Quark Confinement and the Hadron Spectrum II

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N. Brambilla & G. M. Prosperi

Università degli Studi di Milano and Istituto Nazionale di Fisica Nucleare, Italy

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THE SPECTRUM OF NONSTRANGE BARYONS : UNSETTLED ISSUES

P. STASSART and Fl. STANCU
Université de Liège, Physique Nucléaire Théorique,
Institut de Physique au Sart Tilman, Bâtiment B5,
B-4000 LIEGE 1, Belgium

The main features of the spectrum of nonstrange baryons are considered as reasonably well understood ; however several issues stay unclear. Among them, higher mass resonances and the resolution of multiplets of resonances bearing the same quantum numbers. Realistic interpretations of the spectrum should rely on correct values of the hadronic widths of the baryon states, taking into account possible model artefacts in the calculated spectra. We present some new spectrum and widths calculations in the frame of the flux tube model, which may help setting limits on the uncertainty in the interpretation of the spectrum of nonstrange baryons

The scope of the present talk is to address current questions about the nonstrange baryon spectrum in the frame of the constituent quark model.

One of them is whether the constituent quark model, in its static approximation, can accommodate the highest observed baryon states. Indeed, the overall pattern of the spectra obtained from quark models is generally good for all 3 and 4-star resonances, with the remarkable exception of the D35 (1930), which is the first $\Delta\frac{5}{2}^-$ state [1-4]. In the frame of the quark model the $\Delta\frac{5}{2}^-$ sector should start at the N=3 band. The fact that the predicted D35 mass comes about 200 MeV too high might hint at a strong failure of the model as N increases. One should at least question [4,6,7] the form of the confinement potential, which in the flux-tube QCD inspired quark model is linear [8,9], or the value of the string tension, usually taken between 750 MeV/fm and 1 GeV/fm [2,4,8,10,11].

A test for the confinement potential is to have a look at the higher, N=4 band. Four observed states [5] are to be investigated, two of them classified as 4-star, namely H19 (2220) and H3,11 (2420), one 2-star, H39 (2300) and one one-star, F37 (2390), of special interest though, as it is the second $\Delta\frac{7}{2}^+$ in the spectrum. We'll focus on these states in the calculations presented here. Another, more troublesome question is whether, in the spectral identification of the theoretically predicted states with the observed states, the symmetry attributed to them in the calculation matches with their underlying symmetry. As the energy contributions coming from the various terms of the spin-independent part of the Hamiltonians used in the constituent quark models often differ from state to state by only a few percent, a "good" spectrum pattern can rely on a "bad" mixing between the configurations that fit a given spin-isospin sector. This mixing arises from the tuning up of the degeneracy lifting interaction (usually the one gluon exchange induced hyperfine interaction [11] ; another choice is an instanton induced interaction [10]). However, as one turns to dynamical properties such as decay widths, up to order of magnitude differences can arise in the calculated values, depending on which symmetry is assigned to a state. A striking example is the $N\frac{3}{2}^+$ sector in which the calculated value of the $N\pi$ width of the first resonance, P13 (1720), assigned a spectroscopically "good" dominant ${}^2N\,(56,2^+)$ component comes out six times too large [2,12,13].

As models for calculating decay widths using a flux tube breaking mechanism have proven successful for resonances of well identified symmetry (as singlets inside a given N band), it is to some extent possible to use decay width calculations as a test for the symmetry structure of larger multiplets. This can shed light on the question whether width discrepancies can be explained by configuration mixing problems or whether there should be a deeper problem in the constituent quark model.

The talk is presented as follows. First, we recall some features of the constituent quark model and write the Hamiltonian, that we'll be using. Second, we discuss the transition operators arising from the flux tube breaking decay mechanism. Third, we display results for the N=4 band and comment on the adequacy with data. Fourth, we focus on the P13 states and discuss how the P13 width problem might be understood in the frame of the model. Finally we draw some conclusions and outlook.

The Hamiltonian we use here has a spin-independent part H_0 and a hyperfine interaction part H^{hyp}. H_0 reads [8]

$$H_0 = \sum_i \left(p_i^2 + m^2\right)^{1/2} + \frac{1}{2}\sum_{i<j} \frac{-4\alpha_s}{3r_{ij}} + \sqrt{\sigma}\sum_i |\vec{r}_i - \vec{r}_4| + E_{0B} \qquad (1)$$

where r_4 is the point of equilibrium energy of the 3q configuration. The kinetic energy term is relativistic. The values of α_s and $\sqrt{\sigma}$ are respectively $\frac{4}{3}\ \alpha_s = 0.5$ and $\sqrt{\sigma} = 1$ GeV/fm. E_{0B} is adjusted so that the nucleon mass equals 939 MeV. The hyperfine part has a spin-spin and a tensor term but no spin-orbit terms, the effect of which is expected to be of a lesser magnitude in baryons [14]. A finite quark size Λ is used to regularize H^{hyp} at the origin. For the ground state we use the variational solution ψ_{00}^S of ref. [8].

The breaking of the flux tube produces a $q\bar{q}$ pair which bears the quantum numbers of the vacuum $J^{PC} = 0^{++}$. The transition amplitude for a baryon resonance B^* decaying into a baryon B and a meson M reads [15]

$$\left\langle BM\,|T|\,B^{*}\right\rangle = \sum_m \langle 11\ m\ -\ m\,|00\rangle \times \langle \phi_B\phi_M\,|\phi_{B^*}\phi_{vac}^{-m}\rangle\ \Im\left(B^{*};B,M\right) \qquad (2)$$

where the ϕ's denote the flavour spin structure. The last factor is an overlap integral containing configuration space hadron wavefunctions ψ's and the nonlocal $q\bar{q}$ emission operator [15], containing only one parameter, that is the flux tube breaking amplitude, set to reproduce the $\Delta(1232) \to N\pi$ width.

To test H_0, we calculate the expectation values associated with the N=4 configuration space wavefunctions. Setting E_{0B} so that the degenerate nucleon-delta mass be 1086 MeV, we display results on fig. 1. This shows that the band in which the corresponding values are included, ranging from 2367 MeV for the 4S state to 2580 MeV for the 3M state (M standing for mixed symmetry in configuration space) overlaps with the observed Δ spectrum and is slightly above the $N\frac{9}{2}^+$ state. As one expects the hyperfine interaction to lower the first nucleon state, one can conclude that the basic features of the spin-independent part of the Hamiltonian bear no hint of being inappropriate to the N=4 sector. Tuning up the spin-spin part of the hyperfine interaction, with $\Lambda = 0.09$ fm,

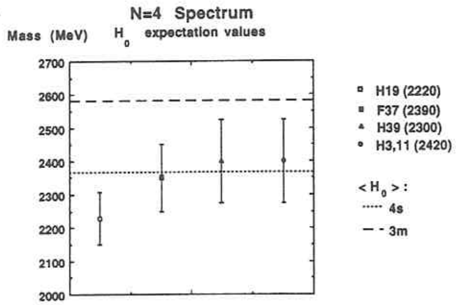

Figure 1 : N=4 states mass spectrum (MeV) ; H_0 expectation values vs data from ref. [19]. The dotted line stands for the L=4 symmetric state. The dashed line stands for the L=3 mixed symmetry state. Vertical lines are error bars.

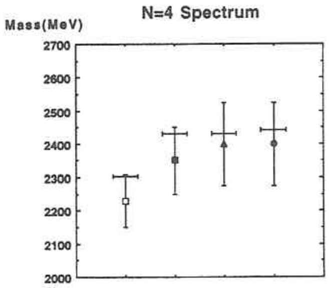

Figure 2 : N=4 states mass spectrum (MeV) ; masses calculated from the Hamiltonian (1)-(3), without tensor (horizontal segments) vs data as in fig. 1.

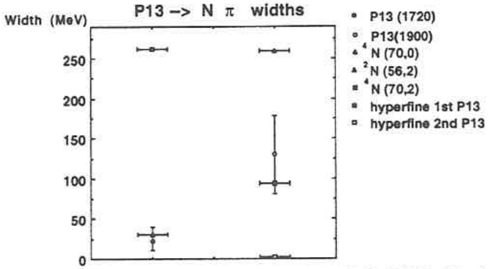

Figure 3 : P13 → Nπ widths (MeV). Circles stand for data : P13 (1720) (black, left ; from ref. [5]) and P13 (1900) (white, right ; from ref. [19]). Calculated widths are represented, using horizontal segments by : black (white) square : full Hamiltonian prediction, first (second) state ; black (white) triangle : pure ^{4}N(70,0) (^{2}N(56,2)) configuration ; dotted square : pure ^{4}N(70,2) configuration.

m = 360 MeV which ensures correct Δ (1232) -N and Roper-N splittings [3], we obtain the masses reported on fig. 2. All model values stay inside the experimental error interval, somewhat higher than the mean value. This is rather satisfying, as the wavefunctions are variational solutions.

Let's come now to the second focus of the talk, the P13 → Nπ width calculation. Fig. 3 displays the width calculation for various allowed symmetries, compared with the experimental data [5]. The experimental Nπ width of P13 (1720) ranges from 10 to 40 MeV in the PDG summary table. A second state, P13 (1900) has been observed by Manley and Saleski [16]. Its Nπ width ranges from 84 to 184 MeV. It is classified as a 2-star by the Particle Data Group. It comes as a striking evidence that the calculated Nπ width of the pure ^{4}N(70,0) symmetry has the order of magnitude of the P13 (1720) observed Nπ width. However, the first P13 eigenstate, of mass 1750 MeV, that is, spectrally "good", exhibits a width of about 260 MeV, one order of magnitude too large. The symmetry of that state is mainly ^{2}N(56,2) with a large ^{2}N(70,2) component. The second predicted P13 state, a mainly

^{4}N(70,0) state with sizeable contributions from all available symmetries, bears a mass of 1915 MeV, spectrally "good" too, but exhibits a very small width. As we stated before, we consider that the decay mechanism of the model, which contains only one parameter, set to reproduce the Δ (1232) → Nπ width, has proven successful enough in predicting widths for states of unambiguous symmetry, so we exclude that order of magnitude deviations could originate from it.

To get a clue of what in particular may be wrong in the model interaction, suppose, as a toy model, we remove the tensor term of the hyperfine potential, keeping the spin-spin term so as to maintain the Δ-N splitting and the Roper-N coupling [3]. This doesn't change the nucleon structure in the Nπ width calculation, but the ^{4}N(70,0$^+$) becomes an unmixed $N\frac{3}{2}^+$ eigenstate, of mass 1710 MeV and width 30 MeV, while the next state becomes a ^{2}N(56,2)-^{2}N(70,2) spin-spin mixed configuration state of mass 1750 MeV and very large (several hundred MeV) width. Such a state could stay unobserved in Partial Wave Analyses.

This tensorless picture would also suggest that P13 (1900) may have a ^{4}N(70,2) symmetry, as the corresponding calculated mass, 1950 MeV, and width, 100 MeV, are compatible with the P13 (1900) data. Of course, we do not claim that this is the solution to the P13 puzzle, but it hints at localizing the origin of the discrepancies in the tensor contribution to configuration mixing.

In conclusion, testing the N=4 part of the spectrum, we found no indication of a specific large N problem in the flux tube constituent quark model. Focusing on the width calculation in the configuration rich $N\frac{3}{2}^+$ sector, we found severe discrepancies which are connected to the tensor part of the hyperfine interaction. One would temptingly conclude that the hyperfine interaction part of the quark model should be revisited before one can trust mixing angle predictions in resonance multiplets.

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