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MESON SPECTROSCOPY WITH THE SUPPRESSED HADRONIC DECAYS OF THE ψ-PARTICLES*

Kenneth Lane†

Laboratory of Nuclear Studies
Cornell University, Ithaca, New York 14853

and

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Serge Rudaz††

Laboratory of Nuclear Studies
Cornell University, Ithaca, New York 14853

ABSTRACT

We propose that missing excited states of ordinary (noncharmed) mesons be looked for in the decay products of narrow members of the ψ-particle family, and point out advantages of this method.

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††Cornell University Graduate Fellow.

Due to their fortunate occurrence in formation experiments, the ψ-particle family has become the most extensively studied [1] in experimental meson spectroscopy, with a richer, more well-defined spectrum than any of the "old" meson families (π, ρ; η, ω; η', ϕ; and K, K*). The charmonium model [2], with its radial and orbital excitations, now appears quite successful in describing both the level structure and decay properties of the new particles [3-5]. With this stunning confirmation of the spectroscopy of charmed-quark-antiquark ($c\bar{c}$) bound states, it becomes compelling to find the expected, but missing, radial and orbital recurrences of light $q\bar{q}$ systems [6].

There are obvious difficulties in finding recurrences of the light mesons. For the most part, one must isolate broad states, with widths ranging from 50 to several hundred MeV, arising in <u>production</u> experiments. This generally requires (almost) complete determination of the identities and momenta of the relatively large number of decay products. On the other hand, the hadronic decays of narrow members of the ψ-family can provide a clean mechanism for producing and isolating the missing recurrences. With ψ and ψ' formed copiously in e^+e^- annihilation, and with their not infrequent decay to η_c, χ_J, and η_c', in all cases one has a precise knowledge of the energy-momentum and quantum numbers of the initial state. As we shall argue this permits extensive use of missing mass techniques in the search.

The basic idea is quite simple and is motivated by the observation that quasi-two-body processes seem to dominate the hadronic decays of ordinary meson resonances: $A \to B + b$ where, for the known resonances A, b is often a "stable" meson and B may be a resonance and undergo similar (quasi-) two-body decay. Examples are $B(1235) \to \omega\pi$; $A(1100) \to \rho\pi$; $Q_{1,2}(1300) \to K\rho$, $K^*(892)\pi$ [7]; $A_3(1640) \to f(1270)\pi$; and $\rho'(1600) \to \rho\epsilon$. All such decays are allowed by the empirical Okubo-Zweig-Iizuka (OZI) rule [8]. Furthermore, we observe that most transitions proceed via an S-wave and that the momenta of the decay products are limited, typically (for decay into nearly on-mass-shell states) $p \cong \left[\left(M_A^2 - (M_B+M_b)^2\right)\left(M_A^2 - (M_B-M_b)^2\right)\right]^{1/2}/2M_A \lesssim 400$ MeV.

These facts are all related: The three-body form factor describing an OZI-allowed decay of A, made up of light quarks, limits the momenta of the outgoing bound states B and b to $p \lesssim 300$-500 MeV [9]. Thus, if it is allowed by conservation laws, an S-wave decay can be expected to dominate over higher partial waves. Note that the momentum is minimized when $M_A \sim M_B + M_b$ and $M_B >> M_b$.

We mention in passing that there is wide theoretical support for the dominance of sequential two-body decays of high mass hadrons. 't Hooft [10] has shown that, in a theory of quarks interacting with SU(N) gauge gluons, the leading meson graphs in an expansion in 1/N are planar, with only quark lines running around the edges (and no internal closed quark loops). A planar graph with n external meson legs and no internal meson propagators is of order $N^{1-n/2}$. Thus, a partial width $\Gamma(A \rightarrow B+b) = 0(N^{-1})$, and it is clear that sequential two-body amplitudes into nearly on-mass-shell states will dominate other possible processes by at least relative order N.

A seemingly much different argument in favor of sequential decays is provided by Frautschi's solution of the statistical bootstrap model [11]. He finds that a heavy meson will decay about 70% of the time to a light meson (mass $\lesssim 1$ GeV, belonging to a low-lying nonet) and another heavy meson, the latter suffering a similar decay.

In view of their generality, it is natural to extend these arguments to the OZI-forbidden decays of narrow members of the ψ-family [12]: Let Ψ denote one of η_c, ψ, χ_0, χ_2, η_c' or ψ' [13]. Then, a large fraction of the direct hadronic decays of Ψ are of the type $\Psi \rightarrow B+b$, where B and b are light-quark $(q\bar{q})$ bound states, and $M_b < M_B$. To the extent that doubly OZI-forbidden decays ($\psi \rightarrow \omega + \phi$, for example) are further suppressed, $B = (\bar{q}_2 q_1)$ if $b = (\bar{q}_1 q_2)$. Decay form factors will again limit the momentum of B and b. However, without a better understanding of the dynamics underlying the OZI rule, it is difficult to estimate the momentum cutoff [14]. We shall assume that $p \lesssim 0.5$-1.0 GeV. One then expects most Ψ decays to be such that M_Ψ is not much larger than $M_B + M_b$, with transitions in which B and b are in a relative S-wave preferred [15]. If b is a light meson, $M_b \lesssim 1$ GeV, B should be considerably heavier ($M_B \sim$ 1-2.5 GeV), an excited level of the b family. Finally, given an estimate for the mass of a predicted but yet-to-be discovered state B and a knowledge of its quantum numbers $I^G J^{PC}$, one or more initial states Ψ and known mesons b can be chosen so as to optimize conditions for finding B. If the decay products of b are identified, a precise determination of the energy-momentum of Ψ permits a search for B in the missing mass recoiling against b [16].

We recognize that this procedure, like more conventional ones, suffers from background problems. To name three examples: (i) The photon in $\psi' \rightarrow \gamma+X$ arises most often from π^0 decay, so that identification of X with χ is difficult, except in special cases. (ii) The pion in $\Psi \rightarrow \pi+X$ usually is the decay product of some resonance Y, so that the mass distribution of X has a large background due to kinematic reflections. (iii) For fixed Ψ and b, there will often be more than one allowed state B near a given mass. Isolating quantum numbers of the distinct states B will require detailed analysis of their decay products. Notwithstanding these difficulties, we reiterate the advantage gained from knowing the quantum numbers and energy-momentum of Ψ.

As a concrete example of our proposal, consider a search for the ϕ', the first radial recurrence (2^3S_1) of $\phi(1019)$. From the linear potential model [17], one estimates $M_{\phi'} \simeq M_\phi + 1.75/\left(m_s a^4\right)^{1/3} = 1.8\text{-}1.9$ GeV. Discounting the possibility of doubly OZI-forbidden decays such as $\Psi \to \phi' + \omega$ or $\Psi \to \phi' + \epsilon$ (which may, in fact, be nonnegligible), there are four processes which lead to ϕ' through an S-wave: $\psi' \to S^*(993) + \phi'$ ($p \simeq 1.1$ GeV), $\chi_2 \to \phi + \phi'$ ($p \simeq 1.0$ GeV), $\chi_0 \to \phi + \phi'$ ($p \simeq 900$ MeV) and $\psi \to S^* + \phi'$ ($p \simeq 600$ MeV) [13, 18].

Since all OZI-allowed decays of ϕ' result in $K\bar{K}$ + pions (with $\phi' \to \bar{K}K^*$, $K\bar{K}^*$ probably dominant), the reactions of interest are ψ, ψ' or $\chi_{0,2} \to K\bar{K}K\bar{K}$ + anything. It is not necessary to identify all four kaons. For example, one can plot the $K\bar{K}$ invariant mass in $\chi_{0,2} \to K\bar{K}$ + anything. In those events of which $m(K\bar{K}) = M_\phi$, the ϕ' is likely to be found in recoil. Thus, the OZI rule together with the momentum cutoff serve to amplify the ϕ' signal when one selects out the decays $\chi_{0,2} \to \phi$ + anything and $\psi, \psi' \to S^*$ + anything. Note that if $M_{\phi'} < 2M_{K^*}$, ϕ' decays to $K\bar{K}$ could be appreciable ($\sim 20\%$) and show up in $m(K\bar{K})$.

A first estimate of the branching ratios for $\chi_{0,2} \to \phi + \phi'$ and $\psi, \psi' \to S^* + \phi'$ and, more generally, for $\Psi \to B+b$ can be obtained from a simple model of particle decay based on the statistical bootstrap [19]. We assume that, as far as their direct hadronic decays are concerned, Ψ's behave much like "fireballs" or "clusters". In ref. [19], a method is given for computing the partial width Γ_b of a heavy cluster decaying into a "light" particle b plus any other heavy cluster B, integrated over the mass spectrum of B. With M_Ψ the initial cluster mass, the integral is dominated by M_B near the kinematic boundary $M_\Psi - M_b$, in accord with the above discussion. For our purposes, it is sufficient to treat all narrow states Ψ on an equal footing and similarly for all light particles b. We allow b to run over all mesons with $M_b \lesssim 1\,\text{GeV}$, and obtain the probabilities $\mathscr{P}_b = \Gamma_b/\Sigma_b\Gamma_b$ for

$\Psi \to b + \Sigma_B B(M_B > 1\,\mathrm{GeV})$ listed in Table 1. Insofar as all Ψ hadronic decays are of quasi-two-body type, these probabilities represent an upper limit on the fraction of those decays yielding a particular final state, $b+B$. To obtain rough lower limits for these fractions, we use the linear potential mass formula [17] to estimate the number of outstanding resonant states contributing, in the average sense implied by our statistical model, to the sum over B: This number is never more than ~ 5, so that lower limits can also be estimated from the table. Thus, in a sample of 10^6 ψ decays there will be $\sim$3000–6000 ϕ' events, and about three-quarters that number from a similar ψ' sample.

In closing, we list some of the important dynamical issues which can be addressed through a high-statistics study of Ψ-decays:

1. A delineation of the spectrum and widths of light quark-antiquark bound states will test basic predictions of a large variety of hadron models.

2. The decay modes and partial widths of excited $q\bar{q}$ levels can provide information about the dependence of the momentum cutoff on radial and orbital quantum numbers and, hence, on details of the bound state wave functions.

3. A deeper understanding of the OZI mechanism is sorely needed: To what extent are forbidden decays quasi-two-body? How large is the effective momentum cutoff? What is the relative strength of doubly OZI-forbidden processes? Hopefully, answers to these questions will clarify the origin of the OZI rule.

Discussions with F. J. Gilman have been both enjoyable and profitable.

REFERENCES AND FOOTNOTES

[1] A comprehensive review of ψ-particle spectroscopy is given in the Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford University, August 21-27, 1975 (W. T. Kirk, Editor). More recent results have been presented: For the SLAC-LBL Collaboration by G. Goldhaber and H. L. Lynch, invited talks at the International Conference on the Production of Particles with New Quantum Numbers, Madison, Wisconsin, April 22-24, 1976; for the DORIS Collaborations, by B. H. Wiik, invited talk at the 1976 International Neutrino Conference, Aachen, Germany, June 8-12, 1976.
In this paper we use the notations: $\eta_c\left(1\,^1S_0;J^{PC}=0^{-+}\right) = X(2.8)$, $\psi\left(1\,^3S_1;1^{--}\right) = J/\psi(3.095)$, $\chi_0\left(1\,^3P_0;0^{++}\right) = \chi(3.41)$, $\chi_1\left(1\,^3P_1;1^{++}\right) = P_c(3.51)$, $\chi_2\left(1\,^3P_2;2^{++}\right) = \chi(3.55)$, $\psi'\left(2\,^3S_1;1^{--}\right) = \psi(3.684)$, and $\eta_c'\left(2\,^1S_0;0^{-+}\right)$, as yet unidentified.

[2] T. Appelquist and H. D. Politzer, Phys. Rev. Lett. 34 (1975) 43; A. DeRujula and S. L. Glashow, ibid. 34 (1975) 46; T. Appelquist et al., ibid. 34 (1975) 365; E. Eichten et al., ibid. 34 (1975) 369.

[3] The influence of coupling to open and closed decay channels on the spectrum and decay rates of charmonium levels is treated by E. Eichten et al., Phys. Rev. Lett. 36 (1976) 500.

[4] The status of the charmonium predictions for the states below 3.7 GeV is discussed by M. Chanowitz and F. J. Gilman, Phys. Lett. 63B (1976) 178.

[5] Interpretation of the structure of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ in the "charm threshold region", $W = \sqrt{s} = 3.70\text{–}4.50$ GeV, within the

generalized charmonium model of ref. [3] is presented by K. Lane and E. Eichten, Phys. Rev. Lett. 37 (1976) 477.

[6] While the nonrelativistic nomenclature, $n^{2S+1}L_J$, well describes the low-lying ψ-particle states, the same may not be true of the excited levels of light $q\bar{q}$ systems. Nevertheless, it is a convenient notation and we continue to use it.

[7] G. W. Brandenburg et al., Phys. Rev. Lett. 36 (1976) 703.

[8] S. Okubo, Phys. Lett. 5 (1963) 165; G. Zweig, CERN reports TH 401 and TH 412 (1964), unpublished; J. Iizuka, Suppl. Prog. Theor. Phys. 37-38 (1966) 21.

[9] That produced hadron momenta are limited is well known experimentally. It happens because S-matrix elements are momentum convolutions over quark bound state wave functions; the regular short distance behavior of these wave functions cuts off high momenta. See, e.g., ref. [3]. These authors find that the effective momentum cutoff increases with both the reduced quark mass and the number of radial nodes in the bound state wave function.

[10] G. 't Hooft, Nucl. Phys. B72 (1974) 461; ibid. B75 (1974) 461. Also, see C. G. Callan, N. Coote and D. Gross, Phys. Rev. D13 (1976) 1649.

[11] S. Frautschi, Phys. Rev. D3 (1971) 2821. A successful description of exclusive multiparticle production in terms of clusters with cascade decays is given in B. Margolis and S. Rudaz, Phys. Rev. D9 (1974) 653.

[12] J. L. Rosner has discussed OZI allowed formation of quasi-two-body final states in e^+e^- annihilation: Electromagnetic and Weak Interactions, Proc. of the 8th Rencontre de Moriond, 1973, Vol. 1, J. Tran Thanh Van, editor, p. 29.

[13] The large branching ratio for $\chi_1 \to \psi + \gamma$ probably rules out its usefulness for reaching excited states of light mesons. For the estimates appearing later in this paper, we assume the following branching ratios (excluding $\psi, \psi' \to \gamma \to$ hadrons and $\psi' \to \psi$+anything): $\eta_c \to$hadrons = 1.0; $\psi \to \eta_c \gamma$ = 0.07; $\psi \to$ hadrons = 0.60; $\chi_0 \to$ hadrons = 0.95; $\chi_2 \to$ hadrons = 0.70; $\psi' \to \chi_0 \gamma$ = 0.07; $\psi' \to \chi_2 \gamma$ = 0.05; $\psi' \to$hadrons = 0.25.

[14] If Ψ decays are assumed to proceed via $c\bar{c}$ annihilation into two or three gluons, the Ψ wave function is not involved in limiting the momentum of outgoing mesons. A rough calculation of the $\Psi \to B + b$ amplitude within the (nonrelativistic) decay model of ref. [3] leads one to conclude that the momentum cutoff will be <u>less</u> than that for an OZI-allowed transition to the <u>same</u> final state. A different mechanism for violation of the OZI rule, say $\Psi \to$ charmed meson pair $\to$ I=0 vector meson $\to$ hadrons (see ref. [10]), can lead to the opposite conclusion.

[15] For larger allowed values of p, higher partial wave decays may compare favorably with S-wave.

[16] In radiative transitions to χ, η'_c and η_c, it is assumed that the accompanying photon is unambiguously identified or that the missing neutral energy in these transitions is consistent with that photon (even-C states are "tagged").

[17] See E. Eichten <u>et al.</u>, ref. [2]. We use this model as a <u>rough</u> guide to the spectrum of light quark bound states. The potential is $V(r) = r/a^2$, $a^{-2} \simeq 0.2$ GeV^2 and quark masses are taken to be $m_u = m_d \simeq 0.3$ GeV, $m_s \simeq 0.4$ GeV. The mass of the nth radially-excited $^3S_1$ or $^1S_0$ state is given by $M_n = M_0 + (\xi_n - \xi_0)/\left[(2\mu a)^{1/3} a\right]$ where μ is the $q\bar{q}$ reduced mass, M_0 is the ground state mass, and ξ_{n-1} is the nth zero of the Airy function. The first few values of $\xi_n - \xi_0$ are 1.75, 3.18 and 4.45 for n=1, 2 and 3, respectively.

[18] For brevity, we omit discussion of the following isospin and G-parity conserving P-wave decays: $\psi, \psi' \to \eta\phi'$ and $\eta'\phi'$; $\eta_c, \eta'_c \to \phi\phi'$.

[19] S. Rudaz, Phys. Rev. D11 (1975) 1915.

Table 1

Values of $\mathscr{P}_b \equiv \Gamma_b/\Sigma_b\Gamma_b$, where Γ_b is the branching ratio for the decay $\Psi \to b + \Sigma_b$ (1 GeV $\lesssim M_B \leq M_\Psi - M_b$); Σ_b indicates an integral over the mass spectrum of the recoiling heavy hadron.

b	π	K	η	η'	ρ	ω	K*	ϕ	$\epsilon(\sim 700)$	S*(993)	$\delta(976)$
$\mathscr{P}_b$	.28	.19	.04	.01	.18	.06	.15	.02	.03	.01	.03