The WA56 Experiment at CERN: How Does It Look in the Unified Picture for Hadron Spectra?

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Abstract

In this note we demonstrate how the experimental material taken from WA56 Experiment at CERN looks in the recently developed unified picture for hadron spectra. Our analysis shows that baryonium states observed in the WA56 Experiment are the states living in the corresponding KK tower built in according to the earlier established general, physical law.

There were several experiments made with the CERN OMEGA spectrometer. The WA56 Experiment was one of them especially performed to study the baryon exchange processes among hadronic reactions. Perhaps, it should be reminded about an old and long-standing problem of narrow \( pp \) (dibaryon) states and \( p\bar{p} \) (baryonium) states. In old, up to the end of the eighties, issues of PDG booklets we can find a separate parts with a compilation of these states. However, that compilation has been rejected by PDG later on probably because several experiments made in the beginning and the middle of the eighties had failed to search for these states. That is why, it might seem the interest to these states disappeared. However, this is not the case. In fact, up to now, narrow dibaryon and baryonium states in two-nucleon system have always attracted incessant interest from both theorists and experimenters. The physical origin of such narrow states is high interest because it has fundamental importance related to the nature of fundamental nucleon-nucleon forces.

We start with a short review of some known experimental studies devoted entirely to search for narrow \( p\bar{p} \) states. In paper an evidence for two narrow \( p\bar{p} \) resonances at 2020 MeV and 2200 MeV had been reported. From the study of the reaction \( \pi^- p \rightarrow p f \pi^- p\bar{p} \) using a fast proton trigger device in the CERN OMEGA spectrometer, these two narrow \( p\bar{p} \) states were observed mainly in association with a \( \Delta^0(1232) \) and \( N^*(1520) \) production in top vertex of the baryon exchange diagram (see Fig. 1a). The statistical significance of each peak was greater than 6 standard deviations. Masses and natural widths of these resonances were respectively \( M_1 = 2020 \pm 3 \) MeV, \( \Gamma_1 = 24 \pm 12 \) MeV and \( M_2 = 2204 \pm 5 \) MeV, \( \Gamma_2 = 16^{+20}_{-16} \) MeV. The upper limits to the production cross sections were estimated about \( \sim 10\text{-}30 \) nb. These results were part of a general experiment made with the CERN

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OMEGA spectrometer and came from a special experiment devoted to a general study of the baryon exchange processes in the reaction chain

\[ \pi^- + p \rightarrow \Delta^0(1232)[N^*(1520)] + M^0, \quad \Delta^0(1232)[N^*(1520)] \rightarrow p\pi^-, \quad M^0 \rightarrow p\bar{p}. \quad (1) \]

The experiment was done with a \( \pi^- \) beam at an incident momentum 9 and 12 GeV colliding with a hydrogen target. The trigger required a fast proton emitted forward with a momentum greater than 0.5 \( p_{\text{beam}} \). A complete description of this experiment and the details of analysis can be found in original paper [2] and references therein.

The results of a search for narrow \( p\bar{p} \) states produced in the baryon exchange reaction with a chain

\[ \pi^+ + p \rightarrow \Delta_{f}^{++}(1232) + X^0, \quad \Delta_{f}^{++}(1232) \rightarrow p_f\pi^+, \quad X^0 \rightarrow p\bar{p} \quad (2) \]

at \( p_{\text{beam}}^{\pi^+} = 9.8 \) GeV have been reported in Ref. [3]. As pointed out, this channel provided an enhanced sensitivity to such states compared with reaction (1) studied in Ref. [2]. The multiparticle spectrometer (MPS) at the Brookhaven National Laboratory alternating-gradient synchrotron was used to detect all four charged tracks from reaction (2). No evidence for narrow \( p\bar{p} \) states at the 20–30 nb level in the mass range 1.9–2.3 GeV was found. It was also emphasized that, assuming a nucleon-exchange production mechanism, the states which have been reported in Ref. [2] would appear as \( > 5 \) standard-deviation peaks in the recorded data sample with the trigger required a forward particle with momentum \( \geq 5.5 \text{ GeV} \).

The \( p\bar{p} \) mass spectrum was also measured in another experiment [4] at the Brookhaven National Laboratory alternating-gradient synchrotron where the inclusive reaction \( \pi^- + p \text{(or C)} \rightarrow p\bar{p} + X^0 \) had been studied. No statistically significant enhancements in the data in the \( p\bar{p} \) mass range from 2000 to 2400 MeV were observed.

A search was made for baryonium production in \( p\bar{p} \) and \( K^-p \) interactions at 12 GeV in the experiment [5] which was performed using the OMEGA spectrometer at CERN, exposed to the separated beam consisting of approximately 45% antiprotons, 15% negative kaons and 40% negative pions. No significant structures in the mass spectra of \( p\bar{p}, p\bar{p}\pi^- \) and \( \bar{p}\Lambda^0 \) systems were seen. The upper limit at the 99.5% confidence level for production of narrow states in the \( p\bar{p} \) system in the mass range 2.0–2.2 GeV was estimated about \( \sim 40 \text{ nb} \).

It should also be mentioned that the negative results on backward production, via baryon exchange, of exotic non-strange mesons were presented in article [6]. The reactions \( \pi^-p \rightarrow p_{\text{forward}}X^- \) and \( \pi^-n \rightarrow p_{\text{forward}}X^{--} \) have been studied with a 12 GeV \( \pi^- \) beam in the OMEGA spectrometer at CERN. No resonant peak in \( X \rightarrow p\bar{p}\pi^- \), \( p\bar{p}\pi^- \), \( p\bar{p}\pi^-\pi^0 \), \( \pi^+\pi^-\pi^-\pi^- \), \( \pi^+\pi^-\pi^-\pi^-\pi^0 \) has been seen. The upper limits obtained on cross sections for exotic meson production \( X \rightarrow N\bar{N}\pi, N\bar{N}\pi\pi, 4\pi \) were lower than the \( \rho^- \) backward production cross section in the \( \pi p \rightarrow pp^- \) reaction. As pointed out, the sensitivity of this experiment increased by an order of amplitude compared to earlier published experiments in the search for exotics produced via baryon exchange.

The WA56 experiment at CERN [7] was also one of the experiments made with the OMEGA spectrometer specially designed to select the baryon exchange processes. It was a long-range aim of the WA56 experiment to confirm the narrow \( p\bar{p} \) states of masses 2020 MeV and 2204 MeV reported in paper [2]. However, the WA56 experiment revealed the lack of these states at the level of production cross sections smaller by an order of
magnitude than those estimated in Ref. [2]. In fact, the results of a search for narrow \( p\bar{p} \) states produced backwards in the baryon exchange reactions \( \pi^- p \rightarrow \Delta_f^0(1232)p\bar{p}, \) \( \pi^- p \rightarrow N_f^0(1520)p\bar{p} \) at 12 GeV and \( \pi^+ p \rightarrow \Delta_f^{++}(1232)p\bar{p} \) at 20 GeV have been reported. No structures of statistical significance exceeding three standard deviations have been found in the \( p\bar{p} \) mass spectra. The cross section limits obtained were three to five times lower than the cross sections of Ref. [2] depending on the channel.

Quite a new analysis of the WA56 experimental data was performed in the nineties [8] with a chief aim to study the channels of the baryon exchange reactions which were not taken into consideration before. In fact, the baryon exchange reactions have been studied where one particle was either undetected or incompletely reconstructed but the \( p\bar{p} \) system was produced in central region (see Fig. 1c). Namely, the following channels have been considered

\[
\pi^+ + p \rightarrow p_f + X^0 + \pi^+_s, \quad X^0 \rightarrow p\bar{p},
\]

\[
\pi^+ + p \rightarrow p_f + \pi^+ + X^0 + \pi^+_s, \quad X^0 \rightarrow p\bar{p},
\]

\[
\pi^+ + p \rightarrow p_f + \pi^+ + \pi^+ + X^0 + \pi^-_s, \quad X^0 \rightarrow p\bar{p},
\]

at 20 GeV and

\[
\pi^- + p \rightarrow p_f + X^0 + \pi^-_s, \quad X^0 \rightarrow p\bar{p},
\]

\[
\pi^- + p \rightarrow p_f + \pi^- + X^0 + \pi^-_s, \quad X^0 \rightarrow p\bar{p},
\]

at 12 GeV, where \( p_f \) was an identified fast proton with the momentum greater than half the beam momentum, and the slow pions \((\pi^+_s, \pi^-_s)\) went undetected by the OMEGA spectrometer but were reconstructed by the corresponding kinematic fits; see, however, the details in original paper [8]. As pointed out, the very good momentum resolution available from OMEGA tracks measurements allowed a clear separation and identification of one missing pion channel in the data. That investigation was motivated in the main by previous analysis [9] of the WA56 experimental data on the central production of \( \rho^0, f_2 \) and \( \rho_3^0 \) mesons in the baryon exchange reaction

\[
\pi^+ + p \rightarrow p_f + M^0 + \pi^+_s, \quad M^0 \rightarrow \pi^+\pi^-,
\]

at 20 GeV (see Fig. 1b) where the similar experimental approach was used for the first time. A clear signal of a narrow \( p\bar{p} \) state with a mass of 2.02 GeV and a width less than 10 MeV was seen in all of the channels [5,7] in a restricted kinematic region close to the central one. From the upper limits on mesonic \((\pi^+\pi^-, \pi^+\pi^-\pi^0, 2\pi^+2\pi^-, K^+K^-)\) decay modes of the observed state it was found that this state was not noticeably coupled to mesons. That is why, it was claimed that this 2.02 GeV \( p\bar{p} \) state coupled strongly to baryons and decoupled from mesons might be a baryonium candidate.

The combined \( p\bar{p} \) mass spectrum for the events in \( \pi^+ p \) (channels [8,11] and \( \pi^- p \) (channels [5,7]) exposures, plotted with the 5 MeV width bins, is shown in Figure 2 extracted from original paper [8]. As seen in Fig. 2, the clear signal is visible at a mass of 2.02 GeV. The statistical significance of this peak was estimated to be exceeded 5 standard deviations. It should also be pointed out that no statistically significant peak at a mass of 2.20 GeV, reported earlier in Ref. [2], was observed in the data. However, at the same time, the mass fit results for the 2.02 GeV \( p\bar{p} \) state accurately collected in Table 1 of Ref. [8] turned out in a good agreement with the similar results of Ref. [2].

Of course, the question arises: could the contradicted experimental results on (non)observation of narrow \( p\bar{p} \) states be really compatible? In Ref. [8] it has been presented a
shining example of that how the discrepancies could be explained. First of all, it has been pointed out that all experimental results on the production cross sections depend on the model which has been used for reaction mechanism in order to extract the experimental acceptances. For example, the experimental acceptances were calculated in Ref. [2], using mechanism of backward production of the 2.02 GeV $p\bar{p}$ state. For a proper comparison of the results the authors of Ref. [8] recalculated the acceptance of the experimental setup assuming their central production mechanism. As a result with the revised acceptance calculation, the production cross section of the 2.02 GeV $p\bar{p}$ state was found to be in experiment [2] such as obtained in experiment [8] with a good agreement. The same has turned out true in a comparison of the results from the experiments [7] and [8]. In other words, the authors of Ref. [8] have simply explained how to get an agreement with the experimental results on the production of the 2.02 GeV $p\bar{p}$ state reported in [2, 7] and their own experiment [8]. An explanation of the absence of the 2.02 GeV $p\bar{p}$ state in other experiments (see e.g. [3, 4, 5]) has also given in Ref. [8], and we refer the interested reader to the original paper.

Concerning formation experiments it was shown in Ref. [8] that the experimental cross section of the (formation) process $N\bar{N}\rightarrow R\rightarrow N\bar{N}$ at the resonance peak crucially depends on the ratio of the resonance width to the experimental resolution

$$\sigma^{N\bar{N}\rightarrow N\bar{N}}_{\text{exp}}(\sqrt{s} = \sqrt{s_R})|_{M_R=2.02} \simeq 2.25(2J + 1)\beta_N^2 \frac{\Gamma}{2\Delta} \frac{\arctan \frac{2\Delta}{\Gamma}}{\Gamma}, \tag{9}$$

where $J, \beta_N, \Gamma$ are spin, elasticity ($\beta_N = 1$ for a pure baryonium decaying into $N\bar{N}$ only), width of the resonance, $\Delta$ is experimental resolution. The experimental restriction on the width of the 2.02 GeV $p\bar{p}$ state obtained in Ref. [8] ($\Gamma \leq 10$)MeV should be taken into account to understand the discrepancies with the formation experiments where no signal of the 2.02 GeV $p\bar{p}$ state was found.

It should also be mentioned a remark in Ref. [8] on the central production mechanism priority over the backward production one. In fact, this peculiarity was established earlier in the study of central production of ordinary mesons [9] where the enhancement factor did not exceed 4, but for the 2.02 GeV $p\bar{p}$ state production this factor turned out at least 20. To explain such peculiarity it may be assumed that the observed narrow $p\bar{p}$ state is coupled with the $\Delta\bar{\Delta}$ system much stronger than with the $N\bar{N}$ one. In that case a process of backward production, where double $\Delta$ exchange does not work, is naturally suppressed, and the dominated process is given by diagram 1c shown in Fig. 1. Here the narrowness of the observed $p\bar{p}$ state might also be explained as follows [8]: this state being produced in the collision of virtual $\Delta$ and $\bar{\Delta}$ cannot decay into the real pair $\Delta\bar{\Delta}$ because this decay channel is forbidden by phase space, and only suppressed $p\bar{p}$ channel is open.

Bear all of that in mind, we would like to emphasize that careful analysis performed in Ref. [8] might be served as an excellent introduction to the recent widely discussed question: why the $\Theta$ baryon states observed in a more than 10 experiments are not seen in the others?

In Ref. [10], where some of our previous studies were partially summarized, it has been claimed that existence of the extra dimensions in the spirit of Kaluza and Klein together with some novel dynamical ideas may provide new conceptual issues for the global solution of the spectral problem in hadron physics to build up a unified picture for hadron spectra. Earlier we have applied these ideas to analyze the nucleon-nucleon dynamics at very low
energies \[11\]. Really, we have found that simple formula for KK excitations provided by Kaluza-Klein approach accurately described the experimentally observed irregularities in the mass spectrum of \(pp\) and \(p\bar{p}\) systems. The result of our analysis is presented in Table 1 extracted from Ref. \[11\] (see also the references therein where the experimental data have been extracted from). As is seen from Table 1, the nucleon-nucleon dynamics at low energies reveals quite a remarkable development of Kaluza-Klein picture. Moreover, \(M_{pp} = M_{p\bar{p}}\) is predicted by Kaluza-Klein scenario, and Table 1 contains an experimental confirmation of this fact as well.

Of course it was intriguing for us to perform the spectral analysis of the experimental material from the WA56 Experiment at CERN in order to learn how does it look in the unified picture for hadron spectra. To attain this goal the calculated spectral lines taken from Table 1 have been plotted in Fig. 3 together with the \(p\bar{p}\) mass spectrum presented in Ref. \[8\]. As is seen, the experimentally observed 2.02 GeV \(p\bar{p}\) state just lives in the \(M_{p\bar{p}}(2019.66 \text{MeV})\)-storey of KK tower for the \(p\bar{p}\) system. What is more important, a strong correlation of the spectral lines with the other peaks on the histogram is also clearly seen in Fig. 3. In our opinion, that correlation is not an accidental coincidence, it displays the existence of the states observed in other experiments. In fact, the different experiments reflect only partial fragments of the whole unified picture.

Our conservative estimate for the widths of KK excitations looks like

\[
\Gamma_n \sim \frac{\alpha}{2} \cdot \frac{n}{R} \sim 0.4 \cdot n \text{ MeV},
\]

where \(n\) is the number of KK excitation, and \(\alpha \sim 0.02, R^{-1} = 41.48 \text{MeV}\) are known from our previous studies \[11\]. This gives \(\Gamma_0 \sim 3.6 \text{ MeV}\) which does not contradict to the experimental estimate.

At last, we also predicted the narrow charged \(p\bar{n}\) and \(\bar{p}n\) states with the similar mass: \(M_{p\bar{n}} = M_{\bar{p}n} = 2020.84 \text{MeV}\) (see Table 2 in Ref. \[11\]). An evidence for the existence of such states has been reported in Ref. \[12\], where the authors claimed that these states were observed in the reactions \(\bar{p}p \rightarrow p_f \bar{n} \pi^+ \pi^-\) at 6 GeV and \(\bar{p}p \rightarrow \pi_f^+ \bar{p} n \pi^+ \pi^-\) at 9 GeV in a triggered bubble chamber experiment at the SLAC Hybrid Facility. Clearly, this experimental observation is an additional argument in favour of the Kaluza-Klein picture.

In summary, the results of the WA56 Experiment at CERN, with account of analysis made in \[8\], are naturally incorporated in the recently developed unified picture for hadron spectra. Our analysis shows that the experimentally observed narrow baryonium states are the states living in the corresponding KK tower built in according to the earlier established general, physical law. We hope that new experiments will appear in the near future to enrich our understanding of the nucleon-nucleon dynamics. We also share that a call for the future hadronic experiments with high resolution and sensitivity has clearly to be supported.

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Table 1. Kaluza-Klein tower of KK excitations for $pp(p\bar{p})$ system and experimental data.

| n  | $M_{pp}^{n}$ MeV | $M_{exp}^{pp}$ MeV | $M_{exp}^{pp}$ MeV | n  | $M_{pp}^{n}$ MeV | $M_{exp}^{pp}$ MeV | $M_{exp}^{pp}$ MeV |
|----|------------------|--------------------|--------------------|----|------------------|--------------------|--------------------|
| 1  | 1878.38          | 1877.5 ± 0.5       | 1873 ± 2.5         | 15 | 2251.68          | 2240 ± 5           | 2250 ± 15          |
| 2  | 1883.87          | 1886 ± 1           | 1870 ± 10          | 16 | 2298.57          | 2282 ± 4           | 2300 ± 20          |
| 3  | 1892.98          | 1898 ± 1           | 1897 ± 1           | 17 | 2347.45          | 2350               | 2340 ± 40          |
| 4  | 1905.66          | 1904 ± 2           | 1910 ± 30          | 18 | 2398.21          |                    | 2380 ± 10          |
| 5  | 1921.84          | 1916 ± 2           | ~ 1920             | 19 | 2450.73          |                    | 2450 ± 10          |
|    | 1926 ± 2         |                    |                    |    |                  |                    |                    |
| 6  | 1941.44          | 1937 ± 2           | 1939 ± 2           | 20 | 2504.90          |                    | ~ 2500             |
|    | 1942 ± 2         | 1940 ± 1           |                    |    |                  |                    |                    |
|    | ~1945            | 1942 ± 5           |                    |    |                  |                    |                    |
| 7  | 1964.35          | 1965 ± 2           | 1968               | 21 | 2560.61          |                    | ~ 2620             |
|    | 1969 ± 2         | 1960 ± 15          |                    |    |                  |                    |                    |
| 8  | 1990.46          | 1980 ± 2           | 1990 ± 15          | 22 | 2617.76          |                    | ~ 2620             |
|    | 1999 ± 2         | 1990 ± 30          |                    |    |                  |                    |                    |
| 9  | 2019.63          | 2017 ± 3           | 2020 ± 3           | 23 | 2676.27          |                    |                    |
|    |                  |                    |                    |    |                  |                    |                    |
| 10 | 2051.75          | 2046 ± 3           | 2040 ± 40          | 24 | 2736.04          | 2735               | 2710 ± 20          |
|    |                  | ~2050              | 2060 ± 20          |    |                  | 2796.99            |                    |
| 11 | 2086.68          | 2087 ± 3           | 2080 ± 10          | 25 | 2859.05          | 2850 ± 5           |                    |
|    |                  | ~2050              | 2090 ± 20          |    |                  | 2922.15            |                    |
|    | 2087 ± 3         | 2080 ± 10          |                    |    |                  | 2986.22            |                    |
|    | 2086.68          | 2080 ± 10          |                    |    |                  | 2986.22            | 2984 ± 2.1 ± 1.0   |
| 12 | 2124.27          | ~2122              | 2105 ± 15          | 26 | 2896.22          |                    |                    |
|    | 2121 ± 3         | 2110 ± 10          |                    |    |                  | 3183.67            |                    |
|    | 2129 ± 5         | 2140 ± 30          |                    |    |                  | 3251.06            |                    |
| 13 | 2164.39          | ~2150              | 2165 ± 45          | 27 | 2129.15          |                    |                    |
|    | 2172 ± 5         | 2180 ± 10          |                    |    |                  | 3319.15            |                    |
|    | 2206.91          | 2207 ± 13          |                    |    |                  | 3370 ± 10          |                    |
| 14 | 2206.91          | 2207 ± 13          |                    |    |                  | 3370 ± 10          |                    |
Figure 1: The diagrams from Ref. [8] which display: the backward production of the $p\bar{p}$ state in $\pi^-p$ interactions (a), the central production of a meson in $\pi^+p$ interactions (b), the central production of the $p\bar{p}$ state in $\pi^-p$ interactions via double $\Delta$ exchange (c).
Figure 2: Combined $p\bar{p}$ mass spectrum for the events of reactions (3,6) and (4,7) presented in Ref. [8].
Figure 3: The same as Fig. 2 but with the vertical (spectral) lines corresponding to KK tower for $p\bar{p}$ system; see Table 1.