Penta Quark Baryon from the QCD Sum Rule

Jun Sugiyama, Takumi Doi and Makoto Oka

Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan

QCD sum rule is applied to the newly found penta-quark state, Θ^+. The parity of the ground state is found to be negative from the positivity condition of the spectral function. The predicted mass of the ground state is consistent with the observed one, 1.54 GeV.

Ordinary hadrons are classified into mesons made of $\bar{q}q$ and baryons of qqq. QCD, however, allows other color singlet states made, for example, of gg, $qqqg$, qqg and $qqq\bar{q}q$. Recently a sharp nK^+ resonance, which is called Θ^+, of mass 1.54 GeV and width $\leq$ 25 MeV was observed at SPring-8.[1] As the Θ^+ is a baryon with strangeness +1, it is exotic in the sense that it contains more than three (constituent) quarks. No corresponding pK^+ resonance is seen, which concludes $I = 0$ for Θ^+. But, other quantum numbers are not determined from the experiments. The structure of Θ^+ is $udud\bar{s}$, if this is the simplest 5-quark system.

This mass and this width indicate serious problem. Although this is 100 MeV heavier than NK^+ continuum threshold, the width is too narrow. The key of this problem is the parity. The naive quark model expects that all the 5 quarks are in the $L = 0$ states and therefore the parity of Θ^+ is negative. It is hard to understand the small width of such Θ^+ because it decays into s-wave NK states. On the other hand, if the parity is positive, the centrifugal barrier may suppress the decay width because Θ^+ decays into NK p-wave state. But the expected mass is much higher in the quark model.

Diakonov[2] predicted a positive parity Θ^+ in the chiral soliton model. Jaffe and Wilczek[3] considered that Θ^+ consists of two diquarks and anti-strange quark. From the bosonic symmetry diquarks, they consider two diquarks are in the relative p-wave state, which gives a positive parity state. Besides these model calculations, it is desirable to determine the parity of Θ^+ directly from QCD.

We apply the QCD sum rule to this problem, considering the following interpolating field operator for the penta quark Θ^+;

$$J(x) = \epsilon_{abc}\epsilon_{def}\epsilon_{cfg}\left\{u_a^T(x)Cd_b(x)\right\}\left\{u_d^T(x)C\gamma_5 d_e(x)\right\}C\bar{s}_g^T(x). \tag{1}$$

This consists of two diquarks and an anti-strange quark. We employ a combination of a scalar and a pseudoscalar diquark so that the bosonic symmetry is satisfied. The advantage of this operator is the coupling to NK of this operator seems to be small.

We perform the parity projection, and the spectral function of each parity is obtained like following form:

$$\rho_{\pm}(q_0) = A(q_0) \pm B(q_0). \tag{2}$$

$A(q_0)$ consists of chiral even terms (ex. $m_s\langle\bar{q}q\rangle$, $\langle\alpha_s\pi^{-1}\sigma G^2\rangle$), and $B(q_0)$ consists of chiral odd terms (ex. $\langle\bar{q}q\rangle$, $\langle\bar{q}\sigma Gq\rangle$). Our assumption of the spectral function of the

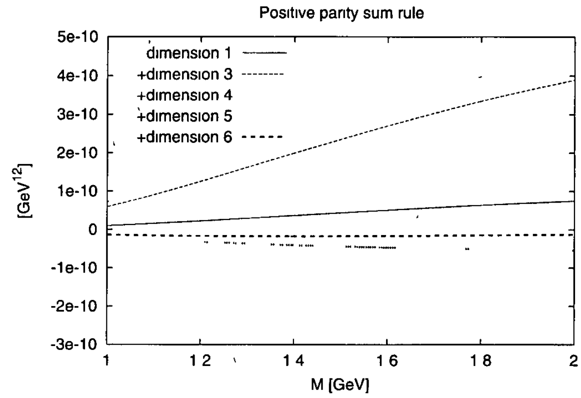

Fig. 1. $\lambda^2 e^{m^2/M^2}$ vs the Borel mass in positive parity sum rule.

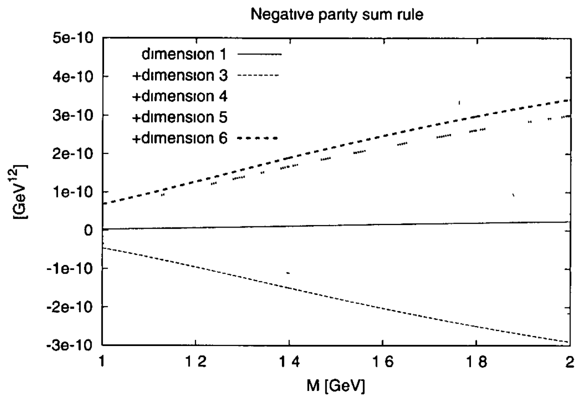

Fig 2 $\lambda^2 e^{m^2/M^2}$ vs the Borel mass in negative parity sum rule.

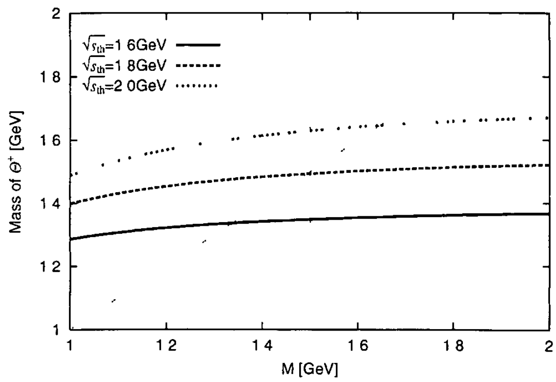

Fig. 3. The mass of Θ^+ vs the Borel mass in negative parity sum rule.

phenomenological side is

$$\rho^{\pm}_{\rm phen}(q_0) = |\lambda_{\pm}|^2 \delta(q_0 - m_{\pm}) + \theta(q_0 - \sqrt{s_{\rm th}}) \rho^{\pm}_{\rm OPE}(q_0). \tag{3}$$

If this assumption that sharp peak exists is correct, $|\lambda|^2$ must be positive. We determine the parity of ground state by this positivity condition.

From Fig. 1, our final result (dimension-6) is a little negative for the positive parity sum rule. On the other hand, from Fig. 2, the final result has significant positive value in the negative parity. So, we conclude the parity of Θ^+ is negative. From these figures, we notice dimension-3 term($\langle \bar{q}q \rangle$) and dimension-5 term($\langle \bar{q}\sigma G q \rangle$) are dominant, and these terms determine the parity. The plot of the mass in the negative parity is Fig. 3. This shows though the Borel stability is quite good, the dependence on $\sqrt{s_{\rm th}}$ is large. Our rough estimate of the Θ^+ mass is consistent with the observed value, 1.54 GeV.

References

1) T. Nakano et al., Phys. Rev Lett **91** (2003), 012002.
2) D. Diakonov, V. Petrov and M. Polyakov, Z. Phys. A **359** (1997), 305.
3) R. Jaffe and F. Wilczek, Phys. Rev. Lett. **91** (2003), 232003.
4) J. Sugiyama, T Doi and M Oka, Phys. Lett. B **581** (2004), 167.