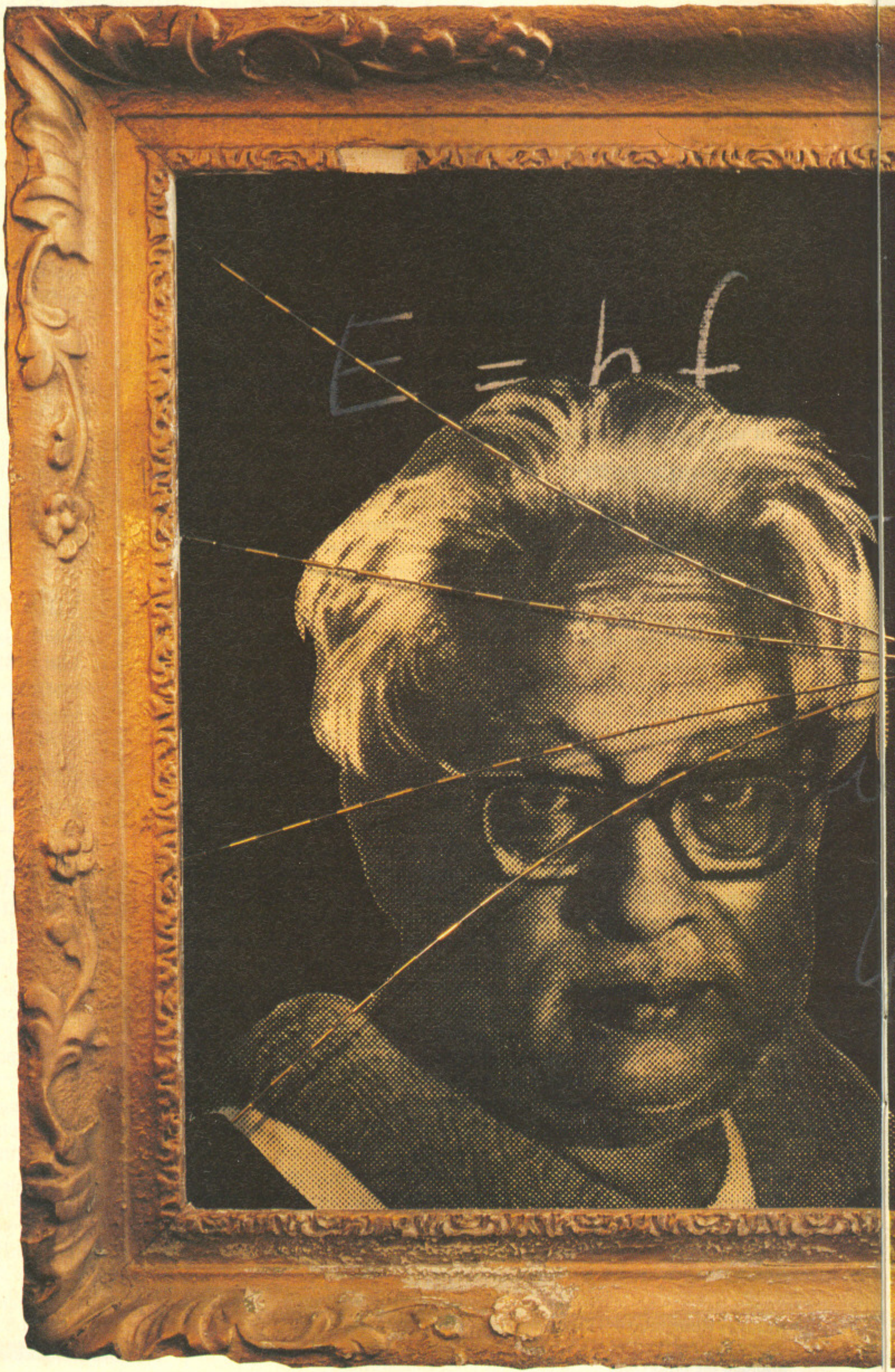
The man who chopped up light

By showing that one and one do not necessarily make two, the Indian physicist Satyendra Nath Bose paved the way towards a theory of everything

Dipankar Home and John Gribbin



QUANTUM electrodynamics is arguably the most successful scientific theory there has ever been. With stunning precision, it explains the interaction of electromagnetic radiation (including light) with electrons and other charged particles. It is on QED that quantum chromodynamics, the theory of the strong interaction, is modelled (see "How to glue quarks together", *New Scientist*, 4 December 1993) and through that physicists hope to develop the elusive "theory of everything" explaining the entire Universe in one equation. The roots of QED go back exactly 70 years, to the work of an Indian physicist, working in obscurity at the University of Dacca in what was then East Bengal.

The physicist was Satyendra Bose, and this year sees important anniversaries of two other major events in his life. Bose was born 100 years ago, on 1 January 1894, and he died 20 years ago, on 4 February 1974, having lived just long enough to see QCD become established. His greatest achievement, in the early 1920s, was to take the ragbag of ideas that at the time comprised the quantum theory of radiation, and provide a mathematical description of light quanta which tied everything into a coherent whole.

It was in the late 19th century that Max Planck introduced the idea of quantisation—the notion that light and other forms of radiation are emitted and absorbed in little lumps—into the discussion of how radiation and matter interact. He used it to explain the pattern of energy emitted by a hot object (known as black body radiation). But he applied the idea in an ad hoc way to fit an equation to the data. Albert Einstein had suggested in 1905 that light itself must be quantised, rather than just being emitted and absorbed in quantised lumps, and won the

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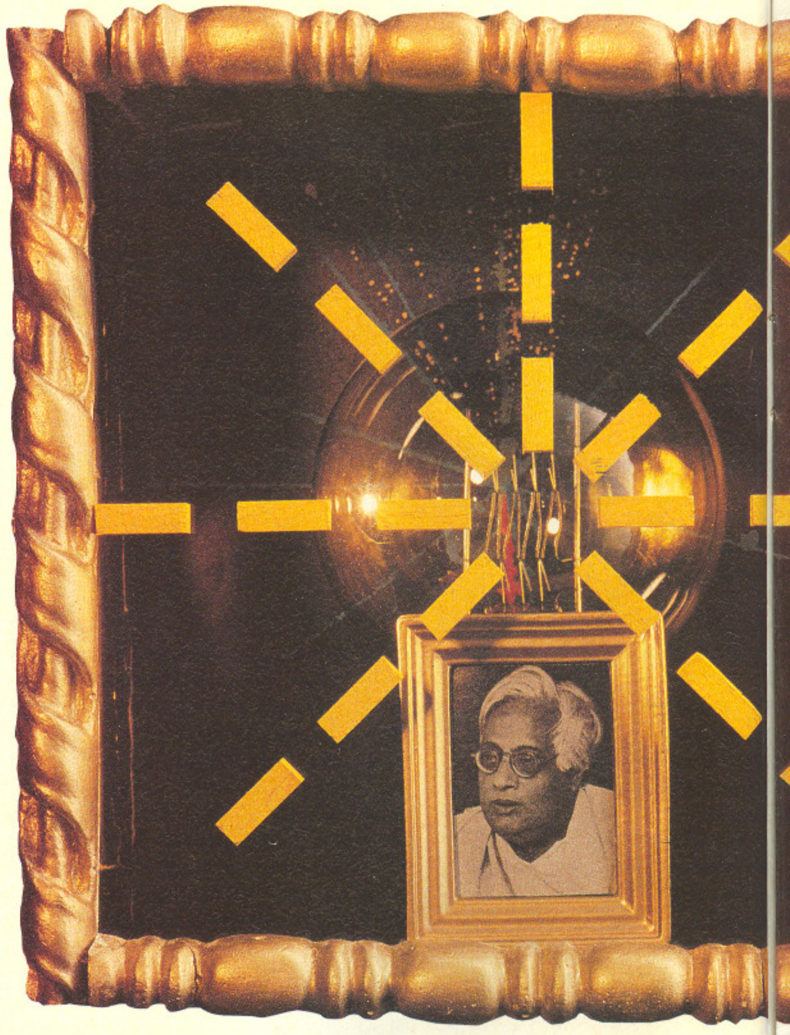
1921 Nobel prize for this work, but even in the early 1920s many physicists—perhaps most—did not really believe that light existed in the form of particles. It is no coincidence that the particle of light was only given a name, the "photon", in 1926, after Bose put the quantum theory of light on a secure mathematical footing.

By the 1890s, physicists knew that the way in which a hot body radiates electromagnetic energy depends in a simple way on its temperature. Strictly speaking, this simple relationship applies only to a perfect radiator, a "black body". The best example of a black body is a hollow sphere with a small hole in its side. If the sphere is heated up, the walls inside radiate electromagnetic energy which will bounce around inside the cavity and fill it up evenly, until a beam of energy streams out from the hole. This beam of energy used to be known as cavity radiation, for obvious reasons, but is now generally known as black body radiation—even though the body doing the radiating may be red or white hot.

Ultraviolet catastrophe

The colour of the radiation emitted by a black body is a direct indication of its temperature. In fact, any object will emit electromagnetic radiation with a spread of wavelengths. The centre of this spread (the peak of the distribution) shifts towards shorter wavelengths as the object gets hotter. But no matter where this peak falls, the energy always tends to zero at either end of the distribution. The result is a spectrum in the shape of a curve, rather like a child's drawing of a hill with a rounded top, sloping away on either side. The spectrum, known as the black body curve, follows a precise mathematical law. It is always the same shape, for any black body, whatever its temperature. In the late 1890s Planck was trying to find the physical reason for that mathematical law.

At the time, this was a major challenge.



The laws of physics as they were known then seemed to imply that the shape of the curve was wrong. Calculations based on these laws predicted that at the short-wavelength end of the spectrum, the radiated energy would not drop, but would rise to infinity. This theoretical prediction was so obviously at variance with what happens in the real world that it was known as "the ultraviolet catastrophe". It comes from the seemingly innocent assumption that electromagnetic waves inside a cavity obey the same rules as waves on a guitar string.

To explain black body radiation one must consider many waves with many different wavelengths. Planck's contemporaries tried to solve the problem using the laws of statistical mechanics from the world of particle physics, and this led them to the prediction that the energy being radiated at any frequency is proportional to the frequency. So all black bodies ought to produce huge amounts of energy at high frequencies, which means at short wavelengths.

Mathematical conjuring

Planck solved the problem by mathematically cutting up the electromagnetic energy into small chunks, or quanta. He thought that what was happening inside a hot object to make it radiate energy only allowed energy to be radiated in pieces of a certain size, but he did not suggest that these pieces of radiation had anything to do with the nature of light itself. This can be likened to the way the cash dispenser at your local bank will "emit" money. Provided your account is sufficiently in credit, you can take out any sum you like as long as it is a multiple of £5. In the real world of your pocket, money normally exists in irregular amounts, such as £47·38, but the machine will only cough up £45, or £50, or some other multiple of £5.

Planck's version of the radiation laws was a little more subtle than this. It said that the size of each piece of electromagnetic energy—each "quantum of radiation"—radiated by a black body must be proportional to its frequency, obeying the rule $E = hf$, where E is the energy, f is the frequency, and h is a constant whose existence had previously not been suspected, but is now well known as Planck's constant.

As a result of Planck's insight, the picture physicists have of a hot object is that it is made up of many atoms, each of which can emit energy. But not all the atoms have exactly the same energy to radiate. The average amount of energy corresponds to the temperature of the black body, and to the peak of the corresponding black body curve. Some atoms radiate more energy than average and some less, the numbers of atoms on either side of the peak being given by a precise statistical formula. For very high frequencies, corresponding to short wavelengths, the energy needed to emit one quantum of radiation is very large, and only a few of the atoms have this much energy. The result is that only a few of these high-energy quanta can ever be emitted. But the higher the temperature of the black body, the more high-energy atoms there are and the more high-energy quanta can be emitted, so the more the actual spectrum resembles the ultraviolet catastrophe. For very low frequencies (long wavelengths), there are many atoms with enough energy to produce the appropriate quanta of radiation, but each quantum is so feeble that even adding them all together doesn't produce much energy. Only in the peak of the distribution will there be a lot of atoms each with enough energy to emit moderate-sized lumps of radiation which add together to produce the peak and give the object the colour characteristic of its temperature.

But there was no suggestion, not even from Planck himself, that light, or other forms of electromagnetic radiation, really did exist in the form of little lumps, or quanta. In 1931, Planck recalled that quantisation "was purely a formal assumption and I really did not give it much thought except that no matter what the cost, I must bring about a positive result". In the early 1920s, almost everyone knew that the light quantum could explain otherwise puzzling features of the interaction between light and matter, but hardly anyone believed that this was more than a mathematical trick; they still thought of light as "really" being a wave, described by the equations set out in the 1870s by James Clerk Maxwell.

There was, however, one exception. In India, physicists took the light quantum seriously. The pioneering astrophysicist Meghnad Saha used the light quantum to describe radiation pressure, in a paper published in the *Astrophysical Journal* in 1919. Saha then collaborated with Bose to produce one of the earliest English translations of Einstein's papers on the general theory of relativity. This led to discussions which made Bose aware of the need for a proper derivation of Planck's law of black body radiation.

While Planck's own derivation was the result of grafting quanta onto a classical framework of continuous waves, Bose

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aimed to avoid this inconsistency. He found that this could be achieved only if the particles of light obeyed statistical laws that are different from those that describe the everyday world. The curious thing about Bose's work was that it did not embody any vestige of a description of electromagnetic radiation in terms of waves, or indeed of electromagnetism. He arrived at Planck's equation by treating the photons that fill a black body cavity as a gas of particles.

Tossing coins

The simplest way to get a picture of what is going on is to think of a pair of identical, newly minted coins. If you toss both coins, there are three different outcomes: two heads, two tails or one of each. You might guess at first sight that all outcomes are equally probable—that there is a 1 in 3 chance of each. But a little thought shows that this is not the case.

Suppose you were to mark one of the coins in some way, so that the two coins are distinguishable. Now it is easy to see that although there is only one way to get the combination head-head, and one way to get the combination tail-tail, there are two ways to get the combination head-tail. So the right way to count the possible results of tossing two coins is as four possible outcomes. The chance of any one outcome is 1 in 4 (a quarter), not 1 in 3. And since there are two ways of getting one head and one tail, the chances of this pattern turning up are 2 in 4, or one-half.

What Bose found was that he could derive Planck's formula by treating photons as particles which have to be counted in a different way. In the photon world the equivalent of this coin-tossing experiment would still yield three possible outcomes, but all three would have equal probabilities. This changes the statistical way in which the photons behave, and the way in which energy is shared out among them or, to put it the other way, the distribution of photons among different energy states. This distribution of photons between energy states corresponded to the black body curve that is observed experimentally.

Bose's statistics apply only to particles which are not conserved. You make more photons, for example, every time you turn on a light, and they stream out from the Sun and stars in vast numbers. Photons can be destroyed, too, as they are absorbed by walls, by your eyes, by the surface of the Earth, and so on. But these two processes are not in balance. The number of photons in the Universe is always changing.

This is quite different from the behaviour of the kind of particles we are used to thinking of as discrete chunks, such as electrons. Electrons cannot be created or destroyed, except in special circumstances where an electron and its "antiparticle" counterpart, a positron, are created (or destroyed) together. In this sense a positron counts as –1 electrons, and the total number of electrons in the Universe stays the same.

The familiar kind of statistics that apply to coin tossing do, it turns out, apply to electrons and other conserved particles. These statistics are known to quantum physicists as Fermi-Dirac statistics, in recognition of the work of the Italian-born Enrico Fermi and the Englishman Paul Dirac. Particles such as photons that obey what are now known as Bose-Einstein statistics are collectively known as bosons. Particles that obey Fermi-Dirac statistics are termed fermions.

But why "Bose-Einstein", and not just Bose statistics? Early in 1924, Bose sent a paper describing his discoveries to the British *Philosophical Magazine*, but received no response. So in June that year he sent a copy to Einstein, asking him to read it and, if he thought it made sense, to pass it on for publication in the German journal *Zeitschrift für Physik*. Einstein was so impressed by the work that he translated it himself, and submitted it to the journal with his endorsement. Anything that had Einstein's support was certain of a welcome, and the paper duly appeared in print that summer.

The implications were awesome. Bose had derived the black body equation for electromagnetic radiation simply by treating photons as real particles obeying a new kind of statistics and behaving as a quantum gas. Einstein himself took up the idea of the new statistics, and applied it to other problems in three papers that represented his last major contributions to quantum theory. Using the new statistics to describe the behaviour of gases under different conditions he showed, among other things, that just as the behaviour of light, which had traditionally been regarded as a wave, could be explained in terms of particles so, under the right circumstances, molecules (traditionally regarded as particles) ought to behave as waves.

Just at the time when he was puzzling over the significance of this discovery, late in 1924, Einstein was sent a copy of the PhD thesis of Louis de Broglie, by de Broglie's supervisor in Paris, Paul Langevin. De Broglie had made the seemingly outrageous claim that particles such as electrons could behave as waves, and Langevin could not decide if this was a stroke of genius or completely crazy. "I believe," Einstein wrote, "that it involves more than a mere analogy."

De Broglie's work was taken seriously on the strength of this seal of approval, and was taken up by Erwin Schrödinger, who developed it into a complete description of the quantum world: wave mechanics. He later remarked that "wave mechanics was born in statistics", and in a letter to Einstein in April 1926 said: "The whole thing would not have started at present or at any other time (I mean as far as I am concerned) had not your second paper on the Bose gas directed my attention to the importance of de Broglie's ideas."

Bose himself, however, did not take part in the exciting development of quantum theory over the following few years. It was left to others to develop QED. Instead, he pursued his other early interest, the general theory of relativity, following Einstein up what turned out to be the blind alley of a premature search for a unified field theory. For the last 20 years of his life, Bose devoted himself to popularising science and to teaching. "I was not really in science any more," he commented a few years before he died. "I was like a comet, a comet which came once and never returned again." But the blazing light shed by that comet changed the way physicists thought in the 1920s, and changed the way physics has progressed ever since. □

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