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Kuang-Ta Chao

and

Hanqing Zheng

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A NOTE ON THE CONSTITUENT QUARK RESONANCES

Kuang-Ta Chao
Center of Theoretical Physics, CCAST (World Laboratory),
Beijing 100080, People's Republic of China
and
Department of Physics, Peking University, Beijing 100871, People's Republic of China
and
Hanqing Zheng ¹
International Centre for Theoretical Physics, Trieste, Italy.

ABSTRACT

If there exists a constituent quark resonance, we find by using the Adler-Weisberger relation and the finite-energy sum rule for pion quark scattering that it must be very massive and have a large decay width. Our results indicate that the presence of the constituent quark excitations does not contradict the observed low lying hadron spectrum.

Keywords: constituent quark, resonance, sum rules, g_A , Regge behavior

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¹Address after 1 November, 1994: P. Scherrer Institut, CH 5232 Villigen, Switzerland.

The successfulness of the simple constituent quark model introduced two decades ago [1] still remains to be somewhat mysterious, since the deep inelastic scattering experiments reveal that there are infinite number of quarks, anti-quarks and gluons inside a nucleon. It is still not very clear whether the constituent quark is just a rough approximation of the valence quark plus sea quark and gluon effects or can be considered as a quasi-particle as highly implied by the success of the model in many circumstances, examples are from baryon magnetic moments to the ratio of the total cross-section $\sigma(\pi N)/\sigma(NN)$ at high energies. If the constituent quark is really a composite quasi-free particle* we then can discuss on the intrinsic properties of the quark itself, like its mass, anomalous magnetic moment, g_A , etc., which should not vary in different surroundings while in the former case may have to vary in order to fit different hadronic properties. The constituent quark as a composite quasi-particle may be explained by the fact that the spontaneous breaking of chiral symmetry in strong interactions occur at the quark level, as illustrated in ref. [2]. Because the chiral symmetry breaking scale ($\Lambda_\chi \sim 1$ GeV) is larger than the confinement scale ($\Lambda_c \sim 100$ MeV), once we run down from the high energy scale (where the strong interactions are described by perturbative QCD of current quarks and gluons) to Λ_χ , chiral symmetry breaks down. As a consequence, quarks get their constituent masses and can still be considered as quasi-free particles because the energy scale is still above the confinement scale. There also appear pions as Goldstone excitations. In the picture of constituent quark model, The physical hadronic states only contain quarks and pions, and maybe glueballs, but no colored gluons or their excitations. This picture explains very well the low lying hadron spectrum. For example, all the meson states below 2 GeV with nonvanishing flavor quantum number are well identified [3].

If we believe that constituent quarks are composite particles, in general we should expect also the existence of the resonances of the constituent quark. Then there is a natural question: why the resonances must be heavy? To explain the success of the constituent quark model it is necessary to answer this question. If there are low-lying resonances, then the hadron spectrum would be more complicated than it exhibits. Another relevant question is that if there exist a heavy constituent quark resonance, how large is its decay width to the constituent quark? We know from experiments that the low lying spectrum is rather simple than complex. For this reason, It is usually believed that the constituent quark has no resonances, or in other word it is not necessary to assume the existence of quark resonances. The main purpose of this note is trying to answer this question more seriously, in a more

*This is the basic assumption we adopt in the present note. If it is not correct then the whole discussion will be invalid.

quantitative way.

Indeed from simple physical argument, we know that the quark excitation must have a large energy gap because the size of the quark is small (comparing with the scale of the nucleon). For the rotational excitations, the energy gap may obey a simple relation,

$$\Delta E \sim \frac{1}{I} \quad (1)$$

where I is the momentum of inertia of a composite object. Roughly, we may expect $I_Q \sim M_Q r_Q^2 \leq \frac{M_N}{3} \frac{r_N^2}{3^{2/3}} \sim \frac{I_N}{6.2}$. Taking $\Delta E_N \sim 300$ MeV we obtain,

$$\Delta E_Q \sim \Delta E_N \frac{I_N}{I_Q} \geq 1.8 \text{ GeV} . \quad (2)$$

In above we have make use of the fact that the sum up of the volume of three quarks is less than the volume of the nucleon. If we use the size of the quark adopted in ref. [4], $r_Q \simeq 0.2$ fm more or less the same value of ΔE_Q can be obtained.

Except for the above naive estimate, we also have another method which contains more information about the dynamics of the strong interaction. That is, if quarks have resonances they will contribute to the g_A of the quark through Adler-Weisberger relation for π quark scattering *. In the picture of QCD the contribution to the imaginary part of the scattering amplitude will be given by the quark and gluon cuts. In the spirit of the constituent quark model, we assume that all these contributions are saturated by the resonance contributions (and also π quark continuum). However, not only the mass of a resonance but also another parameter, its coupling to the quark and pion will be involved. This can be resolved by using another relation, the finite energy sum rule which have been used in understanding the short distance contribution to the g_A of the quark [6].

For simplicity, we assume there is a single resonance dominates the π quark scattering process below the Regge scale. From large N_c argument we know that the intermediate states in the pion quark scattering process must have isospin $1/2$ †. So when we consider more than one resonance their contributions to the sum rules will have the same sign – there will be no large cancellations among their contributions. This is correct in the leading order of the $1/N_c$ expansion and enables

* Assuming the forward two-two quasi-elastic scattering amplitudes vanish rapidly at high energies, Weinberg has derived a super-convergence relation which lead him to conclude that even if there are constituent quark resonances they will not contribute to g_A through the Adler-Weisberger sum rule[5]. However, we know that for diffraction dissociation processes, even though they have much smaller cross-sections than the elastic one they will not vanish at high energies because they are also dominated by the Pomeron exchange.

† See for example the second paper in ref. [5].

us to have a confidential estimate. In the narrow resonance approximation, we have

$$\sigma = \frac{2\pi^2}{p_{c.m.}^2} F_s \Gamma \delta(\sqrt{s} - M_R) \quad (3)$$

where Γ is the partial decay width of the resonance into a quark and a pion, M_R is the mass of the resonance. $F_s = \frac{2S_R+1}{(2S_1+1)(2S_2+1)}$ is the usual statistical factor. Taking eq.(3) into the Adler-Weisberger sum rule, $g_A^2 = 1 - \frac{2f_\pi^2}{\pi} \int_0^\infty \frac{d\nu}{\nu} \{\sigma^{\pi^-u}(\nu) - \sigma^{\pi^+u}(\nu)\}^\dagger$, we find that the resonance contribution to g_A is,

$$\delta g_A^2|_{res} = -\frac{2f_\pi^2}{\pi} \{16\pi^2 F_s \Gamma \frac{M_R^3}{(M_R^2 - m_q^2)^3}\} \quad (4)$$

The lowest moment finite energy sum rule reads,

$$\int_0^L \nu d\nu \Delta\sigma = \frac{\beta_q \beta_\pi}{2m_q^2} \frac{s_0}{1 + \alpha_0} \left(\frac{s}{s_0}\right)^{1+\alpha_0} . \quad (5)$$

where β_π and β_q are (ρ) Reggeon couplings to pions and quarks, respectively. $\beta_\pi = 2\beta_q \simeq g_{\rho\pi\pi} \simeq 6$. L is the scale above which the scattering amplitude has a proper Regge behavior and $s = 2m_q L + m_q^2$ [§]. Taking $s_0 \simeq m_\rho^2$, $m_q = 350 \text{ MeV}$ and the intercept of the Regge trajectory, $\alpha_0 = 0.44$, the right hand side of the finite energy sum rule can be estimated which will be compensated by the resonance contribution to the left hand side (the π quark continuum contribution is much smaller than the Regge contribution in here). We have,

$$\int_0^L \nu d\nu \Delta\sigma|_{res} = 4\pi^2 F_s \Gamma \frac{M_R^3}{m_q^2 (M_R^2 - m_q^2)} . \quad (6)$$

We find from eqs. (5) and (6) that

$$\Gamma \simeq \frac{\beta_q^2 s^{1+\alpha_0} / s_0^{\alpha_0}}{4\pi^2 (1 + \alpha_0) M_R} / F_s . \quad (7)$$

The lower bound on M_R obtained in our approach depends on the value of g_A , the Regge scale L and other parameters we use and will therefore suffer from some

[†]In the non-linear chiral quark model this relation needs to be modified because such a model does not have a good high energy behavior. An additional constant term, $-2 \frac{m_q^2}{(4\pi f_\pi)^2} \log \left(\frac{\Lambda_{\chi SB}^2}{m_q^2} \right)$ should be added on the right hand side. This term includes the main contributions to g_A from the low energy chiral quark model which is $1/N_c$ suppressed. See the discussions in ref. [7] for details.

[§]The explicit value of L (pion excess energy in the laboratory frame) should be at the order of a few GeV but is not well determined. In ref. [6], L is taken to be 3.5 GeV which is a little bit small, the upper bound of g_A is in turn found to be 0.6. To estimate L , we consider the case for π nucleon scattering, where the Regge behavior starts to work at the center of mass energy square $s = 2M_N L + M_N^2 + m_\pi^2 \simeq 10 \text{ GeV}^2$. Assuming the same L ($\simeq 4.85 \text{ GeV}$), rather than s , works also for π quark scattering then using the method in ref. [6] gives $g_A \leq 0.65$. If taking $L=14 \text{ GeV}$ (then the s for π quark scattering is about 10 GeV^2), it gives $g_A \leq 0.75$.

ambiguities. In the non-relativistic quark model of nucleon, $g_A = 0.75$. However, in the heavy – light meson ($Q\bar{q}$) system there are evidences that the light quark is relativistic, the value of g_A is found to be significantly smaller, $g_A \simeq 0.6$ [8], although there is no difficulty to increase this value by reducing the mass parameter of the constituent quark [9] [†]. Here we take the conservative value, $g_A > 0.6$. We plot the g_A of the constituent quark as a function of M_R in fig. 1 for several values of L . The Reggeon contribution to g_A^2 has a L^{α_0-1} dependence, whereas the resonance contribution has a L^{α_0+1} dependence. We may also choose the parameter L in such a way that the value of g_A^2 is not sensitive to L . This leads to,

$$L = (M_R^2 - m_q^2)/2m_q \quad (8)$$

which means that the Regge behavior starts just from $s = M_R^2$. This is however rather artificial because of the single resonance dominance assumption. If more resonances are added in general no stable point ($dg_A/dL = 0$) exist.

Fig. 1: The value of g_A as a function of the resonance mass, M_R for different choice of the Regge scale L . The vertical lines indicate the maximal value of M_R ($\leq \sqrt{s}$) can be reached for different L .

[†]As we have emphasized earlier, the intrinsic properties of the constituent quark as a composite particle should not vary in different surroundings. However the status on the the constituent quark parameters are not very satisfactory.

We read off from fig. 1 that The larger the Regge scale L is used the larger the lower bound on M_R will be, and the larger the resonance mass is the larger the value of g_A can take. However it is difficult for g_A^Q to reach the value 0.75, within reasonable range of various parameters. A conservative lower bound on mass can be obtained,

$$M_R > 1.67 \text{ GeV} . \quad (9)$$

Further, eq. (7) tells that the decay width of the resonance into a quark and a pion is very large, i.e., larger than ~ 650 MeV (If the resonance has spin $3/2$, this value will be reduced by half. And this value is roughly proportional to L as L increase.) We mention that we have made use of the narrow resonance assumption in obtaining the large width, but the result should make sense qualitatively.

Considering more resonances will not change the above results much. We have mentioned earlier that in the leading order of $1/N_c$ all the possible resonances should have isospin $1/2$ and therefore contribute with equal sign to the sum rules. The values obtained above can therefore be considered as a smeared effect with a larger weight on the lowest lying resonance.

The constituent quark resonances can form hadron resonances, like $Q^*\bar{Q}$ or Q^*QQ , etc. We conclude from the above analysis that these stats have a large mass and a large decay width into a normal hadron and a pion (pions) and will therefore difficult to be observed. The presence of these stats will not contradict to the observed low lying hadron spectrum. Our results confirm the self-consistency of our present understanding on the strong interaction physics.

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