МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ОДЕСЬКИЙ ДЕРЖАВНИЙ ЕКОЛОГІЧНИЙ УНІВЕРСИТЕТ

Methodical instructions for practical work, test performance, distance learning of PhD students in the discipline "MATHEMATICAL AND PHYSICAL MODELS OF QUANTUM AND NEURAL NETWORKS", Part 3. (Training of PhD students of the specialty: 113 – "Applied mathematics" and others)

«Затверджено»
на засіданні групи забезпечення спеціальності
Протокол №1 від 28/08/2021 Голова групи _____ Хецеліус О.Ю.

«Затверджено»
на засіданні кафедри вищої та прикладної математики
Протокол №1 від 28/08/2021 Зав. кафедри _____ Пушков О.В.

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THE MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

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for practical work, test performance, distance learning of PhD students in the discipline "MATHEMATICAL AND PHYSICAL MODELS OF QUANTUM AND NEURAL NETWORKS", Part 3.

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PREFACE

Discipline " MATHEMATICAL AND PHYSICAL MODELS OF QUANTUM AND NEURAL NETWORKS " is an elective discipline in the cycle of professional training of graduate students (third level of education) in the specialty 113- Applied Mathematics.

It is aimed at mastering (providing) a number of planned competencies, including the study of the modern apparatus of quantum and neural networks and on their basis to build new computational algorithms and software systems for mathematical modeling of linear and nonlinear processes in complex systems with regular and chaotic dynamics

The place of the discipline in the structural and logical scheme of its teaching: the knowledge gained in the study of this discipline is used in writing dissertations, the subject of which is related to the study of properties and regular and chaotic dynamics of various [classes of mathematical, physical chemical, cybernetic, socio-economic and environmental systems. The basic concepts of the discipline are the desired toolkit of an experienced specialist in the field of applied mathematics.The purpose of studying the discipline is to master (provide) a number of competencies, in particular, the ability to develop new and improve existing mathematical and physical models of quantum and neural networks and build new computational algorithms and software for mathematical modeling of linear and nonlinear processes in complex systems. regular and chaotic dynamics.After mastering this discipline, the graduate student must be able to improve existing modern mathematical and physical models of quantum and neural networks, as well as build new efficient models, and on their basis to develop new computational algorithms and software for analysis, mathematical modeling and prediction of linear and nonlinear processes in complex systems with regular and chaotic dynamics. The study of the discipline "Mathematical and Physical Models of Quantum and Neural Networks" is conducted in the second year of study (4th semester; full-time and part-time forms of study) and includes lectures and practical classes. Types of control of current knowledge - tests and term papers, surveys, tests.

Topics of these issue: Mathematical and physical models of quantum neural networks. An array of quantum dots in a semiconductor heterostructure as an example of a quantum neural network and a way to construct adiabatic quantum computers. Excitonic system in semiconductor and atom in electric field.

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Topic: Математичні та фізичні моделі квантових нейромереж. Масив квантових точок у напівпровідниковій гетероструктурі як приклад квантової нейромережі та шлях до побудови адіабатичних квантових компьютерів. Excitonic system in semiconductor and atom in electric field.

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1 Introduction

1. Introduction

This issue considers a group of topics such as mathematical and physical models of quantum neural networks, the system of quantum dots in a semiconductor heterostructure, the excitonic system in semiconductor and atom in electric field as an example of a quantum neural network. In fact the known Stark effect is used as the fundamental one in mathematical and physical modeling quantum neural networks.

The remarkable Stark effect has a long history and until recently it was believed that the Stark effect is fully understood and fundamental problems remained. However, an observation of the Stark effect in a constant (DC) electric field near threshold in hydrogen and alkali atoms led to the discovery of resonances extending into the ionization continuum by Glab et al and Freeman et al (c.f.[1]). Calculation of the characteristics of these resonances as well as the Stark resonances in the strong electric field remains very important problem of modern atomic physics.

It should be noted that the same class of problems has been arisen in a physics of semiconductors (c.f.[14-17]). It is well known that the availability of excitons in semiconductors resulted experimentally in the special form of the main absorption band edge and appearance of discrete levels structure (f.e. hydrogen-like spectrum in Cu_2O). Beginning from known papers of Gross-Zaharchenya, Thomas and Hopfield et al (c.f.[14-17]), a calculation procedure of the Stark effect for exciton spectrum attracts a deep interest permanently.

Very interesting physics occurs in a case of the excitons in quantum dots, wires etc, where the other geometry and energetics in comparison with the bulk semiconductor makes the field effect more intrigues. The exciton states in the quantum dots have been studied in a number of papers and have been observed by photoluminescence experiments (c.f. [14-17]). Naturally, the electronic states in quantum dots (wires) depends on either the confining potential and the interacting force between the particles. Now the electric field effect on the electron-hole states and on the confined excitonic states is often referred to the quantum confined Stark effect. Now it is represented an interest to study an influence of quantum well concentration profile and width on Stark shifts in case of such a system as system GaAs-AlGaAs etc. In this paper we study the Stark effect for non-H atom of rubidium and for excitons in an external uniform electric field within the operator perturbation theory method. The Stark resonance energies in rubidium and the Stark shift for the n=2 state of the Wannier-Mott excitons in the Cu_20 semiconductor and excitons in the parabolic quantum dot (GaAs) in the electric field are listed.

Method for calculating energies and widths of Stark resonances

The Schrödinger equation for the electron function taking into account the uniform electric field and field of the nucleus (Coulomb units are used: for length, 1 unit is h^2/Ze^2m; for energy 1 unit is mZ^2e^4/h^2) is [6,57]:

$$[-(1 - N/Z) / r+V_m(r) + \varepsilon z -1/2\Delta - E] \psi = 0, \qquad (1)$$

where E is the electron energy, Z is the nucleus charge, N is the number of electrons in the atomic core (for the hydrogen atom: Z=1, N=0), V_m is an model potential (for the hydrogen atom V_m=0). Firstly, we only deal with the Coulomb part of the electron- atomic residue interaction. The non-Coulomb part, as well as relativistic effects, can be approximately accounted for next step. The separation of variables in the parabolic coordinates ($\xi = r + z,\ \eta = r - z,\ \varphi = \tan^{-1}(y/x)$) :

$$\psi(\zeta, \eta, \varphi)=f (\zeta) g(\eta)(\zeta\cdot \eta)^{|m|/2} \exp(im\varphi)/(2\pi)^{1/2} \qquad (2)$$

transforms it to the system of two equations for the functions f, g:

$$f'' + \frac{|m|+1}{t} f' + [1/2E + (\beta_1 - N/Z) / t - 1/4\varepsilon(t)\, t\,]\, f = 0, \qquad (3)$$

$$g'' + \frac{|m|+1}{t} g' + [1/2E + \beta_2 / t + 1/4\varepsilon(t)\ \ t\,]\, g = 0, \qquad (4)$$

coupled through the constraint on the separation constants:

$$\beta_1 + \beta_2 = 1 \qquad (5)$$

For the uniform electric field

$$\varepsilon(t) = \varepsilon .$$

In principle, the more realistic models can be considered in the framework of our approach. Potential energy in equation (4) has the barrier. Two turning points for the classical motion along the η axis, t_1 and t_2, at a given energy E are the solutions of the quadratic equation ($\beta = \beta_1$, $E = E_0$):

$$t_2 = \{[\, E^2_0 - 4\varepsilon(1-\beta)]^{1/2} - E_0 \}/\varepsilon , \qquad (6)$$

$$t_1 = \{-[E^2_0 - 4\varepsilon(1-\beta)]^{1/2} - E_0 \}/\varepsilon, \quad t_1 < t_2 \qquad (7)$$

Here and below t denotes the argument common for the whole equation system. To simplify the calculational procedure, the uniform electric field ε in (3) and (4) should be substituted by the function [57,58]:

$$\varepsilon(t) = \frac{1}{t}\, \varepsilon \left[(t-\tau) \frac{\tau^4}{\tau^4 + t^4} + \tau \right] \qquad (8)$$

with sufficiently large τ (τ=1.5t_2).

The function $\varepsilon(t)$ practically coincides with the constant ε in the inner barrier motion region ($t<t_2$) and disappears at $t>>t_2$.

The minimal acceptable value of τ introduced in the spatial dependence of the electric field, which does not influence the final results, can be established experimentally. Thus, the final results do not depend on the parameter τ (the further calculation has entirely confirmed this fact). Besides the pure technical

convenience, the case of an asymptotically disappearing electric field is more realistic from the physical point of view. Now we deal with the asymptotically free (without electric field) motion of the ejected electron along the η-axis. The corresponding effective wavenumber is:

$$k = (E/2 + \varepsilon\tau/4)^{1/2}. \qquad (9)$$

The scattering states energy spectrum now spreads over the range $(-\varepsilon\tau/2, +\infty)$, compared with $(-\infty, +\infty)$ in the uniform field. In contrast to the case of a free atom in scattering states in the presence of the uniform electric field remain quantified at any energy E, i.e. only definite values of β_1 are possible.

The total Hamiltonian $H(\varsigma, \nu, \varphi)$ does not possess the bound stationary states. According to OPT [6, 56-58]), one has to define the zero order Hamiltonian H_0, so that its spectrum reproduces qualitatively that of the initial one. In contrast to H, it must have only stationary states. To calculate the width Γ of the concrete quasistationary state in the lowest PT order one needs only two zeroth–order EF of H_0: bound state function $\Psi_{Eb}(\varepsilon, \eta, \varphi)$ and scattering state function $\Psi_{Es}(\varepsilon, \eta, \varphi)$ with the same EE. We solve a more general problem: a construction of the bound state function along with its complete orthogonal complementary of scattering functions Ψ_E with $E \subset \left(-\frac{1}{2}\varepsilon\tau, +\infty\right)$. First, one has to define the EE of the expected bound state. It is the well known problem of states quantification in the case of the penetrable barrier [65,66]. Following [57], we solve the system (3) and (4) with the total Hamiltonian H under the conditions:

$$f(t) \to 0 \text{ at } t \Rightarrow \infty, \qquad (10a)$$

$$\partial x(\beta, E) / \partial E = 0 \qquad (10b)$$

with $$x(\beta, E) = \lim_{t \Rightarrow \infty} [\, g^2(t) + \{g'(t) / k\}^2 \,]\, t^{|m|+1}. \qquad (11)$$

The first condition ensures the finiteness of motion along the ς-axis, the second condition minimizes the asymptotic oscillation amplitude for the function describing the motion along the η-axis. These two conditions quantify the bound energy E and separation constant β_1. We elaborated a special numerical procedure for this two-dimensional eigenvalue problem. Our procedure deals

repeatedly with the solving of the system of the ordinary differential equations (3) and (4) with probe pairs of E, β_1. The corresponding EF:

$$\psi_{Eb}(\zeta, \eta, \varphi) = f_{Eb}(\zeta)\, g_{Eb}(\eta)(\zeta\,\eta)^{|m|/2}\, exp\,(im\varphi)(2\pi)^{-1/2}. \qquad (12)$$

Here $f_{Eb}(t)$ is the solution of (3) (with the just determined E, β_1) at $t \subset (0,\infty)$ and $g_{Eb}(t)$ is the solution of (4) (with the same E, β_1) at $t < t_2$ (inside barrier) and $g(t) = 0$ otherwise. These bound state EE, eigenvalue β_1 and EF for the zero-order Hamiltonian H_0 coincide with those for the total Hamiltonian H at $\varepsilon \Rightarrow 0$, where all the states can be classified due to the quantum numbers $n,\ n_1, n_2, m$ (principal, parabolic, azimuthal) connected with E, β_1, m by the well known expressions. We preserve the $n,\ n_1, m$ states classification in the non-zero ε case. The scattering state functions:

$$\psi_{E's}(\zeta, \eta, \varphi) = f_{E's}(\zeta)\, g_{E''s}(\eta)\,(\zeta\,\eta)^{|m|/2}\ \exp\,(im\varphi)(2\pi)^{-1/2} \qquad (13)$$

must be orthogonal to the above defined bound state function and to each other. In addition, these functions must describe the motion of the ejected electron, i.e. $g_{E's}$ must satisfy the equation (4) asymptotically. Following the OPT ideology [57], we choose the next form of $g_{E's}$:

$$g_{E's}(t) = g_1(t) - z_2' g_2(t) \qquad (14)$$

with $f_{E's}$ and $g_1(t)$ satisfying the differential equations (3) and (4). The function $g_2(t)$ satisfies the non-homogeneous differential equation, which differs from (4) only by the right-hand term, disappearing at $t \Rightarrow \infty$. The total equation system, determining the scattering function, reads

$$\begin{aligned} f''_{E's} + \frac{|m|+1}{t} f'_{E's} + [1/2E' + (\beta_1' - N/Z)/t - 1/4\ \varepsilon(t)t]\, f_{E's} = 0, \\ g_1'' + \frac{|m|+1}{t} g_1' + + [1/2E' + \beta_2'/t + 1/4\varepsilon(t)t]\, g_1 = 0, \qquad (15) \\ g_2'' + \frac{|m|+1}{t} g_2' + + [1/2E + \beta_2'/t + 1/4\varepsilon(t)t]\, g_2 = 2g_{Eb}, \end{aligned}$$

($\beta_1' + \beta_2' = 1$). As mentioned above there remains motion quantification for $E' \subset \left(-\frac{1}{2}\varepsilon\tau, +\frac{1}{2}\varepsilon\tau\right)$. At the given E', the only quantum parameter β_1' is determined by the natural boundary condition: $f_{E's} \Rightarrow 0$ at $t \Rightarrow \infty$.

Of course: $\beta_1' = \beta_1$, $f_{E's} = f_{Eb}$ at $E' = E$; only this case is needed in the particular problem we deal with here. The coefficient z_2' ensures the orthogonality condition $\langle \Psi_{Eb} | \Psi_{E's} \rangle = 0$:

$$z_2' = \{ \iint d\zeta d\eta \, (\zeta + \eta) \, f^2_{Eb}(\zeta) g_{Eb}(\eta) g_1(\eta) \} /$$

$$/ \{ \iint d\zeta d\eta \, (\zeta + \eta) \, f^2_{Eb}(\zeta) g_{Eb}(\eta) g_2(\eta) \}. \qquad (16)$$

One can check that

$$\langle \psi_{Es'} | \psi_{E''s} \rangle = 0 \quad \text{for} \quad E' \neq E''$$

The imaginary part of state energy in the lowest PT order is

$$\mathrm{Im}E = \Gamma/2 = \pi | < \Psi_{Eb} | H | \Psi_{Es} > |^2 \qquad (17)$$

with the total Hamiltonian H. The state functions Ψ_{Eb} and Ψ_{Es} are assumed to be normalized to 1 and by the $\delta(k - k')$ condition, accordingly. The action of H on Ψ_{Eb} is defined unambiguously by (15):

$$(H - E')\psi_s = 2|m|(\zeta \cdot \eta^2) \cdot f_{E's}(\zeta) \, g_{Eb}(\eta) z_2' \exp(im\varphi) / [(2\pi)^{1/2} (\zeta + \eta)],$$

$$\langle \psi_{Eb} | H | \psi_{E's} \rangle = \iint d\zeta d\eta \, (\zeta\eta)^{|m|} \eta \, f^2_{Eb}(\zeta) f^2_{E's}(\zeta) g_{Eb}(\eta) \, z_2'. \qquad (18)$$

The matrix elements $\langle \Psi_{Eb} | H | \Psi_{E's} \rangle$ entering the high- order PT corrections can be determined in the same way. All the two-dimensional integrals in (16)-(18) and the normalization coefficients can be expressed through the next set of one-dimensional integrals:

$$I_1 = \int dt \, f_b^2(t) t^{|m|}, \qquad I_2 = \int dt \, f_b^2(t) t^{|m|+1},$$

$$I_3 = \int dt \; g_b(t) \, g_1(t) \, t^{|m|}, \qquad I_4 = \int dt \, g_b(t) g_1(t) t^{|m|+1},$$

$$I_5 = \int dt \; g_b(t) \, g_2(t) \, t^{|m|}, \qquad I_6 = \int dt \; g_b(t) \, g_2(t) t^{|m|+1},$$

$$I_7 = \int dt\, g_b{}^2(t)\, t^{|m|}, \qquad I_8 = \int dt\, g_b{}^2(t) t^{|m|+1}, \tag{19}$$

calculated with the arbitrary normalized functions f_{Eb}, g_{Eb}, f_2, g_2, and $f_1 = f_{Eb}$, $g_1 = g_{Eb}$. In this notation

$$\Gamma = 32\pi z_2^2 N_s^2 I_1^2 I_8^2 / [I_2 I_7 + I_1 I_8],$$
$$z_2 = [I_1 I_4 + I_2 I_3] / [I_1 I_6 + I_2 I_5] \tag{20}$$

with

$$N^2{}_s = \lim_{t \Rightarrow \infty} X(t) / \{2\pi\eta^{2|m|+1} [\, g^2{}_s(\eta) X^2(t) + g'^2_s(\eta)]\}\,,$$
$$X(t) = \{E/2 + (\beta - N/Z)/t - E\, t/4\}^{1/2} \tag{21}$$

Remember that arbitrary normalized state functions are assumed in (20) and (21). The whole calculational procedure at known resonance energy E and separation parameter β_1 has been reduced to the solution of one system of the ordinary differential equations. This master system includes the differential equations for the state functions f_{Eb}, g_{Eb}, f_{Es}, g_{Es}, as well as the equations for the integrals $I_1 - I_8$.

Stark effect for excitonic system in semiconductors

The above analogous method can be formulated for description of the Stark effect for the Wannier-Mott excitons in the bulk semiconductors [4]. Really, the Schrödinger equation for the Wannier-Mott exciton looks as follows:

$$[-\hbar^2 \nabla_e^2 / 2m_e^* - \hbar^2 \nabla_h^2 / 2m_h^* - e^2 / \varepsilon r_{eh} + \\ + eFr_e - eFr_h]\Psi = E\Psi \tag{22}$$

where $m^*{}_e$($m^*{}_h$) are the effective-mass for the electron (hole), ε is the background dielectric constant. Introducing the relative coordinates: $r = r_e - r_h$ and the corresponding momenta p with reduced mass $p = m^*{}_e\, m^*{}_h / M$ (the momenta P with the total-mass M= $m^*{}_e + m^*{}_h$,) and center-of-mass coordinate

$$\rho = (m_e^* r_e + m_h^* r_h)/(m_e^* + m_h^*)',$$

one could rewrite (22 as:

$$[-\hbar^2 \nabla^2 / 2\mu - e^2 / \varepsilon r - \hbar / 2 \cdot (1/m_h^* - 1/m_e^*) K \cdot p - \\ - eFr]\Psi F = [E - \hbar^2 K^2 / 8\mu]\Psi \tag{23}$$

This equation then could be solved by the method, described above. The other details can be found in Refs. [1,4].

A problem of the Stark effect for quantum dots requires more detailed consideration. For definiteness, below we study the Stark effect in the parabolic quantum dot.

Within the effective-mass approximation and neglecting the band-structure effects , the Hamiltonian of an exciton in a parabolic quantum dot with the same quantization energy $\hbar\Omega$ (for the electron and hole), nd subjected to an external electric field , can be expressed as :

$$H = -\hbar^2\nabla_e^2 / 2m_e^* + (1/2)(m_e^*)\Omega^2 r_e^2 - \hbar^2\nabla_h^2 / \\ / 2m_h^* + (1/2)(m_h^*)\Omega^2 r_h^2 - e^2 / \varepsilon r_{eh} + eFr_e - eFr_h \qquad (24)$$

where all notations are defined above.

Further, as above, using the relative coordinate, the momenta with reduced mass and center-of-mass coordinate and the momenta with the total-mass M, the Hamiltonian H (7) can be represented as :

$$H = P^2 / 2M + (1/2)M\Omega^2\rho^2 + p^2 / 2\mu + \\ + (1/2)\mu\Omega^2 r^2 - e^2 / \varepsilon r + eFz \quad . \qquad (25)$$

Further let us note that the part which depends only on the center-of-mass coordinate in Eq.(10) is corresponding to the Hamiltonian of a well-known 3D harmonic oscillator and the exciton properties is essentially determined by the relative Hamiltonian H_r.

The field term added to the z-direction confinement describes a displaced harmonic oscillator centred in $z_0=eF/\mu\Omega^2$ with the frequency Ω_r inferior to Ω. Besides, as usually [17], in order to solve the Hamiltonian H_r , one should introduce an interaction potential which obeys to the known Hooke's force with the parameter λ by adding and substracting the potential:

$$V(r) = \lambda[(1/2)\mu\Omega^2 r^2 - \hbar\Omega] .$$

Surely then the Hamiltonian H is splitted into two terms with the one term being exactly solvable while the other can be treated as a perturbation.

Such a scheme is corresponding to method by Jaziri-Bastard-Bennaceur [17]. Our approach is in he direct numerical solving the problem. Let us remind that the introduced potential is similar to the interaction potential between electron-electron used by Johnson-Payne and it can hardly be considered as the correct potential for the all electron-hole separation. Nevertheless, here one

could adjust the interaction parameter λ so in order to provide the best fit of the true interaction which is the Coulomb interaction, and for the dominant range of separation r [17].

The attraction potential $V(r)$ will have negative value with positive λ, and it yields a physically reasonable fit to the exact interaction for electron-hole separation $r<(2)^{1/2}R_0$ (here R_0 is the quantum dot radius defined as $\sqrt{\hbar/\mu\Omega}$. As usually, the total energy corresponding to exciton ground state is obtained as :

$$E_T = (3/2)\hbar\Omega + (3/2)\hbar\Omega_r - \lambda\hbar\Omega - (e^2F^2)/(2\mu\Omega^2)$$

where $\Omega_r = \Omega\sqrt{1+\lambda}$. The field-induced energy shifts can be expressed as: $\Delta E = E_T(F=O)-E_T(F)$, where E($F$=0)is the corresponding energy in the free (i.e. zero-field) state. The main aim is to determine the exciton binding energy defined by $E_B = E_e+E_h-E_T$, where E_e,E_h are the energies corresponding to the one-particle Hamiltonian.

The calculation results for Stark resonances energies in the rubidium atom for the electric field strength ε=2.189 kV/cm are presented in Table 1. For comparison we have also presented the experimental data [13], the results of calculation within the *1/n*-expansion method by Popov etal [12]. For the most long-living Stark resonances with quantum numbers $n_2 = 0$, m = 0, a width of energy level is significantly less than a distance between them. These states are mostly effectively populated by π-polarized light under transitions from states with (n_1-n_2) = max, m = 0.

As a result, the sharp isolated resonances (their positions under E>0 are determined by energies of quasi-stationary states with n_2=0 , m=0) are appeared under photo ionization from these states in a case of π-polarization

In ref. [4] there are listed the preliminary estimates of the Stark shifts of the n=2 state of excitons in the Cu_20 semiconductor (yellow series) at the electric field strength 600 V/cm results and indicated on the physically reasonable agreement with the known results by Thomas and Hopfield (TH) [14]. Our final value for the Stark shift of the n=2 state excitons in the Cu_20 semiconductor (yellow series) at the electric field strength 600 V/cm results in –0,308 meV in a good agreement with experimental data of Gross et al.[28]. Under increasing the electric field strength changing a potential on a small enough distance (the orbits diameter) will become comparable with the bond energy of particle on this orbit

Table 1. The energies (cm^{-1})of the Stark resonances for the Rb atom (ε=*3,59 kV/cm)*:
A-experimental data ; B- Popov et al; C- OPT approach.

n_1n_2m	δ	A	B		C
23,0,0	0,656	133,1	132,8	132,9	133,0
22,0,0	0,681	157,0	157,1	157,2	157,1
21,1,0	0,517	161,1	159,5	160,6	160,9
20,2,0	0,400	163,9	163,2	163,7	163,9
21,0,0	0,708	185,2	184,2	184,8	185,1
20,1,0	0,531	186,3	185,4	185,8	186,2
20,0,0	0,737	217,2	214,6	214,9	216,9
18,1,0	0,561	248,4	247,2	247,3	248,2
16,2,0	0,428	-	-	-	285,5
18,0,0	0,802	-	-		289,3

. According to our data and data by Gross et al., the corresponding electric field is ~ $9 \cdot 10^3$ V/cm. we have tried to discover the chaotic behavior of the exciton dynamics in an electric field, however near ionization boundary exciton does not demonstrate behaviour of quantum chaotic system, which is similar to hydrogen or on-H atom dynamics in a strong field and manifested as unusual features in a photoionization spectra (alkali atoms) [5,14]. Further we list some data on the Stark shifts excitons in a GaAs semiconductor quantum dot (table 2).

Table 2. The Stark shifts (meV) for exciton in the GaAS quantum dot: A- Jaziri-Bastard-Bennaceur method; B- OPT approach

F (kV/cm)	R (A)	A	B
50	50	3.9	4.0
50	80	14	14.1
50	120	45	45.2
100	50	13	13.1
100	80	56	56.6
100	120	158	159.8

Comparison of the presented preliminary data shows that the different results are in the physically reasonable agreement. The corresponding accuracy

is of the order of 1%, however, is should be noted [17] that though the method [17] is much simpler in comparison with the direct variational approach, but it cannot enviseaged for any strength electric field and/nor any quantum dot size. The important feature of the operator perturbation theory formalism is that it can be applied for any strength electric field.

2. Task options

Task Option 1.

1). Give the key definitions in mathematical and physical models of quantum neural networks. An array of quantum dots in a semiconductor heterostructure as an example of a quantum neural network and a way to construct adiabatic quantum computers. Excitonic system in semiconductor and atom in electric field and Stark effect. Computing the Stark resonances using the standard quantum-mechanical amplitude approach and new formalism of operator perturbation theory by Glushkov-Ivanov:

2). Mathematical and physical essense of quantum-mechanical approach to treatment of the excitonic system in semiconductor and atom in electric field and Stark effect.

3).To apply the operator perturbation theory by Glushkov-Ivanov for computing the Stark resonances energies and widths of the excitonic system in **semiconductor InP** and atom in electric field **Fr.** Construct the simple mathematical and physical models of quantum NNW. To perform its pracrical realization (using Fortran Power Station , Version 4.0; PC Code: "Superatom-Stark" (all necessary numerical parameters should be self-taken).

Task Option 2.

1). Give the key definitions in mathematical and physical models of quantum neural networks. An array of quantum dots in a semiconductor heterostructure as an example of a quantum neural network and a way to construct adiabatic quantum computers. Excitonic system in semiconductor and atom in electric field and Stark effect. Computing the Stark resonances using the standard quantum-mechanical amplitude approach and new formalism of operator perturbation theory by Glushkov-Ivanov:

2). Mathematical and physical essense of quantum-mechanical approach to treatment of the excitonic system in semiconductor and atom in electric field and Stark effect.

3).To apply the operator perturbation theory by Glushkov-Ivanov for computing the Stark resonances energies and widths of the excitonic system in **semiconductor GaN** and atom in electric field **Rb.** Construct the simple mathematical and physical models of quantum NNW. To perform its pracrical realization (using Fortran Power Station , Version 4.0; PC Code: "Superatom-Stark" (all necessary numerical parameters should be self-taken).

Task Option 3.

1). Give the key definitions in mathematical and physical models of quantum neural networks. An array of quantum dots in a semiconductor heterostructure as an example of a quantum neural network and a way to construct adiabatic quantum computers. Excitonic system in semiconductor and atom in electric field and Stark effect. Computing the Stark resonances using the standard quantum-mechanical amplitude approach and new formalism of operator perturbation theory by Glushkov-Ivanov:

2). Mathematical and physical essense of quantum-mechanical approach to treatment of the excitonic system in semiconductor and atom in electric field and Stark effect.

3).To apply the operator perturbation theory by Glushkov-Ivanov for computing the Stark resonances energies and widths of the excitonic system in **semiconductor GaAs** and atom in electric field **K.** Construct the simple mathematical and physical models of quantum NNW. To perform its pracrical realization (using Fortran Power Station , Version 4.0; PC Code: "Superatom-Stark" (all necessary numerical parameters should be self-taken).

Task Option 4.

1). Give the key definitions in mathematical and physical models of quantum neural networks. An array of quantum dots in a semiconductor heterostructure as an example of a quantum neural network and a way to construct adiabatic quantum computers. Excitonic system in semiconductor and atom in electric field and Stark effect. Computing the Stark resonances using the standard quantum-mechanical amplitude approach and new formalism of operator perturbation theory by Glushkov-Ivanov:

2). Mathematical and physical essense of quantum-mechanical approach to treatment of the excitonic system in semiconductor and atom in electric field and Stark effect.

3).To apply the operator perturbation theory by Glushkov-Ivanov for computing the Stark resonances energies and widths of the excitonic system in **semiconductor AlAs** and atom in electric field **Li.** Construct the simple mathematical and physical models of quantum NNW. To perform its pracrical realization (using Fortran Power Station , Version 4.0; PC Code: "Superatom-Stark" (all necessary numerical parameters should be self-taken).

Task Option 5.

1). Give the key definitions in mathematical and physical models of quantum neural networks. An array of quantum dots in a semiconductor heterostructure as an example of a quantum neural network and a way to construct adiabatic quantum computers. Excitonic system in semiconductor and atom in electric field and Stark effect. Computing the Stark resonances using the standard quantum-mechanical amplitude approach and new formalism of operator perturbation theory by Glushkov-Ivanov:

2). Mathematical and physical essense of quantum-mechanical approach to treatment of the excitonic system in semiconductor and atom in electric field and Stark effect.

3).To apply the operator perturbation theory by Glushkov-Ivanov for computing the Stark resonances energies and widths of the excitonic system in **semiconductor CdTe** and atom in electric field **Cs.** Construct the simple mathematical and physical models of quantum NNW. To perform its pracrical realization (using Fortran Power Station , Version 4.0; PC Code: "Superatom-Stark" (all necessary numerical parameters should be self-taken).

Task Option 6.

1). Give the key definitions in mathematical and physical models of quantum neural networks. An array of quantum dots in a semiconductor heterostructure as an example of a quantum neural network and a way to construct adiabatic quantum computers. Excitonic system in semiconductor and atom in electric field and Stark effect. Computing the Stark resonances using the standard quantum-mechanical amplitude approach and new formalism of operator perturbation theory by Glushkov-Ivanov:

2). Mathematical and physical essense of quantum-mechanical approach to treatment of the excitonic system in semiconductor and atom in electric field and Stark effect.

3).To apply the operator perturbation theory by Glushkov-Ivanov for computing the Stark resonances energies and widths of the excitonic system in **semiconductor InGa** and atom in electric field **Na** Construct the simple mathematical and physical models of quantum NNW. To perform its pracrical realization (using Fortran Power Station , Version 4.0; PC Code: "Superatom-Stark" (all necessary numerical parameters should be self-taken).

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Methodical instructions
for practical work, test performance, distance learning of PhD students
in the discipline “MATHEMATICAL AND PHYSICAL MODELS OF QUANTUM AND NEURAL NETWORKS”, **Part 3.**
(Training specialty: 113 - “Applied mathematics” and others)

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