

Contents

1	Introducing Decoherence	1
2	The Basic Formalism and Interpretation of Decoherence ..	13
2.1	The Concept and Interpretation of Quantum States	14
2.1.1	Classical Versus Quantum States	14
2.1.2	The Probabilistic Nature of Quantum States	16
2.1.3	The Ontological Status of Quantum States	18
2.2	The Superposition Principle	20
2.2.1	The Interpretation of Superpositions	20
2.2.2	Experimental Verification of Superpositions	21
2.2.3	The Scope of the Superposition Principle	26
2.3	Quantum Entanglement	28
2.3.1	Quantum Versus Classical Correlations	30
2.3.2	Quantification of Entanglement and Distinguishability	32
2.4	The Concept and Interpretation of Density Matrices	33
2.4.1	Pure-State Density Matrices and the Trace Operation .	34
2.4.2	Mixed-State Density Matrices	36
2.4.3	Quantifying the Degree of “Mixedness”	39
2.4.4	The Basis Ambiguity of Mixed-State Density Matrices	41
2.4.5	Mixed-State Density Matrices Versus Physical Ensembles	43
2.4.6	Reduced Density Matrices	44
2.5	The Measurement Problem and the Quantum-to-Classical Transition	49
2.5.1	The Von Neumann Scheme for Ideal Quantum Measurement	50
2.5.2	The Problem of the Preferred Basis	53
2.5.3	The Problem of the Nonobservability of Interference ..	55
2.5.4	The Problem of Outcomes	57
2.6	Which-Path Information and Environmental Monitoring	60
2.6.1	The Double-Slit Experiment, Which-Path Information, and Complementarity	60
2.6.2	The Description of the Double-Slit Experiment in Terms of Entanglement	63
2.6.3	The Environment as a Which-Path Monitor	65

2.7	Decoherence and the Local Damping of Interference	68
2.8	Environment-Induced Superselection	71
2.8.1	Pointer States in the Quantum-Measurement Limit	76
2.8.2	Pointer States in the Quantum Limit of Decoherence	81
2.8.3	General Methods for Determining the Pointer States	81
2.8.4	Selection of Quasiclassical Properties	83
2.9	Redundant Encoding of Information in the Environment and “Quantum Darwinism”	85
2.10	A Simple Model for Decoherence	88
2.11	Decoherence Versus Dissipation	93
2.12	Decoherence Versus Classical Noise	95
2.13	Virtual Decoherence and Quantum “Erasure”	98
2.14	Resolution into Subsystems	101
2.15	Formal Tools and Their Interpretation	103
2.15.1	The Schmidt Decomposition	104
2.15.2	The Wigner Representation	106
2.15.3	“Purifying” the Environment	109
2.15.4	The Operator-Sum Formalism	110
2.16	Summary	112
3	Decoherence Is Everywhere:	
	Localization Due to Environmental Scattering	115
3.1	The Scattering Model	119
3.2	Calculating the Decoherence Factor	122
3.3	Full Versus Partial Which-Path Resolution	128
3.3.1	The Short-Wavelength Limit	128
3.3.2	The Long-Wavelength Limit	130
3.4	Decoherence Due to Scattering of Thermal Photons and Air Molecules	132
3.4.1	Photon Scattering	132
3.4.2	Scattering of Air Molecules	136
3.4.3	Comparison with Experiments	138
3.5	Illustrating the Dynamics of Decoherence	139
3.6	Summary	150
4	Master-Equation Formulations of Decoherence	153
4.1	General Formalism	154
4.2	The Born–Markov Master Equation	155
4.2.1	Structure of the Born–Markov Master Equation	156
4.2.2	Derivation of the Born–Markov Master Equation	158
4.3	Master Equations in the Lindblad Form	165
4.4	Non-Markovian Dynamics	169

5 A World of Spins and Oscillators:
Canonical Models for Decoherence 171

5.1 Mapping onto Canonical Models 173

 5.1.1 Mapping of the Central System 173

 5.1.2 Mapping of the Environment 174

5.2 Quantum Brownian Motion 178

 5.2.1 Derivation of the Born–Markov Master Equation 178

 5.2.2 Harmonic Oscillator as the Central System 182

 5.2.3 Ohmic Decoherence and Dissipation 188

 5.2.4 The Caldeira–Leggett Master Equation 191

 5.2.5 Dynamics of Quantum Brownian Motion 194

 5.2.6 Limitations of the Quantum Brownian Motion
 and Caldeira–Leggett Models 203

 5.2.7 Exact Master Equation 206

5.3 The Spin–Boson Model 207

 5.3.1 Simplified Spin–Boson Model Without Tunneling 208

 5.3.2 Born–Markov Master Equation
 for the Spin–Boson Model 218

5.4 Spin–Environment Models 222

 5.4.1 A Simple Dynamical Spin–Spin Model 223

 5.4.2 Spin–Environment Models in the Weak-Coupling
 Limit: Mapping to Oscillator Environments 228

 5.4.3 Beyond Markov:
 Solving General Spin–Environment Models 237

5.5 Summary 237

6 Of Buckey Balls and SQUIDs:
Observing Decoherence in Action 243

6.1 The First Milestone: Atoms in a Cavity 244

 6.1.1 Atom–Field Interactions and Rabi Oscillations 246

 6.1.2 Creating the Cat State 247

 6.1.3 Observing the Gradual Action of Decoherence 251

 6.1.4 Bringing Schrödinger Cats Back to Life 255

6.2 Interferometry with C₇₀ Molecules 258

 6.2.1 The Double-Slit Experiment with Electrons 258

 6.2.2 Experimental Setup 259

 6.2.3 Confirming the Wave Nature of Massive Molecules 262

 6.2.4 Which-Path Information and Decoherence 263

 6.2.5 Decoherence Due to Emission of Thermal Radiation 265

 6.2.6 Beyond Buckey Balls 267

6.3 SQUIDs and Other Superconducting Qubits 270

 6.3.1 Superconductivity and Supercurrents 271

 6.3.2 Basic Physics of SQUIDs 272

 6.3.3 Superposition States and Coherent Oscillations
 in SQUIDs 275

6.3.4	Observing and Quantifying Decoherence	279
6.4	Other Experimental Domains	282
6.4.1	Decoherence in Bose–Einstein Condensates	282
6.4.2	Decoherence in Quantum-Electromechanical Systems	284
6.5	Outlook	289
7	Decoherence and Quantum Computing	293
7.1	A Brief Overview of Quantum Computing	294
7.1.1	The Power of Quantum Computing	294
7.1.2	Reading Out a Quantum Computer	297
7.1.3	Simulating Physical Systems	298
7.1.4	Examples of Famous Quantum Algorithms	300
7.1.5	Physical Realizations of Quantum Computers	300
7.2	Decoherence Versus Controllability in Quantum Computers	301
7.3	Decoherence Versus Classical Fluctuations	302
7.4	Quantum Error Correction	304
7.4.1	Classical Versus Quantum Error Correction	305
7.4.2	Representing the Influence of Decoherence by Discrete Errors	307
7.4.3	“Undoing” Decoherence in a Quantum Computer	311
7.4.4	When Does an Error-Correcting Code Exist?	314
7.4.5	Importance of Redundant Encoding and the Three-Bit Code for Phase Errors	315
7.4.6	Apparatus-Induced Decoherence and Fault Tolerance	320
7.5	Quantum Computation on Decoherence-Free Subspaces	321
7.5.1	What Does a Decoherence-Free Subspace Look Like?	322
7.5.2	Experimental Realizations of Decoherence-Free Subspaces	325
7.5.3	Environment Engineering and Dynamical Decoupling	326
7.6	Summary and Outlook	327
8	The Role of Decoherence in Interpretations of Quantum Mechanics	329
8.1	The Standard and Copenhagen Interpretations	330
8.1.1	The Problem of Outcomes	331
8.1.2	Observables, Measurements, and Environment-Induced Superselection	333
8.1.3	The Concept of Classicality in the Copenhagen Interpretation	335
8.2	Relative-State Interpretations	336
8.2.1	Everett Branches and the Preferred-Basis Problem	337
8.2.2	Probabilities in Relative-State Interpretations	339
8.2.3	The “Existential Interpretation”	343
8.3	Modal Interpretations	344

8.3.1	Property Assignment Based on Environment-Induced Superselection	345
8.3.2	Property Assignment Based on Instantaneous Schmidt Decompositions	345
8.3.3	Property Assignment Based on Decompositions of the Decohered Density Matrix	346
8.4	Physical Collapse Theories	347
8.4.1	The Preferred-Basis Problem	349
8.4.2	Simultaneous Presence of Decoherence and Spontaneous Localization	350
8.4.3	The Tails Problem	351
8.4.4	Connecting Decoherence and Collapse Models	352
8.4.5	Experimental Tests of Collapse Models	353
8.5	Bohmian Mechanics	354
8.5.1	Particles as Fundamental Entities	355
8.5.2	Bohmian Trajectories and Decoherence	356
8.6	Summary	357
9	Observations, the Quantum Brain, and Decoherence	359
9.1	The Role of the Observer in Quantum Mechanics	359
9.2	Quantum Observers and the Von Neumann Chain	361
9.3	Decoherence in the Brain: The Brain as a Quantum Computer?	365
9.3.1	Decoherence Timescales for Superposition States in Neurons	368
9.3.2	Decoherence Timescales for Superposition States in Microtubules	371
9.4	“Subjective” Resolutions of the Measurement Problem	375
	Appendix: The Interaction Picture	379
	References	383
	Index	409



<http://www.springer.com/978-3-540-35773-5>

Decoherence and the Quantum-To-Classical Transition

Schlosshauer, M.A.

2007, Approx. 430 p., 72 illus., Hardcover

ISBN: 978-3-540-35773-5