PHYSICAL REVIEW D VOLUME 28, NUMBER 1 1 JULY 1983

Decays of particles with exotic quantum numbers

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(Received 13 August 1982)

The most convincing place to find a glueball would be in a channel with exotic quantum numbers ($J^{PC}=0^{--}$, even^{+-}, odd^{-+}). We enumerate the allowed and forbidden few-body decay modes of such exotic mesons. In the particular case of the 0^{+-}, the set of allowed few-body decay modes is itself a unique signature. For other J^{PC} values the signature depends on somewhat more detailed characteristics of the allowed decays, which we enumerate.

The question of the existence of glueballs, i.e., mesons which are in some sense predominantly composed of gluons rather than of quarks and antiquarks, is of considerable importance. A recent upsurge of interest[1] in this question has been generated by the experimental discovery of two particles $\iota(1440)$ (Ref. 2) and $\theta(1640)$ (Ref. 3) which have been claimed as candidates for glueballs. These particles both are indicated to have quantum numbers ($J^{PC}=0^{-+}$ and 2^{++}) which are "nonexotic," i.e., which are allowed for ordinary nonrelativistic $q\bar{q}$ bound states. Thus the argument that one or both of these particles are glueballs (or have sizable glue components) necessarily involves rather detailed discussion[1] of ordinary light-$q\bar{q}$-meson spectroscopy—masses and decay modes and widths, single-octet mixing, radial excitations, etc.—and also guesses of glueball characteristics—masses, widths, favored production channels, etc. The dynamical details go rather beyond the level in which one has confidence in the naive light-quark model or the capability to calculate in the gluon sector of quantum chromodynamics (QCD). Thus it is obviously desirable to search for particles with exotic quantum numbers[4] [0^{--}, (even)$^{+-}$, (odd)$^{-+}$]. Of course, a particle with exotic quantum numbers is not guaranteed to be a glueball; it could be $qq\bar{q}\bar{q}$, or something completely unexpected; but (a) any of these possibilities would be of great interest, and (b) the $qq\bar{q}\bar{q}$ states which are narrow enough to be observable are expected[5] to be nonexotic, so the argument for a gluonic degree of freedom would be strong. It is the purpose of this paper to sharpen the considerations involved in finding and identifying a meson with exotic quantum numbers.

Given two- or three-body decay modes and sufficient statistics, one can determine a particle's spin and parity from angular correlations or a partial-wave analysis. However, one may have enough events to find a particle and determine a number of its decay modes without having enough events in any one channel to do a partial-wave analysis. Moreover, in this paper we point out that a characteristic feature of some low-spin exotic mesons is the absence of many, or all, possible decay modes into two or three "stable" particles. We use "stable" in the same sense as the Particle Data Group[6] (stable against hadronic decay); in particular, we consider final states consisting of π, K, η (and also $N\bar{N}$). We consider hadronic decays of a hypothetical particle θ, with baryon number, charge, and isospin all zero, and no flavor (strangeness, charm, ...). We assume that we are dealing with a particle (θ) of mass in the range[1] 1 to 2 or 2.5 GeV, for which two-, three-, and four-body decay modes would be expected to be a substantial fraction of the total. In Table I we have listed allowed (+) and forbidden (−) few-body decay modes for all P,C combinations for $J=0$ and 1. The table also gives the lowest-spin quasi-two-body decay mode[7] which leads in two steps to the given final channel. In Table II we list the number of powers of four-momentum required in the invariant matrix element for the direct decay, and also the minimum numbers of powers of three-momentum in the nonrelativistic limit ($E=m+p^2/2m+\cdots$). We have assumed that the decays conserve energy, momentum, angular momentum, parity, charge conjugation, and isospin (G parity) and respect Bose symmetry for identical mesons in the final state.

The first striking feature of the table is that the exotic 0^{+-} is the only J^{PC} which has no PP or PPP decay modes, either direct or by a two-step quasi-two-body decay PS, PV, PT ($P=0^{-+}$, $V=1^{--}$, $T=2^{++}$). (From the Particle Data Group[6] list of mesons, these are the only quasi-two-body decay modes which feed the PPP channels. Other quasi-two-body decays lead to final states with more than three stable pseudoscalars.) This result remains when one considers also higher spins. Every J^{PC} combination for $J>0$ can decay into PPP by one or the other of the quasi-two-body modes, PV (for $C=-1$) or PT (for $C=+1$), for some orbital state. Thus a particle which is found in the $\pi\pi\pi\eta$ and/or $\pi\pi K\bar{K}$ channels and is determined not to decay into any PP or PPP channel (to some appropriate level of sensitivity) is determined to have the exotic quantum numbers $J^{PC}=0^{+-}$. One can see from the table that a possible production

TABLE I. Allowed (+) and forbidden (−) few-body decay modes for $\theta(J^{PC})$ $(I=0)$. The PX, $X=S$, V, T, A, are the lowest-spin quasi-two-body decay modes which contribute to the indicated final state of stable pseudoscalars. The states above (below) the break and nonexotic (exotic).

$\theta(J^{PC})$	$\pi\pi$	$K\bar{K}$	$\eta\eta$	$\pi\pi\pi$	$\pi\pi\eta$	$\pi K\bar{K}$	$K\bar{K}\eta$	$\eta\eta\eta$	4π	$\pi\pi\pi\eta$	$\pi\pi K\bar{K}$	$\cdots$	$N\bar{N}$	$\pi N\bar{N}$
0^{-+}	−	−	−	−	+ PS	+ PS	+ PS	+	+ VV	−	+ VV		+	+
0^{++}	+	+	+	−	−	−	−	−	+ SS	−	+ SS		+	+
1^{--}	−	+[a]	−	+ PV	−	+ PV	+ PV	−	−	+ SV	+ SV		+	+
1^{+-}	−	−	−	+ PV	−	+ PS,[a] PV	+ PV	−	−	+ SV	+ SV		+	+
1^{++}	−	−	−	−	+ PS	+ PS	+ PS	+	+ PA	−	+ PA		+	+
0^{--}	−	−	−	+ PV	−	+ PS,[a] PV	+ PV	−	−	+ PV	+ PV		−	+
0^{+-}	−	−	−	−	−	−	−	−	−	+ SV	+ SV		−	+
1^{-+}	−	−	−	−	+ PT	+ PV,[a] PT	+ PT	+	+ PA	−	+ PA		−	+

[a]Forbidden by SU(3) (flavor) invariance.

mechanism for a $\theta(0^{+-})$ would be the reaction $p+\bar{p}\rightarrow\theta+\pi^0$.

The exotic combination 1^{-+} is of interest because of its positive charge conjugation; it can be produced in the glueball-favored[8] $\psi\rightarrow\gamma+\theta$ channel. We see from the table that the set of allowed PPP decay modes of the 1^{-+} is not a unique signature; both the 0^{-+} and 1^{++} have exactly the same PPP decay modes and no allowed PP decay modes. So one needs more detailed information to distinguish 1^{-+} from 0^{-+} and 1^{++}. (1) A distinguishing feature is that both the 0^{-+} and 1^{++} have the quasi-two-body modes

TABLE II. Structure of the amplitudes for decays to three or four pseudoscalars. The first number is the number of powers of four-momentum required in the invariant matrix element (equal to the number of derivatives in the effective Lagrangian). The second number is the minimum number of powers of three-momentum in the nonrelativistic limit. See the examples in the text.

$\theta(J^{PC})$	$\pi\pi\pi$	$\pi\pi\eta$	$\pi K\bar{K}$	$K\bar{K}\eta$	$\eta\eta\eta$	4π	$\pi\pi\pi\eta$	$\pi\pi K\bar{K}$
0^{-+}		0,0	0,0	0,0	0,0	6,5		4,3
0^{++}						0,0		0,0
1^{--}	3,2		3,2	3,2			3,3	1,1
1^{+-}	3,3		1,1	1,1			3,2	3,2
1^{++}		1,1	1,1	1,1	3,3	5,4		3,2
0^{--}	6,6		2,2	2,2			4,3	6,5
0^{+-}							4,4	2,2
1^{-+}		5,4	5,4	5,4	9.8	3,3		1,1

$PS \rightarrow PPP$, while the 1^{-+} does not. So a signature for a $\theta(1^{-+})$ would be to find it in $\pi\pi\eta$, $\pi K\bar{K}$, and/or $K\bar{K}\eta$, and to find (a) in the $\pi\pi\eta$ events the quasi-two-body decays $\eta f(1270)$ but not $\pi\delta(970)$, (b) in the $\pi K\bar{K}$ events the quasi-two-body decays $\bar{K}K^*(1430)$ [and, if SU(3) is sufficiently broken, $\bar{K}K^*$ (890)] but not $\bar{K}\kappa(1500)$ or $\pi\delta(970)$, (c) in the $K\bar{K}\eta$ events the quasi-two-body decays $\eta f'(1515)$ but not $\eta S^*(980)$. (2) For the direct $\pi\pi\eta$, $\pi K\bar{K}$, and $K\bar{K}\eta$ decays (after quasi-two-body decays, if any, are subtracted), the Dalitz plots are quite different, because of the large number of powers of momentum in the matrix element for the 1^{-+} decays. For example, for the $\pi\pi\eta$ decay mode the effective Lagrangians and invariant matrix elements (in the θ rest frame) are

$$L_{0^{-+}} \sim \theta\pi_a\pi_a\eta \ , \quad M \sim 1$$

(uniform density in the Dalitz plot);

$$L_{1^{++}} \sim \theta^\mu\pi_a\pi_a\partial_\mu\eta \ , \quad \vec{M} \sim \vec{p}_1 + \vec{p}_2$$

($\vec{p}_1$, $\vec{p}_2$ are momenta of the two pions);

$$L_{1^{-+}} \sim \theta^\mu\epsilon_{\mu\nu\lambda\sigma}\partial^\nu\pi_a\partial^\alpha\partial^\lambda\pi_a\partial_\alpha\partial^\sigma\eta \ ,$$

$$\vec{M} \sim (\vec{p}_1 \times \vec{p}_2)(\vec{p}_1^{\,2} - \vec{p}_2^{\,2})$$

(density in the Dalitz plot is zero if either $\vec{p}_1$ or $\vec{p}_2 \rightarrow 0$, or if $\vec{p}_1 \parallel \vec{p}_2$, or $p_1 = p_2$). The situation is similar in the $\pi K\bar{K}$ and $K\bar{K}\eta$ channels. (3) If the mass is in the high end of the range 2 to 2.5 GeV, one may find the $\theta(1^{-+})$ in the $\pi N\bar{N}$ channel and determine that it does not decay into the $N\bar{N}$ channel which is allowed for the nonexotic 0^{-+}, 1^{++}. (4) We consider the generalization of points (1) and (3) to include higher spins ($J > 1$). For positive C we have the J^{PC} combinations (even)$^{++}$, (even)$^{-+}$, (odd)$^{++}$ (nonexotic), and (odd)$^{-+}$ (exotic). The (even)$^{++}$ $\rightarrow PP$ and the (even)$^{-+}$, (odd)$^{++} \rightarrow PS$, both of which are forbidden for the (odd)$^{-+}$. Thus if a particle is found in a $C = +1$ channel and it is determined not to have PP or PS (and, if massive enough, $N\bar{N}$) decay modes, then it is necessarily (odd)$^{-+}$. This does not distinguish 1^{-+}, 3^{-+}, . . . , but all are equally exotic.

In conclusion, we have followed the idea that the most profitable place to look for glueballs (or some other "new" kind of meson) is in channels with exotic quantum numbers. Given a detector with good sensitivity to π's, K's, and η's, it may be possible to identify a particle with exotic quantum numbers by studying its set of allowed decay modes, which may be feasible with lower statistics than are required for a detailed partial-wave analysis in a single three-body channel. In particular, we have discussed how this could work for a possible $\theta(0^{+-})$ which could be produced in $p + \bar{p} \rightarrow \pi^0 + \theta$ and for a possible $\theta(1^{-+})$ which could be produced in $\psi \rightarrow \gamma + \theta$.

Note added in proof. Professor S. F. Tuan has called my attention to an early paper[9] discussing allowed decay modes of a hypothetical $I = 0$, $J^{PC} = 1^{-+}$ meson.

[1]Some recent reviews are M. S. Chanowitz, in *Proceedings of the SLAC Summer Institute, 1981,* edited by A. Mosher (SLAC, Stanford, 1981), p. 41; J. F. Donoghue, in *Particles and Fields—1981: Testing the Standard Model,* proceedings of the Meeting of the APS Division of Particles and Fields, Santa Cruz, California, edited by C. A. Heusch and W. T. Kirk (AIP, New York, 1982); D. L. Scharre, talk at Orbis Scientiae, Coral Gables, 1982 (unpublished).

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