



Universiteit
Leiden
The Netherlands

Random-matrix theory and stroboscopic models of topological insulators and superconductors

Dahlhaus, J.P.

Citation

Dahlhaus, J. P. (2012, November 21). *Random-matrix theory and stroboscopic models of topological insulators and superconductors*. Casimir PhD Series. Retrieved from <https://hdl.handle.net/1887/20139>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/20139>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/20139> holds various files of this Leiden University dissertation.

Author: Dahlhaus, Jan Patrick

Title: Random-matrix theory and stroboscopic models of topological insulators and superconductors

Date: 2012-11-21

Random-matrix theory and stroboscopic models of topological insulators and superconductors

PROEFSCHRIFT

TER VERKRIJGING VAN
DE GRAAD VAN DOCTOR AAN DE UNIVERSITEIT LEIDEN,
OP GEZAG VAN DE RECTOR MAGNIFICUS
PROF. MR P. F. VAN DER HEIJDEN,
VOLGENS BESLUIT VAN HET COLLEGE VOOR PROMOTIES
TE VERDEDIGEN OP WOENSDAG 21 NOVEMBER 2012
KLOKKE 10.00 UUR

DOOR

Jan Patrick Dahlhaus

GEBOREN TE ESSEN, DUITSLAND IN 1982

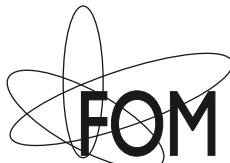
Promotiecommissie

Promotor: Prof. dr. C. W. J. Beenakker
Overige leden: Prof. dr. E. R. Eliel
Prof. dr. ir. L. P. Kouwenhoven (Technische Universiteit Delft)
Prof. dr. H. Schomerus (Lancaster University)
Prof. dr. J. Zaanen

Casimir PhD Series, Delft-Leiden, 2012-29
ISBN 978-90-8593-137-9

Dit werk maakt deel uit van het onderzoekprogramma van de Stichting voor Fundamenteel Onderzoek der Materie (FOM), die deel uit maakt van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

This work is part of the research programme of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organisation for Scientific Research (NWO).



Cover: *Topological invariant of a nodal Rashba superconductor in contact with a metal, as a function of interface orientation and momentum. Compare with the left panel of Fig. 5.4.*

To Nina and my parents.

Contents

1	Introduction	1
1.1	Preface	1
1.2	Concept of topology in insulating systems	2
1.2.1	Example: winding number	3
1.2.2	Boundary states	4
1.2.3	Role of symmetries and dimensionality	5
1.2.4	Anderson localization and topology	8
1.3	Topological superconductors	9
1.3.1	Example: Majorana wire	10
1.4	Random-matrix theory	12
1.4.1	Symmetry classes	12
1.4.2	Circular ensembles	14
1.5	Stroboscopic models	15
1.5.1	The quantum kicked rotator	15
1.5.2	Stroboscopic models in higher dimensions and the Anderson metal-insulator transition	16
1.6	This thesis	18
1.6.1	Chapter 2	18
1.6.2	Chapter 3	19
1.6.3	Chapter 4	20
1.6.4	Chapter 5	21
1.6.5	Chapter 6	22
1.6.6	Chapter 7	24
1.6.7	Chapter 8	25
2	Random-matrix theory of thermal conduction in superconducting quantum dots	29
2.1	Introduction	29

2.2	Formulation of the problem	32
2.2.1	Andreev quantum dot	32
2.2.2	Scattering matrix ensembles	33
2.3	Transmission eigenvalue distribution	35
2.3.1	Joint probability distribution	35
2.3.2	Eigenvalue density	35
2.4	Distribution of the thermal conductance	37
2.4.1	Minimal channel number	37
2.4.2	Large number of channels	38
2.4.3	Arbitrary number of channels	40
2.5	How to reach the single-channel limit using topological phases	40
2.6	Conclusion	42
	Appendix 2.A Calculation of the transmission eigenvalue distribution	44
3	Random-matrix theory of Andreev reflection from a topological superconductor	51
3.1	Introduction	51
3.2	Andreev reflection eigenvalues	54
3.3	Random-matrix theory	56
3.3.1	Class D, ensemble CRE	56
3.3.2	Class DIII, ensemble T-CRE	58
3.3.3	Class C, ensemble CQE	60
3.3.4	Class CI, ensemble T-CQE	60
3.4	Dependence of conductance distributions on topological invariant	61
3.4.1	Broken time-reversal symmetry	61
3.4.2	Preserved time-reversal symmetry	63
3.4.3	Weak localization and UCF	63
3.5	Conclusion and comparison with a model Hamiltonian	64
	Appendix 3.A Calculation of the invariant measure	67
3.A.1	Class D (ensemble CRE)	67
3.A.2	Class DIII (ensemble T-CRE)	71
	Appendix 3.B Proof of the topological-charge theorem for circular ensembles	73

4 Quantum point contact as a probe of a topological superconductor	79
4.1 Introduction	79
4.2 Integer versus half-integer conductance plateaus	80
4.3 Effect of disorder	82
4.4 Effect of finite voltage and temperature	83
4.5 Conclusion	86
Appendix 4.A Model Hamiltonian	88
Appendix 4.B Béri degeneracy	90
5 Scattering theory of topological invariants in nodal superconductors	95
5.1 Introduction	95
5.2 Topological invariant for Andreev reflection	97
5.2.1 Chiral symmetry	97
5.2.2 Topological invariant	98
5.3 Topologically protected boundary states	99
5.4 Relation between conductance and topological invariant .	100
5.5 Effects of additional unitary symmetries	101
5.5.1 Spatial symmetries	102
5.5.2 Symmetries that preserve k_{\parallel}	104
5.6 Application: 2D Rashba superconductor	104
5.6.1 Hamiltonian and edge states	104
5.6.2 Reflection matrix and conductance	107
5.6.3 Anisotropic spin-orbit coupling	109
5.7 Effects of angular averaging and disorder	110
5.8 Three-dimensional superconductors	112
5.8.1 Topological invariant for arc surface states	112
5.8.2 Example	113
5.9 Conclusion	115
Appendix 5.A Topological invariant counts number of unit Andreev reflection eigenvalues	116
5.A.1 Proof for the \mathbb{Z} invariant	116
5.A.2 Proof for the \mathbb{Z}_2 invariant	116
Appendix 5.B Proof of Eq. (5.34)	117
Appendix 5.C Equality of conductance and topological invari- ant in class BDI	117

6 Quantum Hall effect in a one-dimensional dynamical system	121
6.1 Introduction	121
6.2 Formulation of the 2D stroboscopic model	122
6.2.1 Quantum anomalous Hall effect	122
6.2.2 Stroboscopic Hamiltonian	123
6.2.3 Relation to quantum kicked rotator	124
6.2.4 Floquet operator	125
6.3 Mapping onto a 1D model	126
6.4 Localization in the quantum Hall effect	127
6.4.1 Numerical simulation	127
6.4.2 Localization-delocalization transition	128
6.4.3 Scaling and critical exponent	129
6.5 Hall conductance and topological invariant	131
6.6 Discussion	132
Appendix 6.A Tight-binding representation	134
Appendix 6.B Finite-time scaling	135
Appendix 6.C Scattering matrix from Floquet operator	136
7 Metal-topological-insulator transition in the quantum kicked rotator with \mathbb{Z}_2 symmetry	143
7.1 Introduction	143
7.2 Construction of the \mathbb{Z}_2 quantum kicked rotator	145
7.2.1 Stationary model without disorder	145
7.2.2 Time-dependent model with disorder	147
7.2.3 Mapping from 2D to 1D	148
7.3 Phase diagram with disorder	149
7.4 Scaling law and critical exponent	151
7.5 Conclusion	153
8 Geodesic scattering by surface deformations of a topological insulator	159
8.1 Introduction	159
8.2 Geodesic scattering	160
8.2.1 Geodesic motion	160
8.2.2 Scattering angle	162
8.3 Calculation of the conductivity	163
8.3.1 Linearized Boltzmann equation	163
8.3.2 Isotropic dispersion relation	165
8.3.3 Anisotropic dispersion relation	166

8.4 Results	168
8.4.1 Isotropic dispersion relation	168
8.4.2 Anisotropic dispersion relation	170
8.5 Comparison with potential scattering	171
8.5.1 Carrier density dependence	171
8.5.2 Anisotropy dependence of conductivity	173
Appendix 8.A Calculation of scattering cross section	176
8.A.1 Christoffel symbols in rotated basis	176
8.A.2 Geodesic equation for shallow deformation	176
8.A.3 Circularly symmetric deformation	177
Samenvatting	181
Summary	185
List of Publications	187
Curriculum Vitæ	189

