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Search for Exotic Mesons

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Abstract
A survey is given of the current status of the $J^{PC} = 1^{-+}$ exotic mesons and the future prospects.

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1 Introduction

Before describing recent results on the J^{PC}-exotic mesons, it is first necessary to comment on the notations which one may employ to denote these states. The PDG advocates a naming scheme in which a new notation involving a caret be introduced[1]. However, one must point out that it is *not* necessary to introduce a new naming scheme; the present conventions for the nomenclature are sufficient for *all* possible J^{PC}-exotic mesons. Denoting particle names within parentheses preceded by exotic J^{PC}'s, one may write 0^{--} $(\rho_0, \omega_0, \phi_0)$, 0^{+-} (b_0, h_0, h_0'), 1^{-+} (π_1, η_1, η_1'), 2^{+-} (b_2, h_2, h_2'), 3^{-+} (π_3, η_3, η_3') and so on.

The most important candidate for a J^{PC}-exotic meson has been the $J^{PC} = 1^{-+}$ $M/\pi_1(1405)$ seen decaying into $\eta\pi$. The first result on this, reported by the GAMS group, is not confirmed. At present, the best candidate comes from KEK data, but it mass is some 80 MeV below that claimed by GAMS. Both VES and BNL experiments report a broad enhancement near threshold in the $J^{PC} = 1^{-+}$ $f_1(1285)\pi$ system. Results of BNL analysis is consistent with presence of a genuine resonance at around 2.0 GeV.

There exist in the literature two types of nomenclatures commonly used to describe a partial wave; therefore, a short comment on these is in order for a review article such as this. A partial-wave state for any resonance R decaying into an isobar and a pseudoscalar, is completely described by $I^G\, J^{PC}[\text{isobar}]M^\epsilon$, where M is the z-component of the spin in a suitably chosen coordinate system and ϵ is the naturality of the exchanged particle in a two-body process induced by π or K beams. It is assumed that only the lowest orbital angular momentum allowed by parity conservation is introduced in the partial wave, and hence it need not be specified in the notation above. The isospin I and the G-parity is dropped frequently, if the system under study has unique I and G. A different set of notations is commonly used to describe the partial waves of a two-pseudoscalar system. Let L be the orbital angular momentum between the two final particles— then one has $J = L$, parity= $(-)^L$ and $\epsilon = -1$ if $M = 0$. For this reason, it is sufficient (and more compact) to denote a partial wave for $|M| \leq 1$ by L_0 or $L_\pm$, where the letters S, P, D and F are used as usual for $L = 0$, 1, 2 and 3. Note the correspondence

$$\begin{array}{cccc} L_0 & \Longleftrightarrow & L^+\,0^- & L = \text{even} \\ L_0 & \Longleftrightarrow & L^-\,0^- & L = \text{odd} \\ L_\pm & \Longleftrightarrow & L^+\,1^\pm & L = \text{even} \\ L_\pm & \Longleftrightarrow & L^-\,1^\pm & L = \text{odd} \end{array} \tag{1}$$

where the right-hand side stands for $J^P\, M^\epsilon$ and I, G and C have been suppressed. Of course, the concept of an isobar is superfluous for a system consisting of two spin-zero particles.

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

The $J^{PC} = 1^{-+}$ $M(1405)$ meson was originally seen[2] in the reaction

$$\pi^- p \to \pi^0 \eta\, n \tag{2}$$

at 100 GeV/c. Because the $a_2(1320)$ and the M are seen to be produced via unnatural-parity exchange, it was thought that $b_1(1235)$ exchange was responsible for the production. However, a recent analysis of the same data[3] shows that the original analysis was incorrect; the natural-parity exchange now dominates, and the claimed M meson is in doubt.

Recently two additional information regarding the exotic state has emerged. The VES experiment[4] studied the following reactions

$$\pi^- N \to \pi^- \eta\, N \tag{3}$$

and

$$\pi^- N \to \pi^- \eta'\, N \tag{4}$$

at 37 GeV/c. The $M/\pi_1(1405)$ signal, with large error bars, is present in the $\pi\eta$ channel but not in the $\pi\eta'$ channel (see Figs. 1 and 2), indicating that the M might be a multiquark state[5]. There is a broad enhancement at around 1600 MeV in the $\pi\eta'$ system, which could be an alternative decay of the $\pi_1(1600)$ claimed[6] in the $\pi\rho$ system (see Fig. 3). Both are produced by natural-parity exchange—presumably ρ or f_2 exchange.

The second evidence comes from an experiment at KEK[7]. The E179 collaboration at KEK studied the $\pi^-\eta$ system (see Fig. 4) in the reaction

$$\pi^- p \to \pi^- \eta\, p \tag{5}$$

at 6.3 GeV/c. A P-wave is definitely required, as demonstrated by a substantial forward-backward asymmetry in the $a_2(1320)$ region (Fig. 5). Both D_+ and P_+ waves peak at the $a_2(1320)$ mass region, as seen in the partial-wave decomposition of the $\eta\pi^-$ system (Fig. 6); once again ρ- or the 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 (Fig. 7) 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 $M/\pi_1(1405)$.

Both KEK[7] and GAMS[8] collaborations observe production of the $a_2(1320)$ with a dip in the forward direction for $-t \simeq 0$. The $-t$ dependence can be characterized by

$$\frac{\mathrm{d}\,\sigma}{\mathrm{d}\,t'} \sim (t')^{|\lambda|}\, \mathrm{e}^{-b' t'} \tag{6}$$

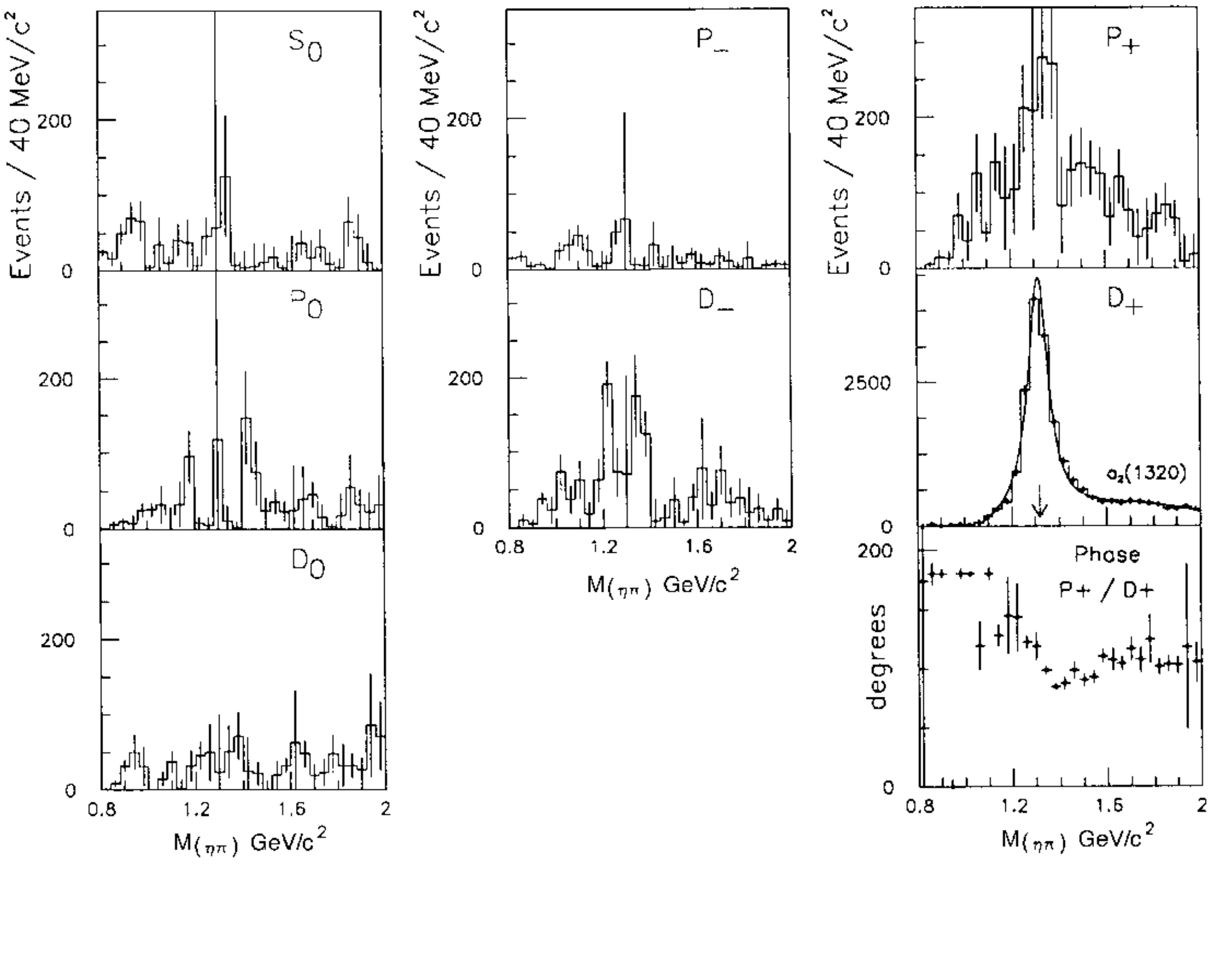

Figure 1: Partial-wave decomposition of the $\eta\pi^-$ system (VES data).

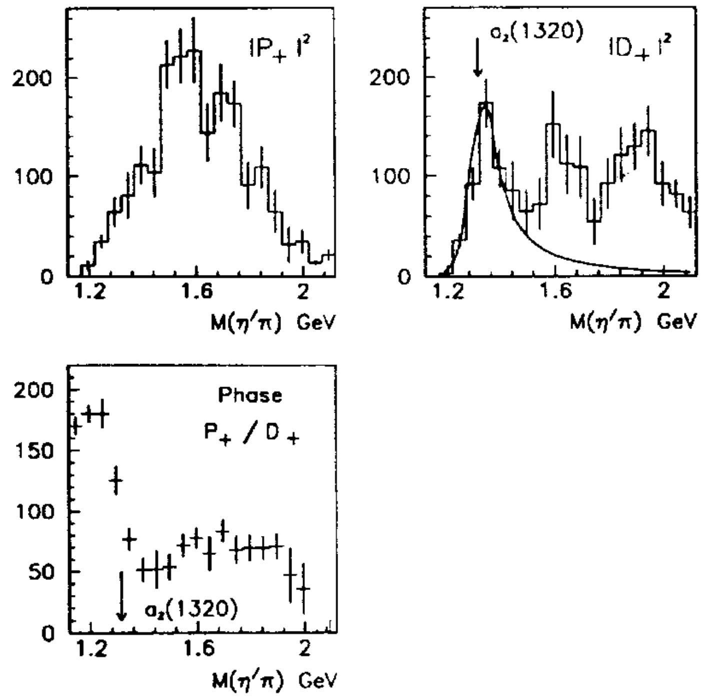

Figure 2: P_+ and D_+ waves and their relative phase in the $\eta'\pi^-$ system (VES data).

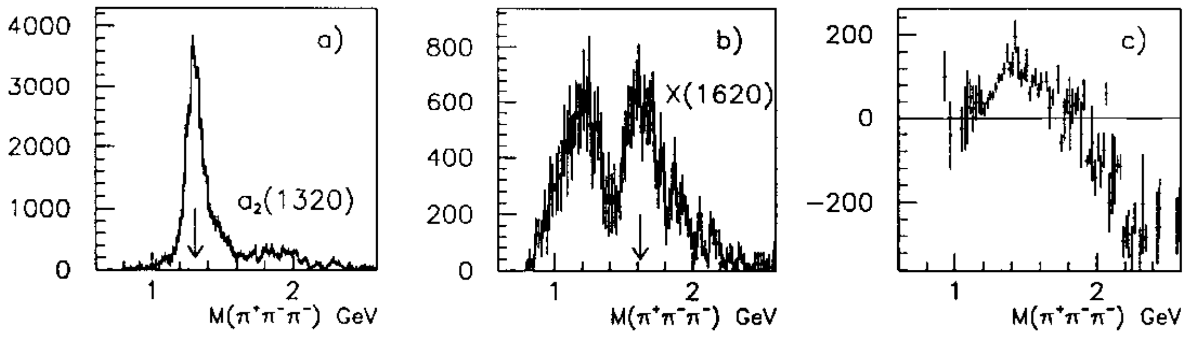

Figure 3: The partial waves $2^{++}[\rho^0]1^+$ and $1^{-+}[\rho^0]1^+$ and their relative phase in the $\pi^+\pi^-\pi^-$ system (VES data).

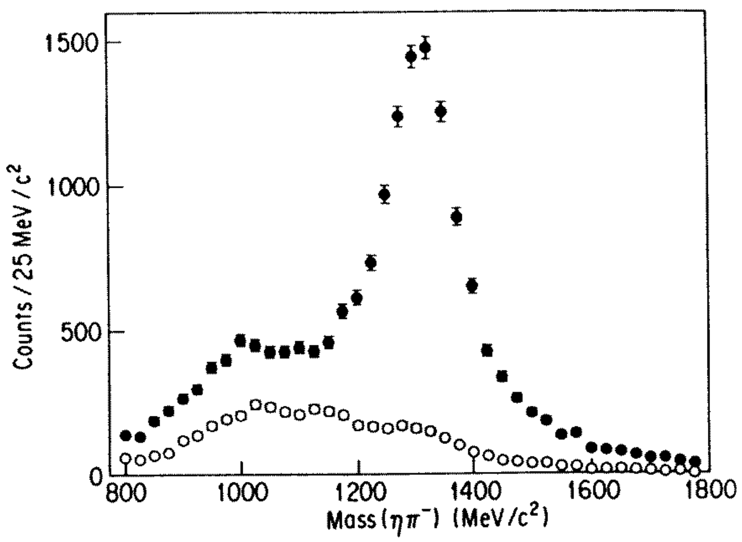

Figure 4: The $\eta\pi^-$ mass distribution (solid circles) from KEK data, with $0.075 < |t'| < 0.60(\mathrm{GeV}/c)^2$. Open circles show background events in the η control region.

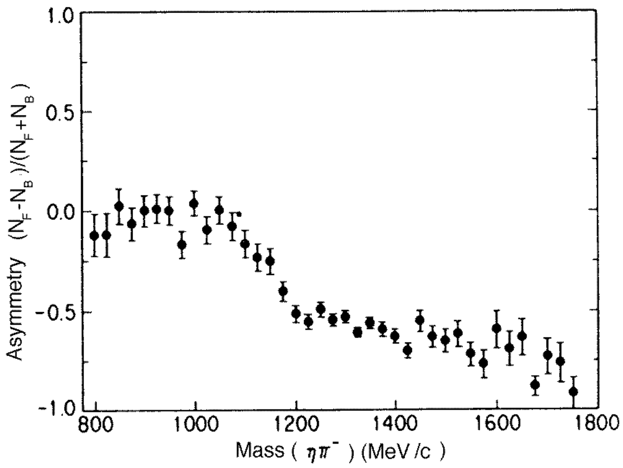

Figure 5: Forward-backward asymmetry in the $\eta\pi^-$ GJ frame for $|\cos\theta(GJ) < 0.8|$, corrected for finite acceptance (KEK data).

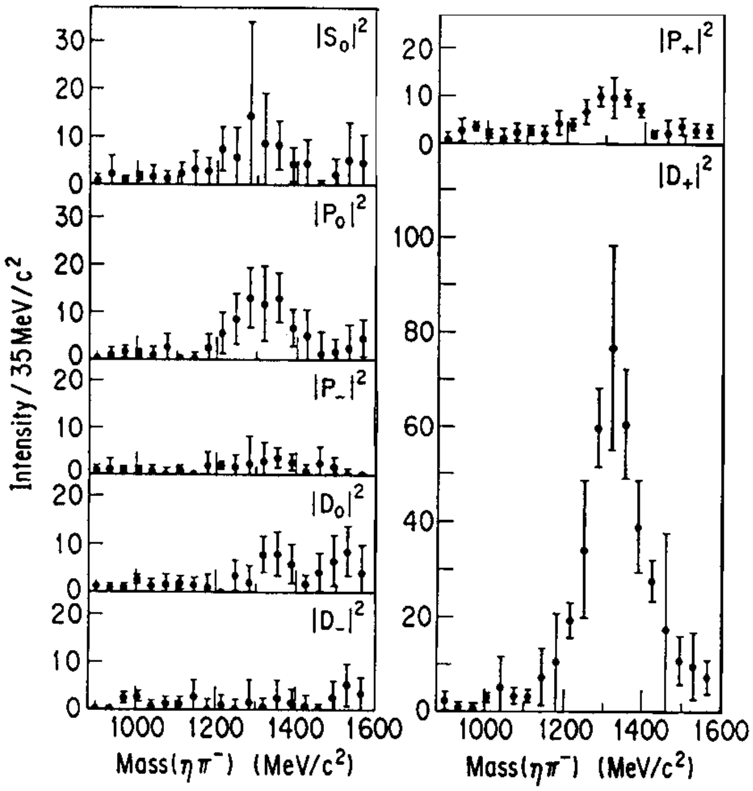

Figure 6: Partial-wave decomposition of the $\eta\pi^-$ system, subtracting the background events in the η control region (KEK data).

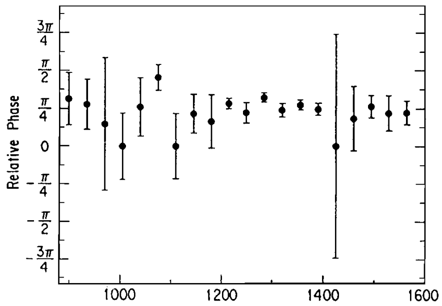

Figure 7: Phase variation of the $2^{++}1^+$ wave relative to the $1^{-+}1^+$ (KEK data).

where $t' = |t| - |t|_{\min}$; λ is the helicity of the exchanged particle in the s-channel; and b' is the slope parameter. It is commonly thought[9] that natural-parity states are produced predominantly with $\lambda = \pm 1$, whereas the unnatural-parity states are produced mostly with $\lambda = 0$. In this regard then, it is natural that both D and P waves are produced with a forward dip. From the KEK data the b' is measured to be 6.47 ± 0.53 (GeV)$^{-2}$.

3 Additonal π_1 states at 1600 and 2000 MeV

The VES Collaboration[6] claims a $\pi_1(1600)$ coupling to $\eta'\pi$ and $\rho\pi$. The $\pi\rho$ system with $J^{PC} = 1^{-+}$ exhibits two bumps; one at 1300 MeV and the other at 1600 MeV. But the phase motion of this wave relative to the $a_2(1320)$ 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.

A BNL E818 Collaboration[10] carried out a systematic search for the putative $\pi_1(1900)$ predicted by the flux-tube model of N. Isgur, et al.[11]. Its likely decay modes are thought to be $b_1(1235)\pi$ and $f_1(1285)\pi$. Hence, they studied the reaction

$$\pi^- p \rightarrow f_1(1285)\pi^- p \tag{7}$$

at 18 GeV/c, where

$$f_1(1285) \rightarrow K^+ K_s \pi^- \tag{8}$$

and the neutral K was detected through its $\pi^+\pi^-$ decay mode.

The $f_1(1285)\pi^-$ spectrum, shown in Fig. 8, exhibits a strong threshold enhancement centered around 1.7 GeV. The results of a partial-wave analysis[10] are given in Fig. 9. It is remarkable that the $f_1\pi$ spectrum can be described by just four partial-waves (all produced via natural-parity exchange), with two isobars $a_0(980) \rightarrow K\bar{K}$ and $K^*(890) \rightarrow K\pi$. In addition, it is found that the pseudoscalar state $\eta(1295)$ is required by the data in the $f_1(1285)$ region.

The strongest wave in the 1.7 GeV region turns out to be $1^{++}[f_1(1285)]0^+$, which could be interpreted as the first radial excitation[12] of the $a_1(1260)$. The $1^{-+}1^+$ wave is also prominent, from threshold to 2.2 GeV. But the structure seems more complicated; the lower-mass peak below 1.9 GeV consists of two decay modes $f_1(1285)\pi$ and $\eta(1295)\pi$, while the upper-mass portion of the enhancement shows a rapidly rising phase motion, characteristic of a genuine resonance (see Fig. 10). These states are produced by natural-parity exchange, suggesting that they should couple to $\rho\pi$ as well. The VES collaboration also observes a broad peak in the $f_1(1285)\pi$ system in the $J^{PC} = 1^{-+}$ wave between 1600 and 2100 MeV.

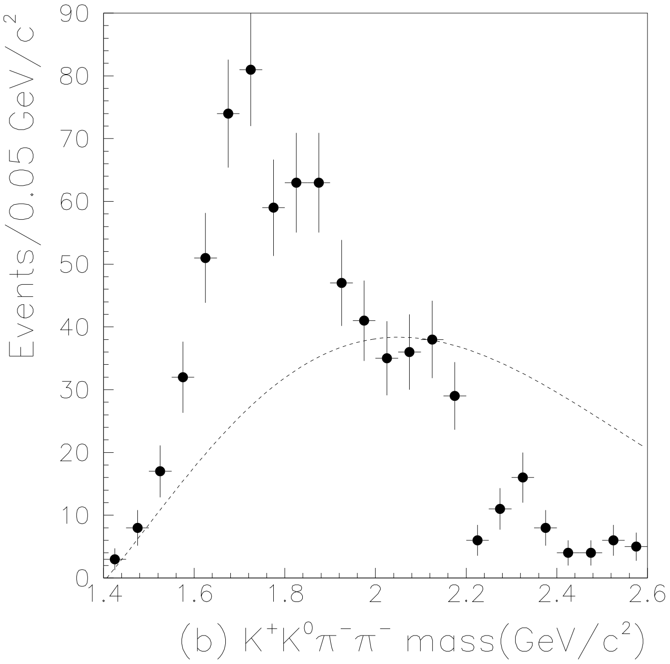

Figure 8: $f_1(1285)\pi^-$ spectrum from BNL data, with $f_1(1285) \to K^+K_S\pi^-$. The dotted line is that of the phase space modified by the acceptance.

4 Conculsions and future prospects

The $J^{PC} = 1^{-+}$ state $M/\pi_1(1405) \to \eta\pi$ was originally reported by GAMS group, seen in the unnatural-parity exchange process. But a later analysis of the same data casts doubt on the claimed resonance. Currently, the best evidence for this state comes instead from the KEK data, but at a mass 1323 MeV, considerably lower than that reported by the GAMS group. Furthermore, it is produced entirely by natural-parity exchange, indicating that this state must couple to $\rho\pi$ as well. VES claimed a $J^{PC} = 1^{-+}$ $\rho\pi$ state at 1.6 GeV; however, it is unlikely to be the one seen by KEK, as it is some 300 MeV below that of VES.

A broad enhancement in the $J^{PC} = 1^{-+}$ wave has been seen near threshold by both VES and BNL experiments. The results of the BNL analysis show that the structure consists of two states, at 1.7 and 2.0 GeV, with the latter showing a rapid phase motion characteristic of a genuine resonance. One may therefore conclude that the $f_1(1285)\pi$ state at 2.0 GeV can be identified with the gluonic excitation at 1.9 GeV predicted by Isgur, et al[11]. However, the BNL statistics were limited, and the conclusions regarding

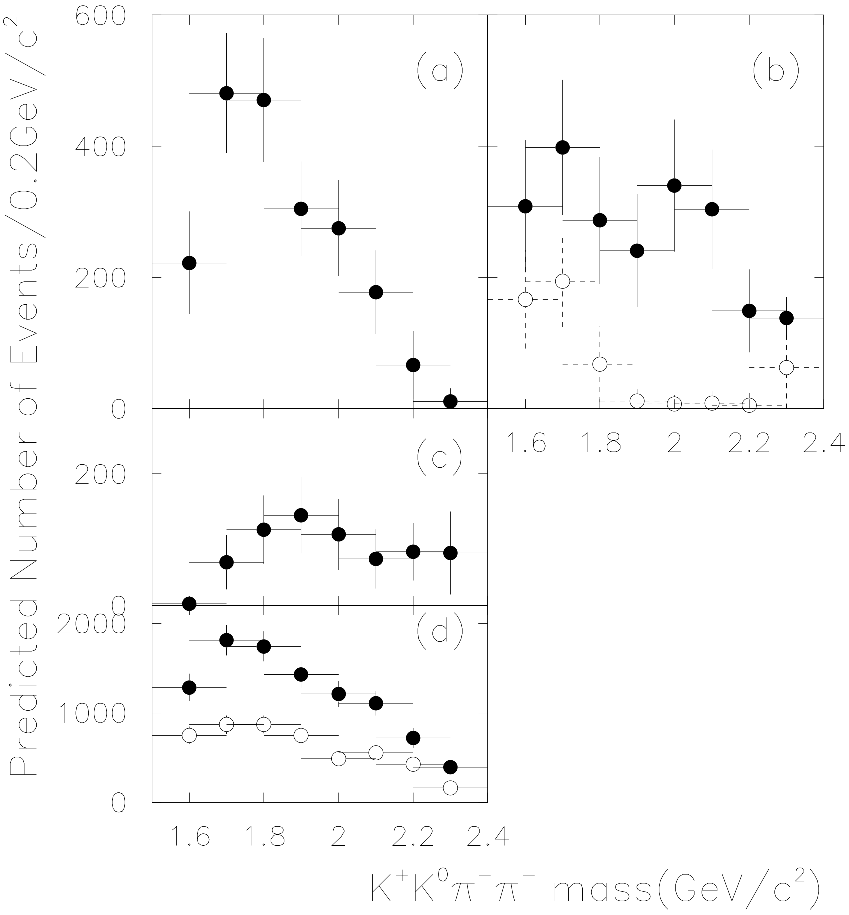

Figure 9: Partial waves as a function of $f_1(1285)\pi^-$ mass (BNL data). (a) $J^{PC}M^{\epsilon} = 1^{++}0^+$ wave. (b) $J^{PC}M^{\epsilon} = 1^{-+}1^+$ wave with combined $f_1(1285)\pi$ and $\eta(1295)\pi$ decay modes. The dotted spectrum shows $\eta(1295)$ wave only. (c) $J^{PC}M^{\epsilon} = 2^{++}1^+$. (d) All partial waves included in the fit. The open circles in the plot show the background.

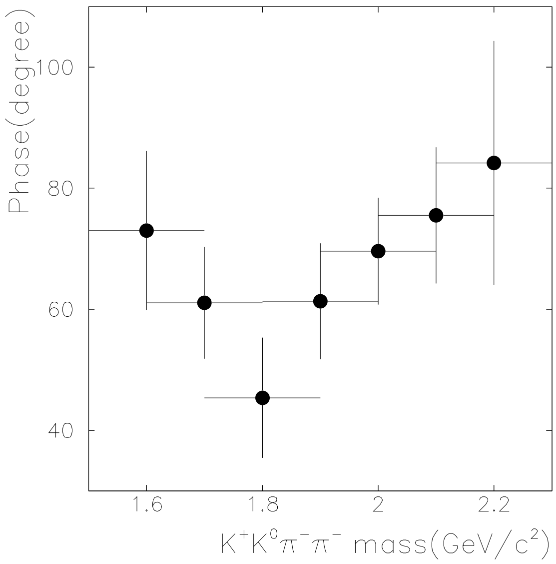

Figure 10: The relative phase of the $1^{-+}[f_1(1285)]1^+$ wave against the $1^{++}[f_1(1285)]0^+$ wave (BNL data).

presence of two structures must await further analysis based on much larger statistics.

It should be pointed out that new results on exotic mesons should be forthcoming soon from a major endeavor now under way at BNL. The BNL experiment E852 at the BNL Multiparticle Spectrometer aims to carry out a systematic search with capabilities to detect both charged and neutral particles. The collaboration took data in spring 1994 and expects to take more data in spring 1995.

Experiments at LEAR have produced scalar and tensor glueball candidates, but so far they report no J^{PC}-exotic meson candidates. It is hoped that additional experiments at IHEP/Protvino, Fermilab and Beijing will produce complementary results on our continuing search for gluonic excitations of hadronic matter.

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REFERENCES

[1] Review of Particle Properties, Particle Data Group, Phys. Rev. **D50**, Part I (1994).

[2] D. Alde, *et al.*, Phys. Lett. **B205**, 397 (1988).

[3] Yu. D. Prokoshkin and S. A. Sadovsky, IHEP preprints 94-41 and 94-42, Protvino, 1994.

[4] G. M. Beladidze, *et al.*, Phys. Lett. **B313**, 276 (1993).

[5] F. Close and H. Lipkin, Phys. Lett. **B196**, 245 (1987); F. Iddir, et al., Phys. Lett. **B205**, 564 (1988).

[6] Yu. P. Gouz, et al., Proceedings of the XXVI International Conference on High Energy Physics, Volume I (1992), p. 572.

[7] H. Aoyagi, *et al.*, Phys. Lett. **B314**, 246 (1993).

[8] M. Boutemeur, 'Etude des résonances $\pi^0\eta$ produites dans les collisions $\pi^- p$ à 100 GeV' (Ph. D. Thesis), Université de Savoie, Annecy-le-Vieux, France.

[9] M. J. Corden, *et al.*, Nuclear Physics **B138**, 235 (1978).

[10] J. H. Lee, *et al.*, Phys. Lett. **B323**, 227 (1994).

[11] N. Isgur, R. Kokoski and J. Paton, Phys. Rev. Lett. **54**, 869 (1985); N. Isgur and J. Paton, Phys. Rev. **D31**, 2910 (1985); R. Kokoski and N. Isgur, Phys. Rev. **D35**, 907 (1987).

[12] S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189 (1985).