EXPERIMENTAL STATUS OF EXOTICS

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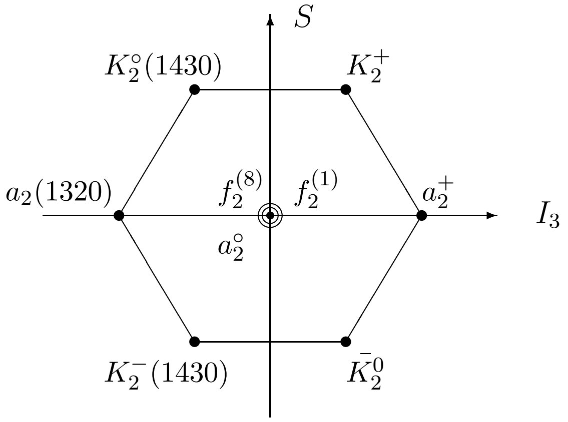
Abstract

A short introduction to exotic mesons is given and the experimental evidence for mesons with the non-$q\bar{q}$ quantum number combination $J^{PC} = 1^{-+}$ is scrutinized. From studies of annihilation reactions and of peripheral production, evidence for at least two 1^{-+} resonances is accumulating.

1. INTRODUCTION

CERN has a great tradition in meson spectroscopy. Much of today's knowledge is descended from the bubble chamber and LEAR eras. The constituent quark model is a very useful tool to systemize the experimental data. As a result, the $q\bar{q}$ nonets for q = u,d,s with given $J^{PC}(C = (-1)^{L+S})$ are mostly established up to $L = 3$ and many radial excitations are identified as well. As an example, Fig. 1 shows the $J^{PC} = 2^{++}$ nonet.



(1)/(8) mixing:
$f_2(1270) \approx n\bar{n}$
$f_2(1525) \approx s\bar{s}$

Fig. 1: The $J^{PC} = 2^{++}$ nonet.

Exotics can be grouped into a) $qg\bar{q}$, b) $gg(g)$ and c) $q\bar{q}q\bar{q}$:

a) hybrids
The excitation of the gluonic string that binds quark and antiquark in an ordinary meson is a natural degree of freedom. Our understanding of QCD and of confinement demands the existence of states formed by coupling string excitations to $q\bar{q}$. These may have non-$q\bar{q}$ quantum numbers, i.e. quantum numbers forbidden for $q\bar{q}$ by the generalized Pauli principle[1]. The lowest hybrid states expected by flux tube or lattice calculations [1] have $J^{PC} = 1^{-+}, 0^{-+}$, and 1^{--}, the first of which is a non-$q\bar{q}$ quantum number combination. For charged mesons C-parity must be replaced by G-parity and the non-$q\bar{q}$ combination is $J^{PG} = 1^{--}$ for isospin $I = 1$.

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[1] Allowed quantum number combinations of the $q\bar{q}$ system are $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, with $\vec{L}$ and $\vec{S}$ coupling to the total spin $\vec{J}$ of the meson.

b) glueballs

Gluon self-interaction is inherent to QCD. Building states from constituent gluons has been part of the QCD game since its introduction [2]. Although non-$q\bar{q}$ quantum numbers, e.g. 0^{--}, are to be expected in the glueball spectrum, the lowest lying states come in the order 0^{++}, $2^{++}, 0^{-+}$ in lattice and other calculations [1]. Thus supernumerary states intrude into the $q\bar{q}$ scheme. Indeed, some $q\bar{q}$ nonets appear to be overpopulated [3]. Configuration mixing will take place and this sets the difficult task to decifer the gluonic nonet from characteristic decay branchings or production strengths [4].

c) quartets and molecules

By flavour coupling a large number of $q\bar{q}q\bar{q}$ multiplets can be created, but it is expected [5, 6] that these are not bound except for the $(q\bar{q})$x$(q\bar{q})$ S-wave. It is tempting to identify the narrow f_0 and a_0 states near the $K\bar{K}$ threshold, close to 1 GeV, with such configurations. A unique signature of quartet states would be flavour exotics. The only recent claim is an isospin 2 resonance in the $\pi^+\pi^+$ and $\rho^0\rho^0$ S-waves produced in the annihilation process $\bar{n}p \to \pi^+\pi^+\pi^-$ and $\rho^0\rho^0\pi^+$ [7].

The present text provides a review of the recent experimental results on resonances with the exotic quantum numbers $J^{PC} = 1^{-+}$ which are of prime importance for the initial stage of the COMPASS hadron program. For a more extensive review on ordinary and exotic mesons, and on glueballs in particular, excellent recent articles [4, 6, 8] are recommended.

2. ANNIHILATION AT REST

The $\eta\pi$ system is attractive for the exotics search since its P-wave must carry non-$q\bar{q}$ quantum numbers $J^{PC} = 1^{-+}$ $(G = -)$. It cannot form a glueball, however, because of its isospin 1. Resonances with these quantum numbers are designated here as $\hat{\rho}$, although π_1 appears to become prevailing [3].

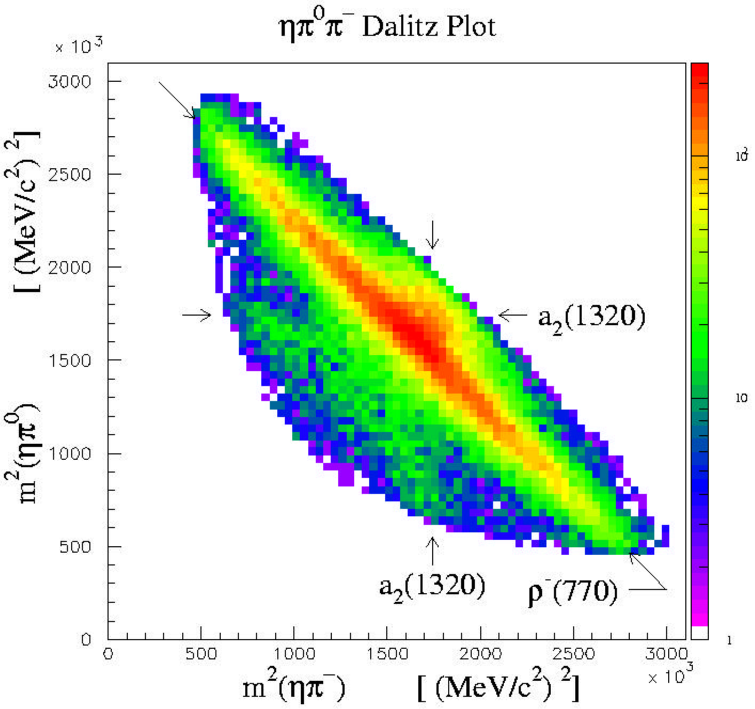
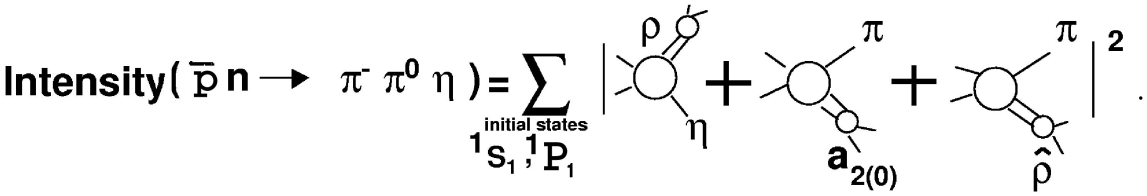


Fig. 2: Experimental intensity distribution (binned and acceptance corrected).

The reaction $\bar{p}n \rightarrow \eta\pi^-\pi^0$, with antiprotons from the LEAR facility stopped in a liquid deuterium target, was studied [9] with the Crystal Barrel detector which was equipped for charged particle and photon spectroscopy with close-to-4π geometry. A sample of 5×10^4 events of the type $\bar{p}d \rightarrow \pi^-\pi^0(\gamma\gamma)\eta(\gamma\gamma)p$ with a proton spectator momentum $< 100\ \mathrm{MeV}/c$ was fully reconstructed and kinematically selected. The momentum cut was chosen to guarantee the spectator role of the proton, i.e. the negligibility of final-state interactions with the produced mesons. The experimental intensity distribution is displayed as a Dalitz plot in Fig. 2. A simple pattern is observed which is dominated by a diagonal $\rho^-(770)$ band and two broad orthogonal bands in the region of the $a_2(1320)$. The latter show large modulations indicative of interference between odd- and even-L $\eta\pi$ waves.

The partial-wave analysis assumes intermediate states of $\pi^-\pi^0$ resonances with a recoiling η or $\eta\pi$ resonances with a recoiling π:



All allowed (see above) known or candidate resonances with nominal mass inside or close to the phase space boundary were tried. The isobar transition amplitude is expressed by use of the Zemach formalism (see Ref. [9] and references given there). A simple model space containing only the $\rho^-(770)\eta$, $a_2(1320)\pi$ and $(\eta\pi)_{P-wave}\pi$ intermediate states is sufficient for a good fit ($\chi^2/N_{dof} = 506/391$). The contribution of the exotic $\eta\pi$ resonance amounts to 11% (without the interferences with the other two resonances), which is almost as much as the a_2 contribution. Without the $\eta\pi$ P-wave no satisfactory fits are obtained and the χ^2 distribution gives evidence for missing interference structure (Fig. 3). Inclusion of the $\eta\pi$ P-wave yields a flat χ^2 distribution with only statistical fluctuations [9].

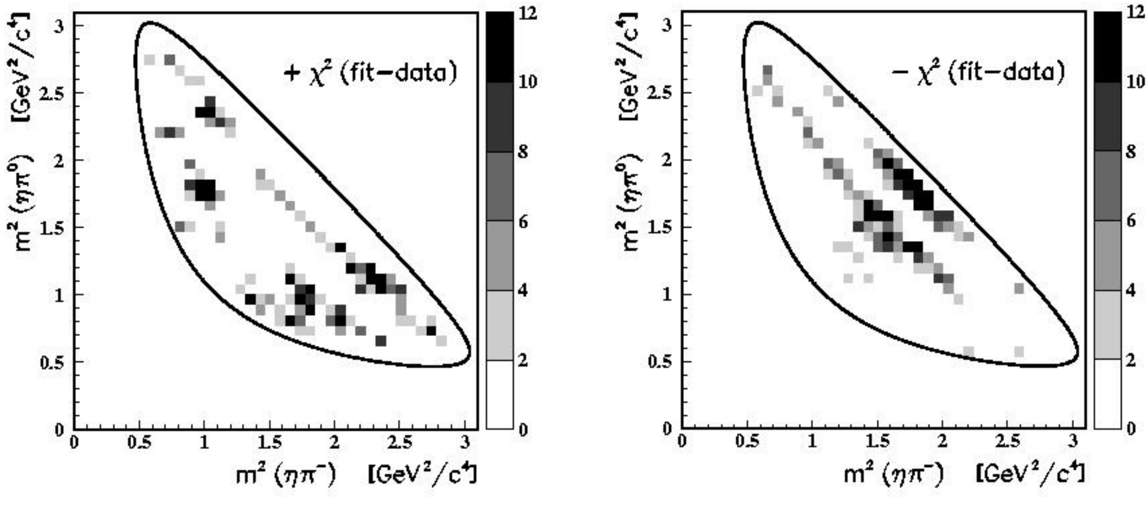


Fig. 3: Deviations between the data and a fit that does not include the $\eta\pi$ P-wave but all other allowed resonances. Left panel: fit exceeds data, right panel: the reverse.

The interference of the $\eta\pi$ P-wave with both the ρ^- and the a_2 resonances pins down the resonance characteristics. The relative phase of the latter two resonances is fixed by their crossing in the Dalitz plot. Both probe the $\eta\pi$ phase motion in different regions. Constructive and destructive interference on opposite sides of the ρ^- band centre is visible in Fig. 4 which shows the intensity distribution of the exotic

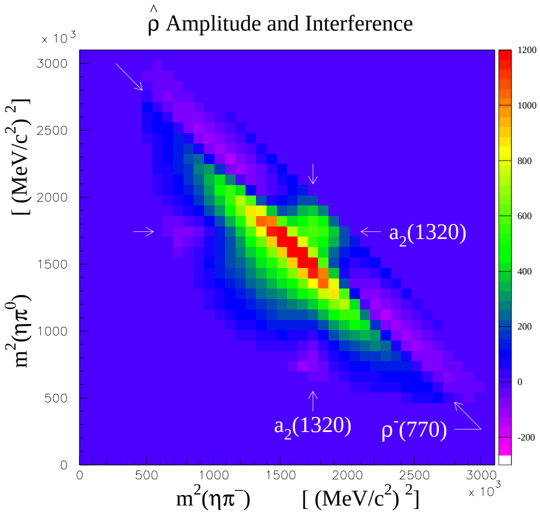


Fig. 4: Intensity distribution of the $\eta\pi$P-wave, as obtained by subtracting from the experimental intensity the ρ^- and a_2 contributions according to the partial-wave analysis.

resonance including the interferences. Moving along a parallel just below the position of the ρ^- band, one observes the rise and fall of the constructive term, which reflects the almost complete phase rotation of the $\eta\pi$ resonance. Close to the phase space boundaries, one finds at $m^2(\eta\pi)$ =(1.7–1.8) GeV^2/c^4 the interference maximum and minimum arising from the overlap with the a_2.

The fitted parameters of the exotic resonance are

$$M = (1400 \pm 20_{stat} \pm 20_{syst})\ \mathrm{MeV}/c^2, \qquad \Gamma = (310 \pm 50_{stat} + 50/-30_{syst})\ \mathrm{MeV}/c^2.$$

These values are not inconsistent with the results for pion-induced reactions (see below). In those cases the relative contribution from the $\eta\pi$ wave is smaller and the evidence is based only on interferences with the a_2.

As an alternative model of the $\eta\pi$ P-wave, an effective range amplitude is found to yield convergent or divergent fits in the range of scattering parameters that characterize resonant or non-resonant behaviour, respectively. The resonant solution is practically identical to the Breit–Wigner fit amplitude.

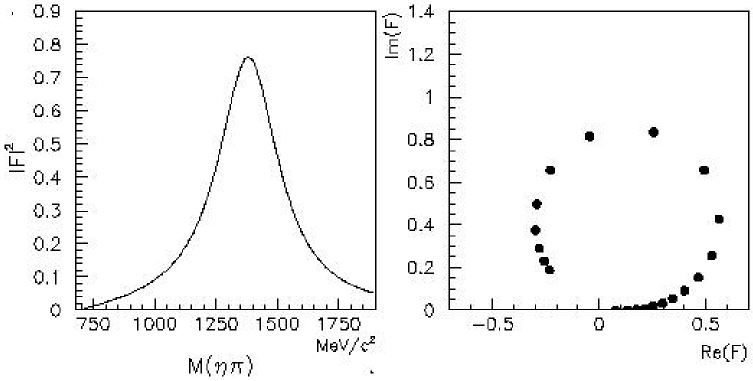


Fig. 5: Left: $(\eta\pi)_P$ effective range amplitude (squared absolute value) fitted to the data. Right: Corresponding Argand plot, showing the imaginary versus the real part of the effective range amplitude. The range from M = 690 to 1800 MeV/c^2 is divided into equal Δm steps. An almost complete anti-clockwise phase rotation is observed.

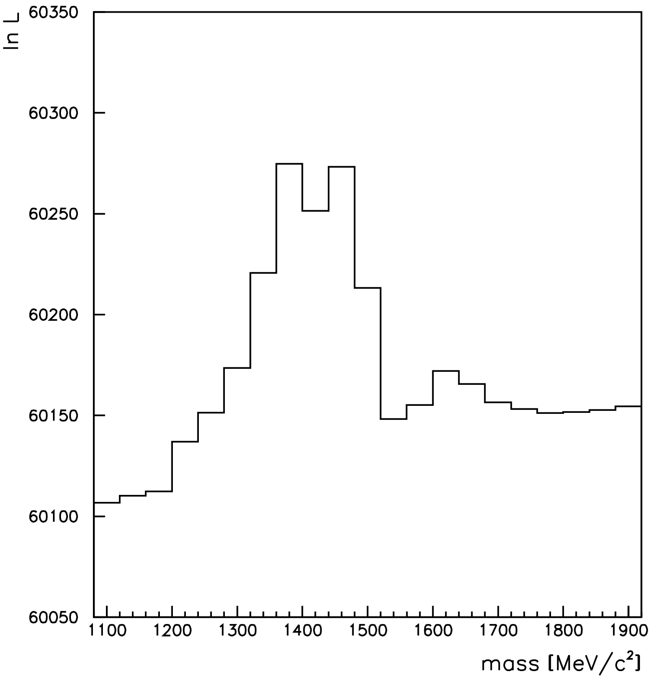


Fig. 6: Mass scan of the ln *Likelihood* for a $(\rho\pi)$ resonance with $J^{PC} = 1^{-+}$ in $\bar{p}n$ (at rest) $\rightarrow$ $(\rho\pi)\pi$.

Its phase motion shows the typical resonance behaviour in an Argand diagram (Fig. 5). It is evident from this representation that the complete phase motion is probed in the present Dalitz plot.

The results of exotics hunting in other annihilation channels may be summarized as follows:

- $\mathbf{\bar{p}p \rightarrow \hat{\rho}(\rightarrow \eta\pi^0)\pi^0}$
  Supportive evidence for the $\hat{\rho}(1400)$ was obtained, with resonance parameters as above, but the observed rate was much smaller than for $\bar{p}n$ annihilation [10]. The difference in the relative rates points to an interesting angular momentum selectivity. For the incoming S-wave the $\hat{\rho}\pi$ channel is accessible only from the singlet spin configuration of $\bar{p}p$ and the triplet configuration of $\bar{p}n$.
- $\mathbf{\bar{p}p \rightarrow \hat{\rho}(\rightarrow \eta'\pi^0)\pi^0}$
  The $\hat{\rho}(1400)$ is not seen but evidence (Δ ln *Likelihood* = 20) is obtained for $\hat{\rho}(1600)$ [11].
- $\mathbf{\bar{p}n \rightarrow \hat{\rho}(K^*K)\pi}$
  No evidence for the $\hat{\rho}(1400)$ is found [12], which disfavours a $\mathrm{K}^*\mathrm{K}$ molecular picture [13] for this resonance.
- $\mathbf{\bar{p}n \rightarrow \hat{\rho}(\rightarrow \rho\pi)\pi}$
  A high-statistics study [14] of this 4π final state yields evidence for complex 1^{-+} resonance structure in the m =1400–1700 MeV/c^2 region (Fig. 6), including the above $\hat{\rho}(1400)$. The full partial-wave analysis also yields evidence for the hybrid candidate $\pi(1800)$, with ordinary $\bar{q}q$ quantum numbers 0^{+-}, decaying mainly to $\sigma(\rightarrow \pi^0\pi^0)\pi$.

3. DIFFRACTIVE PROCESSES

The $\eta\pi$ spectrum from π-induced peripheral processes (Fig. 7) is dominated by the $a(1320)$ which is produced mainly by ρ exchange. An additional 1^{-+} resonance becomes visible by its interference with the a_2. After the early claim of the GAMS Collaboration [15] the clearest evidence came from a study of 18 GeV/c $\pi^-p \rightarrow \eta\pi^-p$ at BNL [16]. The analyses differ in the quantum numbers of the exchange

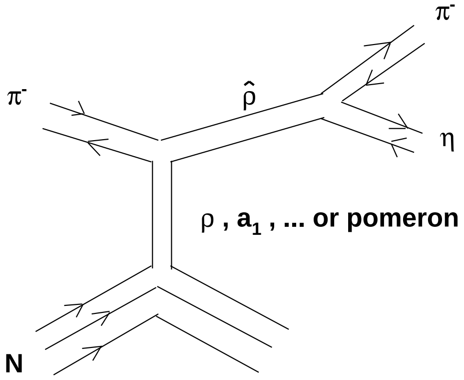


Fig. 7: Quark line diagram of exotics production in a peripheral process.

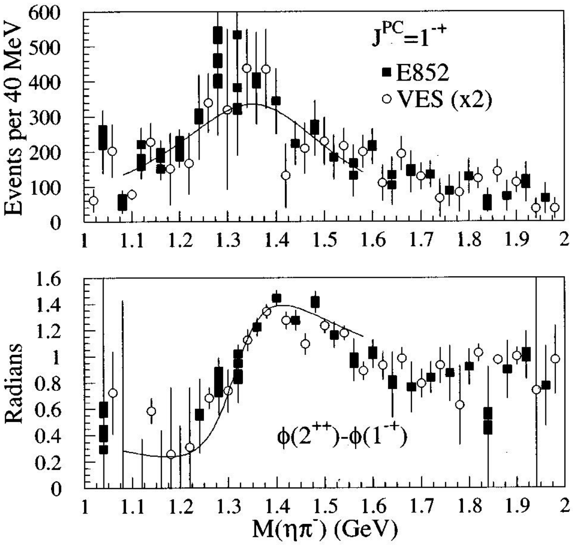


Fig. 8: The exotic 1^{-+} signal as extracted from $\pi^- p \rightarrow \eta\pi^- p$ data at $p(\pi^-) = 18$ GeV/c from BNL [16] and from $\pi^- N \rightarrow \eta\pi^-$X data at 37 GeV/$c$ from VES [17]. The solid line shows the resonance fit of BNL.

particle which were claimed to be unnatural (a_1-like) in one case [15] and natural (ρ- or pomeron-like) in the other [16]. The 1^{-+} intensity and the phase motion with respect to the a_2 as extracted by the BNL group is in good agreement with corresponding results from VES [17] (Fig. 8). However, recent work from VES which uses better statistics and a new analysis technique shows that a non-resonant $\eta\pi$ P-wave may account equally well for the data [18].

While peripheral production of $\hat{\rho}(1400)$ has only been seen in $\eta\pi$, the evidence for $\hat{\rho}(1600)$ comes from three channels: $b_1\pi, \eta'\pi$ and $\rho\pi$. Consistent resonance parameters, $m = 1600$ and $\Gamma \approx 300\ \mathrm{MeV}/c^2$, were reported by VES [19] and BNL [20]. The $\hat{\rho}$ branchings of the observed three decay channels are of similar strength. However, as in the case discussed above, in the more recent work from VES [18] the resonant solution appears to be not unique in their new partial-wave analysis of $\eta'\pi$ and $\rho\pi$. It is possible to tune different non-resonant background amplitudes in the alternative analysis to mimic the phase motion of an exotic resonance with respect to the dominant a_2 and π_2 resonances, respectively, in these two channels. However, in the case of $b_1\pi$, the exotic $\hat{\rho}(1600)$ was resistent against any such conspiracy of background amplitudes [18].

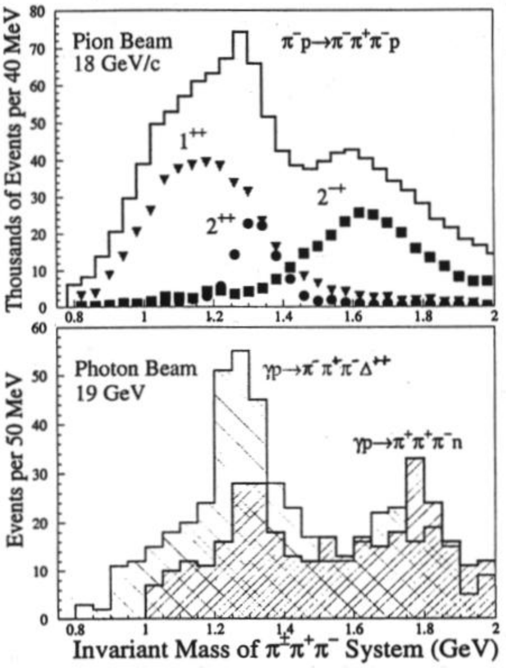


Fig. 9: Comparison of the 3π invariant mass spectra from π^- and γ-induced peripheral photoproduction [21].

Photoproduction can be regarded as a special peripheral production process where the photon interacts like a vector meson. Selective production of hadrons with aligned q and $\bar{q}$ spins, as in the 1^{-+} hybrid model configuration, is expected because of the spin triplet $q\bar{q}$ configuration of a vector meson. Indeed a comparison of the 3π invariant mass spectra (which are mainly $\rho\pi$ spectra) from π and γ-induced production (Fig. 9) shows a dramatic difference in the selectivity. In the former case, the exotic resonance hides, as a 5% contribution, below a dominant $2^{-+}(\pi_2)$ peak. In the latter case [22] π_2 production is not observed. Above the $a_2(1320)$ broad structure appears, peaking at 1.8 GeV/c^2, with most probably $J^P = 1^-$ which would imply the exotic quantum number combination in this case, since $\pi^+\pi^-\pi^-$ couple to isospin 1 and G-parity -1, see Ref. [22]. Because of limited statistics, no full partial-wave analysis is possible for these data, and any other photoproduction data collected so far. The Hall D project at Jefferson Lab will change this situation [21].

At present one can only speculate whether the resonance at 1.8 GeV/c^2, indicated in the lower part of Fig. 9, will turn out to be the third exotic. Possibly the same resonance was seen in the $b_1\pi$ system in a photoproduction experiment at CERN [23]. In π-induced reactions a corresponding peak was found in the $f_1\pi$ spectrum [24] and, with less significance, in the $\rho\pi$ spectrum [20].

4. CONCLUSION

There is hard evidence for exotic resonances with exotic $J^{PC} = 1^{-+}$ at 1400 and 1600 MeV/c^2. The lower one was observed in $\eta\pi$ and probably in $\rho\pi$ but not in $\eta'\pi$, $b_1\pi$ and $f_1\pi$, the upper one in $b_1\pi$ and probably in $\eta'\pi$ and $\rho\pi$ but not in $\eta\pi$. The strongest case for the lower one is $\bar{p}n$ annihilation into $(\eta\pi)_{1^{-+}}\pi$, and for the upper one peripheral production of $(b_1\pi)_{1^{-+}}$. There are indications of a third 1^{-+} resonance, decaying into $b_1\pi, f_1\pi$ and $\rho\pi$, at 1800–1900 MeV/c^2 in peripheral production induced by pions or photons. One expects a $qg\bar{q}$ hybrid configuration to branch preferably into $b_1\pi$ and $f_1\pi$ and not into $\eta\pi$, and $q\bar{q}q\bar{q}$ flavour decouplet or octet configurations to branch preferably into $\eta\pi$ or $\eta'\pi$, respectively [25–27]. These expectations suggest a labelling of the above three resonances. However, configuration mixing of exotica is to be expected. Exotica with different isospin and flavour, demanded by the hybrid and quartet schemes, still await experimental discovery.

References

[1] S. Godfrey, these proceedings.

[2] H. Fritzsch and P. Minkowski, Nuovo Cim. **30A** (1975) 393.

[3] Particle Data Group, Eur. Phys. J. C **15** (2000) 1.

[4] S. Godfrey and J. Napolitano, Rev. Mod. Phys. **71** (1999) 1311.

[5] J. Weinstein and N. Isgur, Phys. Rev. Lett. **48** (1982) 659.

[6] F.E. Close and N.A. Törnqvist, J. Phys. G **28** (2002) R249.

[7] A. Filippi, Proc. 9th Int. Conf. on Hadron Spectroscopy, AIP Vol. 619 (2002) 582.

[8] E. Klempt, Proc. Meson 2000, Acta Phys. Polon. **B31** (2000) 2587.

[9] A. Abele *et al.*, Phys. Lett. B **423** (1998) 175.

[10] A. Abele *et al.*, Phys. Lett. B **446** (1999) 349.

[11] J. Reinnarth, Proc. 9th Int. Conf. on Hadron Spectroscopy, AIP Vol. 619 (2002) 792.

[12] F. Meyer-Wildhagen, Diploma thesis (Universität München 1999).

[13] M.S. Chanowitz, Phys. Lett. B **187** (1987) 409.

[14] F. Meyer-Wildhagen, Proc. PANIC 2002 (in press).

[15] D. Alde *et al.*, Phys. Lett. B **205** (1988) 397.

[16] D.R. Thompson *et al.*, Phys. Rev. Lett. **79** (1997) 1630.

[17] G.M. Beladidze *et al.*, Phys. Lett. B **313** (1993) 276.

[18] V. Dorofeev, Proc. 9th Int. Conf. on Hadron Spectroscopy, AIP Vol. 619 (2002) 143.

[19] Yu. Khokhlov, Nucl. Phys. A **663** (2000) 596c.

[20] A.V. Popov, Proc. 9th Int. Conf. on Hadron Spectroscopy, AIP Vol. 619 (2002) 135.

[21] C.A. Meyer, Proc. 9th Int. Conf. on Hadron Spectroscopy, AIP Vol. 619 (2002) 408.

[22] G.T. Condo *et al.*, Phys. Rev. D **43** (1991) 2787.

[23] M. Atkinson *et al.*, Z. Physik C **34** (1987) 157.

[24] J.H. Lee *et al.*, Phys. Lett. B **323** (1994) 227.

[25] S.U. Chung, E. Klempt and J. Körner, preprint BNL-QGS-01-0501 (2002).

[26] F.E. Close and H.J. Lipkin, Phys. Lett. B **196** (1987) 245.

[27] P.R. Page, Phys. Lett. B **415** (1997) 205.