『量子革命—アインシュタインとボーア、偉大なる頭脳の激突—』
原注

＊邦訳においては、紙幅の都合により、
原書「Notes」のうち原則として文章を含む注のみを訳出しました。
以下に原注の全文を掲げます。

NOTES

PROLOGUE: THE MEETING OF MINDS

Pais (1982), p. 443.
Mehra (1975), quoted p. xvii.
Mehra (1975), quoted p. xvii.
Excluding the three professors (de Donder, Henriot and Piccard) from the Free University of Brussels invited as guests, Herzen representing the Solvay family, and Verschaffelt there in his capacity as the scientific secretary, then seventeen out of the 24 participants had already or would in due course receive a Nobel Prize. They were: Lorentz, 1902; Curie, 1903 (physics) and 1911 (chemistry); W.L. Bragg, 1915; Planck, 1918; Einstein, 1921; Bohr, 1922; Compton, 1927; Wilson, 1927; Richardson, 1928; de Broglie, 1929; Langmuir, 1932 (chemistry); Heisenberg, 1932; Dirac, 1933; Schrödinger, 1933; Pauli, 1945; Debye, 1936 (chemistry); and Born 1954. The seven who did not were Ehrenfest, Fowler, Brillouin, Knudsen, Kramers, Guye and Langevin.
Fine (1986), quoted p. 1. Letter from Einstein to D. Lipkin, 5 July 1952.
Snow (1969), p. 94.
Fölsing (1997), quoted p. 457.
Pais (1994), quoted p. 31.
Pais (1994), quoted p. 31.
Jungk (1960), quoted p. 20.
Gell-Mann (1981), p. 169.
Hiebert (1990), quoted p. 245.
Mahon (2003), quoted p. 149.
Mahon (2003), quoted p. 149.

CHAPTER 1: THE RELUCTANT REVOLUTIONARY

Planck (1949), pp. 33–4.
Hermann (1971), quoted p. 23. Letter from Planck to Robert Williams Wood, 7 October 1931.
Mendelssohn (1973), p. 118.
Heilbron (2000), quoted p. 5.
Mendelssohn (1973), p. 118.
Hermann (1971), quoted p. 23. Letter from Planck to Robert Williams Wood, 7 October 1931.
Heilbron (2000), quoted p. 3.
In the seventeenth century it was well known that passing a beam of sunlight through a prism resulted in the production of a spectrum of colours. It was believed that this rainbow of colours was the result of some sort of transformation of light as a result

of passing through the prism. Newton disagreed that somehow the prism adds colour and conducted two experiments. In the first he passed a beam of white light through a prism to produce the spectrum of colours and allowed a single colour to pass through a slit in a board and strike a second prism. Newton argued that if the colour had been the result of some change that light had undergone by passing through the first prism, passing it through a second would produce another change. Alas he found that, no matter which colour was selected as he repeated the experiment, passing it through a second prism left the original colour unchanged. In his second experiment Newton succeeded in mixing light of different colours to create white light.

Herschel made his serendipitous discovery on 11 September 1800, but it was published the following year. The spectrum of light can be viewed horizontally and vertically, depending on the arrangement apparatus. The prefix 'infra' came from the Latin word meaning 'below', when the light spectrum was viewed as a vertical strip with violet at the top and red at the bottom.

The wavelengths of red light and its various shades lie between 610 and 700 nanometres (nm), where a nanometre is a billionth of a metre. Red light of 700nm has a frequency of 430 trillion oscillations per second. At the opposite end of the visible spectrum, violet light ranges over 450nm to 400nm with the shorter wavelength having a frequency of 750 trillion oscillations per second.

Kragh (1999), quoted p. 121.

Teichmann et al. (2002), quoted p. 341.

Kangro (1970), quoted p. 7.

Cline (1987), quoted p. 34.

In 1900, London had a population of approximately 7,488,000, Paris of 2,714,000, and Berlin of 1,889,000.

Large (2001), quoted p. 12.

Planck (1949), p. 15.

Planck (1949), p. 16.

Planck (1949), p. 15.

Planck (1949), p. 16.

Planck (1949), p. 16.

Heat is not a form of energy as is commonly assumed, but a process that transfers energy from A to B due a temperature difference.

Planck (1949), p. 14.

Planck (1949), p. 13.

Lord Kelvin had also formulated a version of the second law: it is impossible for an engine to convert heat into work with 100 per cent efficiency. It was equivalent to Clausius. Both were saying the same thing but in two different languages.

Planck (1949), p. 20.

Planck (1949), p. 19.

Heilbron (2000), quoted p. 10.

Heilbron (2000), quoted p. 10.

Planck (1949), p. 20.

Planck (1949), p. 21.

Jungnickel and McCormmach (1986), quoted p. 52, Vol. 2.
Otto Lummer and Ernst Pringsheim christened Wien's discovery 'the displacement law' (*Verschiebungsgesetz*) only in 1899.
Given the inverse relationship between frequency and wavelength, as the temperature increases so does the frequency of the radiation of maximum intensity.
When the wavelength is measured in micrometres and the temperature in degrees Kelvin, then the constant is 2900.
In 1898 the Berlin Physical Society (Berliner Physikalische Gesellschaft), founded in 1845, changed its name to the German Physical Society (Deutsche Physikalische Gesellschaft zu Berlin).
The infrared part of the spectrum can be subdivided into roughly four wavelength bands: the near infrared, near the visible spectrum (0.0007–0.003mm), the intermediate infrared (0.003–0.006mm), the far infrared (0.006–0.015mm) and the deep infrared (0.015–1mm).
Kangro (1976), quoted p. 168.
Planck (1949), pp. 34–5.
Jungnickel and McCormmach (1986), Vol. 2, quoted p. 257.
Mehra and Rechenberg (1982), Vol. 1, Pt. 1, quoted p. 41.
Jungnickel and McCormmach (1986), Vol. 2, quoted p. 258.
Kangro (1976), quoted p. 187.
Planck (1900a), p. 79.
Planck (1900a), p. 81.
Planck (1949), pp. 40–1.
Planck (1949), p. 41.
Planck (1949), p. 41.
Planck (1993), p. 106.
Mehra and Rechenberg (1982), Vol. 1, p. 50, footnote 64.
Hermann (1971), quoted p. 23. Letter from Planck to Robert Williams Wood, 7 October 1931.
Hermann (1971), quoted p. 23. Letter from Planck to Robert Williams Wood, 7 October 1931.
Hermann (1971), quoted p. 24. Letter from Planck to Robert Williams Wood, 7 October 1931.
Hermann (1971), quoted p. 23. Letter from Planck to Robert Williams Wood, 7 October 1931.
Heilbron (2000), quoted p. 14.
Planck (1949), p. 32.
Hermann (1971), quoted p. 16.
Planck (1900b), p. 84.
The numbers have been rounded up.
Planck (1900b), p. 82.
Born (1948), p. 170.
Planck was also pleased because he had devised a way of measuring length, time and mass using a new set of units that would be valid and easily reproducible anywhere

in the universe. It was a matter of convention and convenience that had led to the introduction of various measuring systems at different places and times in human history, the latest being the measurement of length in metres, time in seconds, and mass in kilograms. Using h and two other constants, the speed of light c and Newton's gravitational constant G, Planck calculated values of length, mass and time that were unique and could serve as the basis of a universal scale of measurement. Given the smallness of the values of h and G, it could not be used for practical everyday purposes, but it would be the scale of choice to communicate with an extraterrestrial culture.

Heilbron (2000), quoted p. 38.

Planck (1949), pp. 44–5.

James Franck, Archive for the History of Quantum Physics (AHQP) interview, 7 September 1962.

James Franck, AHQP interview, 7 September 1962.

CHAPTER 2: THE PATENT SLAVE

Hentschel and Grasshoff (2005), quoted p. 131.

Collected Papers of Albert Einstein (CPAE), Vol. 5, p. 20. Letter from Einstein to Conrad Habicht, 30 June–22 September 1905.

Fölsing (1997), quoted p. 101.

Hentschel and Grasshoff (2005), quoted p. 38.

Einstein (1949a), p. 45.

CPAE, Vol. 5, p. 20. Letter from Einstein to Conrad Habicht, 18 or 25 May 1905.

CPAE, Vol. 5, p. 20. Letter from Einstein to Conrad Habicht, 18 or 25 May 1905.

Brian (1996), quoted p. 61.

CPAE, Vol. 9, Doc. 366.

CPAE, Vol. 9, Doc. 366.

Calaprice (2005), quoted p. 18.

CPAE, Vol. 1, xx, M. Einstein.

Einstein (1949a), p. 5.

Einstein (1949a), p. 5.

Einstein (1949a), p. 5.

Einstein (1949a), p. 8.

Oktoberfest started in 1810 as a fair to celebrate the marriage between the Bavarian Crown Prince Ludwig (the future King Ludwig I) and Princess Thérèse on 17 October. The event was so popular that it has been repeated annually ever since. It begins not in October, but September. It lasts sixteen days and ends on the first Sunday in October.

CPAE, Vol. 1, p. 158.

Fölsing (1997), quoted p. 35.

With 6 being the highest mark, Einstein received the following marks: algebra 6, geometry 6, history 6, descriptive geometry 5, physics 5–6, Italian 5, chemistry 5, natural history 5, German 4–5, geography 4, artistic drawing 4, technical drawing 4, and French 3.

CPAE, Vol. 1, pp. 15–16.
Einstein (1949a), p. 17.
Einstein (1949a), p. 15.
Fölsing (1997), quoted pp. 52–3.
Overbye (2001), quoted p. 19.
CPAE, Vol. 1, p. 123. Letter from Einstein to Mileva Maric, 16 February 1898.
Cropper (2001), quoted p. 205.
Einstein (1949a), p. 17.
CPAE, Vol. 1, p. 162. Letter from Einstein to Mileva Maric, 4 April 1901.
CPAE, Vol. 1, pp. 164–5. Letter from Hermann Einstein to Wilhelm Ostwald, 13 April 1901.
CPAE, Vol. 1, pp. 164–5. Letter from Hermann Einstein to Wilhelm Ostwald, 13 April 1901.
CPAE, Vol. 1, p. 165. Letter from Einstein to Marcel Grossmann, 14 April 1901.
CPAE, Vol. 1, p. 177. Letter from Einstein to Jost Winteler, 8 July 1901.
The advert appeared in the *Bundesblatt* (Federal Gazette) of 11 December 1901. CPAE, Vol. 1, p. 88.
CPAE, Vol. 1, p. 189. Letter from Einstein to Mileva Maric, 28 December 1901.
Berchtold V, Duke of Zähringen, founded the city in 1191. According to legend, Berchtold went hunting nearby and named the city Bärn after his first kill, a bear (Bär in German).
CPAE, Vol. 1, p. 191. Letter from Einstein to Mileva Maric, 4 February 1902.
Pais (1982), quoted pp. 46–7.
Einstein (1993), p. 7.
CPAE, Vol. 5, p. 28.
Hentschel and Grasshoff (2005), quoted p. 37.
Fölsing (1997), quoted p. 103.
Fölsing (1997), quoted p. 103.
Highfield and Carter (1994), quoted p. 210.
See CPAE, Vol. 5, p. 7. Letter from Einstein to Michele Besso, 22 January 1903.
CPAE, Vol. 5, p. 20. Letter from Einstein to Conrad Habicht, 30 June–22 September 1905.
Hentschel and Grasshoff (2005), quoted p. 23.
CPAE, Vol. 1, p. 193. Letter from Einstein to Mileva Maric, 17 February 1902.
Fölsing (1997), quoted p. 101.
Fölsing (1997), quoted p. 104.
Fölsing (1997), quoted p. 102.
Born (1978), p. 167.
Einstein (1949a), p. 15.
Einstein (1949a), p. 17.
CPAE, Vol. 2, p. 97.
Einstein (1905a), p. 178.
Einstein (1905a), p. 183.

Einstein also used his quantum of light hypothesis to explain Stoke's law of photoluminescence and the ionisation of gases by ultraviolet light.
Mulligan (1999), quoted p. 349.
Susskind (1995), quoted p. 116.
Pais (1982), quoted p. 357.
During his Nobel Lecture, entitled 'The Electron and the light-quanta from the experimental point of view', Millikan also said: 'After ten years of testing and changing and learning and sometimes blundering, all efforts being directed from the first toward the accurate experimental measurement of the energies of emission of photoelectrons, now as a function of the temperature, now of wavelength, now of material, this work resulted, contrary to my own expectations, in the first direct experimental proof in 1914 of the exact validity, within narrow limits of experimental errors, of the Einstein equation, and the first direct photoelectric determination of Planck's constant h.'
CPAE, Vol. 5, pp. 25–6. Letter from Max Laue to Einstein, 2 June 1906.
CPAE, Vol. 5, pp. 337–8. Proposal for Einstein's Membership in the Prussian Academy of Sciences, dated 12 June 1913 and signed by Max Planck, Walther Nernst, Heinrich Rubens and Emil Warburg.
Park (1997), quoted p. 208. Written in English, *Opticks* was first published in 1704.
Park (1997), quoted p. 208.
Park (1997), quoted p. 211.
Robinson (2006), quoted p. 103.
Robinson (2006), quoted p. 122.
Robinson (2006), quoted p. 96.
In German: 'War es ein Gott der diese Zeichen schrieb?'
Baierlein (2001), p. 133.
Einstein (1905a), p. 178.
Einstein (1905a), p. 193.
CPAE, Vol. 5, p. 26. Letter from Max Laue to Einstein, 2 June 1906.
In 1906 Einstein published *On the Theory of Brownian Motion* in which he presented his theory in a more elegant and extended form.
CPAE, Vol. 5, p. 63. Letter from Jakob Laub to Einstein, 1 March 1908.
CPAE, Vol. 5, p. 120. Letter from Einstein to Jakob Laub, 19 May 1909.
CPAE, Vol. 5, p. 120. Letter from Einstein to Jakob Laub, 19 May 1909.
CPAE, Vol. 5, p. 120. Letter from Einstein to Jakob Laub, 19 May 1909.
CPAE, Vol. 5, p. 120. Letter from Einstein to Jakob Laub, 19 May 1909.
CPAE, Vol. 2, p. 563.
CPAE, Vol. 5, p. 140. Letter from Einstein to Michele Besso, 17 November 1909.
Jammer (1966), quoted p. 57.
CPAE, Vol. 5, p. 187. Letter from Einstein to Michele Besso, 13 May 1911.
CPAE, Vol. 5, p. 190. Letter and invitation to the Solvay Congress from Ernst Solvay to Einstein, 9 June 1911.
CPAE, Vol. 5, p. 192. Letter from Einstein to Walter Nernst, 20 June 1911.
Pais (1982), quoted p. 399.

CPAE, Vol. 5, p. 241. Letter from Einstein to Michele Besso, 26 December 1911.
Brian (2005), quoted p. 128.
CPAE, Vol. 5, p. 220. Letter from Einstein to Heinrich Zangger, 7 November 1911.

CHAPTER 3: THE GOLDEN DANE

Niels Bohr Collected Works (BCW), Vol. 1, p. 559. Letter from Bohr to Harald Bohr, 19 June 1912.
Pais (1991), quoted p. 47. Since 1946 it has housed Copenhagen University's museum of medical history.
Pais (1991), quoted p. 46.
Pais (1991), quoted p. 99.
Pais (1991), quoted p. 48.
A second university in Aarhus was founded only in 1928.
Pais (1991), quoted p. 44.
Pais (1991), quoted p. 108.
Moore (1966), quoted p. 28.
Rozental (1967), p. 15.
Pais (1989a), quoted p. 61.
Niels Bohr, AHQP interview, 2 November 1962.
Niels Bohr, AHQP interview, 2 November 1962.
Heilbron and Kuhn (1969), quoted p. 223. Letter from Bohr to Margrethe Nørland, 26 September 1911.
BCW, Vol. 1, p. 523. Letter from Bohr to Ellen Bohr, 2 October 1911.
Weinberg (2003), quoted p. 10.
Aston (1940), p. 9.
Pais (1991), quoted p. 120.
BCW, Vol. 1, p. 527. Letter from Bohr to Harald Bohr, 23 October 1911.
BCW, Vol. 1, p. 527. Letter from Bohr to Harald Bohr, 23 October 1911.
There is no definitive historical evidence, but it is possible that Bohr attended a lecture given by Rutherford in Cambridge about his atomic model in October.
Bohr (1963b), p. 31.
Bohr (1963c), p. 83. The official report of the first Solvay Council was published in French in 1912 and in German in 1913. Bohr read the report as soon as it became available.
Kay (1963), p. 131.
Keller (1983), quoted p. 55.
Nitske (1971), quoted p. 5.
Nitske (1971), p. 5.
Kragh (1999), p. 30.
Wilson (1983), quoted p. 127.
Often in textbooks and scientific histories, the French scientist Paul Villard is credited with the discovery of gamma rays in 1900. In fact Villard discovered that radium emitted gamma rays, but it was Rutherford who reported them in his first paper on uranium radiation, published in January 1899, but finished on 1 September

1898. Wilson (1983), pp. 126–8 outlines the facts and makes a convincing case for Rutherford.
Eve (1939), quoted p. 55.
Andrade (1964), quoted p. 50.
More accurate measurements gave a half-life of 56 seconds.
Howorth (1958), quoted p. 83.
Wilson (1983), quoted p. 225.
Wilson (1983), quoted p. 225.
Wilson (1983), quoted p. 286.
Wilson (1983), quoted p. 287.
Pais (1986), quoted p. 188.
Cropper (2001), quoted p. 317.
Wilson (1983), quoted p. 291.
Marsden (1948), p. 54.
Rhodes (1986), quoted p. 49.
Thomson began working on a detailed mathematical version of this model only after he came across a similar idea proposed by Kelvin in 1902.
Badash (1969), quoted p. 235.
From quoted remarks by Geiger, Wilson (1983), p. 296.
Rowland (1938), quoted p. 56.
Cropper (2001), quoted p. 317.
Wilson (1983), quoted p. 573.
Wilson (1983), quoted p. 301. Letter from William Henry Bragg to Ernest Rutherford, 7 March 1911. Received on 11 March.
Eve (1939), quoted p. 200. Letter from Hantaro Nagaoka to Ernest Rutherford, 22 February 1911.
Nagaoka had been inspired by James Clerk Maxwell's famous analysis of the stability of Saturn's rings, which had puzzled astronomers for more than 200 years. In 1855, in a bid to attract the best physicists to attack the problem, it was chosen as the topic for Cambridge University's prestigious biennial competition, the Adams Prize. Maxwell submitted the only entry to be received by the closing date in December 1857. Rather than diminish the significance of the prize and Maxwell's achievement, it only served to enhance his growing reputation by once again demonstrating the difficulty of the problem. No one else had even succeeded in completing a paper worth entering. Although when seen through telescopes they appeared to be solid, Maxwell showed conclusively that the rings would be unstable if they were either solid or liquid. In an astonishing display of mathematical virtuosity, he demonstrated that the stability of Saturn's rings was due to them being composed of an enormous number of particles revolving around the planet in concentric circles. Sir George Airy, the Astronomer Royal, declared that Maxwell's solution was 'one of the most remarkable applications of Mathematics to Physics that I have ever seen'. Maxwell was duly rewarded with the Adams Prize.
Rutherford (1906), p. 260.
Rutherford (1911a), reprinted in Boorse and Motz (1966), p. 709.

In their paper, published in April 1913, Geiger and Marsden argued that their data was 'strong evidence of the correctness of the underlying assumptions that an atom contains a strong charge at the centre of dimensions, small compared with the diameter of the atom'.

Marsden (1948), p. 55.

Niels Bohr, AHQP interview, 7 November 1962.

Niels Bohr, AHQP interview, 2 November 1962.

Niels Bohr, AHQP interview, 7 November 1962.

Rosenfeld and Rüdinger (1967), quoted p. 46.

Pais (1991), quoted p. 125.

Andrade (1964), quoted p. 210.

Andrade (1964), p. 209, note 3.

Rosenfeld and Rüdinger (1967), quoted p. 46.

Bohr (1963b), p. 32.

Niels Bohr, AHQP interview, 2 November 1962.

Howorth (1958), quoted p. 184.

Soddy (1913), p. 400. He also suggested 'isotopic elements' as an alternative.

Radiothorium, radioactinium, ionium and uranium-X were later identified as only four of the 25 isotopes of thorium.

Niels Bohr, AHQP interview, 2 November 1962.

Bohr (1963b), p. 33.

Bohr (1963b), p. 33.

Bohr (1963b), p. 33.

Niels Bohr, AHQP interview, 2 November 1962.

Niels Bohr, AHQP interview, 31 October 1962.

Niels Bohr, AHQP interview, 31 October 1962.

Boorse and Motz (1966), quoted p. 855.

Georg von Hevesy, AHQP interview, 25 May 1962.

Pais (1991), quoted p. 125.

Pais (1991), quoted p. 125.

Bohr (1963b), p. 33.

Blaedel (1985), quoted p. 48.

BCW, Vol. 1, p. 555. Letter from Bohr to Harald Bohr, 12 June 1912.

BCW, Vol. 1, p. 555. Letter from Bohr to Harald Bohr, 12 June 1912.

BCW, Vol. 1, p. 561. Letter from Bohr to Harald Bohr, 17 July 1912.

CHAPTER 4: THE QUANTUM ATOM

Margrethe Bohr, Aage Bohr and Léon Rosenfeld, AHQP interview, 30 January 1963.

Margrethe Bohr, Aage Bohr and Léon Rosenfeld, AHQP interview, 30 January 1963.

Margrethe Bohr, AHQP interview, 23 January 1963.

Rozental (1998), p. 34.

Bohr decided to delay publication of the paper until experiments being conducted in Manchester on the velocity of alpha particles became available. The paper, 'On the

Theory of the Decrease of Velocity of Moving Electrified Particles on Passing through Matter', was published in 1913 in the *Philosophical Magazine*.

See Chapter 3, note 6.

Nielson (1963), p. 22.

Rosenfeld and Rüdinger (1967), quoted p. 51.

BCW, Vol. 2, p. 577. Letter from Bohr to Ernest Rutherford, 6 July 1912.

Niels Bohr, AHQP interview, 7 November 1962.

BCW, Vol. 2, p. 136.

BCW, Vol. 2, p. 136.

Niels Bohr, AHQP interview, 1 November 1962.

Niels Bohr, AHQP interview, 31 October 1962.

BCW, Vol. 2, p. 577. Letter from Bohr to Ernest Rutherford, 4 November 1912.

BCW, Vol. 2, p. 578. Letter from Ernest Rutherford to Bohr, 11 November 1912.

Pi (π) is the numerical value of the ratio of the circumference of a circle to its diameter.

One electron volt (eV) was equivalent to 1.6×10^{-19} joules of energy. A 100-watt light bulb converts 100 joules of electrical energy into heat in one second.

BCW, Vol. 2, p. 597. Letter from Bohr to Ernest Rutherford, 31 January 1913.

Niels Bohr, AHQP interview, 31 October 1962.

In Balmer's day and well into the twentieth century, wavelength was measured in a unit named in honour of Anders Ångström. 1 Ångström = 10^{-8}cm, one hundred-millionth of a centimetre. It is equal to one-tenth of a nanometre in modern units.

See Bohr (1963d), with introduction by Léon Rosenfeld.

In 1890 the Swedish physicist Johannes Rydberg developed a more general formula than Balmer's. It contained a number, later called Rydberg's constant, which Bohr was able to calculate from his model. He was able rewrite Rydberg's constant in terms of Planck's constant, the electron's mass and the electron's charge. He was able to derive a value for Rydberg's constant that was almost an identical match for the experimentally determined value. Bohr told Rutherford that he believed it to be an 'enormous and unexpected development'. (See BCW, Vol. 2, p. 111.)

Heilbron (2007), quoted p. 29.

Gillott and Kumar (1995), quoted p. 60. Lectures delivered by Nobel Prize-winners are available at www.nobelprize.org.

BCW, Vol. 2, p. 582. Letter from Bohr to Ernest Rutherford, 6 March 1913.

Eve (1939), quoted p. 221.

Eve (1939), quoted p. 221.

BCW, Vol. 2, p. 583. Letter from Ernest Rutherford to Bohr, 20 March 1913.

BCW, Vol. 2, p. 584. Letter from Ernest Rutherford to Bohr, 20 March 1913.

BCW, Vol. 2, pp. 585–6. Letter from Bohr to Ernest Rutherford, 26 March 1913.

Eve (1939), p. 218.

Wilson (1983), quoted p. 333.

Rosenfeld and Rüdinger (1967), quoted p. 54.

Wilson (1983), quoted p. 333.

Blaedel (1988), quoted p. 119.

Eve (1939), quoted p. 223.
Cropper (1970), quoted p. 46.
Jammer (1966), quoted p. 86.
Mehra and Rechenberg (1982), Vol. 1, quoted p. 236.
Mehra and Rechenberg (1982), Vol. 1, quoted p. 236.
BCW, Vol. 1, p. 567. Letter from Harald Bohr to Bohr, autumn 1913.
Eve (1939), quoted p. 226.
Moseley was also able to resolve some anomalies that had arisen in the placing of three pairs of elements in the periodic table. According to atomic weight, argon (39.94) should be listed after potassium (39.10) in the periodic table. This would conflict with their chemical properties, as potassium was grouped with the inert gases and argon with the alkali metals. To avoid such chemical nonsense, the elements were placed with the atomic weights in reverse order. However, using their respective atomic numbers they are placed in the correct order. Atomic number also allowed the correct positioning of two other pairs of elements: tellurium–iodine and cobalt–nickel.
Pais (1991), quoted p. 164.
BCW, Vol. 2, p. 594. Letter from Ernest Rutherford to Bohr, 20 May 1914.
Pais (1991), quoted p. 164.
CPAE, Vol. 5, p. 50. Letter from Einstein to Arnold Sommerfeld, 14 January 1908.
It was discovered later that Sommerfeld's k could not be equal to zero. So k was set equal to l+1 where l is the orbital angular momentum number. l = 0, 1, 2 … n–1 where n is the principal quantum number.
There are actually two types of Stark effect. *Linear Stark effect* is one in which splitting is proportional to the electric field and occurs in excited states of hydrogen. All other atoms exhibit the *quadratic Stark effect*, where the splitting of the lines is proportional to the square of the electric field.
BCW, Vol. 2, p. 589. Letter from Ernest Rutherford to Bohr, 11 December 1913.
BCW, Vol. 2, p. 603. Letter from Arnold Sommerfeld to Bohr, 4 September 1913.
In modern notation m is written m_l. For a given l there are 2l+1 values of m_l that range from –l to +l. If l=1, then there are three values of m_l: –1,0,+1.
Pais (1994), quoted p. 34. Letter from Arnold Sommerfeld to Bohr, 25 April 1921.
Pais (1991), quoted p. 170.
In 1965, when Bohr would have been 80, it was renamed the Niels Bohr Institute.

CHAPTER 5: WHEN EINSTEIN MET BOHR

Frank (1947), quoted p. 98.
CPAE, Vol. 5, p. 175. Letter from Einstein to Hendrik Lorentz, 27 January 1911.
CPAE, Vol. 5, p. 175. Letter from Einstein to Hendrik Lorentz, 27 January 1911.
CPAE, Vol. 5, p. 187. Letter from Einstein to Michele Besso, 13 May 1911.
Pais (1982), quoted p. 170.
Pais (1982), quoted p. 170.
CPAE, Vol. 5, p. 349. Letter from Einstein to Hendrik Lorentz, 14 August 1913.
Fölsing (1997), quoted p. 335.

CPAE, Vol. 8, p. 23. Letter from Einstein to Otto Stern, after 4 June 1914.
CPAE, Vol. 8, p. 10. Letter from Einstein to Paul Ehrenfest, before 10 April 1914.
CPAE, Vol. 5, p. 365. Letter from Einstein to Elsa Löwenthal, before 2 December 1913.
CPAE, Vol. 8, pp. 32–3. Memorandum from Einstein to Mileva Einstein-Maric, 18 July 1914.
CPAE, Vol. 8, p. 41. Letter from Einstein to Paul Ehrenfest, 19 August 1914.
Fromkin (2004), quoted pp. 49–50.
Russia, France, Britain and Serbia were joined by Japan (1914), Italy (1915), Portugal and Romania (1916), the USA and Greece (1917). The British dominions also fought with the allies. Germany and Austria-Hungary were supported by Turkey (1914) and Bulgaria (1915).
CPAE, Vol. 8, p. 41. Letter from Einstein to Paul Ehrenfest, 19 August 1914.
CPAE, Vol. 8, p. 41. Letter from Einstein to Paul Ehrenfest, 19 August 1914.
Heilbron (2000), quoted p. 72.
Fölsing (1997), quoted p. 345.
Fölsing (1997), quoted p. 345.
Gilbert (1994), quoted p. 34.
Fölsing (1997), quoted p. 346.
Fölsing (1997), quoted p. 346.
Large (2001), quoted p. 138.
CPAE, Vol. 8, p. 77. Letter from Einstein to Romain Rolland, 22 March 1915.
CPAE, Vol. 8, p. 422. Letter from Einstein to Hendrik Lorentz, 18 December 1917.
CPAE, Vol. 8, p. 422. Letter from Einstein to Hendrik Lorentz, 18 December 1917.
CPAE, Vol. 5, p. 324. Letter from Einstein to Arnold Sommerfeld, 29 October 1912.
CPAE, Vol. 8, p. 151. Letter from Einstein to Heinrich Zangger, 26 November 1915.
CPAE, Vol. 8, p. 22. Letter from Einstein to Paul Ehrenfest, 25 May 1914.
CPAE, Vol. 8, p. 243. Letter from Einstein to Michele Besso, 11 August 1916.
CPAE, Vol. 8, p. 243. Letter from Einstein to Michele Besso, 11 August 1916.
CPAE, Vol. 8, p. 246. Letter from Einstein to Michele Besso, 6 September 1916.
CPAE, Vol. 6, p. 232.
CPAE, Vol. 8, p. 613. Letter from Einstein to Michele Besso, 29 July 1918.
Born (2005), p. 22. Letter from Einstein to Max Born, 27 January 1920.
Analogy courtesy of Jim Baggott (2004).
Born (2005), p. 80. Letter from Einstein to Max Born, 29 April 1924.
Large (2001), quoted p. 134.
CPAE, Vol. 8, p. 300. Letter from Einstein to Heinrich Zangger, after 10 March 1917.
CPAE, Vol. 8, p. 88. Letter from Einstein to Heinrich Zangger, 10 April 1915.
In a weak gravitational field, general relativity predicts the same bending as Newton's theory.
Pais (1994), quoted p. 147.
Brian (1996), quoted p. 101.
In the wake of the huge interest in his work, the first English translation of *Relativity* appeared in 1920.

CPAE, Vol. 8, p. 412, Letter from Einstein to Heinrich Zangger, 6 December 1917.
Pais (1982), quoted p. 309.
Brian (1996), quoted p. 103.
Calaprice (2005), quoted p. 5. Letter from Einstein to Heinrich Zangger, 3 January 1920.
Fölsing (1997), quoted p. 421.
Fölsing (1997), quoted p. 455. Letter from Einstein to Marcel Grossmann, 12 September 1920.
Pais (1982), quoted p. 314. Letter from Einstein to Paul Ehrenfest, 4 December 1919.
Everett (1979), quoted p. 153.
Elon (2003), quoted pp. 359–60.
Moore (1966), quoted p. 103.
Pais (1991), quoted p. 228. Postcard from Einstein to Planck, 23 October 1919.
CPAE, Vol. 5, p. 20. Letter from Einstein to Conrad Habicht, sometime between 30 June and 22 September 1905.
CPAE, Vol. 5, pp. 20–1. Letter from Einstein to Conrad Habicht, sometime between 30 June and 22 September 1905.
CPAE, Vol. 5, p. 21. Letter from Einstein to Conrad Habicht, sometime between 30 June and 22 September 1905.
Einstein (1949a), p. 47.
Moore (1966), quoted p. 104.
Moore (1966), quoted p. 106.
Pais (1991) quoted p. 232.
CPAE, Vol. 6, p. 232.
Fölsing (1997), quoted p. 477. Letter from Einstein to Bohr, 2 May 1920.
Fölsing (1997), quoted p. 477. Letter from Einstein to Paul Ehrenfest, 4 May 1920.
Fölsing (1997), quoted p. 477. Letter from Bohr to Einstein, 24 June 1920.
Pais (1994), quoted p. 40. Letter from Einstein to Hendrik Lorentz, 4 August 1920.
Arbeitsgemeinschaft deutscher Naturforscher zur Erhaltung reiner Wissenschaft.
Born (2005), p. 34. Letter from Einstein to the Borns, 9 September 1920.
Born (2005), p. 34. Letter from Einstein to the Borns, 9 September 1920.
Pais (1982), quoted p. 316. Letter from Einstein to K. Haenisch, 8 September 1920.
Fölsing (1997), quoted p. 512. Letter from Einstein to Paul Ehrenfest, 15 March 1922.
BCW, Vol. 3, pp. 691–2. Letter from Bohr to Arnold Sommerfeld, 30 April 1922.
What Bohr was calling electron shells were really a set of electron orbits. The primary orbits were numbered from 1 to 7, with 1 being nearest to the nucleus. Secondary orbits were designated by the letters s, p, d, f (from the terms 'sharp', 'principal', 'diffuse' and fundamental', used by spectroscopists to describe the lines in atomic spectra). The orbit nearest to the nucleus is just a single orbit and is labelled 1s, the next is a pair of orbits labelled 2s and 2p, the next a trio of orbits 3s, 3p and 3d, and so on. Orbits can hold increasing numbers of electrons the further from the nucleus they are. The s can hold 2 electrons, the p ones 6, the d ones 10, and the f ones 14.

Brian (1996), quoted p. 138.
Einstein (1993), p. 57. Letter from Einstein to Maurice Solovine, 16 July 1922.
See Fölsing (1997), p. 520. Letter from Einstein to Marie Curie, 11 July 1922.
Einstein (1949a), pp. 45–7.
French and Kennedy (1985), quoted p. 60.
Mehra and Rechenberg (1982), Vol. 1, Pt. 1, p. 358. Letter from Bohr to James Franck, 15 July 1922.
Moore (1966), quoted p. 116.
Moore (1966), quoted p. 116.
BCW, Vol. 4, p. 685. Letter from Bohr to Einstein, 11 November 1922.
Pais (1982), quoted p. 317.
BCW, Vol. 4, p. 686. Letter from Einstein to Bohr, 11 January 1923.
Pais (1991), quoted p. 308.
Pais (1991), quoted p. 215.
Bohr's banquet speech is available at www.nobelprize.org.
Bohr (1922), p. 7.
Bohr (1922), p. 42.
Robertson (1979), p. 69.
Weber (1981), p. 64.
Bohr (1922), p. 14.
Stuewer (1975), quoted p. 241.
Stuewer (1975), quoted p. 241.
See Stuewer (1975).
Visible light does undergo the 'Compton effect'. But the difference in wavelengths for the primary and scattered visible light is so much smaller than for X-rays that the effect is not detectable by the eye, although it can be measured in the lab.
Compton (1924), p. 70.
Compton (1924), p. 70.
Compton (1961). A short paper by Compton recounting the experimental evidence and the theoretical considerations that led to the discovery of the 'Compton effect'.
The American chemist Gilbert Lewis proposed the name *photon* in 1926 for atoms of light.
Fölsing (1997), quoted p. 541.
Pais (1991), quoted p. 234.
Compton (1924), p. 70.
Pais (1982), quoted p. 414.

CHAPTER 6: THE PRINCE OF DUALITY

Ponte (1981), quoted p. 56.
Unlike Duc, Prince was not a French title. With the death of his brother, the French title took precedence and Louis became a Duc.
Pais (1994), quoted p. 48. Letter from Einstein to Hendrik Lorentz, 16 December 1924.
Abragam (1988), quoted p. 26.

Abragam (1988), quoted pp. 26–7.
Abragam (1988), quoted p. 27.
Abragam (1988), quoted p. 27.
Ponte (1981), quoted p. 55.
See Abragam (1988), p. 38.
Corps du Génie in French.
Ponte (1981), quoted pp. 55–6.
Pais (1991), quoted p. 240.
Abragam (1988), quoted p. 30.
Abragam (1988), quoted p. 30.
Abragam (1988), quoted p. 30.
Abragam (1988), quoted p. 30.
Abragam (1988), quoted p. 30.
Wheaton (2007), quoted p. 58.
Wheaton (2007, quoted pp. 54–5.
Elsasser (1978), p. 66.
Gehrenbeck (1978), quoted p. 325.
CPAE, Vol. 5, p. 299. Letter from Einstein to Heinrich Zangger, 12 May 1912.
Weinberg (1993), p. 51.

CHAPTER 7: SPIN DOCTORS

Meyenn and Schucking (2001), quoted p. 44.
Born (2005), p. 223.
Born (2005), p. 223.
Paul Ewald, AHQP interview, 8 May 1962.
Enz (2002), quoted p. 15.
Enz (2002), quoted p. 9.
Pais (2000), quoted p. 213.
Mehra and Rechenberg (1982), Vol. 1, Pt. 2, quoted p. 378.
Enz (2002), quoted p. 49.
Cropper (2001), quoted p. 257.
Cropper (2001), quoted p. 257.
Cropper (2001), quoted p. 257.
Mehra and Rechenberg (1982), Vol. 1, Pt. 2, p. 384.
Pauli (1946b), p. 27.
Mehra and Rechenberg (1982), Vol. 1, Pt. 1, quoted p. 281.
CPAE, Vol. 8, p. 467. Letter from Einstein to Hedwig Born, 8 February 1918.
Greenspan (2005), quoted p. 108.
Born (2005), p. 56. Letter from Born to Einstein, 21 October 1921.
Pauli (1946a), p. 213.
Pauli (1946a), p. 213.
Lorentz assumed that oscillating electrons inside atoms of the incandescent sodium gas emitted the light that Zeeman had analysed. Lorentz showed that a spectral line would split into two closely spaced lines (a doublet) or three lines (a triplet)

depending on whether the emitted light was viewed in the direction parallel or perpendicular to that of the magnetic field. Lorentz calculated the difference in the wavelengths of the two adjacent lines and obtained a value in agreement with Zeeman's experimental results.

Pais (1991), quoted p. 199.

Pais (2000), quoted p. 221.

Pauli (1946a), p. 213.

In 1916, 28-year-old German physicist Walther Kossel, whose father had been awarded the Nobel Prize for chemistry, was the first to establish an important connection between the quantum atom and the periodic table. He noticed that the difference between the atomic numbers 2, 10, 18 of the first three noble gases, helium, neon, argon, was 8, and argued that the electrons in such atoms orbited in 'closed shells'. The first contained only 2 electrons, the second and third, 8 each. Bohr acknowledged the work of Kossel. But neither Kossel nor others went as far as the Dane in elucidating the distribution of electrons throughout the periodic table, the culmination of which was the correct labelling of hafnium as not a rare earth element.

BCW, Vol. 4, p. 740. Postcard from Arnold Sommerfeld to Bohr, 7 March 1921.

BCW, Vol. 4, p. 740. Letter from Arnold Sommerfeld to Bohr, 25 April 1921.

Pais (1991), quoted p. 205.

If n=3, then k=1, 2, 3.

If k=1, then m=0 and the energy state is (3,1,0).

If k=2, then m=–1, 0, 1 and the energy states are (3,2,–1), (3,2,0), and (3,2,1).

If k=3, then m=–2, –1, 0, 1, 2 and the energy states are (3,3,–2), (3,3,–1), (3,3,0), (3,3,1) and (3,3,2). The total number of energy states in the third shell n=3 is 9 and the maximum number of electrons 18. For n=4, the energy states are (4,1,0), (4,2,–1), (4,2,0), (4,2,1), (4,3,–2), (4,3,–1), (4,3,0), (4,3,1), (4,3,2), (4,4,–3), (4,4,–2), (4,4,–1), (4,4,0), (4,4,1), (4,4,2), (4,4,3).

The number of electron energy states for a given n was simply equal to n^2. For the first four shells, n=1, 2, 3 and 4, the number of energy states are 1, 4, 9, 16.

The first edition of *Atombau und Spektrallinien* was published in 1919.

Pais (2000), quoted p. 223.

Recall that in his model of the quantum atom, Bohr introduced the quantum into the atom through the quantisation of angular momentum ($L = nh/2\pi = mvr$). An electron moving in a circular orbit possesses angular momentum. Labelled L in calculations, the angular momentum of the electron is nothing more than the value obtained by multiplying its mass by its velocity by the radius of its orbit (in symbols, L=mvr). Only those electron orbits were permitted that had an angular momentum equal to $nh/2\pi$, where n was 1, 2, 3 and so on. All others orbits were forbidden.

Calaprice (2005), quoted p. 77.

Pais (1989b), quoted p. 310.

Goudsmit (1976), p. 246.

Samuel Goudsmit, AHQP interview, 5 December 1963.

Pais (1989b), quoted p. 310.

Pais (2000), quoted p. 222.
Actually, the two values are +½(h/2π) and –½(h/2π) or equivalently +h/4π and –h/4π.
Mehra and Rechenberg (1982), Vol. 1, Pt. 2, quoted p. 702.
Pais (1989b), quoted p. 311.
George Uhlenbeck, AHQP interview, 31 March 1962.
Uhlenbeck (1976), p. 253.
BCW, Vol. 5, p. 229. Letter from Bohr to Ralph Kronig, 26 March 1926.
Pais (2000), quoted p. 304.
Robertson (1979), quoted p. 100.
Mehra and Rechenberg (1982), Vol. 1, Pt. 2, quoted p. 691.
Mehra and Rechenberg (1982), Vol. 1, Pt. 2, quoted p. 692.
Ralph Kronig, AHQP interview, 11 December 1962.
Ralph Kronig, AHQP interview, 11 December 1962.
Pais (2000), quoted p. 305.
Pais (2000), quoted p. 305.
Pais (2000), quoted p. 305.
Pais (2000), quoted p. 305.
Uhlenbeck (1976), p. 250.
Pais (2000), quoted p. 305.
Pais (2000), quoted p. 305.
Pais (2000), quoted p. 230.
Enz (2002), quoted p. 115.
Enz (2002), quoted p. 117.
Goudsmit (1976), p. 248.
Jammer (1966), p. 196.
Mehra and Rechenberg (1982), Vol. 2, Pt. 2, quoted p. 208. Letter from Pauli to Ralph Kronig, 21 May 1925.
Mehra and Rechenberg (1982), Vol. 1, Pt. 2, quoted p. 719.

CHAPTER 8: THE QUANTUM MAGICIAN

Mehra and Rechenberg (1982), Vol. 2, quoted p. 6.
Heisenberg (1971), p. 16.
Heisenberg (1971), p. 16.
Heisenberg (1971), p. 16.
Heisenberg (1971), p. 16.
Werner Heisenberg, AHQP interview, 30 November 1962.
Heisenberg (1971), p. 24.
Heisenberg (1971), p. 24.
Werner Heisenberg, AHQP interview, 30 November 1962.
Heisenberg (1971), p. 26.
Heisenberg (1971), p. 26.
Heisenberg (1971), p. 26.
Heisenberg (1971), p. 38.

Heisenberg (1971), p. 38.
Werner Heisenberg, AHQP interview, 30 November 1962.
Heisenberg (1971), p. 42.
Born (1978), p. 212.
Born (2005), p. 73. Letter from Born to Einstein, 7 April 1923.
Born (1978), p. 212.
Cassidy (1992), quoted p. 168.
Mehra and Rechenberg (1982), Vol. 2, quoted pp. 140–1. Letter from Heisenberg to Pauli, 26 March 1924.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 133. Letter from Pauli to Bohr, 11 February 1924.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 135. Letter from Pauli to Bohr, 11 February 1924.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 142.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 127. Letter from Born to Bohr, 16 April 1924.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 3.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 150.
Frank Hoyt, AHQP interview, 28 April 1964.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 209. Letter from Heisenberg to Bohr, 21 April 1925.
Heisenberg (1971), p. 8.
Pais (1991), quoted p. 270.
Mehra and Rechenberg (1982), Vol. 2, quoted p. 196. Letter from Pauli to Bohr, 12 December 1924.
Cassidy (1992), quoted p. 198.
Pais (1991), quoted p. 275.
Heisenberg (1971), p. 60.
Heisenberg (1971), p. 60.
Heisenberg (1971), p. 61.
Heisenberg (1971), p. 61.
Heisenberg (1971), p. 61.

$$A=\begin{pmatrix} a & b \\ c & d \end{pmatrix}\ B=\begin{pmatrix} e & f \\ g & h \end{pmatrix}\ A\times B=\begin{pmatrix} (a\times e)+(b\times g) & (a\times f)+(b\times h) \\ (c\times e)+(d\times g) & (c\times f)+(d\times h) \end{pmatrix}$$

$$\text{If } A=\begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}\ \text{If } B=\begin{pmatrix} 5 & 6 \\ 7 & 8 \end{pmatrix}\ \text{then } A\times B=\begin{pmatrix} (1\times5)+(2\times7) & (1\times6)+(2\times8) \\ (3\times5)+(4\times7) & (3\times6)+(4\times8) \end{pmatrix}=\begin{pmatrix} 5+14 & 6+16 \\ 15+28 & 18+32 \end{pmatrix}=\begin{pmatrix} 19 & 22 \\ 43 & 50 \end{pmatrix}$$

$$\text{If } B=\begin{pmatrix} 5 & 6 \\ 7 & 8 \end{pmatrix}\ \text{If } A=\begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}\ \text{then } B\times A=\begin{pmatrix} (5\times1)+(6\times3) & (5\times2)+(6\times4) \\ (7\times1)+(8\times3) & (7\times2)+(8\times4) \end{pmatrix}=\begin{pmatrix} 5+18 & 10+24 \\ 7+24 & 14+32 \end{pmatrix}=\begin{pmatrix} 23 & 34 \\ 31 & 46 \end{pmatrix}$$

$$\text{Therefore } (A\times B)-(B\times A)=\begin{pmatrix} 19 & 22 \\ 43 & 50 \end{pmatrix}-\begin{pmatrix} 23 & 34 \\ 31 & 46 \end{pmatrix}=\begin{pmatrix} -4 & -12 \\ 12 & 4 \end{pmatrix}$$

Enz (2002), quoted p. 131. Letter from Heisenberg to Pauli, 21 June 1925.
Cassidy (1992), quoted p. 197. Letter from Heisenberg to Pauli, 9 July 1925.

Mehra and Rechenberg (1982), quoted p. 291.
Enz (2002), quoted p. 133.
Cassidy (1992), quoted p. 204.
Heisenberg (1925), p. 276.
Born (2005), p. 82. Letter from Born to Einstein, 15 July 1925. Born may have discovered that Heisenberg's multiplication rule was exactly the same as that for matrix multiplication by the time he wrote to Einstein. Born recalled on one occasion that Heisenberg gave him the paper on 11 or 12 July. However, on another occasion he believed the date of his identifying the strange multiplication with matrix multiplication was 10 July.
Born (2005), p. 82. Letter from Born to Einstein, 15 July 1925.
Cropper (2001), quoted p. 269.
Born (1978), p. 218.
Schweber (1994), quoted p. 7.
Born (2005), p. 80. Letter from Born to Einstein, 15 July 1925.
In 1925 and 1926, Heisenberg, Born and Jordan never used the term 'matrix mechanics'. They always spoke about the 'new mechanics' or 'quantum mechanics'. Others initially referred to 'Heisenberg's mechanics' or 'Göttingen mechanics' before some mathematicians started referring to it as '*Matrizenphysik*', 'matrix physics'. By 1927 it was routinely referred to as 'matrix mechanics', a name that Heisenberg always disliked.
Born (1978), p. 190.
Born (1978), p. 218.
Mehra and Rechenberg (1982), Vol. 3, quoted p. 59. Letter from Born to Bohr, 18 December 1926.
Greenspan (2005), quoted p. 127.
Pais (1986), quoted p. 255. Letter from Einstein to Paul Ehrenfest, 20 September 1925.
Pais (1986), quoted p. 255.
Pais (2000), quoted p. 224.
Born (1978), p. 226.
Born (1978), p. 226.
Kursunoglu and Wigner (1987), quoted p. 3.
Paul Dirac, AHQP interview, 7 May 1963.
Kragh (2002) quoted p. 241.
Dirac (1977), p. 116.
Dirac (1977), p. 116.
Born (2005), p. 86. Letter from Einstein to Mrs Born, 7 March 1926.
Bernstein (1991), quoted p. 160.

CHAPTER 9: 'A LATE EROTIC OUTBURST'

Moore (1989), quoted p. 191.
Born (1978), p. 270.
Moore (1989), quoted p. 23.

Moore (1989), quoted pp. 58–9.
Moore (1989), quoted p. 91.
Moore (1989), quoted p. 91.
Mehra and Rechenberg (1987) Vol. 5, Pt. 1, quoted p. 182.
Moore (1989), quoted p. 145.
Mehra and Rechenberg (1987), Vol. 5, Pt. 2, quoted p. 412.
Bloch (1976), p. 23. Although there is some doubt when exactly Schrödinger delivered his talk at the colloquium, 23 November is the most probable date that fits the known facts better than any alternative.
Bloch (1976), p. 23.
Bloch (1976), p. 23.
Abragam (1988), p. 31.
Bloch (1976), pp. 23–4.
The equation was rediscovered in 1927 by Oskar Klein and Walter Gordon and became known as the Klein-Gordon equation. It applies only to spin zero particles.
Moore (1989), quoted p. 196.
Moore (1989), quoted p. 191.
The title of Schrödinger's paper signalled that in his theory the quantisation of an atom's energy levels was based on the allowed values, or *eigenvalues*, of electron wavelengths. In German, *eigen* means 'proper' or 'characteristic'. The German word *eigenwert* was only half-heartedly translated into English as *eigenvalue*.
Cassidy (1992), quoted p. 214.
Moore (1989), quoted p. 209. Letter from Planck to Schrödinger, 2 April 1926.
Moore (1989), quoted p. 209. Letter from Einstein to Schrödinger, 16 April 1926.
Przibram (1967), p. 6.
Moore (1989), quoted p. 209. Letter from Einstein to Schrödinger, 26 April 1926.
Cassidy (1992), quoted p. 213.
Pais (2000), quoted p. 306.
Moore (1989), quoted p. 210.
Mehra and Rechenberg (1987), Vol. 5, Pt. 1, quoted p. 1. Letter from Pauli to Pascual Jordan, 12 April 1926.
Cassidy (1992), quoted p. 213.
Cassidy (1992), quoted p. 213. Letter from Heisenberg to Pascual Jordan, 19 July 1926.
Cassidy (1992), quoted p. 213.
Cassidy (1992), quoted p. 213. Letter from Born to Schrödinger, 16 May 1927.
Mehra and Rechenberg (1987), Vol. 5, Pt. 2, quoted p. 639. Letter from Schrödinger to Wilhelm Wien, 22 February 1926.
Mehra and Rechenberg (1987), Vol. 5, Pt. 2, quoted p. 639. Letter from Schrödinger to Wilhelm Wien, 22 February 1926.
Pauli, Dirac and the American Carl Eckhart all independently showed that Schrödinger was correct.
Mehra and Rechenberg (1987), Vol. 5 Pt. 2, quoted p. 639. Letter from Schrödinger to Wilhelm Wien, 22 February 1926.

Moore (1989), quoted p. 211.

Moore (1989), quoted p. 211.

Cassidy (1992), quoted p. 215. Letter from Heisenberg to Pauli, 8 June 1926.

Cassidy (1992), quoted p. 213. Letter from Heisenberg to Pascual Jordan, 8 April 1926.

Heisenberg's paper was received by the *Zeitschrift für Physik* on 24 July and was published on 26 October 1926.

Pais (2000), quoted p. 41. Letter from Born to Einstein, 30 November 1926. Not included in Born (2005).

Bloch (1976), p. 320. In the original German:

Gar Manches rechnet Erwin schon
Mit seiner Wellenfunktion.
Nur wissen möcht' man gerne wohl
Was man sich dabei vorstell'n soll.

Strictly speaking it should be the square of the 'modulus' of the wave function. Modulus is the technical term for taking the absolute value of a number regardless of whether it is positive or negative. For example, if $x=-3$, then the modulus of x is 3. Written as: $|x| = |-3| = 3$. For a complex number $z=x+iy$, the modulus of z is given by $|z| = \sqrt{x^2+y^2}$.

The square of a complex number is calculated as follows: $z=4+3i$, z^2 is in fact not $z\times z$, but $z\times z^*$ where z^* is called the complex conjugate. If $z=4+3i$, then $z^*=4-3i$.

Hence, $z^2=z\times z^*=(4+3i)\times(4-3i)=16-12i+12i-9i^2=16-9(\sqrt{-1})^2=16-9(-1)=16+9=25$. If $z=4+3i$, then the modulus of z is 5.

Born (1978), p. 229.

Born (1978), p. 229.

Born (1978), p. 230.

Born (1978), p. 231.

Born (2005), p. 81. Letter from Born to Einstein, 15 July 1925.

Born (2005), p. 81. Letter from Born to Einstein, 15 July 1925.

Pais (2000), quoted p. 41.

Pais (1986), quoted p. 256.

Pais (2000), quoted p. 42.

The second paper was published in the *Zeitschrift für Physik* on 14 September.

Pais (1986), quoted p. 257.

Pais (1986), quoted p. 257.

Once again, technically speaking it is the absolute or modulus square of the wave function. Also, technically, rather than the 'probability', the absolute square of the wave function gives the 'probability density'.

Pais (1986), quoted p. 257.

Pais (1986), quoted p. 257.

Pais (2000), quoted p. 39.

Mehra and Rechenberg (1987), Vol. 5, Pt. 2, quoted p. 827. Letter from Schrödinger to Wien, 25 August 1926.

Mehra and Rechenberg (1987), Vol. 5, Pt. 2, quoted p. 828. Letter from Schrödinger to Born, 2 November 1926.
Heitler (1961), quoted p. 223.
Moore (1989), quoted p. 222.
Moore (1989), quoted p. 222.
Heisenberg (1971), p. 73.
Cassidy (1992), quoted p. 222. Letter from Heisenberg to Pascual Jordan, 28 July 1926.
Cassidy (1992), quoted p. 222. Letter from Heisenberg to Pascual Jordan, 28 July 1926.
Mehra and Rechenberg (1987), Vol. 5, Pt. 2, quoted p. 625. Letter from Bohr to Schrödinger, 11 September 1926.
Heisenberg (1971), p. 73.
Heisenberg (1971), p. 73.
See Heisenberg (1971), pp. 73–5 for the complete reconstruction of this particular exchange between Schrödinger and Bohr.
Heisenberg (1971), p. 76.
Moore (1989), p. 228. Letter from Schrödinger to Wilhelm Wien, 21 October 1926.
Mehra and Rechenberg (1987), Vol. 5, Pt. 2, quoted p. 826. Letter from Schrödinger to Wilhelm Wien, 21 October 1926.
Born (2005), p. 88. Letter from Einstein to Born, 4 December 1926.

CHAPTER 10: UNCERTAINTY IN COPENHAGEN

Heisenberg (1971), p. 62.
Heisenberg (1971), p. 62.
Heisenberg (1971), p. 62.
Heisenberg (1971), p. 62.
Heisenberg (1971), p. 63.
Heisenberg (1971), p. 63.
Heisenberg (1971), p. 63.
Werner Heisenberg, AHQP interview, 30 November 1962.
Heisenberg (1971), p. 63.
Heisenberg (1971), p. 63.
Heisenberg (1971), p. 64.
Heisenberg (1971), p. 64.
Heisenberg (1971), p. 64.
Heisenberg (1971), p. 65.
Cassidy (1992), quoted p. 218.
Pais (1991), quoted p. 296. Letter from Bohr to Rutherford, 15 May 1926.
Heisenberg (1971), p. 76.
Cassidy (1992), quoted p. 219.
Pais (1991), quoted p. 297.
Robertson (1979), quoted p. 111.
Pais (1991), quoted p. 300.

Heisenberg (1967), p. 104.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 235. Letter from Einstein to Paul Ehrenfest, 28 August 1926.
Werner Heisenberg, AHQP interview, 25 February 1963.
Werner Heisenberg, AHQP interview, 25 February 1963.
Werner Heisenberg, AHQP interview, 25 February 1963.
Heisenberg (1971), p. 77.
Heisenberg (1971), p. 77.
Heisenberg (1971), p. 77.
Heisenberg (1971), p. 77.
In another of his later writings, Heisenberg expressed the crucial switch in the question to answer: 'Instead of asking: How can one in the known mathematical scheme express a given experimental situation? The other question was put: Is it true, perhaps, that only such experimental situations can arise in nature as can be expressed in the mathematical formalism?' Heisenberg (1989), p. 30.
Heisenberg (1971), p. 78.
Heisenberg (1971), p. 78.
Heisenberg (1971), p. 79.
Momentum is preferred over velocity because it appears in fundamental equations of both classical and quantum mechanics. Both physical variables are intimately connected by the fact that momentum is just mass times velocity – even for a fast-moving electron with corrections imposed by the special theory of relativity.
As pointed out by Max Jammer (1974), Heisenberg used *Ungenauigkeit* (inexactness, imprecision) or *Genauigkeit* (precision, degree of precision). These two terms appear more than 30 times in his paper, whereas *Unbestimmtheit* (indeterminacy) appears only twice and *Unsicherheit* (uncertainty) three times.
Heisenberg in his published paper actually put it as $\Delta p \Delta q \sim h$, or Δp times Δq is approximately Planck's constant.
There were occasions over the years when Heisenberg seemed to suggest that it was our knowledge of the atomic world that was indeterminate: 'The uncertainty principle refers to the degree of indeterminateness in the possible present knowledge of the simultaneous values of the various quantities with which quantum theory deals …', rather than an intrinsic feature of nature. See Heisenberg (1949), p. 20.
Heisenberg (1927), p. 68. An English translation can be found in Wheeler and Zurek (1983), pp. 62–84. All page references refer to this reprint.
Heisenberg (1927), p. 68.
Heisenberg (1927), p. 68.
Heisenberg (1989), p. 30.
Heisenberg (1927), p. 62.
Heisenberg (1989), p. 31.
Heisenberg (1927), p. 63.
Heisenberg (1927), p. 64.
Heisenberg (1927), p. 65.
Heisenberg (1989), p. 36.

Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 146. Letter from Pauli to Heisenberg, 19 October 1926.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 147. Letter from Pauli to Heisenberg, 19 October 1926.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 146. Letter from Pauli to Heisenberg, 19 October 1926.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 93.
Pais (1991), quoted p. 304. Letter from Heisenberg to Bohr, 10 March 1927.
Pais (1991), quoted p. 304.
Cassidy (1992), quoted p. 241. Letter from Heisenberg to Pauli, 4 April 1927.
Werner Heisenberg, AHQP interview, 25 February 1963.
Werner Heisenberg, AHQP interview, 25 February 1963.
Werner Heisenberg, AHQP interview, 25 February 1963.
Heisenberg (1927), p. 82.
The original German title was: 'Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik', *Zeitschrift für Physik*, 43, 172–98 (1927). See Wheeler and Zurek (1983), pp. 62–84.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 182. Letter from Heisenberg to Pauli, 4 April 1927.
Bohr (1949), p. 210.
There was a subtle difference between wave-particle complementarity and that involving any pair of physical observables like position and momentum. According to Bohr, the complementary wave and particle aspects of an electron or light are mutually exclusive. It is one or the other. However, only if either position or momentum of an electron, for example, is measured with pinpoint certainty are position and momentum mutually exclusive. Otherwise, the precision with which both can be measured and therefore known is given by the position-momentum uncertainty relation.
BCW, Vol. 6, p. 147.
BCW, Vol. 3, p. 458.
Werner Heisenberg, AHQP interview, 25 February 1963.
Werner Heisenberg, AHQP interview, 25 February 1963.
Bohr (1949), p. 210.
Bohr (1928), p. 53.
BCW, Vol. 6, p. 91.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 187. Letter from Bohr to Einstein, 13 April 1927.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 187. Letter from Bohr to Einstein, 13 April 1927.
BCW, Vol. 6, p. 418. Letter from Bohr to Einstein, 13 April 1927.
Mackinnon (1982), quoted p. 258. Letter from Heisenberg to Pauli, 31 May 1927.
Cassidy (1992), quoted p. 243. Letter from Heisenberg to Pauli, 16 May 1927. Heisenberg uses the symbol ≈ that means 'approximately'.

Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 183. Letter from Heisenberg to Pauli, 16 May 1927.
Heisenberg (1927), p. 83.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 184. Letter from Heisenberg to Pauli, 3 June 1927.
Heisenberg (1971), p. 79.
Pais (1991), quoted p. 309. Letter from Heisenberg to Bohr, 18 June 1927.
Pais (1991), quoted p. 309. Letter from Heisenberg to Bohr, 21 August 1927.
Cassidy (1992), quoted p. 218. Letter from Heisenberg to his parents, 29 April 1926.
Pais (2000), quoted p. 136.
Pais (1991), quoted p. 309. Letter from Heisenberg to Pauli, 16 May 1927.
Heisenberg (1989), p. 30.
Heisenberg (1989), p. 30.
Heisenberg (1927), p. 83.
Heisenberg (1927), p. 83.
Heisenberg (1927), p. 83.
Heisenberg (1927), p. 83.

CHAPTER 11: SOLVAY 1927

Mehra (1975), quoted p. xxiv.
CPAE, Vol. 5, p. 222. Letter from Einstein to Heinrich Zangger, 15 November 1911.
Mehra (1975), quoted p. xxiv. Lorentz's Report to the Administrative Council, Solvay Institute, 3 April 1926.
Mehra (1975), quoted p. xxiv.
Mehra (1975), quoted p. xxiii. Letter from Ernest Rutherford to B.B. Boltwood, 28 February 1921.
Mehra (1975), quoted p. xxii.
The statute of the League of Nations was drawn up in April 1919.
In 1936 Hitler violated the Locarno treaties when he sent German troops into the demilitarised Rhineland.
William H. Bragg resigned from the committee in May 1927 citing other commitments, and though invited did not attend. Edmond Van Aubel, though still on the committee, refused to attend because the Germans had been invited.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 232.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 241. Letter from Einstein to Hendrik Lorentz, 17 June 1927.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 241. Letter from Einstein to Hendrik Lorentz, 17 June 1927.
Bohr (1949), p. 212.
Bacciagaluppi and Valentini (2006), quoted p. 408.
Bacciagaluppi and Valentini (2006), quoted p. 408.
Bacciagaluppi and Valentini (2006), quoted p. 432.
Bacciagaluppi and Valentini (2006), quoted p. 437.
Mehra (1975), quoted p. xvii.

Bacciagaluppi and Valentini (2006), quoted p. 448.
Bacciagaluppi and Valentini (2006), quoted p. 448.
Bacciagaluppi and Valentini (2006), quoted p. 470.
Bacciagaluppi and Valentini (2006), quoted p. 472.
Bacciagaluppi and Valentini (2006), quoted p. 473.
Pais (1991), quoted p. 426. 'Could one not keep determinism by making it an object of belief? Must one necessarily elevate indeterminism to a principle?' (Bacciagaluppi and Valentini (2006), p. 477.)
Bohr (1963c), p. 91.
Bohr was partly to blame for the confusion, since on occasions he referred to his contribution during the general discussion as a 'report'. He did so, for example, in his lecture 'The Solvay Meetings and the Development of Quantum Physics', reprinted in Bohr (1963c).
Bohr (1963c), p. 91.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 240.
Bohr (1928), p. 53.
Bohr (1928), p. 54.
Petersen (1985), quoted p. 305.
Bohr (1987), p. 1.
Einstein (1993), p. 121. Letter from Einstein to Maurice Solovine, 1 January 1951.
Einstein (1949a), p. 81.
Heisenberg (1989), p. 174.
Bacciagaluppi and Valentini (2006), quoted p. 486. The translation is based on notes in the Einstein archives. The published French translation reads: 'I have to apologize for not having gone deeply into quantum mechanics. I should nevertheless want to make some general remarks.'
Bohr (1949), p. 213.
Bacciagaluppi and Valentini (2006), quoted p. 487.
Bacciagaluppi and Valentini (2006), quoted p. 487.
See Chapter 9, note 43.
Bacciagaluppi and Valentini (2006), quoted p. 487.
Bacciagaluppi and Valentini (2006), quoted p. 489.
Bacciagaluppi and Valentini (2006), quoted p. 489.
Bohr (1949).
Bohr (1949), p. 217.
Bohr (1949), p. 218.
Bohr (1949), p. 218.
Bohr (1949), p. 218.
Bohr (1949), p. 218.
Bohr (1949), p. 222.
De Broglie (1962), p. 150.
Heisenberg (1971), p. 80.
Heisenberg (1967), p. 107.
Heisenberg (1967), p. 107.

Heisenberg (1967), p. 107.
Heisenberg (1983), p. 117.
Heisenberg (1983), p. 117.
Heisenberg (1971), p. 80.
Bohr (1949), p. 213.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, pp. 251–3. Letter from Paul Ehrenfest to Samuel Goudsmit, George Uhlenbeck and Gerhard Diecke, 3 November 1927.
Bohr (1949), p. 218.
Bohr (1949), p. 218.
Bohr (1949), p. 206.
Brian (1996), p. 164.
Cassidy (1992), quoted p. 253. Letter from Einstein to Arnold Sommerfeld, 9 November 1927.
Marage and Wallenborn (1999), quoted p. 165.
Cassidy (1992), quoted p. 254.
Werner Heisenberg, AHQP interview, 27 February 1963.
Gamov (1966), p. 51.
Calaprice (2005), p. 89.
Fölsing (1997), quoted p. 601. Letter from Einstein to Michele Besso, 5 January 1929.
Brian (1996), quoted p. 168.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 256.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted p. 266. Letter from Schrödinger to Bohr, 5 May 1928.
Mehra and Rechenberg (2000), Vol. 6, Pt. 1, quoted pp. 266–7. Letter from Bohr to Schrödinger, 23 May 1928.
Przibram (1967), p. 31. Letter from Einstein to Schrödinger, 31 May 1928.
Fölsing (1997), quoted p. 602. Letter from Einstein to Paul Ehrenfest, 28 August 1928.
Brian (1996), quoted p. 169.
Pais (2000), quoted p. 215. Letter from Pauli to Hermann Weyl, 11 July 1929.
Pais (1982), quoted p. 31.

CHAPTER 12: EINSTEIN FORGETS RELATIVITY

Rosenfeld (1968), p. 232.
Pais (2000), quoted p. 225.
Rosenfeld (1968), p. 232.
Rosenfeld (1968), p. 232.
Rosenfeld, AHQP interview.
Clark (1973) quoted p. 198.
'The Fabric of the Universe', *The Times*, 7 November 1919.
Thorne (1994), p. 100.
Alternatively, since the uncontrollable transfer of momentum to the light box when the pointer and scale is illuminated causes the box to move about unpredictably, the

clock inside is now moving in a gravitational field. The rate at which it ticks (the flow of time) changes unpredictably, leading to an uncertainty in the precise time when the shutter is opened and the photon escapes. Once again, the chain of uncertainties obeys the limits set by Heisenberg's uncertainty principle.

Pais (1982), quoted p. 449.

Pais (1982), quoted p. 515. Einstein had pointed out to the Swedish Academy that the achievements of Heisenberg and Schrödinger were so significant that it would not be appropriate to divide a Nobel Prize between them. However, 'who should get the prize first is hard to answer', he admitted, before suggesting Schrödinger. He had first nominated Heisenberg and Schrödinger in 1928 when he suggested that de Broglie and Davisson be given precedence. The other options he put forward involved one prize to be shared by de Broglie and Schrödinger and another by Born, Heisenberg and Jordan. The 1928 prize was deferred until 1929, when it was awarded to the British physicist Owen Richardson. As Einstein suggested, Louis de Broglie was the first of the new generation of quantum theorists to be honoured when he was awarded the 1929 prize.

Fölsing (1997), quoted p. 630.

Brian (1996), quoted p. 200.

Calaprice (2005), p. 323.

Brian (1996), quoted p. 201.

Brian (1996), quoted p. 201.

Brian (1996), quoted p. 201.

Henig (1998), p. 64.

Brian (1996), quoted p. 199.

Fölsing (1997), quoted p. 629.

Brian (1996), quoted p. 199. Letter from Sigmund Freud to Arnold Zweig, 7 December 1930.

Brian (1996), quoted p. 204.

Levenson (2003), quoted p. 410.

Brian (1996), quoted p. 237.

Fölsing (1997), quoted p. 659. Letter from Einstein to Margarete Lenbach, 27 February 1933.

Clark (1973), quoted p. 431.

Fölsing (1997), quoted p. 661 and Brian (1996), p. 244.

Fölsing (1997), quoted p. 662. Letter from Planck to Einstein, 19 March 1933.

Fölsing (1997), quoted p. 662. Letter from Planck to Einstein, 31 March 1933.

Friedländer (1997), quoted p. 27.

Physics: Albert Einstein (1921), James Franck (1925), Gustav Hertz (1925), Erwin Schrödinger (1933), Viktor Hess (1936), Otto Stern (1943), Felix Bloch (1952), Max Born (1954), Eugene Wigner (1963), Hans Bethe (1967), and Dennis Gabor (1971). Chemistry: Fritz Haber (1918), Pieter Debye (1936), Georg von Hevesy (1943), and Gerhard Hertzberg (1971). Medicine: Otto Meyerhof (1922), Otto Loewi (1936), Boris Chain (1945), Hans Krebs (1953), and Max Delbrück (1969).

Heilbron (2000), quoted p. 210.

Heilbron (2000), quoted p. 210.
Beyerchen (1977), quoted p. 43. This section does not appear in the account published in Heilbron (2000), pp. 210–11, which ends with: 'So saying, he hit himself hard on the knee, spoke faster and faster, and flew into such a rage that I could only remain silent and withdraw.'
Forman (1973), quoted p. 163.
Holton (2005), quoted pp. 32–3.
Greenspan (2005), quoted p. 175.
Born (1971), p. 251.
Greenspan (2005), quoted p. 177.
Born (2005), p. 114. Letter from Born to Einstein, 2 June 1933.
Born (2005), p. 114. Letter from Born to Einstein, 2 June 1933.
Born (2005), p. 111. Letter from Einstein to Born, 30 May 1933.
Cornwell (2003), quoted p. 134.
Jungk (1960), quoted p. 44.
Clark (1973), quoted p. 472.
Pais (1982), quoted p. 452. Letter from Abraham Flexner to Einstein, 13 October 1933.
Fölsing (1997), quoted p. 682.
Fölsing (1997), quoted p. 682. Letter from Einstein to the Board of Trustees of the Institute for Advanced Study, November 1933.
Fölsing (1997), quoted pp. 682–3. Letter from Einstein to the Board of Trustees of the Institute for Advanced Study, November 1933.
Moore (1989), quoted p. 280.
Cassidy (1992), quoted p. 325. Letter from Heisenberg to Bohr, 27 November 1933.
Greenspan (2005), quoted p. 191. Letter from Heisenberg to Born, 25 November 1933.
Born (2005), p. 200. Letter from Born to Einstein, 8 November 1953.
Mehra (1975), quoted p. xxvii. Letter from Einstein to Queen Elizabeth of Belgium, 20 November 1933.

CHAPTER 13: QUANTUM REALITY

Smith and Weiner (1980), p. 190. Letter from Robert Oppenheimer to Frank Oppenheimer, 11 January 1935.
Smith and Weiner (1980), p. 190. Letter from Robert Oppenheimer to Frank Oppenheimer, 11 January 1935.
Born (2005), quoted p. 128.
Bernstein (1991), quoted p. 49.
James Chadwick was awarded the Nobel Prize for Physics in 1935 and Enrico Fermi in 1938.
Brian (1996), quoted p. 251.
Einstein (1950), p. 238.
Moore (1989), quoted p. 305, Letter from Einstein to Schrödinger, 8 August 1935.
Jammer (1985), quoted p. 142.

Reprinted in Wheeler and Zurek (1983), pp. 138–41.
New York Times, 7 May 1935, p. 21.
Einstein et al. (1935), p. 138. References to paper reprinted in Wheeler and Zurek (1983).
Einstein et al. (1935), p. 138. Italics in the original.
Einstein et al. (1935), p. 138. Italics in the original.
EPR resisted the temptation to use the two-particle experiment to challenge Heisenberg's uncertainty principle. It is possible to measure the exact momentum of particle A directly and determine the momentum of particle B. While it is not possible to know the position of A, because of the measurement already performed on it, it is possible to determine the position of B directly, since no previous measurement has been directly performed on it. Therefore it may be argued that the momentum and position of particle B can be determined simultaneously, thereby circumventing the uncertainty principle.
Einstein et al. (1935), p. 141. Italics in the original.
Einstein et al. (1935), p. 141.
BCW, Vol. 7, p. 251. Letter from Pauli to Heisenberg, 15 June 1935.
BCW, Vol. 7, p. 251. Letter from Pauli to Heisenberg, 15 June 1935.
Fölsing (1997), quoted p. 697.
Rosenfeld (1967), p. 128.
Rosenfeld (1967), p. 128.
Rosenfeld (1967), p. 128.
Rosenfeld (1967), p. 128.
Rosenfeld (1967), p. 129. Also in Wheeler and Zurek (1983), quoted p. 142.
See Bohr (1935a).
See Bohr (1935b).
Bohr (1935b), p. 145.
Bohr (1935b), p. 148.
Heisenberg (1971), p. 104.
Heisenberg (1971), p. 104.
Heisenberg (1971), p. 104.
Heisenberg (1971), p. 105.
Bohr (1949), p. 234.
Bohr (1935b), p. 148.
Bohr (1935b), p. 148. Italics in the original.
Bohr (1935b), p. 148.
Fölsing (1997), quoted p. 699. Letter from Einstein to Cornelius Lanczos, 21 March 1942.
Born (2005), p. 155. Letter from Einstein to Born, 3 March 1947.
Petersen (1985), quoted p. 305.
Jammer (1974), quoted p. 161.
Niels Bohr, AHQP interview, 17 November 1962.
Moore (1989), quoted p. 304. Letter from Schrödinger to Einstein, 7 June 1935.
Moore (1989), quoted p. 304. Letter from Schrödinger to Einstein, 7 June 1935.

Schrödinger (1935), p. 161.
Schrödinger (1935), p. 161.
Fine (1986), quoted p. 68. Letter from Einstein to Schrödinger, 17 June 1935.
Murdoch (1987), quoted p. 173. Letter from Einstein to Schrödinger, 19 June 1935.
Moore (1989), quoted p. 304. Letter from Einstein to Schrödinger, 19 June 1935.
Fine (1986), quoted p. 78. Letter from Einstein to Schrödinger, 8 August 1935.
Fine (1986), quoted p. 78. Letter from Einstein to Schrödinger, 8 August 1935.
Schrödinger (1935), p. 157.
Mehra and Rechenberg (2001) Vol. 6, Pt. 2, quoted p. 743. Letter from Einstein to Schrödinger, 4 September 1935.
Fine (1986), quoted pp. 84–5. Letter from Einstein to Schrödinger, 22 December 1950.
Fine (1986), quoted pp. 84–5. Letter from Einstein to Schrödinger, 22 December 1950.
Moore (1989), quoted p. 314. Letter from Schrödinger to Einstein, 23 March 1936.
Fölsing (1997), quoted p. 688.
Fölsing (1997), quoted p. 688.
Born (2005), p. 125. Letter from Einstein to Born, undated.
Born (2005), p. 127.
Fölsing (1997), quoted p. 704.
Brian (1996), quoted p. 305.
Brian (1996), quoted p. 305.
Petersen (1985), quoted p. 305.
Einstein (1993), p. 119. Letter from Einstein to Maurice Solovine, 1 January 1951.
Fine (1986), quoted p. 95. Letter from Einstein to M. Laserna, 8 January 1955.
Einstein (1934), p. 112.
Einstein (1993), p. 119. Letter from Einstein to Maurice Solovine, 1 January 1951.
Heisenberg (1989), p. 117.
Heisenberg (1989), p. 117.
Heisenberg (1989), p. 116.
Einstein (1950), p. 88.
Heisenberg (1989), p. 44.
Przibram (1967), p. 31. Letter from Einstein to Schrödinger, 31 May 1928.
Fölsing (1997), quoted p. 704.
Fölsing (1997), quoted p. 705.
Mehra (1975), quoted p. xxvii. Letter from Einstein to Queen Elizabeth of Belgium, 9 January 1939.
Pais (1994), quoted p. 218. Letter from Einstein to Roosevelt, 7 March 1940.
Clark (1973), quoted p. 29.
Heilbron (2000), quoted p. 195.
Heilbron (2000), quoted p. 195.
Fölsing (1997), quoted p. 729. Letter from Einstein to Marga Planck, October 1947.
Pais (1967), p. 224.
Pais (1967), p. 225.

Heisenberg (1983), p. 121.
Holton (2005), quoted p. 32.
Einstein (1993), p. 85. Letter from Einstein to Solovine, 10 April 1938.
Brian (1996), quoted p. 400.
Nathan and Norden (1960), pp. 629–30. Letter from Einstein to Bohr, 2 March 1955.
Pais (1982), quoted p. 477. Letter from Helen Dukas to Abraham Pais, 30 April 1955.
Overbye (2001), quoted p. 1.
Clark (1973), quoted p. 502.
Bohr (1955), p. 6.
Pais (1994), quoted p. 41.

CHAPTER 14: FOR WHOM BELL'S THEOREM TOLLS

Born (2005), p. 146. Letter from Einstein to Born, 7 September 1944.
Stapp (1977), p. 191.
Petersen (1985), quoted p. 305.
Przibam (1967), p. 39. Letter from Einstein to Schrödinger, 22 December 1950.
Goodchild (1980), quoted p. 162.
Bohm (1951), pp. 612–13.
Bohm (1951), p. 622.
Bohm (1951), p. 611.
Bohm (1952a), p. 382.
Bohm (1952a), p. 369.
Bell (1987), p. 160.
Bell (1987), p. 160.
The German title of von Neumann's book was *Mathematische Grundlagen der Quantenmechanik.*
Von Neumann (1955), p. 325.
Maxwell (1860), p. 19.
Maxwell (1860), p. 19.
Von Neumann (1955), pp. 327–8.
Bernstein (1991), quoted p. 12.
Bernstein (1991), quoted p. 15.
Bernstein (1991), quoted p. 64.
Bell (1987), quoted p. 159.
Bell (1987), quoted p. 159.
Bell (1987), quoted p. 159.
Bernstein (1991), quoted p. 65.
Bell (1987), p. 160.
Bell (1987), p. 167.
Beller (1999), quoted p. 213.
Born (2005), p. 189. Letter from Einstein to Born, 12 May 1952.
Bernstein (1991), quoted p. 66.

Bernstein (1991), quoted p. 72.
Bernstein (1991), quoted p. 72.
Bernstein (1991), quoted p. 73.
Born (2005), p. 153. Letter from Einstein to Born, 3 March 1947.
Bohm's modification of EPR appeared in chapter 22 of his book *Quantum Theory*. It involved a molecule with a spin of zero that disintegrates into two atoms, one with spin-up (+½) and the other with spin-down (–½), whose combined spin remains zero. Since its inception it has become standard practice to replace the atoms with a pair of electrons.
The mutually perpendicular axes x, y, and z are chosen only for convenience and because they are most familiar. Any set of three axes serves just as well for measuring the components of quantum spin.
Bell (1987), p. 139.
Bell (1987), p. 143.
Bell (1987), p. 143.
Also known as 'Bell's inequalities'.
Bell (1964). Reprinted in Bell (1987) and Wheeler and Zurek (1983).
Bell (1966), p. 447. Reprinted in Bell (1987) and Wheeler and Zurek (1983).
Bell (1966), p. 447.
Born (2005), p. 218. Letter from Pauli to Born, 31 March 1954.
Born (2005), p. 218. Letter from Pauli to Born, 31 March 1954.
Bell (1964), p. 199.
Clauser (2002), p. 71.
Clauser (2002), p. 70.
Redhead (1987), p. 108, table 1.
Aczel (2003), quoted p. 186.
Aczel (2003), quoted p. 186.
Aspect et al. (1982), p. 94.
Davies and Brown (1986), p. 50.
Davies and Brown (1986), p. 51.
Davies and Brown (1986), p. 47.

CHAPTER 15: THE QUANTUM DEMON

Pais (1982), quoted p. 9.
Einstein (1950), p. 91.
Pais (1982), quoted p. 460.
Pais (1982), p. 9.
Feynman (1965), p. 129.
Feynman (1965), p. 129.
Bernstein (1991), p. 42.
Born (2005), p. 162. Comment on manuscript from Einstein to Born, 18 March 1948.
Heisenberg (1983), p. 117. One example of Einstein using his famous phrase.
Born (2005), p. 216. Letter from Pauli to Born, 31 March 1954.

Born (2005), p. 216. Letter from Pauli to Born, 31 March 1954.
Born (2005), p. 216. Letter from Pauli to Born, 31 March 1954.
Born (2005), p. 216. Letter from Pauli to Born, 31 March 1954.
Stachel (2002), quoted p. 390. Letter from Einstein to Georg Jaffe, 19 January 1954.
Born (2005), p. 88. Letter from Einstein to Born, 4 December 1926.
Born (2005), p. 219. Letter from Pauli to Born, 31 March 1954.
Isaacson (2007), quoted p. 460. Letter from Einstein to Jerome Rothstein, 22 May 1950.
Rosenthal-Schneider (1980), quoted p. 70. Postcard from Einstein to Ilse Rosenthal, 31 March 1944.
Aspect (2007), p. 867.
Einstein et al. (1935), p. 141.
Einstein (1949b), p. 666.
Fine (1986), quoted p. 57. Letter from Einstein to Aron Kupperman, 10 November 1954.
Isaacson (2007), quoted p. 466.
Heisenberg (1971), p. 81.
Heisenberg (1971), p. 80.
Born (2005), p. 69.
Born (1949), pp. 163–4.
Clauser (2002), p. 72.
Blaedel (1988), p. 11.
Clauser (2002), p. 61.
Wolf (1988), quoted p. 17.
Pais (2000), quoted p. 55.
Gell-Mann (1979), p. 29.
Tegmark and Wheeler (2001), p. 61.
Among the 30 there were those who supported the 'consistent histories' approach that has its origins in the many worlds interpretation. It is based on the idea that out of all possible means by which an observed experimental result may have been caused, only a few make sense under the rules of quantum mechanics.
Buchanan (2007), quoted p. 37.
Buchanan (2007), quoted p. 38.
Stachel (1998), p. xiii.
French (1979), quoted p. 133.
Pais (1994) quoted p. 57.