Approximate Solutions of the Non-Relativistic Schrödinger Equation with An Interaction of Coulomb and Hulthèn Potentials

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Abstract:
By using the Pekeris approximation type, the Schrödinger equation is solved for the interaction of Coulomb and Hulthèn potentials within the framework of supersymmetric approach and Nikiforov-Uvarov method. The energy levels are obtained with the corresponding wave functions in terms of hypergeometric functions.

Keywords: Schrödinger Equation; Hulthèn Potential; Interaction; Supersymmetric Method

1. INTRODUCTION

The experimental verifications of the Schrödinger equation that were theoretically discussed long ago, have recently aroused interest in Physics. The two most important ingredients in many studies are the wave functions and energy eigenvalues of the corresponding Schrödinger for which we do not know exact solutions in many cases. However, in some instances, the solutions are known in terms of the familiar mathematical functions [1]. The analytic solutions of the wave equations with some physical potentials are only possible for \( \ell = 0 \). For \( \ell \neq 0 \) state, the Pekeris approximation type [2–4] have been used to obtain an approximate solutions. To obtain the bound state energy eigenvalues for any \( \ell \) state, various methods such as Asymptotic iteration method [5–9], Nikiforov-Uvarov method [10–14], exact quantization rule [15, 16], shifted 1/N expansion method [17], supersymmetric method [18, 19] have been used.

In the present work, we attempt to investigate the bound state solutions of the radial Schrödinger equation with the interaction of Coulomb potential and Hulthèn potential using both supersymmetric and Nikiforov-Uvarov methods. Hulthèn potential is one of the important molecular potentials used in different areas of Physics such as nuclear and particle, atomic and condensed matter Physics and chemical Physics to describe the interaction between two atoms. As a result of its applications, several works have been done on this potential. For instance, Agboola [20, 21] solved the Schrödinger equation with Hulthèn plus ringed-shaped potential. Bayrak and Boztosun [5], applied the asymptotic iteration method to obtain a solution with Hulthèn potential. Saad [22] investigated the potential within the framework of the Klein-Gordon equation in D-dimensional space. Haouat and Chetouani [23], solved the problem for both Klein-Gordon and Dirac equation by an approximate technique. Ikhdair and Sever [24, 25] solved...
the Klein-Gordon equation with a position-dependent mass. Hall [26], in an instructive paper, discussed the Yukawa and Hulthèn potentials together. Zarrinkamar et al. [27] obtained analytical treatment of the two-body spinless Salpeter equation with the Hulthèn potential.

The organization of the work is as follows: In the next section, we obtain the bound state solutions. In section 3, we obtain numerical results while in the final section, we give the concluding remark.

2. BOUND STATE SOLUTIONS USING SUPERSYMMETRIC APPROACH

To study any quantum system, we solve the original Schrödinger equation [28, 29]:

$$\left( \frac{p^2}{2m} - E_n + V(r) \right) \psi_{n\ell m}(r) = 0, \tag{1}$$

where the potential $V(r)$ is taking as Coulomb potential minus Hulthèn potential written in the form:

$$V(r) = V_C(r) - V_H(r) = -\frac{A}{r} + \frac{V_0 e^{-\delta r}}{1 - e^{-\delta r}}. \tag{2}$$

Setting the wave function $\psi_{n\ell m}(r) = R_{n\ell}(r)Y_{\ell m}(\theta, \phi)r^{-1}$ to obtain the following radial Schrödinger equation:

$$\frac{d^2R_{n\ell}(r)}{dr^2} + \left[ \frac{2\mu}{\hbar^2} (E_{n\ell} - V(r)) - \frac{\ell(\ell + 1)}{r^2} \right] R_{n\ell}(r). \tag{3}$$

The radial wave function $R_{n\ell}(r)$ satisfying Eq. (3), should be normalizable and finite near $r = 0$ and $r \to \infty$ for the bound-state solutions. The wave Eq. (3) with the interaction of Coulomb and Hulthèn potentials cannot be solved analytically when $\ell \neq 0$ because of the centrifugal term $\frac{\ell(\ell + 1)}{r^2}$. Therefore, to solve Eq. (3) analytically, we must use an approximation scheme to deal with the centrifugal term. It is found that the following

$$\frac{1}{r^2} = \frac{\delta^2}{(1 - e^{-\delta r})^2} \tag{4}$$

is a good approximation to the centrifugal term in a short potential range. This approximation is valid when $\delta \ll 1$. Substituting Eqs. (2) and (4) into Eq. (3), we obtain a differential equation of the form

$$\left[ \frac{d^2}{dr^2} + \frac{2\mu E_{n\ell}}{\hbar^2} + 2\mu A\delta - \ell(\ell + 1)\delta^2 - \frac{2\mu \delta (A - \frac{\hbar^2}{2})}{1 - e^{-\delta r}} - \frac{\ell(\ell + 1)\delta^2 e^{-\delta r}}{(1 - e^{-\delta r})^2} \right] R_{n\ell}(r) = 0. \tag{5}$$

For bound state, the ground state wave function can be written in the form

$$U_{0\ell}(r) = \exp \left( - \int W(r) \, dr \right), \tag{6}$$

where $W(r)$ is called the superpotential in supersymmetric quantum mechanics [30, 31] which satisfy Eq. (5). Substituting Eq. (6) into Eq. (5), we obtain the following equation for $W(r)$:

$$\frac{d^2R_{n\ell}(r)}{dr^2} = W^2(r) - \frac{dW(r)}{dr}. \tag{7}$$
where we take the superpotential $W(r)$ as

$$W(r) = B_0 + \frac{B_1}{1 - e^{-\delta r}}. \quad (8)$$

Substituting Eq. (8) into Eq. (7) lead us to the following relations:

$$B_0^2 = -\frac{2\mu E_{n\ell}}{\hbar^2} - \frac{2\mu \delta}{\hbar^2} + \ell (\ell + 1) \delta^2, \quad (9a)$$

$$B_1 = -\delta (\ell + 1). \quad (9b)$$

$$B_0 = \frac{2\mu (\delta \Lambda - V_0) - B_1^2 \hbar^2 - \ell (\ell + 1) \delta^2 \hbar^2}{2B_1 \hbar^2}. \quad (9c)$$

Using the superpotential given in Eq. (8), we construct the supersymmetric partner potentials in the following form:

$$U_+(r) = W^2(r) + W'(r) = B_0^2 + \frac{2B_0 B_1}{1 - e^{-\delta r}} + \frac{B_1^2 (1 - e^{-\delta r})}{(1 - e^{-\delta r})^2} - \frac{B_1 (B_1 + \delta) e^{-\delta r}}{(1 - e^{-\delta r})^2}, \quad (10)$$

$$U_-(r) = W^2(r) - W'(r) = B_0^2 + \frac{2B_0 B_1}{1 - e^{-\delta r}} + \frac{B_1^2 (1 - e^{-\delta r})}{(1 - e^{-\delta r})^2} - \frac{B_1 (B_1 - \delta) e^{-\delta r}}{(1 - e^{-\delta r})^2}. \quad (11)$$

Eqs. (10) and (11) are shape invariant and thus satisfied the shape invariance condition. Therefore, the two partner potentials are related by:

$$U_+(r, a_0) = U_-(r, a_1) + R(a_1), \quad (12)$$

where $a_1$ is a function of $a_0$, i.e. $a_1 = f(a_0) = a_0 - \delta$ and consequently, $a_n = a_0 - n\delta$ and the residual term $R(a_1)$ is independent of the variable $r$. According to [32], the shape invariance holds via mapping of the form: $B_0 \rightarrow B_0 - \delta$, where $B_0 = a_0$. If all desirable results are obtained, then, one can obtain the following relations:

$$R(a_1) = \left( \frac{\mu (\delta \Lambda - V_0)}{\hbar^2} - \frac{a_0^2}{2a_0} - \ell (\ell + 1) \delta^2 \right)^2 - \left( \frac{\mu (\delta \Lambda - V_0)}{\hbar^2} - \frac{a_1^2}{2a_1} - \ell (\ell + 1) \delta^2 \right)^2, \quad (13)$$

$$R(a_2) = \left( \frac{\mu (\delta \Lambda - V_0)}{\hbar^2} - \frac{a_1^2}{2a_1} - \ell (\ell + 1) \delta^2 \right)^2 - \left( \frac{\mu (\delta \Lambda - V_0)}{\hbar^2} - \frac{a_2^2}{2a_2} - \ell (\ell + 1) \delta^2 \right)^2, \quad (14)$$

$$R(a_n) = \left( \frac{\mu (\delta \Lambda - V_0)}{\hbar^2} - \frac{a_{n-1}^2}{2a_{n-1}} - \ell (\ell + 1) \delta^2 \right)^2 - \left( \frac{\mu (\delta \Lambda - V_0)}{\hbar^2} - \frac{a_n^2}{2a_n} - \ell (\ell + 1) \delta^2 \right)^2. \quad (15)$$

Based on the concept of shape invariance approach and formalism [32, 33], we can determine the energy equation of the $U_-(r)$ potential by using the formalism:

$$E_{n\ell} = E_{n\ell}^{(-)} + E_{0\ell}, \quad (16)$$
Analyzing the asymptotic behavior of as by taking trial wave function of the form Eq. (21) has solution

\[ E_{nl} = \frac{\mu(\delta-A+V_0)}{h^2} - \delta (\ell + n + 1)^2 - \ell (\ell + 1) \delta \]

Substituting for \( a_n \) into Eq. (19), we obtain the energy eigenvalue equation as

\[ E_{nl} = \frac{\ell (\ell + 1) \delta^2 h^2}{2\mu} - \delta A - \frac{h^2}{2\mu} \left[ \frac{2\mu}{h^2} \left( A - \frac{V_0}{s} \right) - \delta (\ell + n + 1)^2 - \ell (\ell + 1) \delta \right]^2 \]

### 3. THE EIGENFUNCTION

In order to obtain unnormalized wave function, we define a new variable of the form \( s = e^{-\delta r} \). Substituting this, into Eq. (5), we obtain equation of the form:

\[
\frac{d^2 R_{nl}(s)}{ds^2} + \frac{1}{s} \frac{dR_{nl}(s)}{ds} + \left[ \frac{N + \beta s + Cs^2}{s(1-s)^2} \right] R_{nl}(r) = 0,
\]

where

\[
N = -\frac{2\mu E_{nl}}{h^2 \delta^2} + \frac{4\mu A}{\delta} - \ell (\ell + 1),
\]

\[
\beta = -4\ell (\ell + 1) - \frac{4\mu [2A + (A-V_0)]}{h^2 \delta^2},
\]

\[
C = \frac{4\mu [A + (A-V_0)]}{h^2 \delta} - \frac{2\mu E_{nl}}{h^2 \delta^2} + 2\ell (\ell + 1).
\]

Analyzing the asymptotic behavior of (21) at origin when \( r \rightarrow 0 \) (\( s \rightarrow 1 \)) and at infinity when \( r \rightarrow \infty \) (\( s \rightarrow 0 \)), Eq. (21) has solution

\[ U_{nl}(r) = (1-s)^a s^\alpha, \]

where

\[ a = \frac{2\mu E_{nl}}{h^2 \delta^2} - \frac{2\mu A}{h^2 \delta} - \ell (\ell + 1), \alpha = -(\ell + 1) \delta. \]

by taking trial wave function of the form \( R_{nl}(s) = (1-s)^a s^\alpha \) and inserting it into Eq. (21), one obtain

\[ f''(s) + f'(s) \left[ \frac{(2\alpha + 1) - s (2\alpha + 2a+1)}{s(1-s)} \right] - f(s) \left[ \frac{(\alpha + a)^2 + N}{s(1-s)} \right] = 0. \]

Eq. (27) is a differential equation satisfied by the hypergeometric function. Thus, its solution is obtain as

\[ f(s) = F_1 (-n, n + 2\alpha + 2a; 2\alpha + 1, s). \]

Replacing the function \( f(s) \) with the hypergeometric function and write the complete radial wave function as

\[ R_{nl}(s) = N s^\alpha (1-s)^a F_1 (-n, n + 2\alpha + 2a; 2\alpha + 1, s), \]

where \( N \) is the normalization constant.
Figure 1. Variation of the energy spectrum as a function of the screening parameter $\delta$ with $A = 1, V_0 = 2\mu = \hbar = 1$.

4. BOUND STATE SOLUTIONS USING NIKIFOROV-UVAROV METHOD

In order to test the accuracy of our result, we solve the same problem using Nikiforov-Uvarov (NU) method and compare it with the result obtained using SUSY. With Eqs. (2) and (4), Eq. (3) becomes

$$\frac{d^2R_n}(r) = 0,$$

For solving the above equation using NU method, let us consider the differential equation [34]:

$$\left\{ \frac{d^2}{ds^2} + \frac{\alpha_1 - \alpha_2 s}{s(1 - \alpha_5 s)} \frac{d}{ds} + \frac{\left[-\xi_1 s^2 + \xi_2 s - \xi_3\right]}{s^2(1 - s)^2} \right\} \psi(s) = 0,$$

where,

$$\alpha_4 = \frac{1}{2}(1 - \alpha_1), \alpha_5 = \frac{1}{2}(\alpha_2 - 2\alpha_3), \alpha_6 = \alpha_2 + \alpha_4, \alpha_7 = 2\alpha_4 \alpha_5 - \xi_2,$$

$$\alpha_8 = \alpha_2 + \xi_3, \alpha_9 = \alpha_4 \alpha_5 + \alpha_2 \alpha_6 + \alpha_6.$$

To obtain the solution of Eq. (30), we first introduce $s = e^{-\delta r}$ to obtain

$$\frac{d^2R_n(s)}{ds^2} + \frac{1 - s}{s(1 - s)} \frac{dR_n(s)}{ds} + \frac{\left[-D(1 - s)^2 + (P - Qs)(1 - s) - \ell(\ell + 1)\delta^2\right]}{s^2(1 - s)^2} R_n(s) = 0,$$

where,

$$D = -\frac{2\mu E_n}{\hbar^2}, P = \frac{2\mu \delta A}{\hbar^2}, Q = \frac{2\mu V_0}{\hbar^2}.$$
Approximate Solutions of the Non-Relativistic Schrödinger Equation with An Interaction of Coulomb and Hulthén Potentials

Figure 2. Variation of the energy spectrum as a function of the Potential strength with $V_0 = \hbar = \delta = 2\mu = 1$.

Comparing Eq. (31) with Eq. (32), we find the following relations:

$$\alpha_1 = 1, \alpha_2 = 1, \alpha_3 = 1, \alpha_4 = 0, \alpha_5 = -\frac{1}{2} \xi_1 = -\frac{2\mu (E_{nl} + A\delta)}{\hbar^2 \delta^2} + \ell (\ell + 1),$$

$$\xi_2 = -\frac{2\mu (2E_{nl} + \delta A + V_0)}{\hbar^2 \delta^2}, \xi_3 = -\frac{2\mu E_{nl}}{\hbar^2 \delta^2}, \alpha_6 = \frac{1}{4} + \frac{2\mu V_0}{\hbar^2 \delta^2},$$

$$\alpha_7 = \frac{2\mu (A\delta + V_0 - 2E_{nl})}{\hbar^2 \delta^2}, \alpha_8 = \ell (\ell + 1) - \frac{2\mu (A\delta + E_{nl})}{\hbar^2 \delta^2}, \alpha_9 = \left( \ell + \frac{1}{2} \right)^2.$$

Following the Nikiforov-Uvarov method [13], we obtain the bound state energy condition

$$\alpha_2 n - (2n + 1) \alpha_5 + (2n + 1)(\sqrt{\alpha_6} + \alpha_3 \sqrt{\alpha_8} + n (n - 1) \alpha_3$$

$$+ \alpha_7 + 2\alpha_3 \alpha_8 + 2\sqrt{\alpha_6} \alpha_9 = 0,$$

which gives the energy eigenvalues of the system as

$$E_{nl} = \frac{\ell (\ell + 1) \delta^2 \hbar^2}{2\mu} - \delta A - \frac{\hbar^2}{2\mu} \left[ \frac{\frac{2\mu}{\delta^2} \left( A - \frac{V_0}{\delta} \right) - \delta (\ell + n + 1)^2 - \ell (\ell + 1) \delta}{2 (\ell + n + 1)} \right]^2. \quad (34)$$

Eq. (20) is identical to Eq. (34). Now, let us consider some special cases. As $\delta$ approaches zero and $V_0 = 0$, the potential given in Eq. (2) reduces to Coulomb potential and the energy equation becomes

$$E_{nl} = \frac{\ell (\ell + 1) \delta^2 \hbar^2}{2\mu} - \delta A - \frac{\hbar^2}{2\mu} \left[ \frac{\frac{2\mu}{\delta^2} A - \delta (\ell + n + 1)^2 - \ell (\ell + 1) \delta}{2 (\ell + n + 1)} \right]^2. \quad (35)$$
Figure 3. Variation of the energy spectrum as a function of the particle mass with $\delta = 1$, $A = 2$, $V_0 = 1$ and $\hbar = 1$.

Table 1. Energy spectrum ($-E_{nl}$ in fm$^{-1}$) with $2\mu = \hbar = 1$.

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<th>$A = 2, V_0 = 6$</th>
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Similarly, when \( A = 0 \), the potential Eq. (2) reduces to Hulthén and the energy equation turns to

\[
E_{n\ell} = \frac{\ell(\ell + 1)\delta^2\hbar^2}{2\mu} - \frac{\hbar^2}{2\mu} \left[ \frac{2\mu}{\hbar^2} \left( \frac{v_0}{\delta} \right) - \delta (\ell + n + 1)^2 - \ell (\ell + 1) \delta \right] \left( \frac{2\mu}{\hbar^2} \right)^2 \]

.. (36)

When \( V_0 = \delta b \), Eq. (34) turns to energy equation for the Hellmann potential which is identical to Eq. (24) of Ref. [13].

\[
E_{n\ell} = \frac{\ell(\ell + 1)\delta^2\hbar^2}{2\mu} - \frac{\hbar^2}{2\mu} \left[ \frac{2\mu}{\hbar^2} (A - b) - \delta (\ell + n + 1)^2 - \ell (\ell + 1) \delta \right] \left( \frac{2\mu}{\hbar^2} \right)^2 . \]

(37)

In Figure 1 - Figure 3, we have plotted energy with \( \delta \), \( A \) and \( \mu \). In Figure 1, the energy increases with \( \delta \) and later decreases. In Figure 2, as \( A \) increases, the energy decreases (attractive). We numerically reported energy eigenvalues for Coulomb potential minus Hulthén potential. It is deduced that as \( \delta \) increases, the energy increases towards positive. The energy is more attractive (negative) when \( A < V_0 \) as shown in the Table 1.

5. CONCLUSION

In this work, we have solved the Schrödinger equation for the combination of Coulomb potential and Hulthén potential in the framework of supersymmetric and Nikiforov-Uvarov methods by considering a suitable approximation scheme to get rid of the centrifugal barrier and obtained energy eigenvalues and the wave functions. It is seen that the energy equation obtained with the two methods are identical. This shows that the two methods are in excellent agreement. Some special cases of interest of the solution are obtained. These are eigenvalues for Coulomb potential, Hulthén potential and Hellmann potential by putting \( V_0 = 0 \), \( A = 0 \) and \( V_0 = \delta b \) respectively. In Figure 1 - Figure 3, we make some plots to see the behavior of energy with screening parameter, potential strength and particle mass.

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