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Search for Exotic Mesons

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abstract

A state with $J^{PC} = 1^{-+}$ is exotic in the sense that a conventional $\bar{q}q$ meson cannot couple to it. There exist currently three such exotic mesons with masses ranging from 1.3 to 2.0 GeV in the decay channels $\pi\eta$, $\pi\eta'$, $\pi\rho$ and $f_1(1285)\pi$. But all are in need of confirmation. The current status and future prospects of these exotic mesons are given.

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1 Introduction

The purpose of this note is to give a short overview of the existing candidates for J^{PC} exotic mesons which cannot be quarkonia, i.e. the states belonging to $J^{PC} = 0^{+-}$, 1^{-+}, 2^{+-} and 0^{--}. The current status and future prospects are given.

A short comment is in order on notations for the partial waves commonly encountered in the literature. For a pure wave coupling to a system of two pseudoscalars, it is sufficient for one to specify the orbital angular momentum (L), its z-component (M) and the reflectivity quantum number (ϵ). 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

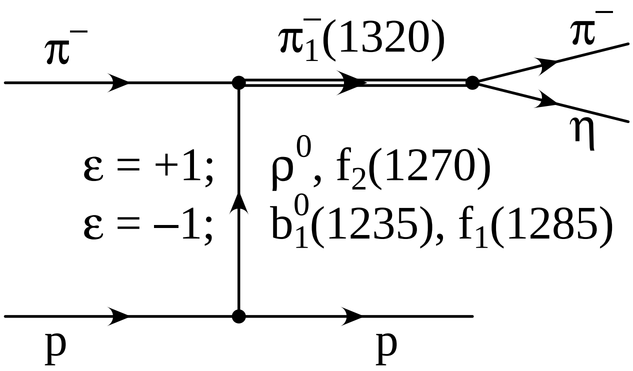

Figure 1: Resonance production via Reggeon exchange—an example.

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_-. One uses the notations S, P, D, F for $L = 0$, 1, 2, 3, etc.

It is much more complicated for one to specify a state, if it decays into three or more particles. Consider, as an example, a state which decays to an isobar and a pseudoscalar and the isobar which in turn decays into two or more pseudoscalars. Then, the state may be denoted by $|J^{PC}[\text{isobar}]LM^{\epsilon}\rangle$ or $|J^{PC}LM^{\epsilon}(\text{isobar})\rangle$, the latter being merely a different way of writing down the former. The L above is the orbital angular momentum between the isobar and the pseudoscalar. If one makes the simplifying assumption that only the lowest allowed L is used in the analysis, then L may be dropped from the label above, for brevity.

We propose that the J^{PC}-exotic mesons be denoted following the standard convention in use, i.e. the name is determined by the combination $\{P, C\}$ of a meson. Hence, an isovector $J^{PC} = 1^{-+}$ state is denoted π_1, while its isoscalar partners are given the names η_1 and η_1'. Likewise, an isovector $J^{PC} = 0^{+-}$ state, to take another example, is denoted b_0, while its isoscalar partners are given the names h_0 and h_0'. We note that the Particle Data Group[1] suggests a different convention.

2 Observation of the $M/\pi_1(1405)$ meson

The $M/\pi_1(1405)$ meson was originally seen[2] in the reaction $\pi^- p \to \pi^0 \eta\, n$ at 100 GeV/c(see figs. 2). Because the $a_2(1320)$ and the M are seen to be produced via unnatural-parity exchange, one must conclude that the $b_1(1235)$ exchange is the dominant one. This also indicates that the M should decay into the $b_1(1235)\pi$ final state.

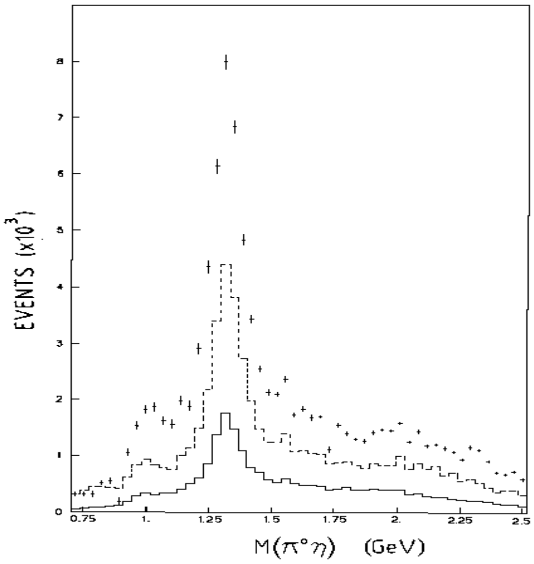

Figure 2: Spectrum of $m(\pi^0\eta)$ by GAMS; raw data (solid), acceptance corrected (dashed) and full fit (points with error bars)

There exist two additional pieces of evidence regarding the $M/\pi_1(1405)$ meson. The VES experiment[3] studied the following reactions $\pi^- N \to \pi^- \eta\, N$ and $\pi^- N \to \pi^- \eta'\, N$ at 37 GeV/c. The $M/\pi_1(1405)$ signal is present but small with large errors in the $\pi\eta$ channel (not shown).[1] Instead, they observe a state at 1600 MeV in the $\pi\eta'$ channel (see fig. 3), suggesting that the $M(1405)$, if confirmed, may turn out to be a multi-quark state[5]. The broad enhancement at around 1600 MeV could be an alternative decay of the $\pi_1(1600)$ claimed in the $\pi\rho$ system. They are produced by natural-parity exchange—presumably ρ or f_2 exchange.

The E179 collaboration[6] at KEK studied the $\pi^-\eta$ system in the reaction $\pi^- p \to \pi^- \eta\, p$ at 6.3 GeV/c (see fig. 4). As seen in fig. 5, both D_+ and P_+ waves peak at the $a_2(1320)$ mass region; once again ρ- or f_2-exchange processes seem to play a central role in the production of these waves. Since the phase variation between these waves seems constant throughout the $a_2(1320)$ mass region, one must conclude that both are resonant. They have determined that $m(a_2) = 1325.1 \pm 5.1$ MeV and $\Gamma(a_2) = 126.2 \pm 14.2$ MeV for the $a_2(1320)$, and $m(\pi_1) = 1323.1 \pm 4.6$ MeV and $\Gamma(\pi_1) = 143.2 \pm 12.5$ MeV for the $M/\pi_1(1405)$.

[1]The Crystal Barrel Collaboration[4] also reports that their data on $\bar{p}p$ annihilations at rest can accommodate some 1^{-+} $\pi\eta$ state, but it is very broad—several hundred MeV wide.

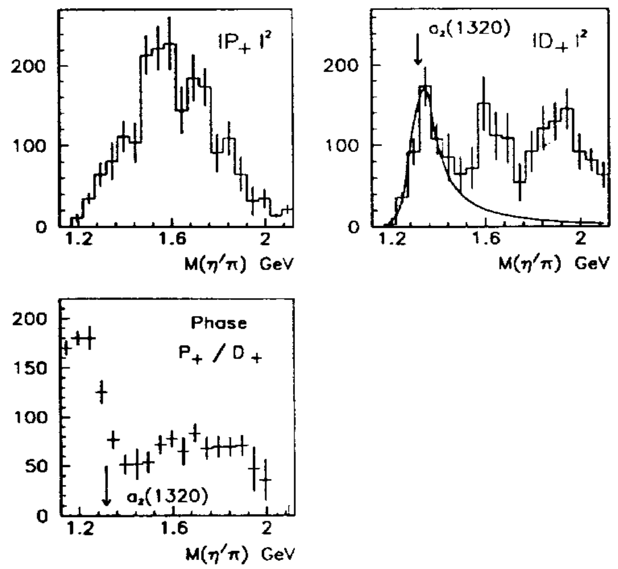

Figure 3: Partial-wave intensities as a function of $m(\pi^-\eta')$ and the phase motion of P_+ relative to D_+ from VES data

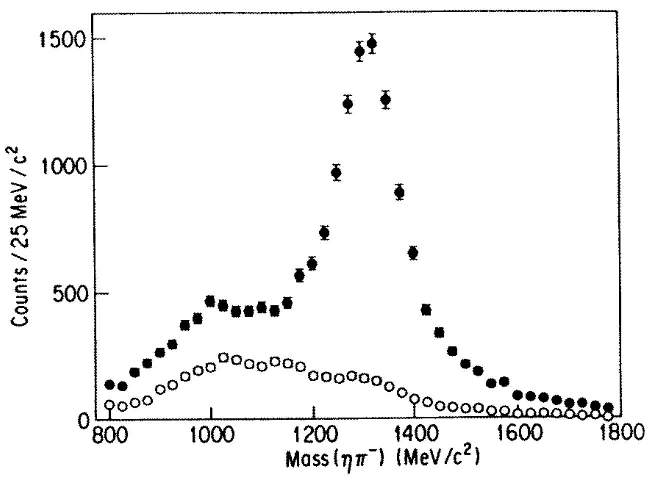

Figure 4: Spectrum of $m(\pi^-\eta)$ from KEK data. Open circles represent their background estimate.

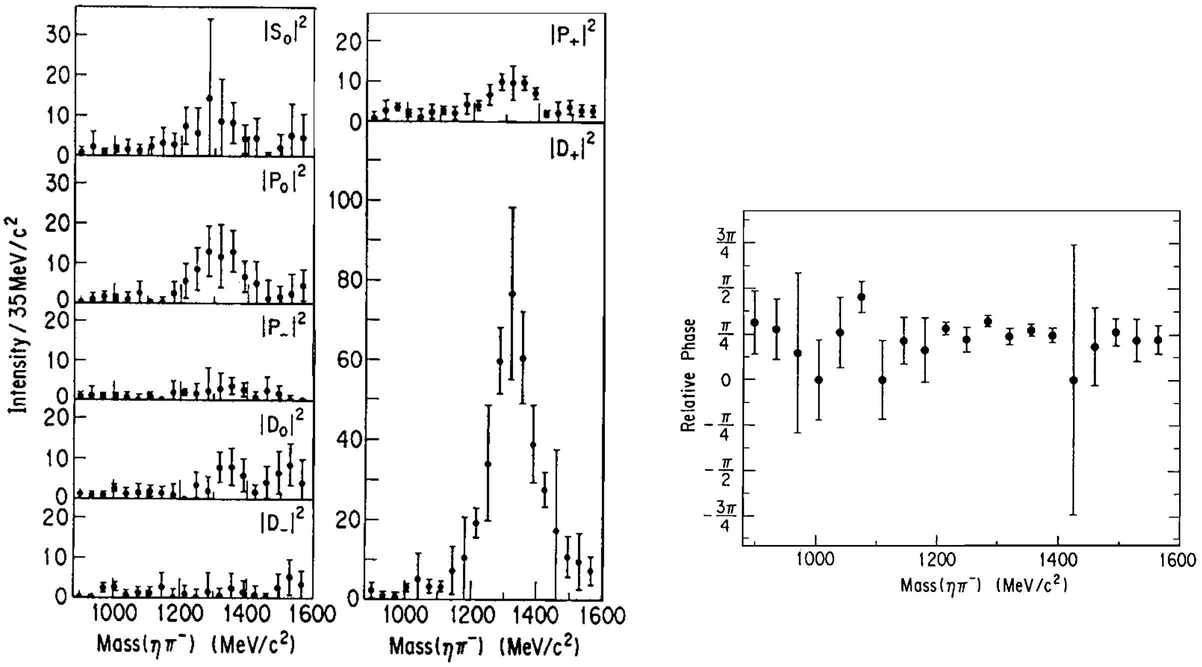

Figure 5: Partial-wave intensities for $m(\pi^-\eta)$ and the phase motion of P_+ relative to D_+ from KEK data

3 Additional $J^{PC} = 1^{-+}$ π_1 states at 1600 and 1900 MeV

The VES Collaboration claims a $\pi_1(1600)$ coupling to $\eta'\pi$ and $\rho\pi$ (see fig. 6). The $\pi\rho$ system with $J^{PC} = 1^{-+}$ exhibits two bumps; one at 1300 MeV and the other at 1600 MeV, both produced via natural-parity exchange. But the phase motion of this wave relative to the $a_2(1320)$ structure is consistent with a resonance interpretation only for the 1600-MeV bump. It is for this reason that the VES collaboration concludes that they see a resonant $J^{PC} = 1^{-+}$ structure at 1620 MeV.

The BNL-E852 collaboration[7] is in the process of carrying out a study of the reaction $\pi^- \to \pi^+\pi^-\pi^- p$ at 18 GeV/c. There are two reasons for this; (a)the VES collaboration reported two bumps at 1300 and 1600 MeV, as stated above (see fig. 6), and (b)the KEK collaboration claims a state at 1.32 GeV in the P_+ wave—this implies a natural-parity exchange for the production and hence, presumably, it could have a substantial coupling to the $\pi\rho$ channel. A sample of 500,000 events shows a clear $a_2(1320)$ rising on the shoulder due to the $a_1(1260)$ and the $\pi_2(1670)$, whose major decay channels include $\pi\rho$ and $\pi f_2(1270)$ (see fig. 7). The partial-wave decomposition of the $\pi + \pi^-\pi^-$ spectrum demonstrates that the $J^{PC} = 1^{++}$, $2^{++}$and 2^{-+} waves dominate, corresponding to the $a_1(1260)$, the $a_2(1320)$ and the $\pi_2(1670)$, respectively—all produced via natural-parity exchange (see fig. 8). It is seen that the ratio of 1^{-+} to 2^{++} waves is much smaller compared to that of the VES data; in addition, the 1^{-+} wave does not show the bump structures seen in the VES data. However, the 1^{-+} wave produced via unnatural-parity exchange does show a bump (not shown) in the vicinity of the $a_2(1320)$, but the results are still highly preliminary.

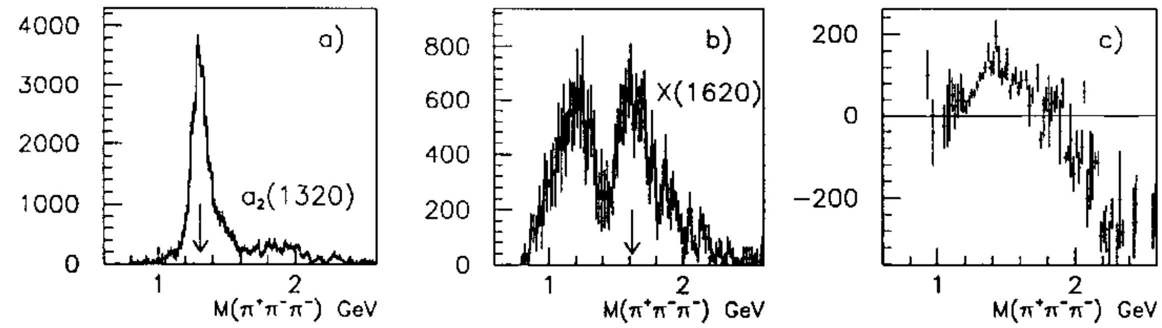

Figure 6: Partial-wave intensities for 2^{++}(a) and 1^{-+}(b) as a function of $m(\pi^-\rho^0)$ and the phase motion(c) of 2^{++} relative to 1^{-+} from VES data

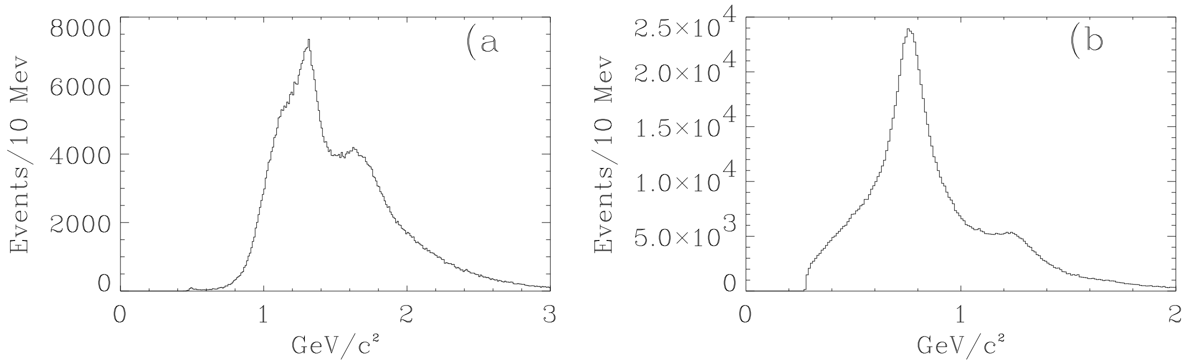

Figure 7: BNL-E852 data. (a) Uncorrected $\pi^+\pi^-\pi^-$ effective mass. (b) Uncorrected $\pi^+\pi^-$ effective mass.

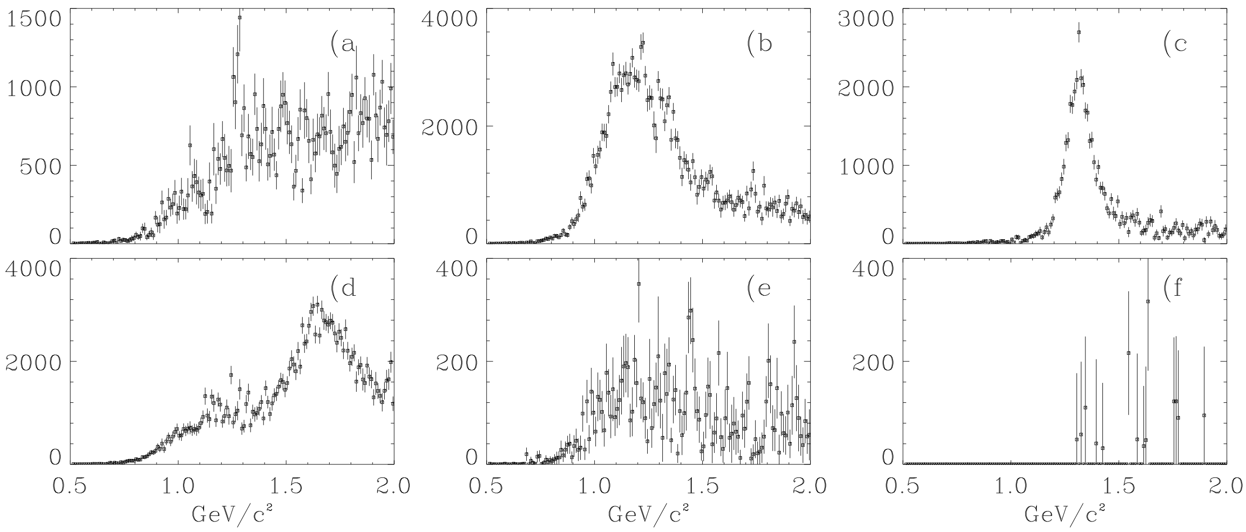

Figure 8: Partial-wave intensities (all produced via natural-parity exchange) for $0.15 < -t < 0.30$ $(\mathrm{GeV}/c)^2$ from BNL-E852 data. (a) $0^{-+}0^{+}$, (b) $1^{++}0^{+}$ plus $1^{++}1^{+}$, (c) $2^{++}1^{+}$, (d) $2^{-+}0^{+}$ plus $2^{-+}1^{+}$, (e) $1^{-+}1^{+}$ and (f) background.

The BNL-E818 collaboration investigated the reaction $\pi^- p \to f_1(1285)\pi^- p$ at 18 GeV/c, with the decay $f_1(1285) \to K^+ K_S \pi^-$. The collaboration finds an enhancement[8] in the $f_1(1285)\pi$ system (see figs. 9 and 10), but the structure seems to consist of two objects—the lower-mass peak having an additional decay mode into $\eta(1295)\pi$ and the upper-mass portion of the enhancement showing a rapid phase motion, characteristic of a genuine resonance. These states are produced by natural-parity exchange, suggesting that they couple to $\rho\pi$ as well. In addition the VES collaboration observes a broad peak in the $f_1(1285)\pi$ system in the $J^{PC} = 1^{-+}$ wave between 1600 and 2100 MeV (not shown).

4 Discussions and Future Prospects

There exist three isovector $J^{PC} = 1^{-+}$ hybrid candidates, the $\pi_1(1300 - 2100)$, and all are in need of confirmation.

The KEK group sees a state at mass 1323 MeV and width 143 MeV in the $\pi\eta$ channel, produced via natural-parity exchange. This result is in conflict with an earlier GAMS result which showed a 1^{-+} state with unnatural-parity exchange. (Sadovsky[9] emphasized that the analysis technique, originally employed by the GAMS group, was unreliable.) The VES group also studied the $\pi\eta$ channel but they report no significant 1^{-+} state in the 1.3–1.4 GeV region. Instead, they see a 1^{-+} state at 1620 MeV decaying into $\pi\rho$ and $\pi\eta'$, produced via natural-parity exchange. The BNL-E852 collaboration finds that the 1^{-+} $\pi\rho$ wave is very much reduced compared to the $a_2(1320)$ signal, in contrast to the VES results. The BNL-E818 reports a 1^{-+} state at 1.9–2.0 GeV coupling to the $f_1(1285)\pi$ channel, with a rapid increase of the phase relative to the 1^{++} wave. The VES group also finds a broad 1^{-+} $f_1(1285)\pi$ state in the mass region 1.6–2.0 GeV but they do not report a study of its phase motion.

It is hoped that the situation will soon be very much clarified by the impending results

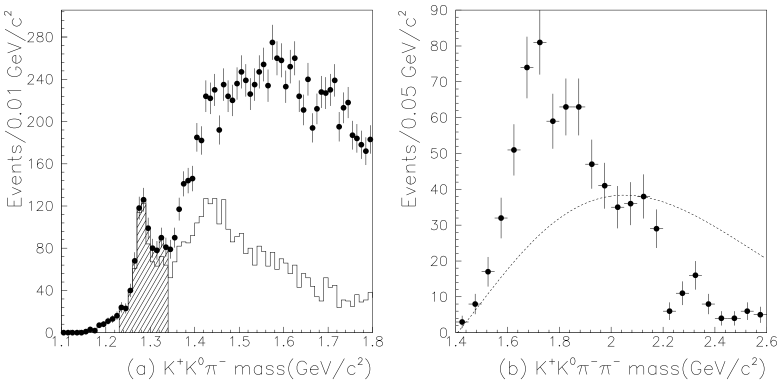

Figure 9: BNL-E818 data. (a) The $K^+\bar{K}\pi^-$ mass distribution. The region for f_1/η selection is shaded. The lower histogram shows the same with an $a_0(980)$ cut. (b) The $K^+\bar{K}\pi^-\pi^-$ mass spectrum with an $f_1(1285)$ cut. The dotted line shows the accepted $f_1(1285)\pi$ phase space (see text).

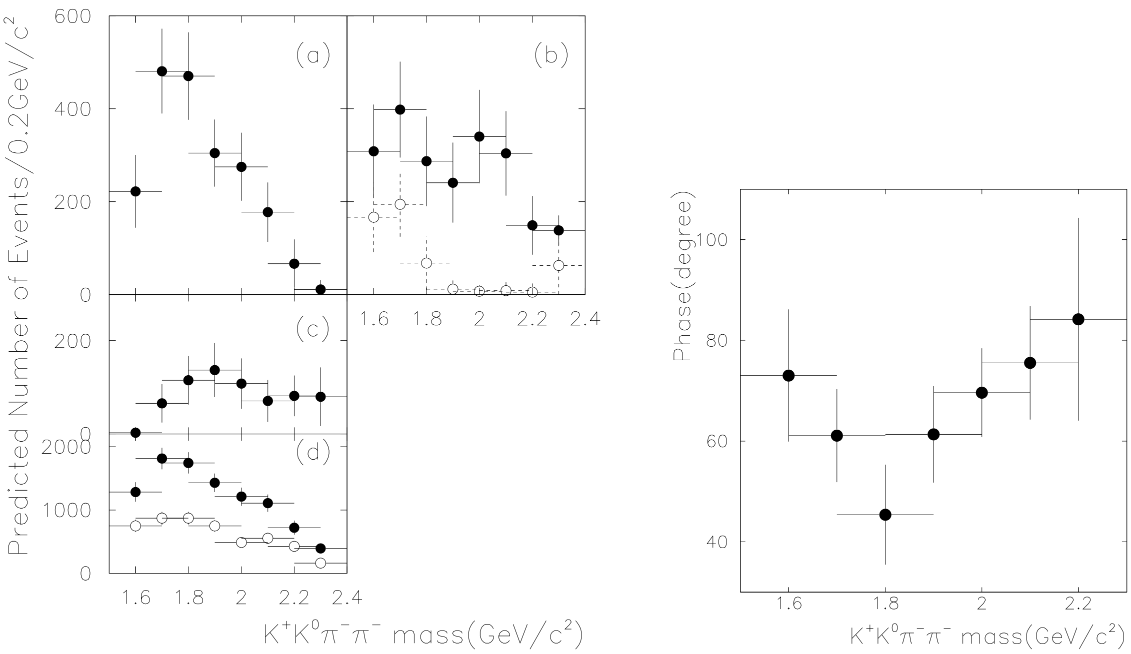

Figure 10: BNL-E818 data.Left-hand figures: The partial-wave intensity distributions as a function of $f_1\pi^-$ mass.(a) $J^{PC}M^\epsilon = 1^{++}0^+$ wave. (b) $J^{PC}M^\epsilon = 1^{-+}1^+$ wave with combined $f_1(1285)\pi$ and $\eta(1295)\pi$ decay modes. The open circles show the $\eta(1295)\pi$ wave only. (c) $J^{PC}M^\epsilon = 2^{++}1^+$. (d) All partial waves included in the fit. The open circles in the plot show the background. Right-hand figure: The relative phase of the $1^{-+}[f_1(1285)]1^+$ wave against the $1^{++}[f_1(1285)]0^+$ wave.

from partial-wave analyses on the BNL-E852 data, especially on the data sample based on the 10^9 triggers which the collaboration took in 1995; the decay channels under study include $\eta\pi$, $\eta'\pi$, $\eta\eta$, $(\pi\pi\pi)^-$, $f_1(1285)\pi$, $b_1(1235)\pi$ and $\omega\eta$. In addition, new results are expected from the analyses being carried out on the IHEP data taken by the VES and the GAMS group. Further new information should be forthcoming from the massive statistics being 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. The WA76 collaboration with the Omega Spectrometer at CERN, and its extension WA91, have been collecting data since 1991, to search for exotic mesons in the central production at the SPS; so far they report no 1^{-+} states in their data.

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[7] The collaboration consists of BNL, IHEP (Protvino), Indiana, U. Mass.(Dartmouth), Moscow State, Northwestern (Evanston), Notre Dame, RPI (Troy, NY). The group is currently carrying out a systematic study of the exotic mesons produced in $\pi^- p$ interactions at 18 GeV/c at the existing BNL Multi-Particle Spectrometer (MPS), augmented by charged-particle and photon detectors around the target and at the downstream end of the MPS magnet.

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