Classic Texts in the Sciences

Claus Kiefer
Editor

Albert Einstein, Boris Podolsky, Nathan Rosen

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

Birkhäuser

Classic Texts in the Sciences

Birkhäuser

Classic Texts in the Sciences offers essential readings for anyone interested in the origin and roots of our present-day culture. Considering the fact that the sciences have significantly shaped our contemporary world view, this series not only provides the original texts but also extensive historical as well as scientific commentary, linking the classical texts to current developments. Classic Texts in the Sciences presents classic texts and their authors not only for specialists but for anyone interested in the background and the various facets of our civilization.

More information about this series at http://www.springer.com/series/11828

Claus Kiefer
Editor

Albert Einstein, Boris Podolsky, Nathan Rosen

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

Birkhäuser

Editor
Claus Kiefer
Institute for Theoretical Physics
University of Cologne
Cologne, Germany

Translated by
Anna Katharina Hudert
Braunschweig, Germany

Sebastian Linden
Braunschweig, Germany

ISSN 2365-9963 ISSN 2365-9971 (electronic)
Classic Texts in the Sciences
ISBN 978-3-030-47036-4 ISBN 978-3-030-47037-1 (eBook)
https://doi.org/10.1007/978-3-030-47037-1

This book is published under the imprint Birkhäuser, www.birkhauser-science.com, by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The year 2015 not only marked the 100th anniversary of the general theory of relativity but also the 80th anniversary of one of the most relevant papers of theoretical physics: the paper by Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) from 1935 printed and annotated in this edition. While the theory of relativity has become part of the textbook canon and thus the historical works of Einstein are cited less frequently, the EPR paper is quoted quite regularly in renowned journals such as Physical Review and Nature. This shows that EPR's question as to the completeness of quantum mechanics is still relevant. The present annotated edition details the historical context and reception of the EPR paper as well as the impact it had on modern research and the conceptual fundamentals of quantum theory, which are still being discussed. While Niels Bohr and others initially dismissed the EPR paper as irrelevant and as based on misunderstandings, it is experiencing an unending renaissance. Turns out, it really is a significant paper!

The text itself is a discussion on theoretical physics and requires prior physical and mathematical knowledge for better understanding. However, since its content stretches an arc far into philosophy, I wanted to do it justice and keep this annotated edition as easily comprehensible as possible under the circumstances. I thus wrote it also with a more general reader in mind, who does not necessarily understand the mathematical aspect of the paper and is rather interested in its epistemic aspects.

The book also includes the full text of Bohr's paper with the same title and published in the same year, as well as a translation of Einstein's article from 1948 published in the journal *Dialectica.*

I would like to thank Prof. Dr. Jürgen Jost for asking me to write this book and accompanying the writing process with kind and constructive support; my thanks also goes to Springer-Verlag for the efficient help and to Sebastian Linden and Anna Katharina Hudert for their excellent translation into English. Last but not least I want to thank H.-Dieter Zeh, Erich Joos, Klaus Volkert, and Paul Busch for a critical review of the original German manuscript and for helpful discussions.

Cologne, Germany
February 2020

Claus Kiefer

Contents

Backstory

1

In 1934, three physicists came together in Princeton, United States, to author a scientific paper that would turn out to be one of the most cited publications of the twentieth century. They were Albert Einstein, Boris Podolsky, and Nathan Rosen. Einstein (1879–1955) was already world-famous back then for developing his theory of relativity. Unwilling to live in Nazi-Germany, he had settled at Princeton's newly founded *Institute for Advanced Study* in October 1933, where he remained until his death in 1955.

Boris Podolsky, born in 1896 in Taganrog, Russia (where also the writer Anton Chekhov was born), had emigrated to the United States in 1913. In 1928, he received a PhD from the *California Institute of Technology* (Caltech) and came to Princeton with a fellowship from the Institute for Advanced Study in 1933, after detours to *i.a.* Leipzig in Germany, Kharkov in Ukraine (back then USSR), and again to Caltech. In Kharkov, he had worked on the then brand new theory of quantum electrodynamics with Vladimir Fock, and Paul Dirac, one of the pioneers of quantum mechanics, who was travelling through the USSR at the time.

Podolsky and Einstein knew each other from Einstein's earlier visits to the United States. Einstein's first trip to the United States was mainly a visit to Caltech. It took place from December 1930 to March 1931 following an invitation by physicist Richard Tolman, who contributed greatly to the theory of relativity. During that time, Tolman, Podolsky, and Paul Ehrenfest (1880–1933), who was visiting from the Netherlands, were working on an application of general relativity, namely on the gravitational field produced by light [156]. They submitted their work for publication in January 1931. Einstein spent most of his second trip to the United States at Caltech, too, from late December 1931 to early March 1932. This time he collaborated with Podolsky, the result being a joint two-paged publication by Einstein, Tolman, and Podolsky on quantum theory [67]. This work, however, was later described by Einstein's biographer Abraham Pais as less-than-successful [122, p. 494].

C. Kiefer (ed.), *Albert Einstein, Boris Podolsky, Nathan Rosen*, Classic Texts in the Sciences, https://doi.org/10.1007/978-3-030-47037-1_1

The third physicist, Nathan Rosen, was born in New York City in 1909. Having received a PhD from the *Massachusetts Institute of Technology* (MIT) in 1932, Rosen came to the University of Princeton in 1934. His work had focused on atomic and molecular physics, but he had also taken an interest in Relativity and had published a paper on the unified field theory of gravitation and electromagnetism that Einstein was pursuing back then. It therefore comes as little surprise that Rosen contacted Einstein in Princeton, hoping for his advice in this matter. Max Jammer describes in his well known book on quantum mechanics that Rosen was quite surprised by how friendly Einstein was when they discussed his work [98, p. 181]. When they met in the institute's courtyard the following day, Einstein asked him: "Young man, what about working together with me?"

This is the personal backstory to the collaboration of Einstein, Podolsky, and Rosen that would go down in history as EPR. The scientific backstory is much more intricate and leads us back to the beginning of the twentieth century. Planck's paper in 1900 and Einstein's in 1905 quietly initiated what would later become quantum theory in 1925 to 1927 – a theory that Einstein, Podolsky, and Rosen were still struggling to understand in Princeton in 1934/1935.

No theory has ever changed our physical world view as much as quantum theory has. Aside from not incorporating gravitation, the theory provides successful descriptions of all interactions, ranging from macroscopic bodies to elementary particles, such as the ones explored at the particle accelerator LHC in Geneva, Switzerland. The basic equations of quantum theory have been tested in countless experiments, so no one doubts their validity. However, there is no mutual consent on how to interpret the theory, not least shown by the numerous citations of the EPR paper. What is it that stirs such a feeling of unease in a theory whose formalism is beyond controversy? We will see that the debate essentially centres on what reality is or rather what we want reality to be.

The impulse for the EPR paper clearly came from Einstein. He was, for one, the threesome's senior and generally distanced Podolsky, and Rosen scientifically, but he had also contributed substantially to the primary stage of quantum theory and accompanied the development of the actual theory with intense attention and criticism since 1925. We will see that quantum theory is a recurring theme in Einstein's work from 1925 to EPR and even further on. However, Einstein depended on critical dialogue with colleagues to work out his theories, which is why the paper wouldn't have been written without Podolsky and Rosen, at least not this way.

1.1 Einstein's Contributions to Early Quantum Theory

Einstein's liaison with quantum theory began about thirty years before the three physicists met in Princeton. Struggling to find a position in academic teaching or research, Einstein took a job as patent examiner (third class) at the Federal Office for Intellectual Property (Swiss patent office) in Bern in 1902. Some, both privately and scientifically, turbulent years followed. He married his fellow student Mileva Marić in early 1903. At the time the two already had a daughter, Lieserl, that Mileva had delivered during a stay in her hometown Novi Sad in Serbia the year before. Einstein never saw his daughter, whose fate remains unknown. In May 1904, Einstein and Mileva's first son Hans Albert was born in Bern.[1]

Despite his turbulent private life and his 48-hour-week at the patent office, Einstein actively pursued his scientific work. In 1905, he published no less than five outstanding papers, all of which made history.[2] 1905 is often referred to as Einstein's *annus mirabilis*, echoing Isaac Newton's *anni mirabiles* 1664 to 1666, during which he laid the groundwork for his theory of gravitation. Of those five papers from 1905, the one that concerns us most is the one on the light quantum hypothesis. It was the first major contribution to quantum theory since Planck's initial papers in 1900 and 1901 and the only one that Einstein himself qualified as revolutionary. In a letter to Conrad Habicht in May 1905,[3] Einstein wrote (The Collected Papers of Albert Einstein vol. V, Doc. 27):

> I promise you four papers in return, the first of which I might send you soon [...]. The paper deals with radiation and the energy properties of light and is very revolutionary, as you will see [...].[4]

What was so revolutionary about this paper? Einstein starts out by expressing his discomfort with an obvious incoherence in the description of nature: the simultaneous occurrence of continuous and discrete quantities. The electromagnetic field strengths are continuous functions and are empirically well described by Maxwell's equations. Matter, however, consists of a finite number of atoms and is, therefore, discrete by nature. The first lines of Einstein's paper read as follows [51, p. 132]:

> There exists a profound formal difference between the theoretical conceptions physicists have formed about gases and other ponderable bodies, and Maxwell's theory of electromagnetic processes in so-called empty space. While we conceive of the state of a body as being completely determined by the positions and velocities of a very large but nevertheless finite number of atoms and electrons, we use continuous spatial functions to determine the electromagnetic state of a space [...].[5]

---

[1] It is worth reading the detailed account of Einstein's life by Fölsing [74].

[2] Cf., e.g., Stachel [153] or Kiefer [104].

[3] Habicht, Einstein, and Romania-born Maurice Solovine regularly met in Bern for informal debates on physics and philosophy, which they called the 'Akademie Olympia'. Fölsing [74, p. 99] wrote in his biography of Albert Einstein: "The three would meet regularly in the evening for a frugal meal of sausage, some Gruyère cheese, a little fruit, honey, and tea. That, according to Solovine's recollections, was enough for them to 'brim over with merriment.' "

[4] "Ich verspreche Ihnen vier Arbeiten dafür, von denen ich die erste in Bälde schicken könnte [...]. Sie handelt über die Strahlung und die energetischen Eigenschaften des Lichtes und ist sehr revolutionär, wie Sie sehen werden [...]."

[5] "Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse

This discrepancy in the roles of fields and matters kept him preoccupied his entire life. Einstein's later efforts to construct a unified field theory were mainly driven by his desire to eliminate this discrepancy. In his 1905 paper he introduced the heuristic point of view[6] that not only the energy of matter but also the energy of electromagnetic radiation should be discontinuously distributed. This assumption gave Einstein the means to better describe certain observations, including black-body radiation and the photoelectric effect, i.e., the emission of electrons from a metal surface by infalling ultraviolet light. Einstein wrote [51, p. 133]:

> Indeed, it seems to me that the observations [. . .] can be understood better if one assumes that the energy of light is discontinuously distributed in space. According to the assumption to be contemplated here, when a light ray is spreading from a point, the energy is not distributed continuously over ever-increasing space, but consists of a finite number of energy quanta that are localised in points in space, move without dividing, and can be absorbed or generated only as a whole.[7]

The term energy quanta that Einstein introduced in this paper would later give its name to quantum theory. Einstein was, of course, aware of Planck's pioneering work from 1900; we know from his letters to Mileva that he had been exploring the topic since 1901.

In his now famous lecture at the German Physical Society (*Deutsche Physikalische Gesellschaft*) on December 14, 1900, Planck had presented a derivation of the black-body radiation formula.[8] Black-body radiation is the electromagnetic radiation within a completely enclosed cavity when the walls are held at a constant temperature T. Back in 1859, German physicist Gustav Robert Kirchhoff, whom Abraham Pais called the

---

im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns nämlich den Zustand eines Körpers durch die Lagen und Geschwindigkeiten einer zwar sehr großen, jedoch endlichen Anzahl von Atomen und Elektronen für vollkommen bestimmt ansehen, bedienen wir uns zur Bestimmung des elektromagnetischen Zustandes eines Raumes kontinuierlicher räumlicher Funktionen [. . .]. "

[6] As highlighted in the title of the paper. A heuristic point of view is a working hypothesis or a preliminary assumption; the Oxford Dictionary defines 'heuristic' as "enabling a person to discover or learn something for themselves, rather than being directed". It is derived from the Greek *heurískein*, meaning 'to find'. Think of the story about Archimedes exposing a dishonest goldsmith who had added silver to a crown supposedly made of pure gold. He did so by use of the principle that today bears his name, which, according to legend, he found while taking a bath and then proclaimed *eureka* ("I found it").

[7] "Es scheint mir nun in der Tat, daß die Beobachtungen [. . .] besser verständlich erscheinen unter der Annahme, daß die Energie des Lichtes diskontinuierlich im Raume verteilt sei. Nach der hier ins Auge zu fassenden Annahme ist bei Ausbreitung eines von einem Punkte ausgehenden Lichtstrahles die Energie nicht kontinuierlich auf größer und größer werdende Räume verteilt, sondern es besteht dieselbe aus einer endlichen Zahl von in Raumpunkten lokalisierten Energiequanten welche sich bewegen, ohne sich zu teilen und nur als Ganze absorbiert und erzeugt werden können."

[8] The story of Planck's discovery has often been told, see, e.g., Giulini's [78] highly readable account.

grandfather of quantum theory, had already concluded that black-body radiation[9] could be described by an energy density function $\rho(\nu, T)$ dependent on temperature T and radiation frequency ν, but independent of the material. The only task left for future physicists was to find said energy density function – as it turned out, this was a very difficult and seemingly interminable task. Planck, too, dedicated himself to it. Finding a solution meant letting go of some of his valued convictions and distancing himself from significant parts of his prior research. He had no choice but to include statistical arguments into his search for the energy function that were brought forward by his colleague and rival in Vienna, Ludwig Boltzmann. Planck had been generally sceptical towards atomism and had seen no significant role for statistics in physical theories. Now, he was forced to completely readjust his views. Planck used simple oscillators ('resonators') to model the behaviour of the cavity walls. This made sense, as the radiation is independent from the nature of the walls, and it made calculations easier. He took a detour and made use of entropy for his calculations. Planck knew how the radiational energy was related to the resonator's mean energy, but he had no idea what the resonator's energy looked like. What he did have, was an idea how to calculate the resonators' entropy, namely using Boltzmann's definition of entropy as the number of real microstates corresponding to a given macrostate. In this particular case, the total energy E needed to be distributed to the individual oscillators. Continually distributed energy would result in an infinite number of real microstates. An obvious absurdity. Planck therefore took a heuristic approach and postulated the existence of a minimal energy value, thus achieving a finite number of real microstates. The key part of his lecture was [133, p. 239]:

> If E is considered to be a continuously divisible quantity, this distribution is possible in infinitely many ways. We consider, however – this is the most essential point of the whole calculation – E to be composed of a very definite number of equal parts and use thereto the constant of nature $h = 6,55 \cdot 10^{-27}$[erg × sec]. This constant multiplied by the common frequency ν of the resonators gives us the energy element ϵ in erg, and dividing E by ϵ we get the number P of energy elements which must be divided over the N resonators.[10]

So this is where the energy quantum used by Einstein in 1905,

$$\epsilon = h\nu, \tag{1.1}$$

[9] The black-body radiation is characterised by a certain energy distribution across all frequencies called energy spectrum.

[10] "Wenn E als unbeschränkt teilbare Grösse angesehen wird, ist die Verteilung auf unendlich viele Arten möglich. Wir betrachten aber – und dies ist der wesentlichste Punkt der ganzen Berechnung – E als zusammengesetzt aus einer ganz bestimmten Anzahl endlicher gleicher Teile und bedienen uns dazu der Naturconstanten $h = 6,55 \cdot 10^{-27}$[erg × sec]. Diese Constante mit der gemeinsamen Schwingungszahl ν der Resonatoren multiplicirt ergiebt das Energieelement ϵ in erg, und durch Division von E durch ϵ erhalten wir die Anzahl P der Energieelemente, welche unter die N Resonatoren zu verteilen sind."