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Effects of Rotating Frame on a Vector Boson Oscillator

Abdullah GUVENDI*[1]

Abstract

We analyze the effects of the spacetime topology and angular velocity of rotating frame on the dynamics of a relativistic vector boson oscillator ($\mathcal{VBO}$). To determine these effects on the energy of the $\mathcal{VBO}$ we solve the corresponding vector boson equation in the rotating frame of 2+1 dimensional cosmic string-induced spacetime background. We obtain an exact energy spectrum, which depends on the angular velocity of the rotating frame and angular deficit parameter of the background. We show that the effects of angular deficit parameter on each energy level of the $\mathcal{VBO}$ cannot be same and the angular velocity of the rotating frame couples with the spin of the $\mathcal{VBO}$. Furthermore, we have obtained that the angular velocity of rotating frame breaks the symmetry of the positive-negative energy states.

Keywords: Non-inertial effects, quantum fields in curved spaces, topological defects.

1. INTRODUCTION

The relativistic wave equations for spin-1/2, spin-1 and spin-3/2 particles can be derived via canonical quantization of the classical spinning particle with zitterbewegung. These equations can be obtained as possible quantum states from the mentioned classical quantization procedure [1]. After demonstrating that there is a unifying principle for this class of relativistic wave equations [1], it has been shown that the well-known duffin-kemmer-proca equations and the many-body dirac equation (fully-covariant) [1-3] can be derived from similar action. Spin-1 sector of the duffin-kemmer-petiau ($\mathcal{DKP}$) equation has been derived as excited state via the mentioned procedure provided that the spinor is a symmetric spinor of rank-two [1,4,5]. Under this condition, the symmetric spinor can be constructed by kronocker product of two dirac spinors [1,4-6]. However, it is important to underline that this symmetric spinor does not include the spin-0 sector in 2+1 dimensions [7]. The vector boson equation ($\mathcal{VBE}$) corresponds to the spin-1 part of the $\mathcal{DKP}$ equation in 2+1 dimensions [1,4-7] and its massless form can also be derived via the same quantization procedure [4]. It has been declared that massless $\mathcal{VBE}$ and Maxwell equations are equivalent [4], and moreover it has been clearly shown that the state functions for massless form of the $\mathcal{VBE}$ have probability interpretation [4]. A few applications of the $\mathcal{VBE}$ can be found in the refs. [5-8]. In this work, we introduce the vector boson oscillator ($\mathcal{VBO}$) and investigate its dynamics in the rotating frame of the 2+1 dimensional cosmic string-generated spacetime.

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Cosmic strings are predicted to be linear topological defects that probably occurred in the early stages of the universe [9]. After Cosmic strings were introduced in $2+1$ dimensional spacetime [10], the obtained solution was naturally expanded to $3+1$ dimensions where there is a dynamical symmetry [11]. The spacetime backgrounds of cosmic strings include a conical singularity on the intersection point of the string with the space-like subspace [9-11]. Even though these spacetime backgrounds are locally flat [9-11] out of the intersection point, they are not flat when viewed globally [9-11]. Because of this feature, the cosmic strings can be responsible for several physical events in the universe [12-15]. The spacetime background of the cosmic string is characterized by α parameter, which is angular deficit parameter depending on the linear mass density (μ_s) of the cosmic string [12-15]. The gravitational [9-14] and electrostatic effects [12,15] of these topological defects on the dynamics of physical systems depend on the parameter α. The influences of topological defects on the dynamics of quantum mechanical systems have been widely studied [15-17]. In one of such works, it has been shown that the spin-symmetric [18] quantum state of a positronium system can be used to detect the topological defects [15]. The effects of topological defects on the spectral lines of quantum systems are not same for each spectral line of the quantum systems [19]. This means that the effects of topological defects are distinguishable from the other effects such as doppler effect and redshift [15,19].

On the other hand, the investigations about the effects of rotating frames on the quantum systems have provided very interesting results and accordingly such studies have attracted great attention for a long time [20-22] since these investigations have discovered very important effects [23-29]. The sagnac effect [23], mashhoon effect [24], persistent currents in the quantum ring and the coupling between the angular momentum of the quantum systems with the velocity of uniformly rotating frame [25] can be considered among these effects. One of the interesting results of these investigations is that the non-inertial effects stemming from the rotating frames restrict the physical region of the spacetime backgrounds where the particles can be placed [20-22]. It has been shown that the phase shift in neutron interferometry is due to the coupling of angular velocity of the earth with the angular momentum of the neutron [26]. The effects of rotating frame on the C_{60} molecules were analized [27,28] and the obtained results have indicated that rapidly rotating molecules can acquire a topological phase [27,28].

In this contribution, we investigate the influences of rotating frame on the relativistic dynamics of a VBO in the $2+1$-dimensional cosmic string spacetime. In order to determine the effects of both uniformly rotating frame and spacetime topology on the system in question we solve the corresponding VBE. We obtain an exact energy spectrum depending on the parameters of spacetime background.

2. GENERALIZED FORM OF THE VBE

In this part of the manuscript, we introduce the generalized form of the VBE and arrive at a set of coupled equations for a VBO in the rotating frame of 2+1 dimensional cosmic string-generated spacetime background.The generalized form of the VBE can be written as the following [1-8],

$$\{\beta^{\mu}\left(\partial_{\mu}-\Omega_{\mu}\right)+i\,\frac{mc}{\hbar}I_4\}\Psi(\mathbf{x})=0,$$
$$\beta^{\mu}=\frac{1}{2}(\gamma^{\mu}\otimes I_2+I_2\otimes\gamma^{\mu}),$$
$$\Omega_{\mu}=\Gamma_{\mu}\otimes I_2+I_2\otimes\Gamma_{\mu}. \tag{1}$$

In eq. (1), γ^{μ} are the generalized dirac matrices, Γ_{μ} are the spinorial affine connections for spin-1/2 field, m is the rest mass of vector boson, c is the speed of light, $\hbar$ is usual planck constant, the symbol $\otimes$ indicates kronocker product [28], $\mathbf{x}$ is the spacetime position vector, I_2 and I_4 stand for the $2x2$ and $4x4$ dimensional identity matrices, respectively, and Ψ is the symmetric spinor of rank-two. The $2+1$ dimensional spacetime geometry of the uniformly rotating cosmic string-generated background is represented through the following line element [20-22],

$$ds^2=(1-\varpi^2\alpha^2r^2)c^2dt^2-2\varpi\alpha^2r^2cdtd\phi$$

$$-\, dr^2 - \alpha^2 r^2 d\phi^2 . \qquad (2)$$

In eq. (2), α is the angular deficit parameter, $\alpha = 1 - 4G\mu_s/c^2$, depending on the linear mass density (μ_s) of the cosmic string and newtonian gravitational constant (G) [15]. The azimuthal angle range is $0 \leq \phi < 2\pi$ in this spacetime background. Here, we deal with $\mu_s > 0$ case, since the $\mu_s < 0$ case describes an anti-conical spacetime background with negative curvature [20-22]. Therefore, the $\alpha > 0$ case does not make sense in the general relativity context [20-22]. The eq. (2) describes a flat spacetime background, in terms of polar coordinates, when $\varpi = 0$ and $\alpha = 1$ [15]. In eq. (2), we should notice that the radial coordinate must satisfy $r \ll 1/(\varpi\alpha)$, since this spacetime geometry can be defined for values of the r inside the range: $0 < r < 1/(\varpi\alpha)$. This condition guarantees that the vector boson considered is placed inside of the light-cone and imposes a spatial constraint. That is, the wave function vanishes at $r = 1/(\varpi\alpha)$ [20-22]. At this point, we should underline that the ϖ in eq. (2) is $\frac{\Omega}{c}$ and Ω is the angular velocity (not frequency) of the uniformly rotating frame. Therefore, the Ω rises to a hard-wall confining potential [20-22]. Now, one can obtain the tetrads $e^{a}_{\ \mu}$ [15],

$$g_{\mu\nu} = e^{a}_{\ \mu}\, e^{b}_{\ \nu}\, \eta_{ab}, \qquad e^{\mu}_{\ a} = g^{\mu\nu} e^{b}_{\ \nu} \eta_{ab},$$
$$\eta_{ab} = diag(1,-1,-1), \ (\mu,\nu,a,b = 0,1,2.). \quad (3)$$

In eq. (3), η_{ab} is the flat spacetime metric tensor and hence the indices a, b indicate the local reference frame. The tetrads, which satisfy the following orthonormality conditions,

$$e^{\mu}_{\ a} e^{a}_{\ \nu} = \delta^{\mu}_{\ \nu}, \ \ e^{a}_{\ \mu} e^{\mu}_{\ b} = \delta^{a}_{\ b}, \qquad (4)$$

are obtained as the following,

$$e^{\mu}_{\ a} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -\varpi & 0 & \frac{1}{\alpha r} \end{pmatrix}, e^{a}_{\ \mu} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \varpi\alpha r & 0 & \alpha r \end{pmatrix}.$$

By using the tetrads one can obtain the generalized dirac matrices γ^{μ} via the relation $\gamma^{\mu} = e^{\mu}_{\ a}\, \gamma^{a}$ where γ^{a} are the space-independent dirac matrices [15]. According to line element in eq. (2) the space-dependent dirac matrices are obtained,

$$\gamma^{t} = \gamma^{0}, \qquad \gamma^{r} = \gamma^{1}, \qquad \gamma^{\phi} = -\varpi\gamma^{0} + \frac{1}{\alpha r}\gamma^{2}. \qquad (5)$$

The choice of space-independent dirac matrices is not unique and different choices can be preferred, of course. According to signature of eq. (2) the space-independent dirac matrices can be chosen as $\gamma^{0} = \sigma^{z}$, $\gamma^{1} = i\sigma^{x}$, $\gamma^{2} = i\sigma^{y}$ [29-31], in which σ^{x}, σ^{y} and σ^{z} are the pauli spin matrices. Also, we can obtain the spinorial connections for spin-1/2 fields via the following expression [15],

$$\Gamma_{\mu} = \frac{1}{4}\ g_{\lambda\sigma} = \left(e^{a}_{\ \nu,\mu}\, e^{\sigma}_{\ a} - \Gamma^{\sigma}_{\ \nu\mu}\right) S^{\lambda\nu},$$
$$(\lambda,\sigma,\mu,\nu,a,b = 0,1,2.), \qquad (6)$$

where $\Gamma^{\sigma}_{\ \nu\mu}$ are the christoffel symbols obtained through $\Gamma^{\sigma}_{\ \nu\mu} = 1/2\, (\partial_{\nu} g_{\mu\sigma} + \partial_{\mu} g_{\sigma\nu} - \partial_{\sigma} g_{\nu\mu})$ and $S^{\lambda\nu}$ are the spin operators determined by $S^{\lambda\nu} = 1/2\ [\gamma^{\lambda}, \gamma^{\nu}]$. Now, one can obtain the spinorial connections (non-vanishing) as the following,

$$\Gamma_{t} = \frac{i}{2}\varpi\alpha\, \gamma^{0}, \quad \Gamma_{\phi} = \frac{i}{2}\alpha\, \gamma^{0}. \qquad (7)$$

The VBO coupling, describing the interaction of magnetic moment (anomalous) with a linearly varying electric field [3,16,17,21], can be introduced through the following non-minimal substitution,

$$\partial_{r} \rightarrow \partial_{r} + \frac{m\omega}{\hbar}(\sigma^{z} \otimes \sigma^{z}) r,$$
$$(\sigma^{z} \otimes \sigma^{z}) = \text{diag}\ (1,-1,-1,1), \qquad (8)$$

where ω is the oscillator frequency (coupling strength) [3]. Eq. (2) allows to factorization of the spinor as the following,

$$\Psi(t,r,\phi) = e^{-i\frac{E}{\hbar}t} e^{is\phi} \begin{pmatrix} \psi_1(r) \\ \psi_2(r) \\ \psi_3(r) \\ \psi_4(r) \end{pmatrix}, \qquad (9)$$

where E and s are the total energy and spin of the system under consideration.

3. ENERGY SPECTRUM

In this section, we obtain an equation system consisting of three equations for the components of the symmetric spinor and arrive at an exact energy spectrum for the $\mathcal{VBO}$ in question. To end this, we substitute eq. (5), (7), (8) and eq. (9) into the eq. (1) and then we can acquire a set of coupled equations, in the most symmetric form, as the following,

$$W\psi_-(r) - M\psi_+(r) - 2(\partial_r - \kappa r)\,\psi_0(r) = 0,$$
$$2M\psi_0(r) - \frac{S}{r}\psi_-(r) + (\partial_r + \kappa r + \frac{1}{r})\,\psi_0(r) = 0,$$
$$W\psi_+(r) - B\psi_-(r) - \frac{2S}{r}\psi_0(r) = 0, \qquad (10)$$

here, $\psi_\pm(r) = \psi_1(r) \pm \psi_4(r)$, $\psi_0(r) = \psi_2(r) = \psi_3(r)$ provided that $m \neq 0$ and the abbreviations are given as the following,

$$W = \frac{E}{\hbar c} + \varpi j, \quad S = \frac{s}{\alpha}, \quad M = \frac{mc}{\hbar}, \quad \kappa = \frac{m\omega}{\hbar}.$$

By considering a new change of variable, $\xi = \kappa r^2$, we can write the equation system in eq. (10) as the following,

$$W\psi_-(\xi) - M\psi_+(\xi) - \kappa\sqrt{\frac{\xi}{\kappa}}(2\partial_\xi - 1)\,\psi_0(\xi) = 0,$$
$$M\psi_0(\xi) + \kappa\sqrt{\frac{\xi}{\kappa}}\left(2\partial_\xi + 1 + \frac{1}{\xi}\right)\psi_+(\xi) - \frac{S}{\sqrt{\frac{\xi}{\kappa}}}\psi_-(\xi) = 0,$$
$$W\psi_+(\xi) - M\psi_-(\xi) - \frac{S}{\sqrt{\frac{\xi}{\kappa}}}\psi_0(\xi) = 0, \qquad (11)$$

one of which is algebraic. By solving these equations in favor of $\psi_0(\xi)$ we can arrive at a wave equation. Through an ansatz reads as, $\psi_0(\xi) = \frac{\psi(\xi)}{\sqrt{\xi}}$, the wave equation becomes as the following,

$$\xi^2\partial_\xi^2\,\psi(\xi) + \left(\xi A + \frac{1}{4} - G^2 - \frac{\xi^2}{4}\right)\psi(\xi) = 0,$$
$$A = -\frac{1}{2} + \frac{M(W^2 - M^2) + 2SW\kappa}{4M\kappa}, \; G = \frac{S}{2}. \qquad (12)$$
$$E_{n,s} = -\Omega\hbar s \mp \omega\hbar\frac{s}{\alpha}$$

Dividing each term in this equation by ξ^2, the well-known whittaker differential equation is obtained [7]. At any rate, the solution function of eq. (20) is found in terms of the whittaker function $\boldsymbol{W}_{A,G}$ as $\psi(\xi) = N\boldsymbol{W}_{A,G}(\xi)$, where N is an arbitrary constant [7]. The function $\boldsymbol{W}_{A,G}$ can only be polynomial degree of n if the parameters satisfy the termination condition that reads as $\frac{1}{2} + G - A = -\,n$ [7]. This termination condition gives a condition for the quantization of the energy of system in question and accordingly one can obtain the following non-perturbative energy spectrum,

$$\pm mc^2\sqrt{1 + \frac{4\omega\hbar}{mc^2}\left(n + 1 + \frac{s}{2\alpha}\right) + \frac{s^2\omega^2\hbar^2}{\alpha^2 m^2 c^4}}, \qquad (13)$$

which can be clarified as,

$$E_{n,0} = \pm mc^2\sqrt{1 + \frac{4\omega\hbar}{mc^2}(n+1)}, \qquad (14)$$

if $\Omega = 0$ and $s = 0$. The result in eq. (14) is exactly same with the previously announced result for one-dimensional kemmer oscillator [32] and form of the eq. (14) is same with the result of one-dimensional dirac oscillator [33]. In the latest comparison (see eq. (14) and [33]), one can realize that the difference is only mass factor of the particles. Also, it is very interesting that the result in eq. (14) is found to be in a good agreement with the recently announced results for a composite structure consisting of a fermion-antifermion pair interacting via dirac oscillator coupling [3]. Therefore, eq. (13) gives an opportunity to analyze the effects of both uniformly rotating frame and spacetime topology on the energy of the $\mathcal{VBO}$. In eq. (13) we see that the effects of Ω and α on each energy level of the $\mathcal{VBO}$ cannot be same. It is clear that the parameters Ω and α do not any impact on the energy of $\mathcal{VBO}$ when $s = 0$.

4. RESULTS AND DISCUSSIONS

In this contribution, we have investigated the influences of uniformly rotating frame and spacetime topology on a relativistic vector boson oscillator. In order to analyze the effects of angular velocity (Ω) of the rotating frame and angular deficit of the spacetime background on the energy of the vector boson oscillator (VBO) we have solved the generalized vector boson equation in the rotating frame of a 2+1 dimensional spacetime. The spacetime has been considered as $2+1$-dimensional static cosmic string-induced spacetime [15]. The rotating frame of this background is introduced in eq. (2), which represents to the flat Minkowski spacetime in terms of polar coordinates when angular velocity of the rotating frame and angular deficit of the background vanish. We have performed an exact solution for the system in question and accordingly we have arrived at a spectrum in energy domain. This energy spectrum has given in eq. (13) and it can be reduced in the form of eq. (14) when $\Omega = 0$ and $s = 0$. We have verified that the eq. (14) is exactly same with the previously announced results for one-dimensional kemmer oscillator [32] and form of the eq. (14) is also same with the results obtained for one-dimensional dirac oscillator [33]. Furthermore, eq. (14) has been found to be in a good agreement with the previously published results for a composite structure consisting of a fermion-antifermion pair that they interacts through dirac oscillator coupling [3]. The non-perturbative energy spectrum in eq. (13) includes the effects of spin coupling, uniformly rotating frame, angular deficit parameter of the spacetime background, frequency (coupling strength) of the oscillator and mass of the vector boson. This property of the energy spectrum provides a suitable basis to discuss the effects of both Ω and α on the system under consideration. The results have shown that the parameter Ω of the rotating frame breaks the symmetry (positive-negative) of the energy levels and it is also clear that the effects of Ω and α on each energy level of the system cannot be same. As it can be seen in eq. (2) that the information about the spacetime topology is carried by the angular coordinate and accordingly parameter α of the background alters differently the energy levels corresponding to possible spin eigen-states, $(s = \pm 1, 0)$, when $\Omega = 0$. We can also see that such a system does not sense the effects of the parameter α when $\Omega = 0$ and $s = 0$. In this paper, all of the discussions have been made for the parameters defined in the range: $\alpha \in [0,1)$ and $0 < r < 1/(\varpi\alpha)$, where r is the distance between the particle and topological defect. Therefore, one can also conclude that the parameter Ω restricts the relativistic dynamics of the quantum system under consideration whether $\alpha = 1$ or $0 < \alpha < 1$.

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The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author declares that he complies with the scientific, ethical and quotation rules of SAUJS in all processes of the present paper and that he does not make any falsification on the data collected. Also, the author declares that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that the present study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

REFERENCES

[1] A. O. Barut, "Excited states of zitterbewegung," Physics Letters B, vol. 237, no. 3, pp. 436-439, 1990.

[2] A. O. Barut and S. Komy, "Derivation of nonperturbative Relativistic Two-Body

Equations from the Action Principle in Quantumelectrodynamics," Fortschritte der Physik/Progress of Physics, vol. 33, no. 6. pp 309-318, 1985.

[3] A. Guvendi, "Relativistic Landau for a fermion-antifermion pair interacting through Dirac oscillator interaction," The European Physical Journal C, vol. 81, no. 2. pp 1-7, 2021.

[4] N. Ünal, "A simple model of the classical zitterbewegung: photon wave function,"Foundations of Physics, vol. 27, no. 5. pp 731-746, 1997.

[5] Y. Sucu and N. Ünal, "Vector bosons in the expanding universe," The European Physical Journal C, vol. 44, no. 2. pp 287-291, 2005.

[6] Y. Sucu and C. Tekincay, "Photon in the Earth-ionosphere cavity: Schumann resonances," Astrophysics and Space Science, vol. 364, no. 4. pp 1-7, 2019.

[7] M. Dernek and S. G. Doğan and Y. Sucu and N. Ünal, "Relativistic quantum mechanical spin-1 wave equation in 2+1 dimensional spacetime," Turkish Journal of Physics, vol. 42, no. 5. pp 509-526, 2018.

[8] G. Gecim and Y. Sucu, "The GUP effect on tunneling of massive vector bosons from the 2+1 dimensional blackhole," Advances in High Energy Physics, vol. 2018, no. 8. pp 1-8, 2018.

[9] A. Vilenkin, "Cosmic strings and domain walls," Physics Reports, vol. 121, no. 5. pp 263-315, 1985.

[10] S. Deser, R. Jackiw and G. Hooft, "Three-dimensional Einstein gravity: dynamics of flat space," Annals of Physics, vol. 152, no. 1. pp 220-235, 1984.

[11] J. R. Gott and M. Alpert, "General relativity in a (2+1)-dimensional space-time," General Relativity and Gravitation, vol. 16, no. 3. pp 243-247, 1984.

[12] B. Linet, "Force on a charge in the space-time of a cosmic string," Physical Review D, vol. 33, no. 6. pp 1833, 1986.

[13] D. D. Harari and V. D. Skarzhinsky, "Pair production in the gravitational field of a cosmic string," Physics Letters B, vol. 240, no. 3-4. pp 322-326, 1990.

[14] L. Parker, "Gravitational particle production in the formation of cosmic strings," Physical Review Letters, vol. 59, no. 12. pp 1369, 1987.

[15] A. Guvendi and Y. Sucu, "An interacting fermion-antifermion pair in the spacetime background generated by static cosmic string," Physics Letters B, vol. 811, no. 135960. pp 135960, 2020.

[16] M. Hosseinpour, H. Hassanabadi and F. M. Andrade,"The DKP oscillator with a linear interaction in the cosmic string space-time," The European Physical Journal C, vol. 78, no. 2. pp 1-7, 2018.

[17] J. Carvalho, C. Furtado and F. Moreas, "Dirac oscillator interacting with a topological defect," Physical Review A, vol. 84, no. 3. pp 032109, 2011.

[18] A. Guvendi, "The lifetimes for each state of $l=0$ levels of the para-positronium," Eur. Phys. J. Plus, vol. 136, no. 4. pp 1-10, 2021.

[19] G. A. Marques and V. B. Bezerra, "Hydrogen atom in the gravitational fields of topological defects," Physical Review D, vol. 66, no. 10. pp 105011, 2002.

[20] K. Bakke and C. Furtado, "Bound states for neutral particles in a rotating frame in the cosmic string spacetime," Physical Review D, vol. 82, no. 8. pp 084025, 2010.

[21] S. Zare, H. Hassanabadi and M. de Montigny, "Non-inertial effects on a generalized DKP oscillator in a cosmic string space-time," General Relativity and Gravitation, vol. 52, no. 3. pp 1-20, 2020.

[22] L. C. N. Santos and C. C. Barros, "Scalar bosons under the influence of noninertial effects in the cosmic string spacetime," The European Physical Journal C, vol. 77, no. 3. pp 1-7, 2017.

[23] E. J. Post, "Sagnac Effect," Reviews of Modern Physics, vol. 39, no. 2. pp 475-493, 1967.

[24] B. Mashhoon, "Neutron interferometry in a rotating frame of reference," Physical Review Letters, vol. 61, no. 23. pp 2639-2642, 1988.

[25] F. W. Hehl and W. T. Ni, "Inertial effects of a Dirac particle," Physical Review D, vol. 42, no. 6. pp 2045-2048, 1990.

[26] S. A. Werner, J. L. Staudenmann and R. Corella, "Effects of Earth's rotation on the Quantum Mechanical Phase of the Neutron," Physical Review Letters, vol. 42, no. 17. pp 1103-1106, 1979.

[27] J. Q. Shen and S. L. He, "Geometric phases of electrons due to spin-rotation coupling in rotating C_{60} molecules," Physical Review B, vol. 68, no. 19. pp 195421, 2003.

[28] J. Q. Shen, S. L. He and F. Zhuang, "Aharonov-Carmi effect and energy shift of valence electrons in rotating C_{60} molecules," The European Physical Journal D, vol. 33, no. 1. pp 35-38, 2005.

[29] A. Guvendi, R. Sahin and Y. Sucu, "Exact solution of an exciton energy for a monolayer medium," Scientific Reports, vol. 9, no. 1. pp 1-6, 2019.

[30] A. Guvendi, R. Sahin and Y. Sucu, "Binding energy and decaytime of exciton in dielectric medium," The European Physical Journal B, vol. 94, no. 1. pp 1-7, 2021.

[31] A. Guvendi and S. G. Doğan, "Relativistic Dynamics of Oppositely charged Two Fermions Interacting with External Uniform Magnetic Field," Few-Body Systems, vol. 62, no. 1. pp 1-8, 2021.

[32] A. Boumali, "One-dimensional thermal properties of the Kemmer oscillator," Physica Scripta, vol. 76, no. 6. pp 669, 2007.

[33] M. H. Pacheco, R. R. Landim and C. A. S. Almeida, "One-dimensional Dirac oscillator in a thermal bath," Physics Letters A, vol. 311, no. 2-3. pp 93-96, 2003.