Regge trajectories of some pentaquarks in the flux tube model

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Introduction

In recent years, significant progress has been made in the field of exotic hadrons, with a particular focus on tetraquarks and pentaquarks. Pentaquarks are the hadrons consisting of four quarks and an antiquark ($Q\bar{Q}qqq$), where Q represents a heavy (charm or bottom) quark, q represents a light (up, down, or strange) quark. The existence of pentaquark states was confirmed by LHCb in 2015 when it reported the observation of two pentaquark states with two charm quarks, $P_c^+(4450)$ and $P_c^+(4380)$ in the decay of Λ_b [1]. Recently, in 2022, $P_{\psi s}^{\Lambda}(4338)$ pentaquark structure is observed with quark content $udsc\bar{c}$ [2].

Various theoretical frameworks, including the flux tube model, play a crucial role in understanding the behavior of these highly confined quarks. The Regge trajectories of some pentaquark states are studied given the flux tube model of hadrons with finite quark masses.

Formulation

Quarks are bound together by color lines of force. However, the interaction between gluons causes these lines to come together and form a tube or string. Let the energy density per unit length of this string is denoted by K. It connects two massless quarks as shown in FIG. 1. We assume that the ends of the string are rotating with the speed of light about its midpoint, and we can determine the relation between angular momentum J and mass M (in natural system of units) as [3],

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

where α_0 and α are constants with α=$1/(2\pi K)$. This relation is known as the Regge trajectories of hadrons. Here the orbital angular momentum of the quark pair will equal the angular momentum of the gluon tube.

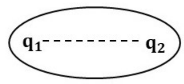

FIG. 1: String model of quarks.

The same idea can be extended to pentaquarks and we can study the Regge trajectories of these states. The modified mass and angular momentum when one quark is at the one end of the string and four quarks at the other end is [4, 5]:

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

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

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Where, $\gamma_\alpha = \frac{1}{\sqrt{1-f^2}}$ and, $\gamma_\beta = \frac{1}{\sqrt{1-\left(\frac{m_{q_1} f}{M-m_{q_1}}\right)^2}}$, $M = m_{q_1} + m_{q_2} + m_{q_3} + m_{q_4} + m_{q_5}$, l is the length of the string and f is the fractional rotational speed (fc is the actual speed with c in natural system of units).

There are five configurations with one quark at one end and four quarks at the other end, and ten configurations with two quarks at one end of the string and three at the other end. We assume that all these fifteen pentaquark 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, and charm quarks considered for calculation are, $m_u = 2.16 MeV$, $m_d = 4.67 MeV$, $m_s = 93 MeV$, and $m_c = 1270 MeV$ respectively, and $K = 0.2 GeV^2$ [1]. The calculated masses in TABLE I agree well with the experimental values. The string length increases as we move to a higher angular momentum state. It is evident from the Regge trajectory equation that the angular momentum of a particle is proportional to the length of the string. Hence, as we move to the higher J state, l increases.

TABLE I: Comparison of the results with the experimental results (Mass is written in MeV).

State	Quark structure	J	M_{cal}	f	l (fm)
$P_c^+(4440)$	$c\bar{c}uud$	$\frac{1}{2}$	4444.16	0.881	0.015
$P_{\psi s}^{\lambda}(4338)$	$c\bar{c}uds$	$\frac{1}{2}$	4331.96	0.871	0.024
$P_{cs}(4459)$	$c\bar{c}uds$	$\frac{3}{2}$	4455.1	0.863	0.196

FIG. 2 shows the Regge trajectories of some pentaquark states. The Regge trajectories of pentaquarks were found to be highly nonlinear.

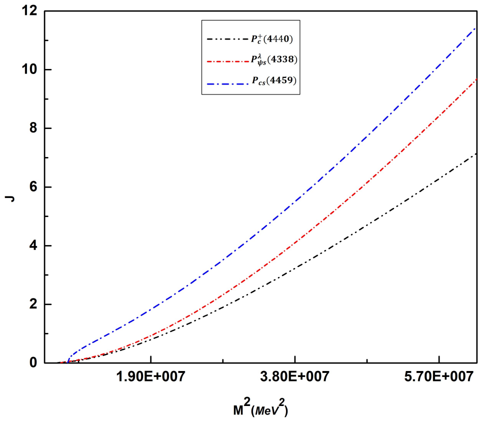

FIG. 2: Regge trajectories of pentaquarks.

Acknowledgments

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