

---

## Contents

### 1 Introduction

<i>J. Gonzalo Muga, Rafael Sala Mayato, and Iñigo L. Egusquiza</i> . . . . .	1
1.1 Role of Time in the Early Days of Quantum Theory . . . . .	1
1.2 The Thirties and Forties . . . . .	5
1.3 The Fifties . . . . .	7
1.4 The Sixties . . . . .	12
1.5 The Seventies: the Zeno Effect, TOA Distributions, POVMs . . . . .	16
1.6 Some Recent Trends . . . . .	18
1.7 Discussion . . . . .	24
References . . . . .	25

### 2 Characteristic Times in One-Dimensional Scattering

<i>J. Gonzalo Muga</i> . . . . .	31
2.1 Introduction . . . . .	31
2.2 Scattering Theory in 1D . . . . .	33
2.3 A Measure of the Collision Duration: The Dwell Time . . . . .	42
2.4 Importance of the Phases: Time Delays . . . . .	46
2.5 Time Dependence of Survival Probability: Exponential Decay and Deviations . . . . .	55
2.6 Other Characteristic Times of Wave Propagation . . . . .	61
References . . . . .	69

### 3 The Time–Energy Uncertainty Relation

<i>Paul Busch</i> . . . . .	73
3.1 Introduction . . . . .	73
3.2 The Three-fold Role of Time in Quantum Theory . . . . .	73
3.3 Relation Between External Time and Energy Spread . . . . .	76
3.4 Relations Involving Intrinsic Time . . . . .	82
3.5 Quantum Clock . . . . .	89
3.6 Relations Based on Time Observables . . . . .	91
3.7 Conclusion . . . . .	103
References . . . . .	104

**4 Jump Time and Passage Time: The Duration of a Quantum Transition**

*Lawrence S. Schulman* ..... 107

4.1 Introduction ..... 107

4.2 Jump Time ..... 109

4.3 Corroborations of the Definition ..... 111

4.4 Passage Time ..... 116

4.5 Experimental Discrimination among Quantum Measurement Theories and “Special States” ..... 120

4.6 Discussion ..... 124

References ..... 126

**5 Bohm Trajectory Approach to Timing Electrons**

*C. Richard Leavens* ..... 129

5.1 Introduction ..... 129

5.2 Motivation for Using a Trajectory Approach ..... 130

5.3 Bohm’s Ontological Interpretation of Quantum Theory ..... 131

5.4 Conventional Approaches to Timing Quantum Particles from the Perspective of Bohmian Mechanics ..... 140

5.5 Spin-Dependent Arrival-Time Distributions for Nonrelativistic Electrons ..... 147

5.6 Protective Measurements and Bohm Trajectories ..... 150

5.7 Concluding Comments ..... 156

References ..... 160

**6 Decoherent Histories for Space–Time Domains**

*Jonathan J. Halliwell* ..... 163

6.1 Introduction ..... 163

6.2 Decoherent Histories Approach to Quantum Theory ..... 167

6.3 Space–Time Coarse Grainings ..... 170

6.4 Decoherence of Space–Time Coarse-Grained Histories in the Quantum Brownian Motion Model ..... 172

6.5 A Detector Model ..... 178

6.6 A Comparison of the Decoherent Histories Result with the Detector Result ..... 182

6.7 Timeless Questions in Quantum Theory ..... 184

6.8 Discussion ..... 187

6.9 An Update for the Second Edition ..... 189

References ..... 190

**7 Quantum Traversal Time, Path Integrals and ‘Superluminal’ Tunnelling**

*Dmitri Sokolovski* ..... 195

7.1 Introduction ..... 195

7.2 Path Decomposition. The Clocked Schrödinger Equation. Coarse Graining ..... 196

7.3	Meters and Measurements. Uncertainty Relation .....	200
7.4	Averages. Complex Times. Weak Measurements .....	202
7.5	Examples: Free motion and Tunnelling .....	204
7.6	Semiclassical Limit. How Long Does it Take for a Particle to Tunnel? .....	207
7.7	Larmor Clock as a Realistic Meter .....	208
7.8	Traversal Time Analysis .....	214
7.9	Traversal Time and the “Superluminal” Tunnelling .....	216
7.10	Relativistic Traversal Time .....	220
7.11	“Superluminal” Paradox and the Speed of Information Transfer ...	225
7.12	Concluding Remarks .....	230
	References .....	231
<b>8 Quantum Clocks and Stopwatches</b>		
	<i>Rafael Sala Mayato, Daniel Alonso, and Iñigo L. Egusquiza</i> .....	235
8.1	Introduction .....	235
8.2	What is a Clock? .....	237
8.3	The Salecker–Wigner Clock .....	238
8.4	The Larmor Clock .....	248
8.5	Other Clocks .....	256
8.6	Simple “Time-dependent” Clocks: the Kick Clock .....	263
8.7	Decoherence in Time .....	270
	References .....	275
<b>9 The Local Larmor Clock, Partial Densities of States, and Mesoscopic Physics</b>		
	<i>Markus Büttiker</i> .....	279
9.1	Introduction .....	279
9.2	The Scattering Matrix and the Local Larmor Clock .....	282
9.3	Absorption and Emission of Particles: Injectivities and Emissivities	286
9.4	Potential Perturbations .....	289
9.5	Generalized Bardeen Formulae .....	290
9.6	Voltage Probe and Inelastic Scattering .....	291
9.7	AC Conductance of Mesoscopic Conductors .....	293
9.8	Transition from Capacitive to Inductive Response .....	294
9.9	Partial Density of States Matrix .....	296
9.10	Local Friedel Sum Rule .....	300
9.11	Discussion .....	301
	References .....	301
<b>10 “Standard” Quantum–Mechanical Approach to Times of Arrival</b>		
	<i>Iñigo L. Egusquiza, J. Gonzalo Muga, and Andrés D. Baute</i> .....	305
10.1	Introduction .....	305
10.2	Kijowski’s Time-of-Arrival Distribution .....	306
10.3	POVMs .....	308

10.4	The POVM of the Aharonov–Bohm Time Operator	315
10.5	Other Time Operators	320
10.6	Arrival States	323
10.7	Times of Arrival for Identical Particles	327
10.8	How can Kijowski’s distribution be measured?	329
10.9	Conclusions and Outlook	329
	References	330
<b>11 Experimental Issues in Quantum–Mechanical Time Measurement</b>		
	<i>Aephraim M. Steinberg</i>	333
11.1	Time Operators Versus Real Measurements	333
11.2	Arrival-Time Measurements	335
11.3	Dwell or Interaction Time Measurements	342
11.4	Weak Measurements	347
11.5	Conclusion	350
	References	351
<b>12 Microwave Experiments on Tunneling Time</b>		
	<i>Daniela Mugnai and Anedio Ranfagni</i>	355
12.1	An Overview of Theoretical Models of Tunneling in the Electromagnetic Framework	355
12.2	Sub cutoff Microwave Propagation in Waveguide	374
12.3	Delay-Time Measurements in a Diffraction Experiment	383
12.4	Tunneling Time in Frustrated Total Reflection	389
12.5	Concluding Remarks	395
	References	395
<b>13 The Two-State Vector Formalism: An Updated Review</b>		
	<i>Yakir Aharonov and Lev Vaidman</i>	399
13.1	Introduction	399
13.2	Descriptions of Quantum Systems	399
13.3	Ideal Quantum Measurements	405
13.4	Weak Measurements	409
13.5	The Quantum Time-Translation Machine	424
13.6	Time Symmetry	433
13.7	Protective Measurements	441
13.8	The TSVF and the Many-Worlds Interpretation of Quantum Theory	443
	References	444
	<b>Index</b>	449