Spectroscopic behaviour of conventional hadrons in Regge phenomenology

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Introduction

Quantum Chromodynamics (QCD), the fundamental theory governing strong interactions, is extensively studied through the spectrum of excited hadrons, including baryons, mesons, and exotic particles. Hadron spectroscopy, a specialized branch of particle physics, investigates the properties of hadrons by analyzing their masses, spins, parities, and quantum numbers. Despite significant research, QCD remains a captivating field due to its still incomplete understanding of internal dynamics.

Recent experiments at facilities like LHCb, BABAR, PANDA, BESIII etc. have produced abundant data, leading to new resonance discoveries and improved measurements [1, 2]. Over the past few years, several singly heavy baryons have been identified and reported with their well established masses [3]. Researchers are now focusing their efforts on detecting doubly and triply heavy baryons. PANDA, an upcoming facility, will aim to map the full spectrum of hyperons via antiproton-proton annihilation [4]. The quantum numbers of many observed resonances remain unresolved. These advancements in hadron physics, both experimental and theoretical [5–7], provide the motivation for this study. In this study, we systematically analyze the mass spectra of light and heavy baryons using Regge phenomenology.

Theoretical Framework

The quasilinear Regge trajectory approach, a widely utilized and effective method for studying hadron spectra, provides a reliable framework for describing hadron spectroscopy. The general form of linear Regge trajectories is given by [8–11],

$$J = \alpha(M) = a(0) + \alpha^{'} M^2, \tag{1}$$

here, $a(0)$ and $\alpha^{'}$ denote the intercept and slope of the Regge trajectory, respectively. For a baryon multiplet, the following are equations which relates the Regge parameters for various quark constituents [12–14],

$$a_{iiq}(0) + a_{jjq}(0) = 2a_{ijq}(0), \tag{2}$$

$$\frac{1}{\alpha^{'}{}_{iiq}} + \frac{1}{\alpha^{'}{}_{jjq}} = \frac{2}{\alpha^{'}{}_{ijq}}, \tag{3}$$

where i, j, and q represents the quark flavors. Now, by merging relations (1), (2) and (3), we obtain two pairs of solutions expressed in terms of baryon masses and slope ratios, given as follows,

$$\frac{\alpha^{'}_{jjq}}{\alpha^{'}_{iiq}} = \frac{1}{2M^2_{jjq}} \times [(4M^2_{ijq} - M^2_{iiq} - M^2_{jjq}) \pm \sqrt{(4M^2_{ijq} - M^2_{iiq} - M^2_{jjq})^2 - 4M^2_{iiq}M^2_{jjq}}], \tag{4}$$

and,

$$\frac{\alpha^{'}_{ijq}}{\alpha^{'}_{iiq}} = \frac{1}{4M^2_{ijq}} \times [(4M^2_{ijq} + M^2_{iiq} - M^2_{jjq}) \pm \sqrt{(4M^2_{ijq} - M^2_{iiq} - M^2_{jjq})^2 - 4M^2_{iiq}M^2_{jjq}}], \tag{5}$$

by substituting the appropriate values for i, j, and q based on the quark composition of a baryonic system, we can determine the Regge slopes for various trajectories. These slopes, along with relations derived from Regge theory, enable us to obtain the mass spectra for all baryons, ranging from light to singly, doubly, and triply heavy. The details of this study can be found in Refs. [9–13, 15, 16]

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Results and Discussion

TABLE I: Assigned J^P values to the experimentally observed baryon resonances.

Resonance	Assigned J^P values	Resonance	Assigned J^P values
$\Sigma(2455)$	$\frac{9}{2}^+$ (1G)	$\Xi_c(3055)$	$\frac{3}{2}^+$ (1D)
$\Sigma(2620)$	$\frac{11}{2}^+$ (1G)	$\Xi_c(3080)$	$\frac{5}{2}^+$ (1D)
$\Xi(1690)$	$\frac{3}{2}^-$ (1P)	$\Xi_c(3123)$	$\frac{5}{2}^+$ (1D)
$\Xi(1950)$	$\frac{5}{2}^-$ (1P)	$\Omega_c(3000)$	$\frac{1}{2}^-$ (1P)
$\Xi(2025)$	$\frac{5}{2}^+$ (1D)	$\Omega_c(3050)$	$\frac{3}{2}^-$ (1P)
$\Xi(2120)$	$\frac{5}{2}^+$ (1D)	$\Omega_c(3065)$	$\frac{3}{2}^-$ (1P)
$\Xi(2250)$	$\frac{7}{2}^+$ (1D)	$\Omega_c(3090)$	$\frac{1}{2}^-$ (1P)
$\Xi(2370)$	$\frac{7}{2}^-$ (1F)	$\Omega_c(3120)$	$\frac{5}{2}^-$ (1P)
$\Xi(2500)$	$\frac{9}{2}^-$ (1F)	$\Omega_c(3327)$	$\frac{5}{2}^+$ (1D)
$\Omega(2012)$	$\frac{1}{2}^-$ (1P)	$\Sigma_b(6097)$	$\frac{3}{2}^-$ (1P)
$\Omega(2250)$	$\frac{5}{2}^+$ (1D)	$\Xi_b(6227)$	$\frac{3}{2}^-$ (1P)
$\Omega(2380)$	$\frac{7}{2}^+$ (1D)	$\Xi_b(6333)$	$\frac{3}{2}^+$ (1D)
$\Sigma_c(2800)$	$\frac{3}{2}^-$ (1P)	$\Omega_b(6330)$	$\frac{3}{2}^-$ (1P)
$\Xi_c(2923)$	$\frac{3}{2}^-$ (1P)	$\Omega_b(6340)$	$\frac{1}{2}^-$ (1P)
$\Xi_c(2965)$	$\frac{5}{2}^-$ (1P)	$\Omega_b(6350)$	$\frac{3}{2}^-$ (1P)

Using Regge theory, we evaluated the mass spectra of light and heavy baryons and proposed parity values for newly observed resonances with undetermined quantum numbers (see Table I). For light baryons, such as Λ and Σ, many resonances have confirmed spin-parity values, though some states still lack complete quantum numbers. Data on Ξ and Ω baryons are limited, leading to debated quantum numbers. However, our results for higher excited states of light strange baryons match experimental data well, allowing us to assign quantum numbers to several excited Ξ and Ω resonances [13].

Recent research on singly heavy baryons, particularly the $\Lambda_{c/b}$ families, has confirmed several higher excited states, validating our model's predictions. New Ξ_c and Ξ_b resonances match our mass predictions closely, though many still need spin-parity assignments. We also accurately predicted spin-parity values for five new Ω_c and four Ω_b resonances, except the $\Omega_b(6315)$. These are likely to be $1P$ states. The latest discovery $\Omega_c(3327)$ fits our $1D$ state prediction with $J^P = 5/2^+$. Our findings offer useful insights for identifying new heavy baryons [9, 10]. Our extensive mass predictions and spin-parity assignments offer valuable insights for experiments aiming to identify new hadronic states and undiscovered heavy baryons.

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