MONASH University

Thesis Examination Report Summary

Thesis title	State-dependent forces in cold quantum gases
Student name	CHRISTOPHER JAMES BILLINGTON
Faculty	Faculty of Science
School	Physics and Astronomy
Course	Doctor of Philosophy
Supervisor name	Kristian Peter Helmerson
Reports released by the Chair of Examiners on	08/10/2018

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CRICOS Provider No. 000008C

Examiner: Professor Gerhard Birkl

Title	Professor
Name	Gerhard Birkl
Current institution	Technical University of Darmstadt/Germany
Recommendation	Pass

The thesis makes a significant contribution to knowledge and understanding of the field of research.

Thesis Merit

Professor Gerhard Birkl

Total number of theses examined	More than 10
Does the thesis contain material worthy of publication in a form appropriate to the discipline?	Yes
Is the format and literary presentation of the thesis satisfactory?	Yes

The thesis as a whole is a substantial and original contribution to knowledge of the subject with which it deals.	★★★☆☆ Very good
The student shows familiarity with and understanding of the relevant literature.	★★★★☆ Excellent
The research methods adopted are appropriate to the subject matter and are properly applied.	★★★★☆ Excellent
The results are suitably set out and accompanied by adequate exposition.	★★★☆☆ Very good
The quality of academic writing and general presentation are of a standard for publication.	★★★★☆ Excellent

1. **Exceptional** - Of the highest merit and at the forefront of international doctorates in the field. Fewer than 5% of students worldwide would fall in this band.
2. **Excellent** - Strongly competitive at an international level. Fewer than 20% of students would fall in this band.
3. **Very good** - Interesting and sound, Approximately 30% of students would fall in this band.
4. **Good** - Sound but lacking in some respect. Approximately 30% of students would fall in this band.
5. **Fair** - Has potential, but requires major revisions. Approximately 15% of students would fall in this band.

TECHNISCHE UNIVERSITÄT DARMSTADT

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EXAMINER REPORT

Doctor of Philosophy (PhDSci)

Student: Mr. Christopher Billington
Thesis title: State-dependent forces in cold quantum gases

The thesis of ***Mr. Billington*** describes in detail significant theoretical, computational, and technological advances in simulation and control of Bose-Einstein condensates (BECs). Although covering various independent aspects, ***Mr. Billington*** nevertheless succeeds in putting the different parts of his PhD. research in a common bracket which he appropriately summarizes as 'state-dependent forces in cold quantum gases'. This includes several sections on various advances in the simulation of state-of-the-art quantum-gas experiments with a specific emphasis on novel approaches to semi-classical simulation of the motional dynamics of atoms, the investigation of turbulence via tracer atoms, as well as important extensions in the computer control software *labscript suite* for operating the respective experimental implementation. Without doubt the thesis makes substantial and original contributions to simulating and understanding the physics, as well as controlling the practical implementation of experiments with ultra-cold quantum gases. ***Mr. Billington***, without doubt, deserves to be awarded the degree of Doctor of Philosophy for his work.

The thesis is organized in the 6 chapters: After an 'Introduction' (Chapter 1) the main part of the thesis consists of five technical chapters:

Chapter 2 describes the theoretical framework of optical cooling and trapping, the theory of interacting quantum gases, and the atomic physics and spectroscopic details of the relevant internal states and the light-atom interaction of rubidium atoms.

Chapter 3 discusses a variety of computational aspects of simulating quantum mechanical problems with emphasis on the type of problems being addressed in the following chapters.

Chapter 4 describes advances in the software implementation of a comprehensive computerized control program for complex cold-atom experiments. The software tool 'labscript suite' is routinely used in laboratories worldwide which strongly profit from the developments reported in this thesis.

Chapter 5 addresses - via numerical simulations - the issue of visualization of vortices in turbulence in Bose-Einstein condensates. This question is one of the main objectives of the Monash BEC group and the work in this thesis provides significant insight for the future direction of this experiment.

Professor Dr. Gerhard Birkl

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30. August 2018

Finally, Chapter 6 introduces – at least to the cold-atom community – a novel method for tracking the evolution of the full quantum states in semi-classical simulation of quantum systems. Although a similar method had been reported in chemical physics earlier, the development described in ***Mr. Billington*** thesis is still original and brings this concept to the attention of the quantum-optics community not familiar with the prior work.

Although each of the chapters has its own discussion of results at the end – which may be considered appropriate since the different chapters discuss diverse projects – an additional concluding chapter would have been advantageous to emphasize the common theme of the thesis as a whole and to point out future directions.

The thesis is well written: The techniques used during the investigations described have been clearly explained and have always been properly applied to the problems at hand. Almost all of the findings presented have been explained and put into context appropriately. ***Mr. Billington*** has demonstrated a good understanding of the relevant literature. He has demonstrated his ability of critical evaluation of the achieved results and has grasped the physics under investigation as well as the computational and experimental techniques to perform experimental research at the forefront of science.

In conclusion, I consider this thesis well presented and written to a very high standard. I believe that this thesis makes substantial and original contributions to the field of cold-atom physics. New experimental developments (e.g. computer control software) and a novel technique for simulation of quantum systems as introduced to the cold-atom community in this thesis support the high degree of impact expected for this work.

I therefore conclude that Mr. Billington without doubt deserves to be awarded the degree of Doctor of Philosophy on the basis of the thesis in its present form.

Darmstadt, 30 August 2018

Prof. Dr. Gerhard Birkl

Examiner: Professor Philipp Treutlein

Title	Professor
Name	Philipp Treutlein
Current institution	University of Basel/Switzerland
Recommendation	Pass, with minor amendments

The thesis makes a significant contribution to knowledge and understanding of the field of research.

Thesis Merit

Professor Philipp Treutlein

Total number of theses examined	More than 10
Does the thesis contain material worthy of publication in a form appropriate to the discipline?	Yes
Is the format and literary presentation of the thesis satisfactory?	Yes

The thesis as a whole is a substantial and original contribution to knowledge of the subject with which it deals.		Very good
The student shows familiarity with and understanding of the relevant literature.		Excellent
The research methods adopted are appropriate to the subject matter and are properly applied.		Excellent
The results are suitably set out and accompanied by adequate exposition.		Excellent
The quality of academic writing and general presentation are of a standard for publication.		Exceptional

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University of Basel
Department of Physics

University of Basel, Department of Physics, Klingelbergstrasse 82, CH-4056 Basel

Monash University
Graduate Research Office

Basel, 7 October 2018
Report on PhD thesis by Christopher James Billington

Dear colleagues,

It is my pleasure to write this report on the PhD thesis entitled “State-dependent forces in cold quantum gases” by Christopher James Billington. In his thesis, Christopher Billington describes different computational methods and studies that are useful for ultracold atom experiments, in particular experiments with Bose-Einstein condensates subject to state-dependent forces. This includes numerical methods for simulating atomic motion with a semiclassical model in the presence of state-dependent forces. Moreover, he developed the experiment control software suite LABSCRIPT, which is already being used in a number of BEC experiments. Finally, Christopher Billington describes simulations of vortex dynamics in a two-species mixture, in particular a vortex imaging and tracking scheme that may be useful in this context.

The thesis starts with an abstract and introduction. While I think it is overall very well written, I repeatedly stumbled over the statement that “Bose-Einstein condensates are well modelled by mean-field theory” (e.g. in the first paragraph of the abstract, the second to last paragraph on page 1 of the introduction, the first sentence of section 2.2). This was true for the early BEC experiments in the 1990s, but it is nowadays only true for a few subfields of BEC research. There is a large number of experiments in the field that explore “beyond mean-field physics” with BECs, in particular in optical lattices, with BECs in entangled states (squeezing etc), in experiments creating Rydberg excitations in BECs, BECs in optical cavities and many more. I therefore recommend to weaken the statement about the applicability of mean-field theory and explicitly mention some of the beyond mean-field experiments. Furthermore, I was confused by the statement about the atomic trajectories in the Stern-Gerlach experiment being “irrefutably classical” (beginning of section 1.1). The atoms in the Stern-Gerlach apparatus are in a superposition of two trajectories before they are measured, like in a double-slit experiment, which is not a classical state of motion. Apart from these issues, the abstract and introduction is well written.

In chapter 2, Christopher Billington explains a number of experimental techniques and theoretical concepts useful for BEC experiments. A particular emphasis is on the description of the Rb D lines with a computer. The concepts are introduced in a careful and pedagogical way, showing a good understanding of the underlying physics. This chapter is very well written and will be useful as an introduction for students. I have a minor comment, end of 2nd paragraph in section 2.3: it should read “… for other alkali metals…” and not “… for other alkali earth metals…” (Rb is an alkali, not an alkaline earth metal).

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Chapter 3 is a beautiful pedagogical introduction into quantum mechanics simulations on a computer. A variety of different numerical techniques are introduced in detail, their strengths and weaknesses are explained, with examples and lots of insightful comments from the author. This chapter will be a very useful resource for graduate students working on BEC experiments who want to perform their own computer simulations. This chapter has textbook quality! At the end, a modification of the 4th order Runge-Kutta method is introduced, which present advantages for certain problems.

Christopher Billington is the lead developer of the experiment control software suite LABSCRIPT, which is described in chapter 4. As the complexity of ultracold atom experiments grows, there is an increasing need for a versatile and powerful, professionally programmed experiment control software. Traditionally, each research group developed their own ad-hoc solution, which often reached its limits rather sooner than later. The open-source software suite LABSCRIPT is a professionally designed and implemented solution to this problem, with a lot of thought put into the design principles, and one can tell that it is based on substantial experience in running ultracold atom experiments. LABSCRIPT is being used by an increasing number of research groups around the world, including my own, and this is greatly facilitating experimental research in this field. It is a pleasure to work with the software. The chapter describes the software very well, I just found a minor typo on page 89, 1st paragraph, where it should read "…MOT beams to output 100 mW at t = 3 s…" (not 3 mW). Developing the LABSCRIPT suite for sure required and still requires a substantial amount of continuous work, which does not immediately lead to papers in research journals. However, the impact on the research field of ultracold atoms is nevertheless substantial. In this way, Christopher Billington has made a very important contribution to the field of ultracold atoms for which many researchers around the world are very thankful.

Chapter 5 reports numerical studies of an imaging method for real-time tracking of vortices in a 41K Bose-Einstein condensate. This is motivated by the goal to study superfluid turbulence. The imaging method involves filling the vortex cores with 87Rb atoms, which are continuously imaged to track the movement of the vortices. To avoid heating of the tracer atoms in this process, different laser cooling methods are proposed and studied. To numerically model the cooling processes, some of which involve state-dependent forces acting on the Rb atoms, a semiclassical simulation method was developed that allows treating the different trajectories of atoms in a superposition of internal states. This simulation method is presented in detail in chapter 6 and compared to existing methods. The reported simulations seem to be carefully conducted, and the simulation method is described in detail with a lot of useful comments. The proposed cooling schemes are relatively sophisticated and it will be interesting to see whether they can be successfully employed in experiments in the future.

In summary, this is a beautifully written thesis describing a range of computational methods for BEC experiments. The thesis is written in a very pedagogical manner and thus will serve as a valuable introduction for future graduate students. The open-source experiment control software LABSCRIPT developed by Christopher Billington is a very valuable tool for the research community. Several research groups around the world are already using it in their experiments, showing that the work of Christopher Billington has already had an impact on the BEC research community. I recommend to accept the thesis with the minor amendments mentioned in this report.

Yours sincerely

P. Treutlein

Philipp Treutlein