# Final activity Report of the CFBS-Project, (Confined Fermion and Boson Systems)

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# Chapter 1

# The Project and its Members

With the continuing progress in nanostructure technology the border-lines between the physics of condensed matter, and few-body quantum systems (as we have first encountered them in atomic and nuclear physics) are crossed. Much of the many-body physics that was developed for the understanding of atoms or nuclei, can be applied to describe quantum dots, wires, or clusters. In turn, much fundamental insight has been gained by studying low-dimensional quantum structures as they have become experimentally feasible. The physics of finite quantum systems, i.e. a few fermions or bosons in a trap, continues to keep ready many surprises.

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# Chapter 2

# Activities of the Nordic Project on Confined Fermion and Boson Systems 2002

## 2.1  Activities of the Groups

Here the activities of the participating groups in the year 2002 are reported. The details for the two preceding years can be found in the earlier reports.

### 2.1.1  Yuri Galperin Oslo

**Nanoelectromechanics and single-charge tunneling**
> L.Y. Gorelik, A. Isacsson, Y.M. Galperin, R.I. Shekhter and M. Jonson, Current Applied Physics, **2**, 3-10 (2002).
>
> A brief review of the authors' recent work on the nanoelectromechanics of "heteroconducting" and "heteroelastic" Coulomb blockade systems is given. The cases where single charge tunneling is the dominant conduction mechanism are considered. The nanoelectromechanical effects both in normal and superconducting systems are exemplified by discussing (i) a self-assembled single-electron tunneling device exhibiting a dynamical instability leading to "shuttling" of electrons by a movable Coulomb dot and (ii) shuttling of Cooper pairs by a movable single-Cooper-pair box.

**Quantum wires and point contacts**

> **Magnetic field effects in energy relaxation mediated by Kondo impurities**
> > G. Goeppert, Y.M. Galperin, B.L. Altshuler, H. Grabert, cond-mat/0202353.
> >
> > The energy distribution function of quasiparticles in voltage biased mesoscopic wires in presence of magnetic impurities and applied magnetic field is considered.

For low magnetic field an enhancement of energy relaxation is found whereas for larger magnetic fields the energy relaxation decreases again meeting qualitatively the experimental findings by Anthore et al. (cond-mat/0109297). This gives a strong indication that magnetic impurities are in fact responsible for the enhanced energy relaxation in copper wires.

## Two-dimensional electron gas

### Memory effects in ac hopping conductance in the quantum Hall...
I. L. Drichko, A. M. Diakonov, I. Yu. Smirnov, V. V. Preobrazenskii, A.I. Toropov, Y. M. Galperin, cond-mat/0204101.

Using simultaneous measurements of the attenuation and velocity of surface acoustic waves propagating along $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructures, complex ac conductance of the latters has been determined. In the magnetic fields corresponding to the middles of the Hall plateaus both the ac conductance, $\sigma(\omega)$, and the sheet electron density, $n_s$, in the two-dimensional conducting layer turn out to be dependent on the samples' cooling rate. As a result, the sample "remembers" the cooling conditions. The complex conductance is strongly dependent on an infrared illumination which also changes both $\sigma(\omega)$ and $n_s$. Remarkably, the correlation between $\sigma(\omega)$ and $n_s$ is *universal*, i.e. it is independent of the way to change these quantities. The results are attributed to two-electron defects (so-called $DX^-$ centers) located in the Si doped layer.

## Nanoscopic detectors

### Capacitively coupled hot-electron nanobolometer as far-infrared...
D. V. Anghel and L. Kuzmin, submitted to Appl. Phys. Lett.

We show theoretically that hot-electron nanobolometers consisting of a small piece of normal metal, capacitively coupled to a superconducting antenna through a pair of normal metal-insulator-superconductor (NIS) tunnel junctions may be used as far-infrared photon counters. To make the device most effective at high counting rates, we suggest the use of the bolometer in simplest configuration, when the NIS tunnel junctions are used as both, electron cooler and thermometer. The absorption of the photon in the normal metal produces a pulse in the electron temperature, which is measured by the NIS junctions. The counter may resolve photons up to $0.3 \div 0.4$ mm wavelength and has a typical re-equilibration time constant of about 20 ns.

**Lower dimensional systems**

**Gases in two dimensions: universal thermodynamics and its...**
D. V. Anghel, J. Phys. A: Math. Gen. **35**, 7255 (2002); cond-mat/0105089.

I discuss ideal and interacting quantum gases obeying general fractional exclusion statistics. For systems with constant density of single-particle states, described in the mean field approximation, the entropy depends neither on the microscopic exclusion statistics, nor on the interaction. Such systems are called *thermodynamically equivalent* and I show that the microscopic reason for this equivalence is a one-to-one correspondence between the excited states of these systems. This provides a method, different from the bosonisation technique, to transform between systems of different exclusion statistics. In the last section the macroscopic aspects of this method are discussed.

In Appendix A I calculate the fluctuation of the ground state population of a condensed Bose gas in grandcanonical ensemble and mean field approximation, while in Appendix B I show a situation where although the system exhibits fractional exclusion properties on microscopic energy intervals, a rigorous calculation of the population of single particle states reveals a condensation phenomenon. This also implies a malfunction of the usual and simplified calculation technique of the most probable statistical distributions.

## 2.1.2  Susanne Viefers - Göteborg

**A carbon nanotube based nanorelay**
With Jari Kinaret and Tomas Nord Preprint cond-mat/0208427

We have investigated the operational characteristics of a nanorelay based on a conducting carbon nanotube placed on a terrace in a silicon substrate. The nanorelay is a three terminal device that acts as a switch in the GHz regime. We describe the system with a model based on classical elasticity theory and the orthodox theory of Coulomb blockade, and study its IV-characteristics and switching dynamics. Potential applications include logic devices, memory elements, pulse generators, and current or voltage amplifiers.

**Rotational and vibrational spectra of quantum rings** pierced by an Aharonov-Bohm flux With M. Manninen, M. Koskinen Paper in preparation.

We study, numerically and analytically, the spectra of electrons in (quasi-) one dimensional quantum rings pierced by a magnetic flux. Their properties, with particular focus on rotational and vibrational states, are examined in terms of the Hubbard model, Calogero- Sutherland model, and semiclassical calculations for various kinds of electron-electron interaction. One aim is to support and explore further the finding by Koskinen et al [Phys. Rev. B 65, 205323 (2001)] that in

the 1D limit the exact many-body spectrum can be described by a very simple model Hamiltonian of rigidly rotating and vibrating localized electrons (with a Heisenberg term).

**Many-body spectrum and particle localization** in quantum dots and finite rotating bose condensates With Matti Manninen and others. Paper: M. Manninen, S.Viefers, M. Koskinen and S.M. Reimann, Phys. Rev. B 64, 245322 (2001).

### 2.1.3   G. M. Kavoulakis - Lund

In the last year G. M. Kavoulakis has worked in a number of problems related to the physics of cold atoms in traps.
More precisely in Ref. [1], he has investigated the stability of a rotating Bose-Einstein condensate under weak asymmetric perturbations.
In Ref. [2] in collaboration with Stephanie Reimann and Ben Mottelson it was demonstrated that the entry of vortices in a rotating Bose-Einstein condensate of atoms takes place from its periphery, in agreement with older mean-field calculations.
In Ref. [3] in collaboration with Andy Jackson he studied the dispersion relation of a solitary wave in a quasi-one-dimensional Bose-Einstein condensate of atoms.
References

1. Stability of rotating states in a weakly-interacting Bose-Einstein condensate, G. M. Kavoulakis, Phys. Rev. A 65, 023602 (2002).

2. Comment on Fragmented Condensate Ground State of Trapped Weakly Interacting Bosons in Two Dimensions, G. M. Kavoulakis, B. Mottelson, and S. M. Reimann, Phys. Rev. Lett. 89, 079403 (2002).

3. Lieb mode in a quasi-one-dimensional Bose-Einstein condensate of atoms, A. D. Jackson and G. M. Kavoulakis, Phys. Rev. Lett. 89, 070403 (2002).

### 2.1.4   Viðar Guðmundsson - Reykjavík

Within the scope of the project Viðar Guðmundsson has done research on the magnetization of quantum dots and their far-infrared absorption in the year 2002. The results are available in:

1. Far infrared spectroscopy of tailored quantum wires, quantum dots, and antidot arrays,
   D. Heitmann, V. Gudmundsson, M. Hochgräfe, R. Krahne, and D. Pfannkuche
   *Physica E* **14**, 37 (2002).

2. Characterization of Bernstein modes in quantum dots,
   Manuel Valín-Rodríguez, Antonio Puente, Llorenç Serra, Vidar Gudmundsson,

Andrei Manolescu,
*European Physical Journal B* **28**, 111 (2002), (cond-mat/0205345).

3. The orbital magnetization of single and double quantum dots in a tight binding model,
A. Aldea, V. Moldoveanu, M. Nita, A. Manolescu, V. Gudmundsson, B. Tanatar, (2002), (cond-mat/0207307).

4. Orbital and spin magnetization of a confined electronic system in the transition between a quantum dot and a ring,
Gabriel Vasile, Vidar Gudmundsson, and Andrei Manolescu,
15th International Conference on High Magnetic Fields in Semiconductor Physics, (cond-mat/0207361).

### 2.1.5 Stephanie M. Reimann - Lund

1. **Spontaneous magnetism of quantum dot lattices**
*M. Koskinen, S.M. Reimann and M. Manninen*
*(Submitted to PRL)*
The magnetism of square lattices of quantum dots with up to 12 electrons per dot is studied using the spin-density functional formalism. Surprisingly, the dot lattices show a rich and very systematic magnetic behaviour. At small values of the lattice constant all lattices are non-magnetic metals. When the lattice constant is increased, however, the shell structure of the single dots governs the magnetism of the lattice. While at closed shells, the lattices are non-magnetic insulators, at the beginning and at the end of a shell they become ferromagnetic and stay metallic up to large values of the lattice constant. Antiferromagnetism was observed only at mid-shell in the insulating phase.

2. **Vertically coupled electron-hole quantum dots**
*K. Kärkkäinen, M. Koskinen, M. Manninen and S.M. Reimann*
*(Manuscript in preparation)*
We studied a vertical double quantum dot system, where one of the dots is occupied with electrons and the other with holes. Depending on the carrier density and the interdot distance, different phases occur. When the system is dominated by shell structure, orbital degeneracies can be removed either by Hundt's rule, or by Jahn-Teller deformation. Both mechanisms can lead to a maximum of the addition energy at mid-shell. At low densities and large interdot distances, bound electron-hole pairs are formed.

3. **Comment on "Fragmented Condensate Ground State of Trapped Weakly Interacting Bosons in Two Dimensions"**
*G. M. Kavoulakis, S. M. Reimann and B. Mottelson*
A Comment on the Letter by Xia-Ji Liu et al., Phys. Rev. Lett. 87, 030404 (2001)

4. **Electronic Structure of Artificial Atoms**

*S. M. Reimann and M. Manninen*

The properties of quasi-two-dimensional semiconductor quantum dots are reviewed. Experimental techniques for measuring the electronic shell structure and the effect of magnetic fields are briefly described. The electronic structure is analyzed in terms of simple single-particle models, density functional theory, and "exact" diagonalization methods. The spontaneous magnetization due to Hund's rule, spin-density wave states, and electron localization are addressed. As a function of the magnetic field, the electronic structure goes through several phases with qualitatively different properties. The formation of the so-called maximum density droplet and its edge reconstruction is discussed, commenting also on the regime of strong magnetic fields in finite dots. In addition, quasi-one-dimensional rings, deformed dots, and dot molecules are considered.

# Chapter 3

# Financial Statement for the year 2002

In the year 2002 we have not held a general meeting of all the project members, but have instead focused on the mobility of individual members and students between the participating groups. As by September 26 2002, we still have left DKK 67371,- of the initial amount awarded to the project. There are presently some activities still going on that will lower this number somewhat down to DKK 30000 - 40000,-. During all the three years the project members have been quite successful in attracting outside funding into events partially financed by the project money. We have thus not had to cancel or change our plans due to lack of funding. At the same time the NORDITA funding of the (CFBS) Nordic Project has been essential in establishing a basis for our cooperation. Then NORDITA facilities in Copenhagen have also been very important to the project in every respect.

# Chapter 4

# Summary

The Nordic Project on Confined Fermion and Boson Systems (CFBS) has been quite successful in bringing together researchers in the Nordic countries working on these systems. This is not a very large group of researchers, but thanks to the project these researchers are now all aware of each other and have had a good opportunity to discuss common problems, to start common projects, and exchange students. From the beginning it was a policy of the members of the project to invite theoretical and experimental physicists outside the Nordic area to participate in the meeting of the Nordic Project. This has lead to a better connection of the project members to recent developments in countries close to the Nordic Region, especially in Germany.

As far as anything can be said about our understanding of the physics of Confined Fermion and Boson Systems it can only be said that we have profitted from communication with each other, and as the field is enjoying very much of a growth in the last years this effort will be continued in one or other way in the Nordic Region.