Decay Properties of Conventional and Hybrid $B_c$ Mesons

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Abstract—Spectrum, radial wave functions at origin, decay constants, weak decay widths, life-time, and branching ratios for radially excited conventional and hybrid $B_c$ mesons are derived within non-relativistic quark model framework employing Schrödinger equation by shooting method. Calculated results are compared with available theoretical results and experimental observations. This work may help in identifying the new discovered $B_c$ meson states at CDF, LHCb, and ATLAS.

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1. INTRODUCTION

$B_c$ meson consists of different flavored heavy quark–antiquark pair. It cannot be annihilated into gluons and can decay through weak interactions [1–3] only. Due to these characteristics, $B_c$ meson is considered a stable meson with narrow widths [4].

$B_c$ meson was discovered in 1998 at Fermilab with mass $6.2749\pm0.0008$ GeV [1]. After decades of ground state $B_c$ meson discovery, ATLAS Collaboration observed a peak for mass of excited state $B_c$ meson at $6.842\pm0.009$ GeV [5]; but LHCb Collaboration [6] observed different results. Recently, CMS Collaboration [7] observed two peaks for the excited states of $B_c$ meson, $B_c^+(21^1S_0)$ and $B_c^+(23^1S_1)$. The mass of $B_c^+(2S)$ is measured to be $6.871\pm0.0012\pm0.0008\pm0.0080$ GeV [7]. A mass difference of $0.0291\pm0.0015\pm0.0007$ GeV is measured between two states [7]; however exact mass of $B_c^{+*}(2S)$ is still unknown.

A detailed report based on experimental and theoretical results of heavy quarkonium obtained by different approaches is presented in [8]. Theoretically, a variety of techniques are available in the literature to study $B_c$ mesons like quark potential model [9–19], QCD sum rule [20–23], the heavy quark effective theory [24], lattice QCD [25–27] and Dyson-Schwinger Equation [28]. $B_c$ meson and decays are studied with potential models and the QCD sum rules in [29].

Meson under study ($B_c$) may be conventional or hybrid and can be identified through their masses and decay widths. Hybrid $B_c$ mesons are studied in ref. [9, 22] using Born–Oppenheimer formalism (BO) and adiabatic approximation. In BO formalism, the energy levels of the gluon field are determined as a function of $r$ (separation between quark–antiquark) by considering slow moving heavy quark–antiquark at fixed positions. Each of these energy levels defines a static potential. Static potentials [30], extracted from Monte Carlo estimates of generalized Wilson loops are used in Schrodinger equation to incorporate the quark motion. In this paper, non-relativistic static potential model and its extended form is used to find masses and radial wave functions at origin for conventional as well as hybrid $B_c$ mesons. Decay constants, weak decay widths, life-time, and branching ratios for radial excited states of conventional and hybrid $B_c$ mesons are calculated using these masses and $|R(0)|^2$.

Potential models used for conventional and hybrid mesons are discussed in the Section 2 of this paper and were further used to calculate masses and radial wave functions at origin for the ground and radially excited state $B_c$ mesons by solving the Schrödinger equation numerically. The expressions used to find decay constants, decay widths, life-time and branching ratios of $B_c$ mesons are written in Section 3. The results are discussed in Section 4.

2. POTENTIAL MODELS FOR CONVENTIONAL AND HYBRID $B_c$ MESONS

To study the properties of conventional $B_c$ mesons, the following potential model [4] is used:

$$V(r) = \frac{-4\alpha_s}{3r} + br + \frac{32\pi\alpha_s}{9m_qm_\tau} \left( \frac{\sigma}{\sqrt{\pi}} \right)^3 e^{-\sigma^2r^2} S_0 \cdot S_T + \frac{4\alpha_s}{m_qm_\tau r^3} H_T$$
Table 1. Masses of ground and radially excited \( S \) states of \( B_c \) mesons; calculated masses are rounded to 0.0001 GeV

| Meson state | \( J^P \) | This paper mass, GeV | Theor. mass [9], GeV | Lattice [33], GeV | Theor. mass (G1) [4], GeV | Exp. mass [34], GeV |
|-------------|-----------|---------------------|---------------------|------------------|---------------------|------------------|
| \((1^3S_1)\) | 1\(^-\) | 6.3062 | 6.314 | 6.331 ± 0.004 ± 0.006 | 6.338 |
| \((1^1S_0)\) | 0\(^-\) | 6.2740 | 6.274 | 6.276 ± 0.003 ± 0.006 | 6.271 | 6.2749 ± 0.0008 |
| \((2^3S_1)\) | 1\(^-\) | 6.8845 | 6.855 | |
| \((2^1S_0)\) | 0\(^-\) | 6.8717 | 6.841 | 6.855 | 6.871 ± 0.0012 ± 0.0008 |
| \((3^3S_1)\) | 1\(^-\) | 7.2905 | 7.206 | 7.272 |
| \((3^1S_0)\) | 0\(^-\) | 7.2818 | 7.197 | 7.250 |
| \((4^3S_1)\) | 1\(^-\) | 7.6323 | 7.495 | |
| \((4^1S_0)\) | 0\(^-\) | 7.6255 | 7.488 | |
| \((5^3S_1)\) | 1\(^-\) | 7.9374 | | |
| \((5^1S_0)\) | 0\(^-\) | 7.9317 | | |
| \((6^3S_1)\) | 1\(^-\) | 8.2178 | | |
| \((6^1S_0)\) | 0\(^-\) | 8.2129 | | |

\[ + \left( \frac{S_q}{4m_q^2} + \frac{S_T}{4m_T^2} \right) \cdot L \left( \frac{4\alpha_s - b}{3r^3} - \frac{b}{r} \right) + \frac{S_q + S_T}{2m_qm_T} \cdot \frac{L^4\alpha_s}{3r^5}. \]  

(1)

Here, \( \alpha_s \), \( b \), \( m_q \), and \( m_T \) are the strong coupling constants, string tension, mass of quark, mass of anti-quark, and the tensor operator respectively. Here \( m_q \) and \( m_T \) are the masses of \( b \) and \( c \) quarks, so can be written as \( m_b \) and \( m_c \). Tensor operator is defined as:

\[ H_T = S_q \cdot \hat{r} S_T \cdot \hat{r} - \frac{1}{3} S_q \cdot S_T, \]  

(2)

such that

\[ \langle LJ|H_T^3|L_J \rangle = \begin{cases} 
-\frac{1}{6(2L+3)}, & J = L + 1 \\
0, & J = L, \\
-\frac{1}{6(2L-1)}, & J = L - 1.
\end{cases} \]  

(3)

Here, \( L \) is the relative orbital angular momentum of the quark–antiquark and \( S \) is the total spin angular momentum. In this paper, properties of \( B_c \) mesons are studied for pseudo-scalar mesons (i.e. \( L = 0 \)). For \( L = 0 \), spin–orbit and tensor terms are equal to zero [31].

To find the mass of \( B_c \) mesons, numerical solution of the radial Schrödinger equation

\[ U''(r) + 2\mu \left( E - V(r) - \frac{L(L+1)}{2\mu r^2} \right) U(r) = 0 \]  

(4)

is found by employing the shooting method. Here \( U(r) = rR(r) \), product of radial wave function \( R(r) \) and \( r \). At small distance (\( r \to 0 \)), wave function becomes unstable due to very strong attractive potential. This problem is solved by applying smearing of position coordinates by using the method discussed in [32]. Parameters \( (m_\pi = m_b = 4.733 \text{ GeV}, \ m_q = m_c = 1.3841 \text{ GeV}, \ \alpha_s = 0.4035, \ b = 0.18, \ \sigma = 1.0765 \text{ GeV}) \) are obtained by fitting the meson masses with corresponding experimentally known masses. Mass of the \( \overline{b}c \) state is obtained after the addition of constituent quark masses in the energy \( E \). Mass of pseudo-scalar and pseudo-vector \( B_c \) meson states are reported in Table 1.

To study hybrid mesons, potential model for conventional mesons (mentioned above) is extended by considering an additional term \( (\vec{g} + A \times \exp^{-B_r0.3723}) \) [35]. Parameters \( A = 3.4693 \text{ GeV}, \ B = 1.0110 \text{ GeV}, \) and \( c = 0.1745 \) are taken from our earlier fit [35] to the lattice data [36] of the parameters of the effective potential form corresponding to the first excited gluonic state. For hybrid mesons, radial Schrödinger equation is written as:

\[ U''(r) + 2\mu \left( E - V(r) - \frac{c}{r} - A \times \exp^{-B_r0.3723} \right. \]  

\[ - \frac{L(L+1) - 2\Lambda^2 + (J_g^2)}{2\mu^2} \left. \right) U(r) = 0. \]  

(5)

Here, \( J_g \) is the gluon angular momentum and \( \Lambda \) is the projection of gluon angular momentum. For
the first gluonic excitation, \( \langle J_g^2 \rangle = 2 \) and \( \Lambda = 1 \) [36]. The masses of hybrid \( B_c \) meson states are found by solving the above equation by shooting method and results are reported in Table 2.

### 3. DECAY PROPERTIES OF CONVENTIONAL AND HYBRID \( B_c \) MESONS

#### 3.1. Decay Constants

Decay constant is an important characteristic of mesons. Decay constants \( f_p \) of pseudo-scalar and pseudo-vector mesons depend on \( |R(0)|^2 \). Following Van-Royen–Weisskopf formula [37] is used to find decay constants.

\[
f_p = \sqrt{\frac{3|R(0)|^2}{\pi M_p}} = \sqrt{\frac{12|\psi(0)|^2}{M_p}},
\]

where \( M_p \) is the mass of the corresponding \( B_c \) meson. By incorporating the first order QCD correction factor, the decay constant can be written as:

\[
f_p = \sqrt{\frac{3|R(0)|^2}{\pi M_p}} \times \left(1 - \frac{\alpha_s}{\pi} \left[ \Delta - \frac{m_Q - m_G}{m_Q - m_G} \ln \left( \frac{m_Q}{m_G} \right) \right] \right),
\]

where \( \Delta = 2 \) for \( ^1S_0 \) mesons and \( \Delta = 8/3 \) for \( ^3S_1 \) mesons. Decay constants for conventional and hybrid mesons are reported in Tables 3, 4.

#### 3.2. Weak Decay

According to the spectator model [2], \( B_c \)-meson decay can be divided into three classes (i) \( b \) quark decay having \( c \) quark as spectator, (ii) \( c \) quark decay having \( b \) quark as spectator, (iii) annihilation decay of \( B_c \) meson. \( b \)-quark and \( c \)-quark decay widths of \( B_c \) meson can be calculated by following expressions [2, 4, 17]:

\[
\Gamma(b \to X) = \frac{9G_F^2|V_{cb}|^2m_b^5}{192\pi^3}, \quad (8)
\]

\[
\Gamma(c \to X) = \frac{5G_F^2|V_{cs}|^2m_c^5}{192\pi^3}, \quad (9)
\]

where \( |V_{cb}| \) and \( |V_{cs}| \) are the \( cb \) and \( cs \) elements of CKM matrix. I used \( |V_{cs}| = 0.9736 \) and \( |V_{cb}| = 0.04214 \) taken from PDG [34]. \( G_F \) is the fermi constant and equal to \( 1.166 \times 10^{-5} \) GeV\(^2\). With this data, i calculated the partial decay widths as

\[
\Gamma(b \to X) = 8.669 \times 10^{-4} \text{ eV},
\]

\[
\Gamma(c \to X) = 5.497 \times 10^{-4} \text{ eV}.
\]

Annihilation decay for pseudoscalar \( B_c \)-meson states (conventional and hybrid) can be calculated by the following relation defined in [2, 4, 17]:

\[
\Gamma(anni) = \frac{G_F^2|V_{cb}|^2f_{bc}^2M_{B_c}m_q^2}{8\pi} \left(1 - \frac{m_q^2}{M_{B_c}^2} \right) C_q,
\]

where \( C_q = 3|V_{cs}|^2 \) for \( c\bar{s}, u\bar{s} \) and \( C_q = 1 \) for \( \ell\nu\ell \) where \( \ell = e, \mu, \tau \). In the present paper, annihilation decay is calculated for \( \tau\nu\tau \) and \( c\bar{s} \). Total decay width can be roughly estimated as the sum of \( b \)-quark, \( c \)-quark and annihilation decay, i.e.:

\[
\Gamma(B_c \to X) = \Gamma(b \to X) + \Gamma(c \to X) + \Gamma(anni).
\]

For conventional mesons, decay widths for Pseudoscalar \( B_c \) mesons are reported in Table 5, while Table 6 contains the decay widths for hybrid mesons.

#### 3.3. Life-Time

Life-time \( (\tau) \) of conventional and hybrid \( B_c \) mesons is found by following relation:

\[
\tau = \frac{h}{\Gamma},
\]

where \( h = 6.582 \times 10^{-25} \) GeV s.

### Table 2. Masses of ground and radially excited \( S \) states of \( B_c \) hybrid mesons

| Meson state | \( J^P \) | This paper mass, GeV | Mass [9], GeV |
|------------|----------|----------------------|--------------|
| \( ^1S_1 \) | 1\(^-\) | 7.410 | 7.422 |
| \( ^1S_0 \) | 0\(^-\) | 7.4026 | 7.415 |
| \( ^2S_1 \) | 1\(^-\) | 7.7081 | 7.654 |
| \( ^2S_0 \) | 0\(^-\) | 7.6999 | 7.646 |
| \( ^3S_1 \) | 1\(^-\) | 7.9854 | 7.874 |
| \( ^3S_0 \) | 0\(^-\) | 7.9779 | 7.866 |
| \( ^4S_1 \) | 1\(^-\) | 8.246 | 8.082 |
| \( ^4S_0 \) | 0\(^-\) | 8.2392 | 8.075 |
| \( ^5S_1 \) | 1\(^-\) | 8.4929 | 8.335 |
| \( ^5S_0 \) | 0\(^-\) | 8.4869 | 8.329 |
| \( ^6S_1 \) | 1\(^-\) | 8.7287 | 8.571 |
| \( ^6S_0 \) | 0\(^-\) | 8.7233 | 8.565 |

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Table 3. Radial wave functions at origin and decay constants of $B_c$ mesons

| Meson state $J^P$ | $|R(0)|^2$, GeV$^2$ | $|R(0)|^2$, GeV$^3$ | Without correction $f_p$, GeV | With correction $f_p$, GeV | $f_p$, GeV | $f_p$, GeV |
|-------------------|-----------------|-----------------|--------------------------|--------------------------|------------|------------|
| $(1^3S_1)$ 1$^-$ | 1.9566 | 1.994 | 0.5443 | 0.4049 | 0.471 | 0.604 |
| $(1^1S_0)$ 0$^-$ | 2.2393 | 2.144 | 0.5839 | 0.4844 | 0.498 | 0.607 |
| $(2^3S_1)$ 1$^-$ | 1.2018 | 1.2605 | 0.4083 | 0.3038 | 0.356 | 0.355 |
| $(2^1S_0)$ 0$^-$ | 1.0083 | 0.9138 | 0.3634 | 0.2703 | 0.326 | 0.325 |
| $(3^3S_1)$ 1$^-$ | 0.10399 | 0.944 | 0.3693 | 0.284 | 0.307 | 0.307 |
| $(3^1S_0)$ 0$^-$ | 0.9358 | 0.8504 | 0.3423 | 0.2515 | 0.308 | 0.308 |
| $(5^3S_1)$ 1$^-$ | 0.8553 | 0.8326 | 0.3208 | 0.2387 | 0.307 | 0.307 |
| $(5^1S_0)$ 0$^-$ | 0.8148 | 0.7014 | 0.3077 | 0.2289 | 0.308 | 0.308 |
| $(6^3S_1)$ 1$^-$ | 0.8239 | 0.7014 | 0.3105 | 0.2576 | 0.308 | 0.308 |

Table 4. Radial wave functions at origin and decay constants of hybrid $B_c$ mesons

| Meson state $J^P$ | $|R(0)|^2$, GeV$^3$ | Without correction $f_p$, GeV | With correction $f_p$, GeV |
|-------------------|-----------------|--------------------------|--------------------------|
| $(1^3S_1)$ 1$^-$ | 0.2061 | 0.163 | 0.1213 |
| $(1^1S_0)$ 0$^-$ | 0.2533 | 0.1807 | 0.1499 |
| $(2^3S_1)$ 1$^-$ | 0.2942 | 0.191 | 0.142 |
| $(2^1S_0)$ 0$^-$ | 0.3426 | 0.206 | 0.1709 |
| $(3^3S_1)$ 1$^-$ | 0.3391 | 0.2015 | 0.1499 |
| $(3^1S_0)$ 0$^-$ | 0.3797 | 0.2131 | 0.1768 |
| $(4^3S_1)$ 1$^-$ | 0.3658 | 0.2059 | 0.1532 |
| $(4^1S_0)$ 0$^-$ | 0.3991 | 0.215 | 0.1783 |
| $(5^3S_1)$ 1$^-$ | 0.3834 | 0.2077 | 0.1545 |
| $(5^1S_0)$ 0$^-$ | 0.4111 | 0.215 | 0.1784 |
| $(6^3S_1)$ 1$^-$ | 0.3972 | 0.2085 | 0.1551 |
| $(6^1S_0)$ 0$^-$ | 0.4206 | 0.2145 | 0.178 |

3.4. Branching Ratio

Branching ratios of $b$-decay, $c$-decay and annihilation decay are found by taking ratio of the corresponding decay width to total decay width, i.e.,

$$\beta(b \rightarrow X) = \frac{\Gamma(b \rightarrow X)}{\Gamma(B_c \rightarrow X)};$$
$$\beta(c \rightarrow X) = \frac{\Gamma(c \rightarrow X)}{\Gamma(B_c \rightarrow X)};$$
$$\beta(anni.) = \frac{\Gamma(anni.)}{\Gamma(B_c \rightarrow X)}.
$$

4. DISCUSSION AND CONCLUSION

Based on nonrelativistic potential model, masses are calculated for the ground as well as radially excited states of conventional and hybrid $B_c$ mesons and reported in Tables (1,2) along with the experimental and theoretical predictions of other works. The results reported in Table 3 illustrate that radial wave functions at origin and decay constants for conventional mesons are decreasing toward higher radial excitations. But the situation is reversed in case of hybrids. For hybrids, radial wave functions at origin are increasing toward higher radial excitation.
tions. Pseudoscalar $B_c$ mesons have higher values of $|R(0)|^2$ and $f_p$ as compared to vector mesons. It is observed that hybrids have lesser value of decay constant than the conventional mesons. Decay width, life-time and branching ratio of conventional and hybrid $B_c$ mesons are reported in Tables 5, 6.

In Table 5, conventional $1^1 S_0$ state decay width, life-time and branching ratio are compared with others. It is observed that the life-time calculated in this paper is more close to the experimental result [34] as compared to other theoretical works. Branching ratio of $b$ decay, $c$ decay and annihilation decay for conventional meson are also very close to other theoretical results [4]. For conventional $B_c$ mesons, branching ratios of annihilation decays are very small as compared to $b$ decay and $c$ decay. In case of hybrid $B_c$ mesons branching ratios for annihilation decays are less than 1. This show that annihilation decay is rare for $B_c$ mesons. The agreement of results with others work shows the validity of my method. Using the extended potential model for hybrids, decay widths, life-time and branching ratios are predicted for the hybrid $B_c$ mesons. It is observed that hybrids have less decay widths as compared to conventional $B_c$ meson. From these results, it is concluded that hybrid $B_c$ mesons are more stable than conventional mesons with the same $L$ and $S$. This work may help in recognizing the higher states of $B_c$ mesons that will be discovered at CDF detector, LHCb, and ATLAS.

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### REFERENCES

1. F. Abe et al. (CDF Collab.), Phys. Rev. Lett. 81, 2432 (1998); Phys. Rev. D 58, 112004 (1998); P. Ball et al., CERN-TH/2000-101, hep-ph/0003238.
2. A. Abd El-Hady, M. A. K. Lodhi and, J. P. Vary, Phys. Rev. D 59, 094001 (1999).
3. D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Rev. D 67, 014027 (2003).
4. S. Godfrey, Phys. Rev. D 70, 054017 (2004).
5. G. Aad et al. (ATLAS Collab.), Phys. Rev. Lett. 113, 212004 (2014).
6. R. Aaij et al. (LHCb Collab.), JHEP 1801, 138 (2018).
7. A. M. Sirunyan et al. (CMS Collab.), Phys. Rev. Lett. 122, 132001 (2019).
8. N. Brambilla et al. (Quarkonium Working Group), CERN-2005-005, hep-ph/0412158 (2005).
9. N. Akbar, F. Akram, B. Masud, and M. A. Sultan, Eur. Phys. J. A 55, 82 (2019).
10. E. J. Eichten and C. Quigg, Phys. Rev. D 99, 054025 (2019).
11. I. Asghar, F. Akram, B. Masud, and M. A. Sultan, arXiv: 1910.02680v1.
12. E. J. Eichten and C. Quigg, Phys. Rev. D 49, 5845 (1994).
13. S. N. Gupta and J. M. Johnson, Phys. Rev. D 53, 312 (1996).
14. L. P. Fulcher, Phys. Rev. D 60, 074006 (1999).
15. A. P. Monteiro, M. Bhat, and K. B. Vijaya Kumar, Phys. Rev. D 95, 054016 (2017).
16. A. P. Monteiro, M. Bhat, and K. B. Vijaya Kumar, Int. J. Mod. Phys. A 32, 1750021 (2017).
17. K. K. Pathak and D. K. Choudhury, Pramana J. Phys. 79, 1385 (2012).
18. M. Abu-Shady, Int. J. Appl. Math. Theor. Phys. 2, 16 (2016).
19. Q. Li, M.-S. Liu, L.-S. Lu, Q.-F. Lü, L.-C. Gui, and X.-H. Zhong, Phys. Rev. D 99, 096020 (2019).
20. C. A. Dominguez, K. Schilcher, and Y. L. Wu, Phys. Lett. B 298, 190 (1993).
21. S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. V. Tkabladze, Phys. Rev. D 51, 3613 (1995).
22. W. Chen, T. G. Steele, and Shi-Lin Zhu, J. Phys. G: Nucl. Part. Phys. 41, 025003 (2014).
23. E. Bagan, H. G. Dosch, P. Gosdzinsky, S. Narison, and J.-M. Richard, Z. Phys. C 64, 57 (1994).
24. J. Zeng, J. W. Van Orden, and W. Roberts, Phys. Rev. D 53, 5229 (1995).
25. I. F. Allison, C. T. H. Davies, A. Gray, A. S. Kronfeld, P. B. Mackenzie, J. N. Simone, (HPQCD, FNAL lattice, and UKQCD Collabs.), Nucl. Phys. Proc. Suppl. 140, 440 (2005).
26. C. T. H. Davies, K. Hornbostel, G. P. Lepage, A. J. Lidsey, J. Shigemitsu, and J. Sloan, Phys. Lett. B 382, 131 (1996).
27. G. M. de Divitiis, M. Guagnelli, F. Palombi, R. Petronzio, and N. Tantalo, Nucl. Phys. B 675, 309 (2003).
28. Muyang Chen, Lei Chang, and Yu-xin Liu, Phys. Rev. D 101, 056002 (2020).
29. S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. V. Tkabladze, Usp. Fiz. Nauk 165, 3 (1995) [Phys. Usp. 38, 1 (1995)].
30. C. Morningstar, Nucl. Phys. B Proc. Suppl. 53, 914 (1997).
31. T. Barnes, S. Godfrey, and E. S. Swanson, Phys. Rev. D 72, 054026 (2005).
32. S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
33. N. Mathur, M. Padmanath, and S. Mondal, Phys. Rev. Lett. 121, 202002 (2018).
34. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).
35. N. Akbar, B. Masud, and S. Noor, Eur. Phys. J. A 47, 124 (2011); Eur. Phys. J. A 50, 121 (Erratum) (2014).
36. K. J. Juge, J. Kuti, and C. J. Morningstar, Nucl. Phys. Proc. Suppl. 63, 326 (1998).
37. R. Van Royen et al., Nuovo Cimento 50 A, 617 (1967).
38. M. J. Baker, J. Bordes, C. A. Dominguez, J. Pearson, and K. Schilcher, JHEP 1007, 032 (2014).
39. N. R. Soni and J. N. Pandya, Proc. DAE Symp. Nucl. Phys. 58, 674 (2013).
40. J. N. Pandya and P. C. Vinodkumar, Pramana J. Phys. 57, 821 (2001).
41. N. R. Soni, B. R. Joshi, R. P. Shah, H. R. Chauhan, and J. N. Pandya, Eur. Phys. J. C 78, 592 (2018).