NATIONAL RESEARCH UNIVERSITY HIGHER SCHOOL OF ECONOMICS

As a manuscript

Murod S. Bahovadinov

Disorder effects in one dimensional quantum systems

PhD Thesis Summary

for the purpose of obtaining academic degree
Doctor of Philosophy in Physics

Moscow, 2024

This PhD Thesis was prepared at the National Research University Higher School of Economics and at Russian Quantum Center.

Academic Supervisors:

Georgy V. Shlyapnikov, Doctor of Science, Professor, Head of the Many-body theory Laboratory and Scientific Director at the Russian Quantum Center

DISSERTATION TOPIC

Theoretical and experimental study of coherent properties of macroscopic systems is one of the main goals of contemporary condensed matter physics. Meanwhile disorder in such systems always is present in the form of defects and impurities with a wide range of concentrations. Therefore, any relevant theoretical study naturally has to include disorder into its framework. Such a study was first performed by P. W. Anderson [1] who has shown that all or part of particle states undergo localization transition at (finite) disorder. Wavefunctions of constituent quantum particles get localized in real space, which becomes dramatic in lower dimensions, $d < 3$. In the localized phase the transport of charge, spin or heat is suppressed. Realization of this state of matter by the groups of A. Aspect and M. Inguscio [2, 3] in dilute quasi-one-dimensional systems of cold bosonic atoms has refreshed research activities in the domain of disordered systems[4, 5]. Anderson localization is the phenomenon of single-particle physics. The question of whether and how interparticle interactions influence localization remained opened for a long of time. In their seminal work Basko, Aleiner and Altshuler [6] have shown that the isolated disordered quantum systems in the presence of interparticle interactions may exhibit metal-insulator transition at finite energy densities - the phenomenon named as many-body localization (MBL). In this work the authors considered many-body Fock space constructed out of localized single-particle states and asked the question of whether matrix elements of the interparticle interaction are sufficient to cause delocalization within the considered Hilbert space. It was shown that this is indeed the case if one considers finite energy densities. Several years later, the first numerical evidence on support of the perturbative study was demonstrated by A. Pal and D. Huse [7], which made the domain of MBL one of the active research frontiers of the modern condensed matter physics [8, 9].

The topics covered in this Thesis are mainly formulated during the PhD study of the author. All considered problems are quasi-one-dimensional, where effects of quantum fluctuations are the strongest. An interplay of disorder with interparticle interactions in such systems is an old problem [10, 11, 12, 13]. However, in this Thesis we address localization-delocalization transitions in a family of non-traditional models.

Aims and objectives

1. Possibility of new quantum phases and transitions in strongly disordered quantum systems with imposed constraints. Obtaining phase diagram of the considered models using the exact diagonalization technique. The study of two-component disorder in the case of the Fermi-Hubbard model with infinite on-site repulsion.

2. Low-temperature phase diagram of the disordered model with pair hoppings in one dimension using the Density-Matrix Renormalization group technique. Possible mechanisms of the Berezinskii-Kosterlitz-Thouless transition which occurs at a finite disorder strength for large pair hopping amplitudes.

3. Effects of a single impurity in the Tomonaga-Luttinger Liquid with coupled spin and charge channels using bosonization method. Obtaining Kane-Fisher phase diagram when such a coupling is caused by spin-orbit interactions.

KEY RESULTS

Key aspects to be defended

1. Many-body localization transition is studied for two 1D quantum systems with imposed constraints on their local degrees of freedom. For the first time we present a family of models which exhibit MBL, although no explicit interaction terms are present in the corresponding Hamiltonians. The first model is the one of hard-core bosons with the nearest and next-nearest neighbor (NNN) hoppings. On the basis of finite-size numerical calculations it is demonstrated that at finite NNN hopping the system is effectively interacting and one observes the MBL transition, although no explicit interaction term is present in the Hamiltonian. For vanishing NNN hoppings, the system undergoes Anderson localization at any finite disoder. The second model is the 1D Fermi-Hubbard model in the regime of infinite on-site repulsion. For this model it is numerically shown that any finite potential disorder drives the system to the Anderson insulator. On the contrary, effects of random magnetic field are two-fold: on the one hand, at small but finite random fields the system remains chaotic, on the other hand, large random fields cause the MBL transition. Interplay between two types of disorder is studied and the finite-size phase diagram of the model is obtained.

2. Effects of disorder are studied in a 1D system of fermions with single particle and pair hoppings. Using large-scale numerical calculations the phase diagram of the model in the clean limit is obtained. It is demonstrated that in the regime of large pair hoppings the disorder term is irrelevant in the renormalization group sense and one has electronic fluid with algebraically decaying correlations at finite but small disorder. At large disorder the system enters the localization phase via the Berezinskii-Kosterlitz-Thouless mechanism. The phase diagram of the disordered model is obtained on the basis of decay of real space correlators and the disorder-averaged liquid parameter K. The found transition occurs via the Giamarchi-Schulz scenario.

3. Effects of a single impurity on Luttinger liquid with coupled spin and charge degrees of freedom are studied using bosonization and perturbative renormalization techniques. The spin-charge coupling is caused by finite spin-orbit interactions. The Kane-Fisher phase diagram obtained for the decoupled modes is extended to the case of spin-charge coupling. The obtained results refute previous predictions on the observation of spin-filtering effect in the considered model. The results show that the effects of spin-orbit interaction in the system with a single impurity are the strongest for strongly interacting systems, whereas for a weakly interacting electronic gas the effects are weak. Expressions for the Luttinger liquid parameters and excitation velocites of newly emerging modes are also obtained.

Author's personal contribution to the aspects to be defended

Significant part of Chapter 1 and Chapter 2 of the presented work, including the selection of numerical methods, realization of the numerical algorithms, selection of necessary quantities for calculations and data analysis was done by the author. Analytical calculations and analysis of the obtained results of Chapter 3 are also performed by the author. This work was performed in the Many-body theory Laboratory of Russian Quantum Center and in the Physics Department of the National Research University Higher School of Economics in the period from 2019 to 2023.

PUBLICATIONS AND APPROBATION OF RESEARCH

The main author or equally contributed authors are printed in bold in the following list of publications.

First-tier publications

1. **Bahovadinov, M. S.**, and Matveenko, S. I., Effects of a single impurity in a Luttinger liquid with spin–orbit coupling. *Journal of Physics: Condensed Matter*, **34**, 315601 (2022).

2. **Bahovadinov, M. S.**, Kurlov, D. V., Matveenko, S. I., Altshuler, B. L., and Shlyapnikov, G. V., Many-body localization transition in a frustrated XY chain. *Phys. Rev. B*, **106**, 075107 (2022).

3. **Bahovadinov M. S.**, Sharipov R. O., Altshuler B. L., and Shlyapnikov G. V., Tomonaga-Luttinger liquid-Bose glass phase transition in a system of 1D disordered fermions with pair hoppings. *Phys. Rev. B*, **109**, 014203 (2024).
4. **Kurlov, D. V.**, Bahovadinov, M. S., Matveenko, S. I., Fedorov, A. K., Gritsev, V., Altshuler, B. L., and Shlyapnikov, G. V., Disordered impenetrable two-component fermions in one dimension. *Phys. Rev. B*, **107**, 184202 (2023).
5. **Bahovadinov, M. S., Buijsman, W.**, Fedorov, A. K., Gritsev, V., and Kurlov, D. V., Many-body localization of Z_3 Fock parafermions. *Phys. Rev. B*, **106**, 224205 (2022).
6. **Matveenko, S. I.**, Bahovadinov, M. S., Baranov, M. A., and Shlyapnikov, G. V., Rotons and their damping in elongated dipolar Bose-Einstein condensates. *Phys. Rev. A*, **106**, 013319 (2022).
7. **Bakker, L. R.**, Bahovadinov, M. S., Kurlov, D. V., Gritsev, V., Fedorov, A. K., and Krimer, D. O., Driven-dissipative time crystalline phases in a two-mode bosonic system with Kerr nonlinearity. *Phys. Rev. Lett.*, **129**, 250401 (2022).

Second-tier publications

1. **Bahovadinov, M. S.**, Kurlov, D. V., Altshuler, B. L., and Shlyapnikov, G. V., Many-body localization of 1D disordered impenetrable two-component fermions. *The European Physical Journal D*, **76**, 116 (2022).

Reports at conferences and seminars

The results of this work were reported in the form of posters and oral presentations at the following conferences and workshops: Third Annual workshop on quantum computations (Sochi, February, 2022), VI International conference on Quantum Technologies (Moscow, July, 2021) and at the VII International conference on Quantum Technologies (Moscow, July, 2023).

CONTENTS

This Thesis contains an introduction, three main chapters and a conclusion. The total length of dissertation is 80 pages with 23 figures. The reference list contains 182 items.

- The first chapter of the Thesis is dedicated to two interesting models which exhibit many-body localization (MBL) transition although no interaction terms are present in the corresponding Hamiltonians. Instead, they obey imposed constraints on their local degrees of freedom. The first set of models are spin $S = 1/2$ models considered in a ladder geometry, whereas the second model is the Fermi-Hubbard model in the limit of infinite on-site repulsion. By means of large-scale exact diagonalization calculations we show that both models exhibit MBL transition at finite disorder strength.

- In the second chapter we consider a quasi-1D fermionic disordered model at low temperatures. On top of the disorder term, which is present in every lattice site, the Hamiltonian of the system consists of single particle and pair hopping terms. By means of large-scale numerical Density Matrix Renormalization Group method we first show that the zero-temperature physics of the clean system is well described within the framework of the Tomonaga-Luttinger liquid (TLL) theory. Then we study the role of constituent Hamiltonian terms and show that the pair hopping term can guarantee the survival of the Luttinger liquid phase at finite disorder, if the hopping amplitude is sufficiently large.

- The last chapter is dedicated to the study of a single impurity in a multichannel Luttinger liquid at low temperatures. The TLL is composed of carriers $\uparrow / \downarrow$ and consequently has two channels: spin and charge. In one dimension these channels are decoupled and carry the corresponding carriers separately. In the presence of spin-orbit interaction the two channels are coupled. In this chapter we study effects of a single impurity in such electronic liquid using bosonization and perturbative renormalization group techniques.

References

1. Anderson, P. W. Absence of Diffusion in Certain Random Lattices / P. W. Anderson // Phys. Rev. — 1958. — Mar. — Vol. 109. — P. 1492–1505.

2. Direct observation of Anderson localization of matter waves in a controlled disorder / Juliette Billy, Vincent Josse, Zhanchun Zuo [et al.] // Nature. — 2008. — Jun. — Vol. 453, no. 7197. — P. 891–894.

3. Anderson localization of a non-interacting Bose–Einstein condensate / Roati Giacomo, D'Errico Chiara, Fallani Leonardo [et al.] // Nature. — 2008. — Jun. — Vol. 453, no. 7197. — P. 895–898.

4. Evers, F. Anderson transitions / Ferdinand Evers, Alexander D. Mirlin // Rev. Mod. Phys. — 2008. — Oct. — Vol. 80. — P. 1355–1417.

5. Segev, M. Anderson localization of light / Mordechai Segev, Yaron Silberberg, Demetrios N. Christodoulides // Nature Photonics. — 2013. — Feb. — Vol. 7, no. 3. — P. 197–204.

6. Basko, D. M. Metal–insulator transition in a weakly interacting many-electron system with localized single-particle states / D M Basko, I L Aleiner, B L Altshuler // Ann. Phys. (N. Y.). — 2006. — May. — Vol. 321, no. 5. — P. 1126–1205.

7. Pal, A. Many-body localization phase transition / Arijeet Pal, David A Huse // Phys. Rev. B Condens. Matter Mater. Phys. — 2010. — Nov. — Vol. 82, no. 17.

8. Luitz, D. J. The ergodic side of the many-body localization transition / David J Luitz, Yevgeny Bar Lev // Ann. Phys. — 2017. — Jul. — Vol. 529, no. 7. — P. 1600350.

9. Abanin, D. A. Recent progress in many-body localization / Dmitry A Abanin, Zlatko Papić // Ann. Phys. — 2017. — Jul. — Vol. 529, no. 7. — P. 1700169.

10. Giamarchi, T. Quantum physics in one dimension / Thierry Giamarchi. — [S. l.] : Clarendon press, 2003. — Vol. 121.

11. Apel, W. Localisation and interaction in one dimension / W Apel, T M Rice // J. Phys. — 1983. — Apr. — Vol. 16, no. 10. — P. L271–L273.

12. Kane, C. Transport in a one-channel Luttinger liquid / CL Kane, Matthew PA Fisher // Physical review letters. — 1992. — Vol. 68, no. 8. — P. 1220.

13. Kane, C. Transmission through barriers and resonant tunneling in an interacting one-dimensional electron gas / CL Kane, Matthew PA Fisher // Physical Review B. — 1992. — Vol. 46, no. 23. — P. 15233.