Search of the tensor glueball: The identification of resonances in the mass region 1.9-2.4 GeV

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The result of the partial wave analysis of Crystal Barrel data on $\bar{p}p \to \pi^0\pi^0$,$\eta\eta$ and $\eta\eta'$ combined with earlier data on $d\sigma/d\Omega$ and polarization for $\bar{p}p \to \pi^-\pi^+$ is presented. The polarization data separate cleanly states with $L = J \pm 1$, while Crystal Barrel data provide possibility to define quark content of the observed resonances. Along with other states, four $I = 0$, $J^{PC} = 2^{++}$ resonances are identified. All 2^+ resonances have flavour composition close to $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$, with rather little $s\bar{s}$ component. The possible nonet classification of the found states is discussed.

1. $q\bar{q}$ STATES IN THE INVESTIGATED MASS REGION

The search for the tensor glueball is one of the primary objectives of the meson spectroscopy in the mass region 1900-2400 MeV. There are rather strong proofs that the scalar glueball is located in the mass region 1500-1650 MeV. It mixes with nearby $q\bar{q}$ states and physical resonances situated nearby carry a large content of the scalar glueball. The lattice QCD calculations [1] give the ratio of tensor and scalar glueball masses ~ 1.4 with rather small errors. It corresponds to the mass of the tensor glueball to be in the region 2150-2350 MeV.

The necessary step in the tensor glueball search is to locate all tensor states in this region. The indication of an exotic state could be an appreciable deviation of the pole positions from the linear trajectories or presence of a state which does not mach linear trajectories at all. The next step is to determine the $q\bar{q}$ and the gluon content of the found states.

In the isoscalar sector the states are the mixing of the nonstrange and strange quarks:

$$R_1 = \cos\Phi|n\bar{n}\rangle + \sin\Phi|s\bar{s}\rangle, \qquad R_2 = -\sin\Phi|n\bar{n}\rangle + \cos\Phi|s\bar{s}\rangle. \tag{1}$$

If there is no mixing ($\Phi \sim 0$) the states R_1 and R_2 could be well separated and observed in different reactions. For example in the analysis of $p\bar{p} \to \pi^0\pi^0$ data we would see only R_1 type states. However in the presence of a glueball some mixing through transition to this state is unavoidable.

The $q\bar{q}$ tensor states can be either ${}^3P_2$ states or ${}^3F_2$ states. The quark model predicts the spacing between radial excitations for the tensor sector in this mass region to be 400-500 MeV. However there is a strong experimental indication that this distance is smaller, namely about 300 MeV. In this case we expect to find two ${}^3P_2$ and two ${}^3F_2$ radial excitations in the region considered. It makes totally 8 $q\bar{q}$ states and the problem of the glueball identification became a rather difficult one. From other side there is a large set of the experimental data obtained by different collaborations which cover well this region and we believe that problem can be solved by performing a combined analysis.

We started our analysis from data on $\bar{p}p$ annihilation in flight into $\pi^0\pi^0$, $\eta\eta$ and $\eta\eta'$ obtained by Crystal Barrel collaboration. It immediately became obvious that there is a set of the solutions which describe the data with almost same quality. It was no surprise: the absence of polarization information from $p\bar{p}$ channel leads to the mixing of the states with $L = J \pm 1$. The problem is also partly connected with low statistics of the $\eta\eta'$ data. As far as resonance masses and widths are concerned, the ambiguity has little effect; masses and widths are determined by the locations of the pole singularities: dominant singularities in these reactions. The ambiguity mainly effects the production and decay constant values and thus the determination of the resonance nature.

The feature which was common for all solutions was that all resonances can not be pure $n\bar{n}$ states obeying SU(3) decay relations. To describe the data it was necessary either to allow the mixing with $s\bar{s}$ states or presume the large violation of SU(3) rules. Another feature was that decay couplings of the resonance into $\pi^0\pi^0$, $\eta\eta$ and $\eta\eta'$ channels have some relative phases.

Our experience of fitting data at lower masses by both T-matrix techniques and the K-matrix one teaches us that mixing between states commonly results to deviations of phase angles ϕ_i between different decay channels. The calculation of the residues of the many channel K-matrix amplitude (with K-matrix poles having zero phases) shows that in the case of strong mixing the phase difference can be rather large. Therefore for most resonances, we have allowed ϕ_i to optimize freely for each decay channel with differences limited to the range $-15°$ to $+15°$. In isolated cases, where they seem to need it, this range has been allowed to extend to $\pm 30°$.

One of our objectives was to investigate the $q\bar{q}$ content of the resonances in the framework of SU(3) rules. In SU(3) approach the amplitudes for decay into $\eta\eta$ and $\eta\eta'$ are related to those for $\pi\pi$ via the quark content of the resonance and via the well-known composition of η and η' in terms of singlet and octet states:

$$
\begin{aligned}
|q\bar{q}\rangle &= \cos\Theta|\eta\rangle + \sin\Theta|\eta'\rangle \\
|s\bar{s}\rangle &= -\sin\Theta|\eta\rangle + \cos\Theta|\eta'\rangle,
\end{aligned}
\qquad (2)
$$

where $\cos\Theta \simeq 0.8$. Amplitudes for decay of $I = 0$ $q\bar{q}$ state into $\pi^0\pi^0$, $\eta\eta$ and $\eta\eta'$ may then be written compactly as:

$$
f(q\bar{q}) = \frac{|\pi^0\pi^0\rangle}{\sqrt{2}} + \frac{\cos^2\Theta}{\sqrt{2}}|\eta\eta\rangle + \cos\Theta\sin\Theta|\eta\eta'\rangle, \qquad (3)
$$

$$
f(s\bar{s}) = \sqrt{\lambda}[\sin^2\Theta|\eta\eta\rangle + \cos^2\Theta|\eta\eta'\rangle - \sqrt{2}\cos\Theta\sin\Theta|\eta\eta'\rangle]. \qquad (4)
$$

Where factor λ takes into account some SU(3) violation in $s\bar{s}$ sector. This factor has been fitted empirically before to a large variety of data on strange and non-strange final states at high energies. We adopted the central value of 0.85 from those analyses. It is appeared to be that all three sets of data can be described very well under these assumptions.

The very important step in the analysis was including the earlier data on $d\sigma/d\Omega$ and polarization for $\bar{p}p \to \pi^-\pi^+$ [2,3,4]. These data separate cleanly $L = J \pm 1$ states and therefore fix the production constants of the resonances from $p\bar{p}$ system. In addition they provide very valuable information near $p\bar{p}$ threshold where the Crystal Barrel data were not taken. From the combined analysis of all data we obtained only two solutions. These solutions differ mainly by the relative sign of coupling of the second 4^{++} state with $p\bar{p}$ $^3F_4$ and $^3H_4$ channels and flavour mixing angle of this state. The positive sign for this ratio in the first solution corresponds well to the earlier analysis of Crystal Barrel data on $p\bar{p} \to \pi^0\pi^0\eta$ reaction. We think that the first solution is the physical one, however until the combined analysis of the present data set with $p\bar{p} \to \pi^0\pi^0\eta$ reaction is completed we can not discard the second solution. Such analysis is planned as the next step of our investigation.

The masses, widths and flavour mixing angles of the resonances for both solutions are given in the Table 1.

Table 1
Masses, widths and mixing angles of the states.

J^P	Mass M (MeV)	Width Γ (MeV)	Φ (deg)	Mass M (MeV)	Width Γ (MeV)	Φ (deg)
	Solution I			Solution II		
6^+	2485 ± 40	410 ± 90	(0)	2530 ± 40	350 ± 60	(0)
4^+	2300 ± 25	270 ± 50	22.9	2280 ± 30	340 ± 40	-15.0
4^+	2020 ± 12	170 ± 15	-26.1	2025 ± 15	180 ± 15	-25.1
2^+	2300 ± 35	290 ± 50	-14.8	2335 ± 35	290 ± 40	-15.1
2^+	2230 ± 30	245 ± 45	7.5	2215 ± 30	285 ± 45	0.5
2^+	2020 ± 30	275 ± 35	7.9	2070 ± 40	245 ± 35	10.1
2^+	1910 ± 30	260 ± 40	1.1	1940 ± 30	230 ± 40	-11.0
0^+	2320 ± 30	175 ± 45	15.1	2315 ± 30	195 ± 40	20.1
0^+	2105 ± 15	200 ± 25	65 ± 6	2100 ± 15	195 ± 25	59 ± 10
0^+	2005 ± 30	305 ± 50	-0.5			

2. RESULTS

The $f_4(2020)$ is well known and there is plenty of evidence for its radial excitation $f_4(2300)$. We found four 2^{++} states in the mass range 1910–2410 MeV: two $^3P_2$ and two $^3F_2$ states. We found also two 0^+. There is some indication for the third 0^+ state in the solution I but it is rather tentative. The 2^{++} states have small flavour mixing angle and therefore are rather close to the $n\bar{n}$ states. These states match rather well the linear trajectories what was discussed in the talk of Bugg [5]. There is an important information about tensor states in this region which comes from the reaction $\pi^- p \to \Phi\Phi n$ [6]. This reaction is favorite in the decay process for the $s\bar{s}$ resonances, however in the production it is flavour for $n\bar{n}$ states produced from $\pi^-\pi^+$. So, really this reaction is favorite for the well mixed states. It is quite possible that our $f_2(2020)$ is the same resonance as $f_2(2010)$ found in [6].It is a bit more difficult to find out whether our $f_2(2230)$ and $f_2(2300)$ correspond to the $f_2(2300)$ and $f_2(2340)$. Unfortunately the errors in both analyses overlap well the mass and width region. From our experience we know that answer can be found in the combined analysis of all these data and such an analysis is one of our objectives for the future. We did not find any indication of $f_2(2150)$ seen by the GAMS: this state probably couples weakly with the $p\bar{p}$ system.

There are evidence from other reactions for the $f_2(1980)$ state with width about 500 MeV. The existence of such broad state would indicate the presence of some exotic in the region. Such exotic will cause the mixing of nearby states and as a result the appearance of the broad state [7]. However the $p\bar{p}$ annihilation is not a best reaction to look for such state: due to the $p\bar{p}$ threshold effect such state can not be separated from the tales of lower resonances. That is probably the reason why we did not find such a state in our analysis.

Let me note that existence of such a state rises another question. Can be quark-gluon content of tensor states reliably defined in the framework of T-matrix approach? Our investigation of the scalar sector in the lower mass region [8] shown that SU(3) decay rules which are valid for the K-matrix poles can be rather strongly violated for the residues of the amplitudes at the physical poles. That is the reason why K-matrix analysis of the data is needed and planned by our group.

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