Foreword

It is a commonly expressed view that Einstein, despite his introducing several seminal notions that were quite fundamental to the emerging quantum theory in the early twentieth century, later turned his back on that theory, being unable to accept the essentially uncertain and apparently subjective picture of the submicroscopic world that quantum theory seemed to demand. According to this view, Einstein was too wedded to a nineteenth-century objectivistic and deterministic picture of reality to be able to accept the then "modern" attitude to basic laws of the universe, as espoused particularly by the Copenhagen school of Bohr, Heisenberg, Born, and Pauli. That attitude seemed to demand a universe governed by purely probabilistic laws relating to fundamentally imprecise entities that were difficult to visualize and whose very objectivity was put into question. It had seemed that Einstein's stubborn insistence on deterministic realism might be likened to that of a father with fixed views of the path that his child should follow, then turning his back when that child failed to adopt the lifestyle that he had set out for it.

Accordingly, despite Einstein's being far ahead of his contemporaries in the first quarter of the twentieth century, he is viewed as being subsequently unattuned to the later developments that took place in physics, held back by an outdated philosophical standpoint unsuited to the emergent theory of quantum mechanics. The quantum world, it would be argued, demanded that Heisenberg's uncertainty principle restrict the precision of how physical entities could behave, with these entities being described by merely randomistic action, as determined by Born's probability law. Accordingly, Einstein's stance, by the mid-twentieth century, was taken to be retrograde.

Moreover, such an attitude toward his later years seemed to be supported by the apparently limited nature of Einstein's late devotion to a particular form of unified field theory, aimed at uniting gravity and electromagnetism into one geometric framework, where quantum phenomena were intended somehow to arise out of such a classically based scheme. One of the main limitations of Einstein's approach was that it seemed to totally ignore the more recent discoveries of the strong and weak nuclear forces. It must indeed be admitted that the proposals that Einstein came up with in this area have not stood the test of time, and many would argue that his superb instincts for uncovering deep underlying truths of the physical world

had, by then, run their course. Yet, a strong case can be made that, at least with regard to the quantum theory, it was *Einstein* who had seen more deeply into the subject than his contemporaries, such as Bohr, by probing that theory's intrinsic weaknesses as an overriding scheme of things.

In his famous debates with Bohr, Einstein was not able to place his finger firmly on the failings of quantum theory that he instinctively felt, and it has been the consensus view that it was Bohr who "won" these debates. Indeed, the exciting new theory of quantum mechanics, which had been crafted through the combined work of Planck, Bohr, Heisenberg, Schrödinger, Born, Dirac, Pauli, and many others—not to mention the early Einstein himself—was found to encompass numerous previously inexplicable phenomena, and it resulted in many extraordinary predictions, over a broad range, these not yet having been found to be at odds with observation some 80 years after the full formulation of the quantum laws.

Yet, there remain many puzzles in the interpretation of the quantum theory, some of which border on the paradoxical, and it was Einstein's continual probing of quantum theory's foundations that have brought out most fully many of these profoundly disturbing features. Despite the extraordinary success of the quantum theory, and of Bohr's effective championing of the theory in his debates with Einstein, we can now look back from our vantage point of the early twenty-first century and see how fruitful Einstein's penetrating criticisms were. Although his was not a lone voice—for Schrödinger and Dirac also regarded the quantum theory as being in an important way "provisional"—Einstein's criticisms were made more openly, and they attained a particular weight owing to his reputation. But Bohr's arguments in support of the conventional quantum theory were not refuted by Einstein, and Einstein's attempts at knock-down arguments were all effectively parried by Bohr. Yet it was Einstein's continually innovative probing that has led to burgeoning areas of fascinating and potentially practical research, largely encompassed within the scope of what is now referred to as "quantum information theory". This area arose, most notably, from the "EPR phenomena" that emerged from the famous collaborative work of Einstein, Rosen, and Podolsky, as refined by Schrödinger, developed by Bohm, and shown to be experimentally testable phenomena, rather than mere manifestations of a philosophical conundrum, through the epoch-making work of Bell.

It is immensely refreshing, therefore, to find a book which at last pays due respect to the later views of Einstein on the quantum theory, and the developments which grew out of them. Dipankar Home and Andrew Whitaker have provided us with masterly expositions of all the issues, analyzing many different viewpoints concerning the profound questions raised by quantum theory. We find that matters of "interpretation" of quantum theory, that have for decades been regarded by physicists as "mere matters of philosophy", can lead to very significant physical effects, some even having important current commercial implications, such as quantum cryptography, and others having more remote potentialities, such as quantum computation. It is reasonable to speculate that there will be future developments of great importance arising from these ideas, perhaps involving a complete

overhaul of the basic principles of quantum theory, resulting in a new perspective that might be more in keeping with Einstein's requirements.

Wherever these developments may carry us in the future, they are bound to continue to have an important input from the deliberations of Einstein and others concerning the puzzles and paradoxes that permeate the foundations of twentieth-century quantum mechanics. This book is likely to retain a very significant role for such developments for many decades to come.

Roger Penrose
Mathematical Institute,
Oxford