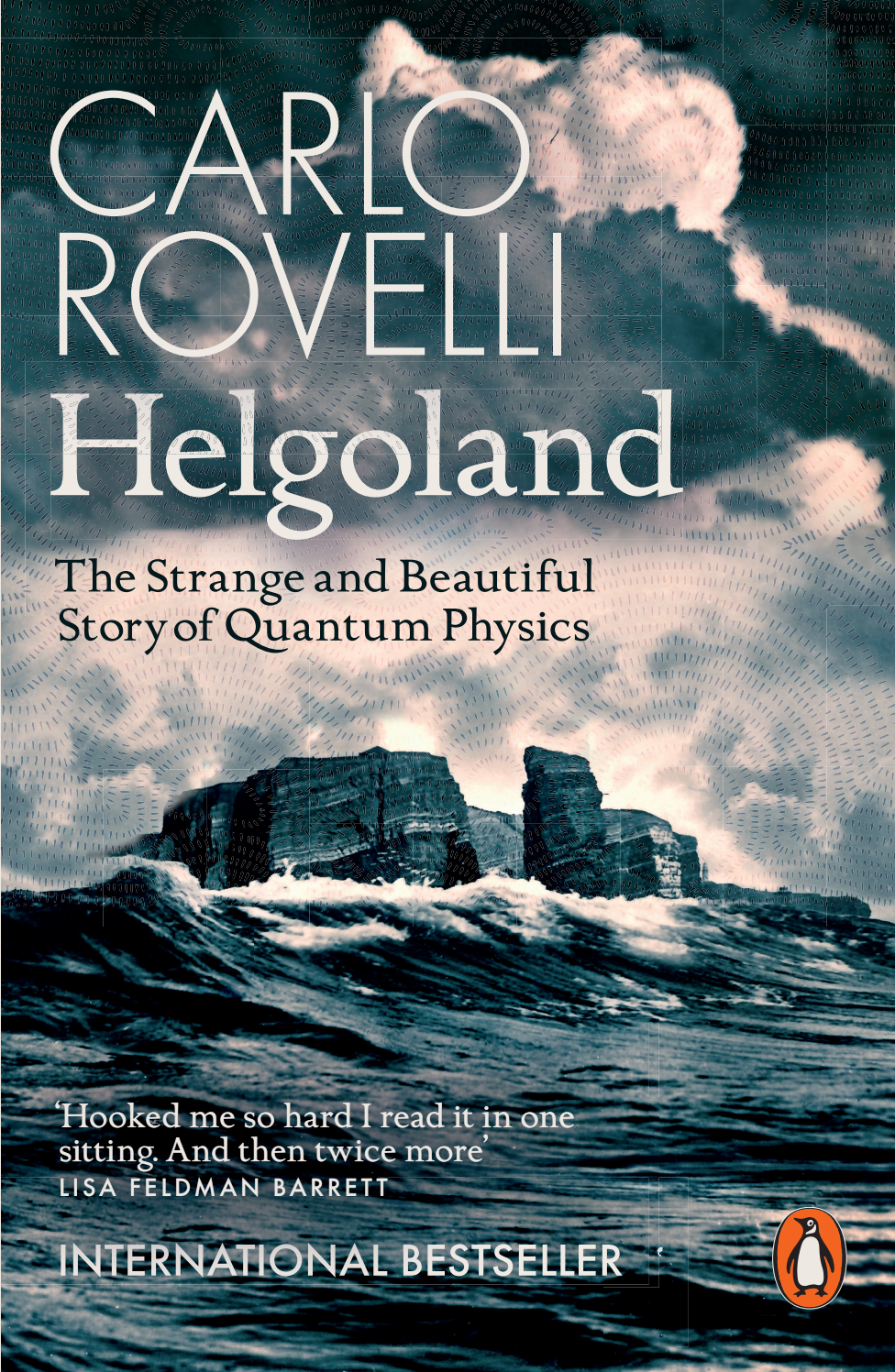
CARLO ROVELLI
Helgoland
The Strange and Beautiful Story of Quantum Physics
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ABOUT THE AUTHOR

Carlo Rovelli is a theoretical physicist who has made significant contributions to the physics of space and time. He has worked in Italy and the US and is currently directing the quantum gravity research group of the Centre de physique théorique in Marseille, France. His books *Seven Brief Lessons on Physics*, *Reality Is Not What It Seems* and *The Order of Time* are international bestsellers that have been translated into forty-one languages.

Helgoland

The Strange and Beautiful Story of Quantum Physics

CARLO ROVELLI

Translated by
Erica Segre and Simon Carnell

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To Ted Newman, who made me understand
that I did not understand quantum theory

Contents

Looking into the Abyss

Časlav and I are sitting on the sand a few steps from the shore. We have been talking intensely for hours. We came to the island of Lamma, across from Hong Kong, during the afternoon break of a conference. Časlav is a world-renowned expert on quantum mechanics. At the conference, he presented an analysis of a complex thought experiment. We discussed and re-discussed the experiment on the path through the coastal jungle leading to the shore, and then here, by the sea. We have ended up basically agreeing. On the beach there is a long silence. We watch the sea. 'It's really incredible,' Časlav whispers. 'Can we believe this? It's as if reality . . . didn't exist . . .'

This is the stage we are at with quanta. After a century of resounding triumphs, having gifted us contemporary technology and the very basis for twentieth-century physics, the theory that is one of the greatest ever achievements of science fills us with astonishment, confusion and disbelief.

There was a moment when the grammar of the world seemed clear: at the root of the variegated forms of reality, just particles of matter guided by a few forces. Humankind could think that it had raised the Veil of Maya, seen the basis of the real. It didn't last. Many facts did not fit. Until, in the summer of 1925, a twenty-three-year-old German spent days of anxious solitude on a windswept island in the North Sea: Helgoland – in English also Heligoland – the Sacred Island. There, on the island, he found the idea that made it possible

to account for all recalcitrant facts, to build the mathematical structure of quantum mechanics, 'quantum theory'. Perhaps the most impressive scientific revolution of all time. The name of the young man was Werner Heisenberg, and the story told in this book begins with him.

Quantum theory has clarified the foundations of chemistry, the functioning of atoms, of solids, of plasmas, of the colour of the sky, the dynamics of the stars, the origins of galaxies . . . a thousand aspects of the world. It forms the basis of our latest technologies: from computers to nuclear power. Engineers, astrophysicists, cosmologists, chemists and biologists all use it daily; the rudiments of the theory are included in high-school curricula. It has never been wrong. It is the beating heart of today's science. Yet it remains profoundly mysterious, subtly disturbing.

It has destroyed the image of reality as made up of particles that move along defined trajectories – without, however, clarifying how we should think of the world instead. Its mathematics does not describe reality. Distant objects seem magically connected. Matter is replaced by ghostly waves of probability.

Whoever stops to ask themselves what quantum theory has to say about the actual world remains perplexed. Einstein, even though he had anticipated ideas that put Heisenberg on the right track, could never digest it himself. Richard Feynman, the great theoretical physicist of the second half of the twentieth century, wrote that nobody understands quanta.

But this is what science is all about: exploring new ways of conceptualizing the world. At times, radically new. It is the capacity to constantly call our concepts into question. The visionary force of a rebellious, critical spirit, capable of

modifying its own conceptual basis, capable of redesigning our world from scratch.

If the strangeness of quantum theory confuses us, it also opens new perspectives with which to understand reality. A reality that is more subtle than the simplistic materialism of particles in space. A reality made up of *relations* rather than objects.

The theory suggests new directions in which to rethink great questions, from the structure of reality to the nature of experience, from metaphysics to perhaps even the very nature of consciousness. Today this is all a matter of the liveliest debate among scientists and among philosophers. I speak about it all in the following pages.

On the island of Helgoland – barren, extreme, battered by the winds of the North – Werner Heisenberg lifted a veil. An abyss opened. The story that this book has to tell starts from the island where Heisenberg conceived the germ of his idea, and progressively widens to take in ever bigger questions opened by the discovery of the quantum structure of reality.

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I have written this book primarily for those who are unfamiliar with quantum physics and are interested in trying to understand, as far as any of us can, what it is and what it implies. I have sought to be as concise as possible, omitting every detail that is not essential to grasping the heart of the issue. I have tried to be as clear as possible, about a theory that is at the centre of the obscurity of science. Perhaps rather than explaining how to understand quantum mechanics, I explain why it is so difficult to understand.

But I have also written it thinking of my colleagues – scientists and philosophers who, the more they delve into the theory, the more they are perplexed – to continue the ongoing conversation on the significance of this astonishing physics. The book has notes intended for those who are familiar with quantum mechanics. They add a bit of precision to what I try to say in a more readable form in the text.

The objective of my research in theoretical physics has been to understand the quantum nature of space and time: to make quantum theory cohere with Einstein's discoveries. For this, I have found myself thinking continually about quanta. This book represents where I have got to so far. It does not ignore other opinions, but it is shamelessly partisan: centred on the perspective that I consider the most effective and I think opens up the most interesting paths: the 'relational' interpretation of quantum theory.

A warning before we begin. The abyss of what we do not know is always magnetic and vertiginous. But to take quantum mechanics seriously, reflecting on its implications, is an almost psychedelic experience: it asks us to renounce, in one way or another, something that we cherished as solid and untouchable in our understanding of the world. We are asked to accept that reality may be profoundly other than we had imagined: to look into the abyss, without fear of sinking into the unfathomable.

– Lisbon, Marseille, Verona,
London Ontario, 2019–20

PART ONE

I. Looking into a Strangely Beautiful Interior

How a young German physicist arrived at
an idea that was very strange indeed,
but described the world remarkably well –
and the great confusion that followed.

The Absurd Idea of the Young Heisenberg: Observables

> It was around three o'clock in the morning when the final results of my calculations were before me. I felt profoundly shaken. I was so agitated that I could not sleep. I left the house and began walking slowly in the dark. I climbed on a rock overlooking the sea at the tip of the island, and waited for the sun to come up . . .[1]

I have often wondered what the thoughts and emotions of the young Heisenberg must have been as he clambered over that rock overlooking the sea, on the barren and wind-battered North Sea island of Helgoland, facing the vastness of the waves and awaiting the sunrise, after having been the first to glimpse one of the most vertiginous of Nature's secrets ever looked upon by humankind. He was twenty-three.

He was there seeking relief from the allergy that afflicted him. Helgoland – the name means Sacred Island – has virtually no trees, and very little pollen. ('Heligoland with its one tree,' as Joyce has it in *Ulysses*.) Perhaps the legends of the dreadful pirate Störtebeker hiding on the island, which he loved as a boy, were in his mind as well. But Heisenberg's main reason for being there was to immerse himself in the problem with which he was obsessed, the burning issue handed to him by Niels Bohr. He slept little and spent his time in solitude, trying to calculate something that would

justify Bohr's incomprehensible rules. Every so often, he would take a break to climb over the island's rocks or learn by heart poetry from Goethe's *West–Eastern Divan*, the collection in which Germany's greatest poet sings his love for Islam.

Niels Bohr was already a renowned scientist. He had written formulas, simple but strange, that predicted the properties of chemical elements even before measuring them. They predicted, for instance, the frequency of light emitted by elements when heated: the colour they assume. This was a remarkable achievement. The formulas, however, were incomplete: they did not give, for instance, the intensity of the emitted light.

But above all, these formulas had about them something that was truly absurd. They assumed, for no good reason, that the electrons in atoms orbited around the nucleus only on *certain* precise orbits, at *certain* precise distances from the nucleus, with *certain* precise energies – before magically 'leaping' from one orbit to another. The first quantum leaps. Why only these orbits? Why these incongruous 'leaps' from one orbit to another? What force could possibly cause such bizarre behaviour as this?

The atom is the building block of everything. How does it work? How do the electrons move inside it? Scientists at the beginning of the century had been pondering these questions for more than a decade, without getting anywhere.

Like a Renaissance master painter in his studio, Bohr had gathered around him in Copenhagen the very best young physicists he could find, to work together on the mysteries of the atom. Among them was the brilliant Wolfgang Pauli – Heisenberg's extremely intelligent, pretty arrogant friend and former classmate. But Pauli had recommended Heisenberg to the great Bohr, saying that to make any real progress,

he was needed. Bohr had taken his advice, and in the autumn of 1924 had brought Heisenberg to Copenhagen from Göttingen, where he was working as an assistant to the physicist Max Born. Heisenberg had spent a few months in Copenhagen, discussing with Bohr in front of blackboards covered with formulas. The young apprentice and the master had taken long walks together in the mountains, talking about the enigmas of the atom; about physics and philosophy.[2]

Heisenberg had steeped himself in the problem. It had become his obsession. Like the others, he had tried everything. Nothing worked. There seemed to be no reasonable force capable of guiding the electrons on Bohr's strange orbits, and in his peculiar leaps. And yet those orbits and those leaps really did lead to good predictions of atomic phenomena. Confusion.

Desperation pushes us to look for extreme solutions. On that island in the North Sea, in complete solitude, Heisenberg resolved to explore radical ideas.

It was with radical ideas, after all, that twenty years earlier Einstein had astonished the world. Einstein's radicalism had worked. Pauli and Heisenberg were enamoured of his physics. Einstein for them was a legend. Had the time perhaps come, they asked themselves, to hazard as radical a step, to escape from the impasse regarding electrons in atoms? Could they be the ones to take it? In your twenties, you can dream freely.

Einstein had shown that even our most rooted convictions can be wrong. What seems most obvious to us now might turn out not to be correct. Abandoning assumptions that seem self-evident can lead to greater understanding. He had taught that everything should be based on what we see, not on what we assume to be the case.

Pauli repeated these ideas to Heisenberg. The two young men had drunk deep of this poisoned honey. They had been following the discussions on the relation between reality and experience that ran through Austrian and German philosophy at the beginning of the century. Ernst Mach, who had exerted a decisive influence on Einstein, insisted that knowledge had to be based solely on observations, freed of any implicit 'metaphysical' assumption. These were the ingredients coming together in the young Heisenberg's thinking, like the chemical components of an explosive, as he isolated himself on Helgoland in the summer of 1925.

And here he had the idea. An idea that could only be had with the unfettered radicalism of the young. The idea that would transform physics in its entirety – together with the whole of science and our very conception of the world. An idea, I believe, that humanity has not yet fully absorbed.

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Heisenberg's leap is as daring as it is simple. No one has been able to find the force capable of causing the bizarre behaviour of electrons? Fine, let's stop searching for this new force. Let's use instead the force we are familiar with: the electric force that binds the electron to the nucleus. We cannot find new laws of motion to account for Bohr's orbits and his 'leaps'? Fine, let's stick with the laws of motion that we're familiar with, without altering them.

Let's change, instead, our way of thinking about the electron. Let's give up describing its movement. Let's describe *only what we can observe*: the light it emits. Let's base everything on quantities that are *observable*. This is the idea.

Heisenberg attempts to recalculate the behaviour of the