Contents

Part I John S. Bell – The Man

1 Some Reminiscences
Mary Bell 3

2 John Bell in Belfast: Early Years and Education
Andrew Whitaker 7

2.1 Introduction 7
2.2 Family and Early Life 7
2.3 Queen's University as a Technician 8
2.4 A Student at Queen's 10
2.5 Early Ideas on Quantum Theory 14
2.6 John Bell and Michael Faraday 18

3 My Interaction with John Bell
Bernard d'Espagnat 21

4 Magic Moments: A Collaboration with John Bell
Reinhold A. Bertlmann 29

4.1 Prologue 29
4.2 Duality in Hadronic Reactions 30
4.2.1 Hadron Production in e^+e^- Collisions 30
4.2.2 Duality 32
4.3 Nonrelativistic Potential Theory 32
4.3.1 Résumé 34
4.4 Magic Moments 35
4.4.1 Moments 37
4.4.2 Ground State 38
4.4.3 Balance 39
4.5 Equivalent Potential 40
4.6 Epilogue 42

Part II Tests of Bell's Inequalities

5 John S. Bell: Some Reminiscences and Reflections
Abner Shimony 51

5.1 Why was Bell the Discoverer of Bell's Theorem? 51
5.2 Some Reminiscences 55
5.3 In What Direction Does Bell's Theorem Point? 57

6 Early History of Bell's Theorem
John F. Clauser 61

6.1 Introduction 61
6.2 An Unresolved Issue Left by the Founding Fathers 63
6.3 An Untidy Legacy Left by the Founders of Quantum Mechanics . . 66
6.4 Evangelical Theoreticians Dominate 69
6.5 The Development of a "Stigma" 71
6.6 Challenging the Common Wisdom 74
6.7 John Bell Unravels the Confusion 75
6.8 Theoretical Truth Versus Experimental Truth 77
6.9 Beware of the Experimentalists Lurking About 81
6.10 Generalization of the Bell and CHSH Results to Constrain Local Realism and Space-Time 82
6.11 Common Confusion About Count-Rate Normalization 87
6.12 Bell's Response to CH and "Local Beables" 88
6.13 The Quantum-Optics Community Encounters Related Problems . . 89
6.14 Splitting Photons? 91
6.15 Remaining Locality Loopholes 94
6.16 Conclusions 96

7 On Four Decades of Interaction with John Bell
Michael Horne 99

8 Atom Based Tests of the Bell Inequalities – the Legacy of John Bell Continues . . .
Edward S. Fry and Thomas Walther 103

8.1 Historical Overview 103
8.2 The Bell–Clauser–Horne Inequality 106
8.3 Loopholes 107
8.3.1 The First Loophole 107
8.3.2 The Second Loophole 108
8.3.3 The Third Loophole 108
8.4 Atom Based Experiments 109
8.4.1 The Paris Experiments 109

8.4.2 The Boulder Experiments . . . 110
8.4.3 The Texas A&M Experiment . . . 111
8.5 Summary . . . 116

9 Bell's Theorem: The Naive View of an Experimentalist
Alain Aspect . . . 119

9.1 Introduction . . . 119
9.2 Why Have Supplementary Parameters?
The Einstein–Podolsky–Rosen–Bohm Gedankenexperiment . . . 121
9.2.1 Experimental Scheme . . . 121
9.2.2 Correlations . . . 122
9.2.3 Difficulty of an Image
Derived from the Formalism of Quantum Mechanics . . . 123
9.2.4 Supplementary Parameters . . . 124
9.3 Bell's Inequalities . . . 125
9.3.1 Formalism . . . 125
9.3.2 A (Naive) Example
of the Supplementary-Parameter Theory . . . 126
9.3.3 The Inequalities . . . 127
9.4 Conflict with Quantum Mechanics . . . 128
9.4.1 Evidence . . . 128
9.4.2 Maximum Conflict . . . 129
9.5 Discussion: The Locality Condition . . . 130
9.6 Gedankenexperiment with Variable Analyzers:
The Locality Condition as a Consequence of Einstein's Causality . 131
9.7 From Bell's Theorem to a Realistic Experiment . . . 133
9.7.1 Experimentally Testing Bell's Inequalities . . . 133
9.7.2 Sensitive Situations Are Rare . . . 133
9.7.3 Production of Pairs of Photons in an EPR State . . . 134
9.7.4 Realistic Experiment . . . 135
9.7.5 Timing Conditions . . . 136
9.8 First-Generation Experiments . . . 136
9.8.1 Experiments with a One-Channel Polarizer . . . 136
9.8.2 Results . . . 137
9.9 Orsay Experiments (1980–1982) . . . 138
9.9.1 The Source . . . 138
9.9.2 Detection–Coincidence Counting . . . 139
9.9.3 Experiment with One-Channel Polarizers . . . 140
9.9.4 Experiment with Two-Channel Analyzers . . . 141
9.9.5 Timing Experiment . . . 143
9.10 Third Generation: Experiments with Pairs of Photons
Produced in Parametric Down Conversion . . . 146
9.11 Conclusion . . . 149

10 Bell's Theorem for Space-Like Separation
Gregor Weihs 155

10.1 From Gedanken to Real Experiments 155
10.2 Efficiency 156
10.2.1 Reducing the Required Efficiency 157
10.2.2 State of the Art and Development of Optical Experiments 158
10.2.3 A Proposal Using Mercury Atoms 158
10.2.4 Closure of the Detection Efficiency Loophole with an Ion Trap Experiment 159
10.3 Locality 159
10.3.1 Experiments with Large Separation Between Measurement Stations 160
10.3.2 Analyzer Switching 161

11 The EPR Paradox in Massive Systems or about Strange Particles
Reinhold A. Bertlmann, Walter Grimus and Beatrix C. Hiesmayr 163

11.1 Introduction 164
11.2 The Bell–CHSH Inequality for Photons and for Kaons 164
11.3 A Neutral Kaon Introduces Itself 167
11.4 The Experiment at CERN and Possible Decoherence 169
11.5 The Generalized Bell Inequality and Unitary Time Evolution 175
11.5.1 The Choice of the Strangeness Eigenstate 178
11.5.2 The Choice Sensitive to the CP Violating Parameter, ε . . 178
11.6 Connection of the Bell Inequality and the Decoherence Approach . 179
11.7 Final Remark 180

Part III Quantum Information

12 Are There Measurements?
Stig Stenholm 185

12.1 An Encounter with John Bell 185
12.2 Measurements or Not? 187
12.3 Describing a Measurement 189
12.4 How to Map Reality 193
12.5 Conclusion 196

13 Sundays in a Quantum Engineer's Life
Nicolas Gisin 199

13.1 I am a Quantum Engineer, but on Sundays I Have Principles 199
13.2 Quantum Cryptography on Sundays 199
13.3 Let's Assume That the Collapse Is Real 201

13.4 ... and Relativity? 204
13.5 Conclusion 206

14 Secret Sides of Bell's Theorem
Artur Ekert 209

14.1 Is the Bell Theorem of any Practical Use? 209
14.2 Is There a Perfect Cipher? 210
14.3 Quantum Key Distribution 213
14.4 Eavesdropping Revisited 216
14.5 Quantum Privacy Amplification 218
14.6 Concluding Remarks 219

15 An Impossible Necklace
Lev Vaidman 221

16 Multi-Photon Entanglement and Quantum Non-Locality
Jian-Wei Pan and Anton Zeilinger 225

16.1 Introduction 225
16.2 The GHZ Theorem 226
16.3 Experimental Multi-Photon GHZ Entanglement 229
16.4 Experimental Test of Quantum Non-Locality 233
16.5 Discussions and Prospects 237

17 Bell's Theorem, Information and Quantum Physics
Anton Zeilinger 241

17.1 Introduction 241
17.2 Information and Interference 242
17.3 Information and Entanglement 244
17.4 Bell's Theorem, Quantum Communication and Quantum Information 246
17.4.1 Quantum Dense Coding 246
17.4.2 Quantum Teleportation 248
17.4.3 Teleportation of Entanglement 249
17.4.4 Quantum Cryptography 251
17.5 John Bell's Desiderata and the Interpretation of Quantum Mechanics 252

Part IV Quantum Ideas

18 The Geometry of the Quantum Paradoxes
John Conway and Simon Kochen 257

18.1 Introduction 257
18.2 Old Paradoxes 258

18.3 New Paradoxes and Their Geometry 262
18.4 Reconstructing Quantum Mechanics 267

19 Whose Knowledge?
N. David Mermin 271

20 The History of the GHZ Paper
Daniel M. Greenberger 281

21 John Stewart Bell and the Dynamical Reduction Program
GianCarlo Ghirardi 287

21.1 John Stewart Bell and His Role 288
21.2 His Role Before 1985 289
21.3 The Birth of Dynamical Reduction Theories 291
21.3.1 Stochastic Equations for the Description of Decay Processes 291
21.3.2 Stochastic Differential Equations 291
21.3.3 The Breakthrough – Quantum Mechanics with Spontaneous Localizations 292
21.4 His Role Immediately After the Publication of Our Paper 293
21.4.1 The Letter 294
21.4.2 The Paper: Are There Quantum Jumps? 296
21.4.3 The Relativistic Issue 297
21.5 From QMSL to Continuous Spontaneous Localization (CSL) 298
21.6 The Subsequent Role of J.S. Bell in the Dynamical Reduction Program 301
21.6.1 Problems of Interpretation 301
21.6.2 The Relativistic Program 302
21.7 Concluding Remarks 303

22 How Does God Play Dice? (Pre-)Determinism at the Planck Scale
Gerard 't Hooft 307

22.1 Dice 307
22.2 Quantum Interference 314
22.3 Quantum Coherence and Entanglement 314
22.4 The Einstein–Rosen–Podolsky Paradox and the Violation of the Bell Inequalities 315

Part V Quantum Specials

23 John Bell, State Reduction, and Quanglement
Roger Penrose 319

23.1 Encounters with John Bell 319
23.2 Gravitationally Induced State Reduction: A Minimalist View 321
23.3 Quanglement 326

24 Interferometry with Macromolecules: Quantum Paradigms Tested in the Mesoscopic World
Markus Arndt, Olaf Nairz, Anton Zeilinger 333

24.1 A Prototype Quantum Experiment 333
24.2 Interference of Fullerenes 336
24.3 Decoherence 340
24.3.1 Vibrational Transitions 342
24.3.2 Emission of Blackbody Radiation 343
24.3.3 Absorption of Blackbody Radiation 344
24.3.4 Rayleigh Scattering of Thermal Radiation 344
24.3.5 Fragmentation and Ionization 345
24.3.6 Influence of Collisions with the Residual Gas 345
24.3.7 Quasi-Static Interactions 346
24.3.8 Magnetic Interactions 346
24.3.9 Electric Interactions 347
24.3.10 Inertial Forces 347
24.3.11 Which-Way Information in Internal Clocks 348
24.4 Conclusion 349

25 Towards More Quantum Complete Neutron Experiments
Helmut Rauch 351

25.1 Introduction – Basic Relations 351
25.2 Classic Neutron Interference Experiments 355
25.2.1 Gravity Experiments 355
25.2.2 Neutron Fizeau Effect 356
25.2.3 4π Spinor Symmetry 356
25.2.4 Spin Superposition 357
25.2.5 Neutron Josephson Effect 359
25.2.6 Stochastic Versus Deterministic Beam-Path Detection 360
25.3 Postselection Experiments 362
25.3.1 Postselection of Momentum States 362
25.3.2 Contrast Retrieval by Phase Echo 366
25.4 Phase-Space Coupling 366
25.5 Topological Effects 368
25.6 Discussion 370

Part VI Particles and Fields

26 John Bell's Observations on the Chiral Anomaly and Some Properties of Its Descendants
Roman Jackiw 377

26.1 John Bell and the Chiral Anomaly 377
26.2 Descendants of the Anomaly 379

27 Fractional Charge
R. Rajaraman 383

27.1 Introduction 383
27.2 Fractional Charge in Field Theory 384
27.2.1 Vacuum Sector 385
27.2.2 Soliton Sector 387
27.3 Polyacetylene 389
27.4 Eigenvalue or Expectation Value? 391
27.4.1 Polyacetylene Re-Visited 396
27.5 Conclusion 397

28 Thermal Excitations of Accelerated Electrons
Jon Magne Leinaas 401

28.1 Electrons as a Thermometer 401
28.2 Linear Acceleration and the Unruh Effect 403
28.3 Stationary World Lines 406
28.4 Electrons in a Storage Ring 407
28.5 Concluding Remarks 411

29 Bell's Spaceships and Special Relativity
Franco Selleri 413

29.1 The Generalised Transformations 413
29.2 Michelson-Type Experiments 416
29.3 Jupiter's Satellites Occultations 417
29.4 Aberration 419
29.5 Radar Ranging of Planets 420
29.6 Proofs of Absolute Simultaneity 421
29.7 The Inertial Transformations 425

30 John Bell and the Ten Challenges of Subnuclear Physics
Antonino Zichichi 429

30.1 Introduction 429
30.2 The Remarkable Value of John Bell's Support to My Physics 431
30.3 The LAA Project in a Few Words 447
30.4 Facilities and the Basic Steps 448

30.5 The Ten Challenges 451
30.5.1 The Physics of Imaginary Masses (SSB) 451
30.5.2 Matter–Antimatter Symmetry 454
30.5.3 Supersymmetry 455
30.5.4 Non-perturbative QCD 457
30.5.5 Anomalies and Instantons 458
30.5.6 Flavour Mixing in the Quark Sector 462
30.5.7 Flavour Mixing in the Leptonic Sector 464
30.5.8 The Problem of the Missing Mass in the Universe 466
30.5.9 The Problem of Hierarchy 468
30.5.10 The Physics at the Planck Scale: The Gap and the Number of Expanded Dimensions 469
30.6 The ELN Project in a Few Words 471
30.7 Conclusions 473

Subject Index 479