

# Contents

|  |     |
|--|-----|
| Preamble .....   | III |
| Coordinators, Contributors, Sponsors and Acknowledgments ..... | VII |
| Preface .....  | XI  |

---

## CHAPTER 1

|   |    |
|---|----|
| Cooling and Trapping Atoms .....  | 1  |
| 1.1 When an Atom Meets a Photon .....   | 1  |
| 1.1.1 The Atom Slows Down.....  | 3  |
| 1.1.2 ... The Gas Temperature Drops .....   | 5  |
| 1.2 Atomic Traps of All Kinds .....   | 7  |
| 1.2.1 With Lasers and a Magnetic Field: The All-Purpose Trap .....                      | 7  |
| 1.2.2 Optical Tweezers to Catch and Immobilize Atoms .....                              | 9  |
| 1.2.3 With Magnetic Fields: From Large Volume Traps to Atomic<br>Chips .....            | 11 |
| 1.3 Even Colder: The Gas Changes State .....  | 14 |
| 1.3.1 Last Step Towards the Absolute Zero: We Evaporate .....                           | 14 |
| 1.3.2 Finally, the Grail, the Bose–Einstein Condensation:<br>The Atoms All as One!..... | 15 |
| 1.3.3 Atom Boxes Made of Light .....  | 18 |
| 1.3.4 Atoms can Attract or Repel .....  | 19 |
| 1.4 And the Whole Jungle of Particles on a Microscopic Scale .....                      | 21 |
| 1.4.1 What is Matter Made of? Bosons and Fermions .....                                 | 21 |
| 1.4.2 Fermions can also Get Ultra-Cold .....  | 22 |
| 1.5 Conclusion .....  | 23 |

---

## CHAPTER 2

|  |    |
|--|----|
| Cold Atom Instruments and Metrology .....                      | 25 |
| 2.1 What is Metrology? .....                                   | 25 |
| 2.1.1 Concepts of Statistical and Systematic Uncertainty ..... | 25 |
| 2.1.2 Atoms as References.....                                 | 26 |
| 2.1.3 Metrology with Quantum Systems .....                     | 27 |
| 2.2 Atomic Clocks .....  | 27 |
| 2.2.1 Principle of an Atomic Clock .....                       | 27 |
| 2.2.2 Why Use Cold Atoms? .....                                | 29 |

|       |  |    |
|-------|--|----|
| 2.2.3 | Cold Cesium Atom Clocks . . . . .  | 29 |
| 2.2.4 | Trapping Atoms to Improve Accuracy . . . . .   | 31 |
| 2.2.5 | Optical Clocks and the Future Definition of the Second . . . . .                                       | 31 |
| 2.2.6 | Links between Clocks and Time Scales . . . . .   | 33 |
| 2.3   | Atom Interferometers . . . . .   | 33 |
| 2.3.1 | Principle of an Atom Interferometer, Similarities and Differences with a Cesium Atomic Clock . . . . . | 33 |
| 2.3.2 | Inertial Sensors Based on Atom Interferometry . . . . .  | 36 |
| 2.3.3 | Maturity of the Sensors and Industrial Transfer . . . . .  | 38 |
| 2.3.4 | Novel Architectures . . . . .  | 39 |
| 2.4   | Probing the Fundamental Laws of Physics with Cold Atoms Sensors . . . . .                              | 40 |
| 2.4.1 | Gravimetry and Chrono-Geodesy . . . . .  | 41 |
| 2.4.2 | General Relativity and Gravitational Waves . . . . .   | 42 |
| 2.4.3 | Standard Model and Dark Matter . . . . .   | 43 |

---

## CHAPTER 3

|  |    |
|--|----|
| Single Atoms and Single Photons: Quantum Information Exchange . . . . .      | 45 |
| 3.1 How to See a Single Atom . . . . .                                       | 46 |
| 3.2 The Benefit of Cavities . . . . .  | 48 |
| 3.3 Strong Coupling Between a Photon and an Atom: The Rabi Doublet . . . . . | 50 |
| 3.4 The Atom Becomes a Qubit . . . . .                                       | 51 |
| 3.5 Microcavities . . . . .  | 52 |
| 3.6 Detecting the State of a Qubit . . . . .                                 | 54 |
| 3.7 Storing Quantum Information in Cold Atoms: Quantum Memories . . . . .    | 56 |
| 3.8 Improving Clocks with Entanglement: Spin-Squeezed States . . . . .       | 59 |

---

## CHAPTER 4

|  |    |
|--|----|
| Quantum Simulation with Cold Atoms . . . . .                                     | 65 |
| 4.1 What is Quantum Simulation? . . . . .  | 65 |
| 4.1.1 From Classical Matter to Quantum Particles . . . . .                       | 65 |
| 4.1.2 Challenges in Understanding Complex Quantum Systems . . . . .              | 67 |
| 4.2 Ultracold Atoms and Quantum Simulation . . . . .                             | 70 |
| 4.2.1 Ultracold Gases: Dilute Systems with Complex Collective Behavior . . . . . | 70 |
| 4.2.2 Why are Cold Atoms Good Quantum Simulators? . . . . .                      | 72 |
| 4.3 Observing a Quantum System Atom by Atom . . . . .                            | 75 |
| 4.3.1 Visualizing Atoms in an Optical Lattice . . . . .                          | 75 |
| 4.3.2 Assembling Artificial Crystals Atom by Atom . . . . .                      | 76 |
| 4.4 What can We Simulate with Cold Atoms? . . . . .                              | 77 |
| 4.4.1 Quantum Magnetism . . . . .  | 77 |
| 4.4.2 Origin of Superconductivity . . . . .                                      | 79 |
| 4.4.3 Improving our Understanding of Strongly Correlated Materials . . . . .     | 80 |
| 4.4.4 Other Prospects . . . . .  | 81 |

---

CHAPTER 5

|   |     |
|---|-----|
| Waves and Disorder . . . . .  | 83  |
| 5.1 Waves and Disorder, very Rich Physical Systems! . . . . .                                 | 83  |
| 5.1.1 Diffusion in Disorder: an Intuitive Approach. . . . .                                   | 83  |
| 5.1.2 ...Which Hides a Much More Complex Physics! . . . . .                                   | 84  |
| 5.1.3 A Physics also Source of Innovation . . . . .   | 85  |
| 5.2 Cold Atoms: Disorder Under Control! . . . . .   | 85  |
| 5.2.1 How to Immerse Atoms in Disorder? . . . . .   | 85  |
| 5.2.2 Random Walk of Cold Atoms in Disorder: Observation<br>of Diffusion . . . . .            | 88  |
| 5.3 Anderson Localization: Halted by Disorder . . . . .                                       | 89  |
| 5.3.1 60 Years of Investigations and Still Open Questions . . . . .                           | 89  |
| 5.3.2 An Intuitive Understanding of Anderson Localization . . . . .                           | 91  |
| 5.3.3 Anderson Localization of Cold Atoms: First Observations . . . . .                       | 94  |
| 5.3.4 Towards the Study of the Anderson Transition in 3D . . . . .                            | 95  |
| 5.4 Coherent Backscattering: Visualizing Interferences . . . . .                              | 98  |
| 5.4.1 Localization in the Space of Velocities . . . . .                                       | 98  |
| 5.4.2 Coherent Backscattering of Cold Atoms . . . . .   | 99  |
| 5.4.3 Anderson Localization in the Space of Velocities . . . . .                              | 101 |
| 5.5 Cold Atoms and Disorder: Other Configurations . . . . .                                   | 102 |
| 5.5.1 Universality of Localization Phenomena . . . . .  | 102 |
| 5.5.2 Light Scattering by Cold Atoms . . . . .  | 102 |
| 5.5.3 “Kicking” Atoms to Localize Them . . . . .  | 104 |
| 5.6 Interactions and Disorder: When Atoms Talk to Each Other . . . . .                        | 107 |
| 5.6.1 Quantum Phases of Disordered Gases at Low Temperature . . . . .                         | 107 |
| 5.6.2 Many-Body Localization: When Disorder Makes Thermal<br>Equilibrium Impossible . . . . . | 109 |
| 5.7 Conclusion . . . . .  | 111 |

---

CHAPTER 6

|  |     |
|--|-----|
| Trapping and Cooling Ions . . . . .                                | 113 |
| 6.1 How to Confine a Charged Particle? . . . . .                   | 115 |
| 6.1.1 Penning Trap . . . . .                                       | 115 |
| 6.1.2 Paul Trap or Radiofrequency Trap . . . . .                   | 116 |
| 6.1.3 Trap Zoology . . . . .                                       | 119 |
| 6.2 How to Cool Trapped Ions? . . . . .                            | 120 |
| 6.3 Let Us Put Several Ions in the Trap! . . . . .                 | 122 |
| 6.4 What can We do with Trapped Ions? . . . . .                    | 123 |
| 6.4.1 Precision Measurements: Masses, Atomic Properties, . . . . . | 124 |
| 6.4.2 Strong Confinement Regime and Ion Clocks . . . . .           | 125 |
| 6.4.3 Quantum Information and Quantum Simulations . . . . .        | 126 |
| 6.4.4 Cold Collisions and Cold Chemical Reactions . . . . .        | 127 |
| 6.4.5 Antimatter Confinement . . . . .                             | 127 |
| 6.5 Conclusion . . . . .   | 127 |

---

**CHAPTER 7**

|   |     |
|---|-----|
| Cold and Ultracold Molecules . . . . .                                | 129 |
| 7.1 How to Characterize a Molecule? . . . . .                         | 131 |
| 7.1.1 The Electronic, Vibrational, Rotational Energy Levels . . . . . | 131 |
| 7.1.2 Can We Laser Cool Molecules? . . . . .                          | 134 |
| 7.2 Associating Cold Atoms . . . . .                                  | 136 |
| 7.2.1 With a Photon: Photoassociation . . . . .                       | 136 |
| 7.2.2 With a Magnetic Field: Magnetoassociation . . . . .             | 137 |
| 7.2.3 How to Control Association? . . . . .                           | 138 |
| 7.3 Direct Cooling of Molecules . . . . .                             | 140 |
| 7.3.1 Formation and Preliminary Cooling . . . . .                     | 140 |
| 7.3.2 Deceleration of Molecular Beams . . . . .                       | 141 |
| 7.3.3 Sub-Kelvin Cooling . . . . .                                    | 143 |
| 7.4 Cold Molecules: For Which Applications? . . . . .                 | 145 |
| 7.4.1 Quantum Simulation . . . . .                                    | 147 |
| 7.4.2 Quantum Information . . . . .                                   | 148 |
| 7.5 Ultracold and Controlled Molecular Chemistry . . . . .            | 149 |
| 7.5.1 Precision Measurements . . . . .                                | 152 |
| 7.6 Conclusion . . . . .  | 153 |

---

**CHAPTER 8**

|  |     |
|--|-----|
| Conclusion and Everything Else This Book Could also Have Been About... . | 155 |
|--|-----|

|                 |     |
|-----------------|-----|
| Index . . . . . | 165 |
|-----------------|-----|