Introduction

Science in the Comfort Zone

At the birth of the 20th century, science was generally accepted to be in a satisfactory state of health. Generations of *natural philosophers* had built a coherent structure which stood on foundations laid 400 years earlier by Galileo Galilei and Isaac Newton.

One of the basic tenets of the scientific method was that the development of a physical system is determined completely by its previous state. There is a well-defined relationship between cause and effect and the physical laws give no 'freedom of choice'; identical experiments give identical results. This principle was taken as an axiom, self-evident and necessary for the very existence of science.

Within this paradigm Newton's laws explained the motion of the planets and even predicted the existence of an undiscovered planet. Thermodynamics described processes involving heat energy with great accuracy. Maxwell's equations led to a complete understanding of how electric and magnetic fields behaved; his ultimate triumph was to show how electromagnetic waves, such as light and radio waves, were produced. Such theories led to many practical applications such as steam engines, electrical power, wireless communication and even flying machines.

Planck's Adventure

The train of events described in this book was triggered by a startling discovery made by Max Planck; it led to an adventure of the mind, unprecedented in the history of physics. The participants were faced with an unexpected new world in which the 'normal' rules of logic and 'common sense' did not apply.

Planck, a Professor of Theoretical Physics at the University of Berlin, did not intentionally set out on an adventure. He was analysing data, taken at the Physikalisch-Technische Reichsanstalt during experiments designed to optimize the efficiency of lighting devices. In trying to understand the basic process of light emission from glowing hot metals, Planck was confronted with the perplexing situation that, according to the 'well-established' theories, the amount of energy emitted from a hot metallic surface should be infinite.

Something was very wrong. '*A solution had to be found at any price*'. In *'an act of desperation'*, Planck proposed that energy is emitted, not smoothly, but in indivisible 'bundles' or *quanta*. This enabled him to construct a formula which gave excellent agreement with the experiment, but it replaced one conundrum with another. What kind of a law would limit physical processes in this fashion? Planck could give no reason why nature should impose such a constraint, other than that it enabled him to construct a formula which agreed with experimental results.

Einstein, Bohr and Born Come on Board

At first, most of Planck's peers did not take him seriously but there were exceptions, notably Albert Einstein, Niels Bohr and Max Born, who embraced the new idea with enthusiasm.

Einstein quickly remodelled Planck's quantum of energy into a particle-like bundle which hurtles through space like an atomic billiard ball, capable of knocking electrons right out of metals.

Bohr introduced the quantum into the planetary model of the atom, providing an explanation for the characteristic appearance of atomic spectra. He went on to create an institute in Copenhagen which was devoted solely to the study of quantum physics. Bohr's mission was to bring together the brightest young scientists from all over the world. It was an unqualified success; Bohr and his young colleagues developed what became known as the 'Copenhagen Interpretation' of quantum mechanics.

Max Born established a second centre for quantum studies at the Institute of Theoretical Physics in Göttingen, which provided additional mathematical back-up to the more philosophical deliberations in Copenhagen.

The Future is a Lottery?

It soon became clear that Planck's 'act of desperation' did much more than introduce a radical new concept regarding the emission of energy. It had knock-on effects which led to far-reaching departures from well-established scientific principles. One of these effects was to introduce spontaneous 'quantum jumps' between 'allowed' energies in the atom. These were assumed to be unpredictable, which meant that atomic phenomena do not follow a predetermined path but are governed by probability, a symbolic 'throw of the dice'.

Albert Einstein could not come to terms with this development. In his view, the scientific method demands that the same initial conditions must always lead to the same sequence of results. One of the rock-solid foundation stones of science was under threat; if that was removed the whole structure would collapse. He could not accept that the future of the universe is determined by successive arbitrary events at the atomic level: '*Der Alte würfelt nicht: God (the Old One) does not throw dice*'.

Erwin Schrödinger, another central figure in the development of the theory, joined Einstein in the camp of the objectors. To demonstrate the absurdity of what he had helped to create, he expressed his doubts in the paradox of *Schrödinger's cat*, which is mysteriously both alive and dead. That same year, Einstein, together with Boris Podolsky and Nathan Rosen came up with an even more subtle paradox, involving '*spooky actions at a distance*'.

The Adventure Continues

Over a century after the quantum adventure began, experiments are verifying quantum phenomena which defy understanding. There may not be cats which are simultaneously both alive and dead, but in the world of the atom such 'multiple existence' is commonplace. Experiments with electrons show 'spooky entanglement at a distance'; the electrons are intertwined regardless of how far apart they are. Light not only hurtles through space like a billiard ball but, at other times, behaves as if it is controlled by the throw of a dice. Apparently nature does not recognize 'perfectly reasonable' axioms.

We set out to tell the story of this adventure and the people who took part in it. It describes a journey into a world we cannot directly experience and which seems to be a world of fiction; '*Curiouser and curiouser!*', as Alice says in Lewis Carroll's book, *Alice in Wonderland.*

We will try to persuade the reader that the quantum mechanical world is not some sort of fictional wonderland but real; incredible only because it is different from what we think the world should be.

Richard Feynman expressed the dilemma in these words:

> *We always have had a great deal of difficulty in understanding the world view that Quantum Mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me ... It has not yet become obvious to me that there is no real problem. I cannot define the real problem, therefore I suspect that there is no real problem, but I'm not sure that there's no real problem.*[1]

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[1] A.J.G. Hey (ed.). *Feynman and Computation: Exploring the Limits of Computers.* Perseus Books, Reading, Mass. 1998.