Available online at www.sciencedirect.com
SCIENCE DIRECT®

Physics Letters B 605 (2005) 137–143

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Roper resonance and $S_{11}(1535)$ from lattice QCD

N. Mathur [a], Y. Chen [b], S.J. Dong [a], T. Draper [a], I. Horváth [a], F.X. Lee [c,d], K.F. Liu [a], J.B. Zhang [e]

[a] *Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA*
[b] *Institute of High Energy Physics, Chinese Academy of Science, Beijing 100039, China*
[c] *Center for Nuclear Studies, Department of Physics, George Washington University, Washington, DC 20052, USA*
[d] *Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, USA*
[e] *CSSM and Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, SA 5005, Australia*

Received 22 October 2004; received in revised form 3 November 2004; accepted 4 November 2004

Editor: P.V. Landshoff

Abstract

Using the constrained-curve fitting method and overlap fermions with the lowest pion mass at 180 MeV, we observe that the masses of the first positive and negative parity excited states of the nucleon tend to cross over as the quark masses are taken to the chiral limit. Both results at the physical pion mass agree with the experimental values of the Roper resonance ($N^{1/2+}(1440)$) and S_{11} ($N^{1/2-}(1535)$). This is seen for the first time in a lattice QCD calculation. These results are obtained on a quenched Iwasaki $16^3 \times 28$ lattice with $a = 0.2$ fm. We also extract the ghost $\eta' N$ states (a quenched artifact) which are shown to decouple from the nucleon interpolation field above $m_\pi \sim 300$ MeV. From the quark mass dependence of these states in the chiral region, we conclude that spontaneously broken chiral symmetry dictates the dynamics of light quarks in the nucleon.

The Roper resonance has been studied extensively, but its status as the first excited state of the nucleon with the same quantum numbers is intriguing. Although awarded four stars in the Particle Data Table, it is not as easily identifiable as other resonances. It does not show up as a peak in the cross sections in various experiments; rather its existence is revealed through phase shift analysis [1,2]. Furthermore, the theoretical situation is in a quandary. First of all, it has been noted for a long time that it is rather unusual to have the first positive parity excited state lower than the negative parity excited state which is the $N^{1/2-}(1535)$ in the S_{11} πN channel. This is contrary to the excitation pattern in the meson sectors with either light or heavy quarks. This parity reversal has caused problems for the otherwise successful quark models based on $SU(6)$ symmetry with color–spin interaction be-

---

E-mail address: liu@pa.uky.edu (K.F. Liu).

0370-2693/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.physletb.2004.11.010

tween the quarks [3] which cannot accommodate such a pattern. Realistic potential calculations with linear and Coulomb potentials [4] and the relativistic quark model [5] all predict the Roper to be ∼ 100–200 MeV above the experimental value with the negative parity state lying lower. On the other hand, the pattern of parity reversal was readily obtained in the chiral soliton model like the Skyrme model via the small oscillation approximation to πN scattering [6]. Although the first calculation [7] of the original skyrmion gives rise to a breathing mode which is ∼ 200 MeV lower than the Roper resonance, it was shown later [8] that the introduction of the sixth order term, which is the zero range approximation for the ω meson coupling, changes the compression modulus, yielding better agreement with experiment for both the mass and width in πN scattering.

Since the quark potential model is based on the $SU(6)$ symmetry with residual color–spin interaction between the quarks, whereas the chiral soliton model is based on spontaneous broken chiral symmetry, their distinctly different predictions on the ordering of the positive and negative parity excited states may be a reflection of different dynamics as a direct consequence of the respective symmetry. This possibility has prompted the suggestion [9] that the parity reversal in the excited nucleon and Δ, in contrast to that in the excited Λ spectrum, is an indication that the inter-quark interaction of the light quarks is mainly of the flavor–spin nature rather than the color–spin nature (e.g., one-gluon exchange type.) This suggestion is supported in the lattice QCD study of "Valence QCD" [10] where one finds that the hyperfine splitting between the nucleon and Δ is largely diminished when the Z-graphs in the quark propagator are eliminated. This is an indication that the color-magnetic interaction is not the primary source of the inter-quark spin–spin interaction for light quarks. (The color-magnetic part, being spatial in origin, is unaffected by the truncation of Z-graphs in Valence QCD, which only affects the time part.) Yet, it is consistent with the Goldstone-boson-exchange picture which requires Z-graphs and leads to a flavor–spin interaction.

The failure of the $SU(6)$ quark model to delineate the Roper and its photo-production has prompted the speculation that the Roper resonance may be a hybrid state with excited glue [11] or a $qqqq\bar{q}$ five quark state [12]. Thus, unraveling the nature of Roper resonance has direct bearing on our understanding of the quark structure and chiral dynamics of baryons, which is one of the primary missions at experimental facilities like Jefferson Lab.

Lattice QCD is perhaps the most desirable tool to adjudicate the theoretical controversy surrounding the issue. In fact, there have been several calculations to study the positive-parity excitation of the nucleon [13–18]. However, they have not been able to probe the relevant low quark mass region while preserving chiral symmetry at finite lattice spacing (except Ref. [14] which uses the domain wall fermion). We employ the overlap fermion [19] on a large lattice which admits calculations with realistically small quark masses [20] to study the chiral region. Since the controversy about the nature of Roper hinges on chiral symmetry, it is essential to have a fermion action which explicitly exhibits the correct spontaneously broken chiral symmetry.

Another difficulty of the calculation of the excited states in lattice QCD is that the conventional two-exponential fits are not reliable. Facing the uncertainty of the fitting procedure for the excited state, it has been suggested to use a non-standard nucleon interpolating field which vanishes in the non-relativistic limit [13–16,18], in the hope that it may have negligible overlap with the nucleon so that the Roper state can be seen more readily. However, the lowest state calculated with this interpolation field (2.2 GeV) [13–16,18] is much higher than the Roper state. Employing the maximum entropy method allows one to study the nucleon and its radial excitation with the standard nucleon interpolation field [17]. However, with the pion mass at ∼ 600 MeV, the nucleon radial excitation is still too high (∼ 2 GeV). In order to have a reliable prediction of the excited state in lattice QCD calculations by way of addressing the above mentioned difficulties, we implement constrained curve fitting based on an empirical Bayes method. It has been advocated [21,22] recently as a powerful tool which utilizes more data points while better controlling the systematics.

Since we adopt the quenched approximation, we should mention that there are quenched artifacts. Due to the absence of quark loops in quenched QCD, the would-be η' propagator involves only double η poles in hairpin diagrams. This leads to quenched chiral logs in hadron masses which are clearly observed and extracted from our recent lattice calculation of pion and