Comenius University

Faculty of Mathematics, Physics and Informatics

DIPLOMA THESIS

Jakub Bahyl

Quantum Turbulence in Superfluid Helium Down to the Zero Temperature Limit

Bratislava, 2018

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Quantum Turbulence in Superfluid Helium Down to the Zero Temperature Limit

Department of Low Temperature Physics, Charles University in Prague

Study programme:	Condensed Matter Physics
Study programme number:	???
Supervisor of the thesis:	RNDr. David Schmoranzer, PhD.
Consultant of the thesis:	Mgr. Emil Varga

Bratislava, 2018

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Comenius University in Bratislava
Faculty of Mathematics, Physics and Informatics

THESIS ASSIGNMENT

Name and Surname:	Jakub Bahyl
Study programme:	Physics (Single degree study, bachelor I. deg., full time form)
Field of Study:	Physics
Type of Thesis:	Bachelor´s thesis
Language of Thesis:	English
Secondary language:	Slovak

Title: Measurement of Quantum Turbulence in Superfluid 4He Using Second Sound Attenuation

Aim: During the work on this Thesis, the student will become familiar with the theoretical foundations of the description of quantum fluids and superfluidity. The student will learn about several experimental methods used for characterization of the flows of superfluid helium, such as second sound attenuation, which differs significantly from any techniques used in classical fluids. Given the focus of the Thesis, classical hydrodynamics will be used as a stepping-stone to help in the understanding of quantum fluids. On the practical side, the student will learn to design and run complex cryogenic experiments. This work will cover a wide range of skills, starting with the understanding of safety procedures for handling cryoliquids, of specific measures needed for operation of experiments with liquid helium at temperatures between 1.2 K and 4.2 K, and including work with sensitive electronic detectors such as quartz tuning forks, as well as a fundamental understanding of modern automated data acquisition and processing.

Literature:
[1] L.D. Landau, E.M. Lifshitz, Fluid Mechanics, Pergamon Books, 1987
[2] L. Skrbek a kol., Fyzika nízkých teplot, Matfyzpress, 2011
[3] D.R. Tilley, J. Tilley, Superfluidity and Superconductivity, Adam Hilger, 1986
[4] R.J. Donnelly: Quantized vortices in helium II, Cambridge University Press, 2005
[5] E. Varga, S. Babuin, L. Skrbek, Second-sound studies of coflow and counterflow of superfluid He-4 in channels, Phys. Fluids 27(6), 065101 (2015)
[6] Vinen, W. F. Mutual friction in a heat current in liquid helium II. II. Experiments on transient effects. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences. 240, 1220 (1957).
[7] R. Blaauwgeers, M. Blažková, M. Človečko, V.B. Eltsov, R. de Graaf, J. Hosio, M. Krusius, D. Schmoranzer,W. Schoepe, L. Skrbek, P. Skyba, R.E. Solntsev, D.E. Zmeev: Quartz Tuning Fork: Thermometer, Pressure- and Viscometer for Helium Liquids, J. Low Temp. Phys. 146, 537-562 (2007)
[8] S.L. Ahlstrom, D.I. Bradley, M. □love£ko, S.N. Fisher, A.M. Guénault, E.A. Guise, R.P. Haley, O. Kolosov, P.V.E. McClintock, G.R. Pickett, M. Poole, V. Tsepelin, and A.J. Woods, Phys. Rev. B 89, 014515 (2014).

Annotation: The main focus of this Thesis will be study of oscillatory flows of superfluid helium at low temperatures. Specifically, we will characterize the transition to

!!TODO!!

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ZADANIE ZÁVEREČNEJ PRÁCE

Meno a priezvisko študenta:	Jakub Bahyl
Študijný program:	fyzika (Jednoodborové štúdium, bakalársky I. st., denná forma)
Študijný odbor:	4.1.1. fyzika
Typ záverečnej práce:	bakalárska
Jazyk záverečnej práce:	slovenský
Sekundárny jazyk:	anglický

Názov: Meranie intenzity kvantovej turbulencie v supratekutom 4He pomocou tlmenia druhého zvuku
Measurement of Quantum Turbulence in Superfluid 4He Using Second Sound Attenuation

Cieľ: V rámci tejto práce sa študent po teoretickej stránke zoznámi so základmi popisu kvantových kvapalín, ich supratekutosti a spôsobmi, akými sa dajú charakterizovať supratekuté prúdenia, ktoré sa veľakrát odlišujú od správania sa bežných kvapalín. S ohľadom na zvolenú problematiku budú predmetom štúdia aj vybrané kapitoly klasickej dynamiky tekutín. Prakticky sa študent naučí vykonávať a obsluhovať komplexný kryogénny experiment počínajúc prácou s kryokvapalinami cez nastavovanie špecifických opatrení pre experimenty s kvapalným héliom pri teplotách 1,2 až 4,2 K až po počítačové riadenie experimentu a jeho vyhodnotenie.

Literatúra:

[1] L.D. Landau, E.M. Lifshitz, Fluid Mechanics, Pergamon Books, 1987
[2] L. Skrbek a kol., Fyzika nízkých teplot, Matfyzpress, 2011
[3] D.R. Tilley, J. Tilley, Superfluidity and Superconductivity, Adam Hilger, 1986
[4] R.J. Donnelly: Quantized vortices in helium II, Cambridge University Press, 2005
[5] E. Varga, S. Babuin, L. Skrbek, Second-sound studies of coflow and counterflow of superfluid He-4 in channels, Phys. Fluids 27(6), 065101 (2015)
[6] Vinen, W. F. Mutual friction in a heat current in liquid helium II. II. Experiments on transient effects. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences. 240, 1220 (1957).

Anotácia: Náplňou tejto bakalárskej práce bude štúdium prúdenia supratekutého hélia pri nízkych teplotách. Konkrétne sa budeme zaujímať o meranie hustoty kvantových vírov v supratekutom héliu metódou tlmenia druhého zvuku. Budú študované rôzne druhy prúdenia supratekutého hélia vrátane tzv. tepelného protiprúdu, v ktorom sa študent zameria najmä na vznik turbulentného prúdenia v prúdovom kanáli. Jedným z hlavných cieľov bude súbežným meraním na viacerých senzoroch druhého zvuku zistiť, či kvantové víry vznikajú v celom objeme tekutiny súčasne, alebo či sa šíri postupne z miesta prvých nestabilít prúdení. Táto práca bude teda priamo nadväzovať na výskum tejto problematiky, ktorý sa robí v Laboratóriach supratekutosti na MFF UK v Prahe [5].

!!TODO!!

Acknowledgment

BACHELOR: My special thanks go to my supervisor, David Schmoranzer, who gave me a lot of experiences, knowledge and much more of his time, without which I definitely could not write this Thesis. Together with consultant Martin Jackson, they guided me during the whole experiment and helped me to understand all the important aspects included in this work. Moreover, I am thankful to Ladislav Skrbek and Patrik Švančara for giving me such a great opportunity to find out how astounding the experimental physics can be and to work with Superfluidity group within Charles University in Prague.

In the end, I would like to hugely thank my friends and family for all their *„Good luck"* and *„Keep going"* motivational quotes and other sort of supports, which I deeply appreciated.

DIPLOMA: Thanks. **!!TODO!!**

I declare that I carried out this master thesis independently, and only with the cited sources, literature and other professional sources.

In .... date ....   Signature of the author:

Názov práce
Kvantová turbulencia v supratekutom héliu v teplotnej limite absolútnej nuly

Autor
Jakub Bahyl

Školiteľ bakalárskej práce
RNDr. David Schmoranzer, Ph.D.

Abstrakt
V tejto práci prezentujeme meranie kvantovej turbulencie generovanej oscilujúcim 6.5 kHz kremenným oscilátorom, ponoreným v supratekutom ^{4}He pri viacerých teplotách pod kritickou $T_\lambda = 2.17\,\mathrm{K}$. Pozorovaná nelineárna odporová sila pôsobiaca na oscilátor je kvalitatívne spôsobená prítomnosťou klasickej turbulencie a kvantovaných vírov. Odporové sily a množstvo vytvorených kvantovaných vírov (hustota vírov čiar L) sú nepriamo určené z útlmu druhého zvuku a mechanicko-elektrických vlastností oscilátora. Výsledky, ktoré prezentujeme, kvantitatívne charakterizujú tvorbu klasickej aj kvantovej turbulencie. Ako prví ukazujeme, že obidve turbulencie vedia vzniknúť samostatne a nezávisle. Tento fakt je prezentovaný, v prvom priblížení, pomocou *prúdového fázového diagramu*, v ktorom pre danú teplotu vieme predpokladať, kedy a ktorá turbulencia vzniká.

Kľúčové slová
supratekutosť ^{4}He • kvantový vír a turbulencia

Title
Quantum turbulence in superfluid helium down to the zero temperature limit

Author
Jakub Bahyl

Supervisor
RNDr. David Schmoranzer, Ph.D.

Abstract
In this work we present measurements of quantum turbulence generated by a 6.5 kHz oscillating quartz tuning fork submerged in superfluid ^{4}He at various temperatures below $T_\lambda = 2.17\,\mathrm{K}$. The observed non-linear drag acting on the tuning fork is qualitatively described by a presence of classical turbulence and quantized vortices. Drag forces and the amount of produced quantized vortices (the vortex line density L) are determined indirectly by the attenuation of second sound and by the measurement of mechanical and electrical properties of the tuning fork. We present results which characterize quantitatively the formation of classical and quantum turbulence. For the first time, we show that both turbulences can arise separately. This is presented, in first approximation, via a *flow phase diagram*, where for a given temperature, one can predict when each type of turbulence forms.

Keywords
superfluidity of ^{4}He • quantum vortex and turbulence

Contents

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Introduction

The discovery of helium's liquid state kick-started modern experimental low temperature physics. In 1908, the Dutch physicist Heike Kamerlingh Onnes reached the liquid state of helium at 4.2K for the very first time. With this, the last known gas was finally liquefied. Later, in 1913, Onnes was awarded the Nobel Prize for *"his investigations on the properties of matter at low temperatures which led to the production of liquid helium"*.

Later studies proved the existence of a new liquid state of ^{4}He - the superfluid phase, known as He-II. The transition (known as the λ transition) occurs at $T_\lambda \approx 2.17\,\mathrm{K}$. The full phase diagram is shown in **Figure 1**.

While the properties and behaviour of He-I are similar to classical viscous fluids, He-II exhibits significantly different properties. For example, the thermal conductivity is amongst the highest of any known material. Later, in 1937 Pyotr Kapitsa[1] conducted a few experiments on superfluid flow through narrow capillaries. He observed that He-II was able to flow with negligible viscosity. This research was also recognized by a Nobel prize in 1978.

The phenomenological description of these effects, the *two-fluid model*, was provided by Tisza and Landau. Together with the theory of Bose-Einstein condensation and quantum mechanics, these theories provide a basic understanding of superfluidity.

Moreover, superfluidity allows for the existence of vortices with discretely quantized circulation. These vortices are composed of circulating superfluid around a narrow core and can tangle to produce quantum turbulence (QT). QT is measurable using specific experimental methods, some of which will be described later in this work.

1. Theoretical Background

The theoretical part of this Thesis is composed of three chapters:

1. The first serves as a brief introduction to the topic of superfluidity using Bose-Einstein statistical physics and basic hydrodynamics.
2. The second chapter focuses on macroscopic quantum effects of superfluids, and introduces the concept of quantized vortices using quantum mechanics.
3. The last theoretical chapter deals with fluid dynamics; particularly the drag coefficients for various structures in fluid flows. We will also introduce the Reynolds number for oscillating objects immersed in both classical and quantum fluids.

All of the ideas discussed in this chapter can be found in standard textbooks [7], [4] except for the derivation of the vortex line density at the end of second part, where the original papers of Feynman, Vinen and Hall are required [**?**], [**?**], [**?**].

Superfluidity

Among all chemical substances, helium is special and unique at low temperatures. Under normal conditions (room temperature and atmospheric pressure), helium gas behaves as an ideal gas and the most common isotope is ^{4}He, formed by 2 protons, 2 neutrons and 2 electrons.[1] Due to the composition of the ^{4}He atom, the resulting nuclear spin is equal to zero. Therefore, ^{4}He is a boson and obeys Bose-Einstein quantum statistics. This will be discussed in more detail in **Section 1.1**.

When cooled below $T_\lambda = 2.17\,\mathrm{K}$, ^{4}He undergoes a second-order phase transition to the superfluid state and quantum effects become much more significant. Since the quantum mechanical wave function for bosons is symmetric, two arbitrary atoms can occupy the same quantum state. The Pauli exclusion principle does not apply to bosons, so the global state of He-II at low temperatures can be described as a considerable amount of particles sitting in the energy ground state.

We can therefore describe the whole He-II fluid as two inter-penetrating fluids, one composed of ground-state particles (and described by the macroscopic wave function) - the condensate

[1] There is another stable isotope of Helium, ^{3}He, which has one less neutron in the nucleus. In this Thesis, we will only focus on the isotope ^{4}He.

or superfluid component, and a second classical-like fluid composed of thermally excited atoms - the normal fluid component. In the following sections, this *two-fluid model* will be used to describe the rotational motion of the superfluid and consequently, the existence of quantum turbulence.

1.1 Helium-II as a Bose-Einstein Condensate

The total spin of ^{4}He is zero, so gaseous helium may be classified as a Bose gas. Additionally, if we assume no interactions between the particles, we may use the *ideal Bose gas* model. This of course cannot provide a perfect description of helium's behaviour (due to its weak interactions), but it will suffice. The thermodynamic limit of the ideal Bose model provides an intuitive insight to helium's special properties, such as superfluidity.

Bibliography

[1] Kapitsa, P. *The Super-Fluidity of Liquid Helium II.* Nature **141**, 74 (1938)

[2] Tong, D. *Statistical physics.* University of Cambridge Part II

[3] Tisza, L. *The viscosity of liquid helium and the Bose-Einstein statistics.* Comptes Rendus Acad. Sciences, **207**:1186-1189 (1952)

[4] Landau, L.D. and Lifshitz, E.M. *Fluid Mechanics*, Second English Edition. Pergamon Books Ltd., (1987). ISBN 0-08-033933-6

[5] Landau, L.D. *The theory of superfluidity of helium II.* J. Phys. USSR, Vol. **11**, 91 (1947)

[6] Andronikashvili, E.L. J. Phys. USSR, **10**, 201 (1946)

[7] Skrbek, L. et al. *Fyzika nízkých teplot*, 1. vydání. Praha: *MatfyzPress*, (2011). ISBN 978-80-7378-168-2.