QUANTUM THEORY: UNDULATING FOUNDATIONS, UNCERTAIN PRINCIPLES?

Sosale Chandrasekhar*

Department of Organic Chemistry, Indian Institute of Science, Bangalore 560 012 (India)

ABSTRACT

Intriguing questions from the early history of quantum theory (QT) raise serious doubts about the accepted theory of black body radiation. (The Planck theory builds on the apparently flawed Rayleigh-Jeans approach.) Furthermore, the validity of the theory of diffraction, the basis of the wave theory of radiation and matter, seems uncertain. Together, these raise fundamental questions about the foundations of QT and its current status. The apparently symbiotic relationship between QT and the theory of atomic and molecular structure, a key paradigm of modern scientific thought, may be a misleading indicator of the validity of QT. The protocols deriving from the Schrödinger equation lead to quantized states, but only along with certain assumptions. It is argued that QT applies uniquely to the interaction of electromagnetic radiation with matter, and that its scope is not universal: thus, it is best regarded as a quasi-empirical formalism. It is possible that the uncertainty surrounding QT is a legacy of the troubled historical period during which it was founded. This apparently has fascinating implications for the history and philosophy of science in general.

*E-mail: sosale@orgchem.iisc.ernet.in

Tel.: +9180 2293 2689; fax: +9180 23600529

INTRODUCTION

It is perhaps historically fitting that quantum theory heralded the dawn of the twentieth century, as this signaled a break with the mechanical era, bound by the conventions of Newtonian mechanics. Thus, the maturing of theoretical science apparently coincided with the arrival of the two great non-conventional paradigms, quantum theory (QT) and the theory of relativity. Of these, QT has had a wider impact within physical science, in particular laying the theoretical foundations of modern chemistry (and, by extension, biology also).[1-3]

Just over a century after its birth, QT today is regarded as the key to understanding not only the fundamental nature of matter, but also – to some – the essence of reality. Thus, QT enabled the systematization of descriptive chemistry, and is also the source of philosophic insight: its theory of wave-particle duality clearly questions the meaning of 'identity'. However, although QT is generally accepted as being well established on a firm theoretical foundation, a careful examination of its early evolution raises intriguing questions about its general validity and scope.

Interestingly, modern QT is an amalgam of two autonomous paradigms in their own right. These are the original quantum hypothesis of Planck and the wave theory of light. The latter's extension to involve all matter by de Broglie, and its juxtaposition with the Planck theory produced the 'new quantum theory' around the 1920's. Thus, QT as we know it today is predicated on two distinct paradigms, which are themselves not beyond question, as will be discussed below.

Despite the triumphs of QT, therefore, it must be borne in mind that its roots lie in the 'pre-modern' age, and that its own evolution occurred during a tumultuous and tragic period in world history. The following ‘critique’ is intended to explore the scope and limitations of QT against a broad conceptual and historical backdrop.

It is also noteworthy that QT, because of its widely influential scope, is part of the general conceptual underpinning of modern science. Thus, it is no longer the preserve of the specialist, the rudiments of QT being essential training across a swath of modern physical science. Hence, this essay is no more than an informed layman’s opinions on the striking paradoxes of a famously enigmatic subject: a ‘spectator’ can perhaps lay claim to detachment, but with what sacrifice of rigor is clearly for the expert to judge!

DISCUSSION[1-3]

Origins: black body radiation. As is well-known, QT originated in the paradox of black body radiation, which could not be explained by the then existing theories, and which had culminated in the Rayleigh-Jeans law. Thus, experimental observations indicated that the energy of black body radiation was distributed with a maximum at intermediate frequencies, which also shifted to higher frequencies at higher temperatures (Fig. 1). However, the Rayleigh-Jeans equation (eqn. 1) required that the energy density Є increase exponentially with frequency; (k_B is Boltzmann’s constant, T absolute temperature, λ wavelength, v frequency and c speed of light).

$$\mathrm{d}\epsilon/\mathrm{d}\lambda = (8\pi k_B T)/\lambda^4 = (8\pi k_B T)(v/c)^4 \qquad (1)$$

$$(\partial^2\varphi)/(\partial x^2) = (1/c^2)(\partial^2\varphi)/(\partial t^2) \qquad (2)$$

$$\mathrm{d}n/\mathrm{d}\lambda = 2a/\lambda^2 \qquad (3)$$

$$\mathrm{d}N/\mathrm{d}v = (8\pi V v^2/c^3) \qquad (4)$$

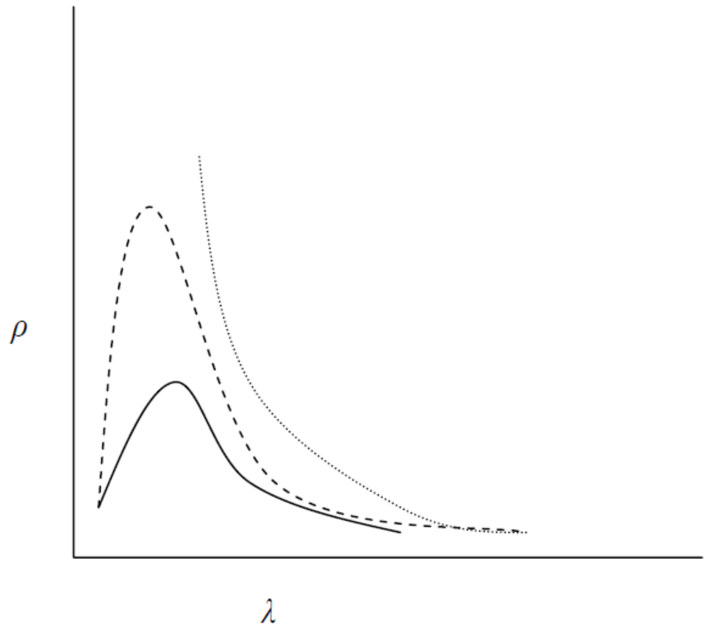

Fig. 1. Black body radiation. The maximum in the energy density (ρ) shifts to lower wavelength (λ) at higher temperatures (dashed line). The dotted line represents the ‘ultraviolet catastrophe’ predicted by the Rayleigh-Jeans equation.

The failure of the Rayleigh-Jeans equation, termed the ‘ultraviolet catastrophe’, is considered to be a turning point in the history of physical science, as it led to the formulation of Planck’s quantum hypothesis. However, a reexamination of the sequence of these events is interesting. The key assumption in the derivation of eqn. 1 is that the radiation inside a black body exists in the form of standing waves. It is particularly noteworthy that the Rayleigh-Jeans treatment of black body radiation dates back to the era of belief in an ether, the putative substratum permeating all space.

The standing waves in a black body were considered to be the oscillations of the ether. It is only thus that the mathematical treatment of d’Alembert (eqns. 2 and 3), was adapted to the Rayleigh-Jeans formulation. (In eqn. 2, φ refers to the wave, x, c and t being the distance traveled by the wave, its speed and the time taken, respectively.) Eqn. 3 refers to the distribution of standing waves in a string of fixed length a, n being the integral number of allowed half wavelengths.

A string of fixed length is a one-dimensional analog of the ether in a black body cavity of fixed dimensions. Eqn. 3 indicates that the higher frequency (lower λ) oscillations exponentially outnumber the lower frequency ones: this, in its three dimensional form (eqn. 4), is the basis of eqn. 1. (N is the density of oscillator states, ν the oscillator frequency, V the volume and c the speed of light).

Thus, eqn. 1 indicates that the average energy output would be exponentially greater at higher frequencies. (This also assumes the equipartition principle, so that the energy density is proportional to the density of oscillator states throughout the wavelength range.) We note again, however, that these conclusions are valid only if the ether substratum is present, not at all otherwise.

Furthermore, eqns. 3 and 4 may not be meaningful in the context of black body radiation, as λ would be of the order of the wavelength of light ($\sim 10^{-5}$ cm), whereas a and V would be of macroscopic dimensions: the errors in defining them would be enormously greater than the magnitude of λ itself. (Thus, eqns, 3 and 4 are based on the idea of fitting an integral number of half wavelengths within a certain length or volume respectively. For this exercise to be meaningful, it would appear that the wavelength needs to be of the same order of magnitude as the length or volume.)

Hence, the Rayleigh-Jeans approach is apparently fundamentally unsound for the above two reasons (the necessity of an ether, and the enormously differing errors in defining the wave length and the cavity dimensions).

The Planck proposal. Intriguingly, these debatable assumptions basing the Rayleigh-Jeans treatment were carried over to the Planck derivation (1900). In a critical departure, however, the earlier equipartition principle was replaced by a Boltzmann distribution of quantized oscillator states. This apparently had the effect of drastically reducing the effect of the high frequency oscillations, thus reining-in the Rayleigh-Jeans equation to conform to the observed distribution. A close examination of the approach, however, raises intriguing questions about its overall validity.

Essentially, it was proposed that each oscillator was defined by a fundamental (base) frequency, which could only be increased by integral multiples thereof. Also, the energy of an oscillator was proportional to its frequency. These proposals were enshrined in the famous Planck equation (eqn. 5) relating the energy of an oscillator (E) to its base frequency v. (The h is Planck's constant and the integer n = 0, 1, 2..; interestingly, a similar integral relationship is the basis of eqn. 3.)

$$E = nhv \qquad (5)$$

$$\varepsilon = hv[\Sigma\, i\exp(-ihv/k_BT)]/\Sigma \exp(-ihv/k_BT)$$

$$= hv/[\exp(hv/k_BT)\text{-}1] \qquad (6)$$

$$\mathrm{d}\text{Є}\,/\mathrm{d}v = [(8\pi hv^3)/c^3][1/[\exp(hv/k_BT)\text{-}1] \qquad (7)$$

The Planck approach then derives the average energy of an oscillator (ε, eqn. 6) *via* the Boltzmann equation, and multiplies it by the oscillator density (N in eqn. 4), derived in the Rayleigh-Jeans approach. This directly leads to the Planck distribution law (eqn. 7, in terms of unit volume).

Thus, the Planck proposal (eqn. 5) was essentially elaborated and combined with the Rayleigh-Jeans approach to arrive at the final equation for the distribution of black body radiation (eqn. 7), which apparently accorded with observations (Fig. 1).

Intriguingly, however, the Planck hypothesis (eqn. 5) – insofar as it was validated by the consonance of eqn. 7 with experiment – was also predicated on the debatable assumptions of the Rayleigh-Jeans treatment. (Furthermore – and questionably – the fundamental frequencies and their derivatives by eqn. 5 are distributed differently, as discussed below.)

As mentioned above, the Planck approach replaces the equipartition principle assumed in the Rayleigh-Jeans treatment with a Boltzmann distribution of quantized oscillator states. This has the effect – rather paradoxically – of decreasing the average energy of a high frequency oscillator relative to a low frequency one (eqn. 6). (Of course, this is due to the fact that excitation of the high frequency oscillator requires larger quanta, resulting in correspondingly fewer excited states by the Boltzmann principle.)

Thus, the contribution of the higher frequency oscillators to the overall energy is drastically reduced, and the 'ultraviolet catastrophe' (Fig. 1) thereby averted. This is the key to the apparent success of the Planck approach.

The limitations of the Planck approach. To reiterate, the Planck treatment depends on the validity of the Rayleigh-Jeans treatment itself, which is grounded in belief in an oscillating ether. It is noteworthy that the idea of an ether was abandoned in the early years of the twentieth century (apparently abruptly), although the quantum hypothesis is very much with us today.

Furthermore, according to current ideas, radiation of any type would originate in atomic and molecular transitions, essentially involving electronic, vibrational, rotational and translational motions. Clearly, the idea of oscillations of an ether is a distant analogy, at best, for these transitions.

In fact, the Planck proposal is unlikely to be applicable *in toto* to the case of molecular electronic transitions: molecular orbital energy levels are not evenly spaced, and there is no ‘electronic quantum number’ (corresponding to n in eqn. 5). Hence, the validity of the Planck proposal in the ultraviolet and visible regions of the black body spectrum is questionable.

Thus, in the absence of an ether, the Rayleigh-Jeans treatment loses its basis, there would be no ‘excess’ of higher frequency oscillators and hence no need to rein in their influence. In fact, the Planck treatment *per se* indicates that the low frequency oscillators would dominate (*cf.* eqn. 6): in the absence of the Rayleigh-Jeans equation (eqn. 1) to rein them in, there is now the possibility of an ‘infra-red catastrophe’!

It is particularly noteworthy that, in the Planck derivation, the fundamental frequencies are distributed according to the laws of standing waves but the higher frequencies of each oscillator according to the Boltzmann law. Strictly, of course, in view of eqn. 5, the former should also be subject to the Boltzmann law. This would decrease the contribution of the high frequency oscillators even further, but – clearly – would not lead to eqn. 7.

Eqn. 7 is the result of overlaying the two different distributions, the overall effect being that the low frequency oscillators are governed by the laws of standing waves and the high frequency ones by the Boltzmann law. This is clearly invalid. Intriguingly, therefore, these arguments practically disprove the Planck approach to black body radiation.

Other approaches. The historic Planck approach is particularly useful in focusing on the derivation of the density of oscillator states (eqn. 4), the key feature apparently retained in some form or other in all alternative approaches. Thus, the Planck derivation has much pedagogical value as well.

In fact, an alternative derivation by Einstein treats the radiation as arising from emission of photons from atoms, which are subject to the Boltzmann law. However, the analogous fundamental frequencies are distributed as in the Rayleigh-Jeans-Planck treatment, so the overall derivation is subject to the same critique as above.

Black body radiation and the Maxwell-Boltzmann distribution. These arguments indicate that there must be an alternative explanation for the observed distribution of black body radiation. Although the Planck derivation is mathematically valid, its applicability to the case of black body radiation is apparently questionable.

The essential problem lies in explaining the (approximately) Gaussian nature of the distribution (Fig. 1): perhaps ironically, this cannot be explained by the quantum hypothesis, as quantized levels are governed by the Boltzmann distribution. The overall Planck approach implies that high frequency oscillations are subject to the Boltzmann distribution and the low frequency ones to the laws of standing waves. This is debatable as discussed at length above.

Interestingly, the close similarity of the distribution of black body radiation with the Maxwell-Boltzmann distribution of molecular velocities is indeed striking. Although this was never accorded due consideration, because of the presumed success of the Planck theory, it now seems worth reconsidering, as discussed below.

Is black body radiation quantized? This intriguing question arises in light of the above discussion. Essentially, the observed distribution implies a most probable value for the energy (Fig. 1). However, quantized transitions from vibrational and electronic states generally occur from the lowest to the next highest level, so a Gaussian distribution is unlikely. On the other hand, the emission of electromagnetic radiation from the black body, particularly at high frequency, implies quantized transitions (based on current ideas).

Thus, in a supreme irony, the paradox of black body radiation apparently remains unexplained even a century after the birth of QT. A rigorous resolution of the paradox must await further work, although a possible explanation may be as follows. As the black body is usually metallic, it seems possible that transitions involving the electronic bands are in equilibrium with translational motions, involving both the metal and the enclosed gas. This would explain the close similarity of Fig. 1 to the Maxwell-Boltzmann distribution of molecular velocities.

In any case, the collapse of earlier treatments necessitates a new approach to black body radiation. This is an intriguing conclusion, as the explication of the distribution of black body radiation is considered to have laid the foundations of QT.

Validity of the quantum hypothesis. ‘Quantization’ attempts – apparently unsuccessfully – to ‘patch up’ the flawed Rayleigh-Jeans formulation without addressing its fundamental inadequacies. Questioning the validity of the quantum hypothesis may seem preposterous in view of the key role assigned to QT in the underpinning of modern science. However, it may well be that QT will bequeath to posterity a puzzling legacy. For instance, QT is supposed to have introduced an idea of reality that is weird and uncommon, but it is interesting to examine this popular conception.

Thus, QT has given rise to a pervasive belief that energy exists in ‘packets’. Interestingly, the human mind is perhaps more attuned to the tangible concept of matter, rather than the abstraction of energy. Indeed, energy is possessed by matter, hence quantization is a condition imposed by matter upon energy.

Furthermore, even accepting the existence of oscillators within a black body, quantization (eqn. 3) indicates that an oscillator emits radiation of a fixed energy and integral multiples thereof. This implies – in all seriousness – that the color of a ray of light is invariable, *i.e.* does not change in ‘mid-flight’. (It can without quantization, as then the oscillator can emit varying energy.) In this context at least, QT does not introduce any idea contrary to normal experience. (Also, that a substance could absorb only some colours and reflect others was known at the time QT was proposed!)

Interestingly, also, the universality of quantization is belied by the fact that translational motion is barely quantized. Heat energy is absorbed by normal objects with a continuous rise in temperature. Molecular absorption spectra generally display broad envelopes. (In the case of electronic spectra, these are assumed to arise from concomitant vibrational and rotational transitions.)

Many of these cases would qualify as failures of QT, in any honest assessment.

The Bohr model of the atom and QT. Although the original Planck proposal (eqns. 5-7) was apparently accepted as a satisfactory explanation for the distribution of black body radiation, the contours of its scope were yet to be drawn in the early 1900's.

An early milestone, however, was the implication of QT in the Bohr model of the atom (~ 1915). In particular, the distinct lines observed in the emission spectra of atoms could be explained as arising from quantized transitions of electrons in orbits around a positively charged nucleus. In this the Bohr and quantum theories apparently reinforced each other, raising the intriguing question whether a theory can be proved by another theory.

The Bohr model of the atom, of course, laid the foundations of the modern theory of matter, based in the structural theory of chemistry. All the same, the model is based on the paradox of two oppositely charged particles (the electron and the nucleus) being restrained from collapsing into each other, as apparently demanded by classical electrodynamics. QT does not resolve this paradox, although it suggests the idea of quantized electronic transitions between orbits. (There appears to be a pervasive belief that QT enabled the circumvention of the laws of electrodynamics.)

It is also interesting to note that the production of oppositely charged species in a process does not prove their prior existence as such. Thus, the generation of ionic species from neutral covalent molecules is commonplace in organic chemistry. Similar logic – at least in principle – would be applicable to the production of α and β rays from atoms. This is apparently the key evidence for the prior and independent existence of protons and electrons, respectively, inside the atom.

Thus, the Bohr and quantum theories apparently evolved symbiotically in their early years. Again, this raises fundamental questions about the validity of both, as any theory must be corroborated independently. The synergy between the Bohr and quantum theories has, at best, enabled a systematic investigation into the nature of matter on an unprecedented scale. However, this could have been at the cost of a more rigorous theory of atoms and molecules, which perhaps lies in a direction unperceived as yet.

The wave theory of matter and the new QT. The marriage of QT – itself born of the wave-oscillator theory of energy – with the wave theory of matter, represents one of the great intellectual revolutions in history. Thus, the de Broglie suggestion of 'matter waves' (1923) and the linking of wave and particulate properties *via* the well-known relation in eqn. 8 (p being momentum), ushered in the 'new quantum theory'. This subsequently evolved into a highly sophisticated mathematical formalism, as epitomized by the famous Schrödinger equation (*vide infra*), which elegantly combined wave and particulate concepts in a rigorous manner.

$$\lambda = h/p \qquad (8)$$

The de Broglie idea suggested that electrons, considered as particles in the Bohr model, could also be treated as waves. This replaced the original concept of orbit by that of orbital, which was possessed of a shape defined by the probability distribution of the dualistic electron. The shapes and energies of atomic orbitals held the key to the laws of chemical combination and the structures of molecules. Thus, the de Broglie idea of wave-particle duality laid the foundations of the modern theory of matter.

It is noteworthy, however, that the 'extended' Bohr concept of atomic orbital does not *per se* make contact with the reality of molecular structure. The additional concept of orbital hybridization needed to be introduced before the derived structures agreed with the experimentally observed ones. This suggests that QT and its derived set of concepts and ideas are essentially empirical constructs.

The wave theory of matter, of course, derives from the wave theory of light, originally pioneered by Maxwell in the nineteenth century. The de Broglie idea (eqn. 8) is also predated by the corpuscular theory of light, supported by the work of Einstein on the photoelectric effect. The idea of duality is perhaps less enigmatic as applied to light, apparently because of its 'fluent' character. All the same, although perhaps with the benefit of hindsight, intriguing questions remain about these early studies.

The photoelectric effect. This is the ejection of electrons from the surfaces of metals when light is shone on them. (It should be noted that in the case of light, the wave theory predated the corpuscular.) The corpuscular explanation was based on a 'billiard ball' effect, *i.e.* the physical ejection of a particulate electron by a light corpuscle. It is interesting to note, however, that modern theories of electronic excitation in molecules do not employ particulate concepts. Apparently, the photoelectric effect can be similarly explained without recourse to the corpuscular idea.

The photoelectric effect is essentially dependent on the frequency rather than only the intensity of the incident light, which can be accommodated by the wave theory of light. At the time the corpuscular theory of light was proposed on the basis of the photoelectric effect, electrons were apparently regarded as particles. Thus, it was perhaps natural to consider that their ejection was performed by a corpuscle rather than a wave of light.

All this is not to say that the corpuscular theory is disproved, only that it is not necessarily proved by the photoelectric effect. However, it is noteworthy that the idea of wave-corpuscular duality of light was the progenitor of the broader de Broglie suggestion (eqn. 9). These considerations indeed raise intriguing questions about the very idea of duality, as also indicated by the following discussion on the wave theory of light.

The wave theory of light. The modern idea that light is composed of orthogonal electrical and magnetic oscillations is largely based on the brilliant work of Maxwell in the nineteenth century. However, the general idea that light was a wave originated in the earlier work on diffraction, particularly by Huygens. The theory of diffraction of light that evolved was apparently based on the observed interference of waves generated on the surface of water. This analogy, although interesting, is based on questionable assumptions.

Thus, diffraction gratings were constructed by etching straight lines on glass, the spacing between the lines apparently being of the order of the wavelength of light. This is typically ~ 10^{-5} cm, and it seems highly unlikely that a uniform spacing of this infinitesimal magnitude can be constructed (particularly manually). Also, the theory of diffraction (the Huygens construction) is based on repeated interference of wavelets that interact constructively or destructively as they advance.

However, the construction is enormously out of proportion, as the line spacing, the wavelength and the area of advancement are all depicted to be of the same order. In reality, the area of advancement would be of macroscopic dimensions relative to the spacing and the wavelength. This implies an infinite number of interference levels, leading to a highly smeared out pattern, rather than the sharp lines observed in practice.

These arguments indicate that the macroscopic model of wave interference is misleading, and that the observed 'diffraction' patterns are not necessarily caused by the presumed wave nature of light. Although the experimentally observed patterns are real, it appears they must await a more rigorous theory of light scattering for explication.

In other words, the wave theory of light hangs too heavily on certain observations that are unlikely to be what they seem. The wave theory of light apparently also leaves untouched the question of quantity: how many rays or oscillations make up a photon? The wave theory apparently represents the idea of 'non-particle' as an alternative formulation of 'substance', be it energy or matter.

The Schrödinger equation. This represents the core principle of the new QT, and is the practical manifestation of the de Broglie idea of wave particle duality. The Schrödinger equation (eqn. 9) describes a moving particle that can also be considered as a wave, and can be derived from the equation of wave propagation in combination with the de Broglie condition (eqn. 8). Its elaboration in various systems apparently justifies the idea of the quantum of energy, as has been ingeniously demonstrated. Although this appears to prove QT, the following arguments are noteworthy. (The ψ is the wave function corresponding to the particle of mass m.)

$$(d^2\psi)/(dx^2) + 8\pi^2 m(E-U)\psi/h^2 = 0 \qquad (9)$$

The Schrödinger equation (eqn. 9) is applied by including the appropriate classical expression for either the total energy (E) or the potential energy (U). This may be followed by imposing necessary spatial restrictions on the motion of the particle ('boundary conditions') and solving eqn. 9. Various general and specific boundary conditions restrict the solution to certain values of the wave function, which manifests as quantized energy levels.

Furthermore, quantization also depends critically on the values assigned to key classical parameters at the atomic level, *e.g.* the force constant in the case of vibrational motion and moment of inertia in the case of rotational motion. These assignments are based on experimental (usually spectroscopic) observations, which assume the quantum condition.

It is particularly noteworthy that the Schrödinger equation *per se* neither proves nor explains quantization. The imposition of boundary conditions allows for quantization, but only in principle. The magnitude of the resulting quantization, *i.e.* whether it is discernible or not, depends critically on the values assigned to the above classical motional parameters. Thus, for instance, in the case of the harmonic oscillator, quantization depends critically on the force constant being of substantial magnitude relative to the reduced mass.

Thus, the de Broglie relation (eqn. 8), and by implication the Schrödinger equation, indicate that as the mass of a particle decreases, the associated wavelength increases. However, whether or not quantization manifests, and if so at what stage, are apparently arbitrary, and depend upon the values chosen for the atomic-molecular equivalents of classical motional parameters.

Therefore, these intricate protocols involve a subtle interaction between theory and experiment. However, to the extent that the classical motional parameters are assumed on the basis of experiment, the exercise is tinged by an element of arbitrariness. These arguments assume importance in light of the fact that direct experimental evidence for quantization is generally scarce (except at the atomic level).

Current status of QT. The above discussion indicates that QT rests on uneven ground, as the key assumptions on which it is based are debatable. This startling conclusion must be judged against the fact that QT clearly functions as a ‘working hypothesis’ in providing a conceptual basis for a range of natural phenomena. Interestingly, however, these almost invariably involve the absorption or emission of electromagnetic radiation by matter.

Thus, in certain cases at least, energy is apparently absorbed or emitted in discrete quantities, in keeping with the Planck idea of quantization. It is noteworthy, however, that this rules out the highly general case of energy transfer occurring *via* conduction and convection from the purview of QT. (Although it may be argued that this is as much an experimental limitation, the fact remains that these do not represent clear-cut applications of QT.)

This much curtailed extent of QT leads to the possibility that quantization merely reflects a requirement of the interaction of radiation with matter. The idea of discrete energy states in matter is derived from this, and extended by implication to the constituent atoms and molecules. However, the idea that energy states pre-exist may have to yield to the possibility that an energy state is created by the interaction of radiation with matter. The observed ‘quantization’ would then reflect a peculiarity of the matter-radiation interaction.

The ‘conceptual inversion’ of the accepted idea that quantization originates at the atomic-molecular level may seem startling, but one notes that quantization is essentially predicated on the Bohr condition of ‘stable orbits’ (apart from other assumptions discussed above). As argued above, this may be fundamentally questionable, so it is entirely possible that discreteness is a macroscopic property.

Thus, matter exists in discrete energy states that may be accessed by absorption of electromagnetic energy. The quantum hypothesis, of course, is consonant with this, although it is usually considered only at the atomic-molecular level. However, to reiterate, the quantum hypothesis exists symbiotically with the Bohr idea of stable atomic orbits, so neither can be considered as proven.

A quasi-empirical formalism. These arguments, when considered against the backdrop of the collapse of the theory of black body radiation, raise the possibility that QT is essentially an empirical construct. The mathematical rigor and sophistication that support QT need also to be evaluated in this light. A scientific theory provides a model of nature, explains experimental observations and suggests new strategies. In view of the strengths and limitations of QT as discussed above, it would appear that QT is best considered as a quasi-empirical formalism.

Thus, the quantized absorption and emission of radiation by matter remains a mystery that the hypotheses and assumptions of QT accord with but not necessarily explain. Therefore, the extension of QT beyond its quasi-empirical purview seems unwarranted, particularly to a wider philosophical discourse on the nature of reality.

Historical backdrop and philosophical considerations. QT, born of mathematical method complementing experimental observation, apparently evolved its enigmatic nature against a tumultuous historical backdrop. The end of the nineteenth century and the first quarter of the twentieth were witness to several wars (including a World War) and the collapse of old empires and social orders. The ensuing decade also witnessed the cataclysmic events leading up to yet another World War. QT evolved almost to its current status in close proximity to these unprecedented upheavals. A historian of science cannot but wonder about the intellectual atmosphere prevailing in those troubled times.

Was QT ushered in too hastily and uncritically? Would a more rigorous assessment of the Planck proposal have proved abortive to QT? Was the birth of QT enabled by 'constructive lapses', the products of an unsettled intellectual climate perhaps to be expected during periods of upheaval? These tantalizing questions are worthy of further consideration.

The history of QT is also relevant to the general question about the meaning of a scientific theory, the definition of its validity and its role in the advancement of knowledge. An analysis of QT indicates that the destiny of modern science was determined by an apparently imperfect theory: this was, perhaps, better than no theory at all; but, then, did QT also prevent alternative approaches?

Thus, the conceptual evolution of QT raises intriguing questions about the nature of knowledge and the measure of its certitude. The early history of QT will forever represent a study in the epistemology of science, *vis-à-vis* a branch defined by a community of influential thinkers, scholars and researchers, the *avant garde* of the evolving technological civilization.

Intriguingly, also, the theory of black body radiation, despite being mathematically beyond reproach, apparently founders on physical meaning and significance. This raises important general questions about the phenomenological interpretation of mathematical methods and approaches, and indicates that the interface is not without its hazards.

In the future, the traditional enigmatic appeal of QT would be tempered by the paradox of a sophisticated paradigm with a largely utilitarian value. This is not to suggest the abandonment of QT, although it may well represent an outcrop of a far greater construct: this, however, cannot be discovered by building on the imperfections of QT.

CONCLUSIONS

Despite the apparent success of quantum theory (QT) it is necessary to examine afresh its ‘founding credentials’ and reassess its scope. The original theory of black body radiation developed by Rayleigh and Jeans, and extended by Planck, may well have to be abandoned. (In particular, the interpretation of the Planck equation linking energy and frequency, and the derived idea of the quantum of energy, may need to be reassessed.)

The apparently symbiotic relationship between QT and the Bohr theory of atomic structure raises doubts about the validity of both. Fundamental questions also remain about the wave theory of radiation and matter, particularly the evidential theory of diffraction, which is apparently oversimplified. This then leaves the vast body of mathematical formalism developed to explain the quantized absorption and emission of electromagnetic radiation, essentially observed in spectroscopic studies.

It is noteworthy that quantized absorption is hardly unexceptional, *e.g.* the broad envelopes generally observed in molecular spectra. Also, although QT doubtless enabled the modern structural theory of chemistry, the additional concept of orbital hybridization, extraneous to the (extended) Bohr model was necessary. These would need to be considered as failures in an honest assessment of QT. (QT also does not apply to the transfer of heat by conduction and convection.)

As QT accords with – but does not necessarily explain – the apparently quantized interaction of electromagnetic radiation with matter, it is best regarded as a quasi-empirical formalism. (It is possible that QT represents a projection of a far greater theoretical construct, as yet undiscovered.) The chequered conceptual evolution of QT seems to be the result of a historical period of upheaval and conflict. The evolution of QT apparently has important implications for the history and philosophy of science in general.

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