

## Introduction

When in the year 5000 people look back three thousand years to our era, we all hope that they will find some epochal events as myth-making for them as the Trojan War for us. Many events of such lasting significance are to be found among the achievements of our twentieth century scientific revolution in physics. The very first of these revolutionary events – certainly in time and arguably in significance – is Planck’s invention of the energy quantum in 1900.

It is customary to undervalue Planck’s achievement as perhaps a lucky guess, a shot-in-the-dark by someone incapable of understanding its real significance, simply an ill-understood parametrization of data, a singular achievement but one that would have been found sooner or not significantly later by someone else – probably Einstein. We take the opposite view. Planck’s discovery was indeed manifested in the first instant as an empirical fit to data, but he was so profoundly prepared and deeply involved that he immediately understood an essential motivation for the derivation of the result. That profound motivation was the *necessity of discrete countability* of the states of the black-body radiation in order that it conform to the Second Law of Thermodynamics and have a *definable* entropy.

It is our view that Planck opened the door to an utterly new, totally unanticipated, wonderfully strange and mysterious but absolutely necessary ultimate reality of the world in the mechanics of the quantum – that is to say in quantum mechanics. Furthermore, that reality still remains all those things today even after one hundred years of the most intense scrutiny by some of the most knowledgeable, brilliant, imaginative and creative people the world has ever produced, functioning at an apex of intellectual intensity unsurpassed in the history of humankind. Where will it lead? And how will it end? We cannot know where it will lead and we cannot believe that it will end. For profound reasons which we leave for you to expand upon, we in fact *must* believe that it will *not* end.

We are devoted to the belief that the *original* accounts of great ideas are themselves not only great sources of further ideas but also unrivaled sources of inspiration and understanding [1]. Scientists at every stage of their careers are the richer for knowing intimately and at first hand the classic works of the immortals

of their subject. For this reason we have here taken a completely historical approach to the still lively and still controversial subject of the meaning of quantum mechanics. In Parts I-III we explore in detail the headwaters of this great river in the first mention by Planck of the quantum  $h$ , then we scrutinize in detail the increasingly rapid succession of discoveries by Einstein, Compton, Bohr, de Broglie, and .....

To speak of classics and original sources is not to suggest that we all do the moral equivalent of reading Homer's Iliad in the ancient Greek. Our focus is ever on the physics, not the poetry. For most people the language barrier is a complete deterrent not only because few people (neither of us) are facile in German, French, Italian etc, but also because the language (even when it is English) is itself frequently difficult. A notorious case in point is the writing of Niels Bohr, even in English, even in later life, which is maddeningly obtuse. The reasons for this almost universal communication problem amongst the founders of quantum mechanics are surely many. The work was new and abstract and as difficult to explain as to understand. In addition, the old greats were extremely careful to anticipate arguments where doubt existed, with the result that their writing was full of qualifications and caveats when one aches for a straightforward definitive statement which – of course – was not possible. And in their explorations, they frequently wandered down secondary paths where to follow would surely exhaust us and defeat our primary purpose. The compromise we have reached is to regard every source as a document to be translated into contemporary English, to be abridged and compressed to suit our purposes, and to be highlighted with explanatory notes where we thought they would be useful to point out the moment of creation, or at least the first mention of a new idea. Let us reassure everyone who might be offended by these elisions in the original texts, that they are made with a profound respect approaching reverence for the original authors. Our sole purpose is to make their classic work more accessible and widely used.

### **On Understanding Quantum Mechanics**

The fascination of the quantum realm is without limit. Multitudes of questions constantly and repeatedly arise which test our understanding and even redefine the

concept of understanding the new in terms of the familiar. The discovery of the quantum realm was forced on Planck by the failure of classical thermodynamics to produce so much as a *finite* result for the universal spectrum of radiation leaking from a hot oven. The myth is that Planck got lucky and fudged a connection between Wien's infra-red and Maxwell-Boltzmann's ultra-violet spectra which fit the data. That much is true, but Planck's immediate understanding was profound, and based on the fundamental definition of the entropy  $S = k \ln w$  which requires definition of the probability  $w$  for an equilibrium configuration of the radiation with its sources. Planck decided that probabilities are only definable for countable alternatives. The probability  $w$  of a configuration is the total number of 'complexions' included in it. To make these complexions countable, Planck was forced to introduce his energy quantum  $E = hf$  (see ChI).

Einstein further explained that Planck's quantum implied the physical result that light occur in irreducible energy quanta (ChII). Then in giant steps Bohr created his picture of the quantum atom as a micro-solar system, and introduced the concept of 'quantum states' with quantized energy and quantized angular momentum, and of 'transitions' between two such energy states with the emission of a light quantum (ChIII). The understanding of these transitions – indeed their understandability – remains a question. Technically, of course, we can calculate the result to a fair-thee-well, and we are instructed on what to believe, and even what questions we may ask [3]. Whether or not this is the end of the story is still being debated [4].

The explosion of progress triggered by Heisenberg's invention of quantum algebra (ChVI) – immediately recognized by Born and Jordan (ChVII) as matrix multiplication and, almost simultaneously and almost independently, further developed by Dirac (ChVIII) and by Schrödinger (ChIX) – changed forever the way to think about the fundamental structure of the microscopic world (ChX-XII).

People who look in casually on the sport of quantum mechanics are excited primarily by the buzz words, catch phrases, and paradoxes; the ones which plague us most include 'Is the moon there when no one looks?', 'Schrödinger's cat is both alive and dead – until you look!', and many more. These are problems of inter-

pretation which occur at the interface between the microscopic quantum realm and the macroscopic classical world of our gross perceptions. They obviously *are* bothersome questions because they and ones like them bothered Einstein (ChXIII), and because they received rather peremptory responses from authority figures such as Bohr and Heisenberg. Although such incomplete understanding never slowed or even really affected the break-neck pace of research into the then accessible applications of quantum mechanics, such questions have always been somewhat embarrassing even to pragmatic physicists, and – of course – have been the primary focus of the philosophical among us. Only recently have questions of the dynamics of the interface between the quantum and the classical worlds become a very interesting and even important subject of *experimental* as well as theoretical research (ChXIV).

### The Quantum View

Quantum mechanics as introduced in the very first instance by Born and Jordan (ChVIII) requires a very formal – to some a dauntingly abstract but rigid – view of the world. In the quantum extension of classical Hamiltonian mechanics, the classical number-valued canonical variables  $q, p$  are replaced by matrix operators in an abstract Hilbert space of ‘state’-vectors characteristic of the particular quantum system being considered. The space is spanned by a set – sometimes non-denumerably infinite – of mutually perpendicular unit vectors chosen as reference axes. Any vector in the space is  $1 \leftrightarrow 1$  with some quantum state of the system. For the simplest case of a spin-1/2 particle, there are two axes which can be chosen as spin-up and spin-down along some arbitrarily chosen  $z$ -direction.

A still simple example is the 1-dimensional simple-harmonic oscillator. Now a choice of axes could be the energy eigenstates  $|n\rangle$ , or the position eigenstates  $|x\rangle$  or momentum eigenstates  $|p\rangle$ , each with its own orthogonality and completeness relations, and each expressible in terms of others by the expansion coefficients, e.g., the familiar oscillator coordinate-space wavefunction  $\psi_n(x) = \langle x|n\rangle$ . Now we can imagine a pure state of the oscillator. It might be a pure energy eigenstate  $|n\rangle$ , in which case a measurement of the energy would always produce the result  $E_n$  – the energy eigenstate is stationary, and only changes its phase. A measurement

of the position would produce the result  $x$  with the probability  $|\psi_n(x)|^2$ . Suppose we prepare the oscillator (somehow) in a position eigenstate  $|x_0\rangle$ . A measurement of the energy will produce the result  $E_m$  with probability  $|\psi_m(x_0)|^2$ . A later measurement of the position however produces a hodge-podge.

It is interesting to imagine the introduction of a small non-linearity into the restoring force of the oscillator, described by an interaction Hamiltonian  $H_{int}$ . Suppose the oscillator initially to be in an energy eigenstate of the simple-harmonic oscillator (hereafter called an SHO-state). We emphasize that it is NO LONGER in an ENERGY eigenstate as defined by the FULL Hamiltonian. A later measurement (how?) of the SHO-state of the non-linear oscillator will no longer produce with certainty the original initial SHO-state. The state-vector remains normalized, but it no longer points in the same direction with respect to the SHO-axes. The state vector ‘rotates’ in the infinite-dimensional Hilbert space of SHO-states – it ‘evolves’ by a unitary transformation generated by the interaction Hamiltonian  $H_{int}$ . The probability of finding the non-linear oscillator in a different SHO-state will now be  $\sim |\langle n_j | H_{int} | n_i \rangle|^2$ .

It is noteworthy that the non-linear oscillator continues to evolve as a pure quantum state; the state vector is always of unit length but not simply along one of the initial SHO-axes.

The problem of what happens to the oscillator during (because of) any particular measurement has been separated from the purely quantum mechanical evolution of the oscillator in a way that has caused much consternation. This dichotomy is finally being addressed in recently devised ‘quantum non-demolition’ experiments (ChXIV).

An older problem is how the above description applies to a classical oscillator. Schrödinger (ChIX) thought to describe the classical oscillator as a ‘coherent state’ – still a pure state, but a carefully constructed special superposition of many quantum states with precarious phase and amplitude relations. This was immediately recognized by Heisenberg as insufficient (ChXI): the classical oscillator must be described by very rapid dephasing and decoherence caused typically by dissipative interactions with a ‘classical’ environment. (ChXV, XVI).

The concept of the quantum state reveals other aspects of nature besides quantization of energy and angular momentum. Dirac pointed out that the basic symmetries of nature are present already in the classical Action and the classical equations of motion. But it is only in the quantum *states* that the symmetries of nature are directly *realized*. Even the elementary symmetries of translation, rotation, and reflection invariance – present in all fundamental classical equations – are rarely if ever observed in classical states.

### Apologia

Quantum mechanics – like physics in general – is seemingly infinite in all directions. In our own experience we have progressed (?) from reading ‘everything’ to reading ‘nothing’ while continuing to read the same amount. In such a world it is impossible to do justice to a whole subject. We have followed one path – primarily non-relativistic and non-field theoretic, hopefully quantum mechanics *per se* rather than specific applications – through a vast jungle, guided more by our limitations than by our ambitions. In doing so, our primary concern has been to traverse the jungle of the first **100 Years of Planck's Quantum**. Much that is both beautiful and important has been omitted and for that we apologize.

In our final chapter, we have tried to anticipate the future course of our subject over the next hundred years. We find ourselves quite incapable of sensible predictions even over the next ten years, and have included our foolishness merely for the sake of amusement.

#### Footnotes and References:

- 1) Our inspiration for this book and our earlier one [2] is Julian Schwinger's invaluable collection *Quantum Electrodynamics* (Dover, New York, 1958).
- 2) I. Duck and E.C.G. Sudarshan, *Pauli and the Spin-Statistics Theorem* (World Scientific, Singapore, 1997).
- 3) Most recently by R. Omnès, *Understanding Quantum Mechanics* (Princeton, Princeton NJ, 1999); and R.B. Griffiths and R. Omnès, *Physics Today* **52-8**, 26 (1999).
- 4) For recent contributions to this debate see the exchange of letters in *Physics Today* **52-2**, 11 (1999) in response to the views of S. Goldstein, *Physics Today* **51-3**, 42 (1998); **51-4**, 38 (1998).