Evidence for Some New Hyperon Resonances - to be Checked by K_L Beam Experiments

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Abstract

Quenched and unquenched quark models predict very different patterns for the spectrum of the low excited hyperon states. Evidence is accumulating for the existence of some new hyperon resonances, such as a Σ^* of spin-parity $J^P = 1/2^-$ around 1400 MeV instead of 1620 MeV as listed in PDG, a new $\Sigma(1540)3/2^-$ resonance, a new narrow $\Lambda(1670)3/2^-$ resonance and a new $\Lambda(1680)3/2^+$ resonance. All these new hyperon resonances fit in the predicted pattern of the unquenched quark models very well. It is extremely important to check and establish the spectrum of these low excited hyperon states by the proposed K_L beam experiments at JLAB.

I.   WHY HYPERON RESONANCES ?

Creation of quark-anti-quark pairs from gluon field plays a crucial role for understanding quark confinement and hadron spectroscopy. In the classical quenched quark model for a $q_1\bar{q}_1$ meson, the q_1 quark cannot be separated from the $\bar{q}_1$ anti-quark due to a infinitely large confinement potential. But in realty, we know the q_1 and $\bar{q}_1$ can be easily separated from each other by creation of another quark-anti-quark pair $q_2\bar{q}_2$ to decay to two mesons, $q_1\bar{q}_2$ and $q_2\bar{q}_1$. With the creation of the $q_2\bar{q}_2$, instead of forming two colorless mesons, the system could also exist in the form of a tetra-quark state $[q_1q_2][\bar{q}_1\bar{q}_2]$. Therefore both lattice QCD and quark models should go beyond the quenched approximation which ignore the creation of quark-anti-quark pairs.

Quenched qqq quark models and unquenched $qqq \leftrightarrow qqqq\bar{q}$ quark models give very different predictions for the hyperon spectroscopy. For example, for the $J^P = \frac{1}{2}^-$ SU(3) nonet partners of the $N(1535)$ and $\Lambda(1405)$. While quenched quark models [1–4] predict the $J^P = \frac{1}{2}^-$ Σ and Ξ resonances to be around 1650 MeV and 1760 MeV, respectively, the unquenched quark models [5–7] expect them to be around 1400 MeV and 1550 MeV, respectively, a meson-soliton bound-state approach of the Skyrme model [8] and other meson-baryon dynamical models [9, 10] predict them to be around 1450 MeV and 1620 MeV, respectively. In Fig.1, we show prediction of the lowest penta-quark states with $J^P = 1/2^\pm, 3/2^\pm$ [5, 6] (red solid) compared with those from the classical quenched qqq model [1] (black solid). The major differences are that the lowest penta-quark hyperon states with $J^P = 1/2^-$ and $3/2^+$ are about 200 MeV lower those from the classical quenched qqq models [1].

Although various phenomenological models give distinguishable predictions for the lowest excited hyperon states, most of them are not experimentally established or even listed in PDG [11]. Most of our knowledge for the hyperon resonances came from analyses of old $\overline{K}N$ experiments in the 1970s [11]. In the new century, some new measurements from Crystal Ball (CB) [12–14], LEPS [15] and CLAS [16] have started to provide us new information on Σ^* and Λ^* resonances. It is crucial to use them to clarify the spectrum of low-lying hyperon resonances to pin down the underlying dynamics for baryon spectrum and structure. Recent analyses of these new data together with old data reveal some interesting new features of the low-lying excited hyperon states. Here I will give a brief review of these new results and

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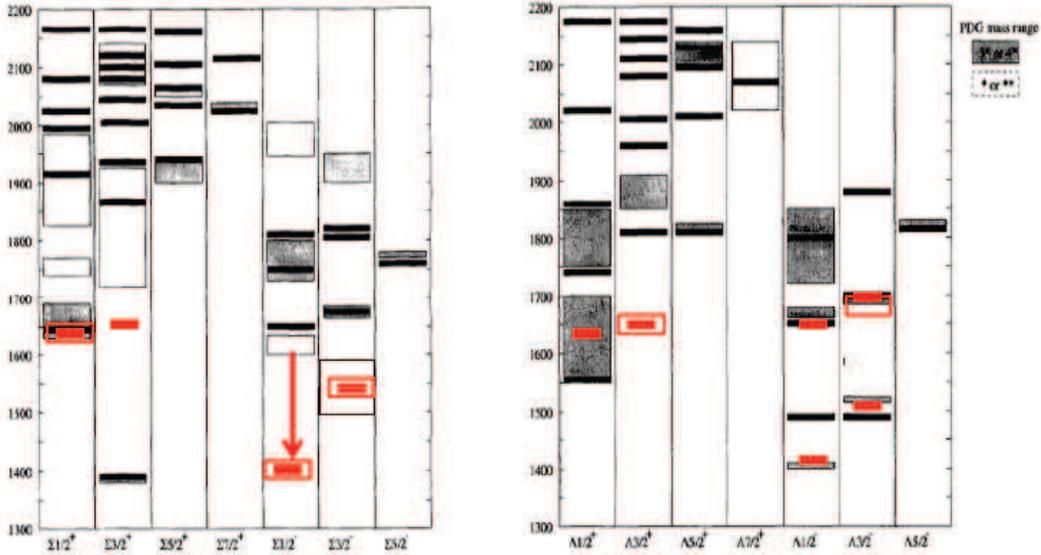
FIG. 1: Prediction of the lowest penta-quark states with $J^P = 1/2^\pm, 3/2^\pm$ [5, 6] (red solid) compared with those from the classical quenched qqq model [1] (black solid). The black boxes are experimental results from PDG while the red box are from recent new analyses.

discuss about their further confirmation from the proposed K_L beam and other experiments.

II. NEW RESULTS ON Σ^* AND Λ^* RESONANCES

A. On the lowest Σ^* resonances with negative parity

The lowest Σ^* resonances with $J^P = 1/2^-$ or $3/2^-$ are still far from established. There is a $\Sigma(1620)\frac{1}{2}^-$ listed as a 2-star resonance in the previous versions of PDG tables and downgraded to 1-star in the newest version [11]. There is also a $\Sigma(1580)\frac{3}{2}^-$ listed as 1-star resonance [11].

The $\Sigma(1620)\frac{1}{2}^-$ seems supporting the prediction of quenched quark models. However, for the 2-star $\Sigma(1620)\frac{1}{2}^-$ resonance, only four references [17–20] are listed in PDG tables with weak evidence for its existence. Among them, Ref. [17] and Ref. [18] are based on multi-channel analysis of the $\overline{K}N$ reactions. Both claim evidence for a $\Sigma(\frac{1}{2}^-)$ resonance with mass around 1620 MeV, but give totally different branching ratios for this resonance. Ref. [17] claims that it couples only to $\pi\Lambda$ and not to $\pi\Sigma$ while Ref. [18] claims the opposite way. Both analyses do not have $\Sigma(1660)\frac{1}{2}^+$ in their solutions. However, Ref. [21] shows no sign of $\Sigma(\frac{1}{2}^-)$

resonance between 1600 and 1650 MeV through analysis of the reaction $\overline{K}N \to \Lambda\pi$ with the c.m. energy in the range of 1540-2150 MeV, instead it suggests the existence of $\Sigma(1660)\frac{1}{2}^{+}$. Later multi-channel analyses of the $\overline{K}N$ reactions support the existence of the $\Sigma(1660)\frac{1}{2}^{+}$ instead of $\Sigma(1620)\frac{1}{2}^{-}$ [11]. In Ref. [19], the total cross sections for K^-p and K^-n with all proper final states are analyzed and indicate some Σ resonances near 1600 MeV without clear quantum numbers. Ref. [20] analyzes the reaction $K^-n \to \pi^-\Lambda$ and gets two possible solutions, with one solution indicating a $\Sigma(\frac{1}{2}^{-})$ near 1600 MeV, and the other showing no resonant structure below the $\Sigma(1670)$. So all these claims of evidence for the $\Sigma(1620)\frac{1}{2}^{-}$ are very shaky. Instead, some re-analyses of the $\pi\Lambda$ relevant data suggest that there may exist a $\Sigma(\frac{1}{2}^{-})$ resonance around 1380 MeV [22], which supports the prediction of unquenched quark models [5, 6]. This is supported by the new CLAS data on $\gamma p \to K\Sigma\pi$ [16], although a more delicate analysis [23] of the data suggests the resonant peak to be at a higher mass around 1430 MeV.

For the study of Σ resonances, the $\bar{K}N \to \pi\Lambda$ reaction is the best available channel, where the s-channel intermediate states are purely hyperons with strangeness $S = -1$ and isospin $I = 1$. Recently, high statistic new data for the reaction $K^-p \to \pi^0\Lambda$ are presented by the Crystal Ball collaboration with the c.m. energy of 1560-1676 MeV for both differential cross sections and Λ polarizations [13]. In order to clarify the status of the $\Sigma(1620)\frac{1}{2}^{-}$ and the $\Sigma(1660)\frac{1}{2}^{+}$, we analyzed the differential cross sections and Λ polarizations for both $K^-p \to \pi^0\Lambda$ and $K^-n \to \pi^-\Lambda$ reactions with an effective Lagrangian approach, using the new Crystal Ball data on $K^-p \to \pi^0\Lambda$ with the c.m. energy of 1560-1676 MeV [13], and the $K^-n \to \pi^-\Lambda$ data of Ref. [20] with the c.m. energy of 1550-1650 MeV, where the evidence of the $\Sigma(1620)\frac{1}{2}^{-}$ was claimed. The new Crystal Ball data clearly shows that the Crystal Ball Λ polarization data demand the existence of a Σ resonance with $J^P = \frac{1}{2}^{+}$ and mass near 1635 MeV [24], compatible with $\Sigma(1660)\frac{1}{2}^{+}$ listed in PDG, while the $\Sigma(1620)\frac{1}{2}^{-}$ is not needed by the data. The differential cross sections alone cannot distinguish the two solutions with either $\Sigma(1660)\frac{1}{2}^{+}$ or $\Sigma(1620)\frac{1}{2}^{-}$.

This analysis also suggests a possible $\Sigma(\frac{3}{2}^{-})$ resonance with mass around 1542 MeV and width about 25.6 MeV. This seems consistent with the resonance structure $\Sigma(1560)$ or $\Sigma(1580)\frac{3}{2}^{-}$ in PDG and compatible with expectation from penta-quark model [5]. Ref. [25] also proposes a $\Sigma(\frac{3}{2}^{-})$ resonance with mass around 1570 MeV and width about 60 MeV from $\overline{K}N\pi$ system.

After our analysis, there were three groups [26–28] having made more sophisticated coupled channel analysis of the $\bar{K}N$ scattering data including those from the Crystal Ball experiment. The newest analysis [28] gives roughly consistent results for the lowest $\Sigma^*(1/2^\pm)$ resonances as ours. In both analyses, there is no $\Sigma(1620)1/2^-$. While in our analysis, the $\Sigma(1635)1/2^+$ is definitely needed, in Ref.[28], the $\Sigma(1635)1/2^+$ is split to two $1/2^+$ resonances: $\Sigma(1567)$ and $\Sigma(1708)$. The other two analyses claim the need of the $\Sigma(1620)1/2^-$, but with much lower energy at 1501 MeV [26] and 1551 MeV [27], respectively.

For the lowest $\Sigma^*(3/2^-)$, Ref.[27] gives a similar result as ours with mass around 1550 MeV. Refs.[26, 28] give a higher mass around 1670 MeV.

So there are strong evidences for the lowest $\Sigma^*(1/2^-)$ to be in the range of 1380 $\sim$ 1500 MeV and the lowest $\Sigma^*(3/2^-)$ to be around 1550 MeV. But this is not conclusive.

B. On the lowest $\Lambda^*(3/2^\pm)$ resonances

Many studies have been carried out to investigate the Λ resonances. Oset et al. [29, 30] used a chiral unitary approach for the meson-baryon interactions and got two $J^P = \frac{1}{2}^-$ resonances with one mass near 1390 MeV and the other around 1420 MeV. They believe the well established $\Lambda(1405)\frac{1}{2}^-$ resonance listed in PDG [11] is actually a superposition of these two $\frac{1}{2}^-$ resonances. Manley et al. [26] and Kamano et al. [27] made multichannel partial-wave analysis of $\overline{K}N$ reactions and got results with some significant differences. Zhong et al. [31] analyzed the $K^-p \to \pi^0\Sigma^0$ reaction with the chiral-quark model and discussed characteristics of the well established Λ resonances. Liu et al. [32] analyzed the $K^-p \to \eta\Lambda$ reaction [12] with an effective Lagrangian approach and implied a D03 resonance with mass about 1670 MeV but much smaller width compared with the well established $\Lambda(1690)\frac{3}{2}^-$. So there are still some ambiguities of the Λ resonant structures needing to be clarified.

Recently, the most precise data on the differential cross sections for the $K^-p \to \pi^0\Sigma^0$ reaction have been provided by the Crystal Ball experiment at AGS/BNL [13, 14]. The Σ^0 polarization data were presented for the first time. However, with different data selection cuts and reconstructions, two groups in the same collaboration, *i.e.*, VA group [14] and UCLA group [13], got inconsistent results for the Σ^0 polarizations. Previous multi-channel analysis-[26, 27, 31] of the $\overline{K}N$ reactions failed to reproduce either set of the polarization data.

In our recent work [33], we concentrate on the most precise data by the Crystal Ball collaboration on the pure isospin scalar channel of $\overline{K}N$ reaction to see what are the Λ resonances the data demand and how the two groups' distinct polarization data [13, 14] influence the spectroscopy of Λ resonances. Consistent differential cross sections of earlier work by Armenteros et al. [34] at lower energies are also used. It is found that the 4-star $\Lambda(1670)\frac{1}{2}^-$ and 3-star $\Lambda(1600)\frac{1}{2}^+$ resonances listed in PDG [11] are definitely needed no matter which set of CB data is used. In addition, there is strong evidence for the existence of a new $\Lambda(\frac{3}{2}^+)$ resonance around 1680 MeV no matter which set of data is used. It gives large contribution to this reaction, replacing the contribution from the 4-star $\Lambda(1690)\frac{3}{2}^-$ resonance included by previous fits to this reaction.

Replacing the PDG $\Lambda(1690)\frac{3}{2}^-$ resonance by a new $\Lambda(1680)\frac{3}{2}^+$ resonance has important implications on hyperon spectroscopy and its underlying dynamics. While the classical qqq constituent quark model [2] predicts the lowest $\Lambda(\frac{3}{2}^+)$ resonance to be around 1900 MeV in consistent with the $\Lambda(1890)\frac{3}{2}^+$ listed in PDG, the penta-quark dynamics [5] predicts to be below 1700 MeV in consistent with $\Lambda(1680)\frac{3}{2}^+$ claimed in this work.

A recent analysis [32] of CB data on the $K^-p \to \eta\Lambda$ reaction requires a $\Lambda(\frac{3}{2}^-)$ resonance with mass about 1670 MeV and width about 1.5 MeV instead of the well established $\Lambda(1690)\frac{3}{2}^-$ resonance with width around 60 MeV. Together with $N^*(1520)\frac{3}{2}^-$, $\Sigma(1542)\frac{3}{2}^-$ suggested in Ref. [24] and either $\Xi(1620)$ or $\Xi(1690)$, they fit in a nice $3/2^-$ baryon nonet with large penta-quark configuration, i.e., $N^*(1520)$ as $|[ud]\{uq\}\bar{q}>$ state, $\Lambda(1520)$ as $|[ud]\{sq\}\bar{q}>$ state, $\Lambda(1670)$ as $|[ud]\{ss\}\bar{s}>$ state, and $\Xi(16xx)$ as $|[ud]\{ss\}\bar{q}>$ state. Here $\{q_1q_2\}$ means a diquark with configuration of flavor representation **6**, spin 1 and color $\bar{3}$. The $\Lambda(1670)$ as $|[ud]\{ss\}\bar{s}>$ state gives a natural explanation for its dominant $\eta\Lambda$ decay mode with a very narrow width due to its very small phase space meanwhile a D-wave decay [35].

Recent analyses [27, 28] also support possible existence of the $\Lambda(1680)\frac{3}{2}^+$, but with a narrower width.

III. SUMMARY AND PROSPECTS

Taking into account new data from Crystal Ball (CB) [12–14], LEPS [15] and CLAS [16], new analyses show strong evidences for the lowest $\Sigma^*(1/2^-)$ to be in the range of 1380 $\sim$ 1500 MeV, the lowest $\Sigma^*(3/2^-)$ to be around 1550 MeV and the lowest $\Lambda^*(3/2^+)$ to be around

1680 MeV. There is also evidence for a very narrow $\Lambda^*(3/2^-)$ around 1670 MeV decaying to $\Lambda\eta$. All these new hyperon resonances fit in the expected pattern of unquenched quark models very well. It is very important to pin down the existence of these new resonances.

Various processes could be used to study these hyperon resonances. The neutrino induced hyperon production processes $\bar\nu_{e/\mu} + p \to e^+/\mu^+ + \pi + \Lambda/\Sigma$ may provide a unique clean place for studying low energy $\pi\Lambda/\Sigma$ interaction and hyperon resonances below KN threshold [36]. With plenty production of Λ_c at BESIII, JPARC, BelleII, $\Lambda_c^+ \to \pi^+\pi^0\Lambda$ could also be used to study Σ^*. The K^-, K_L beam experiments at JPARC and Jlab could provide an elegant new source for Λ^*, Σ^* and Ξ^{**} hyperon spectroscopy. $K_L p \to \Lambda\pi^+$, $\Sigma^0\pi^+$, $\Sigma^+\pi^0$, $\Sigma^{*0}\pi^+$, $\Sigma^{*+}\pi^0$ could pin down the $\Sigma^*(1540)3/2^-$; $K_L p \to \Sigma^0\pi^0\pi^+$, $\Lambda\pi^0\pi^+$ could shed light on the $\Sigma*(1380 \sim 1500)1/2^-$, $\Sigma^*(1540)3/2^-$, $\Lambda^*(1680)3/2^+$; $K_L p \to \Sigma^0\eta\pi^+$, $\Lambda\eta\pi^+$ may check $\Sigma^*(1380 \sim 1500)1/2^-$, $\Sigma^*(1540)3/2^-$, $\Lambda^*(1670)3/2^-$. We believe the proposed K_L beam experiments at JLAB could settle down the spectrum of the low excited hyperon states which provide complimentary information to the study of penta-quark states with hidden charm [37, 38] and play a crucial role for understanding the hadron dynamics and hadron structure.

Acknowledgments

[1] S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. **45**, S241 (2000).

[2] S. Capstick and N. Isgur, Phys.Rev. **D34**, 2809 (1986).

[3] L.Y. Glozman and D.O. Riska, Phys.Rept. **268**, 263 (1996).

[4] U. Loring, B.C. Metsch and H.R. Petry, Eur.Phys.J. A**10**, 395 (2001).

[5] C. Helminen and D.O. Riska, Nucl. Phys. **A699**, 624 (2002).

[6] A. Zhang *et al.*, High Energy Phys. Nucl. Phys. **29**, 250 (2005).

[7] B.S. Zou, Nucl. Phys. **A835**, 199 (2010); Eur. Phys. J. **A35**, 325 (2008); B. C. Liu and B. S. Zou, Phys. Rev. Lett. **96**, 042002 (2006).

[8] Y. Oh, Phys. Rev. **D75**, 074002 (2007).

[9] K.P. Khemchandani *et al.*, Phys. Rev. D **84**, 094018 (2011).

[10] A. Ramos, E. Oset, and C. Bennhold, Phys. Rev. Lett. **89**, 252001 (2002).

[11] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014).

[12] A. Starostin *et al.* [Crystal Ball Collaboration], Phys. Rev. C **64**, 055205 (2001).

[13] S. Prakhov *et al.*, Phys. Rev. C **80, 025204** (2009).

[14] R. Manweiler *et al.*, Phys. Rev. C **77, 015205** (2008).

[15] K. Hicks et al. (LEPS Collaboration), Phys. Rev. Lett. **102, 012501** (2009).

[16] K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. C **87**, 035206 (2013).

[17] J.K. Kim, Phys.Rev.Lett. **27**, 356 (1971).

[18] W. Langbein and F. Wagner, Nucl.Phys. B**47**, 477 (1972).

[19] A.S. Carroll *et al.*, Phys.Rev.Lett. **37**, 806 (1976).

[20] W.A. Morris *et al.*, Phys.Rev. D**17**, 55 (1978).

[21] P. Baillon and P.J. Litchfield, Nucl.Phys. B**94**, 39 (1975).

[22] J.J. Wu, S. Dulat, and B.S. Zou, Phys. Rev. **D80**, 017503 (2009); Phys. Rev. **C81**, 045210 (2010); P. Gao, J.J. Wu, and B.S. Zou, Phys. Rev. **C81**, 055203 (2010); J. J. Xie, J. J. Wu and B. S. Zou, Phys. Rev. C **90**, 055204 (2014).

[23] L. Roca and E. Oset, Phys. Rev. C **88**, 055206 (2013).

[24] P. Gao, J. Shi and B. S. Zou, Phys. Rev. C **86**, 025201 (2012); P. Gao, B. S. Zou, and A. Sibirtsev, Nucl. Phys. **A867**, 41 (2011).

[25] A. Gal, H. Garcilazo, Nucl. Phys. **A864**, 153 (2011).

[26] H. Zhang, J. Tulpan, M. Shrestha and D. M. Manley, Phys. Rev. C **88**, 035205 (2013).

[27] H. Kamano, S. X. Nakamura, T.-S. H. Lee and T. Sato, Phys. Rev. C **92**, 025205 (2015).

[28] C. Fernandez-Ramirez, I. V. Danilkin, D. M. Manley, V. Mathieu and A. P. Szczepaniak, Phys. Rev. D **93**, 034029 (2016).

[29] D. Jido *et al.*, Nucl. Phys. **A 725**, 181 (2003).

[30] V. K. Magas, E. Oset, and A. Ramos, Phys. Rev. Lett. 95, 052301 (2005).

[31] X. H. Zhong and Q. Zhao, Phys. Rev. **C 79**, 045202 (2009); Phys. Rev. **C 88**, 015208 (2013).

[32] B. C. Liu and J. J. Xie, Phys. Rev. **C 85**, 038201 (2012); Phys. Rev. C **86**, 055202 (2012).

[33] J. Shi and B. S. Zou, Phys. Rev. C **91**, 035202 (2015).

[34] R. Armenteros *et al.*, Nucl. Phys. **B 21**, 15 (1970).

[35] B. S. Zou, Nucl. Phys. A **914**, 454 (2013).

[36] J. J. Wu and B. S. Zou, Few Body Syst. **56**, no. 4-5, 165 (2015).

[37] J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. **105**, 232001 (2010); Phys. Rev. C **84**, 015202 (2011).

[38] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115**, 072001 (2015).