Regge Trajectories of Some Recently Observed Pentaquarks

Akhilesh Ranjan[1*] and Hemwati Nandan[2]
[1]Department of Physics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India-576104 and
[2]Department of Physics, Gurukula Kangri Vishwavidyalaya, Haridwar, 249404, Uttarakhand, India

Introduction

Pentaquarks are new type of hadrons containing four quarks and one antiquark. This form of particles was first predicted by Strottman in 1979 [1]. It's existence in nature was confirmed after experimental data received from LHCb in 2015 [2–4] after many debates and controversies. Pentaquarks also confirm the existence of multiquark hadrons in nature. Pentaquarks are helpful to understand the strong nuclear interaction as well as the properties of matter in extreme circumstances. Formalisms based on Regge trajectories are found to be very useful to understand and predict about the hadron spectra [5]. Therefore, in this work we have tried to understand the Regge trajectories of some heavy pentaquark states. The results are found to be in good agreement with experiment.

Formulation

The Regge trajectory of a hadron is given by [5]

$$J = \alpha' M^2 + \alpha_0 \tag{1}$$

where, α_0 is a constant known as the Regge intercept and α' is the Regge slope parameter which is given by $\alpha' = 1/(2\pi K)$ here, K is the linear energy density of the string. In this picture the quarks are considered massless and the ends of string rotate with speed of light. On considering a more realistic picture for a meson with massive quark with mass m_1 and antiquark with mass m_2 rotating about it's center of mass with relativistic speeds f the modified mass of meson (M_{mod}) is given by [6]

$$\begin{aligned} M_{mod} &= \frac{Km_2 l}{f(m_1+m_2)}\left(sin^{-1}f + sin^{-1}\frac{m_1 f}{m_2}\right) \\ &+ \gamma_1 m_1 + \gamma_2 m_2 \end{aligned} \tag{2}$$

The modified angular momentum of meson (J_{mod}) is given by

$$\begin{aligned} J_{mod} &= \frac{Km_2^2 l^2}{f^2(m_1+m_2)^2}\left(\int_0^f \frac{v^2\,dv}{\sqrt{1-v^2}}\right. \\ &+ \left.\int_0^{\frac{m_1}{m_2}f} \frac{dv}{\sqrt{1-v^2}}\right) \\ &+ \frac{m_1 f l}{m_1+m_2}(\gamma_1 m_2 + \gamma_2 m_1) \end{aligned} \tag{3}$$

where l is the string length and $\gamma_1 = \frac{1}{\sqrt{1-f^2}}$. The expressions are shown in natural units $\hbar = 1$ and $c = 1$. If we condsider one string structure of pentaquarks as shown in fig.1, there will be five different possibilities there for configuration (a) and ten different possibilities for configuration (b) under quarks interchange at different ends. On considering all these fifteen configurations and assuming that all configurations are equally probable. We also assume that the string length is same for all the configurations. Obviously the mass and the angular momentum will be the average of all the configurations. We have obtained the Regge trajectories for $uudc\bar{c}$ and $uudb\bar{b}$ pentaquarks. From fig.2 it is clear that the Regge trajectories are highly non-linear. For the calculation we have taken quark masses of different flavors as $m_u = 2.3MeV$, $m_d = 4.8MeV$, $m_s = 95MeV$, $m_c = 1275MeV$, and $m_b =$

*Electronic address: ak.ranjan@manipal.edu

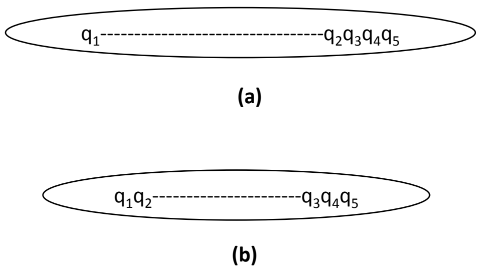

FIG. 1: Representative quark configurations for pentaquarks.

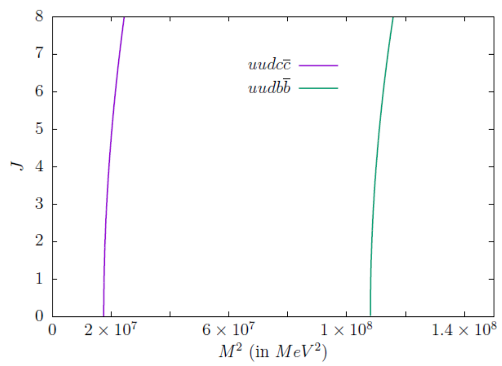

FIG. 2: Regge trajectories of charmonium and bottomonium pentaquarks.

$4180 MeV$ [7]. The string length l was taken 1.6 fm and the string tension $\sigma = 0.2 GeV^2$ [5].

Results and Discussion

In this framework we find that the Regge trajectories of pentaquarks are highly non-linear. Calculations also show that these heavy quark containing pentaquarks are non-relativistic systems as expected. From the table it is clear that the mass of higher spin pentaquarks will not be much different from the low spin pentaquarks. The experimental results are in good agreement with the theoretical results. It is also interesting to note that the theoretical results are lower than the experimental result. It means that some other aspects of theory should also be included into the analysis. The difference between mass of quarks and pentaquarks also shows that the gluonic sector contribution in mass increases as we go for the heavier pentaquarks.

TABLE I: Comparison of theoretical and experimental results of pentaquarks.

Pentaquark	J	M_{theo} (in MeV)	M_{exp} (in MeV)
$uudc\bar{c}$	$\frac{1}{2}$	4187	4380/4450
	$\frac{3}{2}$	4214	[2]
	$\frac{5}{2}$	4267	
$uudb\bar{b}$	$\frac{1}{2}$	10395	10723 to
	$\frac{3}{2}$	10407	11146
	$\frac{5}{2}$	10430	[3]

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