The quantum, its discovery and the continuing quest

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'But it was Planck's law of radiation that yielded the first exact determination – independent of other assumptions – of the absolute magnitude of atoms. He showed convincingly that in addition to atomic structure of matter there is a kind of atomistic structure to energy governed by the universal constant h (the quantum of action). This discovery became the basis of all twentieth-century research in physics and has almost entirely conditioned its development ever since. Without this discovery it would not have been possible to establish a workable theory of molecules and atoms and the energy processes that govern their transformations. Moreover, it has shattered the whole framework of classical mechanics and electrodynamics and set science a fresh task: that of finding a new conceptual basis for all physics. Despite remarkable partial gains, the problem is still far from a satisfactory solution.'

– Einstein on Max Planck (In Memoriam, 1948)

It was exactly one hundred years ago on 14 December 1900 that the great physicist Max Planck (1858–1947) presented to the German Physical Society his revolutionary concept of the quantum of action, using which he successfully explained the spectrum of radiation emitted by a black body. Planck was aided in this momentous discovery by, first, his insistence on empirical veracity and second, the laws of thermodynamics. This history is narrated in several places[1], I shall just briefly recall the main features.

Gustav Kirchhoff, Planck's teacher and a great physicist himself had noted in 1859 that the dark lines of sodium seen in the solar spectrum are darkened further by the interposition of a sodium flame in the path of the sun's rays. This led him to examine the relation between emission and absorption of radiation by matter. He was able to show by theoretical arguments that consistency with principles of thermodynamics demands that the ratio of emissive power E_ν to absorptive power A_ν when a body is in thermal equilibrium, for a given frequency ν of the radiation, is a function of temperature alone and is independent of the nature of the material that emits or absorbs the radiation.

$$E_\nu / A_\nu = J(\nu, T). \qquad (1)$$

$J(\nu, T)$ is a universal function, which therefore must be determined by experiment and deduced from basic principles by theory. (Another example of such a simple observation with profound implication as follows: The period of oscillation of a simple pendulum is independent of the nature of the material of the pendulum bob and is a function only of the length of the pendulum and the local value of the acceleration due to gravity. This gives rise to the principle of equivalence between inertial and gravitational mass, a crucial ingredient in Einstein's gravitation theory.) Important progress was made in 1879 by Stefan with his phenomenological law, which said that the total energy emitted, i.e. E_ν integrated over all frequencies is proportional to the fourth power of T, the absolute temperature. This was put on firm theoretical grounds in 1884 by Boltzmann who showed that Stefan's law was valid for perfectly black bodies only (a perfectly black body has $A_\nu = 1$ for all ν), basing his derivation on Maxwell's electrodynamics and application of thermodynamics to the radiation field. He also showed that the universal function $J(\nu, T)$ is related to the radiation field by

$$J(\nu, T) = \frac{8\pi}{c} \rho(\nu, T). \qquad (2)$$

Here c is the velocity of light and $\rho(\nu, T)$ is the energy density of the radiation field per unit volume for frequency ν.

In 1893 Wien, developing on the ideas of Boltzmann was able to show by a simple thought experiment that the spectral density ρ must have the form

$$\rho(\nu, T) = \nu^3 \phi(\nu/T), \qquad (3)$$

where now ϕ is a universal function of a single variable, the ratio of the frequency ν to the absolute temperature T. This is usually referred to as Wien's displacement law, since it predicts that the frequency ν_m or alternately the wavelength λ_m for which ρ attains its maximum value at a given temperature T satisfies the displacement law

$$\lambda_m T = \text{universal constant}, \qquad (4)$$

which means as the temperature decreases the wavelength corresponding to the spectral maximum increases as the reciprocal.

What about the specific form of $\phi(\nu/T)$ itself? As can be imagined there were no dearth of proposals, but we shall confine ourselves to a form proposed by Wien himself which was based in part on experimental data, especially of Paschen and on suggestions from gas theory of Maxwell and Boltzman on molecular velocity distributions. In 1896 Wien proposed his distribution law

$$\rho(\nu, T) = b\nu^3 \exp(-a \cdot \nu/T). \qquad (5)$$

This is called Wien's law, and is *a priori* not an exact law like the displacement law (eq. (3)) which was derived from basic principles.

Planck became interested in deriving a form for $\rho(\nu, T)$ around the year 1894. His early research work in thermodynamics and electrodynamics had specially prepared him for the task. According to Maxwell's electrodynamics, bound electrically charged particles which constitute matter, when acted on by an external field will undergo forced oscillations and radiate. These oscillating charges are assumed to be bound by harmonic restoring forces with a damping term. Planck was able to deduce that the equilibrium energy density of the oscillator $U(\nu, T)$ is related to $\rho(\nu, T)$ by

$$\frac{8\pi}{c^3}\nu^2 U(\nu, T), \quad (6)$$

a result that was very pleasing to him since it now meant that U was also a universal function related to ρ by simple factors. From 1896 till early 1900, it was widely believed that Wien's law (eq. (4)) fitted the experimental spectrum well. If this was indeed the answer to Kirchhoff's challenge, then it follows from eqs (4)–(6) that

$$U(\nu, T) = b\nu \cdot \exp(-a\nu/T). \quad (7)$$

Now Planck recognized that eq. (7) implies that b and a are universal constants. The constant b has dimensions energy/frequency or erg.sec. It will therefore define, when combined with Newton's gravitation constant G_N and the velocity of light c, a mass scale that Nature itself provides and there will be no need to depend on a man-made standard. Similarly the universal constant a will provide a standard for temperature. It therefore becomes mandatory to provide a firm theoretical basis to eq. (5).

Planck's early researches in thermodynamics which he felt were ignored by his contemporaries, now came in handy. Since according to the second law

$$dU = T\,dS \quad (8)$$

at constant volume, it is enough to find the dependence of the energy U of the oscillator on its entropy S, to find the function ϕ in eq. (3).

Planck was able to show on general grounds that the second derivative of the entropy must satisfy the equation

$$\frac{\partial^2 S}{\partial U^2} = -f(U), \quad (9)$$

where now $f(U)$ is a positive function of U. He then advanced plausibility arguments for the form of f. In particular, he thought that he could prove

$$f(U) = \alpha/U, \quad (10)$$

where α is a positive constant.

Integrating eq. (10) using eq. (8) Wien's law, eq. (5) or (7), follows imme-

Box 1. Max Karl Ernst Ludwig Planck (1858–1947)

Planck received his early education in Munich, studied in the University there and in Berlin and obtained his doctorate in 1879 from the University of Munich. He was an instructor in Munich and moved as extraordinarius (Associate Professor) to Kiel. After the death of Kirchhoff, he was invited to Berlin in the same capacity in 1889 and became a full Professor in 1892. He was nominated by Helmholtz and elected to the Berlin Academy of Sciences in 1894 for his contributions to thermodynamics.

He came from a family of pastors, scholars and jurists and was a deeply religious man and committed to his family. Planck passionately believed that there are absolute laws in Nature and discovering them to be the goal of science. He was a very good student, although there were no signs of the genius in the young man. He carried out research in theoretical physics with single-minded devotion, and was quite content in the early part of his career in putting thermodynamics on firm foundation and was not after any quick success. He was disappointed however by the lack of recognition by his peers of his early research work, though he recalled with some satisfaction in later life that this meant that he was alone in his search for the radiation law, as others did not pay attention to his line of thought and so there was no real competition for him.

Einstein venerated Planck. On the latter's 60th birthday in 1918 he said: 'The longing to behold . . . preestablished harmony is the source of the inexhaustible persistence and patience with which we see Planck devoting himself to the most general problems of our science without letting himself be deflected by goals which are more profitable and easier to achieve. I have often heard that colleagues would like to attribute this attitude to exceptional will-power and discipline; I believe entirely wrongly so. The emotional state which enables such achievements is similar to that of the religious person or the person in love; the daily pursuit does not originate from a design or program but from a direct need'.

Planck held many important positions in the German science establishment for some five decades. He served with great devotion and dedication in all the various positions he held. His colleagues' trust in him can be gauged by the fact that for election as Secretary of the Academy he received 19 out of 20 votes, with the lone vote going to Walter Nernst who probably cast it in his own favour. Planck held German science together in a period of great turbulence, which saw defeat of his nation in the war, economic disaster and personal tragedies, not only his own, but of many colleagues as well. The epic proportions of the battle that Planck had to wage with his fellow academicians, many of whom were celebrities, can be seen from Einstein's observation that 'they (academicians) were not notable for "independence of character, freedom from prejudices of caste and spirit of self-sacrifice"'.

While remaining a patriot, Planck was graceful to acknowledge his mistakes like his signing the declaration by 93 intellectuals in 1914 and made amends in several ways to rectify his errors and brought to his public life a level of integrity consistent with his own absolute standard in science.

Planck had four children. His first son Karl died of wounds received in the battle at Verdun in 1916. His twin daughters Grete and Emma died in quick succession in 1917 and 1919, which made Einstein write to Born, 'Planck's misfortune wrings my heart, I could not hold my tears when I saw him'. The most terrible blow of all fell when his younger son Erwin was executed in January 1945 in the rule of terror, for allegedly plotting against Hitler. It was to the child Erwin, that the father had in December 1900, confided about his having made a contribution to science on par with Copernicus and Newton. Planck also saw his house go up in flames along with his precious scientific collections. His own upbringing was perhaps responsible for his singular dedication to propagating the ideals of science to young people all through his life till the end despite all the disaster and ruin that he witnessed.

As Heilbron[2] puts it: 'while Planck was a deeply religious person, he did not believe in "a personal God, let alone a Christian God". A God without qualities, a religion without trappings, life without compartments, a world view without extremes is what he cherished'. Summing up Planck himself wrote, 'Religion and natural science are fighting a joint battle in an incessant, never relaxing crusade against skepticism and against dogmatism, against disbelief and against superstition, and the rallying cry in this crusade has always been and always will be "On to God".'

diately. These were the arguments that Planck had presented in late 1899 and early 1900, which he hoped would settle the problem of black body radiation. However these hopes were short-lived since within a few months, Lummer and Pringsheim and Rubens and Kurlbaum who had carried out measurements at long wavelengths found that Wien's law failed to fit their data. Faced with incontrovertible experimental evidence Planck set to work again. He was greatly helped by a conversation with Rubens on 7 October 1900, in which the latter had mentioned that the spectral density at the long wavelengths at which he and Kurlbaum had made their measurements was proportional to the temperature T. Returning to the function f in eq. (9) Planck now admitted that his argument that led him to the specific form eq. (10) is not correct, but it is not completely incorrect either, since Wien's law is good at high frequencies where U is small. He modified eq. (10) as follows to the form

$$f(U) = \frac{\alpha_1}{U(\alpha_2 + U)}, \qquad (11)$$

which clearly reduces to eq. (10) when U is negligible compared to α_2. Further, if U is large then we can write

$$f(U) = \frac{\alpha_1}{U^2}. \qquad (12)$$

Using this in eq. (9) and integrating one gets

$$\frac{\partial S}{\partial U} = \frac{\alpha_1}{U}. \qquad (13)$$

Comparing with the second law eq. (8) it follows U is proportional to T, and this is consistent with Kurlbaum and Rubens' experimental observations at long wavelength $\lambda = 51\ \mu$, $2\ \mu$.

It is simple to integrate eq. (9) with the form for f given in eq. (11) and derive the functional form of U and therefore ρ. Using the notations, that Planck himself used later instead of α_1 and α_2 in eq. (11) for the constants one gets (the relation is $\alpha_1 = k$, $\alpha_2 = h\nu$)

$$\rho(\nu, T) = \frac{8\pi\nu^2}{c^3} \frac{h\nu}{\left(\exp\frac{h\nu}{kT} - 1\right)}, \qquad (14)$$

the formula that was presented by him on 19 October during a discussion following the presentation of a paper by Kurlbaum.

Planck argued that his extension was the simplest possible modification of Wien's law. Comparison with experiment was swift, as the following morning itself Rubens told Planck that his new formula fitted all data points. It is to the eternal credit of Planck that he was not satisfied with the success of his formula in fitting the data, but wanted to find a fundamental derivation. This began what he himself called as the most strenuous period of his life. Following his conviction that understanding the entropy of the oscillator is the key to solving the problem, and having obtained the correct formula eq. (14) that agrees with all data points, he now found the expression for S from eq. (14) or equivalently from eq. (9) and eq. (11). One gets

$$S = k\left[\left(1 + \frac{U}{h\nu}\right)\ln\left(1 + \frac{U}{h\nu}\right) - \frac{U}{h\nu}\ln\frac{U}{h\nu}\right]. \qquad (15)$$

The challenge is now to derive this last equation from first principles. Planck knew from the work of Boltzmann that entropy is the logarithm of the thermodynamic probability. Suppose now that there are a large number (N) of oscillators, then the total energy and entropy of all the oscillators is given by

$$U_N = NU; \quad S_N = NS. \qquad (16)$$

Then writing

$$S_N = k \ln W_N, \qquad (17)$$

our task reduces to finding W_N, the total number of ways the energy U_N can be distributed over N oscillators. A simple analogy will explain the next crucial step that Planck took. Imagine that we have N children to whom we want to distribute P identical pieces of chocolates. How many ways can be this done? Combinatorial analysis gives this number as

$$(N - 1 + P)!/P!(N - 1)!\,. \qquad (18)$$

Returning to Planck, to compute W_N, he assumed that the total energy U_N of all the oscillators is made up of some integral multiple P of some *finite* energy units ε so that $U_N = P\varepsilon$. The number of ways W_N of distributing these indistinguishable P quanta over N distinguishable oscillators W_N is then seen to be given as in eq. (18) by

$$W_N = (N - 1 + P)!/P!(N - 1)! \qquad (19)$$

Now one has $P/N = U/\varepsilon$ and $S_N = NS$ from which, using eq. (17) and eq. (19) and Stirling approximation for the factorials

$$S = k(1 + U/\varepsilon)\ln(1 + U/\varepsilon) - (U/\varepsilon)\ln(U/\varepsilon). \qquad (20)$$

Using again the second law eq. (8) and Wien's displacement law, eq. (3) and eq. (6) it follows that S is a function of U/ν only. Therefore from eq.(20).

$$\varepsilon = h\nu, \qquad (21)$$

and one gets eq. (14), the radiation law. The constant h occurring in eq. (21) is a universal constant which Planck called the quantum of action (dimensionally h has erg.sec or momentum.length). This was the derivation that Planck presented to the Physical Society of Berlin on 14 December 1900.

Historically, the constant k which is called Boltzmann's constant was also first introduced by Planck. Table 1 gives the values of h, k and e found by Planck in 1901, from the then available data and the present values.

The last constant, e the charge on the electron was obtained by Planck as follows. Using k, he determined the Avagadro number N from the gas constant and from the value of the Farad F = Ne deduced the value of e. Planck's value for e is to be compared with J. J. Thomson's value of 6.5×10^{-10} esu obtained in 1899. Only in 1908, when Rutherford and Geiger determined the charge of the alpha particle to be 9.3×10^{-10} esu, it was realized how good Planck's value was, a tribute indeed to the accuracy of the experimental data and the distribution law for black body radiation.

What is the status of quantum theory today? While quantum mechanics, developed in the mid-twenties, has been an

Table 1. Values of h, k and e found by Planck

Year	h erg.sec	k erg.K^{-1}	e esu
1901	6.55×10^{-27}	1.34×10^{-16}	4.69×10^{-10}
2000	6.63×10^{-27}	1.38×10^{-16}	4.80×10^{-10}

unqualified success in quantitatively describing the atomic and sub-atomic world, its interpretative aspects have not been regarded as satisfactory by several distinguished physicists. Just as in classical physics, dynamical evolution in quantum theory is also governed by the Hamiltonian, although it is the evolution of the psi-function with time that is the object of study, unlike classical physics where it is the evolution of the trajectories of particles. It is in confronting the psi-function with laboratory experiments that the conceptual and problematic nature of quantum theory arises. Suppose for example, one is asked to find the height of a building, there are several experimental methods to determine it. Implicit here is the assumption that the building's height is a pre-existing property independent of the experimental procedure to be adopted. This assumption that one is measuring a pre-existing property appears to be simply invalid in the microscopic world as described by quantum theory. This may be illustrated as follows. Consider a particle with spin 1/2 (in units of $h/2\pi$) with some magnetic dipole moment. When placed in a magnetic field, while a classical dipole can have any orientation, in quantum theory the particle has just only two possible states, one corresponding to the spin being parallel to the field and the other antiparallel. When the field is not just a constant but also has a gradient, say along the *Z*-axis, it can be used to measure the spin component since a particle travelling along, say the *Y* direction, with its spin polarized along the positive *Z*-axis, will be deflected upwards during its transit through the magnetic field, as it experiences a force along the gradient of the field while the one that travels with polarization along the negative *Z*-axis will be deflected downwards (Stern–Gerlach experiment). Suppose we now repeat the same experiment but with particles which are polarized along the *X*-axis instead of the *Z*-axis, then what should we expect? Quantum theory says that the particle will still be deflected in the *Z* direction, i.e. the direction of the magnetic field, with equal probability for upward or downward deflection, but is unable to tell in advance for a given event which way the particle will be deflected. It is as though potentiality for either outcome exists but only one of them becomes an actuality for any given event. To deepen this mystery a bit more, consider the following experiment which is an adaptation by Bohm of the original Einstein–Podolsky–Rosen (EPR) argument that quantum description of Nature is incomplete. Suppose a source is able to produce a pair of spin 1/2 particles *A* and *B* which are coupled to form a state of total spin zero, and send particle *A* along the positive *Y* direction to the experimenter Alice and particle *B* along the negative *Y* direction to the another experimenter Bob situated far away from Alice. To measure the polarization or the direction of spin of *A*, Alice has a Stern–Gerlach arrangement on her side and similarly Bob has a set-up on his side. If in Alice's set up, the magnetic field gradient is along the *Z*-axis, then particle *A* will be deflected up or down in the *Z* direction. Now if Bob also orients his magnetic field along the *Z* direction, particle *B* will be deflected with certainty in a direction opposite to that of *A*, because the total spin of *A* and *B* is zero. In other words if Alice had told Bob before particle *B* passed through his apparatus that her particle *A* was deflected up, then Bob will find that *B* is deflected down as it passes through his field. Suppose now that Alice decides to have her field pointed along the *X* direction instead, then if *A* is deflected along the positive *X* direction, then particle *B* will be deflected along the negative *X* direction if Bob had also arranged his field to be along the *X* direction. Now let us read these results differently. Alice is able to tell Bob which way particle *B* is polarized, from the result she found for *A*. By setting her magnet at will, either along the *Z* or *X* direction she is able to fix the polarization of *B*, which apparently had no special direction to choose from until *A* passed through Alice's field. But how can Alice's apparatus determine the polarization of *B* which could be miles away from *A*? Would this not be some spooky action at a distance? Einstein said speaking of two spatially separated systems S_1 and S_2 like *A* and *B* above 'But on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S_2 is independent of what is done with system S_1, which is spatially separated from the former'. Returning to Alice and Bob, then from Einstein's perspective, the direction in which Alice sets her magnetic field should have no influence on the outcome of the experiment at Bob's end. So the results of Bob should be explicable by the orientation of Bob's field and probably additional dynamical features that current quantum theory fails to take cognisance of. This claim of EPR can be put to experimental test as was pointed out by J. S. Bell. Now the angle between the magnetic field of Alice and Bob can be arbitrary like 0^0 when they are both parallel, 90^0 if they are perpendicular to each other or any other value θ in between. One can then measure the correlation between the outcomes like both *A* and *B* up in relation to the magnetic field directions chosen independently and arbitrarily by Alice and Bob, both *A* and *B* down, *A* up and *B* down or *A* down and *B* up. These four possibilities are dependent on the angle θ between the analysing magnetic fields of Alice and Bob. Bell showed that predictions of quantum mechanics (QM) are sharply different from a theory of the type that introduces additional local variables in the sense discussed above and might be the missing elements in quantum theory as EPR had hoped. Numerous experiments over the last three decades have confirmed that quantum mechanical predictions are quantitatively correct. It must be stressed that while Nature perhaps does not quite confirm to Einstein's perception of how things are, the interpretative aspects of QM still remain a matter of serious debate. In recent times, the above EPR-type experiments have had a totally unexpected impact in the field of communications and have contributed to the development of quantum cryptography. In cryptography one is concerned with security of communications – ideally only the sender and receiver of a message should be able to make sense out of an encrypted message. To decrypt a message one needs a key, and a one-time pad, that is to say, a key that is just used once much like a disposable syringe, is the best way to assure security according to communication theory. But then one has a catch-22 situation. How does Alice transmit this key to Bob if they cannot meet in person, for any communication may be intercepted without their knowledge? The EPR correlations solve this problem brilliantly. Suppose now that as before a source produces particles *A* and *B*, and sends them at regular intervals to Alice and Bob who receive them with their fields chosen arbitrarily either along the *Z* or the *X* direction, but do not communicate between themselves which way their fields are oriented and whether their particles A and B went up or down. This is called the quantum channel. After receiving say around a couple of hundred events, Alice and Bob now use a public communication channel and disclose the sequence in which their fields were oriented

$$\begin{array}{ll} \text{Alice} & X\ X\ Z\ X\ Z\ X\ Z\ Z\ \ X\ldots \\ \text{Bob} & Z\ X\ Z\ Z\ X\ X\ Z\ X\ \ X\ldots, \end{array}$$

but they do not disclose whether the particles A and B came up or down in their experiments. They can now set aside the events in which their analysers were not parallel like events 1, 4, 5, 8, etc. in the above example. For the events 2, 3, 6, 7, 9, etc., Alice knows for certain that if A is up then B is down and vice versa. Agreeing to call A registering as up as zero and down as one which is same as Bob agreeing call his down events as zero and up events as one, clearly the events 2, 3, 6, 7, 9, etc., give a random sequence of zeroes and ones that only Alice and Bob can know. Note that the key comes into existence only after transmission is over the quantum channel is complete and disclosure of the field orientations on the public channel. Now how can they be certain that an eavesdropper has not intervened. This is precisely where quantum theory helps. Any intervention in the experiment will destroy the quantum correlations. This can be checked by them either by comparing publicly a partial set of their results when their analysers are parallel or when they are perpendicular.

As noted by Planck, himself, the constant h defines a fundamental mass M_P and fundamental length l_P when combined with the values of the velocity of light c and Newton's gravitational constant G_N

$$M_P = \sqrt{\frac{h}{2\pi G_N c}} = 2.18\times10^{-8}\ \text{kg},$$

$$l_P = \sqrt{\frac{hG_N}{2\pi c^3}} = 1.61\times10^{-33}\ \text{cm}. \tag{22}$$

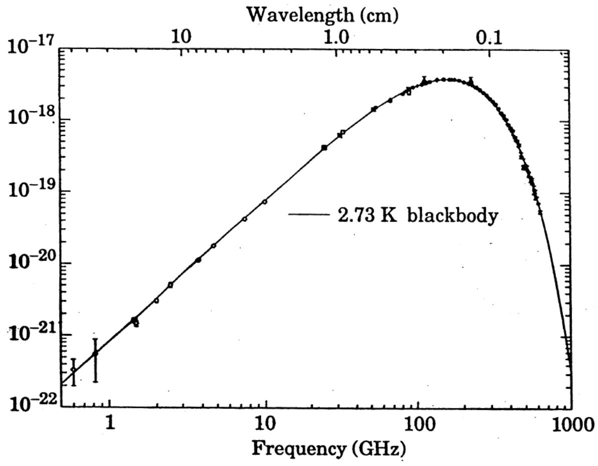
To probe the laws of physics at Planck length, one needs to produce particles with energies which are some 10^{16} times larger than those currently available.

Box 2. Cosmic microwave background

The gravitational field equations of Einstein, applied to the universe at large, predict that under certain conditions the universe will expand. The first evidence that we are living in an expanding universe came from the work of Edwin Hubble. This has now been put on a firm experimental footing thanks to enormous strides that observational astronomy has made and precise measurements of distances of distant galaxies have become available recently.

Extrapolating backwards in time, it would seem plausible to assume that the universe started with a big bang some fifteen billion years ago, using our current knowledge of the Hubble constant. At this initial phase, density and temperature were so high that matter existed in the form of truly elementary constituents, quarks, leptons and perhaps other particles as well. As the universe expanded, in the first few minutes, nucleosynthesis took place. One of triumphs of theory today is our ability to compute the relative abundances of various elements, including their various isotopic distributions, H, D, He^3, He^4, Li^7, etc. These agree well with experimental numbers. The theory also requires three light neutrinos, which is again consistent with laboratory experiments. It was also predicted by Gamow, Alpher and Herman that as the universe continues to expand at a certain point in time radiation will decouple from matter, and we should be able to see relics of this radiation. This remained forgotten for several years.

In the year 1965, the microwave radiation from the cosmos was discovered serendipitously by Penzias and Wilson. Experiments have now firmly established that this radiation is not just extra-terrestrial it comes from outside our galaxy and it follows, to a great accuracy to be precise, to within 0.01%, Planck's radiation law corresponding to a temperature of 2.73 K (Figure 1). Penzias and Wilson themselves established that this cosmic microwave background (CMB) is highly isotropic, meaning that the spectral distribution is the same, no matter which direction in the sky one is looking at and its polarization is less than 10%.



The existence of this microwave radiation is currently understood as follows. As the universe continued to expand, and cooled to a temperature around 4000 K, which was around 300,000 years from the initial hot big bang phase, radiation would have reached equilibrium and essentially decoupled from matter. It starts behaving then exactly like Hohlraumstrahlung of Kirchhoff, Wien and Planck. Its temperature will fall inversely with the scale factor of the universe and so we can be certain that if some billions of years from now, the universe doubles its size, the temperature of the CMB will be 1.365 K, half its current value and will be guaranteed to obey Planck's law corresponding to this temperature.

The study of CMB is of vital importance to understand many fundamental questions in astronomy and physics. Small anisotropies corresponding to a dipole, that is to say the difference between the distribution along the poles and the zenith are expected due to local motion of our solar system in this bath of microwave radiation and have been measured. More important variations over very small angular intervals are expected to reveal how structures like galaxies or clusters of galaxies were formed in the universe. These clumps arose from initial density perturbations, which should have left their imprint in the spectral density of the radiation field. Such anisotropies are only a few parts in a million, but experimental progress has been impressive. In 1992, COBE satellite experiments were able to establish the existence of these anisotropies. Two dedicated satellite-based experiments, one by NASA called 'MAP', will be ready next year and one by ESA called 'Planck' will be ready in 2007.

Although such energies may not be reachable in laboratory experiments, much can be learned from forthcoming experiments in physics and astronomy (cf. Box 2) which will probe distances deeper than what has been studied so far and of course Planck's guiding spirit, that tells us that there are absolute laws in Nature that must be simple and logically consistent.

1. Kuhn, T. S., *Black Body Theory and the Quantum Discontinuing: 1894–1912*, Oxford Univ. Press, 1978; Planck, M., Scientific Autobiography and Other Papers, Philosophical Library Inc., NY, 1949; Pais, A., *Rev. Mod. Phys*., 1979, **51**, 863; Kangro, H., *History of Planck's Radiation Law*, Taylor and Francis, London, 1976; Klein, M., in *History of Twentieth Century Physics*, Academic Press, New York, 1977. There is no unanimity among historians about how Planck arrived at his formula. My account here is based on Planck, Kuhn and Pais.
2. Heilbron, J. L., *The Dilemmas of an upright man – Max Planck as spokesman for German Science*, University of California Press, 1986.

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Random selections

Quantum physics

'One hundred years of quantum physics'
Daniel Kleppner and Roman Jackiew
Science, 2000, **289**, 893–898

An essay in the series 'Pathways of Discovery', the article under selection is unique inasmuch as the subject matter of the essay itself, namely Quantum Physics. Kleppner and Jackiew, both professors at Massachusetts Institute of Technology, USA have put together in a very readable fashion their perspective of a vast subject that has 'been responsible for advances in essentially every other science' in the twentieth century. Its influence has been so much, as the authors point out, that 'there would be no global economy and Information Age, to speak of without quantum mechanics'.

The year 2000 marks the Centenary of Max Plank's 'Quantum Concept'. Thousands of pages of spectral data of elements and compendiums of many thermodynamic properties of materials could all be understood on the basis of a 'quantitative theory', based on quantum mechanics, during the early part of the twentieth century. This essay provides a bird's eye view of all important landmarks dotting the achievements of Quantum Physics within the confines of mere six pages. The span of the subject is captured in the quote: 'Quantum Physics actually encompasses two entities. The first is the theory of matter at atomic level: quantum mechanics. It is the quantum mechanics that allows us to understand and manipulate the material world. The second is the quantum theory of fields. Quantum theory of fields plays a slightly different role in science.'.

The article covers a vast canvass starting from Planck's quantum hypothesis and moves through concepts dealing with dual nature of light, Bohr's atomic structure hypothesis, de Broglie's hypothesis about duality of matter, Bose–Einstein statistics, matrix and wave mechanics, Fermi–Dirac statistics, interpretation and validity of quantum mechanics and finally touching on aspects like quantum entanglement, quantum communication and quantum computation.

In the second part of the essay, the authors have dealt with quantum field theory ('the predictions of quantum field theory are the most precise in all of physics'), covering Dirac's theory, quantum electrodynamics, quantum chromodynamics, the latter two being 'the cornerstones for a grand synthesis known as the Standard Model', ending finally with string theory.

The Timeline of Quantum Physics, a part of the essay, is a catalogue of important landmarks in the saga of interplay between theory and experiment that has been sustaining the continuous growth of 'fundamental concepts and essential tools for all of the sciences'. A variety of materials (and phenomena) such as superconductors, lasers, Bose–Einstein condensates, quark–gluon plasma, etc. have taken shape thanks to this scenario.

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