ESSAY REVIEW

Foundations of quantum optics: a basis for the new quantum technologies

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A review of **The Quantum World of Ultra-Cold Atoms and Light. Book I: Foundations of Quantum Optics**, by C. Gardiner and P. Zoller, Singapore, World Scientific Publ. Co., 2014, xviii + 310 pp., £42.00 (paperback), ISBN 978-1-78326-461-2. Scope: textbook. Level: postgraduate, early-career researcher, researcher.

The Industrial Revolution that took place during the period from the latter part of the 18th to the early part of the 19th centuries saw a fundamental change in the human condition. In what was to become the developed world mankind moved from a predominantly rural society largely based on agriculture, where most people worked at home or in small shops with hand tools or simple machines, to one which was increasingly urban and based on industry. The factories that were developed to house the new complex machines now also became the place of work for many. Built upon the twin inputs of coal and iron, the machines of the factories and the new technologies were firmly based on the theoretical pillars of classical physics: Newtonian mechanics, thermodynamics and electrodynamics. Indeed, in the cases of thermodynamics and electromagnetism, advances in the fundamental science often went hand in hand with advances in the technological applications.

As we moved into the twentieth century, classical physics gave way to quantum physics, and by the latter half of that century, The Information Age in which we still live was beginning. With hindsight its advent can perhaps be dated to the invention of the germanium-based transistor, for which William Shockley, John Bardeen and Walter Brattain won the 1956 Nobel Prize in Physics. The now ubiquitous integrated circuit or microchip was independently invented and developed by Jack Kilby and Robert Noyce only ten or so years later, although the Nobel Committee was slow in awarding the Physics Prize to Kilby in 2000, by which time Noyce had already died ten years previously. Whereas Kilby's original chip was again made from germanium, it was Noyce who introduced silicon for his design, and thereafter, germanium soon gave way to silicon as the semi-conducting material of choice. Nowadays containing up to billions of transistors and other electronic components, the modern microchip has become readily and cheaply

available. It lies at the heart of the gadgets and machines that surround us at home and at work. From the microchip there followed, for example, the development of the microprocessor. In turn, this led to the ready availability of low-cost computers on integrated circuits, which has revolutionised society as part of its transition into The Information Age. Other microprocessors form part of embedded systems that provide digital control of a vast number of technological products, ranging from household appliances to cars, and from mobile phones to industrial processes and machinery. Just as the technology of the microprocessor, which has become inextricably woven into the fabric of society, is based on quantum physics, so are its myriad applications and other existing quantum technologies such as solid-state imaging devices and the laser.

Quantum technologies are thus defined in this sense to be those that utilise and harness quantum physics in order to achieve a functionality or a performance that cannot be attained otherwise. They are underpinned by a theoretical framework that lies beyond the realm of classical physics, as exemplified by Newton's laws of motion, the three laws of thermodynamics and Maxwell's equations of electromagnetism. As we have already discussed above, much of the technology of The Information Age, developed over the latter half of the twentieth century, is certainly based on quantum mechanics. Nonetheless, the emerging quantum technologies of the present era of the early twenty-first century are based on more subtle and less familiar aspect of quantum mechanics. As of today, they may broadly be categorised under the headings of quantum secure communications, quantum metrology, quantum sensors, quantum simulators and quantum information processing.

Since the secrecy of quantum communications is directly measurable, there is an obvious inherent means to utilise them to distribute secure digital keys over open networks. Such quantum key distribution is now recognised as one of the first quantum information technologies with commercial applications. Indeed, working systems exist and are already being applied in special circumstances. Next-generation quantum communication technologies will almost certainly be based on distributed quantum entanglement. Similarly, next-generation metrology will

be based on quantum phenomena, which will allow new standards for such key fundamental measures as time, frequency, length, mass and charge to be developed. All of these will find rapid applications in trade and industry, thereby enabling, for example, the huge anticipated increase in the volume of mobile phone and other means of communications to be routed and managed. Elsewhere, in a plethora of commercial applications, new standards will be introduced and higher accuracy will be achieved. In many other areas, the use of sensors has become pervasive. Quantum sensing technologies will develop to utilise the advantage afforded by quantum systems to provide substantial increases in measurement precision over those using earlier technologies. We will see the development and deployment of sensors that operate at the level of detecting single molecules. Others will be able to measure electromagnetic and gravitational fields with much increased accuracy. These new sensors will find wide applications in such fields as security, health care and medical imaging, and environmental monitoring. In all these areas, and others too, still more applications will undoubtedly also emerge that we have not yet even imagined or conceived.

We are, however, already living at a time when more and more products of quantum technologies are becoming a reality. Whereas the realm where quantum mechanics holds sway was once thought to be confined to the microscopic world of atoms and subatomic constituents, we are now seeing both mesoscopic and macroscopic manifestations of the quantum world. To harness those manifestations and move them into the domain of applied physics has brought a number of fields into much closer relationship with one another, and in so doing this has thereby also revealed deep and often quite unforeseen parallels and connections between them. Such fields include, for example, quantum many-body theory, condensed matter physics, quantum information science, quantum optics and the quantum dynamics of mechanical systems. Their manifold interfaces have enabled us, for example, to explore large-scale quantum phenomena that become possible when particles such as atoms, photons and electrons are strongly correlated and/or strongly entangled. Such diverse, and previously often disparate, areas of quantum physics as quantum electronics, quantum nanomechanical devices, quantum optics and atom optics have found common ground in the ongoing search for a quantum computer, for example. In doing so, they have been brought sufficiently into unity to find a common language in the form of quantum information theory.

In the fields of quantum many-body theory and condensed matter physics, there has been much excitement in recent years around the various forms of emergent quantum phenomena that can arise in such strongly correlated or entangled systems. Examples include exotic magnetic phenomena involving non-classical states and

their quantum phase transitions, quantum Hall effect physics and topological states of matter. At the same time, the field of ultra-cold atomic gases trapped in optical lattices has burgeoned and provided a new laboratory for the study of such collective behaviour. In parallel on the theoretical front, powerful techniques from quantum information science have provided totally new insights and paradigms into quantum many-body physics. All of these exotic quantum states of matter involve aspects of quantum coherence, quantum superposition and quantum entanglement that are now themselves also seen to lie at the heart of quantum information theory. Much of the understanding of these overlaps has come from the sub-fields of quantum computation and quantum communication. We are increasingly seeing exciting interfaces opening up that have the potential both to advance basic quantum science and to lay the foundations for future quantum technologies, including quantum computers themselves as but one example.

Exactly as in The Industrial Revolution, we are again witnessing an exciting period where advances in the fundamental science are proceeding apace with advances in the technological applications. For example, the field of quantum computation is characterised by the processing of information utilising several or all of the effects arising from quantum superposition, quantum entanglement, quantum teleportation and quantum coherence in the face of decoherence arising from interactions with the surroundings. This harnessing of quantum mechanics opens the exciting possibility of the development of a computing engine capable of solving problems that are completely intractable on both current hardware and on any foreseeable, future-generation, direct extension of it. The hardware required to build such a quantum computer would itself also open up capabilities for the other emerging quantum technologies, all of which directly exploit such quantum phenomena as entanglement, coherence and superposition, in order to provide disruptive impacts in such capabilities as precision, speed, sensitivity, accuracy or security.

Another field where the fundamental physics walks hand in hand with its associated quantum technology is that of quantum simulation, which relies on the subtle concept of universality that is inextricably associated with quantum systems, and which is one of their key features. Loosely stated, universality asserts that every quantum system that is sufficiently complex should be able to simulate in a highly efficient manner every other quantum system. On both the technological and purely scientific sides, this has enormous potential impact. For example, an ability to model real materials or even molecules accurately at the atomic scale is a key to many diverse technological problems such as the interaction of drug molecules with their targets and the design of new drugs via quantum pharmacology, and to such scientific

problems as the precise characterisation of the nature of high-temperature superconductivity. Such modelling of quantum phenomena at the chemical scale is extremely difficult using purely classical computers, as the effort required to achieve a specified accuracy typically scales exponentially rapidly with the size of the system.

Although on a longer timescale, when a full quantum computer would be available, we would be able to perform such a simulation exponentially faster for any quantum system that we would wish to target, on the shorter timescale, we could still make very significant gains by suitably engineering a controllable proxy quantum system, the behaviour of which mimics the actual system under study, in some appropriate way. At present, one of the most developed quantum simulators utilises atoms cooled down to ultra-low temperatures. The forces of interaction between such trapped cold atoms can then also be tuned so finely and in such a well-controlled experimental way that they can be made to interact in such diverse ways as to allow them to simulate the behaviour of many other systems. Other promising quantum systems to use as the proxy in such a quantum simulator include trapped ions or polar molecules, electrons in semiconductors, superconducting circuits, nuclear spins and multiple photons interacting via linear optics.

Intriguingly, from the purely scientific curiosity-driven standpoint, we can also simulate the behaviour of systems that we do not know for sure actually exist in the real world. As one illustration, Majorana fermions are hypothesised to be fermionic particles with the key feature that they are their own antiparticles. If they exist, they will have several rather unique characteristics. However, at present, the only particles definitively known to be their own antiparticles are bosonic in character. Examples include photons, neutral pions and Higgs bosons. Even though we have no evidence at present for the existence of any variety of Majorana fermions, we can still simulate their properties with the use of a cold-atom simulator, and then in principle even go further and use such simulators themselves for new technological applications.

We have already seen the development of technologies for manipulating and controlling matter and light at the level of individual photons and atoms, and these have often provided the springboard or impetus for further advances, sometimes by exploring in more detail the interface areas already alluded to above. Such other areas include methods of solid-state physics and associated tools developed by the semiconductor industry, devices and technologies exploiting superconductivity, circuit quantum electrodynamics and assemblies of ultra-cold atoms trapped in an optical lattice. Nevertheless, in this field, the laser remains still as the quintessential experimental tool and the theoretical framework is then quantum optics, the exposition and description of the foundations of which form the *raison d'être* for this

book. The book itself provides a fitting memorial for Charles Townes, who shared the 1964 Nobel Prize in Physics for the invention of the laser, and who died in January 2015. Some 40 years after Townes received his prize, the 2005 Nobel Prize in Physics was again awarded in the field of laser physics, with a half-share going to Roy Glauber, one of the fathers of quantum optics, 'for his contribution to the quantum theory of optical coherence', and quarter-shares each to John Hall and Theodor Hänsch 'for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique'.

The UN General Assembly has proclaimed 2015 as the *International Year of Light and Light-based Technologies (IYL 2015)*. In so doing the UN aims to raise global awareness about how light-based technologies promote sustainable development and provide solutions to global grand challenges in energy, education, agriculture and health. Recognition has thereby been given to the fact that light has become an important interdisciplinary area of science in the twenty-first century. Resolution 68/221 [1], which established IYL2015, specifically recognised in its preamble 'the importance of light and light-based technologies in the lives of the citizens of the world and for the future development of global society on many levels'. It has already opened up huge advances in such areas as medicine and international communication via the Internet. Since the world of light, especially in its most coherent forms, fits so seamlessly with quantum technologies, and since quantum optics provides the basis of their underpinning, it is particularly fitting to review this book in IYL2015.

The present volume is intended as the first in a trilogy whose stated aim is to present a complete description of all of the theoretical techniques needed for quantum technologies. Although the authors have thus set themselves an extremely ambitious and challenging goal, they are certainly well positioned to fulfil it, having contributed themselves to many of the main developments and emerging themes over the last thirty years or so. Peter Zoller in particular, often in collaboration with his colleague Ignacio Cirac, has been a dominant figure in many of the developments at the interface of quantum optics, quantum information theory and quantum many-body physics. Similarly, for example, both of the present authors are pioneers in the field of quantum kinetic theory. Both have written textbooks in allied areas to that covered here, which have become leading reference texts in their fields. For example, their earlier co-authored textbook *Quantum Noise* [2] provides an authoritative and comprehensive exposition of the quantum stochastic methods that have been developed in the field of quantum optics, while Gardiner's sole-authored *Stochastic Methods* [3] has become a standard reference textbook in its field for many years, which has been continuously

updated and expanded to stay topical and relevant. Both provide excellent further reading for the material presented in the current volume, which is itself well up to the high standards set by these earlier books.

What is particularly impressive about this book is the large amount of material that is covered in a relatively small space. The overall style of writing is very compact, but in some ways this makes it easier for the reader to follow than if a plethora of less important detail were included, through which the inexperienced reader could be in danger of being sidetracked. It is clear that some thought has gone into both the choice of material and how much detail to include. Nevertheless, this concise style does come at a price, which is sometimes a heavy one. Thus, on rather too many occasions, my own feeling is that the authors have simply been so terse as to make it extremely difficult for any reader to follow, without very extensive additional reading from outside sources. To my taste, too many opportunities have been missed to add a relatively little extra material that would have aided understanding considerably.

This is particularly true for some of the more mathematical sections such as those, for example, dealing with coherent states and the very important phase-space methods, both of which lie so much at the heart of quantum optics. In these and other sections, the material presented is often little more than a list of theorems and important results, with little or no attempt to tell the reader how to prove them or, less forgivably, even to indicate their relative importance. As one of many examples that could be cited, the crucial resolution of the identity operator in terms of coherent states is simply stated, without any indication of how it might be proved, nor with any discussion about overcompleteness of the states. In the same context, I was surprised that in the discussion of coherent states the opportunity was missed to introduce the displacement operator explicitly, even though it is mentioned that the coherent states may be represented as a unitary transformation of the vacuum. Another surprising omission, considering their importance in quantum optics, is any explicit mention of squeezed states or the squeezing operator. Similarly, although Wigner functions are described in some detail, the equally important, and intimately related, Weyl functions are never explicitly introduced or discussed.

Despite such caveats, this book has a great deal to recommend it. After a short introductory Part I that sets the physical background for what will follow, the book is organised into a further five parts. Parts II and IV, which provide much of the meat of the book deal, respectively, with classical stochastic methods and quantum stochastic processes. Both of these two parts are very well written. In between, in Part III, the authors have three chapters dealing, respectively, with ideal Bose and Fermi systems, quantum fields, and the interactions of atoms and light.

The characteristic phase-space methods of quantum optics are discussed, to my taste much too briefly, in Part V, before the authors conclude with an excellent Part VI that deals in a much more complete and masterly fashion with the ever-thorny problem of the theory of quantum measurement. The three separate chapters in this last part are among the best of the twenty chapters that form the whole book. Taken as a whole, this book can certainly be recommended, despite its shortcomings. Even experts in the field will find something rewarding here, although those newer to the field will surely require a great deal of supplementary reading.

I certainly look forward with pleasure to reading the remaining two volumes of this trilogy, which will cover, respectively, the physics of quantum-optical devices and ultra-cold atoms. It is intended that Book II will develop the basic ideas of both quantum optics and ultra-cold atoms which are at the forefront of current research into quantum technologies, and will cover applications to such quantum devices as quantum computers and quantum simulators, as well as introducing the more advanced techniques needed to describe non-classical light fields. This will include, in particular, the extended quantum stochastic techniques needed to describe the mutual interaction of the light field and the atoms. Again, in Book III, the quantum stochastic paradigm seems set to take centre stage. It will include an up-to-date overview of the many intriguing systems that can be created from optical lattices and ultra-cold atoms, which is itself a field where the quantum simulation of quite complex physical systems is beginning to be realised in practice in the laboratory.

Disclosure statement

No potential conflict of interest was reported by the author.

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References

- [1] See web reference: Available at <http://undocs.org/A/RES/68/221>.
- [2] C. Gardiner, and P. Zoller, *Quantum Noise: A Handbook of Markovian and Non-Markovian Quantum Stochastic Methods with Applications to Quantum Optics*, Springer-Verlag, Berlin, 2004.
- [3] C. Gardiner, *Stochastic Methods: A Handbook for the Natural and Social Sciences*, Springer-Verlag, Berlin, 2009.

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