Comenius University

Faculty of Mathematics, Physics and Informatics

DIPLOMA THESIS

Jakub Bahyl

Quantum Turbulence Measurements in Superfluid Helium and Numerical Simulations

Bratislava, 2018

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Quantum Turbulence Measurements in Superfluid Helium and Numerical Simulations

Department of Low Temperature Physics, Charles University in Prague

Study programme:	Condensed Matter Physics
Study programme number:	mFTL
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:

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[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

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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
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[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].

Acknowledgment

!!TODO!!

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.

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:

!!TODO!!

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

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Introduction / Motivation (3 pgs)

- history
- phase diagram (+pic)
- superfluid transition
- unconventional properties
- theories from Landau, London
- quantum vortices
- QT (+pic)
- QT vs CT
- overview on experiments with QT
- overview on numerical simulations of QT
- motivations
- goals - CT -¿ QT transition, simulations

1. Theoretical Background (15 pgs)

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

1. Microscopic view
2. Mesoscopic view
3. Macroscopic view

Microscopic model

Statistical physics

- Bose-Einstein gas
- critical temperature

Two-fluid model

- Landau's assumptions
- two densities, velocities (+pic)

Wave function

- London's theory
- NLSE (Schr eq)
- macroscopic wave function
- no vorticity
- quantized circulation

Quantum vortex

- definition
- induced velocity
- energy
- quantized circulation
- quantum turbulence

Mesoscopic view

Vortex parametrisation

- curve coordinates
- derivatives
- self-induced velocity
- LIA approximation

Vortex dynamics

- magnus force
- mutual friction
- Schwarz's equation
- Kelvis waves (?)

Macroscopic view

Hydrodynamics of two-fluid

- updated hydrodynamical equations - HVBK
- dynamical similarity
- Reynolds number

Second sound

- mode 1 - classical
- mode 2 - unusual
- velocity of second sound
- attenuation
- vortex line density estimate

Oscillatory motion in superfluid

- penetration depth
- Re for oscillations
- defining depth and Re separately for normal and superfluid components

Quantum turbulence

- critical velocity according to landau
- critical velocity scaling in oscillatory case
- T dependence of critical velocities (Bc. results)

Quantum rings

- definition (+pic)
- generation methods
- dynamics

2. Experimental Setup (15 pgs)

Apparatus

- cryostat
- cooling system
- insert
- resonator

QT Generators

- quartz tuning fork
- other oscillators

QT Detection

- Second sound generating
- SS detection

Measurement methods and Processing

- fork modes - fund, overtone
- SS modes - working with ??-th mode
- frequency sweeps
- amp sweeps
- constant drives with SS on/off

Universal Scaling

- Donnely number
- universal scaling

3. Simulations (10 pgs)

Graph model

- graph description
- data structure
- state

Finite differences

- FD order, radius
- Vandermonde vs analytical method
- comp complexities of LIA and Biot-Savart
- coords and velocities updating

Running in time

- Euler vs. RK4 step
- time stepping
- stability

Resegmentation

- adding and removing segments
- local spline

Vortex ring

- initialisation
- movement, decreasing radius

- comparison with theory
- Kelvin waves (?)

4. Results (10 pgs)

Vortex line density

- steps made for achieving results
- graphs for fundamental and overtone

Drag force graphs

- velocity vs force
- C vs velocity
- Cn vs Reynolds

Correlations

- compare vortex generating with drag force graphs
- fund and overtone

Simulations

- compare rings with various radii
- theoretical vs simulation velocity / range
- stability tests
- Kelvin waves(?)

5. Conclusions (2 pgs)

- summarize main what have we done
- repeat motivations and goals
- list of achievements
- list of failures
- list of improvements
- last words

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

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