JOINT INSTITUTE FOR NUCLEAR RESEARCH
Bogoliubov Laboratory of Theoretical Physics

INTERNATIONAL WORKSHOP

Finite Quantum Systems

Dubna, Russia
June 3-11, 1998

supported by
Heisenberg-Landau Program
and
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General Information
Program
Abstracts and List of Participants

Address: Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
Tel: (7-09621) 65748
Telex: 911621 Dubna SU
Fax: (7-09621) 65084
E-mail *smond@thsun1.jinr.dubna.su*

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Bogoliubov Laboratory of Theoretical Physics of the Joint Institute for Nuclear Research is organizing the International Workshop "Finite Quantum Systems" (Dubna, June 3-11, 1998). The main objective of the Workshop is to provide valuable scientific information as well as a good introduction to current research for postgraduate students and young researchers. Traditionally, Dubna is a meeting place for physicists from East and West, and we hope that the Workshop will provide a unique opportunity for contacts, scientific and human, between outstanding researchers and young scientists.

The main topics of the Workshop will include

- Low-dimensional systems
- Systems with a small number of particles
- Mesoscopic phenomena
- Electron correlations and transport phenomena
- Bose-Einstein condensation in magnetic traps

The working language of the Workshop is English.

Besides of lectures a limited number of brief talks will be given by young participants. There could be changes in the Program and the Schedule which will be announced during the Workshop.

ORGANIZING COMMITTEE:

Chairman:	**M. Smondyrev**	tel. 65748	office 334
Vice-Chairmen:	**G. Röpke**		
	V. Yarunin	tel. 65419	office 213
Scientific Secretary:	**A. Shanenko**	tel. 63947	office 214
Workshop coordinator:	**V. Novikova**	tel. 65170	
Members:			
	M. Dzero	tel. 63191	office 003
	G. Sandukovskaya	tel. 63173	office 340

ACCOMMODATION

Participants will be accommodated in the "DUBNA" hotel close to the Workshop site.

REGISTRATION

On June 3, 1998 the registration is at "DUBNA" hotel (room 103) from 14:00 to 17:00. During the Workshop (June 4-10, 1998) the registration is at the Workshop Secretariat (room 238) in the Laboratory of Theoretical Physics.

SCHEDULE

The Workshop opens at 9:30 a.m. on June 4 in the Conference Hall of the Bogoliubov Laboratory of Theoretical Physics. All sessions (10:00 – 13:00, 15:00 – 18:00) will take place in the same Conference Hall. The closing of the Workshop will take place after the last session on June 10.

Preliminary Schedule

First Week

Wednesday, 03.06 — arrival, registration, Welcome Party (18.00)
Thursday, 04.06 — Opening (9.30)

Time	Thursday, 04.06	Friday, 05.06	Saturday, 06.06
10.00-10.50	Peeters	Gerlach	Ivanov
10.50-11.10	*coffee break*	*coffee break*	*coffee break*
11.10-12.00	Matulis	Gerlach	Röpke
12.00-12.50	Gaponenko	Peeters	Lozovik
13.00-15.00	*lunch*	*lunch*	*lunch*
15.00-15.50	Stier	Kirillov	Lozovik
15.50-16.10	*coffee break*	*coffee break*	
16.10-17.00	Türck	Zakhariev	
17.00-18.00	Brief talks	Brief talks	

Sunday, 07.06 — excursion

Second Week

Time	Monday, 08.06	Tuesday, 09.06	Wednesday, 10.06
10.00-10.50	Shlyapnikov	Bigelow	Kulakovsky
10.50-11.10	*coffee break*	*coffee break*	*coffee break*
11.10-12.00	Shlyapnikov	Bigelow	Bogoliubov
12.00-12.50	Baranov	Timofeev	Pashkevich
13.00-15.00	*lunch*	*lunch*	*lunch*
15.00-15.50	Minogin	Nazmitdinov	Shanenko
15.50-16.10	*coffee break*	*coffee break*	Closing
16.10-17.00	Yarunin	Dubovik	
17.00-18.00	Brief talks	Brief talks	*Banquet (19.00)*

Thursday, 11.06 — departure

Abstracts published in the present booklet are placed in alphabetical order of (supposed) speakers names.

MEAL

Meals are served in the restaurant of the "Dubna" Hotel, in the International Conference Hall Cafeteria and in the Scientist's Club Cafeteria. Working hours are as follows:

Breakfast: **07:30 – 09:30**
at the Hotel Cafeteria

Lunch: **12:00 – 15:00**
at the canteen near the Laboratory,
at the restaurant and Int. Conf. Hall Cafeteria

Dinner: **19:00 – 23:00**
at the restaurant and in the Scientist's Club Cafeteria

SOCIAL PROGRAM

The social program includes a Welcome Party on June 3 at the Laboratory cafeteria, a bus excursion and a closing banquet on June 10.

Besides, one can take a train on his/her own to go to Moscow. We strongly recommend to use express trains which go between Dubna and Moscow without stops. The current (May '98) price for a one-way ticket in express trains is 33.5 R.

Time-Table of Dubna-Moscow trains (valid from May 24, 1998)

Departure from Dubna	Arrival to Moscow	Departure from Moscow	Arrival to Dubna
4-42	7-21	5-04	7-29
5-32	8-03	6-55	9-21
7-09	**9-02**	7-17[6,7]	10-00[6,7]
7-46	10-14	**9-54**	**11-49**
9-42	12-07	9-59	12-21
10-40[6,7]	13-17[6,7]	13-53	16-24
14-08	**16-01**	**16-36**	**18-31**
14-49	17-20	16-41	19-25
17-06	19-34	18-43	21-15
19-06	**21-00**	20-27	22-57
19-40	22-10	**21-36**	**23-31**
21-42	0.14	23-16	1-41

[6,7] — only on weekends in summer time

Non-stop trains are shown by **bold face** numbers

List of Paricipants

Mikhail A. Baranov
Kurchatov Institute of Atomic Energy
Kurchatov Sq. 46, 123182 Moscow, Russia
baranov@kapitza.ras.ru

Alexander I. Biblik
Institute of Molecular and Atomic Physics
National Academy of Sciences of Belarus, 220072 Minsk, Belarus
gaponen@imaph.bas-net.by

Nicholas P. Bigelow
University of Rochester, N.Y. 14627, USA
nbig@lle.rochester.edu

Nikolai N. Bogoliubov Jr.
Steklov Mathematical Institute
Russian Academy of Sciences
Vavilov str. 42, GSP-1, 117966 Moscow, Russia
nickolai@bogol.mian.su

Maksim O. Dzero
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
dzero@thsun1.jinr.dubna.su

Vladimir M. Dubovik
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
dubovik@thsun1.jinr.dubna.su

Sergey V. Gaponenko
Institute of Molecular and Atomic Physics
National Academy of Sciences of Belarus, 220072 Minsk, Belarus
gaponen@imaph bas-net.by

Bernd Gerlach
Institut für Physik, Universität Dortmund
D-4421 Dortmund, Germany
gerlach@fkt.physik.uni-dortmund.de

Ilona Himberg
Institut für Physik, Universität Dortmund
D-4421 Dortmund, Germany
himberg@wap.physik.uni-dortmund.de

Valerii A. Ivanov
Kurnakov Institute of General and Inorganic Chemistry
Russian Academy of Sciences
Leninskii av. 31, 117907 Moscow, Russia
vonavi@ionchran.msk.ru

Andrei I. Kirillov
Department of Higher Mathematics,
Moscow Institute of Power Engineering
Krasnokazarmennaia 14, 105835 Moscow, Russia
and
Higher College for Mathematical Physics,
Independent University of Moscow
Vavilova str. 42, 117966 Moscow, Russia
tmph@class.mian.su

Vladimir D. Kulakovskii
Institute of Solid State Physics
Russian Academy of Sciences
142432 Chernogolovka, Russia
kulakovs@issp.ac.ru

Yurii E. Lozovik
Institute of Spectroscopy
Russian Academy of Sciences
142092 Troitsk, Moscow region, Russia
lozovik@isan.troitsk.ru

Vladimir Yu. Mamakin
Moscow Institute of Power Engineering
Krasnokazarmennaia 14, 105835 Moscow, Russia
vladimir.mamakin@p68.f118.n5020.z2.fidonet.org

Algirdas Matulis
Semiconductor Physics Institute
Goštauto 11, 2600 Vilnius, Lithuania
matulis@pub.osf.lt

Pavel A. Molent'ev
Institute of Spectroscopy
Russian Academy of Sciences
142092 Troitsk, Moscow region, Russia
subbotin@isan.troitsk.ru

Vladimir G Minogin
Institute of Spectroscopy
Russian Academy of Sciences
142092 Troitsk, Moscow region, Russia
minogin@isan.troitsk.ru

Rashid Nazmitdinov
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
rashid@thsun1.jinr.dubna.su

Bart Partoens
Departement Natuurkunde, Universiteit Antwerpen (UIA)
B-2610 Antwerpen, Belgium
partoens@hhipe.uia.ac.be

Vitalii V. Pashkevich
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
pashkevi@thsun1.jinr.dubna.su

Francois M. Peeters
Departement Natuurkunde, Universiteit Antwerpen (UIA)
B-2610 Antwerpen, Belgium
peeters@hhipe.uia.ac.be

Eugene V. Polyachenko
Moscow Institute of Power Engineering
Krasnokazarmennaia 14, 105835 Moscow, Russia
academy@online.ru

Gerd Röpke
Universität Rostock, Fachbereich Physik
Universitätsplatz 1, D-18051 Rostock, Germany
roepke@darss.mpg.uni-rostock.de

Arkady A. Shanenko
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
shanenko@thsun1.jinr.dubna.su

Georgii V. Shlyapnikov
Kurchatov Institute of Atomic Energy,
Kurchatov Sq. 46, 123182 Moscow, Russia
shlyapnikov@amolf.nl

Mikhail A. Smondyrev
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
smond@thsun1.jinr.dubna.su

Oliver Stier
TU-Berlin, Sekr. PN 5-2, Hardenbergstrasse 36
D-10623 Berlin, Germany
stier@physik.TU-Berlin.DE

Heinrich Stolz
FB Physik Universität Rostock,
Universitätsplatz 3,
D-18051 Rostock, Germany
heinrich.stolz@physik.uni-rostock.de

Maksim V. Subbotin
Institute of Spectroscopy
Russian Academy of Sciences
142092 Troitsk, Moscow region, Russia
subbotin@isan.troitsk.ru

Vladislav B. Timofeev
Institute of Solid State Physics,
Russian Academy of Sciences
142432 Chernogolovka, Russia
timofeev@issp.ac.ru

Volker Türck
TU-Berlin, Sekr. PN 5-2, Hardenbergstrasse 36
D-10623 Berlin, Germany
tuerck@physik.TU-Berlin.DE

Alexander A. Vasilchenko
Department of Physics, Kuban State University
149 Stavropolskaya str., 350040 Krasnodar, Russia
vasil@phys.kubsu.ru

Dmitry A. Yarotsky
Institute of Molecular and Atomic Physics
National Academy of Sciences of Belarus, 220072 Minsk, Belarus
lop@dragon.bas-net.by

Vladimir S. Yarunin
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
yarunin@thsun1.jinr.dubna.su

Boris N. Zakhariev
Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research
141980 Dubna, Moscow Region, Russia
zakharev@thsun1.jinr.dubna.su

Mikhail E. Zhuravlev
Kurnakov Institute of General and Inorganic Chemistry
Russian Academy of Sciences
Leninskii av. 31, 117907 Moscow, Russia
FAX: (7)(095) 954 12 79

Superfluid phase transition in trapped Fermi-gases

M. Baranov

Kurchatov Institute of Atomic Energy,
Kurchatov Sq. 46, 123182 Moscow, Russia

We discuss a superfluid phase transition in a trapped neutral-atom Fermi gas. A remarkable feature of the system is that the Cooper pairing and, hence, the superfluid phase transition can occur for both attractive and repulsive interparticle interaction. For an attractive interaction (negative scattering length) the pairing occurs in the s-wave channel, as described by the standard BCS approach, and one has "singlet" Cooper pairs. For positive scattering length (repulsive interaction) the s-wave pairing is impossible, and one has to consider the mechanism of p-wave "triplet" pairing which originates from the effective interaction caused by polarization effects. Actually, this pairing mechanism is insensitive to the sign of the scattering length. It works equally well for an attractive interraction in the situation where the direct s-wave pairing is suppressed. Since the effective interaction based on polarization effects is weaker than the direct interparticle interaction, the p-wave "triplet" pairing results in a lower value of the critical temperature compared to that for the s-wave pairing.

We study the influence of a (harmonic) trapping potential on superfluid pairing. We derive the corresponding Ginzburg-Landau (GL) equation for the order parameter, assuming the critical temperature much higher than the level spacing in the trap. The analysis of this equation provides us with the value of the critical temperature for the trapped gas and gives the coordinate and temperature dependence of the order parameter in the vicinity of the phase transition. As found, the critical temperature is slightly lower than that for a spatially homogeneous Fermi gas with maximum density of the trapped gas.

We obtain the energy spectrum and the wave functions of one-particle excitations in a trapped neutral-atom Fermi-gas and reveal the strong influence of the superfluid phase transition on the character of the spectrum. Above the transition point the interparticle interaction is not important and the excitation eigenfrequencies are just multiplies of the trap frequency. As expected, below the transition

temperature the appearance of the order parameter (spatially inhomogeneous gap) shifts up the excitation energies. Remarkably, we also reveal the existence of a new type of low-energy elementary excitations, with eigenfrequencies of the order of the trap frequency. They appear due to the spatial inhomogeneity of the order parameter and are mainly localized near the boundary of the gas sample. In fact, these eigenmodes are the bound states in the potential well formed by the trapping potential and the spatially inhomogeneous gap. Below the critical temperature the energy spectrum of the excitations shows a strong temperature dependence which can be used for experimental identification of the superfluid phase transition.

Hartree-Fock-Bogolubov approximation for model systems with four-fermion interaction

N. N. Bogoliubov

Steklov Mathematical Institute
Vavilova str. 42, GSP-1, 117966 Moscow, Russia

An approach is proposed which allows one to investigate dynamical and thermodynamical properties of models with four-fermion interaction of general type. The approach combines ideas of the standard Bogolubov' s trial (approximating) Hamiltonians method for the models with separabile interaction with the method of Hartee- Fock approximation based on the ideas of self-consistency.It gives possible to constract system of nonlinear Equations with sources. Varying this system of nonlinear equat ons with respect to the source terms give us possibility constract system for Green functions and then present some solution.

Electron and photon confinement in mesoscopic systems

Sergey V. Gaponenko

Institute of Molecular and Atomic Physics
National Academy of Sciences of Belarus, 220072 Minsk, Belarus

Electron states in bulk solids and nanostructures differ from those relevant to a free space because of the translational symmetry of the given crystal lattice and of the specific boundary conditions determined by the confinement geometry. Therefore electron density of states and optical transition probabilities can be controlled in nanostructures by means of quantum confinement effects. Propagation of electromagnetic waves in media other than vacuum can be significantly altered as well by means of periodic spatial modulation of dielectric constant and by spatial restriction. This leads to a concept of photonic band engineering including photonic crystals and photonic quantum boxes (microcavities). Because of the large difference in characteristic length scales relevant to electrons and photons, i. e. an electron de Broglie wavelengh in solids (10 nm) and an optical photon wavelength (500 nm) electron and photon densities of states can be engineered separately within the same microstructure. Furthermore, since spontaneous emission of quantum systems is proportional to the density of photon states it is possible to create microstructures with complete control of spontaneous emission spectrum and decay rate by means of the proper electron and photon confinement geometries. The examples of such structures are nanocrystals in a microcavity and nanocrystals embedded in a three-dimensional photonic crystal. In this report the problems and advances in syntesis and studies of mesoscopic systems with sumalteneous electron and photon confinement are reviewed.

Excitons and polarons in 2D quantum wells

B. Gerlach*, J. Wüsthoff*, M. O. Dzero†, M. A. Smondyrev†

* *Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany*

† *Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia*

Excitons are low lying excited states of a semiconductor, consisting of an electron and a hole, bound by an effective Coulomb force. We consider a model describing the one-dimensional confinement of an exciton in a symmetrical, rectangular quantum-well structure and derive upper and lower bounds for the binding energy E_b of the exciton. Based on these bounds, we study the dependence of E_b on the width of the confining potential with a higher accuracy than previous reports. For an infinitely deep potential the binding energy varies as expected from $1\,Ry$ at large widths to $4\,Ry$ at small widths. For a finite potential, but without consideration of a mass mismatch or a dielectric mismatch, we substantiate earlier results that the binding energy approaches the value $1\,Ry$ for both small and large widths, having a characteristic peak for some intermediate size of the slab. Taking the mismatch into account, this result will in general no longer be true. For the specific case of a $Ga_{1-x}Al_xAs/GaAs/Ga_{1-x}Al_xAs$ quantum-well structure, however, and in contrast to previous findings, the peak structure is shown to survive.

Due to their dipole character, excitons couple preferably to optical phonons, if such a coupling is symmetry allowed. Quantum-well structures modify the "free" exciton-phonon spectrum in a significant way, leading to physically (and technologically) important changes, e.g., of the optical spectrum. To study the energy spectrum of an exciton-(LO)phonon system in a quantum well we use a Fröhlich type model, the quantum-well confinement being mimicked by one-particle potentials for an electron and a hole. In the path-integral representation of the partition function, the phonon degrees of freedom can exactly be eliminated, leading us to an effective two-polaron system. In a subsequent variational approach we derive upper bounds for the ground-state energy. Note that the use is made of a non-Gaussian trial action which also includes Coulomb-type terms.

Particular attention is paid to the limiting cases of a comparatively wide (narrow)

quantum well, which were extensively discussed in the literature. For intermediate well width we present numerical results and discuss the phonon-induced corrections. In particular, we study the dynamical screening demonstrating that the static dielectric constant can be used for relevant semiconductors.

To investigate the influence of the concrete form of the quantum well we consider a polaron in a Rosen-Morse confining potential. The polaron energy and the effective mass are calculated for an electron confined in a finite quantum well while phonons are assumed to be three-dimensional. Because the exact energy-dependent Green function is known for the Rosen-Morse potential, this allows us to describe the confined electron properties explicitly to the second order of perturbations in powers of the electron-phonon coupling constant. The comparison is made with the often used leading term approximation when the summation with respect to all virtual states is restricted to the ground-state only. It is shown that the results are quite different so the incorporation of all virtual states and especially those of the continuous spectrum is essential. The main result is the existence of peaks of the polaron energy and the effective mass at some values of the potential width and the reproduction of the correct three-dimensional asymptotics both at small and large widths. The numerical results are presented for $GaAs/Al_xGa_{1-x}As$ quantum well structures. The comparison is made with the results by Haj, Peeters and Devreese obtained for rectangular quantum wells.

Possible generalization and preliminary results are also reported for polarons confined within quasi-one-dimensional heterostructures (quantum wires).

Ground-State Energy of a two- or three-dimensional Exciton-Phonon System in a Magnetic Field

B. Gerlach*, I. Himberg* and M. A. Smondyrev†

* *Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany*

† *Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia*

We present upper and lower bounds for the ground-state energy of an exciton-(LO)phonon system in a magnetic field. To derive upper bounds, we perform a series of unitary transformations of Lee-Low- Pines type and subsequently use a variational ansatz. To derive lower bounds, we perform an appropriate decomposition of the total Hamiltonian into tractable parts, the sum of the corresponding eigenvalues being a lower bound to the unknown ground-state energy of interest. The relative deviation of both types of bounds will be shown to be satisfactorily small. We include a comparison with experimental results for GaAs and find good agreement; some unexplained structures can consistently be interpreted.

Low dimensional systems based on the BEDT-TTF = bis(ethylenedithio)tetrathiafulvalene molecule

V. Ivanov, E. Ugolkova and M. Zhuravlev

N. S. Kurnakov Institute of General and Inorganic Chemistry, RAS, Leninskii av. 31, 117907 Moscow, Russia

We review our recent studies of $BEDT-TTF$ based systems (in what follows $ET = C_{10}S_8H_8$) with attention to κ-phase family, manifesting a variety of metallic, insulating and superconducting properties in spite of the existing structural similarity and the same carrier concentration. After discovery of superconducting quasi-$1D$ $\beta - ET_2I_3$ salt at ambient pressure [1] the systematic $\kappa - ET_2X$ experimental studies in recent years [2] have provided an opportunity to obtain unified knowledge on ET-based $2D$ salts.

We have set the goal the manner in which thereof properties are influenced by the internal degrees of freedom in conducting plane, namely cation ET_2^+ pairs with a single hole per dimer, the charge density profile and the central $C = C$ and $C - S$ stretching motions within the ET molecule, two dimers ($2ET_2$) per a unit cell with six neighbouring dimers in ET_2 plane. The low values of carrier hoppings, $t_0 \sim 0.25$ eV (intraET_2) and $t_{1,2,3} \sim 0.1$ eV (interET_2) originate from the small overlap of molecular orbitals and mean that carriers prefer to stay at ET or ET_2 rather than to travel. It leads to enhancement of intraET electron-electron repulsion U_{ET} (> 1 eV).

The story under review is based on the assumption that $\kappa - ET_2X$ properies are governed by the characteristic energy scale of $U_{ET} > t_0 > t_{1,2,3} >$ intramolecular vibrations $> t$ (interplane hopping). The $\kappa - ET_2X$ are firstly modeled as a correlated electron system where ET_2 dimers are considered as entities with energy degenerate ET sites [3]. The electronic structure is obtained in explicit form. The Mott-Hubbard phase transition is calculated with positions of all known $\kappa - ET_2X$ materials near the phase boundary. From knowledge of the derived Fermi surface topology the preferable d-wave pairing is found without going into discussion on the nature of the superconducting mechanism [4]. The interplay between the knodes of order parameter and superconducting quantities is investigated [5] . For spin-

lattice relaxation rate of the isotope ^{13}C nuclei the absence of the Hibel-Slichter peak at $T \sim T_c$ and the nonactivated behaviour at $T \ll T_c$ are concluded. The regulation between superconducting specific heat and spin-lattice relaxation rate is proposed for experimental check to confirm d-wave symmetry of pairing. The study is applicable for an analysis of superconducting specific heat, London penetration depth, NMR, baric and resistance measurements, and magnetic breakdown effects in $\kappa - ET_2X$ compounds and related low dimensional organic materials. The support of the Russian Foundation for Basic Research (Grant No. 98-03-32670a) and Ministry of Science and Technologies of the Russian Federation are acknowledged.

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[5] V. A. Ivanov, E. A. Ugolkova, M. E. Zhuravlev, JETP **86** (1998) 395.

On quantum hydrodynamics of a drop

A. I. Kirillov

Department of Higher Mathematics,
Moscow Institute of Power Engineering
Krasnokazarmennaia 14, 105835 Moscow, Russia
and
Higher College for Mathematical Physics,
Independent University of Moscow
Vavilova str. 42, 117966 Moscow, Russia

The classical model of a drop is specified by the Euler equations

$$\frac{\partial}{\partial t}v_j + \sum_{k=1}^{3} v_k \frac{\partial}{\partial x_k} v_j = -\frac{1}{\varrho}\frac{\partial}{\partial x_j}p + \frac{\partial}{\partial x_j}U \quad (j = 1, 2, 3), \tag{1}$$

where ϱ is the mass density, p is the pressure, and U is the potential of mass forces. Eqs. (1) hold in the domain $V \subset \mathbb{R}^3$, occupied by the drop. The shape of the domain can depend on time. In such case, $V = V(t)$. The Laplace law holds at every point of the boundary $\partial V(t)$ of $V(t)$, i.e.,

$$p = 2\sigma\varkappa,$$

where $\varkappa$ is the mean curvature of $\partial V(t)$ at the point and σ is the surface tension. We consider the Bohr–Sommerfeld and canonical quantum models of the drop.

The Bohr–Sommerfeld model applies to the periodic motions. It is the classical model with an extra condition

$$\int_0^{2\pi/\omega} \int_{V(t)} \widetilde{\varrho}(t, \vec{\xi}\,)\widetilde{v}(t, \vec{\xi}\,)^2 \, d\vec{\xi}\, dt = 2\pi h(n + l), \tag{2}$$

where ω is the frequency, $n = 0, 1, 2, \ldots$ is the main quantum number, $l = 0$ or $l = 1/2$, and the tildes indicate that the Lagrange description is used.

We consider the case where the shape of the drop does not vary, $\widetilde{\varrho} = \text{const}$ in V, $\sigma = \text{const}$ in ∂V, and $\widetilde{\mathbf{v}} = \omega\{-\xi_2, \xi_1, 0\}$. Then Eq. (2) becomes $\omega I_3 = h(n + l)$, where I_3 is the drop moment of inertia w.r.t. the axis $O\xi_3$. We calculate the energies

of spherical and ellipsoidal drops in the case where the potential U in Eqs. (1) is defined by the Coulomb forces. The parameters of ellipsoids are also calculated. We apply these results to the heavy nuclei. This gives an improved Bohr–Weizsäcker formula and the values of nuclear electromagnetic moments. A comparison of these values with the experimental data is presented.

In order to construct the canonical quantum model of the drop, we use the coordinates $q_{j,m}$ that determine the drop shape through the following equation in the spherical coordinates:

$$r(\vartheta,\varphi) = r_0 \left[1 + \sum_{j=0}^{\infty} \sum_{m=-j}^{j} q_{j,m}\, Y^*_{j,m}(\vartheta,\varphi) \right] .$$

We express the drop energy in terms of the coordinates $q_{j,m}$ and velocities $\partial q_{j,m}/\partial t$. If $q_{j,m}$ are small, the energy is a quadratic form in $q_{j,m}$ and $\partial q_{j,m}/\partial t$. Therefore, the canonical quantization is possible of such a model describing the small variations of the drop shape. We review the results obtained in the applications of this model for describing the deformations of heavy nuclei.

A consistent quantum theory of the drop should be based on a canonical formulation of the hydrodynamics. We review such formulations and show that none of them is appropriate for the canonical quantization. This is because the Poisson brackets are not standard in these formulations. Therefore, the geometrical quantization should be used. We discuss the perspectives of such quantization.

We present a variational formulation of the classical drop model. It includes several differential constrains. Therefore, the path-integral quantization should be used.

We consider also a system of n particles and show that some of its properties can be described with the help of the Euler equations. The drop is the cluster in such approach. A more detailed information about the particles of the cluster can be obtained by considering them as the excitations of the liquid. Thus, we show that the quantum drop model can be useful not only for describing the heavy nuclei but also the clusters of particles.

Quantum dot multiexcitons in magnetic field

V. D. Kulakovskii[1], M. Bayer[2], A. Forchel[2]

[1] *Institute of Solid State Physics, RAS, 142432 Chernogolovka, Russia*
[2] *Technische Physik, Universität Würzburg, 97074 Würzburg, Germany*

Optical studies of semiconductor quantum dots (QD) allow us to investigate many-particle atoms consisting of electrons (e) and holes (h) or of multiexcitons. In bulk and in quantum wells (QW) the two excitons in a biexciton are spatially localized by their effective Coulomb interaction alone. Molecules of three or more excitons in semiconductors with simple conduction and valence band structures are not stable because of the strong Pauli repulsion between electrons (holes) with the same spin. In QD's the geometric confining potential localizes excitons in the same spatial region. In addition, it provides a discrete level structure of electron and hole states. The e-h interaction results in a renormalization of the transition energies and of the transition matrix elements of the confined multiexcitons.

In the present talk we discuss the influence of an external magnetic field on multiexciton states in single, free standing InGaAs/GaAs QD's and as well in arrays containing a large number of QD's fabricated by etching of the QW structures. The QD lateral sizes $L_{x,y}$ are choosen comparable with QW exciton Bohr radii a_x. In this case, on one hand, there is a balance between the Coulomb interaction and the QD confining potentials and, on the other hand, the magnetic length becomes comparable both with $L_{x,y}$ and a_x at relatively small magnetic fields. Hence, the magnetic field influences strongly the multiexciton states in the QD.

Multiexciton complexes consisting of two and three excitons have been investigated experimentally in a wide range of magnetic fields. The exciton-exciton interaction in the two exciton complex in the QD is attractive. Magnetic field has been found to decrease its "binding" energy. The studies of the polarized spectra have shown that this decrease is due to the Zeeman splitting of electrons and holes in the QD. The three exciton complex is confined only due to the QD geometric confining potential. The magnetic field reduces strongly the exciton-exciton repulsion in such a complex when the magnetic length becomes smaller than the QD size and leads to the lowering of its ground state energy. In large QDs the magnetic field suppresses the exciton-exciton interaction similar to that in the QW.

Superfluidity and phase diagram of electronic system in coupled quantum wells in high magnetic field

Yu.E.Lozovik

Institute of Spectroscopy, 142092 Troitsk, Moscow region, Russia

Superfluidity of systems of spatially separated electrons and holes and two-layer unbalanced electron systems in high magnetic field are considered. The temperature T_c of the Kosterlitz-Thouless transition Transition temperature to a superfluid state T is obtained as a function of magnetic field H and interlayer separation D. It occurs that Tc decreases as a function of H and D at fixed indirect magnetoexciton density as a result of an increase of the exciton magnetic mass. The highest Kosterlitz-Thouless transition temperature as a function of H increases (at small D) on account of an increase in the maximal magnetoexciton density Nm vs. magnetic field, where the value Nm is determined by a competition between the magnetoexciton energy and the sum of activation energies of incompressible Laughlin liquids of electrons and holes. Virial coefficients of magnetoexciton system is considered and it is shown that as magnetic field grows indirect magnetoexciton system at fixed temperature becomes to be similar to an ideal gas as a result of an increase in the exciton magnetic mass. Magnetoexciton phase existense line Ti corresponding to crossover from dielectric phase to metallic one is obtained. The dependence of maximal Ti (corresponding to maximal magnetoexciton density) is defined by the magnetoexciton binding energy E(H,D) and rises with magnetic field and decreases with interlayer separation rise. Superfluidity and Bose condensation of magnetoexcitons in superlattices are also considered. Josephson-type phenomena and electromagnetic properties of two-layer system are analized. The problem of 2D magnetoexciton localization is considered. The derivation of the magnetoexcitonic relaxation time and diffusion constant is presented. Drag effects in the two-layer e-h system due to Coulomb e-h scattering and to the presence of indirect excitons is analized. Drag of spatially separated electrons and direct excitons in CQW due to polarization interactions are also considered.Possible experimental manifestations of the predicted effects are discussed.

Electron-electron interaction in quantum dots

A. Matulis

Semiconductor Physics Institute,
Goštauto 11, 2600 Vilnius, Lithuania

Quantum dot is a small semiconductor structure, an artificial atom, with totally discrete energy spectrum. The quantum dot parameters, such as quantum dot dimensions, number of electrons in a dot, can be gradually changed by means of the gate potential or additional magnetic field. In a such way the dimensionless electron-electron (ee) interaction constant λ (which is the ratio of characteristic quantum dot dimension and Bohr radius) is a changeable parameter in a rather wide range, with $\lambda \sim 1$ in the case of ultrasmall quantum dots manufactured as small InAs islands in AlGaAs matrices, and $\lambda \geq 3$ for big quantum dots formatted via the gate electrode patterning. That is why the quantum dot as an intermediate system between the bulk sample and an isolated real atom becomes an ideal object for the fundamental studies of many particle systems and ee-interaction. For instance, increasing λ value one may transform the quantum mechanical system of weakly interacting particles into strongly correlated quasiclassical system which exhibits properties analogous to Wigner crystallization.

This talk will concentrate on the general properties of the quantum dot. The energy spectrum and oscillator strengths will be discussed. Their behavior as a consequence of the interplay between the confining potential and Coulomb ee-interaction will be traced in all range of λ values. For those purposes mainly the model of the quantum dot with the parabolic confining potential will be considered, although some properties will be compared with those obtained for other model with hard wall type confining potential. The renormalized perturbation series in λ powers and the hydrodynamic description as main mathematical instruments will be used.

Electromagnetic trapping of cold atoms

V. G. Minogin

Institute of Spectroscopy Russian Academy of Sciences
142092 Troitsk, Moscow region, Russia

Methods of trapping of cold atoms in electromagnetic fields and combined electromagnetic and gravitational fields are reviewed in relation with their promising applications in atomic and optical physics. Structure of dipole electromagnetic forces on neutral atoms in laser fields, inhomogeneous magnetic fields, combined laser-magnetic fields and laser-gravitational fields is considered. Survey of specific dipole electromagnetic forces including dipole gradient force and light pressure force is given, with the main emphasis on their applications in atomic traps. Basic schemes of trapping of cold atoms by dipole gradient force in laser beam traps and evanescent wave atomic waveguides, dipole magnetic force in quadrupole magnetic traps, light pressure force in magneto-optical traps and dipole gradient force and gravitational force in evanescent wave atomic trap are discussed. Basic elements of atomic optics including atomic mirrors and atomic waveguides are described. Specific topics to be discussed are as follows. Atomic dynamics in laser fields (dipole radiation force, forces on atom in laser beam, forces on atom in evanescent laser wave, forces on atom in standing laser wave, kinetic equations). Optical trapping (trapping in laser beams, trapping in evanescent laser waves, trapping in standing laser waves, atomic waveguides). Magnetic trapping (static quadrupole magnetic traps, time-orbiting potential quadrupole magnetic trap, magnetic trap with optical plug). Magneto-optical trapping. Optico-gravitational and magneto-gravitational trapping. Some applications of cold trapped atomic ensembles in atomic and optical physics are briefly discussed.

Manifestation of shell effects in small quantum dots in a magnetic field

R. G. Nazmitdinov

Bogoliubov Laboratory for Theoretical Physics
Joint Institute for Nuclear Research, 141980 Dubna, Russia

The development of semiconductor technology has made possible the confinement of a finite number of electrons in a localized space of a few hundred angstroms [1]. These mesoscopic systems called quantum dots open new avenues in the study of the interplay between quantum and classical behavior at a low-dimensional scale. The smaller the size of the quantum dot, the larger the prevalence of quantum effects upon the static and dynamic properties of the system. Their electronic properties are determined by the interplay of the external confinement and the electron-electron interaction which produces the effective mean field of the "artificial atom" [1, 2].

The quasiparticle concept associated with an effective mean field is well established in many particle physics. For finite Fermi system like nuclei or metallic clusters the bunching of single particle levels known as shells is one consequence of this description, if the mean free path of the particles is comparable with the size of the system. The observational consequence is a remarkable stability as it is found in nuclei and metallic clusters at magic numbers which correspond to closed shells in the effective potential. For small quantum dots the mean free path of the electrons appears to be comparable with the diameter of the dot. Indeed, in recent experiments [3, 4, 5] shell structure effects have been observed clearly for quantum dots. In particular, the energy needed to place the extra electron (addition energy) into a vertical quantum dot at zero magnetic field has characteristic maxima which correspond to the sequence of magic numbers of a two-dimensional harmonic oscillator [4]. In fact, when the confining energy is comparable to or larger than the interaction energy, these atomic-like features have been predicted in a number of publications [6]. While the electron-electron interaction is important for the explanation of certain ground state properties like special values of angular momenta of quantum dots in a magnetic field, for small dot size and small number of electrons the confinement energy becomes prevalent over the Coulomb energy [3].

The role of the electron interaction will be discussed for two-electron quantum

dots [7] and fo small quantum dots with partially filled electronic shells [8]. For small dots, where large gaps between closed shells occur [6], the electron interaction plays then the role of a weak perturbation which can be neglected. We will show within a simple model [9] for such dots that the disappearance and re-appearance of the shell structure under variation of the magnetic field strength leads to a novel feature: the orbital magnetization disappears for particular values of the magnetic field strength, which are associated to particular magic numbers.

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The two-electron artificial molecule

B. Partoens,[1] A. Matulis,[2] and F. M. Peeters[1]

[1] *Universiteit Antwerpen (UIA), Departement Natuurkunde, Universiteitsplein 1, B-2610 Antwerpen, Belgium*

[2] *Semiconductor Physics Institute, Goštauto 11, 2600 Vilnius, Lithuania*

Recently we found first and second order transitions occurring in two vertically coupled *classical* dots as a function of the interatomic distance (d). We investigated numerically the ground-state and eigenmodes of classical artificial molecules consisting of identical atoms containing three up to ten electrons [1].

Now we show that also in the classical artificial molecule with in each dot one electron a second order transition takes place as a function of d. Because this system consists of only two electrons it is possible to solve it exactly quantum mechanically, which gives the possibility to investigate how quantum effects influence the classical transition. We find that in the quantum case this transition is smeared out and shifted to smaller d values.

It is known that in the quantum dot consisting of two electrons spin-singlet $\leftrightarrow$ spin-triplet oscillations occur as a function of the magnetic field strength. We find that these oscillations move to higher magnetic field values with increasing d and that these transitions do no longer occur for sufficiently large d.

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Stability of metalic drops and surface-charged clusters

V. V. Pashkevich[1], H. J. Krappe[1,2]

[1] *Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia*

[2] *Hahn-Meitner Institut, Berlin, Germany*

Potential energy hypersurfaces are traditionally used to discuss the decay modes of charged droplets and metal clusters [1, 2, 3, 4, 5].

The most important points on potential hypersurfaces are the stationary points, where the derivatives with respect to all deformation parameters vanish. If there is a local minimum it corresponds in the liquid-drop model always to the spherical shape. Additional stationary points are saddle-points (of order n, if n second derivatives are negative). It is useful to study the height of saddle points (the fission barrier) and the corresponding shape of the drop as a function of the dimensionless parameter x, the fissility, defined as the ratio of the Coulomb energy for a spherical drop of the same charge and volume divided by twice its surface energy, $x = E^0_{coul}/2E^0_{surf}$. We confirm the fission-barriers hights for surface-charged droplets obtained in earlier work within a very differently defined shape class. In addition we show that the Rayleigh-Taylor instability [6] which occurs for spherical droplets for fissilities $x >$ is already seen for $x = 0.9$ in spheroids with sufficiently large excentricity. We finally present an analytic formula for the electrostatic energy of two touching, surface-charged, conducting droplets.

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Classical artificial atoms and molecules in two dimensions

F. M. Peeters

Departement Natuurkunde, Universiteit Antwerpen (UIA), B-2610 Antwerpen, Belgium

A classical two-dimensional (2D) system consisting of charged particles which are laterally confined by an artificial potential is investigated. This system is the classical analog of the well known quantum dot problem. Related physical systems are: radio-frequency traps for ions and electrons in plasma, charged ions in heavy-ion storage rings and electrons above liquid He which can be trapped in bubbles.

Using Monte Carlo techniques and molecular dynamics simulations the possible ordered structures and phase transitions for such a system is investigated. Simulations were performed on finite systems with up to 3000 particles. We found that the particles group together in rings (or shells). A *Mendeleev-type table* for such classical atoms was obtained. When the size of the atom is sufficiently large, the simple ring structure gradually disappears in the center and features of a 2D Wigner lattice appear. At the edge of the system a 1D Wigner lattice is formed.

The excitation spectrum and corresponding normal modes for these classical atoms are obtained. For atoms with a small number of charged particles the lowest excitation corresponds to an intershell rotation. For large systems the lowest excitation consists of a *vortex/anti-vortex pair*. The system also exhibits a number of excitation frequencies which are *independent* of the number of particles in the system!

The effect of a magnetic field on the excitation spectrum was calculated. We found that the spectrum collapses into two branches with increasing field. The upper branch corresponds to the cyclotron resonance energy, and the lower branch corresponds to the one particle skipping orbits in a dot.

Two of such classical atoms placed parallel to each other at a certain distance d exhibit structural transitions as function of d. First order and second order type of transitions are found. The second order transition is induced by the softening of one of the normal modes.

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Mesoscopic superconductivity: Cooper pairs in a box

F. M. Peeters

Departement Natuurkunde, Universiteit Antwerpen (UIA), B-2610 Antwerpen, Belgium

Phase transitions between different superconducting states and between the superconducting-normal state of mesoscopic disks are studied by solving the two Ginzburg-Landau equations self-consistently. These solutions reveal intriguing magnetic response which are qualitatively different from the two-dimensional approximation but in agreement with recent experiments. Depending on the radius and thickness, first or second order transitions are found for the normal to superconducting state. For a sufficiently large radius of the disk, several transitions in the superconducting phase are obtained which correspond to different angular momentum giant vortex states. The incorportation of the finite thickness in the calculation is crucial in order to obtain agreement with the position and the size of these jumps, and the line shape and magnitude of the magnetization curves.

The experimental magnetization curves exhibit nonlinear behaviour and hysteresis. The nonlinear behavior is explained theoretically by correctly taking into account the de-magnetization effects due to geometrical form factors. In large disks the Bean-Livingston surface barrier is responsible for the hysteresis. While in small disks a volume barrier is responsible. It is shown that although the sample magnetization is diamagnetic (negative), the measured magnetization can be positive at certain fields as observed experimentally, which is a consequence of the de-magnetization effects and the experimental set up.

We have found a smooth transition from a multi-vortex superconducting state to a giant vortex state with increasing both the disk thickness and the magnetic field. A vortex phase diagram is obtained which shows, as function of the magnetic field, a re-entrant behavior between the multi-vortex and the giant vortex state.

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Macroscopic quantum phenomena in trapped Bose-condensed gases

G. Shlyapnikov

Kurchatov Institute of Atomic Energy,
Kurchatov Sq. 46, 123182 Moscow, Russia

The talk concerns macroscopic quantum phenomena in dilute trapped Bose-condensed gases. This subject attracts now a great deal of interest, especially in view of recent successful experiments on Bose-Einstein condensation (BEC) in rubidium, lithium and sodium vapors. These experiments open a unique possibility to investigate dynamic and kinetic properties of a Bose-condensed phase, such as the response of the system to time-dependent variations of the confining field or variations of the interparticle interaction. I will focus attention on this problem and put an emphasis on how the presence of an evolving macroscopic quantum state effects the behavior of the system. I will show that the condensate evolves in a completely different way compared to above-condensate particles and discuss the physics behind this evolution process.

I will emphasize a principal difference between the condensates with repulsive and attractive interparticle interaction. In the latter case I will discuss the existence of a metastable Bose-condensed phase and address the problem of collapse of a Bose-condensed cloud.

Special attention will be given to the problem of damping and the loss of coherence in evolving Bose condensates. I will discuss both the case of a pure condensate and the case of a condensate interacting with the thermal cloud.

Finally, I will discuss the interference effects in evolving condensates and the problem of phase separation in a two-component Bose-condensed gas.

Ultrafast dynamics of excitons in quantum wells

Heinrich Stolz

FB Physik Universität Rostock,
Universitätsplatz 3, D-18051 Rostock, Germany

The dynamics of electronic excitations in semiconductors with reduced dimensionality can be investigated by their interaction with ultrashort laser pulses on time scales of the order of ten femtoseconds. As example, the electric field of light reflected from a 2d system, where propagation effects can be neglected, is proportional to the time-derivative of the polarization and its time-dependence directly reflects the decay of the optically created polarization.

In order to gain the maximum amount of information, the temporal dependence both of the amplidute and the phase of the light field should be measured. The latter quantity is especially valuable, because it gives information on the frequency dynamics and the coherence properties of the light investigated.

Recently, several methods have been developed [1, 2] that allow to characterize both amplitude and phase of ultrafast light signals. All these methods rely on the simultaneous measurement of the spectral and temporal behaviour of the light, which can be considered as a special type of 2d phase retrieval problem [3], allowing the field to be reconstructed by well known phase retrieval techniques. Hereby, the time-resolution is not limited by laser pulse width, but only by the sampling theorem and, most important, the pulse can be reconstructed without any 'a priori' knowledge. In the picosecond domain, the field is spectrally resolved first and the temporal intensity then measured by a streak camera with subpicosecond resolution. This method of 'bandwidth–limited spectroscopy' has single photon sensitivity, but the time–resolution is at present limited to about 1ps. For faster time-scales, the method of 'frequency resolved optical gating' (FROG) was where a higher order correlation (e.g. by second harmonic generation,SHG) of the light pulse, either with itself or with a reference pulse, is spectrally resolved, and from this FROG trace both the test and reference light field can be retrieved.

In this contribution the first application of the FROG method to study the reflected light from GaAs/AlGaAs quantum well samples grown by MBE is presented [4]. The incident laser pulses with 20 to 70 fs duration were tuned spectrally to

cover the exciton resonances, the incident laser power was varied by two oders of magnitude to investigate density dependend effects. The FROG signals obtained showed characteristic structures due to the superposition of the instantaneously reflected field and the polarization decay of the excited states, which occurrs on a time-scale of some hundred femtoseconds at room temperature. At high intensities we observe a faster decay of the excitonic polarization. The excitation energy and fluence dependence of the reflected signal is compared with theoretical calculations.

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Interwell radiative recombination in the presence of random potential fluctuations in GaAs/AlGaAs biased double quantum well

V. B. Timofeev[1], A. V. Larionov[1], A. S. Ioselevich[2], J. Zeman[3], G. Martinez[3], J. Hvam[4], D. Birkedal[4], K. Soerensen[4]

[1] *Institute of Solid State Physics, RAS, 142432 Chernogolovka, Russia*

[2] *Landau Institute of Theoretical Physics, RAS, 142432 Chernogolovka, Russia*

[3] *High Magnetic Field Laboratory, MPI/CNRS, Grenoble, France*

[4] *Microelectronic Centre, Lyngby, Denmark*

A systematic study of the photoluminescence from double quantum well (DQW) in *pin GaAs/AlGaAs* heterostructures under variation of an external electric and magnetic fields, excitation power, at different temperatures has been performed. Interwell luminescence line corresponding to radiative recombination of spatially separated photoexcited $e-h$ pairs at low concentrations (less than $10^9 cm^{-2}$) demonstrates systematic drastic narrowing when the temperature is increased (from 2K to 30K). Presented theoretical model performed in an exponential approximation explains the observed phenomena in terms of lateral thermoactivated tunneling of spatially separated $e-h$ pairs localized on the random potential fluctuations (RPF) in QW's. This model is confirmed by analysis of kinetic of interwell luminescence measured under pulse photoexcitation at different temperatures. The linear scale of an optimal fluctuations has been found ¿from study of the diamagnetic behavior of the interwell luminescence in magnetic field up to 23T.

Under high excitation the lateral localized states, related with RPF, are occupied by photoexcited carriers. When concentration of photoexcited carriers exceeds percolation threshold, depending on temperature, $2D$-gas start to appear in one of quantum wells. Close to the percolation threshold (well defined in coordinates: concentration-temperature), a dramatically redistribution in luminescence spectra were observed. Appearance of $2D$-electron gas in one of QW's is confirmed by direct observations of an optical analog of Shubnikov oscillations of the luminescence intensity under sweeping of magnetic field.

Energy Spectra of Undoped and Modulation Doped Quantum Wires

Volker Türck, Oliver Stier and Dieter Bimberg

Institut für Festkörperphysik, TU-Berlin, Hardenbergstraße 36, 10623 Berlin, Germany

In recent years nanostructures became the most rapidly progressing subject in semiconductor research. Fundamental quantum mechanical effects show up beautifully and have at the same time a large impact on a wide range of device applications. In photonics quantum well lasers are today standard devices but first electrically pumped quantum wire lasers show ultralow threshold currents[1] and quantum dot lasers operating at room temperature have been presented recently[2] showing properties superior to quantum well lasers in many aspects.

Essential for the development of novel devices is a detailed understanding of the electronic properties of nanostructures which can only be obtained by theoretical modelling. The goal of modelling is to use the knowledge and the methods of theoretical physics combined with applied and numerical mathematics to obtain accurate quantitative predictions for the characteristics of a future device.

In this lecture we will — based on our recent research — outline methods which yield useful results for complex realistic situations like pseudomorphic quantum wires (QWRs) in V-grooves. We describe the physical models and the numerical methods used for the computations. Furthermore we discuss the results and compare them to experimental data. We also briefly review how modern super computer architectures influence the selection of the numerical algorithms.

The calculation of energy spectra of a quantum system in the most simple approach requires the solution of the stationary single particle effective mass Schrödinger equation (SEQ) also known as BenDaniel-Duke-Form. The wavefunction $\Psi(\mathbf{r})$ of a charge carrier inside a QWR can be separated as $\Psi(\mathbf{r}) = \psi(\mathbf{y})\phi(\mathbf{x},\mathbf{z})$. In this case $\psi(y)$ describes the free motion of the carrier along the wire axis (i. e. y) and $\phi(x,z)$ gives the quantized part in the two perpendicular directions (x and z). The motion of the carrier along the wire can be described by plane waves. So the main task that remains is the determination of ϕ which is the solution of the twodimensional SEQ $(\frac{p^2}{2m^*} + E_C)\phi = E\phi$ where m^* is the material dependend and thus

spatially varying effective mass, E_C is the confinement potential and E the energy eigenvalue for the solution. One important input parameter for this equation is the confinement potential E_C which is determined by the band gaps and band offsets of the materials forming the QWR and the barrier.

In a next step *strained* QWR structures like in the InGaAs/AlGaAs material system are considered. Here the strain effectively alters the bandgap and thus also the confinement potential. In order to describe these effects properly the strain distribution of the wire structure must be calculated first. Then the new confinement potential can be obtained from the strain tensor and the deformation potentials. Additionally strain introduces piezoelectric charges which also change the confinement potential. When strain effects are taken into account some interesting effects can be expected in larger quantum wires: a symmetry breaking of the ground state[3].

Another interesting task is the modelling of charged structures like type II systems or heavily doped structures. The electrostatic potential induced by the confined carriers effectively changes the confinement potential. These charge effects can be described by classical electrostatics that is the Poisson equation (PEQ). The exact description of charged structures requires the selfconsistent solution of SEQ and PEQ.

All these calculations require the solution of twodimensional boundary value problems of SEQ (and eventually also PEQ). When realistic structures i.e. structures with no idealized or simplified geometry are considered these equations are no longer solveable analytically. Due to their complexity the solution of these problems usually goes beyond the capability of standard "off the rack" programs or libraries. We developed own programs based on finite difference methods. Finite differencing has the advantage of producing relatively sparse systems of linear or nonlinear equations that can be solved very effectively employing methods known as sparse matrix techniques.

We present results that were obtained from the computation of various actual types of QWRs by different methods in the recent years. We also compare the computed values with experimental results obtained in our group. The model systems we have studied are V-groove quantum wires in the type I material systems GaAs/AlGaAs. InGaAs/AlGaAs, and InGaAs/InP as well as wires in the type II material system InAlAs/InP.

Finally we briefly discuss how modern super computer architectures influence the selection of the numerical algorithms used.

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Bose-condensation in a system with broken translation symmetry

V. S. Yarunin

Bogoliubov Laboratory of Theoretical Physics,
Joint Institute for Nuclear Research, 141980 Dubna, Russia

There is no ordinary selection rules for a momentum of atoms in a box without translation symmetry. Therefore the extraordinary terms appear in the Hamiltonian of such Bose-system in the framework of Bogoliubov model. The general formulae for an arbitrary inter-Boson interaction are deduced on this subject. These terms are linear and three-linear in Bose-condensate amplitudes. The approximative form of these terms is used for Bose-condensation of superfluid ^4He in porous glasses. The deminishing of the λ-transition temperature in this case is connected with the special condensate- noncondensate atomic interaction, supplied by the loss of translation symmetry [1]. The scale of this interaction is a measure of the atomic scattering on the porous walls.

In the gaseous phase (alkali metals in magnetic traps) the role of the interatomic interaction is comparatively small. In this case the Bose-condensation of an ideal gas may be considered. The effective "frequency" of Bosons represent the parameters of a trap: a frequency of atomic oscillationa in it and it's radius. The temperature dependence of noncondensate atomic density for such a gas in a parabolic trap is found to be as $\sim T^3$, as it was shown earlier in [2]. No periodic boundary conditions with a plain wave basis may be used in this system.

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Qualitative theory of spectral, scattering and decay management (universal elementary constituents of quantum systems)

V. M. Chabanov, B. N. Zakhariev

Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research, 141980 Dubna, Russia

The possibility to reveal the simplest and universal building "blocks and bricks" in quantum mechanics is considered. Arbitrary quantum reconstructions can be extremely clearly qualitatively explained as combinations of simple constituents by means of the exactly solvable models and instructive "quantum pictures" [1]. For example, transformations of potentials will be demonstrated ("golden rules") which: destroy, create or shift the chosen energy levels or resonances when other ones remain on their previous places; change in the desired way the space localization of the chosen bound and quasi-bound states (decay rates management) etc. The peculiarities of multichannel systems are revealed.

References

[1] B.N.Zakhariev, *Lessons on Quantum Intuition*, JINR, Dubna, 1996; *New ABC of Quantum Mechanics*, UdmStUni, Izhevsk, 1998 (in Russian, please contact the reporter).

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N. Bigelow. Cooling, trapping and Bose-Einstein condensation of ultra-cold atomic vapors.

E.N. Bukina, V.M. Dubovik and B. Saha. Macroscopic description of media constructed by means of quantum engineering.

A. A. Shanenko, A. Yu. Cherny. Spatial particle correlations in Bose liquids.

O. Stier, M. Grundmann and D. Bimberg. Theory of energy levels in strained quantum dots.

A. A. Vasilchenko Electronic structure of quantum dots in strong magnetic field: magic numbers and Wigner cristallization.

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