Some indication for a missing chiral partner η_4 around 2 GeV

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(Received 5 May 2010; revised manuscript received 15 July 2010; published 9 August 2010)

The high-lying mesons in the light quark sector previously obtained from the partial wave analysis of the proton-antiproton annihilation in flight at 1.9–2.4 GeV region at CERN reveal a very high degree of degeneracy. This degeneracy can be explained as due to an effective restoration of both $SU(2)_L \times SU(2)_R$ and $U(1)_A$ symmetries combined with a principal quantum number $\sim n + J$. In this case there must be chiral partners for the highest spin states in the 2 and 2.3 GeV bands presently missing in the data. Here we reanalyze the Crystal Barrel data and show an indication for existence of the missing 4^{-+} state around 2 GeV. This result calls for further experimental search of the missing states both in the proton-antiproton annihilation and in the production reactions.

DOI: 10.1103/PhysRevD.82.037501 PACS numbers: 14.40.Be, 11.30.Rd

I. INTRODUCTION

Until 10 years ago, little was known about mesons in the light quark sector with masses in the region of 2 GeV. A development in the field was promoted by a publication of four papers [1–4] that contained results of a partial wave analysis of the proton-antiproton annihilation into mesons at LEAR (CERN) in the energy range 1.9–2.4 GeV with four different sets of quantum numbers. A lot of new mesons have been discovered. This is not accidental because the proton-antiproton annihilation into mesons is a formation experiment and consequently it allows for a systematic exploration of the whole kinematical region. This is in contrast with the production experiments, where one typically looks for a meson resonance in correlations of some secondary particles in high-energy reactions. In the latter case it is difficult to explore systematically a large kinematical region and a search was typically guided by predictions of theoretical models, such as the linear Regge trajectories model [5], or by the Goddfrey-Isgur constituent quark model for mesons [6]. There is no other systematic experiment in the same kinematical region so all these new resonances await for their confirmation before they penetrate into a meson summary table of the Particle Data Group (they are listed as "other light mesons") [7]. Nevertheless, some of these new mesons are regarded by the authors as very reliable, because they are seen at least in a few independent decay channels in data with polarization, while the others are less reliable [8]. A striking feature of these data is that they reveal a high degree of degeneracy, namely, states with different spins, parities, and isospins "perfectly group into two clusters around the masses of $\simeq 2$ GeV and of $\simeq 2.2$–2.3 GeV" [9], see also figures in Refs. [10–12] and Fig. 1 below. Such a degeneracy indicates a symmetry. Understanding a source of this symmetry would clarify a fundamental question of mass generation in QCD, an interconnection of confinement and chiral symmetry breaking and physics responsible for the angular momentum generation.

There are two different scenarios. The first one is based on the conjecture of effective chiral restoration in highly excited hadrons [11,13–15], which was promoted earlier given data for established highly excited baryons. The new high-lying mesons have been analyzed in Refs. [16,17] and the analysis has revealed that the data is well consistent with the conjecture of effective restoration of both $SU(2)_L \times SU(2)_R$ and $U(1)_A$ symmetries. It is well seen from Fig. 1, however, that the chiral partners are missing for the highest spin states at 2 GeV and 2.3 GeV bands. Consequently, a prediction was made that the missing states should in reality exist and the pattern for the $J = 4$ mesons at 2 GeV should be similar to the pattern of $J = 2$ mesons, while the pattern of $J = 5$ states at 2.3 GeV should be the same as the pattern of $J = 3$ mesons. The chiral $SU(2)_L \times SU(2)_R$ and $U(1)_A$ symmetries cannot explain a degeneracy of mesons with different spins. Such a degeneracy can be obtained if one assumes a principal quantum

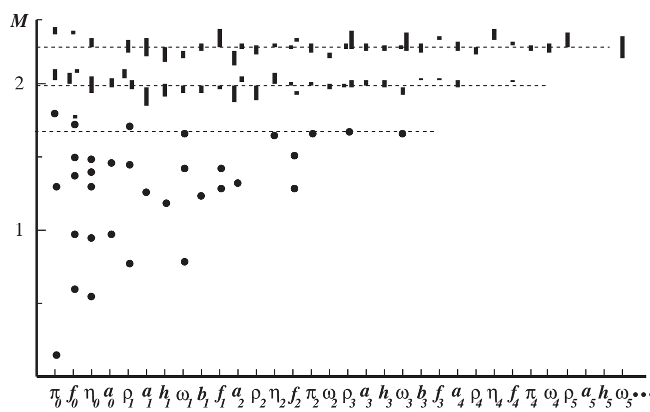

FIG. 1. Masses (in GeV) of the well-established states from PDG (circles) and new $\bar{n}n$ states from the proton-antiproton annihilation at LEAR (strips).

number $\sim n + J$ on top of $SU(2)_L \times SU(2)_R$ and $U(1)_A$ restorations [18].

The alternative possibility would be to explain the large degeneracy as due to a principal quantum number $\sim n + L$, if a classification of states and assignments of their angular momenta quantum numbers are done according to standard nonrelativistic two-body quantum mechanical problem with the LS coupling scheme [12,19,20]. In this case, every state is characterized by a set of three independent conserved angular momenta $^{2S+1}L_J$ [1–4,8]. It is easy to see that there must not be any parity partners for the highest spin states in every band within this scenario. Such a degeneracy with the principal quantum number $\sim n + L$ exists in the nonrelativistic Hydrogen atom if one neglects a small spin-orbit force. The degeneracy is due to a very specific "accidental" symmetry of the *Coulomb* $\sim 1/r$ interaction in a two-body system. It is hard, however, to imagine that the high-lying states are driven by a simple Coulomb part of the one-gluon exchange between the constituent quarks. In addition, the Coulomb problem does not exhibit any Regge-like behavior both for the angular and radial trajectories.

The Nambu-Goto bosonic string type picture implies that the ends of the string are moving at the speed of light. If one identifies the ends of the string with the valence quarks, then the valence quarks must be ultrarelativistic and consequently must have a definite chirality. Chiral symmetry is not broken. Consequently, all states must appear in chiral multiplets [11].

A presence or absence of the chiral partners for the highest spin states is a key feature that distinguishes both scenarios. Consequently, any reliable experimental information on this issue would be of fundamental importance. At the moment, such states are not present in the analysis of data [1–4,8]. In the present paper, we reanalyze the LEAR data and suggest some evidence for existence of the missing η_4 state around 2 GeV.

II. ANALYSIS OF THE PROTON-ANTIPROTON ANNIHILATION IN FLIGHT

The 4^{-+} states do not decay into two-pseudoscalar meson channels or into channels with a neutral pseudoscalar meson and omega. Therefore, these states should be identified from the reactions with at last three pseudoscalar mesons in final states. Up to now there are no observations of any 4^{-+} states from analyses of πN collision reactions at large energies of incident pion. The reason can be that these states are produced only at large energy transferred where statistics is rather low and partial wave analysis is a rather complicated procedure. The analysis of the proton-antiproton annihilation in flight into $\pi^0\pi^0\eta$ channel [1] observed a 4^{-+} isosinglet state in the region 2.3 GeV but did not reveal any 4^{-+} state with mass around 2 GeV.

If effective $SU(2)_L \times SU(2)_R$ and $U(1)_A$ trestorations are correct, then there must be four approximately degenerate mesons f_4, a_4, η_4, π_4 that are members of the $(1/2, 1/2)_a + (1/2, 1/2)_b$ representation [11,17]. Let us shortly discuss properties of the $f_4(2050)$ resonance. The $f_4(2050)$ was observed very clearly in the $\pi N \to \pi\pi N$ reaction (GAMS [21], BNL [22]), in $\pi N \to \eta\eta n$ (GAMS [23]) in $\pi N \to \omega\omega n$ (VES [24]), in proton-antiproton annihilation in flight into two pseudoscalar mesons [25], and in a set of reactions with three or more mesons in final state (see [7]). The mass of this state is located between 1950–2020 MeV and the two pion branching is $17 \pm 1.5\%$. This resonance practically does not decay into the final $4\pi^0$ state and therefore about 80% of the width should be defined by the decay into $2\pi\eta$ and charged modes. This resonance contributes about 10% to the total cross section of the proton-antiproton annihilation into the $\pi^0\pi^0\eta$ final state integrated over mass region 1950–2300 MeV [1] and decays dominantly into the $a_2(1320)\pi$ final state.

The 4^{++} state can be produced in the proton-antiproton annihilation either in $^3F_4$ or $^3H_4$ partial waves. The 4^{-+} state can be produced only from $^1G_4$ partial wave, and therefore it should be suppressed by the $\bar{p}p$ centrifugal barrier in comparison to the $^3F_4$ amplitude. The kinematical suppression factor is proportional to the relative momentum of the initial particles squared calculated in a center-of-mass system of the reaction which at energy 2 GeV is equal to 0.12 GeV^2. The analysis of the proton-antiproton annihilation in flight showed that the resonance production vertices are described better with the Blatt-Weiskopf form factor. In this case, the production vertex has a centrifugal factor:

$$cf_L = \frac{k^{2L}}{F(L, r^2, k^2)} \tag{1}$$

Here k is the relative momentum of antiproton calculated in a center-of-mass system of the reaction, L is the orbital momentum, and r is the effective resonance radius. For $L = 3$ and $L = 4$ the form factor has the following form:

$$\begin{aligned} F(3, r^2, k^2) &= \frac{225}{r^6} + \frac{45k^2}{r^4} + \frac{6k^4}{r^2} + k^6 \\ F(4, r^2, k^2) &= \frac{11\,025}{r^8} + \frac{1575k^2}{r^6} + \frac{135k^4}{r^4} + \frac{10k^6}{r^2} + k^8 \end{aligned} \tag{2}$$

At 2 GeV, the ratio of centrifugal factors cf_4/cf_3 is equal to ~ 0.06 for the resonance radius 0.8 fm and ~ 0.13 for the radius 1.2 fm. Because of this centrifugal suppression the η_4 resonance around 2 GeV cannot produce any peak in this region, even if it exists. Note that this suppression applies not only to the possible η_4, but also to all other missing states around 2 GeV, ρ_4, π_4, ω_4, because they are produced in the $L = 4$ partial wave. Similar suppression exists for the missing $J = 5$ states in the 2.3 GeV band.

However, the cf_4 factor increases much faster with energy than cf_3, and at 2.3 GeV this ratio is equal to

0.25 for the radius 0.8 fm and 0.60 for the radius 1.2 fm. Thus, if the production couplings of the 4^{-+} and 4^{++} states with mass around 2 GeV are equal to each other as well as branching ratios to the final channel, the 4^{-+} state should contribute between 6%–13% from its 4^{++} partner at energies around 2 GeV and between 25%–60% at energies around 2.3 GeV.

III. FIT OF THE DATA

For the unpolarized proton-antiproton data the 4^{-+} amplitude does not interfere with either 2^{++} or 4^{++} amplitudes. However, a 4^{-+} state can interfere with 0^{-+} and 2^{-+} amplitudes which are dominant contributions to the $\bar{p}p \rightarrow \pi^0\pi^0\eta$ cross section in the mass region around 2 GeV. Therefore, one can hope that even a small contribution of the 4^{-+} partial wave can be identified from such interference. The solution reported in [1] and investigated in [26] found a rather small 4^{-+} partial wave which was described by the Breit-Wigner resonance with mass 2328 ± 38 MeV and width 240 ± 90 MeV. The contributions from the 4^{++} $f_4(2050)$ and 4^{-+} $\eta_4(2328)$ states to the $\bar{p}p \rightarrow 2\pi^0\eta$ cross section integrated over all decay modes are shown in Fig. 2. In this solution the 4^{-+} partial wave is suppressed by order of magnitude stronger below 2.2 GeV than what is expected from the centrifugal barrier factors, which is not very natural.

Now we want to see what will happen if we substitute the $\eta_4(2328)$ 4^{-+} resonance by a state with mass 1980 MeV and allow decays of this state into $f_2(1275)\eta$, $a_2(1320)\pi$, $a_0(980)\pi$, $\sigma\eta$, and $f_0(1500)\eta$ channels. The radius for the centrifugal factor was fixed to be 0.8, 1.0, 1.2, and 1.4 fm and width of the resonance was parametrized as a constant or as a dynamical width defined by the decay into the $a_0(980)\pi$ channel. The optimization procedure produced an acceptable likelihood value with $M = 1950$ MeV, $\Gamma = 380$ MeV, $r = 1.2$ fm for the parametrization with constant width and $M = 1980$ MeV, $\Gamma = 360$ MeV, $r = 1.2$ fm for the parametrization with $a_0(980)\pi$ width. The result hardly changed with $r =$ 1.4 fm. The contributions from the 4^{++} and 4^{-+} states to the $\bar{p}p \rightarrow 2\pi^0\eta$ cross section for the solution with constant width is shown in Fig. 3. It is evident from Fig. 3 that in this case there is no unnatural additional (beyond the centrifugal) suppression of the cross section below 2.2 GeV. We also introduced a more complicated parametrization of the numerator for the 4^{-+} state in the form $a + b\sqrt{s}$. However, the b parameter for such a weak signal only created a convergency problem and finally was fixed to be zero.

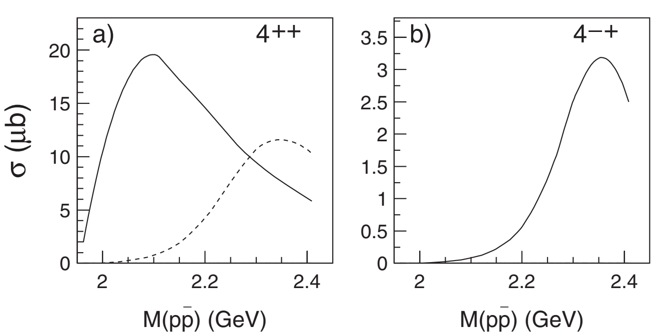

FIG. 2. Contribution of (a) the 4^{++} states and (b) the 4^{-+} $\eta_4(2328)$ state to the $\bar{p}p \rightarrow 2\pi^0\eta$ cross section for the best solution. In (a) the contribution from $f_4(2050)$ is given by solid line and the contribution from $f_4(2300)$ as dashed line.

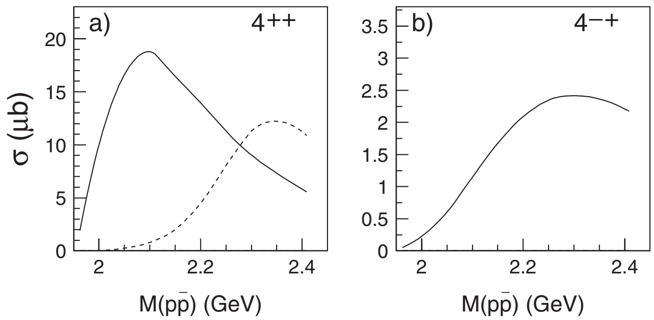

FIG. 3. Contribution of (a) the 4^{++} states and (b) the 4^{-+} state to the $\bar{p}p \rightarrow 2\pi^0\eta$ cross section for the solution with $\eta_4(1950)$. In (a) the contribution from $f_4(2050)$ is given by solid line and the contribution from $f_4(2300)$ as dashed line.

Although this result looks rather promising, one should take it with a caution. First, the total likelihood for this solution was found to be $-89\,406$, which is worse by 135 than that for the best solution, which is not a significant amount, however. Second, only the lowest set of data for antiproton beam at 600 MeV was described with a slightly better likelihood compared to the best solution. Let us mention that this lowest set has a mass gap of 86 MeV with the second data set while all other data sets have gaps about 50 MeV.

The mass scan of the 4^{-+} state for the two width parametrizations and $r = 1.2$ fm is shown in Fig. 4. It is

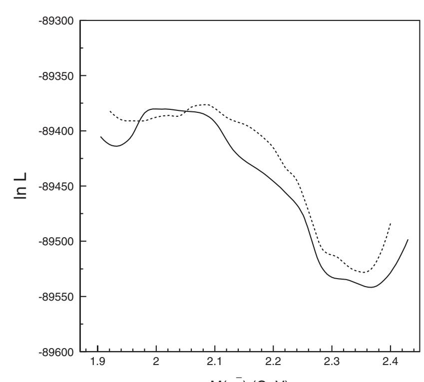

FIG. 4. The mass scan of the 4^{-+} state obtained by changing mass in steps and optimizing of all other parameters. The solid curve corresponds to the constant width parametrization and the dashed curve to the resonance width parametrized as $a_0(980)\pi$ channel.

seen that the distribution of the likelihood value (logarithm likelihood) has two minima in the mass region investigated. The minimum at the region 2330 MeV is rather well defined, while the minimum at 1950–1980 MeV is less pronounced. If a state at 1950 MeV is introduced as additional to $\eta_4(2328)$ the likelihood did not show any improvement due to a convergency problem. There is no surprise here since this partial wave provides too small contribution to allow us a complicated parametrization. However this result does not contradict to the assumption that both states around 1950 MeV and 2330 MeV are present.

Let us discuss shortly properties of the solution with $\eta_4(1950)$ (see Fig. 3). The 4^{-+} partial wave contribution at 2.3 GeV is about 30% from the $f_4(2050)$ state, which corresponds to suppression imposed by the centrifugal barrier with radius 0.8 fm. However, the situation is a more complicated here. The main decay mode of $\eta_4(1950)$ was found to be $a_0(980)\pi$, which is forbidden for 4^{++} states. This can explain a larger width of the 4^{-+} state; however, the product of $\bar{p}p$ and the $a_2(1320)\pi$ couplings [which is the dominant decay mode for $f_4(2050)$] was optimized to be about 5 times smaller than that for $f_4(2050)$.

To check whether the 4^{-+} state at 1950 MeV can be described with the similar couplings as $f_4(2050)$, we fixed the absolute values for the couplings into $\bar{p}p$, $f_2(1275)\eta$, and $a_2(1320)\pi$ channel to be equal to the lowest orbital momentum couplings of $f_4(2050)$. After optimization of other parameters, we found the solution, which was by 720 worse than the solution with free couplings. Systematical deviations were seen in description of angular distributions. Then we decreased the $f_2(1275)\eta$ and $a_2(1320)\pi$ couplings step by step and obtained a more or less acceptable solution with a factor 1.5 suppression for the $f_2(1275)\eta$ channel and 2 for the $a_2(1320)\pi$ channel.

IV. CONCLUSION

Although a 4^{-+} state at mass 2 GeV was not observed in the analysis of the proton-antiproton data in flight [1], there is a question whether such state could escape identification due to the centrifugal suppression in the production channel. Indeed, our mass scan suggests some indication for existence of the 4^{-+} state with mass about 1950–1980 MeV and width about 360–380 MeV.

This possible evidence for the missing η_4 meson around 2 GeV invites further detailed studies of this missing state. This state can be confirmed (or disproved) from analysis of new data on the proton-antiproton annihilation taken from the threshold with a small step of beam momentum. It would be important to measure not only neutral final states but also charged modes, in particular K^*K decay. Because of a suppression in the $\bar{p}p$ coupling, this state should also be searched in different production reactions, in particular, in the πN collision at large energies of the incident pion, and in central collision experiments. Another important question is to initiate a search of other missing high-spin states around 2 and 2.3 GeV bands, which are also a subject to the centrifugal suppression in $\bar{p}p$. Similarly, a lot of missing states should be found at the 1.7 GeV level.

ACKNOWLEDGMENTS

L. Ya. G. acknowledges support of the Austrian Science Fund through Grant No. P21970-N16.

[1] A. V. Anisovich *et al.*, Phys. Lett. B **491**, 47 (2000).
[2] A. V. Anisovich *et al.*, Phys. Lett. B **517**, 261 (2001).
[3] A. V. Anisovich *et al.*, Phys. Lett. B **542**, 8 (2002).
[4] A. V. Anisovich *et al.*, Phys. Lett. B **542**, 19 (2002).
[5] P. D. B. Collins, *An Introduction to Regge Theory and High Energy Physics* (Cambridge University Press, Cambridge, England, 1977).
[6] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985).
[7] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).
[8] D. V. Bugg, Phys. Rep. **397**, 257 (2004).
[9] L. Ya. Glozman, Phys. Lett. B **541**, 115 (2002).
[10] S. S. Afonin, Eur. Phys. J. A **29**, 327 (2006).
[11] L. Ya. Glozman, Phys. Rep. **444**, 1 (2007).
[12] E. Klempt and A. Zaitsev, Phys. Rep. **454**, 1 (2007).
[13] L. Ya. Glozman, Phys. Lett. B **475**, 329 (2000).
[14] T. Cohen and L. Ya. Glozman, Phys. Rev. D **65**, 016006 (2001); Int. J. Mod. Phys. A **17**, 1327 (2002).
[15] T. Cohen, Nucl. Phys. B, Proc. Suppl. **195**, 59 (2009).
[16] L. Ya. Glozman, Phys. Lett. B **539**, 257 (2002).
[17] L. Ya. Glozman, Phys. Lett. B **587**, 69 (2004).
[18] L. Ya. Glozman and A. V. Nefediev, Phys. Rev. D **76**, 096004 (2007).
[19] S. S. Afonin, Phys. Rev. C **76**, 015202 (2007).
[20] M. Shifman and A. Vainshtein, Phys. Rev. D **77**, 034002 (2008).
[21] D. Alde *et al.* (GAMS Collaboration), Eur. Phys. J. A **3**, 361 (1998).
[22] V. V. Anisovich and A. V. Sarantsev, Int. J. Mod. Phys. A **24**, 2481 (2009).
[23] F. G. Binon *et al.*, Yad. Fiz. **68**, 998 (2005) [Phys. At. Nucl. **68**, 960 (2005)].
[24] D. V. Amelin *et al.*, Yad. Fiz. **69**, 715 (2006) [Phys. At. Nucl. **69**, 690 (2006)].
[25] A. V. Anisovich *et al.*, Nucl. Phys. **A662**, 344 (2000).
[26] D. V. Bugg, Phys. Lett. B **680**, 297 (2009).