

# Contents

<b>1</b>	<b>Introduction</b>	1
	References	6
<b>2</b>	<b>Classical Clocks in General Relativity</b>	9
2.1	Point Particles with Internal Degrees of Freedom	9
2.1.1	Hamiltonian	9
2.1.2	Lagrangian	11
2.1.3	Energy-Momentum Tensor	13
2.1.4	Routhian or Point Particles as Ideal Clocks	14
2.1.5	Low Energy and Non-relativistic Limits and Symmetries of the Framework	17
2.2	Derivation of the Point-Particle Framework	22
2.2.1	Effective Dynamics of Relativistic N-Particle Systems	22
2.2.2	Quantitative Discussion of the Approximations	25
2.3	Relevance of the Framework for Experiments	26
	References	28
<b>3</b>	<b>Quantum Clocks in General Relativity</b>	29
3.1	Quantisation of the Composite Point-Particle Framework	29
3.2	Low-Energy and Non-relativistic Limits, and Symmetries of the Framework	31
3.3	Mass Superselection Rule in the Context of Composite Particles	34
	References	35
<b>4</b>	<b>Quantum Complementarity and Time Dilation</b>	37
4.1	Quantum Complementarity—Interferometric Visibility Versus Which-Way Information	37
4.2	Which-Way Information from Time Dilation—Gedankenexperiment	43
	References	46

<b>5</b>	<b>Interference of “Clocks”—Experimental Proposals</b>	47
5.1	Massive Particle as a “clock”	47
5.1.1	Time Dilation Effects for Massive Quantum Systems	47
5.1.2	Two-Level Quantum System as a Clock	50
5.1.3	Quantitative Predictions	53
5.1.4	Discussion	55
5.2	Photons as Clocks	56
5.2.1	Gravitational Time Dilation for Light—Shapiro Delay	57
5.2.2	Gaussian Photon Wave-Packet as a Clock	59
5.2.3	Quantitative Predictions	61
5.2.4	Discussion	63
5.3	General Relativistic and Quantum Aspects of the Proposals	65
	References	67
<b>6</b>	<b>Decoherence from Time Dilation</b>	71
6.1	Visibility for General Internal States	71
6.2	Visibility and Decoherence Time for Thermal States	73
6.3	Ideas for Experimental Verification	75
6.4	Discussion	76
	References	78
<b>7</b>	<b>Quantum Formulation of the Einstein Equivalence Principle</b>	81
7.1	Motivation	81
7.2	Quantum Formulation and Test Theory of the EEP	83
7.3	Testing the Quantum Formulation of the EEP	87
7.3.1	Testing the Quantum Formulation of the WEP	88
7.3.2	Testing the Quantum Formulation of the LPI and LLI	90
7.4	Discussion	94
	References	95
<b>8</b>	<b>Clocks Beyond Classical Space-Time</b>	99
8.1	Superpositions of Temporal Order	99
8.2	Bell Inequalities for Temporal Order	103
8.2.1	Violation of Bell Inequalities for Temporal Order	106
8.3	Discussion	110
	References	113
<b>9</b>	<b>Conclusions and Outlook</b>	115
	References	117
	<b>Appendix A</b>	119
	<b>Appendix B</b>	121
	<b>Appendix C</b>	123
	<b>Appendix D</b>	127

Contents	xiii
<b>Appendix E</b> . . . . .	129
<b>Appendix F</b> . . . . .	137

Quantum Systems under Gravitational Time Dilation

Zych, M.

2017, XIII, 139 p. 17 illus., 15 illus. in color., Hardcover

ISBN: 978-3-319-53191-5