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Isgur–Wise function in a quantum chromodynamics-inspired potential model with confinement as parent in the variationally improved perturbation theory

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Abstract. We have recently reported the calculation of slope and curvature of Isgur–Wise function based on variationally improved perturbation theory (VIPT) in a quantum chromodynamics (QCD)-inspired potential model. In that work, Coulombic potential was taken as the parent while the linear one as the perturbation. In this work, we choose the linear one as the parent with Coulombic one as the perturbation and see the consequences.

Keywords. Variationally improved perturbation theory; Isgur–Wise function; charge radii; convexity parameter.

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1. Introduction

Being a universal form factor, the Isgur–Wise (I–W) function has been instrumental in the analysis of semileptonic decays [1] and so far various QCD-inspired models have been developed for its proper understanding. In this spirit, the I–W function had been investigated for the last few years in a QCD-inspired model [2,3] where two-body Schrödinger equation was solved for the spin-independent Fermi–Breit Hamiltonian consisting of the linear cum Coulombic potential with the contact term being neglected [3,4]. The Dalgarno method was the method used to obtain the wave function which could predict the I–W function [15] with either Coulombic piece as the parent [3,5–7] or the linear one as the parent [8]. While refs [5–7] demanded either small confinement (i.e. b) or large coupling constant (α_s), ref. [8] was quite successful in predicting satisfactory results for the slope and curvature with the same range of values for the parameters b and α_s.

As an alternative to Dalgarno method, one can use the recently introduced [9–11] variationally improved perturbation theory (VIPT) to solve the Schrödinger equation to obtain the wave function. The disadvantage of conventional perturbation theory is that it needs a very small expansion parameter which leads to diverging results after a certain order.

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Similarly, the variational method needs an appropriate trial wave function in terms of unknown parameter(s) which is quite tedious and this makes it an inconvenient method. However, in VIPT one uses the variational method in terms of a known trial function and through optimization process, new parameters are obtained which are then applied to the perturbation theory to make the perturbation expansion a convergent one [12]. Thus, the VIPT removes the specific problems of variational method and perturbation theory by combining both of them properly and thus hope to handle large perturbation.

With linear cum Coulombic potential [13], we have two options to use in VIPT: (i) Coulombic potential as the parent and linear one as the perturbation and (ii) linear one as the parent and Coulombic potential as perturbation in the potential model we have adopted. We have already reported such an attempt [12] in the calculation of slope and curvature of I–W function with Coulombic parent. It had successfully analysed the said for D, D_s, B mesons taking into account the three terms in the summation of equation expressing the first-order corrected wave function. Although the results were shown to be improved with more terms in that equation, it was quite cumbersome. Further, larger α_s values were felt necessary for B-meson for which the result was not so satisfactory when compared to D, D_s mesons.

A careful investigation shows that the linear part with significant confinement effect ($b = 0.183$ GeV^2) is usually dominant over the Coulombic one for mesons having greater reduced mass μ. Further, as pointed out in ref. [10], the linear parent is quite handy in predicting the mass, energy etc. for different states compared to the Coulombic one. So, it is definitely worthwhile to test the model with linear parent including also the B_s, B_c mesons which have greater reduced mass μ.

We recall that [10] for the linear potential to be dominant we require $\langle r \rangle > r_0$, where $\langle r \rangle$ is the expectation value of the distance r which reasonably gives the size of a state (in this case meson) and r_0 is a point at which linear cum Coulomb potential becomes zero (figure 1 of Aitchison and Dudek [10]). The condition of applicability of VIPT to linear potential as parent conforms to low value of α_s and high value of b because r_0 is directly proportional to α_s and inversely proportional to b and we need a small r_0 for the linear potential to dominate. So, with a linear parent, one can suitably handle large b and small α_s which is necessary in this QCD-inspired potential model for the B-sector mesons (e.g. B, B_s, B_c) usually incorporated with small running coupling constant α_s due to their large mass. The linear parent is thus expected to be effective for heavier mesons.

Our approach is further boosted by the success of the work [8] where we have used the Dalgarno method with linear parent for D, D_s, B, B_s, B_c mesons.

The rest of the paper is organized as follows: Section 2 contains the formalism, §3 the result and calculation while §4 includes the discussion and conclusion.

2. Formalism

2.1 *Isgur–Wise function; its slope and curvature*

The Isgur–Wise function is written as [1]

$$\begin{aligned}\xi(v_\mu \cdot v'_\mu) &= \xi(y)\\ &= 1 - \rho^2 (y-1) + C (y-1)^2 + \cdots ,\end{aligned} \tag{1}$$

where

$$y = v_\mu \cdot v'_\mu \tag{2}$$

and v_μ and v'_μ are the four velocity of the heavy meson before and after the decay. The quantity ρ^2 is the slope of the I–W function at $y = 1$ and known as charge radius:

$$\rho^2 = \left.\frac{\partial \xi}{\partial y}\right|_{y=1} . \tag{3}$$

The second-order derivative is the curvature of the I–W function known as convexity parameter:

$$C = \frac{1}{2}\left.\left(\frac{\partial^2 \xi}{\partial y^2}\right)\right|_{y=1} . \tag{4}$$

For the heavy–light flavour mesons the I–W function can also be written as [3,14]

$$\xi(y) = \int_0^{+\infty} 4\pi r^2 \left|\psi(r)\right|^2 \cos pr \, \mathrm{d}r, \tag{5}$$

where

$$p^2 = 2\mu^2 (y - 1) . \tag{6}$$

Now the wave function ψ of the hadronic system is determined by taking the linear potential as the parent.

2.2 *First-order corrected wave function and energy in VIPT*

The wave function corrected upto the first order of jth state is given by (eq. (10) of ref. [12])

$$\psi_j = \psi_j^{(0)} + \sum_{k \neq j} \frac{\int \psi_k^{(0)*} H'_{P'j} \psi_j^{(0)} \mathrm{d}v}{E_j^{(0)} - E_k^{(0)}} \psi_k^{(0)} . \tag{7}$$

The energy corrected upto the first order for the same state is

$$\begin{aligned} E_j &= \int \psi_j^{(0)*} H \psi_j^{(0)} \mathrm{d}v \\ &= \int \psi_j^{(0)*} (H_{0P'} + H'_{P'}) \psi_j^{(0)} \mathrm{d}v, \end{aligned} \tag{8}$$

where ψ_k, E_k are the wave function and energy eigenvalues of the kth states which are orthonormal to the jth state. The superscript (0) means zeroth-order correction of the corresponding quantities. Also, we note that P' is the variational parameter and $H_{0P'}$, $H'_{P'}$ are as defined in eq. (9) of ref. [12].

The summation in eq. (7) can include any number of kth states. In this work, we consider terms upto three states in the summation as was done in ref. [12].

2.3 *Wave functions using VIPT with linear potential as the parent*

2.3.1 *With one term in the summation.* As explained earlier, we take b' as the variational parameter instead of the physical parameter b in the parent linear potential to write the Hamiltonian as [3,12]

$$\begin{aligned} H &= H_0 + H' \\ &= -\frac{\nabla^2}{2\mu} + br - \frac{4\alpha_s}{3r} + c \\ &= -\frac{\nabla^2}{2\mu} + br - \frac{\alpha}{r} + c \\ &= -\frac{\nabla^2}{2\mu} + b'r - \frac{\alpha}{r} - b'r + br + c \\ &= H_{0b'} + H'_{b'}, \end{aligned} \tag{9}$$

where $\alpha = 4\alpha_s/3$. Now, $H_{0b'} = -(\nabla^2/2\mu) - b'r$ is the parent Hamiltonian with the new parameter b' and $H'_{b'} = (\alpha/r) - b'r + br + c$ is the perturbed Hamiltonian with the same variational parameter b' instead of the physical parameter b.

We consider jth state as the $1s$ state ($n = 1, l = 0$) and in the summation of eq. (7), we consider a single kth state which is the $2s$ state ($n = 2, l = 0$).

We note that in the variational method, we are interested only in the 'r' dependence of the Hamiltonian, and so 'c' in $H'_{b'}$ has no role to play in the calculation [15].

The unperturbed wave functions with linear parent with appropriate boundary conditions are the Airy functions given by [10]

$$\psi_{n0}(r) = \frac{N_n}{2\sqrt{\pi}r}\mathrm{Ai}\left((2\mu b')^{1/3}r + \rho_{0n}\right), \tag{10}$$

where ρ_{0n}s are the zeroes of the Airy function $\mathrm{Ai}(\rho_{0n}) = 0$ given by [10,16]:

$$\rho_{0n} = -\left[\frac{3\pi(4n-1)}{8}\right]^{2/3} \tag{11}$$

and N_n is the normalization constant.

As an illustration, we reproduce for s states a few of the zeroes of the Airy function in table 1. The corresponding energies are given as

$$E_n = -\left(\frac{b'^2}{2\mu}\right)^{1/3}\rho_{0n}. \tag{12}$$

Table 1. A few of the zeroes of Airy function for s states.

State	ρ_{0n}
$1s$ ($n = 1, l = 0$)	−2.3194
$2s$ ($n = 2, l = 0$)	−4.083
$3s$ ($n = 3, l = 0$)	−5.5183
$4s$ ($n = 4, l = 0$)	−6.782

Of course $n = 1, 2, 3, 4, \ldots$ is the principal quantum number.

Thus the trial $1s$ state ($n = 1, l = 0$) wave function is (which is also the unperturbed wave function):

$$\begin{aligned}\psi^{(0)} &= \psi_{10}^{(0)} \\ &= \frac{N_1}{2\sqrt{\pi}r}\mathrm{Ai}\left((2\mu\bar{b}')^{1/3}r - 2.3194\right) \\ &= \frac{N_1}{2\sqrt{\pi}r}\mathrm{Ai}\left(z_1\right), \end{aligned} \tag{13}$$

where

$$z_1 = ((2\mu\bar{b}')^{1/3}r - 2.3194) \tag{14}$$

and the subscript 10 indicates the quantum number (n, l) of the jth state.

We note that b' is replaced by $\bar{b}'$ which is obtained by minimizing E_j given by eq. (8). It is essential since in VIPT we have to use the values of variational parameter leading to minimum energy (for example in ref. [12], α_s was replaced by $\bar{\alpha}'_{10}$). The values of $\bar{b}'$ for different mesons are listed in table 2.

Now we consider the single kth state in the summation of eq. (7) which is the $2s$ state given by

$$\psi_{20}^{(0)} = \frac{N_2}{2\sqrt{\pi}r}\mathrm{Ai}\left((2\mu\bar{b}')^{1/3}r - 4.083\right) = \frac{N_2}{2\sqrt{\pi}r}\mathrm{Ai}\left(z_2\right), \tag{15}$$

where

$$z_2 = \left((2\mu\bar{b}')^{1/3}r - 4.083\right). \tag{16}$$

The wave function corrected upto first order is

$$\psi_S = N\left[\psi^{(0)} + \frac{(2\mu)^{1/3}}{(\rho_{02}-\rho_{01})\,\bar{b}'^{2/3}}\left((b-\bar{b}')\langle r\rangle_{2,1} - \alpha\left\langle\frac{1}{r}\right\rangle_{2,1}\right)\psi_{20}\left(r\right)\right], \tag{17}$$

where

$$\langle r\rangle_{2,1} = N_1 N_2\int_0^{+\infty} r\mathrm{Ai}((2\mu\bar{b}')^{1/3}r - 2.3194)\mathrm{Ai}\left((2\mu\bar{b}')^{1/3}r - 4.083\right)\mathrm{d}r \tag{18}$$

and N is the normalization constant.

2.3.2 *With two terms in the summation.* We next consider the $3s$ state ($n = 3, l = 0$) in addition to $2s$ state (as done in the single term case) given by

$$\psi_{30}^{(0)} = \frac{N_3}{2\sqrt{\pi}r}\mathrm{Ai}\left((2\mu\bar{b}')^{1/3}r - 5.5153\right) = \frac{N_3}{2\sqrt{\pi}r}\mathrm{Ai}\left(z_3\right), \tag{19}$$

Table 2. Values of $\bar{b}'$ with $b = 0.183$ GeV^2.

Mesons	Reduced mass μ	$\alpha = 4\alpha_s/3$	$\bar{b}'$ without relativistic effect	$\bar{b}'$ with relativistic effect
D	0.2761	0.924	5.306	16.24
D_s	0.368248	0.924	5.876	19.8
B	0.31464	0.348	4.33	5.587
B_s	0.4401	0.348	4.497	5.954
B_c	1.1803	0.348	5.39	8.103

where

$$z_3 = \left((2\mu\bar{b}')^{1/3}r - 5.5153\right). \tag{20}$$

With the inclusion of this state, the wave function corrected upto the first order is

$$\psi_D = N'\left[\psi^{(0)} + \frac{(2\mu)^{1/3}}{(\rho_{02}-\rho_{01})\,\bar{b}'^{2/3}}\left((b-\bar{b}')\langle r\rangle_{2,1} - \alpha\left\langle\frac{1}{r}\right\rangle_{2,1}\right)\psi_{20}(r) + \frac{(2\mu)^{1/3}}{(\rho_{03}-\rho_{01})\,\bar{b}'^{2/3}}\left((b-\bar{b}')\langle r\rangle_{3,1} - \alpha\left\langle\frac{1}{r}\right\rangle_{3,1}\right)\psi_{30}(r)\right], \tag{21}$$

where

$$\langle r\rangle_{3,1} = N_1N_3\int_0^{+\infty} r\,\mathrm{Ai}\left((2\mu\bar{b}')^{1/3}r - 2.3194\right)\mathrm{Ai}\left((2\mu\bar{b}')^{1/3}r - 5.5153\right)\mathrm{d}r \tag{22}$$

and N' is the normalization constant.

2.3.3 *With three terms in the summation.* In addition to the $2s$ and $3s$ states we now add the $4s$ state:

$$\psi_{40}^{(0)} = \frac{N_4}{2\sqrt{\pi}r}\mathrm{Ai}\left((2\mu\bar{b}')^{1/3}r - 6.782\right) = \frac{N_4}{2\sqrt{\pi}r}\mathrm{Ai}(z_4), \tag{23}$$

where

$$z_4 = \left((2\mu\bar{b}')^{1/3}r - 6.782\right). \tag{24}$$

With the inclusion of this state, the first-order wave function now becomes

$$\psi_T = N''\left[\psi^{(0)} + \frac{(2\mu)^{1/3}}{(\rho_{02}-\rho_{01})\,\bar{b}'^{2/3}}\left(\left(b-\bar{b}'\right)\langle r\rangle_{2,1} - \alpha\left\langle\frac{1}{r}\right\rangle_{2,1}\right)\psi_{20}(r) + \frac{(2\mu)^{1/3}}{(\rho_{03}-\rho_{01})\,\bar{b}'^{2/3}}\left(\left(b-\bar{b}'\right)\langle r\rangle_{3,1} - \alpha\left\langle\frac{1}{r}\right\rangle_{3,1}\right)\psi_{30}(r) + \frac{(2\mu)^{1/3}}{(\rho_{04}-\rho_{01})\,\bar{b}'^{2/3}}\left(\left(b-\bar{b}'\right)\langle r\rangle_{4,1} - \alpha\left\langle\frac{1}{r}\right\rangle_{4,1}\right)\psi_{40}(r)\right], \tag{25}$$

where

$$\langle r\rangle_{4,1} = N_1 N_4 \int_0^{+\infty} r\,\mathrm{Ai}((2\mu\bar{b}')^{1/3} r - 2.3194)\mathrm{Ai}((2\mu\bar{b}')^{1/3} r - 6.782)\mathrm{d}r \quad (26)$$

and N'' is the normalization constant.

The relativistic version of these wave functions is obtained by multiplying the above expression by $(r\mu\alpha)^{-\epsilon}$ [17,18]. The relativistic modification is felt necessary as the light quark moves faster relative to the static heavy quark. Thus, relativistic version of all these wave functions is

$$\psi_{i,\mathrm{rel}} = \psi_i (r\mu\alpha)^{-\epsilon}, \quad (27)$$

where $i = S, D, T$ and

$$\epsilon = 1 - \sqrt{1 - \frac{4\alpha_s}{3}}. \quad (28)$$

Putting all these wave functions, i.e. eqs (17), (21), (25) and (27) in (5) we can calculate the Isgur–Wise function for different cases.

3. Calculation and results

We have listed the values of charge radius and convexity parameter of the calculated I–W function for various heavy–light flavour mesons in the present method considering single state, two states, and three states of eq. (7) with and without relativistic effect.

Table 1 gives the zeroes of Airy function while table 2 gives the values of $\bar{b}'$. In tables 3–5, we record our predictions of slope and curvature for single term, two terms and three terms of eq. (7) respectively. Table 6 gives a summary of these in other models while in table 7, we give a comparison of VIPT and Dalgarno methods for both the options.

The α_s values are taken from the V-scheme [6,19–21] and the integrations are done numerically for all these calculations.

Table 3. Values of slope ρ^2 and curvature C with single term in eq. (7).

Meson	ρ_S^2	C_S	$\rho_{S,\mathrm{rel}}^2$	$C_{S,\mathrm{rel}}$
D	1.36	0.01	0.53	0.0022
D_s	1.867	0.03	0.702	0.0036
B	1.93	0.02	1.41	0.013
B_s	2.923	0.046	2.113	0.0283
B_c	9.442	0.484	6.274	0.2522

Table 4. Values of slope ρ^2 and curvature C with two terms in eq. (7).

Meson	ρ_D^2	C_D	$\rho_{D,\mathrm{rel}}^2$	$C_{D,\mathrm{rel}}$
D	1.201	0.013	0.57	0.0026
D_s	2.001	0.0242	0.74	0.0041
B	2.004	0.0244	1.44	0.0133
B_s	3.031	0.0565	2.16	0.0297
B_c	10.2	0.61	6.51	0.275

Table 5. Values of slope ρ^2 and curvature C with three terms in eq. (7).

Meson	ρ_T^2	C_T	$\rho_{T,\mathrm{rel}}^2$	$C_{T,\mathrm{rel}}$
D	1.33	0.016	0.604	0.00326
D_s	2.023	0.0305	0.78	0.0054
B	2.027	0.031	1.54	0.0217
B_s	3.087	0.071	2.29	0.047
B_c	10.25	0.767	6.99	0.441

Table 6. Predictions of the slope and curvature of the I–W function in various models.

Model	Value of ρ^2	Value of curvature C
Le Yaouanc *et al* [22]	≥ 0.75	–
Le Yaouanc *et al* [23]	≥ 0.75	≥ 0.47
Rosner [29]	1.66	2.76
Mannel [30,31]	0.98	0.98
Pole ansatz [32]	1.42	2.71
MIT bag model [28]	2.35	3.95
Ebert *et al* [34]	1.04	1.36
Simple quark model [27]	1	1.11
Skryme model [25]	1.3	0.85
QCD sum rule [26]	0.65	0.47
Relativistic three-quark model [24]	1.35	1.75
Neubert [33]	0.82±0.09	–
Infinite momentum frame quark model [35]	3.04	6.81
UKQCD Collaboration [36]	0.83^{+15+24}_{-11-22}	–
CLEO Collaboration [37]	$0.76 \pm 0.16 \pm 0.08$	–

Table 7. Comparison of the values of ρ^2 and C in VIPT and Dalgarno methods for both the options. For comparison we take the best representative values of ρ^2 and C from the available data for D, D_s, B mesons.

VIPT					
		I. Linear parent (this work)		II. Coulombic parent [12]	
Terms considered in eq. (7)	Meson	ρ_S^2	C_S	ρ_S^2	C_S
Single term	D	0.53	0.0022	0.433	0.525
	D_s	0.702	0.0036	0.56	0.85
	B	1.41	0.0126	3.6	15.3
Two terms	D	0.57	0.0026	0.432	0.524
	D_s	0.74	0.0041	0.55	0.84
	B	1.44	0.0133	3.16	12.32
Three terms	D	0.604	0.0033	0.43	0.516
	D_s	0.78	0.0054	0.545	0.815
	B	1.54	0.0213	3.12	11.8
Dalgarno Method					
		I. Linear parent [8]		II. Coulombic parent [6]	
–	Meson	ρ_S^2	C_S	ρ_S^2	C_S
–	D	0.896	0.0031	1.136	5.377
	D_s	1.352	0.0077	0.912	0.0007
	B	1.41	0.013	128.13	5212

4. Discussion and conclusion

This analysis with linear parent shows a completely different picture in comparison to that with Coulombic parent [12]. With more terms in (7), the slope and curvature have increased contrary to Coulombic parent. Also, an analysis of table 6 indicates that for a definite term, the slope has assumed larger values than those of ref. [12] while for the curvature, the pattern is reversed, i.e. it has assumed smaller values than those of ref. [12].

Regarding the number of terms considered in the summation (7), we have seen that the result is the most satisfactory and comparable for the single term consideration. This is undoubtably a great phenomenological advantage as involvement of more terms in eq. (7) makes the calculation quite cumbersome which happened in ref. [12]. However, relativistic correction in this case also decreases the slope and curvature of Isgur–Wise function as observed earlier [12]. If we look back at our Dalgarno method with linear parent [8], we have observed larger values of slope and curvature for D, D_s mesons and smaller values for B, B_s, B_c mesons in this work compared to that in [8].

To conclude, the present approach based on VIPT for calculating of I–W function within the QCD-inspired potential model appears to be preferable over the one in ref. [12] where the linear potential was considered as perturbation.

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