On the nature of the lowest $1/2^-$ baryon nonet and decuplet*

B.S. Zou

Institute of High Energy Physics, CAS, Beijing 100049, China and
Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China

Received: 18 December 2007
Published online: 24 March 2008 – © Società Italiana di Fisica / Springer-Verlag 2008
Communicated by U.-G. Meißner

Abstract. From our recent study of properties of the lowest spin-parity $1/2^-$ baryons, $N^*(1535)$ and $\Delta^*(1620)$, new pictures for the internal structure of the lowest $1/2^-$ baryon nonet and decuplet are proposed. While the lowest $1/2^-$ baryon nonet may have large diquark-diquark-antiquark component, the lowest $1/2^-$ baryon decuplet is proposed to have large vector-meson-baryon components. Evidence for “missing” members of the new pictures is pointed out and suggestions are made for detecting these predicted states from forthcoming experiments.

PACS. 14.20.-c Baryons (including antiparticles) – 13.25.Gv Decays of $J/\psi$, $\Upsilon$ and other quarkonia – 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.)

1 Introduction

The classical simple 3q constituent quark model has been very successful in explaining the static properties, such as mass and magnetic moment, of the spatial ground states of the flavor $SU(3)$ octet and decuplet baryons. Its predicted $\Omega$ baryon with mass around 1670 MeV was discovered by later experiments. However, its predictions for the spatial excited baryons are not so successful. In the simple 3q constituent quark model, the lowest spatial excited baryon is expected to be a $(uud)$ state with one quark in orbital angular momentum $L = 1$ state, and hence should have negative parity. Experimentally [1], the lowest negative-parity $N^-$-resonance is found to be $N^*(1535)$, which is heavier than two other spatial excited baryons: $\Lambda^*(1405)$ and $N^*(1440)$. In the classical 3q constituent quark model, the $\Lambda^*(1405)$ with spin-parity $1/2^-$ is supposed to be a $(uds)$ baryon with one quark in orbital angular momentum $L = 1$ state and about 130 MeV heavier than its $N^*$ partners $N^*(1535)$; the $N^*(1440)$ with spin-parity $1/2^+$ is supposed to be a $(ud\bar{s})$ state with one quark in radial $n = 1$ excited state and should be heavier than the $L = 1$ excited $(u\bar{d}s)$ state $N^*(1535)$, noting the fact that for a simple harmonic-oscillator potential the state energy is $(2n + L + 3/2)\hbar\omega$. So for these three lowest spatial excited baryons, the classical quark model picture is already failed.

Evidence is accumulating for the existence of significant intrinsic non-perturbative 5-quark components in baryons [2]. A well-established fact from electron-proton deep inelastic scattering and Drell-Yan process is that in the proton the number of $\bar{d}$ is more than $\bar{u}$ by an amount $\bar{d} - \bar{u} \approx 0.12$ [3]. This obviously cannot be explained by the classical quark models, but can be easily explained by a mixture of $n(udd)\pi^+(ud)$ in the meson-cloud model [4] or $[ud][ud]\bar{d}$ penta-quark configuration [5]. If there are already significant 5-quark components in the proton, one would expect more significant 5-quark components in excited baryons.

To understand the full baryon spectroscopy, it is crucial to understand the lowest $1/2^-$ baryon nonet and decuplet first!

2 The nature of $N^*(1535)$ and its $1/2^-$ nonet partners

Recently, the BES experiment at Beijing Electron-Positron Collider (BEPC) has been producing very useful information on $N^*$-resonances [6–9]. In $J/\psi \to \bar{p}\eta\eta$, as expected, the $N^*(1535)$ gives the largest contribution [6]. In $J/\psi \to pK^-\bar{A} + c.c.$, a strong near-threshold enhancement is observed for $KA$ invariant-mass spectrum [7] as duplicated in fig. 1. The $KA$ threshold is 1609 MeV. The near-threshold enhancement is confirmed by $J/\psi \to nK^-\bar{A} + c.c.$ [9]. Since the mass spectrum divided by efficiency and phase space peaks at threshold, it is natural to assume it comes from the sub-threshold nearby the $N^*(1535)$-resonance. Then from BES measured branching ratios of $J/\psi \to \bar{p}\eta\eta$ [6] and $\psi \to pK^-\bar{A} + c.c.$ [7], the ratio

* Original article based on material presented at NSTAR 2007.

a e-mail: zoubs@ihep.ac.cn
between effective coupling constants of \( N^*(1535) \) to \( K\Lambda \) and \( N\eta \) is deduced to be \([10]\)

\[
g_{N^*(1535)K\Lambda}/g_{N^*(1535)N\eta} = 1.3 \pm 0.3.
\]

With the previous known value of \( g_{N^*(1535)N\eta} \), the obtained new value of \( g_{N^*(1535)K\Lambda} \) is shown to reproduce recent \( pp \to pK^+\Lambda \) near-threshold cross-section data \([11]\) as well. There are also indications for the large \( g_{N^*(1535)K\Lambda} \) from partial-wave analysis of \( \gamma p \to K\Lambda \) reactions \([12]\). Taking into account this large \( N^*K\Lambda \) coupling in the coupled-channel Breit-Wigner formula for the \( N^*(1535) \), its Breit-Wigner mass is found to be around 1400 MeV, much smaller than the previous value of about 1535 MeV obtained without including its coupling to \( K\Lambda \).

The nearly degenerate mass for the \( N^*(1535) \) and the \( N^*(1440) \) resonances can be easily understood by considering 5-quark components in them \([10,16]\). The \( N^*(1535) \) could be the lowest \( L = 1 \) orbital excited \([ud][us]s\) pentaquark component, with a large admixture of \([ud][us]\bar{s}\) in the ground state. The \( N^*(1440) \) could be the lowest radial excited \([ud][us]d\) pentaquark component having two \([ud][us]\bar{s}\) pentaquark component having two \([ud][us]\bar{s}\) diquarks in the relative P-wave.

The lighter \( \Lambda^*(1405)1/2^- \) is also understandable in this picture. Its main 5-quark configuration is \([|ud][us]\bar{s}|\) which is lighter than the corresponding 5-quark configuration \([|ud][us]\bar{s}|\) in the \( N^*(1535)1/2^- \).

If this picture of large 5-quark mixture is correct, there should also exist the \( SU(3) \) nonet partners of the \( N^*(1535) \) and \( \Lambda^*(1405) \), i.e., an additional \( \Lambda^*1/2^- \) around 1570 MeV, a triplet \( \Sigma^* 1/2^- \) around 1360 MeV and a doublet \( \Xi^* 1/2^- \) around 1520 MeV \([16]\). There is no hint for these baryon resonances in the PDG tables \([1]\). However, as pointed out in ref. \([2]\), there is in fact evidence for all of them in the data of \( J/\psi \) decays. According to PDG \([1]\), the branching ratios for \( J/\psi \to \Sigma^-\Sigma^*(1385)^+ \) and \( J/\psi \to \Xi^+\Xi^*(1530)^- \) are \((3.1 \pm 0.5) \times 10^{-4} \) and \((5.9 \pm 1.5) \times 10^{-4} \), respectively. These two processes are \( SU(3) \) breaking decays since \( \Sigma \) and \( \Xi \) belong to \( SU(3) 1/2^+ \) octet, while \( \Sigma^* \) (1385) and \( \Xi^* \) (1530) belong to \( SU(3) 3/2^+ \) decuplet. Comparing with the similar \( SU(3) \) breaking decay \( J/\psi \to \rho \Delta^+ \) with branching ratio of less than \( 1 \times 10^{-4} \) and the \( SU(3) \) conserved decay \( J/\psi \to \rho N^*(1535)^+ \) with branching ratio of \((10 \pm 3) \times 10^{-4} \), the branching ratios for \( \Lambda^*1/2^- \) are puzzling too high. A possible explanation for this puzzling phenomena is that there were substantial components of \( 1/2^- \) under the \( 3/2^+ \) peaks but the two branching ratios were obtained by assuming pure \( 3/2^+ \) contribution. This possibility should be easily checked with the high-statistics BESIII data in the near future.

The nature of \( \Delta^{++}(1620) \) and its \( 1/2^- \) decuplet partners

The spectrum of the isospin \( 3/2 \) \( \Delta^{++} \) resonances is of special interest since it is the most experimentally accessible system composed of 3 identical valence quarks. However, our knowledge on these resonances mainly comes from old \( \pi N \) experiments and is still very poor \([1]\). A possible new excellent source for studying \( \Delta^{++} \) resonances is the \( pp \to nK^+\Sigma^+ \) reaction, which has a special advantage for the absence of complication caused by \( N^* \) contribution because of the isospin and charge conservation.

At present, little is known about the \( pp \to nK^+\Sigma^+ \) reaction. Experimentally, there are only a few data points about its total cross-section vs. energy \([17,18]\). Theoretically, a resonance model with an effective intermediate \( \Delta^{++}(1920) \)-resonance \([19]\) and the Jülich meson exchange model \([20]\) reproduce the old data at higher beam energies \([17]\) quite well, but their predictions for the cross-sections close to threshold fail by order of magnitude compared with very recent COSY-11 measurement \([18]\). Recently, this reaction was restudied \([21]\). With an effective Lagrangian approach, contributions from a previous ignored \( sub-K^+\Sigma^+ \) threshold resonance \( \Delta^{++}(1620)1/2^- \) are fully included in addition to those already considered in previous calculations. It is found that the \( \Delta^{++}(1620) \)-resonance gives an overwhelmingly dominant contribution for energies very close to threshold, with a very important contribution from the \( t \)-channel \( \rho \) exchange as shown in

![Invariant-mass spectrum divided by efficiency and phase space vs. \( M_{K\Lambda} - M_K - M_\Lambda \) for \( J/\psi \to pK^-\Lambda + \text{c.c.} \) \([7]\).](image-url)