

Cambridge University Press
978-0-521-85512-9 - Mesoscopic Physics of Electrons and Photons
Eric Akkermans and Gilles Montambaux
Frontmatter
[More information](#)

MESOSCOPIC PHYSICS OF ELECTRONS AND PHOTONS

Quantum mesoscopic physics covers a whole class of interference effects related to the propagation of waves in complex and random media. These effects are ubiquitous in physics, from the behavior of electrons in metals and semiconductors to the propagation of electromagnetic waves in suspensions such as colloids, and quantum systems like cold atomic gases. This book is a modern account of the problem of coherent wave propagation in random media.

As a solid introduction to quantum mesoscopic physics, this book provides a unified overview of the basic theoretical tools and methods. It highlights the common aspects of the various optical and electronic phenomena involved. With over 200 figures, and exercises throughout, the book is ideal for graduate students in physics, electrical engineering, optics, acoustics and astrophysics. It presents a large number of experimental results that cover a wide range of phenomena from semiconductors to optics, acoustics, and atomic physics. It will also be an important reference for researchers in this rapidly evolving field.

ERIC AKKERMANS is Professor of Physics in the Department of Physics at the Technion, Israel Institute of Technology, Israel. GILLES MONTAMBAUX is Directeur de Recherche at the CNRS, Laboratoire de Physique des Solides, Université Paris-Sud, France. Their research interests include the theory of condensed matter physics, mesoscopic quantum physics, and coherent effects in the propagation of waves in random media.

Cambridge University Press

978-0-521-85512-9 - Mesoscopic Physics of Electrons and Photons

Eric Akkermans and Gilles Montambaux

Frontmatter

[More information](#)

Mesoscopic Physics of Electrons and Photons

Eric Akkermans

Technion, Israel Institute of Technology

Gilles Montambaux

CNRS, Université Paris-Sud



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-85512-9 - Mesoscopic Physics of Electrons and Photons
Eric Akkermans and Gilles Montambaux
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521855129

© E. Akkermans and G. Montambaux 2007

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 2007

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

ISBN 978-0-521-85512-9 hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or
third-party internet websites referred to in this publication, and does not guarantee that any content on such
websites is, or will remain, accurate or appropriate.

Contents

<i>Preface</i>	<i>page</i> xiii
<i>How to use this book</i>	xv
1 Introduction: mesoscopic physics	1
1.1 Interference and disorder	1
1.2 The Aharonov–Bohm effect	4
1.3 Phase coherence and the effect of disorder	7
1.4 Average coherence and multiple scattering	9
1.5 Phase coherence and self-averaging: universal fluctuations	12
1.6 Spectral correlations	14
1.7 Classical probability and quantum crossings	15
1.7.1 Quantum crossings	17
1.8 Objectives	18
2 Wave equations in random media	31
2.1 Wave equations	31
2.1.1 Electrons in a disordered metal	31
2.1.2 Electromagnetic wave equation – Helmholtz equation	32
2.1.3 Other examples of wave equations	33
2.2 Models of disorder	36
2.2.1 The Gaussian model	37
2.2.2 Localized impurities: the Edwards model	39
2.2.3 The Anderson model	41
Appendix A2.1: Theory of elastic collisions and single scattering	43
A2.1.1 Asymptotic form of the solutions	44
A2.1.2 Scattering cross section and scattered flux	46
A2.1.3 Optical theorem	47
A2.1.4 Born approximation	51
Appendix A2.2: Reciprocity theorem	54
Appendix A2.3: Light scattering	56
A2.3.1 Classical Rayleigh scattering	56

	A2.3.2 Mie scattering	60
	A2.3.3 Atom–photon scattering in the dipole approximation	61
3	Perturbation theory	70
3.1	Green’s functions	71
3.1.1	Green’s function for the Schrödinger equation	71
3.1.2	Green’s function for the Helmholtz equation	77
3.2	Multiple scattering expansion	79
3.2.1	Dyson equation	79
3.2.2	Self-energy	82
3.3	Average Green’s function and average density of states	86
	Appendix A3.1: Short range correlations	88
4	Probability of quantum diffusion	92
4.1	Definition	92
4.2	Free propagation	95
4.3	Drude–Boltzmann approximation	96
4.4	Diffuson or ladder approximation	97
4.5	The Diffuson at the diffusion approximation	102
4.6	Coherent propagation: the Cooperon	104
4.7	Radiative transfer	110
	Appendix A4.1: Diffuson and Cooperon in reciprocal space	113
	A4.1.1 Collisionless probability $P_0(\mathbf{q}, \omega)$	114
	A4.1.2 The Diffuson	115
	A4.1.3 The Cooperon	117
	Appendix A4.2: Hikami boxes and Diffuson crossings	120
	A4.2.1 Hikami boxes	120
	A4.2.2 Normalization of the probability and renormalization of the diffusion coefficient	125
	A4.2.3 Crossing of two Diffusons	128
	Appendix A4.3: Anisotropic collisions and transport mean free path	132
	Appendix A4.4: Correlation of diagonal Green’s functions	138
	Appendix A4.5: Other correlation functions	142
	A4.5.1 Correlations of Green’s functions	142
	A4.5.2 A Ward identity	145
	A4.5.3 Correlations of wave functions	145
5	Properties of the diffusion equation	148
5.1	Introduction	148
5.2	Heat kernel and recurrence time	149
5.2.1	Heat kernel – probability of return to the origin	149
5.2.2	Recurrence time	151
5.3	Free diffusion	152
5.4	Diffusion in a periodic box	155

	<i>Contents</i>	vii
5.5	Diffusion in finite systems	156
5.5.1	Diffusion time and Thouless energy	156
5.5.2	Boundary conditions for the diffusion equation	156
5.5.3	Finite volume and “zero mode”	157
5.5.4	Diffusion in an anisotropic domain	158
5.6	One-dimensional diffusion	159
5.6.1	The ring: periodic boundary conditions	160
5.6.2	Absorbing boundaries: connected wire	161
5.6.3	Reflecting boundaries: isolated wire	162
5.6.4	Semi-infinite wire	164
5.7	The image method	165
Appendix A5.1:	Validity of the diffusion approximation in an infinite medium	166
Appendix A5.2:	Radiative transfer equation	168
A5.2.1	Total intensity	168
A5.2.2	Diffuse intensity	170
A5.2.3	Boundary conditions	172
A5.2.4	Slab illuminated by an extended source	175
A5.2.5	Semi-infinite medium illuminated by a collimated beam	176
Appendix A5.3:	Multiple scattering in a finite medium	177
A5.3.1	Multiple scattering in a half-space: the Milne problem	177
A5.3.2	Diffusion in a finite medium	180
Appendix A5.4:	Spectral determinant	182
Appendix A5.5:	Diffusion in a domain of arbitrary shape – Weyl expansion	184
Appendix A5.6:	Diffusion on graphs	187
A5.6.1	Spectral determinant on a graph	187
A5.6.2	Examples	191
A5.6.3	Thermodynamics, transport and spectral determinant	193
6	Dephasing	195
6.1	Dephasing and multiple scattering	195
6.1.1	Generalities	195
6.1.2	Mechanisms for dephasing: introduction	196
6.1.3	The Goldstone mode	199
6.2	Magnetic field and the Cooperon	199
6.3	Probability of return to the origin in a uniform magnetic field	203
6.4	Probability of return to the origin for an Aharonov–Bohm flux	205
6.4.1	The ring	206
6.4.2	The cylinder	208
6.5	Spin-orbit coupling and magnetic impurities	210
6.5.1	Transition amplitude and effective interaction potential	210
6.5.2	Total scattering time	212
6.5.3	Structure factor	214

6.5.4	The Diffuson	219
6.5.5	The Cooperon	221
6.5.6	The diffusion probability	223
6.5.7	The Cooperon X_c	224
6.6	Polarization of electromagnetic waves	226
6.6.1	Elastic mean free path	227
6.6.2	Structure factor	228
6.6.3	Classical intensity	231
6.6.4	Coherent backscattering	233
6.7	Dephasing and motion of scatterers	234
6.7.1	General expression for the phase shift	234
6.7.2	Dephasing associated with the Brownian motion of the scatterers	237
6.8	Dephasing or decoherence?	238
	Appendix A6.1: Aharonov–Bohm effect in an infinite plane	240
	Appendix A6.2: Functional representation of the diffusion equation	242
	A6.2.1 Functional representation	242
	A6.2.2 Brownian motion and magnetic field	244
	Appendix A6.3: The Cooperon in a time-dependent field	247
	Appendix A6.4: Spin-orbit coupling and magnetic impurities, a heuristic point of view	251
	A6.4.1 Spin-orbit coupling	251
	A6.4.2 Magnetic impurities	254
	Appendix A6.5: Decoherence in multiple scattering of light by cold atoms	256
	A6.5.1 Scattering amplitude and atomic collision time	256
	A6.5.2 Elementary atomic vertex	257
	A6.5.3 Structure factor	262
7	Electronic transport	270
7.1	Introduction	270
7.2	Incoherent contribution to conductivity	273
	7.2.1 Drude–Boltzmann approximation	273
	7.2.2 The multiple scattering regime: the Diffuson	276
	7.2.3 Transport time and vertex renormalization	278
7.3	Cooperon contribution	279
7.4	The weak localization regime	281
	7.4.1 Dimensionality effect	282
	7.4.2 Finite size conductors	284
	7.4.3 Temperature dependence	285
7.5	Weak localization in a magnetic field	286
	7.5.1 Negative magnetoresistance	286
	7.5.2 Spin-orbit coupling and magnetic impurities	290

<i>Contents</i>		ix
7.6	Magnetoresistance and Aharonov–Bohm flux	292
7.6.1	Ring	293
7.6.2	Long cylinder: the Sharvin–Sharvin effect	294
7.6.3	Remark on the Webb and Sharvin–Sharvin experiments: ϕ_0 versus $\phi_0/2$	295
7.6.4	The Aharonov–Bohm effect in an infinite plane	296
Appendix A7.1:	Kubo formulae	296
A7.1.1	Conductivity and dissipation	296
A7.1.2	Density-density response function	301
Appendix A7.2:	Conductance and transmission	302
A7.2.1	Introduction: Landauer formula	302
A7.2.2	From Kubo to Landauer	305
A7.2.3	Average conductance and transmission	307
A7.2.4	Boundary conditions and impedance matching	311
A7.2.5	Weak localization correction in the Landauer formalism	313
A7.2.6	Landauer formalism for waves	314
Appendix A7.3:	Real space description of conductivity	315
Appendix A7.4:	Weak localization correction and anisotropic collisions	317
8	Coherent backscattering of light	320
8.1	Introduction	320
8.2	The geometry of the albedo	321
8.2.1	Definition	321
8.2.2	Albedo of a diffusive medium	322
8.3	The average albedo	324
8.3.1	Incoherent albedo: contribution of the Diffuson	324
8.3.2	The coherent albedo: contribution of the Cooperon	326
8.4	Time dependence of the albedo and study of the triangular cusp	330
8.5	Effect of absorption	333
8.6	Coherent albedo and anisotropic collisions	334
8.7	The effect of polarization	336
8.7.1	Depolarization coefficients	336
8.7.2	Coherent albedo of a polarized wave	337
8.8	Experimental results	339
8.8.1	The triangular cusp	340
8.8.2	Decrease of the height of the cone	341
8.8.3	The role of absorption	343
8.9	Coherent backscattering at large	347
8.9.1	Coherent backscattering and the “glory” effect	347
8.9.2	Coherent backscattering and opposition effect in astrophysics	348
8.9.3	Coherent backscattering by cold atomic gases	349
8.9.4	Coherent backscattering effect in acoustics	352

9	Diffusing wave spectroscopy	354
9.1	Introduction	354
9.2	Dynamic correlations of intensity	355
9.3	Single scattering: quasi-elastic light scattering	357
9.4	Multiple scattering: diffusing wave spectroscopy	358
9.5	Influence of the geometry on the time correlation function	359
9.5.1	Reflection by a semi-infinite medium	359
9.5.2	Comparison between $G_1^r(T)$ and $\alpha_c(\theta)$	361
9.5.3	Reflection from a finite slab	363
9.5.4	Transmission	364
	Appendix A9.1: Collective motion of scatterers	367
10	Spectral properties of disordered metals	370
10.1	Introduction	370
10.1.1	Level repulsion and integrability	371
10.1.2	Energy spectrum of a disordered metal	373
10.2	Characteristics of spectral correlations	374
10.3	Poisson distribution	376
10.4	Universality of spectral correlations: random matrix theory	377
10.4.1	Level repulsion in 2×2 matrices	377
10.4.2	Distribution of eigenvalues for $N \times N$ matrices	380
10.4.3	Spectral properties of random matrices	382
10.5	Spectral correlations in the diffusive regime	385
10.5.1	Two-point correlation function	386
10.5.2	The ergodic limit	390
10.5.3	Free diffusion limit	391
	Appendix A10.1: The GOE–GUE transition	394
11	Universal conductance fluctuations	396
11.1	Introduction	396
11.2	Conductivity fluctuations	399
11.2.1	Fluctuations of the density of states	402
11.2.2	Fluctuations of the diffusion coefficient	405
11.3	Universal conductance fluctuations	406
11.4	Effect of external parameters	409
11.4.1	Energy dependence	409
11.4.2	Temperature dependence	409
11.4.3	Phase coherence and the mesoscopic regime	411
11.4.4	Magnetic field dependence	415
11.4.5	Motion of scatterers	418
11.4.6	Spin-orbit coupling and magnetic impurities	419
	Appendix A11.1: Universal conductance fluctuations and anisotropic collisions	422
	Appendix A11.2: Conductance fluctuations in the Landauer formalism	424

12	Correlations of speckle patterns	427
12.1	What is a speckle pattern?	427
12.2	How to analyze a speckle pattern	428
12.3	Average transmission coefficient	433
12.4	Angular correlations of the transmitted light	435
12.4.1	Short range $C^{(1)}$ correlations	435
12.4.2	Long range correlations $C^{(2)}$	439
12.4.3	Two-crossing contribution and $C^{(3)}$ correlation	441
12.4.4	Relation with universal conductance fluctuations	445
12.5	Speckle correlations in the time domain	446
12.5.1	Time dependent correlations $C^{(1)}(t)$ and $C^{(2)}(t)$	447
12.5.2	Time dependent correlation $C^{(3)}(t)$	450
12.6	Spectral correlations of speckle patterns	452
12.7	Distribution function of the transmission coefficients	453
12.7.1	Rayleigh distribution law	454
12.7.2	Gaussian distribution of the transmission coefficient \mathcal{T}_a	455
12.7.3	Gaussian distribution of the electrical conductance	456
Appendix A12.1: Spatial correlations of light intensity		458
A12.1.1	Short range correlations	459
A12.1.2	Long range correlations	461
13	Interactions and diffusion	465
13.1	Introduction	465
13.2	Screened Coulomb interaction	466
13.3	Hartree–Fock approximation	468
13.4	Density of states anomaly	470
13.4.1	Static interaction	470
13.4.2	Tunnel conductance and density of states anomaly	475
13.4.3	Dynamically screened interaction	478
13.4.4	Capacitive effects	481
13.5	Correction to the conductivity	483
13.6	Lifetime of a quasiparticle	487
13.6.1	Introduction: Landau theory and disorder	487
13.6.2	Lifetime at zero temperature	487
13.6.3	Quasiparticle lifetime at finite temperature	494
13.6.4	Quasiparticle lifetime at the Fermi level	495
13.7	Phase coherence	498
13.7.1	Introduction	498
13.7.2	Phase coherence in a fluctuating electric field	499
13.7.3	Phase coherence time in dimension $d = 1$	502
13.7.4	Phase coherence and quasiparticle relaxation	506
13.7.5	Phase coherence time in dimensions $d = 2$ and $d = 3$	509
13.7.6	Measurements of the phase coherence time τ_ϕ^{ee}	510

Appendix A13.1: Screened Coulomb potential in confined geometry	512
Appendix A13.2: Lifetime in the absence of disorder	514
14 Orbital magnetism and persistent currents	516
14.1 Introduction	516
14.2 Free electron gas in a uniform field	518
14.2.1 A reminder: the case of no disorder	518
14.2.2 Average magnetization	521
14.2.3 Fluctuations of the magnetization	522
14.3 Effect of Coulomb interaction	524
14.3.1 Hartree–Fock approximation	525
14.3.2 Cooper renormalization	526
14.3.3 Finite temperature	528
14.4 Persistent current in a ring	528
14.4.1 Clean one-dimensional ring: periodicity and parity effects	529
14.4.2 Average current	534
14.5 Diffusive limit and persistent current	536
14.5.1 Typical current of a disordered ring	537
14.5.2 Effect of the Coulomb interaction on the average current	539
14.5.3 Persistent current and spin-orbit coupling	542
14.5.4 A brief overview of experiments	543
Appendix A14.1: Average persistent current in the canonical ensemble	545
15 Formulary	547
15.1 Density of states and conductance	547
15.2 Fourier transforms: definitions	548
15.3 Collisionless probability $P_0(\mathbf{r}, \mathbf{r}', t)$	548
15.4 Probability $P(\mathbf{r}, \mathbf{r}', t)$	548
15.5 Wigner–Eckart theorem and $3j$ -symbols	551
15.6 Miscellaneous	552
15.7 Poisson formula	558
15.8 Temperature dependences	558
15.9 Characteristic times introduced in this book	559
<i>References</i>	561
<i>Index</i>	582

Preface

Wave propagation in random media has been the subject of intense activity for more than two decades. This is now an important area of research, whose frontiers are still fuzzy, and which includes a variety of problems such as wave localization (weak and strong), mesoscopic physics, effects of electron–electron interactions in metals, etc. Moreover, since many disorder effects are not truly specific to a given kind of wave, various approaches have been developed independently in condensed matter physics, in optics, in atomic physics and in acoustics.

A large number of monographs or review articles already exist in the literature and they cover in detail various aspects of the field. Our aim is rather to present the basic common features of the effects of disorder on wave propagation and also to provide the non-specialist reader with the tools necessary to enter and practice this field of research.

Our first concern has been to give a description of the basic physical effects using a single formalism independent of the specific nature of the waves (electrons, electromagnetic waves, etc.). To this purpose, we have started with a detailed presentation of “single-particle” average quantities such as the density of states and elastic collision time using the framework of the so-called “Gaussian model” for the two most important examples of waves, namely Schrödinger and scalar Helmholtz wave equations. We have tried, as much as possible, to make precise the very basic notion of multiple scattering by an ensemble of independent effective scatterers whose scattering cross section may be obtained using standard one-particle scattering theory.

Nevertheless, the quantities of physical interest that are accessible experimentally and used to describe wave propagation in the multiple scattering regime depend essentially on the probability of quantum diffusion which describes the propagation of a wave packet. This probability thus plays a central role and Chapter 4 is devoted to its detailed study. We then see emerging notions such as classical (Diffuson) and coherent (Cooperon) contributions to the probability, which provide basic explanations of the observed physical phenomena such as weak localization corrections to electronic transport, negative magnetoresistance in a magnetic field, coherent backscattering of light, as well as universal conductance fluctuations, optical speckles and mesoscopic effects in orbital magnetism.

It thus happens that all these effects result from the behavior of a single quantity, namely the probability of quantum diffusion. However, in spite of the common background shared

by optics and electronics of random media, each of these domains has its own specificity which allows us to develop complementary approaches. For instance, the continuous change in the relative phases of electronic wave functions that can be achieved using a magnetic field or a vector potential has no obvious equivalent in optics. On the other hand, it is possible in optics to change directions of incident and outgoing beams and from this angular spectroscopy to trace back correlations between angular channels.

We have made a special effort to try to keep this book accessible to the largest audience, starting at a graduate level in physics with an elementary acquaintance of quantum mechanics as a prerequisite. We have also skipped a number of interesting but perhaps too specialized issues among which are the study of quantum dots, relations between spectral and transport quantities, strong localization and the Anderson metal–insulator transition, electronic ballistic billiards where “quantum complexity” does not result from disorder but instead from the boundary shape, and metal–superconductor interfaces. All these aspects reflect the richness of the field of “quantum mesoscopic physics” to which this book constitutes a first introduction.

A pleasant task in finishing the writing of a book is certainly the compilation of acknowledgments to all those who have helped us at various stages of the elaboration and writing, either through discussions, criticisms and especially encouragement and support: O. Assaf, H. Bouchiat, B. Huard, J. Cayssol, C. Cohen-Tannoudji, N. Dupuis, D. Estève, A. Georges, S. Guéron, M. Kouchnir, R. Maynard, F. Piéchon, H. Pothier, B. Reulet, B. Shapiro, B. van Tiggelen, D. Ullmo, J. Vidal, E. Wolf. We wish to single out the contribution of C. Texier for his endless comments, suggestions, and corrections which have certainly contributed to improve the quality of this book. Dov Levine accepted to help us in translating the book into English. This was a real challenge and we wish to thank him for his patience. We also wish to thank G. Bazalitsky for producing most of the figures with much dedication.

This venture was in many respects a roller-coaster ride and the caring support of Anne-Marie and Tirza was all the more precious.

Throughout this book, we use the (SI) international unit system, except in Chapter 13. The Planck constant \hbar is generally taken equal to unity, in particular throughout Chapter 4. In the chapters where we think it is important to restore it, we have mentioned this at the beginning of the chapter. In order to simplify the notation, we have sometimes partially restored \hbar in a given expression, especially when the correspondence between energy and frequency is straightforward.

To maintain homogeneous and consistent notation throughout a book which covers fields that are usually studied separately is a kind of challenge that, unfortunately, we have not always been able to overcome.

We have chosen not to give an exhaustive list of references, but instead to quote papers either for their obvious pedagogical value or because they discuss a particular point presented for instance as an exercise.

How to use this book

This book is intended to provide self-contained material which will allow the reader to derive the main results. It does not require anything other than an elementary background in general physics and quantum mechanics.

We have chosen to treat in a parallel way similar concepts occurring in the propagation of electrons and light. The important background concepts are given in Chapter 4, where the notion of *probability of quantum diffusion* in random media is developed. This is a central quantity to which all physical quantities described in this book may be related.

This book is not intended to be read linearly. We have structured it into chapters which are supposed to present the main concepts, and appendices which focus on specific aspects or details of calculation. This choice may sometimes appear arbitrary. For example, the Landauer formalism is introduced in an appendix (A7.2), where it is developed for the diffusive regime, which to our knowledge has not been done in the textbook literature. The standard description of weak localization is presented within the Kubo formalism in the core of Chapter 7, while the Landauer picture of weak localization is developed in Appendix A7.2.

We suggest here a guide for lectures. Although we have tried to emphasize analogies between interference effects in the propagation of electrons and light, we propose two outlines, for two introductory courses respectively on the physics of electrons and the physics of light. We believe that, during the course of study, the interested reader will benefit from the analogies developed between the two fields, for example the relations between speckle fluctuations in optics and universal conductance fluctuations in electronics.

Quantum transport in electronics *Main course*

1 *Introduction: mesoscopic physics* Provides a unified and general description of interference and multiple scattering effects in disordered systems. Introduces the physical problems and the main quantities of interest, the different length scales such as the mean free path and the phase coherence length, the notions of multiple scattering and disorder average. Relates the physical properties to the probability of returning to the origin in a random medium. Notion of quantum crossing. Analogies between electronics and optics.

2 Wave equations and models of disorder Schrödinger equation for electrons in solids and Helmholtz equation for electromagnetic waves. Gaussian, Edwards, Anderson models for disorder.

3 Perturbation theory Presents the minimal formalism of Green's functions necessary for the notions developed further in the book. Multiple scattering and weak disorder expansion.

4.1–4.6 Probability of quantum diffusion Definition and description of essential concepts and tools used throughout the book. Iterative structure for the quantum probability, solution of a diffusion equation. Diffuson and Cooperon contributions. Formalism developed in real space. May also be useful to look at the reciprocal space formalism developed in Appendix A4.1.

6 Dephasing Proposes a general picture for dephasing and describes several mechanisms due to electron coupling to external parameters or degrees of freedom: magnetic field, Aharonov–Bohm flux, spin-orbit coupling and magnetic impurities. May be skipped at the introductory level, except for magnetic field and Aharonov–Bohm effects.

7 Electronic transport Deals with calculations of the average conductivity and of the weak localization correction. The latter is related to the probability of return to the origin for a diffusive particle. Applications to various geometries, plane, ring, cylinder, dimensionality effects. Section A7.2 is a comprehensive appendix on the Landauer formalism for diffusive systems.

10 Spectral properties of disordered metals Generalities on random matrix theory. Spectral correlation functions for disordered systems. The last part requires knowledge of correlation functions calculated in Appendix A4.4.

11 Universal conductance fluctuations Detailed calculation of the conductance fluctuations in the Kubo formalism, using the diagrammatics developed in Chapters 4 and 7. Many physical discussions on the role of various external parameters.

13 Interactions and diffusion Important chapter on the role of electron–electron interaction and its interplay with disorder. Density of states anomaly, correction to the conductivity. Important discussions about lifetime of quasiparticles and phase coherence time.

14 Persistent currents Can be considered optional. Thermodynamics and orbital magnetism of mesoscopic systems. Problematics of persistent currents, from the very simple one-dimensional description to the effect of disorder and interaction.

Optional

5 Properties of the diffusion equation Provides a comprehensive and self-contained account of properties of the diffusion equation. Diffusion in finite systems, boundary conditions, diffusion on graphs.

Miscellaneous Various appendices are beyond an introductory level, or are not necessary in a first course on mesoscopic physics. They either develop technicalities such as Hikami boxes (A4.2), Cooperon in a time dependent magnetic field (A6.3), or important extensions

such as anisotropic collisions developed in A4.3 and their effect on weak localization (A7.4) and universal conductance fluctuations (A11.1). The Landauer formalism for diffusive systems is developed in A7.2 for the average conductance and the weak localization correction and in A11.2 for conductance fluctuations.

Propagation of light in random media
Main course

This course provides a comprehensive introduction to the propagation of light in random media. It describes coherent effects in multiple scattering: coherent backscattering, diffusing wave spectroscopy and angular and time correlations of speckle patterns. Compared to coherent electronic transport, this course emphasizes notions specific to electromagnetic waves such as angular correlations of transmission (or reflection) coefficients in open space geometry, correlation between channels in a wave guide geometry, as well as the effects of the dynamics of scatterers.

1–4 These chapters are common to the two courses. In addition section 4.6 introduces the important formalism of radiative transfer which is developed in Appendix A5.2.

6 Dephasing Generalities on the mechanism of dephasing. Application to the polarization of electromagnetic waves, dynamics of the scatterers and dephasing associated with quantum internal degrees of freedom for the case of scattering of photons by cold atoms (the last topic is treated in Appendix A6.5).

8 Coherent backscattering of light Physics of the albedo, reflection coefficient of a diffusive medium. Coherent contribution (Cooperon) to the albedo, and its angular dependence. Uses the formalism developed in Chapter 4. Polarization and absorption effects (see also section 6.6). Extensive discussion of experimental results and coherent backscattering in various physical contexts. This chapter relies upon the results of section 5.6.

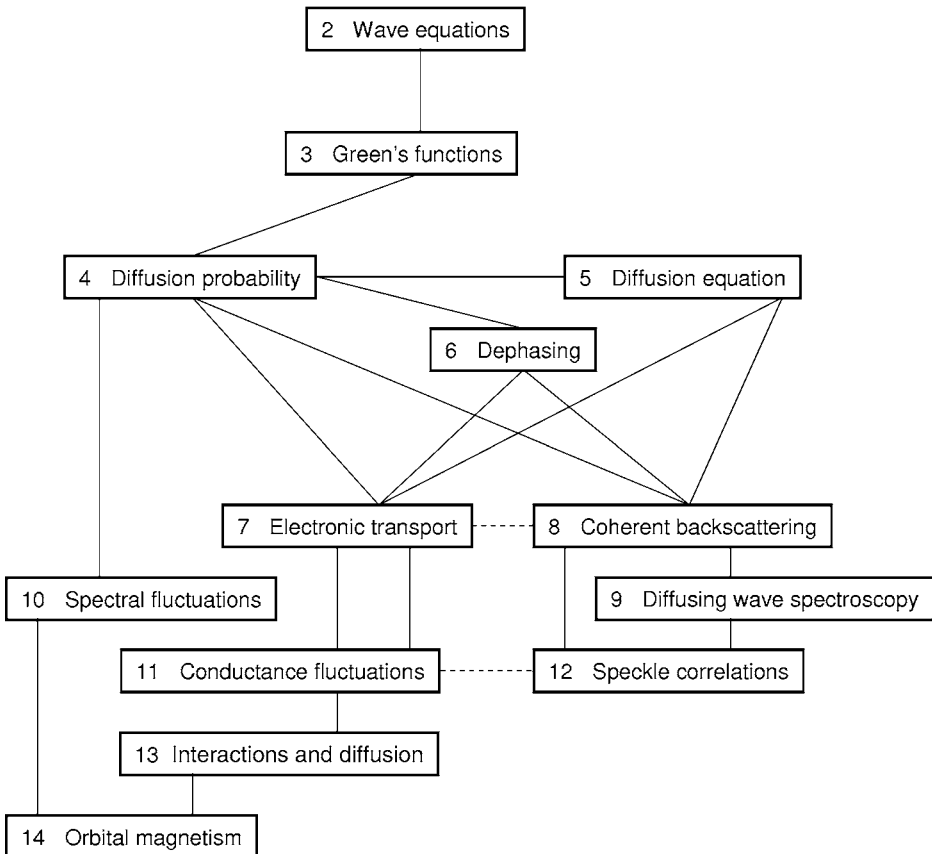
9 Diffusing wave spectroscopy An experimental technique routinely used to probe the dynamics of scatterers. Calculations result from a simple generalization of the formalism of Chapter 4. Interesting conceptually since diffusing wave spectroscopy exhibits the simplest example of decoherence introduced in a controlled way. Also interesting because this method probes the distribution of multiple scattering trajectories (reflection versus transmission experiments). Study of sections 5.6 and 5.7 is recommended.

12 Correlations of speckle patterns Analysis of a speckle pattern. Angular correlations of transmission coefficients. Classification and detailed calculation of the successive contributions C_1 , C_2 and C_3 . Simple description in terms of quantum crossings. Rayleigh law. Use of the Landauer formalism to relate speckle correlations to universal conductance fluctuations.

Optional

5 Properties of the diffusion equation Solutions of the diffusion equation in quasi-one-dimensional geometries, useful for calculations developed in Chapters 8, 9 and 12. Important appendix A5.2 on radiative transfer.

Miscellaneous Various appendices are useful reminders for beginners, for example A2.1 on scattering theory and A2.3 on light scattering by individual scatterers (Rayleigh, Rayleigh–Gans, Mie, resonant). Other appendices go beyond a course at the introductory level, either because they develop additional technicalities such as Hikami boxes (A4.2), useful for the reader interested in detailed calculations of Chapter 12, or because they present additional aspects of multiple scattering of light by random media such as spatial correlations of light intensity (A12.1) or anisotropic collisions (A4.3) and their consequences. The Landauer formalism for diffusive systems is used extensively in Chapter 12 on speckle correlations. Appendix A6.5 gives an overview of the technical tools needed to study the specific problem of multiple scattering of photons by cold atoms.



Topics developed in this book. Lines represent logical links between chapters.