FUTURE PROSPECTS FOR EXOTIC MESONS

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Abstract

A brief description is given of the current status of exotic mesons produced in $\pi^- p$ interactions at 18 GeV/c—carried out with the BNL multiparticle spectrometer. The next logical step in our endeavor to understand the gluonic degrees of freedom in mesons is to extend the search for exotic mesons with hidden strangeness in $K^- p$ interactions at beam momenta in the range 15 to 25 GeV/c.

1 Introduction

The main purpose of this article is to present the current status of exotic mesons produced in $\pi^- p$ interactions at 18 GeV/c, and give compelling arguments why the next logical step is to search for exotic mesons in $K^- p$ interactions at beam momenta in the range between 15 to 25 GeV/c. General background material on exotic mesons is given in Section 2.

There are three main experiments with results on exotic mesons produced in $\pi^- p$ interactions at intermediate energies; they are the experiments carried out at KEK [1], IHEP/Protvino [2] and BNL [3, 4]. The results of the BNL data are given here as an example of the way in which exotic mesons are produced in these interactions (Section 3).

Mesons produced in the forward direction by $\pi^- p$ interactions at intermediate energies are mediated by Reggeon exchanges with recoil protons or neutrons. Therefore, the produced mesons are either isoscalar or isovector (both exotic and conventional) with constituents that consist mainly of $n\bar{n}$ where $n = \{u, d\}$. Fig. 1 illustrates production of a resonance with an $n\bar{n}$ constituent in $\pi^- p$ interactions. It is clear that, if one is to look for exotic mesons with $s\bar{s} + g$ or $s\bar{s} + n\bar{n}$ (strangeonium hybrids or multiquarks), then one needs to start with a K^- beam (Section 4).

A summary and conclusions are given in Section 5.

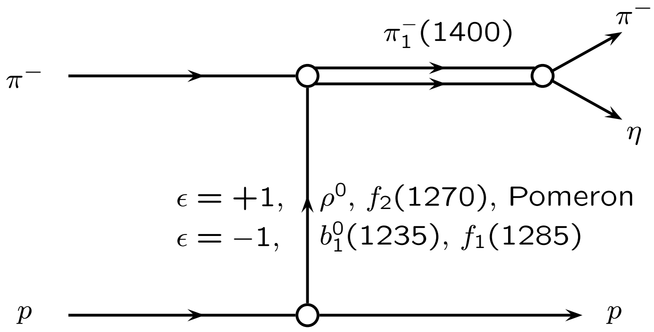

Figure 1: Resonance production via Reggeon exchange—an example.

2 Exotic Mesons

There is now mounting evidence that the simple picture of a meson consisting of a quark and an anti-quark must be extended to include multi-quark states and those containing valence gluons. J^{PC}-exotic mesons, i.e. the states with quantum numbers $J^{PC} = 0^{+-}$, 1^{-+}, 2^{+-} and 0^{--}, cannot be quarkonia.

The subject of exotic mesons has received considerable attention from theorists over the years, who have employed a variety of techniques to investigate the nature of these mesons. Hybrid meson spectra which contain valence gluons have been studied using the bag model [5], the constituent gluon model [6], the QCD sum rule calculations [7], the flux tube model [8] and the lattice gauge calculations [9]. A multiquark system with exotic quantum numbers has been investigated in the diquark cluster model [10]. In all these models, a $J^{PC} = 1^{-+}$ exotic meson is predicted to lie in the mass range 1.4 to 2.0 GeV/c^2. They are expected to decay into $b_1(1235)\pi$, $f_1(1285)\pi$, $\eta'\pi$, $\eta\pi$, $\rho\pi$, $\omega\rho$ and $a_1(1260)\eta$. The predicted masses and the branching ratios vary widely among different models. For example, in one calculation with the QCD sum rule, the mass of an exotic hybrid is predicted to be 1.4–1.6 GeV/c^2 and it couples mainly to $\rho\pi$, whereas in the diquark cluster model the mass of the lightest exotic 'diquonium' comes out around 1.4 GeV/c^2 but its main decay mode is into $\omega\rho$. The mass of the lightest gluonic hybrid is predicted be around 1.9 GeV/c^2 in the flux-tube model, with the quantum numbers $J^{PC} = 1^{-+}$. Close and Page [8] predict that such a gluonic hybrid should decay into the following channels

$b_1\pi$	$f_1\pi$	$\rho\pi$	$\eta\pi$	$\eta'\pi$
170	60	$5 \rightarrow 20$	$0 \rightarrow 10$	$0 \rightarrow 10$

where the numbers refer to the partial widths in MeV/c^2. According to them, then, its total width must be at least 235 MeV/c^2, possibly larger.

A short comment is in order on notations for the partial waves commonly encountered in the literature. A pure partial wave coupling to a system of two pseudoscalars can be completely specified by the orbital angular momentum L, its z-component M and the reflectivity quantum number ϵ [11]. The latter is usually chosen such that it coincides with the naturality of the exchanged particles (Reggeons) in πN or $K N$ production processes (see Fig. 1). The spin J is simply L and the parity P is given by $(-)^L$. The usual notation is $|J^{PC}M^\epsilon\rangle$ or $|\epsilon LM\rangle = L_{M\epsilon}$. Here C is the charge conjugation. If $M = 0$, there is only one ϵ, i.e. $\epsilon = -1$. In addition, one makes the usual assumption that the partial waves for $M > 1$ are negligible, so that M can be dropped from the subscript above. One then merely deals with the following three partial waves, without ambiguity: L_0, L_+ and L_-, where the notations S, P, D, F are used for $L = 0$, 1, 2, 3, etc. For a three-body system, a partial wave is traditionally characterized by a two-body isobar and a bachelor particle in a relative orbital angular momentum L. Thus a complete specification of a partial wave can be written $J^{PC}[\text{isobar}]L\,M^\epsilon$.

In this note, a J^{PC}-exotic meson is denoted according to the standard convention, i.e. the name is determined by the combination $\{P, C\}$ of the meson [12] . Hence, an isovector $J^{PC} = 1^{-+}$ state is denoted π_1, while its isoscalar partners are given the names η_1 and η_1'.

3 Results of BNL-E852 data

The BNL-E852 experiment was conducted with the BNL multi-particle spectrometer (MPS), a modern fixed-target experiment in which scrupulous care had been given to ensure hermeticity for both charged and neutral particle production along with particle D; details of the experimental setup have been given elsewhere [4].

The main purpose of the experiment was to search for exotic mesons produced exclusively in $\pi^- p$ interactions at 18 GeV/c. Data were taken in 1994 and 1995 (Phase I) and 1997 and 1998 (Phase II). One major difference between the two data sets is that the latter has been taken with a segmented Cerenkov counter for K/π separation for momenta between 3 to 10 GeV/c.

The $\pi_1(1400)$ state was originally reported by the GAMS group [13], seen in the reaction $\pi^- p \to \pi^0 \eta\, n$ at 100 GeV/c^2. The forward-backward asymmetry, obtained from the cosine of the Jackson angle in the $\pi^0\eta$ system, shows a substantial non-zero swing in the $a_2(1320)$ region. This can happen only if there is a strong interference effect between even-odd waves in the $a_2(1320)$ region. After a partial-wave analysis of the $\pi^0\eta$ system, the GAMS group reported that both the D_0 and the P_0 waves are resonant in the vicinity of the $a_2(1320)$. Because the $a_2(1320)$ and the $\pi_1(1400)$ are seen to be produced via unnatural-parity exchange, it could be concluded that the $b_1(1235)$ exchange is the dominant one. This also indicates that the $\pi_1(1400)$ should decay into the $b_1(1235)\pi$ final state. It should be noted, however, that the original analysis was brought into question [14].

The E179 collaboration [1] at KEK studied the $\pi^-\eta$ system in the reaction $\pi^- p \to \pi^- \eta\, p$ at 6.3 GeV/c. Both D_+ and P_+ waves peak at the $a_2(1320)$ mass region; therefore, ρ- or f_2-exchange processes seem to play a central role in the production of these waves. The phase variation between these waves seems constant throughout the $a_2(1320)$ mass region, and they conclude that both are resonant.

More recently, there appeared two additional pieces of evidence regarding the $\pi_1(1400)$ meson. The BNL-E852 Collaboration [3] is in the process of carrying out a systematic study of exotic mesons in $\pi^- p$ interactions at 18 GeV/c. They have studied the reactions $\pi^- p \to \eta\pi^- p$ and $\pi^- p \to \eta\pi^0 n$ at 18 GeV/c, where the η decay is observed in the channels $\gamma\gamma$ or $\pi^+\pi^-\pi^0$. The results of their analysis on the '94 data, based on 45,000 events fitting the reaction $\pi^- p \to \eta\pi^- p$ with $\eta \to \gamma\gamma$, have already been published [15], [16]. The $\eta\pi$ mass spectrum shows a strong $a_2(1320)$ signal and the t distribution indicates typical peripheral production. Their key observation is that the relative phase motion of the P_+ wave with respect to the D_+ wave [the $a_2(1320)$ meson] requires the presence of a resonant P wave, i.e. a $J^{PC} = 1^{-+}$ exotic state(see Fig. 2). The BNL-E852 Collaboration studied, in addition, the same exclusive reaction with the their '95 data—with very similar results, as shown in table I.

The VES experiment [2] studied the reaction $\pi^- N \to \pi^- \eta\, N$ at 37 GeV/c. The $\pi_1(1400)$ signal is present, but it is small with large errors in the $\pi\eta$ channel. The VES group report no significant 1^{-+} state in the 1.3–1.4 GeV/c^2 region. However, their phase motion is very similar to that of the BNL data.

The Crystal Barrel Collaboration studied $\bar{p}N$ annihilations at rest, specifically the reactions $\bar{p}n \to \pi^-\pi^0\eta$ and $\bar{p}p \to \pi^0\pi^0\eta$. They report [17, 18] that the standard isobar decays, $\epsilon \to \pi\pi$, $\rho \to \pi\pi$ and $a_2(1320) \to \eta\pi$ are not sufficient to describe the data; they need, in addition, presence of the $\pi_1(1400)$ meson. The masses and widths of the $\pi_1(1400)$ meson in the decay channel $\pi\eta$ are summarized in Table I.

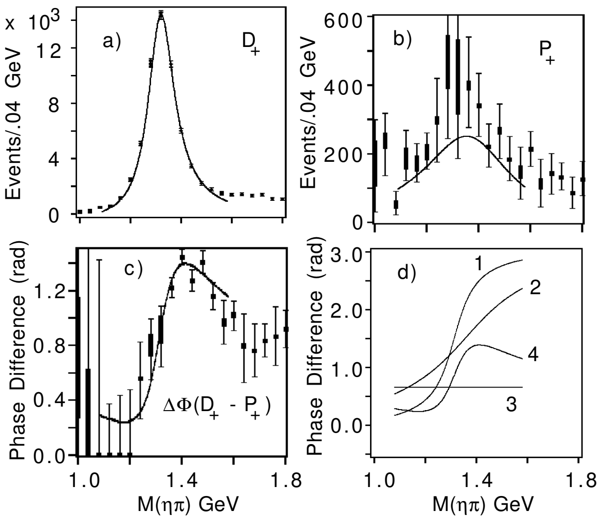

Figure 2: Results of the partial-wave amplitude analysis. Shown are a) the fitted intensity distributions for the D_+ and b) the P_+ partial waves, and c) their phase difference $\Delta\Phi$. The range of values for the eight ambiguous solutions is shown by the central bar and the extent of the maximum error is shown by the error bars. Also shown as curves in a), b), and c) are the results of the mass dependent analysis described in the text. The lines in d) correspond to (1) the fitted D_+ Breit-Wigner phase, (2) the fitted P_+ Breit-Wigner phase, (3) the fitted relative production phase ϕ, and (4) the overall phase difference $\Delta\Phi$.

Table I: Parameters for $\pi_1(1400) \to \eta\pi$

Expt.	Mass(MeV/c^2)	Width(MeV/c^2)
BNL('94)	$1370 \pm 16 {}^{+50}_{-30}$	$385 \pm 40 {}^{+65}_{-105}$
BNL('95)	$1359 {}^{+16}_{-14} {}^{+10}_{-24}$	$314 {}^{+31}_{-29} {}^{+9}_{-66}$
CB	$1400 \pm 20 \pm 20$	$310 \pm 50 {}^{+50}_{-30}$
CB	1360 ± 25	220 ± 90

A second $J^{PC} = 1^{-+}$ exotic meson at mass 1.6 GeV/c^2 was reported decaying into $\eta'\pi$ [2] and $\rho\pi$ [19] channels. Accordingly, the BNL-E852 Collaboration carried out a partial-wave analysis of the 3π system on some 250,000 events

('94 data) in the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c with the momentum-transfer in the range $0.05 < -t < 1.0$ (GeV/c)^2. They find a $J^{PC} = 1^{-+}$ state at 1.6 GeV/c^2, the $\pi_1(1600)$ meson, with its phase motion characteristic of a resonance [20] with respect to the $J^{PC} = 0^{-+}$, 1^{++}, 2^{++} and 2^{-+} waves [20] (see Fig. 3 and Table II).

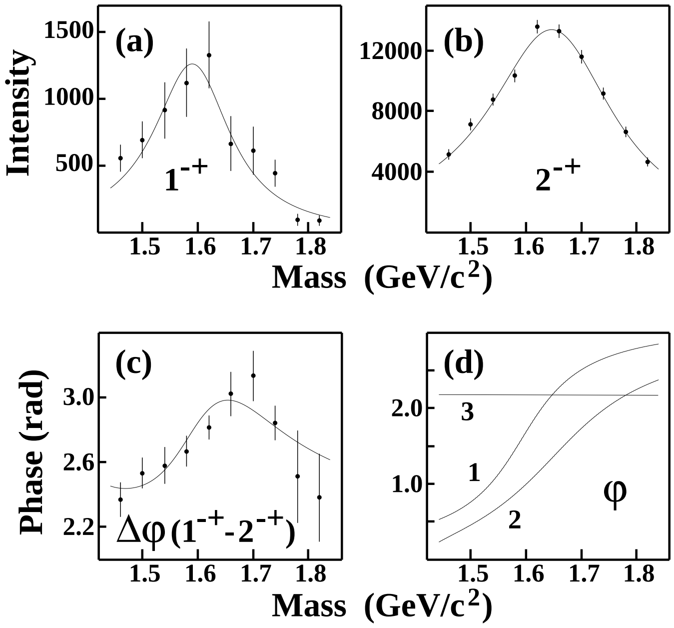

Figure 3: Partial-wave intensities for (a) $1^{-+}[\rho]P\,1^+$ and (b) $2^{-+}[f_2(1270)]D\,0^+$ and (c) their phase difference from the BNL-E852 data. The curve in (c) results from Curve 1 (1^{-+}) minus Curve 2 (2^{-+}) plus Curve 3 (the overall mass-independent phase between the two waves), as shown in (d).

The BNL-E852 Collaboration studied, in addition, the $\eta'\pi^-$ system, in the reaction $\pi^- p \to \eta'\pi^- p$ where $\eta' \to \eta\pi^+\pi^-$ and $\eta \to \gamma\gamma$. A partial-wave analysis was performed on some 5,800 events (collected during the 1995 run) found to fit this reaction with the momentum-transfer in the range $0.06 < |t| < 2.5$ (GeV/c)^2. A good mass-independent fit is obtained using the partial waves S_0, P_0, P_-, D_0 and D_- in the unnatural-parity sector, and P_+, D_+ and G_+ in the natural-parity sector [21]. By far the most dominant waves are P_+ and D_+, which are shown in Fig. 4 along with the phase difference. The phase motion exhibits a 1^{-+} wave characteristic of a resonance near 1.6 GeV/c^2. A mass-dependent fit, shown as solid curves in the figure, gives a resonant P_+

(see table II) and two interfering D_+ waves, one of which is consistent with the usual $a_2(1320)$.

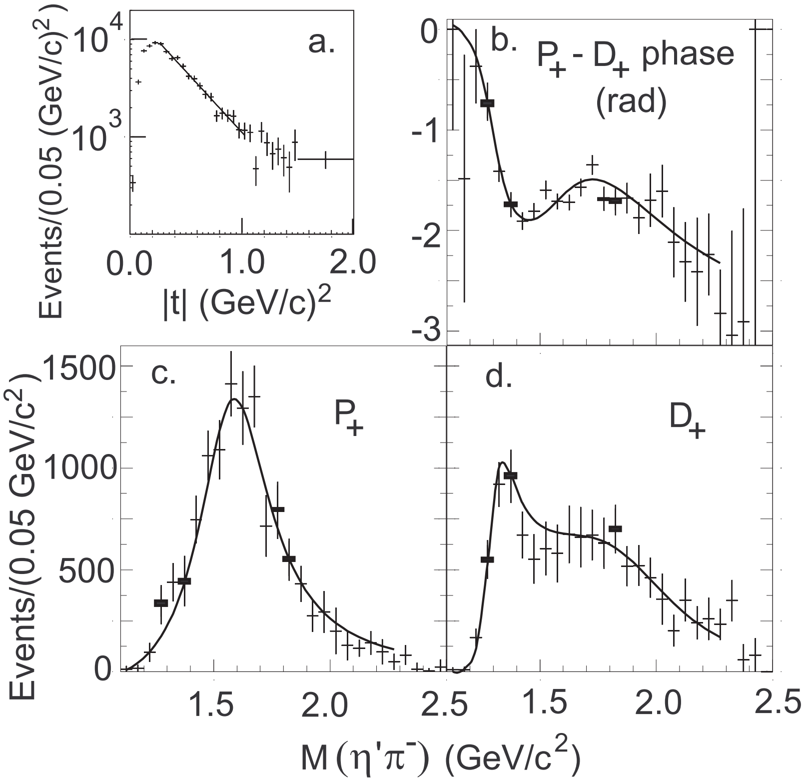

Figure 4: (a) Acceptance-corrected $|t|$ distribution. (b) The $(P_+ - D_+)$ phase difference. (c) and (d) The intensity distributions of P_+ and D_+ partial waves, respectively. The results of the mass-independent PWA are shown as horizontal lines with error bars, and the solid rectangles indicate the range of ambiguous solutions. A typical mass-dependent fit is shown as solid curves.

The VES group [22] presented the results of a coupled-channel analysis of the $\pi_1(1600)$ meson in the channels $\rho\pi$, $\eta'\pi$ and $b_1(1235)\pi$. Their results are consistent with the BNL results, as seen in Table II.

Table II: Parameters for $\pi_1(1600)$

Expt.	Mass(MeV/c^2)	Width(MeV/c^2)	Decay
BNL	$1593 \pm 8 \begin{smallmatrix} +20 \\ -47 \end{smallmatrix}$	$168 \pm 20 \begin{smallmatrix} +150 \\ -12 \end{smallmatrix}$	$\rho\pi$
BNL	$1597 \pm 10 \begin{smallmatrix} +45 \\ -10 \end{smallmatrix}$	$340 \pm 40 \pm 50$	$\eta'\pi$
VES	1610 ± 20	290 ± 30	$\rho\pi$
			$\eta'\pi$
			$b_1\pi$

4 Search for Strangeonium Hybrids

Recent analyses by the VES, BNL and Crystal Barrel collaborations have given convincing evidence that exotic mesons exist whose constituents correspond either to $n\bar{n} + n\bar{n}$ or to $n\bar{n} + g$. The next obvious task is to search for the exotic strangeonium hybrids, $s\bar{s} + n\bar{n}$ or to $s\bar{s} + g$, which are expected to occur with masses some 200 MeV/c^2 heavier than the $n\bar{n}$ variety.

The most efficient way to search for them would be with the K^- beams impinging on protons. Again, the appropriate diagrams for production of strangeonia are the exclusive reactions of the type shown in Fig. 5, mediated by Reggeon exchanges. It is well known that this requires a RF-separated K^- beam [23] at intermediate beam energies, e.g. with the momenta in the range 15 to 25 GeV/c.

Consider an experiment [24] with a K^- beam at 15 GeV/c exposed to a 30 cm-long liquid-hydrogen target within a modern detector with good acceptance for both charged and neutral particles as well as good particle ID. Assume a K^- flux of 1×10^6/sec and a total run of 1×10^7 sec at 10% overall acceptance. This translates into a visible sensitivity of 1,300 events/nb, more than two orders of magnitude bigger than the LASS sample [25] at 4.1 events/nb, to-date the most significant experiment on resonance production from K^-p interactions (at 11 GeV/c).

5 Discussions and Future Prospects

It is clear that there exist $J^{PC} = 1^{-+}$ exotic mesons at masses 1.4 and 1.6 GeV/c^2. Since they cannot be quarkonia, they are either four-quark states or

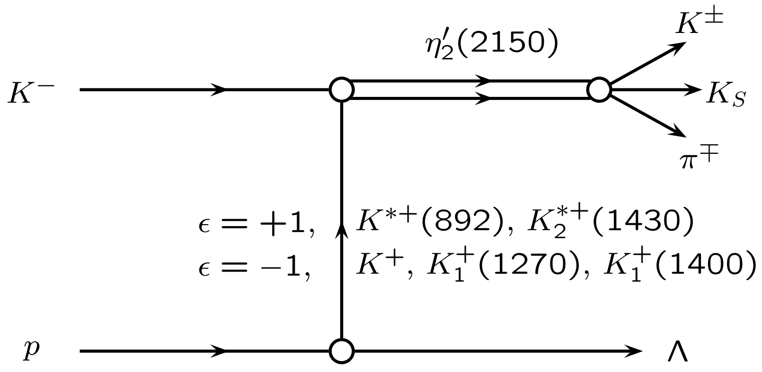

Figure 5: Strangeonium production in K^-p interactions at medium energies—an example.

gluonic hybrids. Because the gluons couple equally to all flavors, a comprehensive study of gluonic hadrons necessarily involves $s\bar{s}$ final states. The decay channels of interest include $K\bar{K}\pi$, $K\bar{K}\pi\pi$, $K\bar{K}\eta$, $K\bar{K}\omega$, etc.

The next logical step in a study of exotic mesons is to look for those containing $s\bar{s}$, i.e. exotic strangeonia and strangeonium hybrids. But this requires a separated K^- beam at momenta in the range 15–25 GeV/c. It must be emphasized that a study of π^-p interactions is necessarily *not complete* without a complementary study of K^-p interactions at similar energies. Consider, for example, the case of a $n\bar{n}+g$ state $\omega(2000)$. It is known, from the general principles of the flux-tube model [26], that it decays only to the final state containing strange particles; so it is an $n\bar{n}+g$ object, which behaves like a $s\bar{s}$ or $s\bar{s}+g$ state. The only way of understanding its constituents is to compare its production cross section in π^-p interactions with that in K^-p interactions (which should be highly suppressed).

The relevant experiments, both on-going and planned throughout the world, should shed further light on the missing and uncertain members of the quarkonium family and those that lie beyond. New results are expected from the analyses being carried out on the BNL-E852 data and on the IHEP data being taken by the VES group. Further new information should be forthcoming from the data accumulated by the Crystal Barrel and Obelix collaborations at LEAR, on the $\bar{p}p$ and $\bar{p}n$ annihilations at rest and in flight.

New data of interest to hadron spectroscopy should also be forthcoming in the near future from CLEO-III, BaBar and Belle, Jefferson Lab and DAΦNE. In addition, one can look forward to new experiments such as COMPASS at the CERN SPS (scheduled to take data in 2001), the Japan Hadron Facility with

50 GeV/c^2 protons at KEK (recently approved for construction), the Beijing τ-charm factory (proposed), and the upgraded AGS and the RHIC at BNL and the LHC at CERN. The GSI/Darmstadt has proposed a heavy-ion synchrotron facility (SIS200), with protons up to 50 GeV/c, and a cooled antiproton ring (HESR) for a study of meson spectroscopy including $c\bar{c} + g$.

Finally, it may be appropriate to comment on the possible existence of an exotic meson with one particular combination of J^{PC}, which could shed light on its constituents. An exotic meson with the quantum numbers $J^{PC} = 0^{--}$ is a particularly interesting one, because such a state is not allowed for a gluonic hybrid in the lowest-order flux-tube model [27] and possibly in other models as well containing a valence gluon. So if a gluonic hybrid exists with the quantum numbers $J^{PC} = 0^{--}$, then its mass must be large. Indeed, according to the calculations of the QCD sum rule by Latorre *et al.* [7], a $J^{PC} = 1^{-+}$ $n\bar{n} + g$ should come with a mass in the range 1.6–2.1 GeV/c^2, whereas a $J^{PC} = 0^{--}$ $n\bar{n} + g$ should have a mass around 3.8–4.2 GeV/c^2, well into the mass range of charmonia.

In the diquark cluster model, several $I^G(J^{PC}) = 1^+(0^{--})$ exotic mesons are predicted [28] in the mass region 1.3 to 1.7 GeV/c^2, coupling to $a_0(980)\pi$, $\rho\eta$, $\omega\pi$, and $a_1(1260)\omega$—among others—depending on the mass. Any future search for exotic mesons should include those with $J^{PC} = 0^{--}$. Discovery of a $J^{PC} = 0^{--}$ with mass < 2.0 GeV/c^2 signals existence of an exotic meson which cannot be ascribed to a gluonic excitation, at least in the flux-tube model. A meson ρ_0 with $I^G(J^{PC}) = 1^+(0^{--})$ can couple to the decay channel $\omega\pi$ via P wave, while a meson ω_0 with $I^G(J^{PC}) = 0^-(0^{--})$ should decay into $\rho\pi$ via P wave. Such a discovery would be exciting indeed.

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