Are the exotic mesons and baryons, recently observed, a signature of quark-hadron duality ?

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Abstract. Narrow low mass exotic hadronic structures were recently observed in mesons, baryons and dibaryons. Narrow mesons, in the mass range 300≤M≤ 750 MeV, were observed using the pp → ppX reaction. Narrow baryons in the mass range 1000≤M≤ 1400 MeV were observed using the pp → pπ⁺X and dp → ppX reactions. The statistical significances of these structures vary up to 4.6 standard deviations (S.D.) for mesons and up to 16.9 S.D. for baryons. These exotic states are associated with precursor quark deconfinement.

INTRODUCTION

It is often believed than the observation of quark degrees of freedom cannot start at energies lower than several GeV ($\approx$ 10 GeV). However such limit is somewhat unprecise. A relation was proposed by Baldin [1] some years ago. In this theory, the deconfinement is determined as being a process allowing particle creation for $b_{ij} \geq 5$, where

$$b_{ij} = -(P_i/m_i - P_j/m_j)^2 \tag{1}$$

P_i, P_j are the four momentum of both particles involved in the reaction, and m_i, m_j their masses. If we consider a N-N reaction, the previous relation reduces in the laboratory system to $T_i \geq 2.35$ GeV. Following the previous relation, the search for possible signatures of the beginning of the quark deconfinement, could be significant at energies close to 2 GeV. These correspond to the energies of the experiments which results are presented in this paper.

The measurements were performed at Saturne, with proton and deuteron beams. Their energies varied from 1.52 up to 2.1 GeV. The large momentum range SPES3 spectrometer (600 $\leq$ pc $\leq$ 1400 MeV) and its detection were settled at different angles from 0^0 up to 17^0 (lab.). Two positively charged particles (pp or pπ⁺) were detected and identified in the same detection. A MIT type drift chamber was located in the focal plane of the spectrometer (σ_x=90 μm), (σ_θ=18 mrd). Its efficiency was smooth, without displaying any structure. Two multidrift CERN

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type drift chambers were located perpendicular to the mean particle trajectories. Each of these two chambers consisted of three wire planes (x, u, v). The trigger consisted of four planes of plastic scintillator hodoscopes (20 scintillator/plane). A first time of flight between both extreme trigger planes were used to identify the detected particles. The time resolution for each scintillator was $\sigma \approx 180$ ps. A second time of flight between both particles overdetermined the reaction under study. For T_p=1.52 GeV protons at 0^0, the events from the pp→pπ^+n reaction came across all the momentum range in the p_p versus p_π scatter plot, and the missing mass histogram was smooth without structure.

The σ of the invariant masses was close to 1 MeV, when the σ of the missing masses was close to 2 MeV at forward angles.

Regular empty target measurements allowed us to observe that the target windows were not a source of noticeable contamination. They also allowed us to conclude that the data were not contaminated by any hot area of incident beam which could have been scattered by some mechanical piece at the entrance of the spectrometer. A simulation code was written in order to perform the corrections for the lost events and for the acceptance. It showed that we did not have any narrow structure in the simulated histograms, and that we have a good control of both the spectrometer and the detection. The simulation code was also used to check that the structures were not produced by eventual particles emitted vertically outside the solid angle and partially absorbed by the lead diaphragm and other mechanical pieces between the target and the spectrometer. The randoms histograms - a few % of the total spectra - did not exhibit any structure. We conclude on the lack of possible contamination, and on the genuine existence of the small and narrow observed structures.

NARROW MESONS

The missing mass of the pp → ppX reaction was studied at T_p=1.52, 1.805 and 2.1 MeV. A broad enhancement was observed between 300 and 500 MeV, which is usually called the ABC effect. The corresponding histograms displayed an oscillatory pattern, compatible with the presence of several unresolved structures [2]. The position of the extracted peaks did not depend on the multipion phase space, which exhibits a smooth behaviour. Four peaks were extracted at 313, 353, 426 and 495 MeV. When different incident proton energies and angles were considered, the stability of the two first masses was better than the stability of the two last masses.

Between the η and the ω mesons, narrow structures were observed at 588, 608, 647, 681, 700, $(715)^1$, and (750) MeV [3].

There is no room for these new mesons within $q\bar{q}$ models. Indeed there is an excellent agreement between the complete classical meson spectrum and the calculations using a relativistic quark model for mesons [4]. Therefore more complex quark configurations are to be considered. We call these states: exotic mesons.

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[1] between parenthesis since its existence is less well defined

Figure 1 shows an attempt to describe the experimental masses using the following phenomenological mass formula [5] for two coloured constituent quark cluster configurations:

$$M = M_0 + M_1[i_1(i_1 + 1) + i_2(i_2 + 1) + (1/3)s_1(s_1 + 1) + (1/3)s_2(s_2 + 1)], \quad (2)$$

where M_0 and M_1 are parameters and $i_1(i_2)$, $s_1(s_2)$ are isospin and spin of the first and second quark clusters respectively.

The first four meson masses, extracted from the ABC broad bump, are well described using the $q^2 - \bar{q}^2$ configurations. These states are "broad" (σ(width)$\approx$ 20 MeV) and highly excited. The mesons between 480 and 620 MeV which correspond to narrow and weakly excited peaks, are described using the $q^3 - \bar{q}^3$ configurations. In both cases ($q^2 - \bar{q}^2$ and $q^3 - \bar{q}^3$ configurations) the same parameters: M_0=310 MeV and M_1=30 MeV are used. Finally the mass range between 620 and 750 MeV is described by $q^4 - \bar{q}^4$ configurations with slightly different parameters (by 10%) : M_0=357 MeV and M_1=27 MeV.

q²-q̄² calculated   q³-q̄³ experimental   calculated q⁴-q̄⁴
  (+)   parity   (−)   parity (+)

                                    (----)759   ── 753   (1..3)(0..4)
                                    (----)750   ── 735   (2) (0..4)
                                    ---- 715   ── 717   (0..2)(0..4)
                                    ── 700   ── 699   (1)(0..4)
                                    ── 681   ── 681   (0)(0..4)/(1..3)

                                    ── 647   ── 645   (1..3)(1..3)
                                                     ── 627   (2)(1..3)/(0..4)(2)

── 610 (0..3)(0..3)/(0,1)(2,3)   ---- 608
── 580 (1,2)(0..3)   ── 588
── 550 (0..3)(0,1)   ── 555
── 520 (1,2)(0..3)
── 490 (1,2)(1,2)   ---- 495
── 470 (0,2)(0,2)
                                 ── 460 (1,2)(0,1)
── 430 (0,2)(0)   ── 430 (0,1)(0..3)   ── 426

── 350 (0)(0,2)   ── 353

── 310 (0)(0)   ── 313

FIGURE 1. Compared experimental and calculated exotic narrow mesonic mass spectra. Into parenthesis, calculated possible (Spin) and (Isospin) respectively.

NARROW BARYONS

The first results of narrow exotic low mass baryons were obtained using the missing mass M_X of the pp $\rightarrow$ pπ^+X reaction [6]. Three baryons were observed, with S.D. as large as 10, at 1004, 1044 and 1094 MeV. The corresponding structures were observed at nearly all incident proton energies and scattering angles.

Other baryons - which are less highly excited - were also recently extracted from the same reaction at the following masses: 1136, 1173, 1249, 1277, and (1384) MeV. Since they were each observed in only some experimental spectra corresponding to different angle and-or incident proton energy, their existence is less firmly established than was the existence of the first three lowest narrow baryons. In the mass range 1.1$\leq$ M$\leq$ 1.45 GeV they were observed in the missing mass M_X or-and in the invariant mass $M_{p\pi+}$ of the previous reaction. They were also observed in the missing mass M_X of the dp $\rightarrow$ ppX reaction, although with smaller S.D. These last results cannot be used to establish firmly the existence of these states. But since the masses of the structures observed in the dp $\rightarrow$ ppX experiment lie close to those found in the first reactions, these results seem to confirm the previous ones. Figure 2 illustrates some of these peak extractions and table 1 describes the conditions of each histogram.
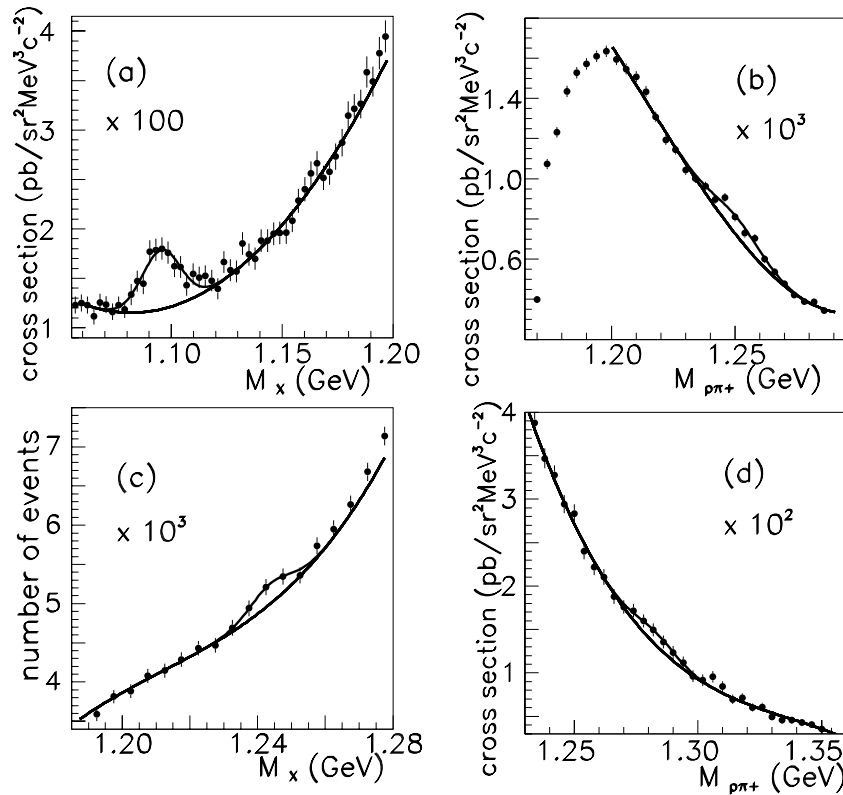
FIGURE 2. A selection of four experimental spectra, showing small and narrow baryonic structures.

	Mass (MeV)	S.D.	T_p (MeV)	θ^0	reaction	observable
(a)	1094	10.9	1805	3.7	pp→pπ^+X	M_X
(b)	1249	8.3	1520	2	pp→pπ^+n	$M_{p\pi+}$
(c)	1249	3.2	2100	17	dp→ppX	M_X
(d)	1277	3.5	1805	6.7	pp→pπ^+X	$M_{p\pi+}$

TABLE 1. Description of the data of Figure 2 showing new structures as observed in different reactions, different observables, incident energies and spectrometer angles.

Only those structures extracted several times at masses less than M±5 MeV were taken into account. The widths of the structures - about a few MeV - are not precise enough to discriminate the experimental from the physical widths.

As it was the case for mesons, there is no room for new baryons in this mass range within the many quark models [7]. Missing baryons are baryons which were calculated by different constituent quarks models, but which were not seen experimentally through elastic πN scattering. They are predicted for masses larger than 1700 MeV, and not in the mass range studied here. Moreover there is - a priori - no reason for them to be narrow since they are calculated within the three quarks assumption. We have therefore several reasons not to associate our narrow baryons to missing baryons, but to associate them to an exotic (not q^3) origin. We considered the same phenomenological mass formula as the one already used for mesons. The two parameters were adjusted in order to get the mass, and different possible (because of large degenerascy) spin and isospin values of nucleon and Roper resonance at 1440 MeV. We got the calculated spectra shown in Figure 3 and observed a very good agreement between measured and calculated masses - mainly for the four lower baryons - although no adjustable parameter was used here.

DISCUSSION

Thanks to good resolution and statistics, narrow structures were observed in hadrons using the pp → pπ^+X, pp → ppX and dp → ppX reactions. Many checks were performed to make sure that these structures were not produced by artefacts. Their small width and their mass stability, whatever the experiment, were used to conclude that they are genuine hadronic structures which were not produced by dynamical rescatterings. Since they cannot be associated to classical quark configurations: $q\bar{q}$ for mesons and q^3 for baryons, we tentatively associated them to coloured cluster quark configurations. The agreement between measured and calculated masses is outstanding since both spectra were obtained quite close although only two (zero) free parameters are used for mesons (baryons). It remains that our attempt to identify the experimental narrow structures to partial quark deconfinement, in these experiments of low temperature and small baryochemical potential (low baryonic number density), although being quite impressive, is not understood today and needs a theoretical explanation.

FIGURE 3. Compared experimental and calculated masses of exotic narrow baryonic structures.

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