Report on the Summer School Quantum Theory From Small To Large Scales at Les Houches, August 2 to 27, 2010

Manfred Salmhofer
Institut für Theoretische Physik, Universität Heidelberg
Philosophenweg 19, 69120 Heidelberg, Germany
M.Salmhofer@thphys.uni-heidelberg.de

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1 Summary

Fundamental quantum phenomena are at the forefront of physics and mathematics research, as well as at the heart of much of modern technology, both on the hardware and the software side. New materials, such as cuprates, pnictides, and graphene, present challenges, as well as promises for future applications. Algorithms based on quantum principles have, on the one hand, made hard problems theoretically solvable and may, on the other hand, put cryptography on a new basis. Reliable knowledge about quantum theory is therefore of central importance in science and technology.

Quantum effects appear on all scales, from microscopic to mesoscopic and macroscopic. In the latter, external random influences and dissipation are often present, such as impurities in samples, radiation loss etc, and may lead to decoherence. The understanding of such phenomena has been advanced by the study of model systems and by the derivation and analysis of emergent dynamics for large systems and long times. In this field, research in mathematical physics has regularly contributed results that were recognized as essential in the physics community. A precise understanding of the behaviour of natural model systems is valuable independently of their quantitative realization, which often comes later and sometimes in unexpected ways (an example is the Lieb-Liniger treatment of the one-dimensional Bose gas).

The summer school *Quantum Theory From Small To Large Scales* at Les Houches, August 2 to 27, 2010 focused on recent progress in this area and brought together leading experts with young scientists. 52 students from 16 countries attended the school (see Appendix A.1). 17 lecturers (see Appendix A.2) gave long and short series of 90-minute presentations. The lectures at this school provided both a perspective of present-day mathematical physics for quantum systems, as well as a number of very interesting subjects in physics that may stimulate further mathematical physics research. There were expositions both of timely but already well-developed mathematical techniques and of new physical questions that will require new methods, or at the very least a nontrivial extension of current ones. In addition, specific topics complementing the lectures were presented in seminars. The students had two evening poster-type sessions to present their own interests and research.

The book containing the lecture notes, traditional for Les Houches schools, is in preparation.

The school was funded by DFG (FOR718 and FOR723), SETE S.A., Annales Henri Poincaré, ESF Intelbiomat, Daniel Iagolnitzer Foundation, the Center for Theoretical Studies at ETH Zürich, the Institut für Theoretische Physik at Universität Heidelberg, an ERC startup grant at Rome University, and Université Joseph Fourier through Ecole de Physique des Houches itself.

The school was a success and will have a lasting impact on the field.

2 Description of the Scientific Content

2.1 Lectures

The lectures at the school were series of 90-minute presentations. The long lectures consisted of 5 such sessions, the shorter ones consisted of 2 or 3 such 90 minutes' sessions.

2.1.1 Long lecture series

Thomas Spencer (IAS, Princeton) gave a series of five lectures on *Disordered Quantum Systems and Nonlinear Sigma Models*, in which he explained the supersymmetric hyperbolic sigma models of Efetov and Zirnbauer, as well as the role of Ward identities in the proof of a metal-insulator transition.

Joel Feldman (UBC, Vancouver) gave a series of five lectures on *Quantum Many-Body Systems*. The focus of his lectures was the coherent-state functional integral. He explained the physical motivation and the mathematically rigorous treatment of such integrals using the renormalization group.

Robert Seiringer (McGill University, Montreal) gave a series of five lectures on *Cold Quantum Gases and Bose-Einstein Condensation*. In these lectures, he gave an overview of the many results on the ground state that have been achieved during the last decade, as well as a view of current directions.

Laszlo Erdös (Universität München) gave a series of five lectures on *Quantum Dynamics*. He explained recent results on the emergence of Boltzmann equations and quantum diffusion in the long-time quantum time evolution of the Anderson model ande related models, and also discussed rigorous results about the dynamics of Bose-Einstein condensates.

Claude-Alain Pillet (Université de Toulon) gave a series of five lectures on *Open Systems*. Both for classical and quantum models consisting of a small system coupled to reservoirs, he discussed nonequilibrium states, entropy production Landauer-Büttiker and Green-Kubo formulas.

Matthew Hastings (Microsoft Station Q, Santa Barbara) gave a series of five lectures on *Locality in Quantum Systems*. Starting with Kitaev's toric code example for topological order, he explained the significance of locality of interactions for the proofs of clustering of expectation values. He derived Lieb-Robinson bounds and used them for the proof of clustering. A higher-dimensional version of the Lieb-Schulz-Mattis theorem and stability of topological phases were further topics.

Achim Rosch (Universität Köln) gave a series of five lectures on *Quantum Criticality*. Starting with the quantum Ising model in a transverse field, he developed the main ideas of Hertz-Millis theory and discussed modern aspects of quantum criticality.

Shorter lecture series

Israel Michael Sigal (University of Toronto) gave a lecture on *Renormalization Group and Non-relativistic Quantum Electrodynamics* and one on *Statics and Dynamics of Magnetic Vortices*. These lectures were overview talks. The first lecture was an introduction to Bach's lectures.

Volker Bach (Universität Mainz) gave three lectures on *Non-relativistic Quantum Electrodynamics and Feshbach-Schur Maps*. He developed in detail the renormalization group approach to the theory of the ground state and the resonances of small systems coupled to the electromagnetic radiation field, based on the Schur-Feschbach isospectral map.

Horng-Tzer Yau (Harvard University) gave two lectures on *Universality of Random Matrices and Dyson Brownian Motion*. After a historical introduction he explained the main ideas in the proof of bulk universality, in particular the microscopic version of Wigner's semicircle law and the proof of the sine kernel theorem using its combination with Dyson's Brownian motion.

Gian Michele Graf (ETH Zürich) gave three lectures on *Transport in Quantum Devices*. After an introductory discussion of quantum pumps, he compared scattering and topological approaches to quantum pumps and proved the Büttiker-Pretre-Thomas formula. In a second part, he discussed quantum shot noise and the counting statistics of Levitov and Lesovik, and showed how a long-standing controversy about tunnel junctions could be resolved using a careful mathematical physics analysis of the Schwinger terms.

Michael Wolf (Niels-Bohr-Institute, Copenhagen) gave two lectures on *Bell Inequalities*. After an introduction on Bell and CHSH inequalities and the geometrical structures associated to local hidden variable models, he discussed the impossibility of certain devices when Bell inequalities are violated. Using a theorem of Grothendieck he derived inequalities relevant for communication complexity.

Schoucheng Zhang (Stanford University) gave two lectures on *Topological Insulators and Superconductors*. After an introduction about topological phases, their theoretical prediction for specific semiconductor systems, and their subsequent experimental realization, he explained the role of Majorana fermions in the details of the mathematical modelling.

Alessandro Giuliani (Roma III) gave two lectures on *The Ground State Construction of the Two-dimensional Hubbard Model on the Honeycomb Lattice*. In a rewriting of the model as a Grassmann integral, he explained the role of the renormalization group in the proofs.

Wojciech de Roeck (Universität Heidelberg) gave two lectures on *Quantum Diffusion*, in which he explained very recent results on diffusion in quantum systems, which hold up to arbitrarily long times.

2.2 Seminars

There were a number of one-hour seminars that complemented the lectures.

John Imbrie gave two seminars complementing Spencer's lectures, where he explained the use of the supersymmetric method in the analysis of the self-avoiding walk and of branching polymer models.

Alessandro Pizzo gave two seminars on *Compton scattering, atomic ground state and Cerenkov radiation in non-relativistic QED*. These seminars complemented and extended the lectures of Sigal and Bach.

Antti Knowles gave a seminar on *Random Band Matrices*. He used an expansion approach that was similar to the approach taken for quantum dynamics in Erdös's lectures to prove localization/delocalization results for the eigenvectors of a class of band matrices.

The long-time director of the Ecole de Physique des Houches, *Jean Zinn-Justin*, gave a special lecture on the Higgs phenomenon and its theoretical history.

The senior organizer of the school, *Jürg Fröhlich*, gave a seminar on perspectives of mathematical physics, in which he summarized achievements and interesting open problems in the field.

2.3 Public Lecture

On Thursday, August 19, a public lecture took place in the Les Houches town hall. *Philippe Blanchard* gave a lecture with the title *Cent dix ans de physique quantique: de la préhistoire à la décohérence*.

2.4 Contributions from the students

Besides the usual get-together session where all students at the school briefly introduced themselves and their scientific interests, there were two evening sessions where participants could present their work in poster-like format, that is, they could put up a paper poster, explain their work in front of their laptop, or use the blackboard. These sessions took place in the office space provided for the participants. They were very well-attended and well-received, and stimulated further discussions among students with similar interests.

3 Organizers' Assessment of the results

The lectures at this school provided both a perspective of present-day mathematical physics for quantum systems, as well as a number of very interesting subjects in physics that may stimulate further mathematical physics research. There were both expositions of timely but already well-developed mathematical techniques and of new problems that require new methods, or at the very least a nontrivial extension of current ones.

Judging from the feedback by the students, the school went very well. The lectures and seminars were interesting for them, and to a large extent on the level where people could follow. The lecturers also made a point of being available for questions of all kinds. In general, the atmosphere was one of friendly and open exchange, as it should be.

The students had a lot of scientific exchange among themselves, during the breaks between the lectures and they also used the opportunities for common recreational activities, both in the Les Houches center and in the mountains.

The environment and the infrastructure of the Ecole des Houches, as well as the professional and very approachable administrative staff contributed a lot to the success of the school.

The school will have a significant impact on the further development of this field: it has provided the students with a broad overview of the main recent results and interesting themes of mathematical quantum theory, as well as with an introduction to techniques for further research. Schools providing such a broad spectrum do not take place often in mathematical physics. The formative character of this school and the *vue d'ensemble* it provided to its attendants, who range from students on the beginning master's degree level and PhD candidates to accomplished researchers on a postdoctoral level, is therefore bound to make a large impact on the field. We expect a significant part of our students to continue their careers in mathematical physics and make important contributions.

Last but not least, the books containing the lecture notes of Les Houches summer schools have over time become most valuable resources for many more students and researchers than were present at the schools themselves. This will be the same for this school. The book of lecture notes will be published by Oxford University Press. Several of the lecturers have already submitted very detailed and pedagogical notes for publication in this volume. Clearly, this book will be of interest for a very wide scientific readership.

We should like to take this opportunity to thank the sponsoring organizations for their generous support that made this school possible.

Heidelberg, October 27, 2010 Manfred Salmhofer

A Participants

A.1 Students

AJANKI Oskari (University of Helsinki, Finland)

ANSARI Mohammad (University of Waterloo, Canada)

BACHMANN Sven (University of California, Davis, USA)

BACSI Adam (University of Budapest , Hungary)

BAND Ram (Weizmann Institute, Rehovot, Israel)

BEZVERSHENKO Iuliia (Bogolyubov Institute, Kyiv, Ukraine)

BIERI Samuel (ETH Zurich, Switzerland)

BLOIS Cindy (University of British Columbia, Vancouver, Canada)

CENATIEMPO Serena (University of Rome, Italy)

DE CAUSMAECKER Karen (Ghent University, Belgium)

de MELO Fernando (University of Leuven, Heverlee, Belgium)

DYBALSKI Wojciech (University of Munich, Germany)

EGLI Daniel (ETH Zurich, Switzerland)

FAUSER Michael (University of Munich, Germany)

GAMAYUN Oleksandr (Bogolyubov Institute, Kiev, Ukraine)

GEIGER Tobias (Physikalisches Institut, Freiburg, Germany)

GREENBLATT Rafael (Rutgers University, Piscataway, USA)

HANSON Jack (Princeton University, USA)

HASLER David (University of Munich, Germany)

HUTCHINSON Joanna (University of Bristol, UK)

IMBRIE John (University of Virginia, Charlottesville, USA)

JÄKEL Christian (Cardiff University, UK)

JÖRG David (University of Heidelberg, Germany)

KNORR Hans Konrad (Johannes Gutenberg University, Mainz, Germany)

KNOWLES Antti (Harvard University, Cambrigde, USA)

KRÖNKE Sven (University of Dresden, Germany)

LAJKO Miklos (Research Institute for Solid State Physics and Optics, Budapest, Hungary)

LEIN Max (University of Munich, Germany)

LEMM Marius (University of Munich, Germany)

LIGABO Marilena (University of Bari, Italy)

LIPOVSKY Jiri (Nuclear Physics Institute, Rez, Czech Republic)

LOHMANN Martin (ETH Zurich, Switzerland)

LU Long (University of Heidelberg, Germany)

LÜHRMANN Jonas (University of Munich, Germany)

NAPIORKOWSKI Marcin (University of Warsaw, Poland)

OGATA Yoshiko (University of Tokyo, Japan)

PHAN THANH Nam (Universtiy of Copenhagen, Denmark)

PORTA Marcello (University of Rome, Italy)

SCHERER Daniel (Friedrich Schiller University, Jena, Germany)

SCHNELLI Kevin (ETH Zurich, Switzerland)

SERI Marcello (Friedrich Alexander University, Erlangen, Germany)

SIMONELLA Sergio (University of Rome, Italy)

SLOBODENIUK Artur (Bogolyubov Institute, Kyiv, Ukraine)

SNIZHKO Kyrylo (University of Kyiv, Ukraine)

TAJ David (University of Fribourg, Switzerland)

TRENDELKAMP-SCHROER Benjamin (University of Dresden, Germany)

VERSHYNINA Anna (University of California, Davis, USA)

VIGNES-TOURNERET Fabien (Institut Camille Jordan, Villeurbanne, France)

WALTER Michael (University of Göttingen, Germany)

WANG Zhituo (Laboratoire de Physique Theorique d'Orsay, France)

WILHELM Lukas (Weierstrass Institute, Berlin, Germany)

ZHOU Gang (ETH Zurich, Switzerland)

A.2 Lecturers

BACH Volker Johannes (Gutenberg-University, Mainz, Germany)

BLANCHARD Philippe (University of Bielefeld, Germany)

DE ROECK Wojciech (University of Heidelberg, Germany)

ERDÖS Laszlo (University of Munich, Germany)

FELDMAN Joel (University of British Columbia, Vancouver, Canada)

GIULIANI Alessandro (University of Rome, Italy)

GRAF Gian-Michele (ETH Zurich, Switzerland)

HASTINGS Matthew (Microsoft Station Q and University of California, Santa Barbara, USA)

PILLET Claude-Alain (Universit du Sud Toulon-Var, La Garde, France)

PIZZO Alessandro (University of California, Davis, USA)

ROSCH Achim (University of Cologne, Germany)

SEIRINGER Robert (Princeton University, USA)

SIGAL Israel Michael (University of Toronto, Canada)

SPENCER Thomas (Princeton University, USA)

WOLF Michael Marc (Niels Bohr Institute, Copenhagen, DK)

YAU Horng-Tzer (Harvard University, Cambridge, USA)

ZHANG Shoucheng (Stanford University, USA)

A.3 Organizers

FRÖHLICH Jürg (ETH Zurich, Switzerland)

SALMHOFER Manfred (University of Heidelberg, Germany)

MASTROPIETRO Vieri (University of Rome II, Italy)

DE ROECK Wojciech (University of Heidelberg, Germany)

For counting purposes, please note that W. De Roeck is both an organizer and a lecturer.

B Sponsors

DFG: Forschergruppe FOR 718 *Analysis and Stochastics in Complex Physical Systems*

SETE S.A., Switzerland

Annales Henri Poincaré

DFG: Forschergruppe FOR 723 *Functional Renormalization Group for Correlated Fermion Systems*

ESF Intelbiomat

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ETH Zürich: Center for Theoretical Studies

Universität Heidelberg: Institut für Theoretische Physik

Université Joseph Fourier, Grenoble: Ecole de Physique des Houches

C Program of the Meeting

Aug		9:00 – 10:30	11:00 – 12:30		16:00-17:00	17:30-19:00	21:00-23:00
3		Spencer	Feldman			Seiringer	
4		Erdös	Spencer			Feldman	
5		Seiringer	Erdös		Pizzo	Spencer	
6		Feldman	Seiringer		Pizzo	Erdös	
9		Spencer	Seiringer			Erdös	Posters
10		Pillet	Feldman			Spencer	Posters
11		Pillet	Erdös		Knowles	Sigal	
12		Feldman	Seiringer		Imbrie	Yau	
13		Pillet	Yau		Imbrie	Sigal	
16		Bach	Graf		Wolf – 17:30	18:00 Fröhlich	
17		Hastings	Bach		Zinn-Justin	Graf	
18		Wolf	Hastings			Bach	
19		Graf	Zhang			17:00 Pillet	Blanchard
20		Zhang	Pillet			Rosch	
23		Rosch	Giuliani			Hastings	
24		Rosch	Giuliani			Hastings	
25		Rosch	Hastings			De Roeck	
26		Rosch	De Roeck				
27							