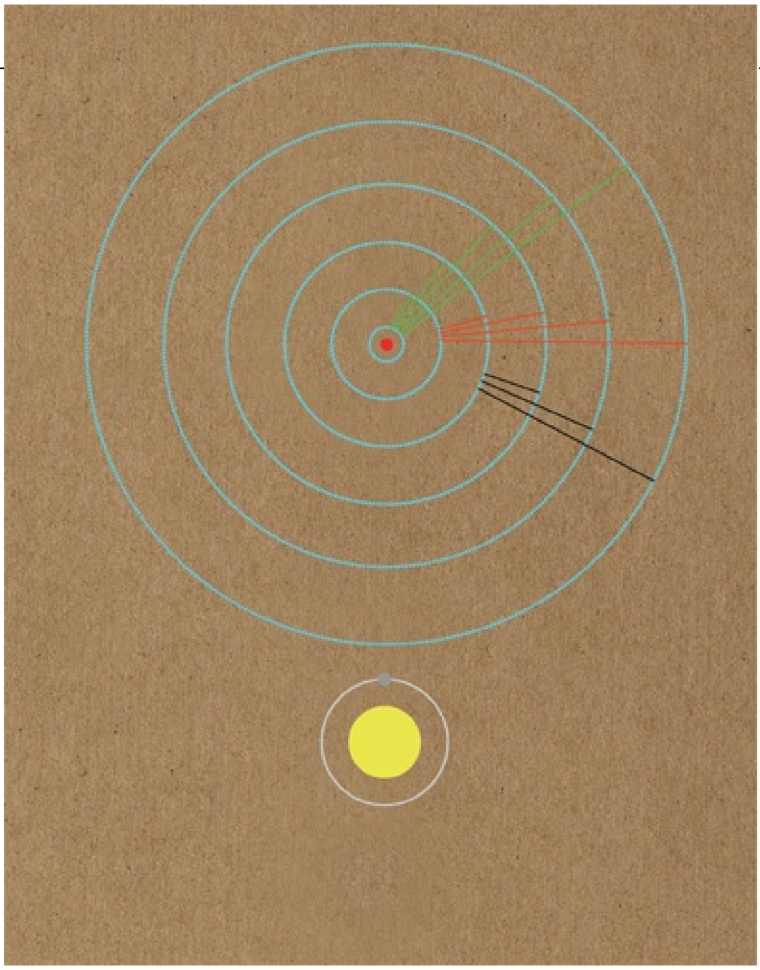


30-SECOND QUANTUM THEORY

*The **50** most thought-provoking **q**uantum concepts, each explained in half a minute*

Editor
Brian Clegg

Contributors
Philip Ball
Brian Clegg
Leon Clifford
Frank Close
Sophie Hebden
Alexander Hellemans
Sharon Ann Holgate
Andrew May

ICON

You know all about Schrödinger's cat, but how about his equation? How do lasers, transistors and electron micr~~oscopes work? What are the perils of renormalization? What makes a fluid a superfluid? And what w~~ill a quantum computer be capable of? Discover the history of some of science's greatest discoveries and ponder the future of physics and technology with this fascinating guide to quantum theory.

30-Second Quantum Theory tackles a mindbendingly mysterious area of physics, introducing the 50 most significant quantum quandaries and ideas. At a time when the quantum physics of electronics is an everyday essential and new quantum developments make headline news, you will visit parallel worlds, ride wave theory and learn enough to talk with certainty about Uncertainty Principle and to untangle the mysteries of quantum entanglement.

CONTENTS

INTRODUCTION

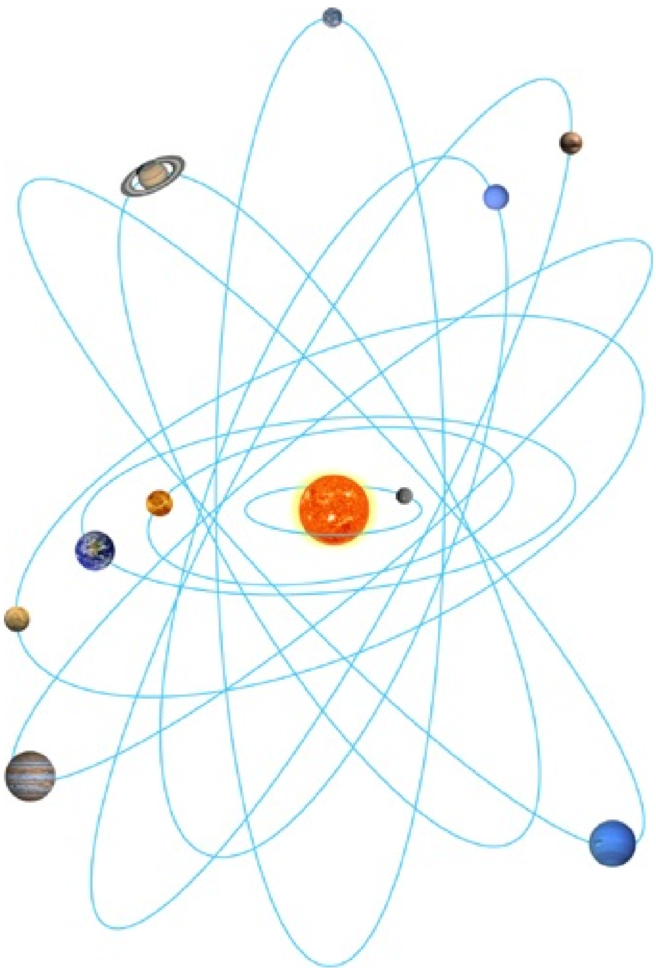
Brian Clegg

The physics we are taught at school can be, frankly, rather boring. It is worthy, 19th-centur science – necessary, certainly, but hardly earth-shattering. What a shame we don't introduce schoolchildren earlier to the more exciting bits: and there is nothing more thrilling and mind-boggling in all of science than quantum theory.

Small things

The idea that matter, stuff, is made up of tiny fragments goes all the way back to the ancient Greeks, but the ideas of the atomists (the name 'atom' comes from the greek word atomos, 'uncuttable') were largely sidelined by the four element theory that considered everything to be made up of earth, air, fire and water. the end of the 19th century, atoms had made a comeback as useful concepts in chemistry and physics, but one was quite sure what they were or how they worked. Some even doubted they existed. To the surprise of the scientists, atoms not only proved to be a reality, but these tiny components of everything from a human being to a speck of dust also behaved more strangely than anyone could expect.

It was initially assumed that atoms and their component parts would behave just like much smaller version of the ordinary things that we see around us. Therefore, scientists thought that atoms would fly through the air just as a tennis ball does, if on a smaller scale. When it was discovered that atoms had internal structure, was first theorized that they might be like plum puddings, with negative charges scattered through a positive body, but the revelation that most of their mass was in a central nucleus made it seem obvious that an atom was like a miniature solar system.



*The **q**uantum revolution*

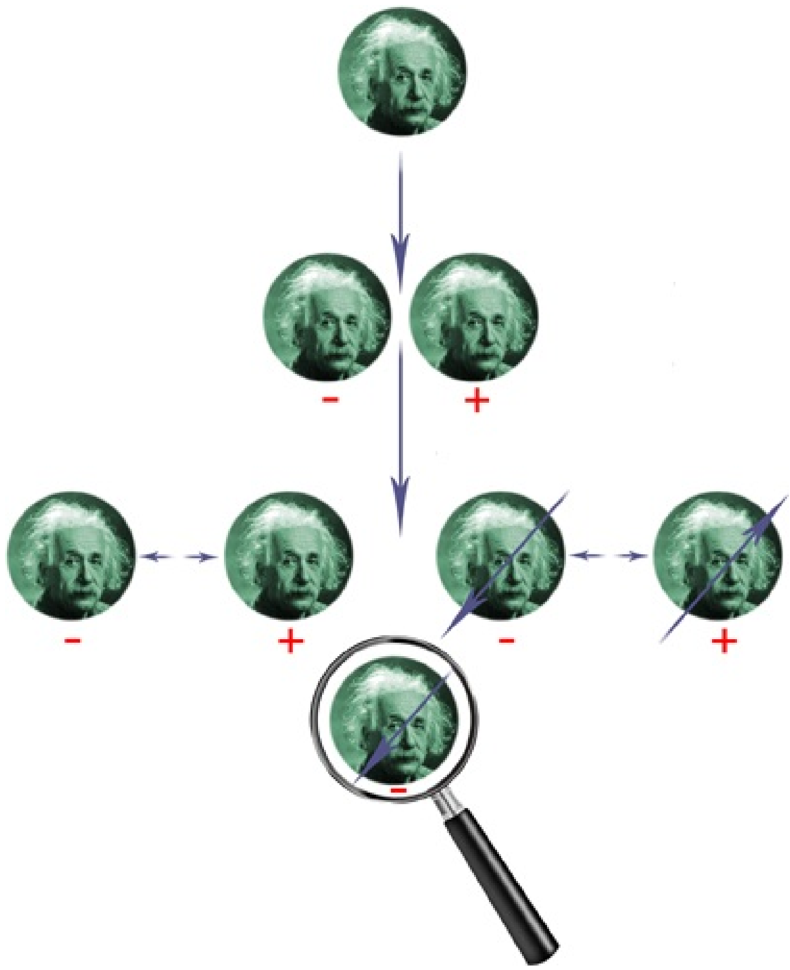
Unsettlingly for the old guard of physics (though delightfully for the rest of us), this picture turned out to be impossible to maintain. An atom built like a solar system would not be stable, and quantum particles refused to behave as predictably as a tennis ball. As quantum theory was developed it became clear that there was a fundamental difference between the microscopic and the macroscopic world. Tennis balls followed clear paths depending on their mass and the forces acting on them. But quantum particles could only be given probabilities of behaving in a particular way. At the heart of their behaviour was randomness and before the were observed it was never possible to be certain exactly what they were up to.

This horrified Einstein, inspiring him to write 'I find the idea quite intolerable that an electron exposed to radiation should choose of its own free will, not only its moment to jump off, but also its direction. In that case, I would rather be a cobbler, or even an employee in a gaming house, than a physicist,' and produced hi famous comments along the lines of 'God does not play dice.' But others were fascinated.

The great American quantum physicist Richard Feynman said 'I'm going to describe to you how Nature is – and if you don't like it, that's going to get in the way of your understanding it… [Quantum theory] describes Nature as absurd from the point of view of common sense. And it agrees fully with experiment. So I hope yo can accept Nature as she is – absurd.' I hope that this book will give you a chance to experience and echo Feynman's enjoyment of the sheer strangeness and absurdity of the quantum world.

Dividing the quantum

*There surely can be few topics that are more suited to being divided up in bite-sized, easily digested chunks than quantum theory. The 50 articles that follow are split into seven sections, each taking on a part of this significant undertaking. We begin, aptly enough, with **The Birth of the Theory**, which describes how the classical view that atoms were no different from the objects we see around us was undermined by observation and how the endeavour to find a way that atoms could be stable at all required a very different approach.*



*From the origins we move on to **The Essentials**, the key components of quantum theory, some of which, like Heisenberg's Uncertainty Principle, have escaped the confines of physics to become part of popular* culture. With these fundamentals in place we can open up the science of practically all of our everyday exp~~erience, **The Physics of Light & Matter**. Quantum electrodynamics, the theory that explains everything~~ from the way sunlight can warm us to the reason why you don't fall straight through your chair, required a whole new way of looking at the quantum world and has become the most successful theory ever in terms o the accuracy with which it predicts what is observed.

From here we move onto some key **Quantum Effects & Interpretation**, explaining how we can both see through and see a reflection in a window, or how quantum tunnelling keeps the Sun working – and the thorn matter of quantum interpretation. Quantum theory is almost unique in this respect. It is excellent at predictin what we observe, but no one is sure exactly what the theory itself represents. Descriptions like the Copenhagen, Many Worlds and Bohm interpretations attempt to put what is observed into a framework that explains why such observations are made, yet we have no way to distinguish between these options, choosin on personal preference rather than good scientific logic.

In the next section we encounter quantum theory's most remarkable phenomenon, **Quantum Entanglement**. Described by Einstein (who hoped to use the concept to disprove quantum theory) as 'spoo action at a distance', entanglement makes it possible for one quantum particle to influence another instantly at any distance, seemingly in contradiction to special relativity's limit of the speed of light – and yet experiment after experiment has confirmed its existence, and applications like quantum encryption and quantum computers rely on entanglement to work.

The final two sections look at the ways in which technology based on quantum theory has penetrated our everyday lives, and the extreme possibilities that quantum physics makes possible. In **Quantum Applications**, we discover the laser, the transistor, the MRI scanner and more. Whenever we use electricity we are making use of a quantum phenomenon, but electronics has made an explicit knowledge of quantum theory an important part of the design of technology, to the extent that it is estimated that around one-third of the GDP of developed nations comes from technology based on quantum theory.

As for those **Quantum Extremes**, here we can take in the mystery of zero point energy, beloved of fringe science, but a real quantum effect that means that even a vacuum is not empty, the peculiar behaviour of extreme low temperatures, and the extension of quantum theory into the atomic nucleus, gravity and even biology.

Jumping in

Each topic, supported by a exciting illustration, is broken down to make it accessible. The 30-second theory section gives the main description, while the 3-second flash summarizes the topic at a glance. If you would like to find out more, the 3-minute thought takes a particularly intriguing aspect of the topic and expands o it. The related theories point to other topics that will follow on naturally, while the 3-second biographies identify key names in the development of this area.

The format of 30-Second Quantum Theory is itself quantized, breaking up the essentials to discover, enjo and absorb what is arguably the most fascinating and mind-bending aspect of all science. Everything we do, everything we see, has quantum particles at the heart of the action – and yet these particles are so very different from anything we ever directly experience. That's the paradox and the delight of quantum theory, as you are about to discover.

THE BIRTH OF THEORY

GLOSSARY

black body A hypothetical object absorbing all light that hits it, whatever the frequency or direction. A black body at a constant temperature emits a light spectrum (black body radiation) purely dependent on its temperature and not influenced by the nature of the body.

black holes A location at which matter has been made so compact that it collapses to a point under gravitational pull. Most frequently formed by the collapse of a massive star. The apparent size of the black hole is its 'event horizon', which is the distance from the centre where nothing, not even light, can escape. The black hole itself is a singularity, a dimensionless point.

complementarity Because in quantum theory the act of measurement influences the result, different measurements are complementary to each other. So, for instance, depending how you make a measurement on light it can appear to be a wave or a particle, but not both at the same time. Complementarity states that reality is neither of these but a whole of which we can only detect a part with any one experiment.

frequency The number of times a repeating phenomenon occurs in a second. Often used for a wave, describing the number of cycles the wave makes in a second (measured in hertz, where 1 Hz is one cycle per second). A wave's frequency is its velocity divided by its wavelength. For a quantum object the frequency is proportional to the energy of the object.

Hawking radiation This quantum effect, predicted by Stephen Hawking, is produced when virtual particles briefly appear and disappear in space. Usually they leave no trace, but if this happens near a black hole's event horizon, one particle can be pulled into the hole while the other flies off, creating radiation. (So black holes aren't truly black.) Hawking radiation is an example of black body radiation, equivalent to that of a black body at a temperature inversely proportional to the black hole's mass.

lepton A fundamental particle with a quantum spin value of 1/2, the best known example of which is the electron. Other leptons are the muon, the tau and the three types of neutrino.

photon A quantum particle of light and the carrier of the electromagnetic force. Until the 20th century light was thought to be a wave, but both theory and experiment show that it is also a massless particle.

Planck's constant A fundamental constant of nature, technically the 'quantum of action', where action is a mathematical representation of a system's energy as it moves along a path. The constant, denoted by Planck himself as h, describes the relationship of the energy of a photon to its frequency (colour). It is very small: just over 6.6×10^{-34} joule seconds.

Planck's formula/relation The relationship between the energy of a photon and its frequency, given by $E=h\nu$ where h is Planck's constant and ν is the frequency.

quantum leap Despite its popular use to describe a significant change, a quantum leap is usually a tiny jump the change between two levels of a quantized system, for instance the jump an electron makes between adjacent electron orbits.

quanta The plural of 'quantum' (literally 'how much', as in quantity), but used to indicate a particle or *'packet' providing the minimum unit of energy or matter. Hence 'quantum theory', describing the behaviour of p~~articles of matter and of light. When a value is 'quantized' it comes in discrete amounts. An averag~~e family, for instance, may have 2.3 children, but children are quantized, so an actual family can only have a whole number of children.*

wavelength The length of a repeating wave in which it passes through a complete cycle, returning to the starting point of the cycle. Wavelength is velocity divided by frequency.

THE ULTRAVIOLET CATASTROPHE

the 30-second theory

Popular histories of quantum mechanics generally award a central role to the so-called ultraviolet catastrophe. Physicists at the end of the 19th century realized classical physics predicts that electromagnetic energy radiated by a 'black body' – which we can envisage as a warm, totally light-absorbing object – becomes infinite for wavelengths shorter than those of visible light, in the ultraviolet part of the spectrum. This was obviously wrong, and in 1900 Max Planck found he could avoid the 'catastrophe' by assuming tha the oscillating atoms in the black body could only emit energy in discrete packets – quanta – of a size proportional to their vibration frequency. He denoted the constant of proportionality as h, now called Planck constant. Exactly how Planck viewed his 'quanta' is still disputed, but he seems to have resisted for years the idea that they corresponded to reality, seeing them instead as a mathematical convenience. That they resolve the ultraviolet catastrophe – by imposing restrictions on the ways a black-body atom can oscillate at high frequency and thereby reducing the energy they radiate – was only pointed out later. Still, the idea won Planck a Nobel prize in 1918.

3-SECOND FLASH

The hypothesis proposed by Planck that energy is quantized (divided into chunks) avoided the ultraviolet catastrophe predicted by classical physic for black-body radiation.

3-MINUTE THOUGHT

A perfect black body seems an oddly exotic entity, but it is really just an idealization of a warm body. The basic idea that the hotter the body is, t more short-wavelength radiation it emits, is familiar from the glow of an electric bar heater as it warms, and applies to stars too. Even black hole emit black-body radiation, in the form of so-called Hawking radiation. The black hole acts rather like a black body with a temperature inversely proportional to its mass.

RELATED THEORIES

PLANCK'S QUANTA

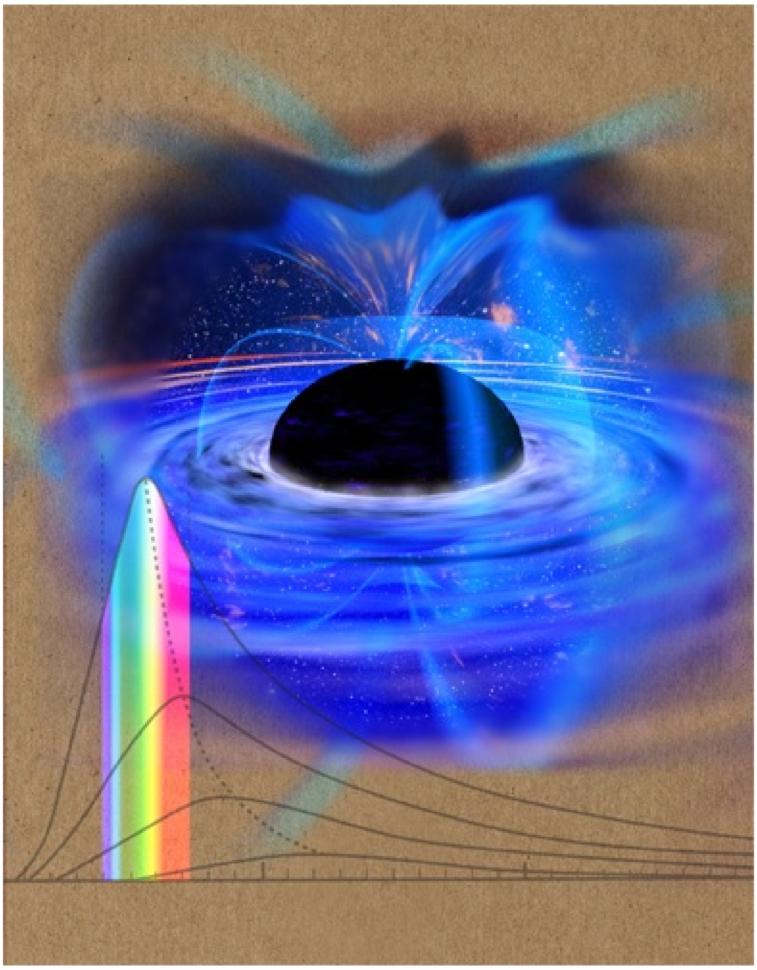
EINSTEIN EXPLAINS THE PHOTOELECTRIC EFFECT

3-SECOND BIOGRAPHIES

MAX PLANCK
1858–1947
Regarded in the early 20th century as the elder statesman of German physics

WILHELM WIEN
1864–1928
German physicist who found experimentally how the intensity of black-body radiation at different wavelengths depends on its temperature

Philip Ball



Unless light is quantized, a black body should emit radiation uncontrollably.

PLANCK’S QUANTA

the 30-second theory

In the late 1890s a German manufacturer of light bulbs asked a young German physicist, Max Planck, to compute the energy emitted by the hot filaments in light bulbs. Here Planck was faced with a problem that physicists at the time could not solve: to find a formula for the distribution of wavelengths of light and infrared light given off by a black body at any given temperature. Planck tried everything physics theory could offer, to no avail. In what he called an ‘act of desperation’ he introduced the notion that the radiation from a hot body is not given off as a continuous stream, like water running from a tap, but rather like a dripping tap, in tiny packets – quanta – which he initially called ‘energy elements’. He assumed that th energy of these packets was inversely proportional to their wavelength, the energy of the packets with the shortest wavelengths being the highest. The relation between the wavelength of these quanta and their energy became known as the Planck relation. When Planck applied this idea to the computation of the energ of the wavelengths of light emitted by hot bodies, he found that his formula fitted laboratory measurement exactly.

3-SECOND FLASH

Planck discovered the quantization of energy – the fact that energy is given off or absorbed by matter in discrete packets or quanta – which revolutionized physics.

3-MINUTE THOUGHT

Initially Planck viewed the quantum as a mathematical construct. Physicists paid little attention to it until Einstein, in 1905, explained the photoelectric effect by equating Planck's quanta with photons. The real physical nature of quanta subsequently became clear, when Bohr explained how electrons can only move in fixed orbits around atomic nuclei, and every time they change orbit they do so by giving off or absorbing photon.

RELATED THEORIES

THE ULTRAVIOLET CATASTROPHE

EINSTEIN EXPLAINS THE PHOTOELECTRIC EFFECT

BALMER'S PREDICTABLE SPECTRUM

BOHR'S ATOM

3-SECOND BIOGRAPHY

NIELS BOHR

1885–1962

Danish pioneer of quantum theory and frequent opponent of Einstein

30-SECOND TEXT

Alexander Hellemans

Rather than continuous waves, Planck envisaged light as self-contained packets: quanta.

EINSTEIN EXPLAINS THE PHOTOELECTRIC EFFECT

the 30-second theory

In 1905 it must have seemed as though Einstein was an unstoppable source of revolutionary ideas. Five years previously Planck had proposed that bodies emit electromagnetic radiation such as light in packets or 'quanta' with an energy proportional to their frequency. For Planck this hypothesis was a mathematical trick that made the equations produce sensible results. But when Einstein postulated that the quantization of energy was not some quirk of light emission but a fundamental property of light itself – tha light was composed of a stream of discrete particles called photons, and not a continuous beam – it was a step too far for most scientists. However, Einstein suggested a way of testing his hypothesis. In the early 1900s Philipp Lenard had shown that light shone onto pieces of metal will eject electrons: the so-called photoelectric effect. But there was something odd: if the light was made brighter the electrons didn't escap with more energy, simply there were more of them. In Einstein's new model that made sense: a brighter bea contains more photons, albeit with the same energy as before. After Einstein's predictions about the photoelectric effect were verified experimentally by Robert Millikan over the ensuing decade, Einstein was awarded the 1921 Nobel prize in physics for his work.

3-SECOND FLASH

By suggesting that light is composed of energy packets called photons, Einstein was able to explain the puzzling features of the photoelectric effect.

3-MINUTE THOUGHT

Millikan spent ten years testing Einstein's theory in painstaking experiments that required extremely clean metal electrodes – but he did so because he was convinced the theory was wrong. Even when Millikan's results supported the predictions, he didn't believe Einstein's quantum view of light, saying that they lacked any 'satisfactory theoretical foundation'. Revolutionary ideas often do.

RELATED THEORIES

THE ULTRAVIOLET CATASTROPHE

PLANCK'S QUANTA

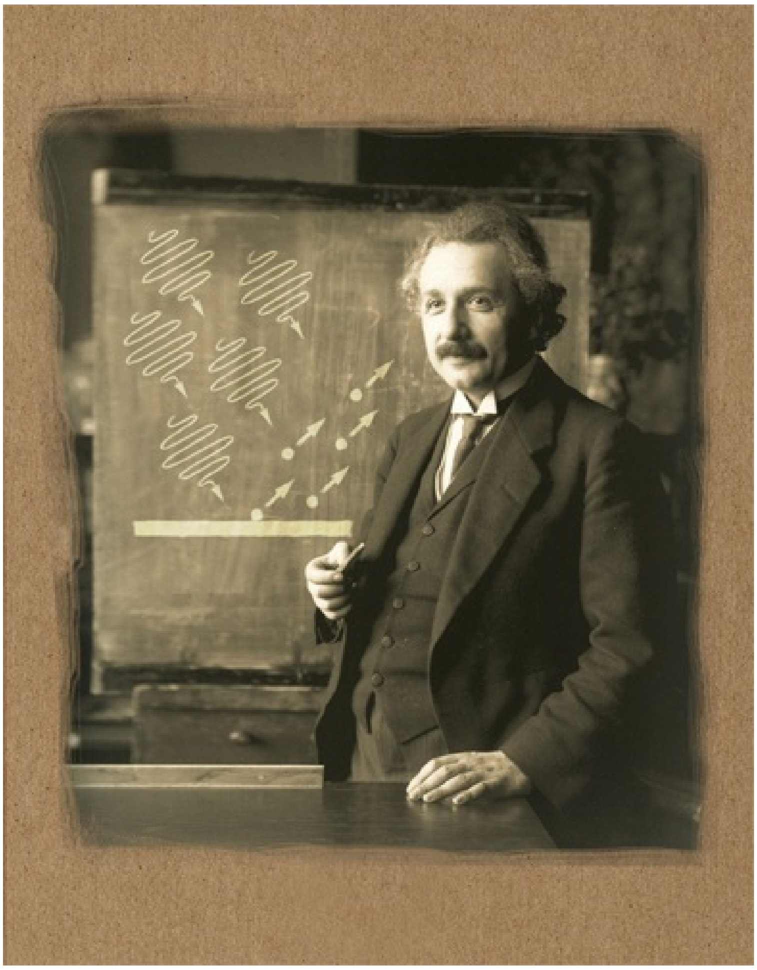
3-SECOND BIOGRAPHIES

PHILIPP LENARD
1862–1947
German experimental physicist, Nobel laureate in 1905, and Nazi sympathizer who referred to Einstein's work as 'Jewish physics'

ALBERT EINSTEIN
1879–1955
German-born physicist who developed special and general relativity and contributed to the origins of quantum theory

30-SECOND TEXT

Philip Ball



Einstein realized it was the energy of individual quanta of light that ejected electrons in photoelectric experiments.

BALMER'S PREDICTABLE SPECTRUM

the 30-second theory

When Niels Bohr was working on his quantum model of the atom, his aim was to provide a stable structure for electrons to exist around a central, positively charged nucleus. But in February 1913 he picked up on a discovery published by a schoolteacher, Johann Balmer, 28 years earlier. Bohr was chatting with a colleague, Hans Hansen, who mentioned that Balmer had produced a formula predicting the spectral lines emitted by hydrogen. When an element is heated it does not produce continuous colours, but narrow lines from the colour spectrum. Balmer had discovered that the frequency of these lines corresponded to a simple numerical formula. Until hearing this, Bohr had assumed that atoms emit light with frequencies corresponding to the rate of vibration or rotation of an electron – the accepted theory at the time. Balmer's equation caused Bohr to realize that the frequency of the light, linked to the energy of photons by Planck's simple formula, corresponded to the different energy gaps between the fixed electron orbits that he had devised. Bohr's new model not only explained why the atom was stable, but why specific frequencies of ligh were emitted in its spectrum.

3-SECOND FLASH

The accidental discovery of an old formula led Bohr to realize that his new atomic model explained both the stability of atoms and the energy of t photons they emitted.

3-MINUTE THOUGHT

Bohr told fellow physicist LÈon Rosenfeld 'As soon as I saw Balmer's formula, the whole thing was immediately clear to me … I didn't know anything about the spectral formulae. Then I looked it up … And I found that there was this very simple thing about the hydrogen spectrum.' The formula was in a textbook Bohr had used as a student, so he would have seen it, but it was Hansen's casual remark that triggered Bohr's major contribution to atomic theory.

RELATED THEORIES

THE ULTRAVIOLET CATASTROPHE

BOHR'S ATOM

THE DIRAC EQUATION

3-SECOND BIOGRAPHIES

JOHANN JAKOB BALMER
1825–98
Swiss schoolteacher who also lectured in mathematics at the University of Basel

L…ON ROSENFELD
1904–74
Belgian quantum physicist and documenter of the history of modern physics who named the lepton class of particle

30-SECOND TEXT

Brian Clegg

If electrons had fixed orbits, jumping between orbits would produce characteristic colours of light.