Hidden-Charm Pentaquark masses using the Extension of Gursey-Radicati mass formula

Ankush Sharma[1],* Rashmi [2],† and Alka Upadhyay[3‡]
[1] *School of Physics and Material Science,*
Thapar Institute of Engineering and Technology, Patiala-147004, India

Introduction

Many exotic hadronic states like tetraquarks and pentaquarks have been observed in the last two decades. Recently in 2022, LHCb collaboration discovered two tetraquark structures having quark content $ud\bar{c}\bar{s}$ with significance of 6.5 σ and $\bar{u}dc\bar{s}$ with significance of 8 σ and a pentaquark structure $udsc\bar{c}$ with the significance of 15 σ which is far beyond the 5 standard deviations that are required to claim the observation of a particle in particle physics.Also, in 2021, $Z_{cs}(3985)$ and $Z_{cs}(4003)$ tetraquarks having quark content $c\bar{c}s\bar{q}(c\bar{c}q\bar{s})$ and $P_{cs}(4459)$ pentaquark state have been observed, where q is the light quark (u, d). The $P_{cs}(4459)$ was discovered in the J/ψ Λ invariant mass distribution from an amplitude analysis of the $\Xi_b^- \to J/\psi\ \Lambda\ K^-$ decays. The observed structure is consistent with a hidden-charm pentaquark with strangeness, characterized by a mass of $4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV and a width of $17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV. Its spin is expected to be 1/2 or 3/2, and its parity can be either -1 or +1.
In SU(3) representation, each quark is assigned as 3 and each antiquark by a $\bar{3}$. Therefore, the allowed SU(3) representation for $qqqq\bar{q}$ system in flavor space is :

$$[3] \otimes [3] \otimes [3] \otimes [3] \otimes [\bar{3}] = [35] \oplus 3[27] \oplus 2[10] \oplus 4[10] \oplus 8[8] \oplus 3[1]$$

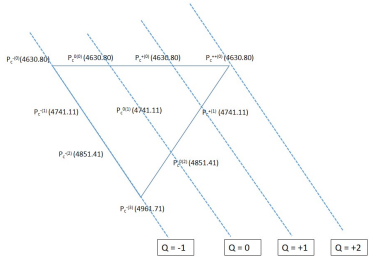

FIG. 1: Hidden-Charm Pentaquark Decuplet

In spin space, allowed SU(2) representation for (1/2, -1/2) basis for $qqqq\bar{q}$ system is :

$$[2] \otimes [2] \otimes [2] \otimes [2] \otimes [2] = [6] \oplus 4[4] \oplus 5[2]$$

This work has classified the hidden-charm pentaquarks into decuplet ($J^P = 3/2^-$). Using the extension of the Gursey-Radicati mass formula, we have computed the masses of hidden-charm pentaquarks by using the different values of possible quantum numbers like spin, isospin, hypercharge, Casimir operator, etc. Our analysis closely agrees with the available experimental and theoretical data.

Methodology

A. The Extension Of Gursey-Radicati Mass Formula

We used an extension of the Gursey-Radicati mass formula [3] to find the masses of hidden-charm pentaquarks. Assuming that the GR mass formula's coefficients are identical and have the same value for different quark systems[4]. The simplest form of GR formula which differentiates the different

*Electronic address: ankushsharma2540.as@gmail.com
†Electronic address: quantumgravity552@gmail.com
‡Electronic address: alka.iisc@gmail.com

Quark content	Spin	I	C2	Y	Nc	Masses
$uuuc\bar{c}$	3/2	3/2	6	1	2	4630±37
$duuc\bar{c}$	3/2	3/2	6	1	2	4630±37
$ddcu\bar{c}$	3/2	3/2	6	1	2	4630±37
$dddc\bar{c}$	3/2	3/2	6	1	2	4630±37
$uusc\bar{c}$	3/2	1	6	0	2	4677±37
$ddsc\bar{c}$	3/2	1	6	0	2	4677±37
$udsc\bar{c}$	3/2	1	6	0	2	4677±37
$dssc\bar{c}$	3/2	1/2	6	-1	2	4851±37
$ussc\bar{c}$	3/2	1/2	6	-1	2	4851±37
$sssc\bar{c}$	3/2	0	6	-2	2	4961±39

TABLE I: Masses for hidden-charm pentaquark decuplet.

multiples of $SU_f(3)$ is

$$M_{GR} = \xi M_0 + AS(S+1) + DY + E[I(I+1) - \tfrac{1}{4}Y^2] + GC_2(SU(3)) + FN_i$$

Where M_0 is the scale parameter, each quark contributes $\frac{1}{3}M_0$ to the whole mass, and ξ is the correction factor to the value of M_0. For baryons, $\xi = 1$; for tetraquarks, $\xi = 4/3$; and for pentaquark $\xi = 5/3$. S, I, and Y are the spin, isospin, and hypercharge, respectively. C_2(SU(3)) is the eigenvalue of the SU_f Casimir operator. N_i accounts for the counter of $c(\bar{c})$ quark or $b(\bar{b})$ quarks. Fitting the mass formula with masses of available baryons produces the best-fit of coefficients A, D, E, G, F, and M_0 [5].
The coefficients which we have used in the Gursey-Radicati formula are A = 23.0, D = -158.3, E = 32.0, F = 1354.6, G = 52.5. These coefficients are evaluated using the mass difference between the states of the known spectrum of baryon[3].

Analysis

By taking the $N_c = 2$ for hidden-charm pentaquarks, and their allowed possible combinations of quantum numbers into the mass formula, we have computed their masses by classifying them into decuplets having $J^P = 3/2^-$. Table 1 shows the calculated masses using all the possible combinations of quantum numbers. All states with $J^P = 3/2^-$ are members of decuplet, and states with $J^P = 1/2^-$ are members of pentaquark octet. Our analysis is useful to predict J^P values isospin multiplets and their masses. By comparing our results with the experimentally available data, we can study mass splitting by assigning their spin parities.

Acknowlegment

The author is grateful for the financial support provided by the Department Of Science and Technology (DST), New Delhi, India. Project No. CRG/2019/005159

References

[1] Ablikim M, et al., Phys Rev Lett 2021;126:102001.
[2] Aaij R, et al, LHCb Collaboration, Phys Rev Lett 2021; 127:082001.
[3] Elena Santopinto and Alessandro Giachino , Phys.Rev. D.96.014014.
[4] M.M. Giannini, E. Santopinto, A.Vassallo, arXiv:nucl-th/0506032v1.
[5] Pontus Holma, Tommy Ohlsson, arXiv:1906.08499 [hep-ph].