Regge trajectories of tetraquarks with massive quarks

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INTRODUCTION

The search for multiquark systems beyond baryons has always been an area of interest for many physicists [1, 2]. Tetraquarks are the hadrons containing two quarks and two antiquarks. Owing to their large mass and short lifetime, tetraquarks remain undetected till the last century. Recently many experimental findings have confirmed the existence of tetraquarks [3–6]. The study of tetraquarks is very important because it helps us to understand the physics of higher-order quark matter, the nature of color confinement, and strong forces. To study the properties of highly confined quarks, different models are used. The string model of hadrons is one such model which gives the Regge trajectories of hadrons.

FORMULATION

In the flux tube model, it is assumed that the massless quarks are lying at the ends of the string. Here the potential is the linear confining potential of the form, $V(r) = Kr$, where r is the inter quark distance and K is the string tension. Let l be the length of the string. If the string is rotating about the midpoint, with the speed of light, then the mass of the hadron is (in natural units) [2],

$$M = 2\int_0^{\frac{l}{2}} \frac{Kdr}{\sqrt{1-v^2}}$$

The angular momentum of the hadron is,

$$J = 2\int_0^{\frac{l}{2}} \frac{Kvdr}{\sqrt{1-v^2}}$$

Hence the relation between angular momentum J and mass M as,

$$J = \alpha_0 + \alpha M^2$$

where α_0 and α are constants with $\alpha=1/(2\pi K)$. This relation is known as Regge trajectories of hadrons.
The same idea can be extended for tetraquarks and we can study the Regge trajectories of these states. The mass and angular momentum when one quark is at the one end of the string, and three quarks at the other end is,

$$M_{1i} = \frac{K(M-m_{q_1})l}{fM}\left(\sin^{-1} f + sin^{-1}\left(\frac{m_{q_1} f}{M-m_{q_1}}\right)\right) + \gamma_\alpha m_{q_1} + \gamma_\beta (M-m_{q_1})$$

$$J_{1i} = \frac{kl^2}{f^2} \times \left(\frac{M-m_{q_1}}{M}\right)^2 \left\{\frac{1}{2}\sin^{-1} f - \frac{f}{2}\sqrt{1-f^2} + \frac{1}{2} sin^{-1}\left(\frac{m_{q_1} f}{M-m_{q_1}}\right) - \frac{f m_{q_1}}{2(M-m_{q_1})}\sqrt{1-\left(\frac{m_{q_1} f}{M-m_{q_1}}\right)^2}\right\} + \frac{m_{q_1} f l}{M-m_{q_1}}\left\{\gamma_\alpha (M-m_{q_1}) + \gamma_\beta m_{q_1}\right\}$$

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Where, $M = m_{q_1} + m_{q_2} + m_{q_3} + m_{q_4}$, $\gamma_\alpha = \frac{1}{\sqrt{1-f^2}}$ and, $\gamma_\beta = \frac{1}{\sqrt{1-\left(\frac{m_{q_1} f}{M - m_{q_1}}\right)^2}}$

There are four configurations with one quark at one end and three quarks at the other end, and three configurations with two quarks at the two extreme end of the string. We assume that all these seven tetraquark configurations have equal probability to occur, therefore, the actual mass and angular momentum must be averaged.

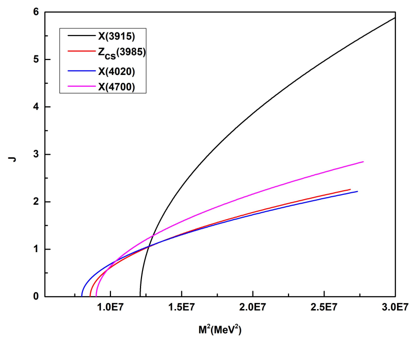
RESULTS AND DISCUSSION

The masses of up, down, strange, charm, and bottom quarks considered for calculation are, $m_u = 2.16 MeV$, $m_d = 4.67 MeV$, $m_s = 93 MeV$, $m_c = 1270 MeV$ and $m_b = 4180 MeV$ [7] respectively, and $K = 0.2 GeV^2$. Here, f is the fractional rotational speed of the low mass end of the string (actual speed is fc, c=1). In Table 1, masses of different tetraquark states are calculated and are compared with the experimental results [7]. We have considered different l values for different states. We can see that the present results are in good agreement with the experimental results. From the table we can also see that, as the mass of the tetraquark increases, string length l decreases. It shows that for higher mass states, the confinement effect is more. Figure 1 shows the Regge trajectories of some tetraquark states. The Regge trajectories of tetraquarks are highly non linear. The higher angular momentum states of tetraquarks can also be generated, for which we need more experimental data.

TABLE I: Comparison of the results with the experimental results

State	Quark structure	J	M_{cal} (MeV)	f	l (fm)
$X(3915)$	$cs\bar{c}\bar{s}$	2	3914.2	0.565	0.74
$Z_{cs}(3985)$	$c\bar{c}s\bar{u}$	1	3987.85	0.774	0.29
$X(4020)$	$c\bar{c}u\bar{d}$	1	4024.92	0.792	0.276
$X(4700)$	$cs\bar{c}\bar{s}$	2	4771.97	0.850	0.36

FIG. 1: Regge trajectories of different tetraquark states



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