Observation of tensor glueball in the reactions
\[ p\bar{p} \rightarrow \pi\pi, \eta\eta, \eta\eta' \]

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Abstract

Partial wave analysis of the reactions \( p\bar{p} \rightarrow \pi\pi, \eta\eta, \eta\eta' \) in the region of invariant masses 1900–2400 MeV indicates to the existence of four relatively narrow tensor-isoscalar resonances \( f_2(1920), f_2(2020), f_2(2240), f_2(2300) \) and the broad state \( f_2(2000) \). The determined decay couplings of the broad resonance \( f_2(2000) \rightarrow \pi^0\pi^0, \eta\eta, \eta\eta' \) satisfy the relations appropriate to those of tensor glueball, while the couplings of other tensor states do not, thus verifying the glueball nature of \( f_2(2000) \).

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In [1], the combined partial wave analysis was performed for the high statistics data on the reactions \( p\bar{p} \rightarrow \pi^0\pi^0, \eta\eta, \eta\eta' \) taken at antiproton momenta 600, 900, 1150, 1200, 1350, 1525, 1640, 1800 and 1940 MeV/c together with data obtained for polarised target in the reaction \( \bar{p}p \rightarrow \pi^+\pi^- \) that resulted in the determination of a number of isoscalar resonances \( f_J \) with \( J = 0, 2, 4 \) (for the review see [3, 4, 5]). In the 02\(^++\)-sector, five states are required to describe the data [1, 3]:

| Resonance | Mass(MeV) | Width(MeV) |
|-----------|-----------|------------|
| \( f_2(1920) \) | 1920 ± 30 | 230 ± 40 |
| \( f_2(2000) \) | 2010 ± 30 | 495 ± 35 |
| \( f_2(2020) \) | 2020 ± 30 | 275 ± 35 |
| \( f_2(2240) \) | 2240 ± 40 | 245 ± 45 |
| \( f_2(2300) \) | 2300 ± 35 | 290 ± 50 |

The resonance \( f_2(1920) \) was observed earlier in spectra \( \omega\omega \) [6, 7, 8] and \( \eta\eta' \) [9, 10], see also compilation [11]. For the broad tensor-isoscalar resonance in the region around 2000 MeV the recent analyses give: \( M = 1980 \pm 20 \) MeV, \( \Gamma = 520 \pm 50 \) MeV in \( pp \rightarrow pp\pi\pi\pi\pi \) [12] and \( M = 2050 \pm 30 \) MeV, \( \Gamma = 570 \pm 70 \) MeV in \( \pi^-p \rightarrow \phi\phi n \) [13]. Following [1, 12, 13], we denote the broad resonance as \( f_2(2000) \).
The description of data in the reactions $p\bar{p} \to \pi^0\pi^0, \eta\eta, \eta\eta'$ is illustrated by Fig. 1. In Fig. 2, 3, one can see differential cross sections $p\bar{p} \to \pi^+\pi^-$, while Fig. 4 presents the polarisation data. In Fig. 5, we show cross sections for $p\bar{p} \to \pi^0\pi^0, \eta\eta, \eta\eta'$ in the $^3P_2\bar{p}p$ and $^3F_2\bar{p}p$ waves (dashed and dotted curves) and total ($J = 2$) cross section (solid curve) as well as the Argand-plots for the $^3P_2$ and $^3F_2$ wave amplitudes at invariant masses $M = 1.962, 2.050, 2.100, 2.150, 2.200, 2.260, 2.304, 2.360, 2.410$ GeV.

Partial wave analysis [11, 13] together with recent data for $\gamma\gamma \to K_SK_S$ [14] and re-analysis of $\phi\phi$-spectra [13] have clarified the situation with $f_2$-mesons in the mass region $1700 - 2400$ MeV. Based on these data, there was performed in [15] a systematisation of the non-exotic $f_2$-mesons on the $(n, M^2)$-trajectories, where $n$ is the radial quantum number of the $q\bar{q}$-state. The systematisation [15] shows us that the broad resonance $f_2(2000 \pm 30)$ is an extra state for the $(n, M^2)$-trajectories being apparently the lowest tensor glueball. However, the statement about glueball nature of $f_2(2000)$ was based on indirect arguments:

(i) The leading Pomeron trajectory $\alpha_P(M^2) = \alpha_P(0) + \alpha'_P(0)M^2$ has the following values for the intercept and slope: $\alpha(0) \simeq 1.10 - 1.30$ and $\alpha'_P(0) \simeq 0.15 - 0.25$ (see, for example, [16, 17, 18]). These Pomeron parameters give for the tensor glueball $M \simeq 1.7 - 2.5$ GeV.

(ii) In the lattice calculations, a close value was obtained, namely, $M \simeq 2.2 - 2.4$ GeV [19].

(iii) The large width of $f_2(2000)$ can be considered as a signature of the glueball origin of this state. Exotic state appearing in a set of $q\bar{q}$ resonances accumulates their widths, thus transforming into broad resonance [20]. The phenomenon of width accumulation has been studied in [21, 22] for scalar glueball $f_0(1200 - 1600)$, and much earlier this phenomenon was observed in nuclear physics [23, 24, 25].

Direct arguments for the glueball nature of $f_2(2000)$ can be provided by the relations between decay coupling constants, and for tensor glueball such relations were presented in [15]. In [11, 13], the extraction of the decay couplings $f_J \to \pi\pi, \eta\eta, \eta\eta'$ was not performed — in the present paper we fill in this gap. The $\bar{p}p \to \pi^0\pi^0, \eta\eta, \eta\eta'$ amplitudes provide us the following ratios for the $f_2$ resonance couplings, $g_{\pi^0\pi^0} : g_{\eta\eta} : g_{\eta\eta'}$:

\[
\begin{align*}
 f_2(1920) & : 1 : 0.56 \pm 0.08 : 0.41 \pm 0.07 \\
 f_2(2000) & : 1 : 0.82 \pm 0.09 : 0.37 \pm 0.22 \\
 f_2(2020) & : 1 : 0.70 \pm 0.08 : 0.54 \pm 0.18 \\
 f_2(2240) & : 1 : 0.66 \pm 0.09 : 0.40 \pm 0.14 \\
 f_2(2300) & : 1 : 0.59 \pm 0.09 : 0.56 \pm 0.17.
\end{align*}
\]

These ratios are to be compared with those given in [15].

In the leading terms of $1/N_c$-expansion [20], there exist definite ratios for the glueball decay couplings. The next-to-leading terms in the decay couplings give the corrections of the order of $1/N_c$ (see, for example, [4]); numerical calculations of diagrams tell us that $1/N_c$ factor leads to a smallness of the order of $1/10$, and we neglect them. For the transitions tensor glueball $\to \pi^0\pi^0, \eta\eta, \eta\eta'$ the relations in the leading terms of $1/N_c$-expansion read (see Table in [15]):

\[
g_{\eta\eta}^{(glueball)} : g_{\eta\eta}^{(glueball)} : g_{\eta\eta'}^{(glueball)} = 1 : (\cos^2 \Theta + \lambda \sin^2 \Theta) : (1 - \lambda) \sin \Theta \cos \Theta. \quad (3)
\]
Here $\Theta$ is the mixing angle for $\eta-\eta'$ mesons: $\eta = n\bar{n}\cos \Theta - s\bar{s}\sin \Theta$ and $\eta' = n\bar{n}\sin \Theta + s\bar{s}\cos \Theta$, where $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$. We neglect a possible admixture of the gluonium component in $\eta$ and $\eta'$ (according to [27], the gluonium admixture in $\eta$ is less than 5%, and in $\eta'$ it is less than 20%). For the mixing angle $\Theta$ we use $\Theta = 37^\circ$.

Suppression parameter $\lambda$ determines relative production probability of strange quarks by gluon field $u\bar{u}: d\bar{d}: s\bar{s} = 1 : 1 : \lambda$ with $0 \leq \lambda \leq 1$. The data provide us with the following values of this parameter: $\lambda \simeq 0.5$ [28] for central hadron production in hadron–hadron high energy collisions, $\lambda = 0.5 - 0.8$ [29] for the decay of tensor mesons and $\lambda = 0.5 - 0.9$ [30] for the decays of $0^{++}$ mesons.

For ($\lambda = 0.5$, $\Theta = 37^\circ$) eq. (3) gives us $1 : 0.82 : 0.24$, and for ($\lambda = 0.85$, $\Theta = 37^\circ$), correspondingly, $1 : 0.95 : 0.07$. Consequently, the relations between the coupling constants $g_{\pi^0\pi^0} : g_{\eta\eta} : g_{\eta\eta'}$ for the glueball are to be as follows:

$$2^{++}\text{glueball} \quad g_{\pi^0\pi^0} : g_{\eta\eta} : g_{\eta\eta'} = 1 : (0.82 - 0.95) : (0.24 - 0.07).$$

(4)

We see from [2] that precisely the coupling constants of the broad $f_2(2000)$ resonance are inside the intervals: $0.82 \leq g_{\eta\eta}/g_{\pi^0\pi^0} \leq 0.95$ and $0.24 \geq g_{\eta\eta'}/g_{\pi^0\pi^0} \geq 0.07$. Hence, it is just this resonance which can be considered as tensor glueball, with $\lambda$ being fixed in the interval $0.5 \leq \lambda \leq 0.7$.

Taking into account that there is no room for $f_2(2000)$ on the $(n, M^2)$-trajectories [15], it becomes clear that this resonance is indeed the lowest tensor glueball.

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References

[1] A.V. Anisovich et al., Phys. Lett. B 491, 47 (2000).
[2] E. Eisenhandler et al., Nucl. Phys. B98, 109 (1975).
[3] A.V. Anisovich, V.A. Nikonov, A.V. Sarantsev, V.V. Sarantsev, in "PNPI XXX, Scientific Highlight, Theoretical Physics Division, Gatchina (2001), p. 58.
[4] V.V. Anisovich, UFN, 174, 49 (2004) [Physics-Uspekhi, 47, 45 (2004)].
[5] D.V. Bugg, Phys. Rep., 397, 257 (2004).
[6] G.M. Beladidze et al. (VES Collab.), Z. Phys. C 54, 367 (1992).
[7] D.M. Alde et al. (GAMS Collab.), Phys. Lett., B 241, 600 (1990).
[8] D. Barberis et al. (WA 102 Collab.), Phys. Lett., B 484, 198 (2000).
[9] D.M. Alde et al. (GAMS Collab.), Phys. Lett. B 276, 375 (1992).
[10] D. Barberis et al. (WA 102 Collab.), Phys. Lett. B 471, 429 (2000).
[11] S. Eidelman et al. (PDG), Phys. Lett. B 592, 1 (2004).
[12] D. Barberis et al. (WA 102 Collab.), Phys. Lett. B 471, 440 (2000).
[13] R.S. Longacre and S.J. Lindenbaum, Report BNL-72371-2004.
[14] V.A. Schegelsky, A.V. Sarantsev, V.A. Nikonov, "Phenomenological investigation of the $K_S K_S$ final state in two-photon collisions and nonet classification of tensor resonances", L3 Note 3001, October 27, 2004.
[15] V.V. Anisovich, Pis'ma v ZhETF, 80, 845 (2004), hep-ph/0412093.
[16] A.B. Kaidalov and K.A. Ter-Martirosyan, Sov. J. Nucl. Phys. 39, 979 (1984).
[17] P.V. Landshoff, "Soft hadron reactions", in QCD: 20 Years Later, eds. P.M. Zerwas and H.A. Kastrup, (World Scientific, Singapore, 1993).
[18] L.G. Dakhno and V.A. Nikonov, Eur. Phys. J. A5, 209 (1999).
[19] G.S. Bali, K. Schilling, A. Hulsebos et al. (UK QCD Collab.), Phys. Lett. B 309, 378 (1993); C.J. Morningstar, M.J. Peardon, Phys. Rev. D 60, 034509 (1999).
[20] V.V. Anisovich, D.V. Bugg and A.V. Sarantsev, Phys. Rev. D 58, 111503 (1998).
[21] V.V. Anisovich, Yu.D. Prokoshkin and A.V. Sarantsev, Phys. Lett. B 389, 388 (1996); Z. Phys. A 357, 123 (1997).
[22] A.V. Anisovich, V.V. Anisovich, and A.V. Sarantsev, Phys. Lett. B 395, 123 (1997); Z. Phys. A 359, 173 (1997).
[23] I.S. Shapiro, Nucl. Phys. A 122 645 (1968).
[24] I.Yu. Kobzarev, N.N. Nikolaev, L.B. Okun, Yad. Fiz. 10, 864 (1969); [Sov. J. Nucl. Phys. 10, 499 (1966)].
[25] L. Stodolsky, Phys. Rev. D 1, 2683 (1970).
[26] G. 't Hooft, Nucl. Phys. B 72, 461 (1974); G. Veneziano, Nucl. Phys. B 117, 519 (1976).
[27] V.V. Anisovich, D.V. Bugg, D.I. Melikhov, V.A. Nikonov, Phys. Lett. B 404, 166 (1997).
[28] V.V. Anisovich, M.G. Hiber, M.N. Kobrinsky and B.Ch. Metsch, Phys. Rev. D 42, 3045 (1990).
[29] K. Peters, E. Klempt, Phys. Lett. B 352, 467 (1995).
[30] V.V. Anisovich and A.V. Sarantsev, Eur. Phys. J. A 16, 229 (2003).
Figure 1: Angle distributions in the reactions $p\bar{p} \rightarrow \pi\pi, \eta\eta, \eta'\eta'$ and their fit to resonances of eq. (1).
Figure 2: Differential cross sections in the reaction $p\bar{p} \rightarrow \pi^+\pi^-$ at proton momenta 360-1300 MeV and their fit to resonances of eq. (1).
Figure 3: Differential cross sections in the reaction $p\bar{p} \to \pi^+\pi^-$ at proton momenta 1350-2230 MeV and their fit to resonances of eq. (1).
Figure 4: Polarisation in $p\bar{p} \rightarrow \pi^+\pi^-$ and its fit to resonances of eq. (1).
Figure 5: Cross sections and Argand-plots for $^3P_2$ and $^3F_2$ waves in the reaction $p\bar{p} \rightarrow \pi^0\pi^0, \eta\eta, \eta\eta'$. The upper row refers to $p\bar{p} \rightarrow \pi^0\pi^0$: we demonstrate the cross sections for $^3P_2$ and $^3F_2$ waves (dashed and dotted lines, correspondingly) and total ($J = 2$) cross section (solid line) as well as Argand-plots for the $^3P_2$ and $^3F_2$ wave amplitudes at invariant masses $M = 1.962, 2.050, 2.100, 2.150, 2.200, 2.260, 2.304, 2.360, 2.410$ GeV. The figures on the second and third rows refer to the reactions $p\bar{p} \rightarrow \eta\eta$ and $p\bar{p} \rightarrow \eta\eta'$.