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Bohr and Einstein: Einstein and Bohr

Albert Einstein and relativity

If I were to ask a number of people in the street what they think was the most important new theory in physics in the twentieth century, and who has been the greatest physicist, I am fairly sure that – of those able to express an opinion at all – a substantial majority would say that relativity has been the greatest theory, and Einstein the greatest physicist.

Indeed Albert Einstein has probably achieved the remarkable feat of not just becoming the best-known practitioner of any branch of science among the general public, but retaining that position for 85 years, 50 of those years since his death in 1955.

It was in 1905, when he was 26, that Einstein astonished the scientific community by producing four pieces of work of the very highest quality. These included his first paper on relativity, in which he introduced what is now called the *special theory of relativity* (a term I shall explain in Chapter 3). The three other papers will be referred to in due course. What was astonishing was not *just* the quality of the work, but that the author was not an academic of note, or even of promise, but was working as a patent inspector after rather a mediocre student career. (A recent pleasantly written biography of Einstein is that of Abraham Pais [1], himself a well-known physicist; Pais gives references to many other accounts of Einstein's life. Another, more recent, biography is that by Fölsing [2].

After this explosion of 1905, Einstein was reasonably soon settled into a series of university positions of rapidly increasing prestige in Switzerland, Austria and Germany, and recognised as highly exceptional by the scientific community, though scarcely by the general public. His major return to relativity theory came just before and during the First World War, when he spent several years developing his *general theory of relativity*, essentially a theory of gravitation. (See Chapter 3.) This work required him to undertake a lengthy study of the rather complicated mathematics of the tensor calculus, followed by numerous attempts to apply it to the problem of gravity, but by 1916 the work was complete.

A crucial test – to check the bending of light from various stars as it passed the Sun – was undertaken by a team under Arthur Eddington on the island of Principe during the solar eclipse of 1919. The news that not only did the bending take place, but also the amount agreed quite well with Einstein's predictions, was bound to make his position at the head of the community of physicists unassailable. Also, and much more surprisingly, it made him famous among ordinary people across the world.

It is fascinating to ponder why, at the end of a war of unspeakable ferocity, and facing, in many cases, a totally uncertain future, the nations of the world should have elected as unofficial hero a man of massive intellect, with rather weak ties to any particular country, whose work was felt to be not only abstruse beyond belief, but of no application whatsoever to real life, for good or for evil.

There were early well-known newspaper reports that only a handful of people understood relativity. These were always nonsense; probably the bulk of specialists came to understand and appreciate both special and general relativity rather quickly considering their revolutionary nature. For the non-scientist, though, perhaps the attribution of crucial significance to such apparently meaningless phrases as 'non-simultaneity of time' and 'curvature of spacetime' gave an awareness of a realm of pure thought transcending the horrors of the past and the struggles of the present and immediate future.

For others, the mistaken feeling that the real meaning of the theory was covered in the simple slogan 'everything is relative' may have created a (false) sense of security, the hope that, while the details of the theory might be complicated, its basis was comprehensible, indeed something they had taken for granted all along.

Whatever the reasons, with the populace in general, relativity was undoubtedly a hit, and so, even more so, was Einstein. To the initial interest in his ideas was added delight in his character. For a world tired of boastful politicians and warmongering statesmen, his charm, his courtesy, his sense of fun and his modesty were supremely attractive. Add a sensitive smile and breathtakingly liquid eyes, and it is scarcely surprising that Einstein's face became one of the best-known worldwide in the 1920s, rivalled only perhaps by that of Charlie Chaplin.

In the political turbulence of the inter-war years, such a relatively carefree existence could not survive long. As the Nazis rose to power in Germany, Einstein – a Jew, a liberal, an intellectual – typified everything they detested. He was forced to emigrate to America in 1933, and he spent the rest of his life there,

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at the Institute for Advanced Study at Princeton. The best-known pictures of him date from this period and suggest rapid ageing. Though Einstein remained physically strong, his face became gaunt and lined, his hair and moustache turned white, and his eyes lost all sparkle and seemed to give visual proof of his fears for humanity.

He retained his modesty and simplicity. He played music with a few friends and made time for the neighbourhood children but kept himself aloof from close companionship. Of his scientific work at this stage of his life – he continued hard at it right up till his death – much more will be said later; here I shall just mention that his attitude to quantum theory removed him from influence over, and significant interaction with, the great majority of his fellow physicists. He devoted considerable effort during this period to political matters, appeals for world government and international control of nuclear weapons, and calls for scientists to work for peace.

But it is, of course, for relativity that he is chiefly remembered, and I would like to stress that he stands virtually alone as its sole creator. It is only fair to mention that the Dutch physicist Hendrik Lorentz and the Frenchman, more mathematician than physicist, Henri Poincaré produced, independently of Einstein (and each other), most of the equations of special relativity. However, the work of these scientists, and brilliant scientists they both certainly were, was rather plodding and piecemeal, and not particularly convincing. To compare it with the approach of Einstein, where, from a very few postulates, easily stated though conceptually challenging, all the results flowed in a straightforward and meaningful way, serves to increase, rather than decrease, one's impression of Einstein's genius. Lorentz and Poincaré produced new equations; Einstein gave us a new physics.

For general relativity, the only name other than that of Einstein needing to be considered is that of David Hilbert, the great German mathematician. Hilbert produced equations similar enough to those of Einstein to make Einstein briefly suspicious that Hilbert had cynically taken advantage of his own mathematical struggles. Hilbert himself, however, recognised Einstein as discoverer of the general theory, and this has never been questioned.

Relativity and quantum theory

But I now want to go right back to the beginning of the book and the question raised there, because, if it were physicists rather than laypeople being questioned on the greatest physical theory of the twentieth century, I don't believe they would pick relativity at all. Instead, they would go for the other major development in physics of this period – quantum theory. This would especially be the case if their field of interest concerned the behaviour of substances or systems existing naturally, or fairly easily manufactured, on Earth – semi-conducting solids, lasers and the like. Those more interested in astrophysics or cosmic speculation *might* stick to relativity.

To explain the reasons for this choice, I first need to explain under what circumstances relativity is required, and then do the same thing for quantum theory. I shall start from the point that the pre-1900 physics, the mechanics of Isaac Newton and the electromagnetism of James Clerk Maxwell in particular, gave correct answers for the areas of experience available for study at that time. (This physics is often called classical physics, and I shall outline its principal features in the following chapter.) Specifically classical physics worked well when the speeds of the particles were much lower than that of light (which is always referred to as c), and provided that their dimensions were much greater than those of atoms.

(In this book, I shall use scientific notation. If a little off-putting at first sight for those who don't understand it, it is not difficult to learn, and then it really does make things much easier. In this notation, a thousand, 1 followed by three noughts, is written as 10^3, and a million, 1 followed by six noughts, as 10^6. A one-thousandth, 0.001, is written as 10^{-3}, and a one-millionth, 0.000 001, as 10^{-6}, and so on. According to these rules, 1 may be written, if we wish, in the rather unlikely form of 10^0. So c, the speed of light, which is 300 000 000 metres per second, is best written as 3×10^8 metres per second, or, conveniently applying the same argument to the units, $3 \times 10^8\ \mathrm{m\,s^{-1}}$. Atomic dimensions may be thought of, roughly, as between 10^{-10} m and 10^{-9} m, that is, between a ten-thousand-millionth and a thousand-millionth of a metre.)

If we start from the motion of a football, or that of the Moon in orbit round the Earth, speeds are certainly much less that that of light, c, and dimensions much greater than those of atoms. So Newton's laws apply extremely accurately to these processes; if they had not done so, Newton would never have become particularly famous! For these speeds, the predictions of relativity are (almost exactly) the same as those of Newton.

But when speeds approach that of light, relativity theory tells us that Newtonian theory is only an approximation, a good one if the speed is $c/10$, say, but rather bad by the time it reaches, say, $c/3$. On the other hand, the equations of relativity give the correct answers, that is to say, the results that are found in any experiment.

According to relativity, by the way, bodies can never travel as fast as light. This is true, at least, for all the objects we are familiar with, which have masses greater than zero. (If you are not familiar with the term 'mass', it just means what in everyday speech we call 'weight'; we shall meet it a little more formally in Chapter 2.) Rather peculiar particles with mass zero *have* turned up in physics, and we shall meet them in Chapter 4; they *must* have speed equal to c at all times. (I should mention that, comparatively recently, the existence of particles called *tachyons* has been suggested; such particles would *always* have speed *greater* than c. Many people think that the existence of such particles would cause conceptual paradoxes. Be that as it may, it can definitely be said that those looking for tachyons have not so far found any.)

Similarly, as dimensions are decreased, Newtonian ideas become unsatisfactory; their predictions become a deteriorating approximation to the truth. This is when quantum theory is required. Often the terms ‘microscopic’ and ‘macroscopic’ are used to denote, roughly, objects the size of atoms and objects large enough to be dealt with directly by our senses. So quantum theory and Newton agree for the macroscopic case, but for the microscopic case they disagree, and it is quantum theory that is correct.

At first sight, then, it might be suspected that *neither* relativity *nor* quantum theory should be very important for our everyday life on Earth. After all, we don’t travel at speeds of $10^8\ \mathrm{m\,s^{-1}}$, and the objects we interact with directly are macroscopic, as I just defined it. But at least for the case of quantum theory, this impression would be most misleading.

It *is* true that, when one drives a car, the dynamical properties, the relation of the acceleration to the power of the engine and the gradient and slipperiness of the road, are covered in a totally satisfactory way by Newton’s mechanics. But one could scarcely even attempt to understand in any fundamental way the strength of the metal of the car body, or the energy provided by the petrol, without the use of quantum theory.

Even more so, the electrical properties of the car radio or the on-board computer would be incomprehensible without a good knowledge of quantum theory; indeed, the materials and electronic circuitry that constitute these devices could not have been designed without such knowledge. The individual atoms, their configuration and their electronic properties are crucial in the tasks of the (macroscopic) system.

Quantum theory has enabled us to understand the properties of atoms, molecules and nuclei, and, to some extent, the *constituents* of nuclei. (For readers not quite sure of the meaning of some of these terms, explanation will come in the following chapters.) For instance it tells us why two oxygen atoms combine to form a molecule, and why only certain nuclei are stable. In this paragraph I am unashamedly using microscopic terms – atom, molecule and so on. Of course human beings cannot sense or react to individual atoms, but our bodies certainly require oxygen molecules, and would respond badly to too much radioactivity caused by decay of unstable nuclei. Thus quantum theory is decidedly relevant

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to our life as human beings on Earth. In contrast, for most of the questions I've mentioned here, relativity provides only a very small correction factor compared with the Newtonian case, so it does not really play a role.

When we move from planet Earth to larger-scale physics like cosmology, or the origin of the Universe, relativity theory does play an important part. But so does quantum theory; so indeed do such areas of physics as quantum field theory and the study of elementary particles (which will be touched on in Chapter 4). Overall, then, I believe it should be quantum theory, not relativity, that should receive the laurels from the physicist.

Albert Einstein: universal genius

Does this mean then, I hope the reader is now asking, that Einstein must be dethroned as leading physicist of the century? My answer would be, emphatically, no, for three good reasons. The first is that, while, unlike relativity, quantum theory was not the creation of one scientist, but of many over a period of a quarter of a century, Einstein was one of its main creators. Especially if one includes the achievements of physicists he influenced and encouraged as well as his own direct contributions, his role will be seen as immense and often crucial. (See Chapter 4 in which the development of the theory is sketched.)

It is well known that his 1921 Nobel Prize was awarded, not for relativity, but for his theory of the photoelectric effect, an important step in the development of quantum theory (and the second of the 1905 papers mentioned in the first section of this chapter). What happened is that the Royal Swedish Academy of Sciences was under great pressure to award Einstein the Prize for Physics, but did not quite have the courage, or the necessary advice, to award it for relativity. In any case, Einstein ignored the details of the citation, and gave his Nobel Prize address on relativity. This last remark should not, though, be taken as an admission that the work on the photoelectric effect was *not* good enough for the Nobel Prize; it definitely was!

After making such massive contributions to the development of the quantum theory, it must seem strange that Einstein rejected its final form, or, at least, some elements of what most physicists of the time thought had to be its final form. I shall say no more on that subject now, as it is one of the main topics of the rest of the book and Chapter 6 in particular.

The second reason for retaining Einstein at the top of one's list is that, even apart from relativity and quantum theory, he did exceptionally important work in other areas of physics. Of his remaining two major papers of 1905, the first was a seminal study of the diffusion of solid particles through liquids. The second was an analysis of Brownian motion, the means by which molecules were (indirectly) observed for the first time; particles large enough to be visible, and suspended in a liquid, appear to move erratically under bombardment from the (invisible) molecules of the liquid.

Only by the standards of relativity and the photoelectric effect do these papers rate as less than amazing triumphs. Indeed the Nobel Prize committee considered awarding Einstein the Prize for his work on Brownian motion. Its reason for refraining from doing so was not that the work was too weak for a Nobel Prize, just that it would look most strange to award the prize for this, when the papers on relativity and the quantum theory were obviously more important. Happy indeed should be the theoretical physicist whose third-rate work (third-best paper in a given year) is good enough for a Nobel Prize!

My third reason is just that – almost, seemingly, independently of his actual achievements – it was recognised by every other physicist that he stood supreme. His loftiness of approach, his intellectual superiority, his independence of mind, were enough to make him their acknowledged leader, even though his attitude to quantum theory meant that, for most of them, and for almost half his career, he seemed a lost leader.

So there are undoubtedly good reasons for expecting a physicist to choose Einstein ahead of all others – but I expect that any who didn't would choose instead Niels Bohr.

Niels Bohr and quantum theory

If one were to suggest that what Einstein was to relativity, Bohr was to quantum theory, the remark would be most misleading unless highly qualified. While Einstein, as I've already said, built relativity practically single-handed, very many scientists, including, of course, Einstein himself, contributed to the development of quantum theory, a process that began in 1900.

Bohr himself took one major step, the introduction of the so-called Bohr atom, in 1913. Important as this was in stimulating the discoveries that led to the final form of the theory, which was reached around 1925, the Bohr atom does not actually appear in this final form, indeed is rather at odds with it. It is fair to add, though, that certain components of Bohr's theory *were* lasting and important – the energy-level diagram and the concept of the transition between different levels and its corresponding frequency. For all this, see Chapter 4. (For further information on all aspects of Bohr, Pais [3] has written a readable and detailed biography, and another account of Bohr's life and work has been written by Blaedel [4].)

Bohr was equally or more important in two other ways. From 1921, the date of the foundation of his Institute of Theoretical Physics in Copenhagen when

Bohr was 35, right up to his death in 1962, the institute was *the* world centre for research in theoretical physics (though with competition from Munich and, in particular, Göttingen in the early years, while, in the later period, the pendulum had swung in the American direction to a considerable extent). Many of those chiefly involved in the development of quantum theory spent long periods at Copenhagen, learning from Bohr, arguing with him, often assimilating much of his approach to physics. Among the major figures were Werner Heisenberg, Wolfgang Pauli and Hendrik Kramers, all of whom will figure substantially in later chapters of this book. Paul Dirac was another very important contributor to quantum theory who spent long periods in Copenhagen, though he retained very much his own approach. There were scores of visitors of somewhat less significance.

It is also interesting to note the main exceptions. There were those whose main inspiration came from Einstein – Louis de Broglie and Erwin Schrödinger. Max Born had a strong base in Göttingen, at least till the rise of Hitler, and Arnold Sommerfeld reigned supreme at Munich.

(Mention of Born reminds me to point out that a number of the physicists we are discussing have unfortunately similar names: Bohr, Born, and shortly we shall meet Bohm, who is not, as you may be inclined to suspect, a misprint for Bohr, but a very important quantum physicist in his own right. Please don't get confused!).

Perhaps Bohr's greatest lasting significance, though, lay in the interpretation, not the creation, of quantum theory. In order to explain this remark, it may be necessary to say why such a thing as an 'interpretation' is required, and again a comparison with relativity may be useful.

Everybody will agree that the ideas of relativity are difficult to come to terms with. The way of looking at things is just very different from what one is used to under Newton. Nevertheless, once one has taken the required mental steps, the new set of concepts is perfectly well defined. The equations of the general theory may be difficult to solve for important cases, and the more arcane cosmological aspects – black holes, the birth of the Universe and so on – are certainly thought-provoking, but I don't think practioners of relativity lie awake at night worrying at least about the *bases* of their subject.

Such is not the case with quantum theory – at least not necessarily. It is certainly possible to concentrate on the immensely successful and unproblematic calculational aspects of the theory, and thus sleep perfectly well at night. Bohr, however, was not content with this approach. He realised that, until the mathematical parameters and processes were given coherent physical meaning, any deductions from them were illegitimate. It was, however, by no means obvious that such 'interpretation' was possible, or, if so, how it should be carried out.

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Bohr's solution to the problem was his fairly general framework of what he called 'complementarity', and the specific application to quantum theory became known as its 'Copenhagen interpretation'. The parameters kept their conventional meanings, but their simultaneous application was restricted. (This admittedly brief and obscure statement will be extended and, I hope, clarified in Chapter 5.) Such was Bohr's prestige that this set of ideas became very generally 'accepted wisdom'. Even most of those who had not studied them at all carefully had no hesitation is giving lip service to the Copenhagen virtues.

The leading exception was, of course, Einstein. He and Bohr has several well-publicised debates in the late 1920s and into the 1930s. (The orthodox view was that Bohr won them hands down.) Of those physicists noted above as being principally inspired by Einstein, Schrödinger remained reasonably close to Einstein, agreeing with him to a large extent on the defects of the Copenhagen interpretation, if not necessarily on what should replace it. De Broglie initially put forward his own interpretation, but was persuaded by Pauli to reject it and become a rather reluctant convert to Copenhagen. (In the 1950s, David Bohm was to renew interest in de Broglie's ideas and overcome Pauli's objections. This development will be an important part of Chapter 7.)

There were other towering names who were hostile towards Copenhagen – Max Planck and Max von Laue, but their important contributions, which will be described in Chapters 2 and 4, had been made in previous decades, and the overwhelming majority of quantum physicists had no hesitation in considering them, like Einstein, to be giants of the past, who had lost the mental flexibility to adapt to novel conceptual developments.

As Einstein's direct influence fell off from the 1930s, Bohr's, if anything, increased. Rather differently from Einstein, he had a strong attachment to family and nation. His base was in Copenhagen throughout his life, and he was recognised as Denmark's leading citizen for many years. But he had an important year in England in 1913, during which his great contribution to quantum theory was made, and he was forced to leave Denmark for three years of the Second World War which he spent in the USA. As an international man of science, he travelled widely.

During the 1930s, he did important work himself in nuclear physics, inventing the so-called compound nucleus model which was important for describing nuclear reactions, and playing a central part in the elucidation of nuclear fission, the process at the heart of the atomic bomb.

After 1945, Bohr did little science himself, though he continued to interact with the world's leading physicists. He spent much of his time preaching disarmament and international control of atomic weapons, a self-imposed task that had been begun during the war itself, when Winston Churchill came close to accusing him of treachery. Through the years of the cold war up to the time of his death he really had little success.

Such work obviously linked him with Einstein, though Bohr's constant travelling from country to country in search of their common goals contrasted with Einstein, who stayed at home signing letters and making occasional broadcasts, and this political unity, and the respect they always felt for each other as individuals, added extra poignancy to their continued scientific differences.

Bohr still maintained total scientific, as well as personal, respect for Einstein. Right up to Einstein's death, Bohr's work seemed motivated towards converting him to complementarity, and even when Einstein had died he was still Bohr's unseen opponent, at whom his argument were aimed.

On the other hand, Einstein's attitude to Bohr's scientific views may *possibly*, I feel, have lapsed into irritation at times. There is little direct evidence for this, but perhaps some indirect suggestions. For much of their lives, Einstein and Max Born exchanged letters [5]. A good deal of the content of these was concerned with world politics following the outbreak of fascism in Europe, which sent both men into exile, Einstein in America and Born in Scotland, and continuing into the cold-war period. This portion is moving and stimulating. However, there were also some fairly sharp exchanges on the interpretation of quantum theory. (Born was a strong advocate of Copenhagen.) Einstein occasionally showed clear signs of extreme impatience.

Another hint comes from the comments of Schrödinger – who, as I've already said, was reasonably close in spirit to Einstein – on Bohr, which are reported in Moore's biography of Schrödinger [6]. Schrödinger denounced complementarity as a 'thoughtless slogan', and says that, if he were not convinced that Bohr was honest, he would describe its use as 'intellectually wicked'. It would not surprise me greatly if such ideas were reasonably close to those of Einstein.

The debate continues

Bohr himself died in 1962. Since then the practically monolithic subservience to his views on quantum interpretation has fragmented somewhat. The leading spirit in the process of re-evaluation has been a physicist from Ireland, John Bell, who was stimulated both by the views of Einstein and by Bohm's work mentioned already. His work is discussed with that of Bohm in Chapter 7.

Many other physicists have joined in the discussion of these ideas, analysing the ingenious difficulties for the Copenhagen interpretation thought up by Einstein, Schrödinger, Bell and others, and putting forward interpretations of their own. A few of these ideas are discussed in Chapter 8. Some of these writers