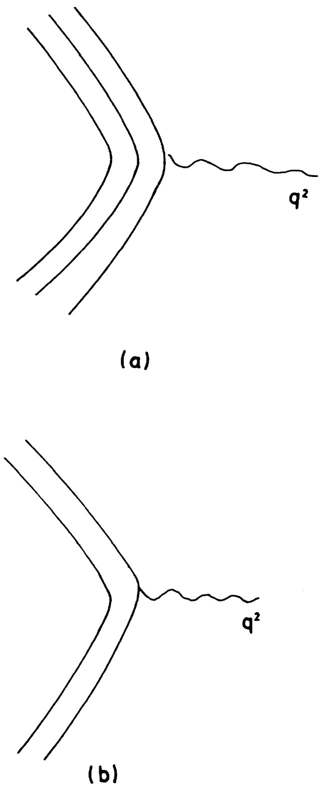

FIG. 2. Quark diagrams for the form factor of the proton ($m=3$) (a) and the form factor of the pion ($m=2$).

spacelike region ($-t$). All the inelastic two-body scatterings are investigated in Ref. 5, and it is found that the power n in the energy dependence of cross sections

$$\sigma(s) \propto s^{-n} \tag{2.14}$$

is indeed approximately given by

$$n = 4m/3 \pm 1 . \tag{2.15}$$

The approximate nature of the equality is due to the neglect of the spin-parity of the hadron involved. Nevertheless, it gives us some guidance to use Eq. (2.4) as a preliminary prescription to investigate whether suppression due to momentum transfer plays any role in the decays of the ψ family.

III. LEPTONIC DECAYS OF THE ψ FAMILY

The leptonic decay mode of the ψ family is the simplest of all. As shown in Fig. 4 it contains only one quark line which undergoes four-momentum change ($m=1$). The momentum-transfer squared q^2 is just given by its mass squared $-m_\psi^2$. Hence the suppression factor for the decay rate

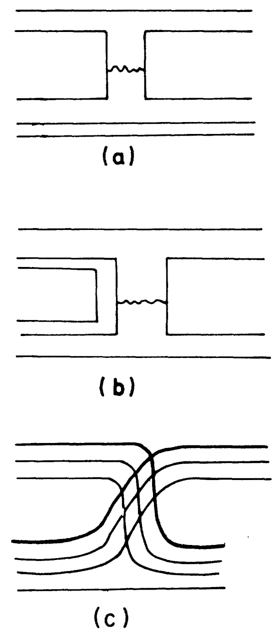

FIG. 3. Inelastic hadron scatterings (a) $m=2$ processes, e.g., $\pi^- p \to \pi^0 \eta$, (b) $m=3$ processes, e.g., $\bar{p}p \to \pi^- \pi^+$, (c) $m=5$ processes, e.g., $K^- p \to p K^-$ backward scattering.

is

$$Q^2(+m_\psi^2) = F_p^{\,2/3}(+m_\psi^2) , \tag{3.1}$$

which should be inserted into the decay formula[9]

$$\Gamma(\psi \to \bar{l}l) = \frac{16\pi\alpha^2 e_Q^{\,2}}{M^2} \, |\psi(0)|^2 , \tag{3.2}$$

in addition to all the ordinary quark-model calculations. The wave function $|\psi(0)|^2$ is an unknown quantity, which can be eliminated if the ratio of decay rates of the ψ family is calculated, assuming as usual that they are radially excited states of the $\psi(3.1)$. We list in Table I the various experimental values, and their comparison with theoretical values. The agreement is good. If the suppression factor of Eq. (3.1) is not included, there would be disagreement between the quark-model calculation and the experimental values. [One is naturally led to the question: should the suppression factor Eq. (3.1) be inserted for the ordinary vector-meson decays $\rho \to l\bar{l}$, $\omega \to \bar{l}l$, and $\phi \to \bar{l}l$? In

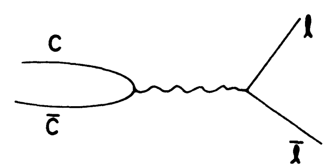

FIG. 4. The quark diagram for the decay of the ψ family into $l\bar{l}$. It is an $m=1$ process.

TABLE I. Leptonic decays of ψ family.

Decays	$s(\mathrm{GeV}^2)$	m	$F_p^{2m/3}(s)$	Calculated ratios	Experimental ratios
$\psi(3.1) \to e^+ + e^-$	9.58	1	2.82×10^{-2}	$\Gamma_{e^+e^-}(\psi(3.1)/\Gamma_{e^+e^-}(\psi's)$	$\Gamma_{e^+e^-}(\psi(3.1))\Gamma_{e^+e}(\psi's)$
$\psi(3.7) \to e^+ + e^-$	13.64	1	1.81×10^{-2}	2.18	2.23 ± 0.85
$\psi(4.1) \to e^+ + e^-$	16.81	1	1.39×10^{-2}	3.55	1.43 ± 2.61
$\psi(4.4) \to e^+ + e^-$	19.36	1	1.15×10^{-2}	4.97	10.9 ± 4.2

principle, it should be there. However, it is not possible at the moment to calculate accurately the $\phi(\bar{s}s) \to \bar{l}l$ decay rate from the $\psi(\bar{c}c) \to \bar{l}l$ decay rate because the $|\psi(0)|^2$ is not dimensionless and should be proportional to quark mass cubed. We shall discuss this further in the future.]

IV. HADRONIC DECAY MODES OF THE ψ FAMILY

All hadronic decay modes of the ψ family are classified into five different classes:

$$\psi_i \to \psi_j + M, \tag{4.1a}$$

$$\psi_i \to M_1 + M_2, \tag{4.1b}$$

$$\psi_i \to \chi_j + M, \tag{4.1c}$$

$$\chi_i \to \chi_j + M, \tag{4.1d}$$

$$\chi_i \to M_1 + M_2, \tag{4.1e}$$

where

$$\psi_i = \psi(3.096), \quad \psi(3.694), \quad \psi(4.1), \quad \psi(4.4)$$

and

$$\chi_i = \chi(3.550), \quad \chi(3.508), \quad \chi(3.415), \quad \chi(2.75).$$

For the discussion below, the ψ states are assumed to be $\bar{c}c$ states with $J^P = 1^-$, and the higher-mass states are radially excited states of the ground-state $\psi(3.1)$. The χ states have the following quantum-number assignments:

$$\begin{aligned} &\chi(2.75) \quad J^P = 0^-, \\ &\chi(3.415) \quad J^P = 0^+, \\ &\chi(3.508) \quad J^P = 1^+, \\ &\chi(3.55) \quad J^P = 2^+. \end{aligned} \tag{4.2}$$

It is clear that the quantum-number assignment is not definitive, and almost certainly will change. Nevertheless, for definiteness of numerical calculation, it will suffice. When, in the future, better measurement is made, adjustment can be easily made.

Let us now discuss the class

$$\psi_i \to \psi_j + M.$$

The quark diagram for such a process is shown in Fig. 5(a). The momentum-transfer squared $s = q^2$ is equal to the mass squared of the meson

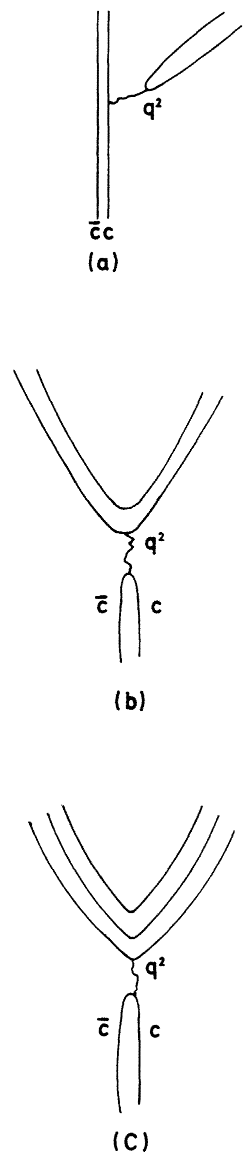

FIG. 5. The quark diagrams for hadronic decays of the ψ family. (a) $m=3$. This includes the decays of $\psi_i \to \psi_j + M$, $\psi_i \to \chi_j + M$, and $\chi_i \to \chi_j + M$. The q^2 is mass squared of the hadron M. (b) $m=3$. This includes the decays of $\psi_i \to M_1 + M_2$ and $\chi_i \to M_1 + M_2$, where M_1, M_2 are mesons. The q^2 is the mass squared of the decaying ψ or χ state. (c) $m=4$. This includes the decays of $\psi_i \to \bar{B} + B$, and $\chi_i \to \bar{B} + B$, where B is the baryon. The q^2 is the mass squared of the decaying ψ or χ state.

TABLE II. Strong decays of the type $\psi_i \to \psi_j + M$.

Decays	s (GeV^2)	m	$F_p{}^{2m/3}(s)$	$\Gamma_{(g^2/4\pi)}\,F_p{}^{2m/3}$(MeV)	Reduced width (MeV)
$\psi(3.7)\to\psi(3.1)+\eta$	0.301	3	0.243	0.2443	5.94×10^{-2}
$\psi(4.1)\to\psi(3.1)+\eta$	0.301	3	0.243	7.89	1.91
$\psi(4.4)\to\psi(3.1)+\eta$	0.301	3	0.243	17.4	4.22
$\psi(4.4)\to\psi(3.7)+\eta$	0.301	3	0.243	1.17	2.84×10^{-1}
$\psi(4.1)\to\psi(3.1)+\eta'$	0.916	3	0.363×10^{-1}	0.373	1.35×10^{-2}
$\psi(4.4)\to\psi(3.1)+\eta'$	0.916	3	0.363×10^{-1}	7.24	2.62×10^{-1}
$\psi(4.1)\to\psi(3.1)+S^*$	0.986	3	0.307×10^{-1}	6.69×10^{1}	2.05
$\psi(4.4)\to\psi(3.1)+S^*$	0.986	3	0.307×10^{-1}	3.63×10^{2}	11.1
$\psi(4.4)\to\psi(3.1)+S$	1.21-1.69	3	0.0076-0.0188	$0\text{-}0.97\times10^{2}$	0-1.82

M. It is an $m=3$ process because three quark lines are involved. The suppression factor is $Q^6(s) = F_p{}^2(s)$. The decay formula is

$$\Gamma = \frac{1}{3}\frac{g^2}{4\pi}\frac{|\mathbf{P}_2|^3}{m_1{}^2}Q^6(s) \tag{4.3}$$

for $1^-\to1^-+0^-$ decay;

$$\Gamma = \frac{1}{3}\left(\frac{g^2}{4\pi}\right)|\,\mathbf{P}_2|\left(1+\frac{P_1P_2}{2m_1{}^2m_2{}^2}\right)Q^6(s) \tag{4.4}$$

for $1^-\to1^-+0^+$ decay. It is convenient to define a reduced decay width

$$\overline{\Gamma} = \frac{\Gamma}{g^2/4\pi}, \tag{4.5}$$

which contains all the kinematic factors and the suppression factor and leaves the coupling constant $g^2/4\pi$ free. The Clebsch-Gordan coefficient that arises from any symmetry scheme is included in the coupling constant. The suppression factor is the same, 0.243, for

$$\psi_i \to \psi_j + \eta\,,$$

but it increases to 0.03 for the heavier meson

$$\psi_i \to \psi_j + S\,.$$

For the decay which emits η, the suppression factor is small. This is in accord with the experimental observation of a large branching ratio for $\psi(3.7)\to\psi(3.1)+\eta$. The interesting ones to look for are the

$$\begin{aligned}\psi(4.4) &\to \psi(3.1)+\eta\\ &\to \psi(3.1)+S\,,\end{aligned} \tag{4.6}$$

which has fairly large reduced widths of 4 or 11 MeV. Some of the more usual ones are listed in Table II.

The second class

$$\psi_i \to M_1 + M_2$$

is the most studied one. We list the common ones in Table III. The quark diagrams for the mesonic decays and the baryonic decays are shown in Fig. 5(b) and Fig. 5(c), respectively. They belong to $m=3$ and $m=4$. Hence, the suppression factor for the mesonic decay width is $[Q^3(s)]^2$ and that for the baryonic decay width is $[Q^4(s)]^2$. Since there is one more quark in the baryon than in the meson, one expects that the baryonic decay is slightly more suppressed. Also, the heavier ψ mesons are suppressed more because the momentum-transfer squared $s=m^2$ is equal to the mass of the decaying ψ. For instance, the reduced decay width for $\psi(4.4)\to\phi+\eta$ is only $\frac{1}{8}$ that of $\psi(3.1)\to\phi+\eta$. Also, we have

$$\overline{\Gamma}(\psi(4.4)\to\rho\pi) \sim \tfrac{1}{9}\overline{\Gamma}(\psi(3.1)\to\rho\pi). \tag{4.7}$$

For other decays $\omega\eta, \phi\eta, \omega\eta', \phi\eta', \rho\delta, KK^*, \bar{p}p, \Lambda\bar{\Lambda}$ similar trends also exist.

For the classes of

$$\psi_i \to \chi_j + M\,,$$

$$\chi_i \to \chi_j + M\,,$$

we calculate cases for $M=\omega, \phi, \eta$. The results are listed in Table IV. The suppression factor now is $Q^3(s)$, with $s=m^2$ of the meson M. It is interesting to note that the reduced widths are quite large if the transition has sufficient phase space, e.g., the transition

$$\psi(4.4)\to\chi(3.415)+\omega \tag{4.8}$$

has the reduced width ~30 MeV, and that of

$$\chi(3.415)\to\chi(2.75)+\eta \tag{4.9}$$

has the reduced width 60 MeV. It seems to us that the large hadronic widths of the χ states are an important characteristic of the present suppression scheme due to momentum transfer, provided that the state 2.75 GeV exists. The large width (compared relatively with the width of $\psi\to\rho\pi$) occurs not only for $M=\eta$, but also for ω and ϕ states. It has been argued by Harari[2] that decays having η may have a large width because η has a slight amount of $\bar{c}c$ mixture. However, there should be

TABLE III. Strong decays of the type $\psi_i \to M_1 + M_2$.

Decays	s (GeV^2)	m	$F_p^{2m/3}(s)$	$\Gamma_{(g^2/4\pi)} F_p^{2m/3}$(MeV)	Reduced width (MeV)
$\psi(3.1) \to \rho + \pi$	9.58	3	2.26×10^{-5}	1.056×10^{2}	2.38×10^{-3}
$\psi(3.7) \to \rho + \pi$	13.64	3	6.00×10^{-6}	1.338×10^{2}	8.02×10^{-4}
$\psi(4.1) \to \rho + \pi$	16.81	3	2.7×10^{-6}	1.52×10^{2}	4.1×10^{-4}
$\psi(4.4) \to \rho + \pi$	19.36	3	1.6×10^{-6}	1.66×10^{2}	2.65×10^{-4}
$\psi(3.1) \to \omega + \eta$	9.58	3	2.26×10^{-5}	8.81×10^{1}	1.99×10^{-3}
$\psi(3.7) \to \omega + \eta$	13.64	3	6.00×10^{-6}	1.24×10^{2}	7.44×10^{-4}
$\psi(4.1) \to \omega + \eta$	16.81	3	2.7×10^{-6}	1.43×10^{2}	3.86×10^{-4}
$\psi(4.4) \to \omega + \eta$	19.36	3	1.6×10^{-6}	1.58×10^{2}	2.52×10^{-4}
$\psi(3.1) \to \phi + \eta$	9.58	3	2.26×10^{-5}	7.97×10^{1}	1.80×10^{-3}
$\psi(3.7) \to \phi + \eta$	13.64	3	6.00×10^{-6}	1.11×10^{2}	6.66×10^{-4}
$\psi(4.1) \to \phi + \eta$	16.81	3	2.7×10^{-6}	1.32×10^{2}	3.56×10^{-4}
$\psi(4.4) \to \phi + \eta$	19.36	3	1.6×10^{-6}	1.46×10^{2}	2.33×10^{-4}
$\psi(3.1) \to \omega + \eta'$	9.58	3	2.26×10^{-5}	7.25×10^{1}	1.63×10^{-3}
$\psi(3.7) \to \omega + \eta'$	13.64	3	6.00×10^{-6}	1.08×10^{2}	6.48×10^{-4}
$\psi(4.1) \to \omega + \eta'$	16.81	3	2.7×10^{-6}	1.26×10^{2}	3.40×10^{-4}
$\psi(4.4) \to \omega + \eta'$	19.36	3	1.6×10^{-6}	1.41×10^{2}	2.25×10^{-4}
$\psi(3.1) \to \phi + \eta'$	9.58	3	2.26×10^{-5}	5.86×10^{1}	1.32×10^{-3}
$\psi(3.7) \to \phi + \eta'$	13.64	3	6.00×10^{-6}	9.26×10^{1}	5.55×10^{-4}
$\psi(4.1) \to \phi + \eta'$	16.81	3	2.7×10^{-6}	1.14×10^{2}	3.07×10^{-4}
$\psi(4.4) \to \phi + \eta'$	19.36	3	1.6×10^{-6}	1.30×10^{2}	2.08×10^{-4}
$\psi(3.1) \to \rho + \delta$	9.58	3	2.26×10^{-5}	1.17×10^{3}	2.64×10^{-2}
$\psi(3.7) \to \rho + \delta$	13.64	3	6.00×10^{-6}	2.04×10^{3}	1.22×10^{-2}
$\psi(4.1) \to \rho + \delta$	16.81	3	2.70×10^{-6}	2.68×10^{3}	0.72×10^{-2}
$\psi(4.4) \to \rho + \delta$	19.36	3	1.60×10^{-6}	3.28×10^{3}	0.52×10^{-2}
$\psi(3.1) \to p + \bar{p}$	9.58	4	0.63×10^{-6}	0.518×10^{3}	3.26×10^{-4}
$\psi(3.7) \to p + \bar{p}$	13.64	4	0.108×10^{-6}	0.786×10^{3}	8.48×10^{-5}
$\psi(4.1) \to p + \bar{p}$	16.81	4	0.037×10^{-6}	0.960×10^{3}	3.55×10^{-5}
$\psi(4.4) \to p + \bar{p}$	19.36	4	0.0178×10^{-6}	1.08×10^{3}	1.93×10^{-5}
$\psi(3.1) \to \Lambda + \bar{\Lambda}$	9.58	4	0.63×10^{-6}	0.344×10^{3}	2.16×10^{-4}
$\psi(3.7) \to \Lambda + \bar{\Lambda}$	13.64	4	0.108×10^{-6}	0.622×10^{3}	6.72×10^{-5}
$\psi(4.1) \to \Lambda + \bar{\Lambda}$	16.81	4	0.037×10^{-6}	0.807×10^{3}	2.98×10^{-5}
$\psi(4.4) \to \Lambda + \bar{\Lambda}$	19.36	4	0.0178×10^{-6}	0.939×10^{3}	1.67×10^{-5}
$\psi(3.1) \to K^+ + K^{-*}$ $\to K^0 + \bar{K}^{0*}$	9.58	3	2.26×10^{-5}	8.97×10^{1}	2.02×10^{-3}
$\psi(3.7) \to K^+ + K^{-*}$ $\to K^0 + \bar{K}^{0*}$	13.64	3	6.00×10^{-6}	1.20×10^{2}	0.721×10^{-3}
$\psi(4.1) \to K^+ + K^{-*}$ $\to K^0 + \bar{K}^{0*}$	16.81	3	2.70×10^{-6}	1.40×10^{2}	0.379×10^{-3}
$\psi(4.4) \to K^+ + K^{-*}$ $\to K^0 + \bar{K}^{0*}$	19.36	3	1.60×10^{-6}	1.54×10^{2}	0.247×10^{-3}

TABLE IV. Strong decays of the types $\psi_i \to \chi_j + M$ and $\chi_i \to \chi_j + M$.

Decays	s (GeV^2)	m	$F_p^{2m/3}(s)$	$\Gamma_{(g^2/4\pi)} F_p^{2m/3}$(MeV)	Reduced width (MeV)
$\psi(4.4) \to \chi(3.415) + \omega$	0.612	3	8.33×10^{-2}	0.266×10^{3}	2.22×10^{1}
$\psi(3.7) \to \chi(2.75) + \omega$	0.612	3	8.33×10^{-2}	2.30	1.91×10^{-1}
$\psi(4.1) \to \chi(2.75) + \omega$	0.612	3	8.33×10^{-2}	1.50×10^{1}	1.24
$\psi(4.4) \to \chi(2.75) + \omega$	0.612	3	8.33×10^{-2}	2.78×10^{1}	2.31
$\psi(4.1) \to \chi(2.75) + \phi$	1.04	3	2.73×10^{-2}	7.75	2.11×10^{-1}
$\psi(4.4) \to \chi(2.75) + \phi$	1.04	3	2.73×10^{-2}	1.95×10^{1}	5.32×10^{-1}
$\chi(3.55) \to \chi(2.75) + \eta$	0.301	3	0.243	0.361	8.77×10^{-2}
$\chi(3.415) \to \chi(2.75) + \eta$	0.301	3	0.243	0.252×10^{3}	6.12×10^{1}

TABLE V. Strong decays of the type $\chi_i \to M_1 + M_2$.

Decays	s (GeV^2)	m	$F_p{}^{2m/3}$	$\Gamma_{(g/4\pi)} F_p{}^{2m/3}$ (MeV)	Reduced width (MeV)
$\chi(3.55) \to \pi^+ + \pi^-, \pi^0 + \pi^0$	12.6	3	0.81×10^{-5}	0.174×10^3	1.40×10^{-3}
$\chi(3.55) \to \eta + \eta$	12.6	3	0.81×10^{-5}	0.137×10^3	1.10×10^{-3}
$\chi(3.55) \to \eta' + \eta'$	12.6	3	0.81×10^{-5}	0.075×10^3	6.00×10^{-4}
$\chi(3.415) \to \pi^+ + \pi^-, \pi^0 + \pi^0$	11.6	3	1.11×10^{-5}	1.26×10^3	1.39×10^{-2}

no argument that ω, ϕ are pure states of u, d, s quarks only.

For the class of decays

$$\chi \to M_1 + M_2 ,$$

the suppression factor now is $Q^3(s)$, with $s = m^2$ equal to the mass squared of the decaying χ state. Hence the suppression factor is large, $\sim 10^{-5}$. The reduced widths then are in the keV range. We list the results in Table V.

In the calculation of the above decays, in addition to Eqs. (4.3) and (4.4), we also use the following formulas:

(a) For the decays of $1^- \to \frac{1}{2}^- + \frac{1}{2}^+$, it is

$$\Gamma = \frac{1}{3}\left(\frac{g^2}{4\pi}\right)\frac{(m_1{}^2 - 4m_2{}^2)^{3/2}}{m_1{}^2} .$$

(b) For the decays of $2^+ \to 0^- + 0^-$, it is

$$\Gamma = \frac{g^2}{4\pi} \times \frac{8}{5} \frac{|\vec{P}_2|^5}{m_1{}^4} .$$

(c) For the decays of $0^+ \to 0^- + 0^-$, it is

$$\Gamma = \frac{g^2}{4\pi} \tfrac{3}{4} |\vec{P}_2| .$$

The indices 1, 2, 3 refer to the particles in the decay $1 \to 2 + 3$ and the momenta are evaluated in the rest frame of particle 1.

V. CONCLUSION AND DISCUSSION

In ordinary hadronic scattering, we have observed that processes are greatly inhibited whenever there is a large momentum transfer. In the above, we argue that this should be a general feature of all hadronic interactions. A quantitative prescription is obtained for quark-line bending. It is not unreasonable to expect that such a suppression factor may eventually be derived from field theory.

Then we derive many leptonic and hadronic decays of the ψ family, depending on the momentum transfer involved; the suppression factor varies greatly from 10^{-2} to 10^{-6}. This should show up ultimately in the partial decay widths. The leptonic decay widths have been shown to be consistent with experimental results.

It is difficult to compare the hadronic reduced widths directly with experiments because the coupling constant is not known precisely, and the precise group-theoretical classification of the ψ family does not have a general consensus. However, if the suppression factor is large, one can invert the procedure and calculate the coupling constant from the suppression factor and the experimentally measured decay width as follows:

$$\frac{g^2}{4\pi} = \Gamma_{\exp}/\overline{\Gamma}. \tag{5.1}$$

TABLE VI. Comparison of the hadronic decays of the ψ family with experimental data.

Decays	Reduced width (keV)	Experimental width (keV)	$g^2/4\pi$
$\psi(3.1) \to \rho + \pi$	2.38	0.287 ± 0.046	0.12 ± 0.02
$\psi(3.1) \to \phi + \eta$	1.80	0.048 ± 0.027	0.026 ± 0.015
$\psi(3.1) \to \phi + \eta'$	1.32	0.034 ± 0.027	0.025 ± 0.020
$\psi(3.1) \to K^+ + K^{-*}$	2.02	0.12 ± 0.02	0.06 ± 0.01
$\psi(3.1) \to K^0 + \bar{K}^{0*}$	2.02	0.09 ± 0.02	0.05 ± 0.01
$\psi(3.7) \to \psi(3.1) + \eta$	59.4	9.34 ± 1.59	0.157 ± 0.026
$\psi(3.7) \to \rho^0 + \pi^0$	0.802	<0.228	<0.28
$\psi(3.1) \to p + \bar{p}$	0.326	0.15 ± 0.01	0.46 ± 0.03
$\psi(3.1) \to \Lambda + \bar{\Lambda}$	0.216	0.11 ± 0.05	0.50 ± 0.23
$\psi(3.7) \to p + \bar{p}$	0.0848	0.0524 ± 0.0159	0.617 ± 0.187
$\psi(3.7) \to \Lambda + \bar{\Lambda}$	0.0672	<0.09	<1.5

We list the results for all the two-body final states of the ψ family in Table VI, and from the tables one can see that the coupling constants from the mesonic decays range from 0.03 to 0.15, only a factor of 5, and those from the baryonic decays are about ~0.5. It is not uncommon from the Clebsch-Gordan coefficient to produce a factor of 2 to 10 different for couplings among members in the same group representation. Also, in the ordinary hadronic coupling, the baryonic coupling ($g_{p\pi\pi}^2/4\pi \sim 14$) is also larger than the mesonic coupling ($f_\rho^2/4\pi \simeq 2.5$).

Therefore we conclude that the suppression due to momentum transfer is consistent with the currently available data.

We do not try here to compare the present scheme with decays involving more than two particles because of the ambiguity in the coupling constant. We shall return to this problem in a future study.

We then predict a whole series of partial reduced widths for decays of the ψ family. In general, the decays of the types $\chi_i \to \chi_j + M$, $\psi_i \to \psi_j + M$, $\psi_i \to \chi_j + M$ have a smaller suppression factor than those of the types $\psi \to M_1 + M_2$, $\chi \to M_1 + M_2$. The decay widths of the heavier ψ states to two hadrons are in general smaller than the decay widths of the lighter ψ states despite more phase space.

These kinds of general qualitative features, if found in future experiments, will provide a great support for the suppression scheme advocated here.

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*On leave from Melbourne University, Australia.

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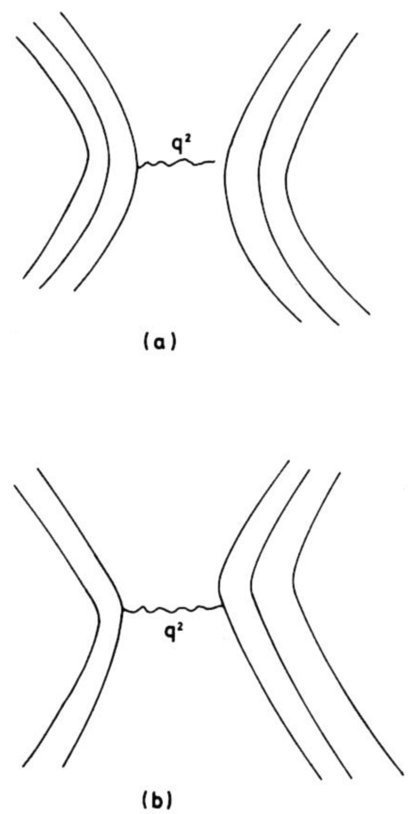

FIG. 1. Elastic pp scattering at small q^2 involves the bending of six quarks as shown in (a) with $m = 6$, while πp scattering involves the bending of five quarks as shown in (b) with $m = 5$.

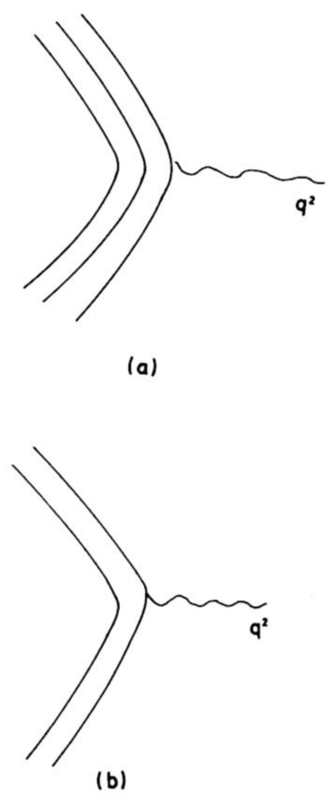

FIG. 2. Quark diagrams for the form factor of the proton ($m = 3$) (a) and the form factor of the pion ($m = 2$).

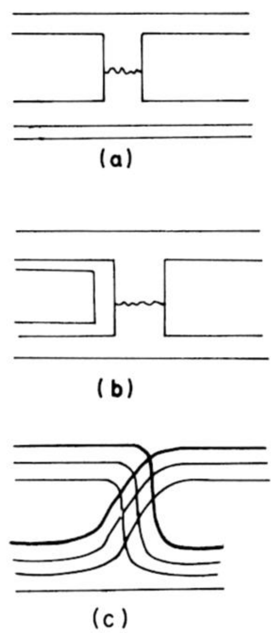

FIG. 3. Inelastic hadron scatterings (a) $m = 2$ processes, e.g., $\pi^- p \to \pi^0 \eta$, (b) $m = 3$ processes, e.g., $\bar{p} p \to \pi^- \pi^+$, (c) $m = 5$ processes, e.g., $K^- p \to p K^-$ backward scattering.

FIG. 4. The quark diagram for the decay of the ψ family into $l\bar{l}$. It is an $m=1$ process.

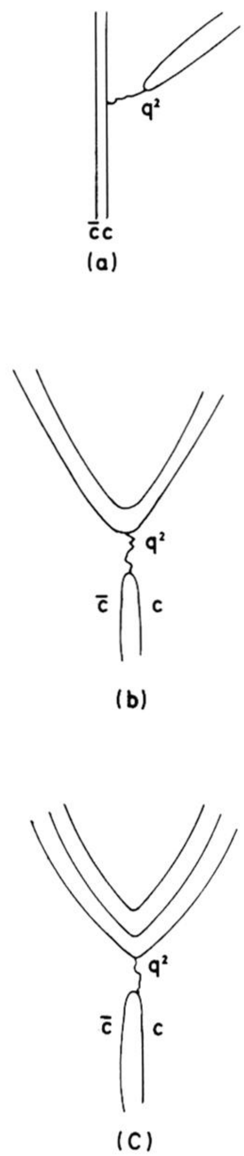

FIG. 5. The quark diagrams for hadronic decays of the ψ family. (a) $m=3$. This includes the decays of $\psi_i \to \psi_j + M$, $\psi_i \to \chi_j + M$, and $\chi_i \to \chi_j + M$. The q^2 is mass squared of the hadron M. (b) $m=3$. This includes the decays of $\psi_i \to M_1 + M_2$ and $\chi_i \to M_1 + M_2$, where M_1, M_2 are mesons. The q^2 is the mass squared of the decaying ψ or χ state. (c) $m=4$. This includes the decays of $\psi_i \to \overline{B} + B$, and $\chi_i \to \overline{B} + B$, where B is the baryon. The q^2 is the mass squared of the decaying ψ or χ state.