Saint Petersburg National Research University of Informational Technologies, Mechanics, and Optics

MATHEMATICAL CHALLENGE OF QUANTUM TRANSPORT IN NANOSYSTEMS - PIERRE DUCLOS WORKSHOP

Conference in memory of Boris Pavlov

International Conference

Saint Petersburg, November 14 – 15, 2016

Book of Abstracts

ITMO UNIVERSITY

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2016

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- Hagen Neidhardt (Berlin, Germany)
- Sylwia Kondej (Zielona Gora, Poland)
- Luka Grubišić (Zagreb, Croatia)
- Andre Hänel (Hannover, Germany)
- Sergey Simonov (St.Petersburg, Russia)
- Carsten Trunk (Ilmenau, Germany)
- Giuseppe Cardone (Benevento, Italy)
- Fabio Rinaldi (Rome, Italy)
- Sergey Leble (Kaliningrad, Russia)

THE MAIN TOPICS OF THE CONFERENCE:

Spectral theory
Scattering
Quantum transport
Quantum communications and computations

Conference Program
Pierre Duclos Workshop

November 14, 2016

9^{30} – 9^{55} *Registration (Pierre Duclos Workshop and Young Researches Symposium)*

9^{55} – 10^{00} *Opening*

Chairman: Igor Popov

10^{00} – 10^{50} **S. Albeverio**[1;2;3], **S. Fassari**[2;4], **F. Rinaldi**[2;4] *([1]Bonn, Germany; [2]Locarno, Switzerland; [3]Dhahran, KSA; [4]Rome, Italy)*
Spectral properties of a symmetric threedimensional quantum dot with a pair of identical attractive δ-impurities symmetrically situated around the origin II

10^{50} – 11^{40} **Sylwia Kondej** *(Zielona Góra, Poland)*
Geometry and spectrum in systems with leaky quantum wires

11^{40} – 12^{10} *Coffee*

Chairman: Sylwia Kondej

12^{10} – 13^{00} **Luka Grubišić** *(Zagreb, Croatia)*
Eigenvalue problems for networks of PDEs modeling a coronary stent

13^{00} – 13^{50} **Sergey Simonov** *(St. Petersburg, Russia)*
Spectral properties of the half-line Schrödinger operator with slowly decaying Wigner-von Neumann potential

13^{50} – 15^{00} *Lunch*

Chairman: Luka Grubišić

15^{00} – 15^{50} **Sergey Leble** *(Kaliningrad, Russia)*
Kolmogorov equation for Bloch electrons and Electrical Resistivity Models for nanowires

15^{50} – 16^{20} *Coffee*

Young Researchers Symposium-1 (YRS-1)

Chairman: Sergey Leble

16^{20} – 16^{30} **Stepan Botman** *(Kaliningrad, Russia)*
Electrical Resistivity Model for Quasi-one-dimensional structures

16^{30} – 16^{40} **Alena Ivanova** *(St. Petersburg, Russia)*
Quantum random number generator based on homodyne detection

16^{40} – 16^{50} **Oksana Borzenkova** *(Saint Petersburg, Russia)*
The experimental investigation of homodyne detector noises for measuring the quantum state of light

16^{50} – 17^{00} **Varvara Dubrovskaia** *(St. Petersburg, Russia)*
Synchronization signal distortion in quantum communication systems

17^{00} – 17^{10} **Ksenia Gubaidullina** *(St. Petersburg, Russia)*
Stability of the Grover's algorithm in respect to perturbations in quantum circuit

17^{10} – 17^{20} **Eduard Samsonov** *(St. Petersburg, Russia)*
Error analysis in schemes building at the quantum computing platform IBM Quantum Experience

17^{40} *Conference Diner*

November 15, 2016

Chairman: Carsten Trunk

10^{00} – 10^{50} **Hagen Neidhardt** *(Berlin, Germany)*
To the spectral theory of vector-valued Sturm-Liouville operators with summable potentials and point interactions

10^{50} – 11^{40} **André Hänel** *(Hannover, Germany)*
Spectral asymptotics for an elastic strip with an interior crack

11^{40} – 12^{10} *Coffee*

Chairman: Hagen Neidhardt

12^{10} – 13^{00} **Carsten Trunk** *(Ilmenau, Germany)*
On PT symmetric operators related to Hamilitonians with complex potentials

13^{00} – 13^{50} **Giuseppe Cardone** *(Benevento, Italy)*
Uniform resolvent convergence for a planar strip with fast oscillating boundary

13^{50} – 15^{00} *Lunch*

Chairman: André Hänel

15^{00} – 15^{20} **Victor Mikhaylov** *(St. Petersburg, Russia)*
Dynamical inverse problem for Jacobi matrices

15^{20} – 15^{40} **Ekaterina Sassi, Sergey Chivilikhin** *(St. Petersburg, Russia)*
Spreading of viscous droplet on the solid surface

15^{40} – 16^{00} **Dmitry Eremin, Dmitry Ivanov, Evgeny Grishanov, Anton Popov, Igor Popov** *(St. Petersburg, Saransk, Russia)*
Periodic array of quantum dots with attached wires: Model of tunnelling

16^{00} – 16^{30} *Coffee*

Young Researchers Symposium-2 (YRS-2)

Chairman: Sergey Chivilikhin

16^{30} – 16^{40} **Alina Melikhova** *(Saint Petersburg, Russia)*
Zigzag chain model and its spectrum

16^{40} – 16^{50} **Ivan Melikhov** *(St. Petersburg, Russia)*
Asymptotic solution of ultrasonic near-field levitation problem

16^{50} – 17^{00} **Svetlana Ezhenkova** *(St. Petersburg, Russia)*
The theory of the boundary layer for the problem of finding the density distribution of settling nanoparticles in a liquid

17^{00} – 17^{10} **Anna Belolipetskaya, Nikita Lisitsa, Igor Popov** *(St. Petersburg, Russia)*
Modeling of helix molecules formation on a surface of nanotube and inside it

17^{10} – 17^{20} **Dmitry Eremin, Evgeny Grishanov, Oleg Kostrov**, **Evgeny Alexandrov**, **Igor Popov** *(St. Petersburg, Saransk, Russia)*
Time evolution of wave packet for time-dependent quantum graph with loop

17^{20} – 17^{30} **Irina Blinova** *(St. Petersburg, Russia)*
Bound states of the Dirac operator on bent chain graph

17^{30} – 17^{35} *Closing*

Abstracts

Spectral properties of a symmetric threedimensional quantum dot with a pair of identical attractive δ-impurities symmetrically situated around the origin II

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In this note, we continue our analysis (started in [1]) of the isotropic threedimensional harmonic oscillator perturbed by a pair of identical attractive point interactions symmetrically situated with respect to the origin, that is to say, the mathematical model describing a symmetric quantum dot with a pair of point impurities. In particular, by making the coupling constant (to be renormalized) dependent also upon the separation distance between the two impurities, we prove that it is possible to rigorously define the unique selfadjoint Hamiltonian that, differently from the one introduced in [1], behaves smoothly as the separation distance between the impurities shrinks to zero. In fact, we rigorously prove that the Hamiltonian introduced in this note converges in the normresolvent sense to that of the isotropic threedimensional harmonic oscillator perturbed by a single attractive point interaction situated at the origin having double strength, thus making this threedimensional model more similar to its onedimensional analog (not requiring the renormalization procedure) as well as to the threedimensional model involving impurities given by potentials whose range may even be physically very short but different from zero. Moreover, we show the manifestation of the Zeldovich effect, known also as level rearrangement, in the model investigated herewith. More precisely, we take advantage of our renormalization procedure to demonstrate the possibility of using the concept of 'Zeldovich spiral', introduced in the case of perturbations given by rapidly decaying potentials, also in the case of point perturbations.

[1] Albeverio S., Fassari S., Rinaldi F. Spectral properties of a symmetric threedimensional quantum dot with a pair of identical attractive δ-impurities symmetrically situated around the origin. *Nanosystems: Physics, Chemistry, Mathematics*, 2016, **7** (2), P. 268–289.

Nanotubes for "on-surface" helix molecules synthesis: a model

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"On-surface" synthesis of large molecules and assemblies is a great challenge in molecular electronics, biomedical devices, sensors, energy harnessing and catalysis. Usually, plane surfaces are used for these purposes. We study a possibility of macro molecules formation on the surface of nanotube and inside it. It can be used for synthesis of helix molecules, particularly, organic and biological. Nanotubes of different structures were considered. Point-like approximation is used for atoms. The Lennard-Jones 6-12 potential is taken as the interaction potential. Possibilities of helix molecules and ring-like molecules formations were shown. A hypothesis of such processes influence on the organic molecules formation during the early Earth history is suggested and discussed.

Bound states of the Dirac operator on bent chain graph

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We study Dirac operators on an infinite quantum graph of a bent chain form which consists of identical rings connected at the touching points by δ-couplings with a parameter $\alpha \in$. It is established that negativity of α is the necessary and sufficient condition for the existence of eigenvalues of the Dirac operators. Conditions for appearance of more than one eigenvalue are obtained. It is related with the bending angle. The investigation is based on the transfer-matrix approach.

The experimental investigation of homodyne detector noises for measuring the quantum state of light

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Balanced homodyne detector is used in quantum optics and quantum information theory for measuring the electromagnetic field quadrature signal. According to the measurements it is possible to retrieve information about the quantum state of the measured signal. With the development of quantum optics, performance requirements homodyne detectors increases. The design of modern homodyne detectors based on four criteria: bandwidth and the flat part of frequency response, the ratio of the electron quantum noise, the come-mode rejection ratio (CMRR ratio), the quantum efficiency of the diodes.

In this study we investigated the factors affecting the value of the noise in the scheme of homodyne detector and development of the scheme, taking into account these factors. Scheme for researching noises and modeling the behavior of these noise is currently used in the homodyne detector circuit. One of noise occurrence factors which is difficult to describe mathematically is circuit topology. Analysis of this noise factor has been carried out experimentally. We have developed a new scheme that takes into account all the drawbacks of the existing topology.

Electrical Resistivity Model for Quasi-one-dimensional structures

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In this work electron-impurity scattering coefficient of Bloch waves for one dimensional Dirac comb potential is used for calculation of temperature dependency of resistivity within Boltzmann theory. Results are obtained within advanced numerical procedure. Our results discovered important feature of the temperature dependence link with a scatterers parameters. We observe that in rather narrow range of parameters the dependence of the resistivity on temperature varies significantly. It, perhaps, opens a way to explanation of the strong variation of the dependence in experiments.

Uniform resolvent convergence for a planar strip with fast oscillating boundary

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We consider an elliptic operator in a planar infinite strip perturbed by substituting one side of the boundary by a fast oscillating curve. We assume that both the period and the amplitude of the oscillations are small and impose the Dirichlet condition on the upper boundary and Dirichlet, Neumann or Robin boundary condition on the oscillating boundary. In all cases we describe the homogenized operator, establish the uniform resolvent convergence of the perturbed resolvent to the homogenized one, and prove the estimates for the rate of convergence. These results are obtained as the order of the amplitude of the oscillations is less, equal or greater than that of the period. It is shown that under the homogenization the type of the boundary condition can change.
Based on joint work with D.Borisov, L.Faella, C.Perugia.

Spreading of viscous droplet on the solid surface

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The model of 2D Stokes flow due to gravitation and capillary forces is developed. Method of flow calculating based on presentation of the pressure in the form an expansion in the complete system of harmonic functions. The model is used for describing of droplet spreading on the solid surface. The possibility of implementation this algorithm on the quantum computer is discussed.

Synchronization signal distortion in quantum communication systems

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The quantum communication systems operate at great distances with the signal passing through the optical fiber from the transmitter to the receiver. The main problem of practical implementation is to synchronize these modules.

We investigated dependence of synchronization signal on the dispersive effects in a subcarrier wave quantum communication system (SCWQC). The ITU-T. G.652D standard single mode optical fiber is used. Maximum calculated time delay of the synchronization signal for the system operating on 100 km distance is 1.7 ps. The results show that signal spread in time due to the chromatic dispersion by 1.366 ps. This delay does not have significant impact. However, time signal delay due to polarization mode dispersion is 2 ps. Obtained results were used to optimize the calibration procedure parameters and increase overall sifted key generation rate.

Periodic array of quantum dots with attached wires: Model of tunnelling

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Several explicitly solvable models of electron tunnelling in a system of single and double two-dimensional periodic arrays of quantum dots with two laterally coupled leads in a homogeneous magnetic field are constructed. First, a model of single layer formed by periodic array of zero-range potentials is described. The Landau operator (the Schrodinger operator with a magnetic field) with point-like interactions is the system Hamiltonian. We deal with two types of the layer lattices: square and honeycomb. The periodicity condition gives one an invariance property for the Hamiltonian in respect to magnetic translations group. The consideration of double quantum layer reduces to the replacement of the basic cell for the single layer by a cell including centers of different layers. Two variants of themodel for the double layer are suggested: with direct tunneling between the layers and with the connecting channels (segments in the model) between the layers. The theory of self-adjoint extensions of symmetric operators is a mathematical background of the model. The third stage of the construction is the description of leads connection. It is made by the operator extensions theory method too. Electron tunneling from input lead to the output lead through the double quantum layer is described. Energy ranges with extremely small (practically, zero) transmission were found. Dependencies of the transmission coefficient (particularly, “zero transmission bands” positions) on the magnetic field, the energy of electron and the distance between layers are investigated. The results are compared with the corresponding single-layer transmission.

Time evolution of wave packet for time-dependent quantum graph with loop

Dmitry Eremin, Evgeny Grishanov, Oleg Kostrov,
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Quantum graph composed from a ring and segment is considered. We deal with free Schrödinger operator at the edges and the Kirchhoff conditions at the internal vertex. The lengths of the graph edges varies in time. Time evolution of wave packet is studied for different parameters of length varying law.

The theory of the boundary layer for the problem of finding the density distribution of settling nanoparticles in a liquid

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In this work we consider the sedimentation process of nanoparticles in a liquid with regard to their Brownian diffusion.
As object of research we take a glassful with liquid which contains particles of different sizes.
Using the equation of convective diffusion and know the initial and boundary conditions we are finding the solution of this equation. This boundary conditions are manifested in a rather small coordinate interval (a boundary layer) adjacent to the coordinate $x=L$. For finding the solution inside the boundary layerwe provide the diffusion equation to the dimensionless form. For this we introduce the dimensionless parameters for the values of x and t.
Then we produce cross-linking solutions inside the boundary layer with the solution outside the boundary layer, consider the behavior of individual parts of the equation, find the necessary coefficients and obtain the final form of the particle size distribution using the Newton polygon method.

Eigenvalue problems for networks of PDEs modeling a coronary stent

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Coronary stents are thin metallic structures which are used for treating a narrowing of blood vessels (stenosis). They are made out of thin metallic cylinders by laser cuts. Stents are typically modeled as an assembly of struts and since they are a metallic structure their small

deformations are sufficiently well described by 3D linearized elasticity. However, a direct numerical treatment of such model would lead to considering equations of 3D linearized elasticity in a thin almost graph-like domain. This is a very challenging and time consuming numerical task. Furthermore, this problem has an interesting algebraic structure induced by the underlying connectivity graph which is ignored by treating it as a full 3D problem.
As an alternative we start from a simpler analytical approximation – a reduced model – which can beobtained using a one-dimensional model of a curved elastic rod which are then combined in a problem posed on a product space defined by a metric graph describing the topology of the stent.
We obtain a variational eigenvalue problem in a mixed form. To facilitate spectral analysis we reformulate this as an eigenvalue problem for a pencil of block operator matrices. We approximate this eigenvalue problem using finite element projection and present convergence estimates for the approximate eigenvalues and eigenfunctions. This is a joint work with J. Tambača and J. Iveković.

Stability of the Grover's algorithm in respect to perturbations of quantum circuit

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Grover's algorithm has many valuable applications, and one of them is the ability to use it for finding the shortest path in network rooting. Therefore the problem of researching the stability in respect to perturbation in the scheme is very important for quantum network implementation. This article presents the results of modeling the impact of distortions on the calculation of the algorithm and its dependencies from the number of qubits, used in quantum circuit.

Spectral asymptotics for an elastic strip with an interior crack

André Hänel

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We consider an infinite elastic strip $\Omega := R \times \left(-\frac{\pi}{2}, \frac{\pi}{2} \right)$ with zero Poisson ratio and a crack $\Gamma_l := [-l, l] \times \{0\}$. We impose traction-free boundary conditions and consider the existence of trapped modes, i.e., we search for square-integrable solutions $u : \Omega \setminus \Gamma_l \to C^2$ of the eigenvalue problem

$$\begin{cases} (-\Delta - grad\ div)\,\mathrm{u} = \omega(l)u & in \quad \Omega \setminus \Gamma_l \\ 2\varepsilon(u)\cdot \mathbf{n} = 0 & on\ \partial(\Omega \setminus \Gamma_l) \end{cases}$$

Here **n** is the outer normal unit vector, *u* is the displacement field of the elastic material and $\varepsilon(u)=\frac{1}{2}\left(\partial_i u_j+\partial_j u_i\right)_{i,j=1,2}$ the strain tensor.

In [Hänel, A. and Schulz, C. and Wirth, J. Embedded eigenvalues for an elastic strip with cracks. *Quart. J. Mech. Appl. Math.*, **65**, (2012), P. 535-554] the existence of two eigenvalues $\omega_1(l)$ and $\omega_2(l)$ embedded in the essential spectrum of the corresponding self-adjoint operator was proved. In the present talk we show that these eigenvalues satisfy the asymptotic estimates:

$$\omega_1(l)=\Lambda-\nu_1 l^4+O\left(l^5\right) \quad as \quad l\to 0$$
$$\omega_2(l)=\Lambda-\nu_2 l^8+O\left(l^9\right) \quad as \quad l\to 0$$

where Λ is some spectral threshold and $\nu_1,\nu_2>0$. This is a joint work with T. Weidl.

Quantum random number generator based on homodyne detection

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Quantum random number generator (QRNG) based on quantum nature of fluctuations of vacuum allow obtaining random bit sequences that can be used in applications that require high degree of randomness. In that type of quantum random generation systems, spatial optical beam splitters with two inputs and two outputs (X-splitters) are normally used. We obtain mathematical descriptions of the Y-splitter and a spatial beam splitter in the quantum model for QRNGs based on vacuum fluctuation. A comparison of results shows that for the two types of optical splitters the quantum mathematical description of the output signals is identical. That allows using fiber Y-splitters in practical QRNG schemes, significantly simplifying the setup. Also we receive the relations between the input radiation and the resulting differential current in the homodyne detector. Considering the fact that components in real systems are not ideal, we derive the expressions that allow estimation of the scheme parameters imperfection impact on measurement results. Possibility of generating true random bits was demonstrated experimentally by using quantum random number generator based on homodyne detection.

Geometry and spectrum in systems with leaky quantum wires

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We discuss two classes of quantum systems with, so called, delta interactions supported on lines located in a plane. Our aim is find out how the geometrical properties of the system are

reflected in spectrum. First, we analyze the models which can represented by a potential supported on angle in R^2. Our aim is to derive the eigenvalues asymptotics if the angle-shape line approach to the straight line. In the second stage, we study the systems with potentials supported on two parallel lines and the eigenvalues asymptotics is obtained if both lines approach to each other. Finally, we discuss some generalizations of the above mentioned systems to higher dimensional systems. The results presented in the talk are based on the common works with P.Exner and D.Krejcirik.

Kolmogorov equation for Bloch electrons and Electrical Resistivity Models for nanowires

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The kinetic transport equation is applied to a transport problems of nanowires. The multiple scattering expansion is used in a framework of Landauer approach. The statement of problem is formulated in space of distributions with specification of a wire geometry. The stationary solution of the kinetic problem incorporate temperature via Fermi-Dirac distribution. Some simple model for electron-impurity scattering coefficient of Bloch waves is used for calculation of resistivity within the theory.

Asymptotic solution of ultrasonic near-field levitation problem

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Ultrasonic near-field levitation is the phenomenon of steady suspension of moderately large objects, which float over ultrasonic transducer at extremely low height, from 10 to 300 microns. The goal of this work is to get fundamental understanding of this phenomenon. We consider the airflow in the gap between a sound source and a levitating object. This type of levitation includes two mechanisms: viscous and inertial (acoustic), which act simultaneously. However, using the assumptions of small gap thickness comparing to object's length and acoustic wavelength, it is possible to simplify the governing equations. Then we introduce a small parameter, ratio of vibration amplitude to the gap thickness, and solve equations in frequency domain. In addition, special non-reflective boundary conditions at the end of the gap are developed. Finally, the initial system of nonlinear transient equations is reduced to a set of five linear equations with no time dependence. It allows fast and accurate prediction of levitation force. The developed model is compared with published experimental data and numerical simulations with very good agreement.

Zigzag chain model and its spectrum

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This work describes developing of a model of a zigzag chain of weakly-coupled spherical resonators with Neumann boundary condition. The chain is assumed to be constructed with identical resonators connected by point-like apertures. The joint points are described by delta-coupling with a constant intensity. The model is based on the theory of self-adjoint expansions of symmetrical operators. Due to effectively one-dimensional joints, the 3D problem can be solved with the help of monodromy matrix. It allows us to study spectrum of the physical system. In particular, it is proven that the discrete spectrum is empty. In additional, the continuous spectrum has band structure. With the help of asymptotic study, we obtain the dependence of the spectrum structure on the physical parameters of the system: zigzag angle and coupling intensity.

Dynamical inverse problem for Jacobi matrices

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We consider the dynamical inverse problems for the systems with discrete time, associated with Jacobi matrices and with a subclass of JM, discrete Schrodinger operators. We answer the question on characterization of the dynamical inverse data for these systems. As a consequence we obtain a result of the characterization of the spectral measure of discrete Schrodinger operators. (this is a joint work with A.S. Mikhaylov).

To the spectral theory of vector-valued Sturm-Liouville operators with summable potentials and point interactions

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The paper is devoted to the spectral theory of vector-valued Sturm-Liouville operators on the half-line with a summable potential and a finite number of point interactions. It is shown that the positive spectrum is purely absolutely continuous and of constant multiplicity. The negative spectrum is either finite or discrete with the only accumulation point at zero. Our approach relies on a detail investigation of the corresponding Weyl function.

Error analysis in schemes building at the quantum computing platform IBM Quantum Experience

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Nowadays, there are many quantum computing systems at an early stage of research. Many large companies, connected with IT technology, such as IBM, Google, Microsoft are interested in quantum computing. For the development of quantum computing, IBM provides access to the 5-qubit quantum computer named as «IBM Quantum Experience». The company provides the opportunity to conduct their own experiments on the real quantum computer for all who are interested in it.

The aim of this work is to analyze errors in schemes building at the real quantum computer.

Quantum computers must deal with the loss of information due to environmental disturbances. There is noise in the real circuit.The actual quantum circuit cannot be completely isolated. Expected condition at the output of the circuit would not be observed on the real device.

The errors of quantum circuits have been observed in this work.

The difference between real quantum computer and ideal quantum computer has been shown. Also a simple error-correction code has been described.

The platform can be useful for the investigating distortion of quantum algorithm. If the artificial distortion of the system is created, it is possible to observe the effect of the noises on the algorithm. Such effect has been observed in this work.

Spectral properties of the half-line Schrödinger operator with slowly decaying Wigner-von Neumann potential

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In the talk we will consider asymptotic behavior of the spectral density of the operator

$$L_\alpha = -\frac{d^2}{dx^2} + q_{per}(x) + \frac{c\sin(2\omega x + \delta)}{x^\gamma} + q_1(x)$$

$dom\ L_\alpha = \left\{u \in H^2_{loc}(R_+) : u, L_\alpha u \in L_2(R_+),\ u(0)\cos\alpha = u'(0)\sin\alpha\right\}$, near critical points which lie inside its absolutely continuous spectrum. Here q_{per} is a periodic background potential, $q_1 \in L_1(R_+)$ and $\gamma \in \left(\frac{1}{2}, 1\right)$. Each spectral band of L_α contains two critical points locations of which are determined by the frequency ω and the potential q_{per}. Spectral density ρ'_α of L_α has exponential zeros at these critical points ν_{cr}:

$$\rho'_{\alpha}(\lambda) = const \cdot \exp\left(-\frac{2c_{cr}}{|\lambda - \nu_{cr}|^{\frac{1-\gamma}{\gamma}}} \right)\left(1 + o(1)\right) \ as \ \ \lambda \to \nu_{cr}$$

with

$$c_{cr} = \frac{(2\beta_{cr})^{\frac{1}{\gamma}}}{4\gamma} B\left(\frac{3}{2}, \frac{1-\gamma}{2\gamma}\right)\left(\frac{a}{2\pi k'(\nu_{cr})}\right)^{\frac{1-\gamma}{\gamma}}, \qquad \beta_{cr} = \frac{|c|}{2\alpha |W\{\psi_+, \psi_-\}(\nu_{cr})|}\left|\int_0^{\alpha} \psi_+^2(x, \nu_{cr}) e^{2i\omega x} dx\right|,$$

where $\psi_{\pm}$ are Bloch solutions of the unperturbed periodic equation and *k* is the quasi-momentum. Earlier the case $\gamma = 1$ was studied for which power type zeros of ρ'_{α} take place.

On PT symmetric operators related to Hamilitonians with complex potentials

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Consider PT symmetric Hamiltonians $(\tau y)(x) := -y''(x) + x^2 (ix)^{\varepsilon} y(x), \quad \varepsilon > 0$:

where ε is a real number not smaller than 2, the eigenvalue problem is defined using a contour in the complex plane (not in R). It is assumed that this contour is between two so-called Stokes lines.

In the Sturm-Liouville theory for Hamiltonians with a complex potential there exists a limit point/limit circle classification which gives a mathematical interpretation to the Stokes lines (and Stokes wedges). Moreover, we identify a setting where the corresponding Hamiltonian turns out to be selfadjoint in the Krein space $(L_2(R), [\cdot,\cdot])$. The corresponding Krein space inner product is defined with the parity P as the

Gramian. Finally, we present some results on the location of the resolvent set.