# Chronology

## *Paul Adrien Maurice Dirac*

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| 1902 | Born in Bristol, England, 8 August, son of Charles Adrien Ladislav Dirac and Florence Hannah née Holten |
| 1914–18 | Merchant Venturer's College, Bristol |
| 1918–23 | University of Bristol |
| 1921 | B.Sc. in Engineering |
| 1923–6 | Research Student, University of Cambridge |
| 1926 | Ph.D. |
| 1927 | Fellow, St. John's College, Cambridge |
| 1930 | Elected Fellow, Royal Society |
| 1931 | Corresponding Member, Soviet Academy of Sciences |
| 1932–69 | Lucasian Professor of Mathematics, Cambridge |
| 1933 | Nobel Prize in Physics |
| 1934–5, 46–8, 58–9 | Member, Institute for Advanced Study, Princeton |
| 1937 | Married Margit Wigner |
| 1939 | Royal Medal, Royal Society; Hon. Member, Indian Academy of Science |
| 1943 | Hon. Member, Chinese Physical Society |
| 1944 | Hon. Member, Royal Irish Academy |
| 1946 | Hon. Fellow, Royal Society of Edinburgh |
| 1947 | Hon. Fellow, National Institute of Sciences of India |
| 1948 | Hon. Member, American Physical Society |
| 1949 | Foreign Associate, U.S. National Academy of Sciences |
| 1950 | Foreign Hon. Member, American Academy of Arts and Sciences |
| 1952 | Copley Medal, Royal Society |
| 1961 | Member, Pontifical Academy of Sciences |
| 1968–72 | Member, Center for Theoretical Studies, University of Miami |
| 1969 | Oppenheimer Prize, Center for Theoretical Studies, University of Miami |
| 1972–84 | Professor of Physics, Florida State University, Tallahassee |
| 1973 | Order of Merit |
| 1984 | Died 20 October |

great distinction and complete dedication for nearly half a century. During the two decades in which he served in the House of Lords as a judge, in the opinion of his brethren and the advocates who appeared before the judicial committee he was second only to the Scottish jurist Lord Reid [q.v.] as the most distinguished judge of his day.

His was a supremely logical mind. With due respect for precedent, he would remorselessly pursue this path of logic confident that all legal issues were capable of solution. Many were the reversals in the House of Lords which he initiated on appeals from adventurous experiments by the Court of Appeal. Few thought that he was wrong, although some felt that he was so deft in demonstrating the misuse of logic in the Court of Appeal that he sometimes failed to appreciate that the lower court might have a point which required attention. But if there were, he would have said that that was a matter for Parliament and not for the judiciary. He was immensely industrious (he read Sir W. S. Holdsworth, q.v., for his light literary entertainment), and he was so well versed in the law that in discussion with his brethren some of them claimed that he had an almost hypnotic effect in swaying others to his point of view. At the same time, he always fiercely rejected any advantage gained by a legal trick. He had a clear idea of what the law should do to protect the citizen in dispute with modern authority and a clear concept of the consequences for municipal law arising from the new place of the United Kingdom within Europe. He believed that the progress towards a comprehensive system of administrative law, in which he played such an influential part, was the greatest achievement of the English courts in his judicial lifetime. From 1971 to 1982 he was chairman of the Permanent Security Commission and led inquiries into a number of security scandals, among them the Sir Roger Hollis [q.v.] affair.

In October 1972 the government of Edward Heath, which was anxious over the intimidation of juries in the courts of Northern Ireland, appointed Diplock to chair a commission of three to consider legal proceedings to deal with terrorist activities in the province. By December of that year the Diplock commission was ready with its report which recommended that terrorist offences as defined in a schedule should henceforth be tried by judge alone. This was at once implemented and the courts became known as Diplock courts. The speed and certainty of the recommendations were principally due to the guidance and clarity of the commission's chairman. He gained honorary degrees from Alberta (1972), London (1979), and Oxford (1977).

While his career was the law and his home was in the Temple, Diplock's other enthusiasms were horses and the sport of fox-hunting which he pursued until late in life, indeed too late for the comfort of some lord chancellors. At the time of the Diplock commission he attended one meeting adorned with a resplendent black eye sustained by a fall from his horse. In 1974, when treasurer of the Middle Temple, on one Grand Day he headed his guest list with the Duke of Beaufort [q.v.], master of the horse, and packed it with seven masters of hounds.

He married in 1938 Margaret Sarah, a nurse, the daughter of George Atcheson, who started and owned a shirt factory in Londonderry. The couple had no children. During their long life together they were rarely separated until 1984 when illness and particularly Sarah's loss of memory and ability to look after herself required her admission to hospital. There Diplock would visit her daily but she gradually became incapable of even remembering his visits. Her condition was a source of much grief to him in his last years at a time when he was presiding over the judicial committee of the House of Lords. In the end she survived him.

He died in King Edward VII's Hospital for Officers, London, 14 October 1985, only a few weeks after he had brought to a close his outstanding judicial career.

[Personal knowledge.] RAWLINSON

DIRAC, PAUL ADRIEN MAURICE (1902–1984), theoretical physicist, a founder of quantum mechanics, and Nobel prize-winner, was born at Bishopston, Bristol, 8 August 1902, the younger son of the family of two sons and one daughter of Charles Adrien Ladislas Dirac, a native of Monthey in the canton of Valais, Switzerland, and a teacher of French in the Merchant Venturers' Technical College at Bristol, and his wife, Florence Hannah, daughter of Richard Holten, master mariner in a Bristol ship. Dirac's secondary education was in the Technical College, from which he went on to the University of Bristol, graduating as an electrical engineer in 1921. As he found no job, he accepted the Bristol mathematics department's proposal that he stay on and take their course, and graduated in 1923. During this period he attended lectures on relativity by C. D. Broad [q.v.] which profoundly influenced his later thinking about problems in physics. In the autumn of 1923 he went up to Cambridge, to become a research student in mathematics at St John's College under the supervision of (Sir) R. H. Fowler [q.v.].

In August 1925 Fowler received a proof copy of Werner Heisenberg's seminal paper which was the first spark in the development of modern quantum mechanics, and passed it on to Dirac

for study. It contained a mysterious equation, not fully understood by Heisenberg at the time, according to which two quantities P and Q describing a dynamical system, were to be multiplied in such a way that the products P.Q and Q.P are different. After several weeks Dirac suddenly realized the mathematical meaning of their commutator, (P.Q–Q.P), as a generalization of the Poisson Bracket in classical dynamics. This understanding led him to an independent approach to quantum mechanics, apparently different from those developed by Heisenberg (matrix mechanics) and by Erwin Schrödinger (wave mechanics). This was based on an operator formalism, dynamical quantities such as P and Q becoming operators whose results depend on the sequence in which they operate, their commutator being derivable from the classical theory, apart from a factor $h$, the quantum unit. When $h$ is taken to zero, Dirac's formalism reduces to classical dynamics. Dirac next developed his 'transformation theory', which showed that the Heisenberg and Schrödinger formalisms were special cases of his more general theory. He took his Ph.D. degree at Cambridge in the spring of 1926 on the basis of the earlier parts of this work. His international reputation rose meteorically as these developments proceeded and he was invited to visit Göttingen, Copenhagen, and Leiden, centres for this work, for discussions in the following academic year. In 1927 he was invited to speak at the Solvay conference at Brussels. He was elected a fellow of his college in 1927 and appointed university lecturer in 1929.

While at Copenhagen he began to develop 'second quantization' for boson fields, which he applied to calculate from first principles Albert Einstein's coefficients for stimulated emission and absorption of photons by atoms. This work laid the foundation for quantum field theory, the formalism which later underlay all theoretical work on 'elementary particles'. Dirac's outstandingly significant achievement was his relativistic wave equation for the electron, published early in 1928. His deep concern for relativity drove him to make his quantum mechanics compatible with it. His transformation theory had impressed him with the necessity for such an equation to be of first order in the time derivative, and hence also of first order in space derivatives, if space and time were to appear on the same footing. The equation he obtained satisfied these requirements and implied that the electron should have intrinsic spin 1/2, as was already known empirically. Sir Nevill Mott has described it as 'the most beautiful and exciting piece of theoretical physics that I have seen in my lifetime—comparable with Maxwell's deduction that the displacement current, and therefore electromagnetism, must exist'. An even more remarkable prediction from Dirac's equation was the existence of an 'anti-electron', as Dirac termed it in 1931, with the same mass value as the electron but opposite charge. It was first observed in the cosmic radiation in 1932 and was later named the 'positron'. It was the first of the many antiparticles which later became well established.

Dirac's name is also well known for work on many other topics, such as magnetic monopoles, the Large Numbers Hypothesis, the separation of isotopes by diffusion and centrifuge processes (work done during World War II), and the quantization of constrained dynamical systems. These all pale into insignificance in comparison with his equation for the electron.

Dirac was a tall, slender man, with little regard for comfort, a great walker and solitary thinker. He was a legend in his lifetime, and difficult to know. He had no casual conversation and in his responses to others his thoughts followed a path all of their own. He applied strict logic to all aspects of life, often with surprising outcome. In lectures he often spoke about the importance of beauty in the fundamental equations of physics, and there is no doubt among scientists about the beauty of the Dirac equation. He lectured clearly but sparingly in words and with compelling logic; many physicists chose to attend the same lecture by Dirac more than once.

Dirac was elected FRS in 1930 and Lucasian professor of mathematics at Cambridge University in 1932. In 1933 he was awarded the Nobel prize, jointly with Schrödinger, for their discoveries in quantum mechanics. In 1930 Dirac published *The Principles of Quantum Mechanics*, an authoritative text.

From Cambridge Dirac travelled widely to scientific meetings. His early friendship with Piotr Kapitza [q.v.] at Cambridge led him to visit the USSR in 1928 and he returned there almost every year up to 1936. He spent many sabbatical periods in the USA. After retirement in 1969 he took up in 1971 a research professorship at Florida State University, Tallahassee. During his life he received many honours, among them the Copley medal of the Royal Society (1952), membership of the Pontifical Academy of Sciences (1958), and admission to the Order of Merit (1973).

Early in 1937, in London, Dirac married Margit Balazs, daughter of Antal Wigner, manager of a leather factory at Budapest, and sister of the nuclear physicist Eugene Paul Wigner. Her son and daughter from her previous marriage at Budapest also adopted the surname Dirac. The Diracs had two daughters. Dirac died at Tallahassee 20 October 1984.

[R. H. Dalitz and R. E. Peierls in *Biographical Memoirs of Fellows of the Royal Society*, vol. xxxii, 1986; J. Mehra and H. Rechenberg, *The Historical Development of Quantum Theory*, vol. iv, 1982; J. G. Taylor (ed.), *Tributes to Paul Dirac*, 1985; A. Salam, F. Sunoglu and E. P. Wigner (eds.), *Paul Adrien Maurice Dirac, Reminiscences About a Great Physicist*, 1987; private information

R. H

DIXEY, SIR FRANK (1892–1982), geomorphologist, and hydrogeologist, 7 April 1892 at Bedminster, Bristol, of three children and second of two George Dixey, journeyman boilerm riveter in the ship repair yards of Ba morgan, and his wife, Mary Nippress. ily moved to Barry when Frank was he grew up, with a father whose favo creation was walking, within easy rea rocky coast. His elder brother died wh was fourteen. From Barry Grammar S entered University College, Cardiff, chemistry and physics with the intenti coming a teacher, but he changed to and gained a first-class degree in 1914.

After a short academic spell he becam ner in the Royal Garrison Artillery, s the western front from 1915 to 1918 gazetted out, to go to Sierra Leone an reconnaissance survey of the territory traverse, using compass and baron produced single-handed a geolog topographic map, and he recognized th ance of erosion surfaces in the physio Africa.

Having been appointed government to Nyasaland (later Malawi) in 1921 ( director), the remarkable landscape s the headquarters at Zomba stimulate terest in landscape evolution which bec an important element in his scientific investigated the coal deposits and desc dinosaur beds of Lake Nyasa. He p the bauxite deposits of Mlanje moun described the carbonatites, making th cord of these remarkable rocks in Af W. Campbell Smith.

Owing to the economic depression logical Survey, in the early 1930s, t attention to matters immediately pr and especially to the provision of gro supplies from boreholes. This initiat Dixey's major and continuing inter influence of his work spread throughou with hand-pumped boreholes, often crystalline rocks, contributing great supply of pure water for rural po Dixey set down the knowledge perience he gained in his *Practical Ha Water Supply* (1931, 2nd edn. 1950).

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R. H. DALITZ

DIXEY, SIR FRANK (1892–1982), geologist, geomorphologist, and hydrogeologist, was born 7 April 1892 at Bedminster, Bristol, the third of three children and second of two sons of George Dixey, journeyman boilermaker and riveter in the ship repair yards of Barry, Glamorgan, and his wife, Mary Nippress. The family moved to Barry when Frank was two, and he grew up, with a father whose favourite recreation was walking, within easy reach of the rocky coast. His elder brother died when Frank was fourteen. From Barry Grammar School he entered University College, Cardiff, to read chemistry and physics with the intention of becoming a teacher, but he changed to geology and gained a first-class degree in 1914.

After a short academic spell he became a gunner in the Royal Garrison Artillery, serving on the western front from 1915 to 1918. He was gazetted out, to go to Sierra Leone and make a reconnaissance survey of the territory. By foot traverse, using compass and barometer, he produced single-handed a geological and topographic map, and he recognized the importance of erosion surfaces in the physiography of Africa.

Having been appointed government geologist to Nyasaland (later Malawi) in 1921 (and later director), the remarkable landscape seen from the headquarters at Zomba stimulated his interest in landscape evolution which became such an important element in his scientific work. He investigated the coal deposits and described the dinosaur beds of Lake Nyasa. He prospected the bauxite deposits of Mlanje mountain, and described the carbonatites, making the first record of these remarkable rocks in Africa, with W. Campbell Smith.

Owing to the economic depression the Geological Survey, in the early 1930s, turned its attention to matters immediately productive, and especially to the provision of groundwater supplies from boreholes. This initiated one of Dixey's major and continuing interests. The influence of his work spread throughout Africa, with hand-pumped boreholes, often drilled in crystalline rocks, contributing greatly to the supply of pure water for rural populations. Dixey set down the knowledge and experience he gained in his *Practical Handbook of Water Supply* (1931, 2nd edn. 1950).

Dixey served in Northern Rhodesia (later Zambia) as director of water development (1939–44), and travelled widely in north-east Africa on advisory services, which further enlarged his experience of African landscape. He then became director of geological survey in Nigeria (1944–7).

The interplay of tectonics, erosion cycles, and sedimentation was the theme explored by Dixey in a series of papers. He recognized, classified, and dated the major planation surfaces and showed that they were developed throughout Africa; also that they were deformed and disrupted by the Rift Valley movements, and that they could be used to elucidate the history of rifting and the geomorphic development of the continent.

After World War II, to meet the demands for increased mineral exploration and mapping, geological surveys were initiated or expanded in many British colonies with funding from the colonial development and welfare funds. A headquarters was set up in London with Dixey as director of colonial (later overseas) geological surveys. This provided (both before and after the territories reached independence) co-ordinated recruiting, and specialist services such as geophysics, geochemistry, and notably photogeology in which training was provided for the many young geologists on their way from the universities to overseas posts. Dixey's practical experience and scientific prestige, as well as his diplomatic personality, contributed to the strength of the organization and to its *ésprit de corps*.

Dixey officially retired in 1959 but thirteen more years of activity lay ahead, much of it serving the United Nations in a consultative capacity, especially in hydrology. He was joint founder of the *Journal of Hydrogeology* and was one of its editors almost until his death. As consultant geologist to the Cyprus government (1967–73) he undertook active field-work in his seventies.

In appearance Dixey was not commanding in stature, and was slightly stooping, with heavy shoulders. He was reserved, almost diffident in manner, and invariably courteous. He was not an easy man to know, had few interests apart from his work, and was kind and thoughtful to his staff. His steady determination, meticulous observation, interest in his subject, and ability to write at length, established him as an important figure in African geology. He was honoured by many learned societies and he served on their councils. He received the Murchison medal (1953) and was elected FRS (1958). He was appointed OBE in 1929, CMG in 1949, and KCMG in 1972.

In 1919 Dixey married (Henrietta Fredrika Alexandra) Helen, daughter of Henry Golding,

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# GENERAL BIBLIOGRAPHY


Adams, P. J. (1982), "Large number hypothesis, I," *International Journal of Theoretical Physics 21*, 607–32.

Alpher, R. A., and Herman, R. (1972), "Reflections on 'Big Bang' cosmology," pp. 1–14 in F. Reines, ed., *Cosmology, Fusion and Other Matters. George Gamow Memorial Volume*. New York: Colorado Associated Press.

Alvarez, L. W. (1987), *Alvarez. Adventures of a Physicist*, New York: Basic Books.

Anderson, C. D. (1932), "The apparent existence of easily deflectable positives," *Science 76*, 238–9.

(1933), "The positive electron," *Physical Review 43*, 491–4.

(1961), "Early work on the positron and muon," *Amercian Journal of Physics, 29*, 825–30.

Aramaki, S. (1987), "Formation of the renormalization theory in quantum electrodynamics," *Historia Scientiarum*, No. 32, 1–42.

Bachelard, G. (1976), *Nej'ets Filosofi*, Copenhagen: Vinten (Danish translation of *La Philosophie du Non*, first published 1940 in Paris).

Badash, L. (1985), *Kapitza, Rutherford, and the Kremlin*, New Haven: Yale University Press.

Baker, H. F. (1922), *Principles of Geometry*, vol. 1, Cambridge: Cambridge University Press.

Balibar, F. (1985), "Bohr entre Einstein et Dirac," *Revue d'Histoire des Sciences 38*, 293–307.

Barrow, J. D., and Tipler, F. J. (1986), *The Anthropic Cosmological Principle*, Oxford: Oxford University Press.

Beck, G., and Sitte, K. (1933), "Zur Theorie des $\beta$-Zerfalls," *Zeitschrit für Physik 86*, 105–19.

Becquerel, J. (1908), "Sur un phénomène attribuable á des électrons positifs," *Comptes Rendus 146*, 683–5.

Beller, M. (1985), "Pascual Jordan's influence on the discovery of Heisenberg's indeterminacy principle," *Archive for History of Exact Sciences, 33*, 337–49.

Belloni, L. (1978), "A note on Fermi's route to Fermi–Dirac statistics," *Scientia 113*, 421–30.

Bhabha, H. (1939A), "Classical theory of mesons," *Proceedings of the Royal Society of London A172,* 384–409.

(1939B), "The fundamental length introduced by the theory of the mesotron (meson)," *Nature 143,* 276–7.

Biedenharn, L. C. (1983), "The 'Sommerfeld Puzzle' revisited and resolved," *Foundations of Physics 13,* 13–34.

Bilaniuk, O., and Sudarshan, E. C. (1969), "Particles beyond the light barrier," *Physics Today,* May 1969, 43–51.

Birtwistle, G. (1928), *The New Quantum Mechanics,* Cambridge: Cambridge University Press.

Blackett, P. M. S., and Occhialini, G. P. S. (1933), "Some photographs of the tracks of penetrating radiation," *Proceedings of the Royal Society of London A139,* 699–726.

Blatt, J. (1945), "On the meson charge cloud around a proton," *Physical Review 67,* 205–16.

Bloch, F. (1931), [review of Dirac, *Die Prinzipien der Quantenmechanik*], *Physikalische Zeitschrift 32,* 456.

(1934), "Die physikalische Bedeutung mehrerer Zeiten in der Quantenelektrodynamik," *Physikalische Zeitschrift der Sowietunion 5,* 301–15.

Blochinzew, D. (1937), "Advance of theoretical physics in the Soviet Union in 20 years," *Physikalische Zeitschrift der Sowietunion 5,* 542–9.

Bohr, N. (1915), "On the decrease of velocity of swiftly moving electrified particles in passing through matter," *Philosophical Magazine 30,* 581–612.

(1928), "The quantum postulate and the recent development of atomic theory," *Nature 121,* 580–90.

(1932), "Atomic stability and conservation laws," *Covegno di Fisica Nucleare,* Rome: Reale Accademia d'Italia.

(1936), "Conservation laws in quantum theory," *Nature 138,* 25–6.

(1972+), *Niels Bohr, Collected Works,* gen. ed. E. Rüdinger, Amsterdam: North-Holland.

Bohr, N., Kramers, H. A., and Slater, J. C. (1924), "The quantum theory of radiation," *Philosophical Magazine 47,* 795–802.

Bondi, H. (1957), "Negative mass in general relativity," *Review of Modern Physics 29,* 423–8.

Bondi, H., and Gold, T. (1952), "Is there an aether?" *Nature 169,* 146.

Born, M. (1924), *Einstein's Theory of Relativity,* London: Methuen, 1924 (translation of German original from 1920).

(1928), "VI. Kongreß der Assoziation der russischen Physiker," *Die Naturwissenschaften 16,* 741–3.

(1936/1937), "Some philosophical aspects of modern physics," *Proceedings of the Royal Society (Edinburgh) 57,* 1–18.

(1943), *Experiment and Theory in Physics,* Cambridge: Cambridge University Press.

(1956), *Physics in My Generation,* London: Pergamon Press.

(1972), *Albert Einstein – Max Born, Briefwechsel 1916–1955,* Hamburg, Rowohlt.

(1978), *My Life. Recollections of a Nobel Laureate,* New York: Scribner.

Born, M., Heisenberg, W., and Jordan, P. (1925), "Zur Quantenmechanik, II," *Zeitschrift für Physik 35*, 557–615.

Born, M., and Infeld, L. (1934), "Foundations of the new field theory," *Proceedings of the Royal Society of London A144*, 425–51.

Born, M., and Jordan, P. (1925), "Zur Quantenmechanik," *Zeitschrift für Physik 34*, 858–88.

Bothe, W., and Maier-Leibnitz, H. (1936), "Eine neue experimentelle Prüfung der Photonenvorstellung," *Zeitschrift für Physik 102*, 143–55.

Brans, C., and Dicke, R. H. (1961), "Mach's principle and a relativistic theory of gravitation," *Physical Review 124*, 925–35.

Breit, G. (1926), "A correspondence principle in the Compton effect," *Physical Review 27*, 362–72.

Bromberg, J. (1975), "Remarks on the hole theory and Dirac's methodology," *Proceedings XIV International Congress of History of Science (1974)*, vol. 2, 233–6.

(1976), "The concept of particle creation before and after quantum mechanics," *Historical Studies in the Physical Sciences 7*, 161–83.

Brown, L. M., and Hoddeson, L., eds. (1983), *The Birth of Particle Physics*, Cambridge: Cambridge University Press.

Brown, L. M., and Moyer, D. F. (1984), "Lady or tiger? The Meitner-Hupfeld effect and Heisenberg's neutron theory," *American Journal of Physics 52*, 130–6.

Brown, L. M., and Rechenberg, H. (1987), "Paul Dirac and Werner Heisenberg – a Partnership in Science," pp. 117–62 in Kursunoglu and Wigner (1987).

Bursian, V. (1927), "Notiz zu den Grundlagen der Dispersionstheorie von E. Schrödinger," *Zeitschrift für Physik 40, 708–13.*

Cabrera, B. (1982), "First results from a superconductive detector for moving magnetic monopoles," *Physical Review Letters 48*, 1378–81.

Cabrera, B., and Trower, W. P. (1983), "Magnetic monopoles: evidence since the Dirac conjecture," *Foundation of Physics 13*, 196–216.

Carrigan, R. A., and Trower, W. P. (1982), "Superheavy magnetic monopoles," *Scientific American*, April, 91–9.

Casimir, H. (1983), *Haphazard Reality. Half a Century of Science*. New York: Harper and Row.

(1985), "Paul Dirac 1902–1984," *Naturwissenschaftliche Rundschau 38*, 219–23.

Cassidy, D. C. (1981), "Cosmic ray showers, high energy physics, and quantum field theories: programmatic interactions in the 1930s," *Historical Studies in the Physical Sciences 12*, 1–40.

Chandrasekhar, S. (1934), "Stellar configurations with degenerate cores," *The Observatory 57*, 373–7.

(1937), "The cosmological constants," *Nature 139*, 757–8.

(1973), "A chapter in the astrophysicists's view of the universe," pp. 34–44 in Mehra, ed. (1973).

(1979), "Beauty and the quest for beauty in science," *Physics Today*, July, 25–30.

(1987), *Truth and Beauty*, Chicago: University of Chicago Press.

Cini, M. (1982), "Cultural traditions and environmental factors in the development of quantum electrodynamics 1925–1933," *Fundamenta Scientiae 3*, 229–53.

Condon, E. U., and Mack, J. E. (1930), "An interpretation of Pauli's exclusion principle," *Physical Review 35*, 579–82.

Craigie, N. S., Goddard, P., and Nahm, W., eds. (1983), *Monopoles in Quantum Field Theory*, Singapore: World Scientific.

Crawford, E., Heilbron, J. L., and Ullrich, R. (1987), *The Nobel Population 1901–1937*, Berkeley: Office for History of Science and Technology, University of California.

Crease, R. P., and Mann, C. C. (1986), *The Second Creation*, New York: Macmillan.

Crowther, J. G. (1970A), *British Scientists of the Twentieth Century*, London: Routledge & Kegan Paul.

(1970B), *Fifty Years with Science*, London: Barie & Jenkins.

Cunningham, E. (1915), *Relativity and the Electron Theory*, London: Longmans, Green & Co.

Curtin, D. W., ed. (1980), *The Aesthetic Dimension of Science*, New York: Philosophical Library.

Dalitz, R. H. (1987A), "Another side to Paul Dirac," 69–92 in Kursunoglu and Wigner, eds., (1987).

(1987B), "A biographical sketch of the life of professor P. A. M. Dirac, OM, FRS," pp. 3–29 in Taylor, ed. (1987B).

Dalitz, R. H., and Peierls, R. (1986), "Paul Adrien Maurice Dirac," *Biographical Memoirs of Fellows of the Royal Society, 32*, 139–85.

Darrigol, O. (1984A), "La genèse du concept de champ quantique," *Annales de Physiques 9*, 433–501.

(1984B), "A history of the question: can free electrons be polarized?" *Historical Studies in the Physical Sciences 15*, 39–80.

(1986), "The origin of quantized matter waves," *Historical Studies in the Physical Sciences 16*, 1–56.

(1988A), "The quantum electrodynamical analogy in early nuclear theory and the roots of Yukawa's theory," *Revue d'Histoire des Sciences 41*, 225–97.

(1988B), "Elements of a scientific biography of Tomonaga Sin-itiro," *Historia Scientiarum*, No. 35, 2–29.

Darrow, K. K. (1933), "Contemporary advances in physics, XXVI," *Bell System Technical Journal 12*, 288–330.

Darwin, C. G. (1927), "The electron as a vector wave," *Proceedings of the Royal Society of London A116*, 227–53.

(1928), "The wave equation of the electron," *Proceedings of the Royal Society of London A118*, 654–80.

(1935), "The quantum theory," *Nature 136*, 411–12.

(1937), "Physical science and philosophy," *Nature 139*, 1008.

De Broglie, L. (1924), "A tentative theory of light quanta," *Philosophical Magazine 47*, 446–58.

(1925), "Sur la fréquence propre de l'électron," *Comptes Rendus 180*, 498–500.

Delbrück, M. (1972), "Out of this world," pp. 280–8 in F. Reines, ed., *Cosmology, Fusion and other Matters. George Gamow Memorial Volume*, New York: Colorado Associated Press.
De Maria, M., and La Teana, F. (1982), "Schrödinger's and Dirac's unorthodoxy in quantum mechanics," *Fundamenta Scientiae 3*, 129–48.
De Maria, M., and Russo, A. (1985), "The discovery of the positron," *Rivista di Storia della Scienza 2* (2), 237–86.
Dicke, R. H. (1959), "Gravitation – an enigma," *American Scientist 47*, 25–40.
Dingle, H. (1937A), "Modern Aristotelianism," *Nature 139*, 784–6.
(1937B), "Deductive and inductive methods in science. A reply," *Nature 139*, 1011–12.
Dirac, M. (1987), "Thinking of my darling Paul," pp. 3–8 in Kursunoglu and Wigner, ed. (1987).
Dirac, P. A. M. (see Appendix II).
Dorfman, I. V. (1981), "Die Theorie Diracs und die Entdeckung des Positrons in der kosmischen Strahlung," *Zeitschrift für Geschichte der Naturwissenschaft, Technik und Medizin 18*, 50–7.
Douglas, A. V. (1956), *The Life of Arthur Stanley Eddington*, London: Thomas Nelson & Sons.
Dresden, M. (1987), *H. A. Kramers. Between Tradition and Revolution*, New York: Springer.
Dymond, E. G. (1934), "On the polarization of electrons by scattering, II," *Proceedings of the Royal Society of London A145*, 657–67.
Dyson, F. J., (1986), "Paul A. M. Dirac," *American Philosophical Society, Yearbook 1986*, 100–4.
Earman, J. (1976), "Causation: a matter of life and death," *Journal of Philosophy 73*, 5–25.
Earman, J., and Glymour, C. (1981), "Relativity and eclipses: the British eclipse expeditions of 1919 and their predecessors," *Historical Studies in the Physical Sciences 11*, 49–86.
Eddington, A. S. (1923), *The Mathematical Theory of Relativity*, Cambridge: Cambridge University Press.
(1928), *The Nature of the Physical World*, Cambridge: Cambridge University Press.
(1929), "The charge of an electron," *Proceedings of the Royal Society of London A122*, 358–69.
(1936), *Relativity Theory of Protons and Electrons*, Cambridge: Cambridge University Press.
Eden, R. J., and Polkinghorne, J. C. (1972), "Dirac in Cambridge," pp. 1–5 in Salam and Wigner, eds. (1972).
Ehrenhaft, F. (1944), "The magnetic current," *Nature 154*, 426–7.
Einstein, A. (1909), "Zum gegenwärtigen Stand des Strahlungsproblems," *Physikalische Zeitschrift 10*, 185–93.
(1916), "Strahlungs-Emission und -Absorption nach der Quantentheorie," *Verhandlungen der Deutschen Physikalischen Gesellschaft 18*, 318–23.
(1917), "Zur Quantentheorie der Strahlung," *Physikalische Zeitschrift 18*, 121–8.

(1918), "Dialog über Einwände gegen die Relativitätstheorie," *Die Naturwissenschaften 6,* 702.
(1922), *Sidelights on Relativity,* London: Methuen.
(1925), "Elektron und Allgemeines Relativitätstheorie," *Physica 5,* 330–4.
(1931), "Maxwell's influence on the development of the conception of physical reality," pp. 66–73 in *James Clerk Maxwell: a Commemoration Volume,* Cambridge: Cambridge University Press.
(1934), "On the method of theoretical physics," pp. 12–22 in Einstein, *Essays in Science,* New York: Philosophical Library.
(1950), "On the generalized theory of gravitation," *Scientific American 182,* April 13–17.
Eliezer, C. J. (1943), "The hydrogen atom and the classical theory of radiation," *Proceedings of the Cambridge Philosophical Society 39,* 173–80.
(1946), "The classical equations of motion of an electron," *Proceedings of the Cambridge Philosophical Society 42,* 278–85.
(1987), "Some reminiscences of professor P. A. M. Dirac," pp. 58–62 in Taylor, ed. (1987B).
Elsasser, W. M. (1978), *Memoirs of a Physicist in the Atomic Age,* Bristol: Adam Hilger.
Feinberg, E. L., ed. (1987), *Reminiscences about I. E. Tamm,* Moscow: Nauka Publishers.
Fellows, F. H. (1985), *J. H. Van Vleck: The early life and work of a mathematical physicist,* unpublished Ph.D. Thesis, University of Minnesota.
Fermi, E. (1926A), "Sulla quantizzione del gas perfetto monatomico," *Rendiconti Lincei 3,* 145–9.
(1926B), "Zur Quantelung des idealen einatomigen Gases," *Zeitschrift für Physik 36,* 902–12.
(1932), "Quantum theory of radiation," *Review of Modern Physics 4,* 87–132.
(1933), "Tentativo di una Teoria dell'Emissione dei Raggi 'Beta,'" *Ricerca Scientifica 2,* 491–5.
(1934), "Versuch einer Theorie der β-Strahlen, I," *Zeitschrift für Physik 77,* 161–71.
(1965), *Enrico Fermi. Collected Papers,* 2 vols., Rome: University of Chicago Press.
Feuer, L. S. (1977), "Teleological principles in science," *Inquiry 21,* 377–407.
Feynman, R. P. (1966), "The development of the space–time view of quantum electrodynamics," *Science 153,* 699–708.
Fierz, M., and Pauli, W. (1939), "On relativistic wave equations of particles of arbitrary spin in an electromagnetic field," *Proceedings of the Royal Society of London A173,* 211–32.
Fischer, P. (1985), *Licht und Leben. Ein Bericht über Max Delbrück, den Wegbereiter der Molekylarbiologie,* Konstanz: Universitätsverlag Konstanz.
Fock, V. (1929), "Geometrisierung der Diracschen Theorie des Elektrons," *Zeitschrift für Physik 57,* 261–77.
(1932), "Konfigurationsraum und Zweite Quantelung," *Zeitschrift für Physik 75,* 622–47.

Fock, V. and Podolsky, B. (1932A), "Zur Diracschen Quantenelektrodynamik," *Physikalische Zeitschrift der Sowietunion 1,* 798–800.
(1932B), "On the quantization of electro-magnetic waves and the interaction of charges on Dirac's theory," *Physikalische Zeitschrift der Sowietunion 1,* 801–17.
Fokker, A. D. (1929), "Eine invarianter Variationssatz für die Bewegung mehrerer elektrischer Massenteilchen," *Zeitschrift für Physik 58,* 386–93.
Ford, K. W. (1963), "Magnetic monopoles," *Scientific American,* December, 122–31.
Fowler, R. H. (1926), "On dense stars," *Monthly Notices of the Royal Astronomical Society of London 87,* 114–22.
Fradkin, D. M. (1966), "Comments on a paper by Majorana concerning elementary particles," *American Journal of Physics 34,* 314–18.
Franklin, A. (1979), "The discovery and nondiscovery of parity nonconservation," *Studies in the History and Philosophy of Science 10,* 21–57.
(1986), *The Neglect of Experiment,* Cambridge: Cambridge University Press.
Frenkel, Y. (1925), "Elektrodynamik punktförmiger Elektronen," *Zeitschrift für Physik 32,* 518–34.
(1928), "Zur Wellenmechanik des rotierenden Elektrons," *Zeitschrift für Physik 47,* 786–803.
Freundlich, Y. (1980), "Theory evaluation and the bootstrap hypothesis," *Studies in the History and Philosophy of Science 11,* 267–77.
Fürth, R. (1933), "Einige Bemerkungen zum Problem der Neutronen und positive Elektronen," *Zeitschrift für Physik 85,* 294–9.
Galison, P. L. (1979), "Minkowski's space–time: from visual thinking to the absolute world," *Historical Studies in the Physical Sciences 10,* 85–121.
(1983), "The discovery of the muon and the failed revolution against quantum electrodynamics," *Centaurus 26,* 262–316.
(1987), *How Experiments End,* Chicago: University of Chicago Press.
Gamow, G. (1934), "Ueber den heutigen Stand (20. Mai 1934) der Theorie des $\beta$-Zerfalls," *Physikalische Zeitschrift 35,* 533–42.
(1935A), "General stability-problems of atomic nuclei," pp. 60–71 in *International Conference on Physics, London 1934,* vol. 1, Cambridge: Cambridge University Press.
(1935B), "The negative proton," *Nature 135,* 858–61.
(1966), *Thirty Years That Shook Physics: the Story of Quantum Theory,* New York: Doubleday.
(1967A), "Electricity, gravity, and cosmology," *Physical Review Letters 19,* 759–61.
(1967B), "History of the universe," *Science 158,* 766–9.
(1967C), "Does gravity change with time?" *Proceedings of the National Academy of Sciences 57,* 187–93.
Gapon, E., and Iwanenko, D. (1934), "Alpha particles in light nuclei," *Comptes Rendus de l'Académie des Sciences de l'URSS 4,* 276–7.
Goldberg, S. (1976), "Max Planck's philosophy of nature and his elaboration of the special theory of relativity," *Historical Studies in the Physical Sciences 7,* 125–61.

Gordon, W. (1927), "Der Comptoneffekt nach der Schrödingerschen Theorie," *Zeitschrift für Physik 40,* 117–33.
Gould, P. L. et al. (1986), "Diffraction of atoms by light: the near-resonant Kapitza–Dirac effect," *Physical Review Letters 56,* 827–30.
Gowing, M. (1964), *Britain and Atomic Energy, 1939–1945,* London: Macmillan.
Grünbaum, A. (1976), "Is preacceleration of particles in Dirac's electrodynamics a case of backward causation?" *Philosophy of Science 43,* 165–201.
Grythe, I. (1982/83), "Some remarks on the early S-matrix," *Centaurus 26,* 198–203.
Hadamard, J. (1954), *The Psychology of Invention in the Mathematical Field,* New York: Dover Books.
Haldane, J. B. S. (1939), *The Marxist Philosophy and the Sciences,* New York: Random House.
Halpern, L. (1985), "Paul Adrien Maurice Dirac (1902–1984)," *Foundations of Physics 15,* 257–9.
Halpern, O., and Thirring, H. (1932), *The Elements of the New Quantum Mechanics,* London: Methuen.
Hanson, N. R. (1963), *The Concept of the Positron,* Cambridge: Cambridge University Press.
Harish-Chandra (1987), "My association with Professor Dirac," pp. 34–6, in Kursunoglu and Wigner, eds. (1987).
Hasenfratz, P., and Kuti, J. (1978), "The quark bag model," *Physics Reports 40,* 75–179.
Heaviside, O. (1893–1912), *Electromagnetic Theory,* 3 vols., London: "The Electrician" Printing and Publishing Co.
Heelan, P. A. (1975), "Heisenberg and radical scientific change," *Zeitschrift für Allgemeine Wissenschaftstheorie 6,* 113–36.
Heisenberg, E. (1984), *Inner Exile. Recollections of a Life with Werner Heisenberg,* Boston: Birkhäuser.
Heisenberg, W. (1925), "Ueber quantentheoretischer Umdeutung und mechanischer Beziehungen," *Zeitschrift für Physik 33,* 879–93.
(1926A), "Mehrkörperproblem und Resonanz in der Quantenmechanik," *Zeitschrift für Physik 38,* 411–26.
(1926B), "Schwankungserscheinungen und Quantenmechanik," *Zeitschrift für Physik 40,* 501–6.
(1927), "Ueber den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik," *Zeitschrift für Physik 43,* 172–98.
(1934), "Bemerkungen zur Diraschen Theorie des Positrons," *Zeitschrift für Physik 90,* 209–31.
(1938), "Ueber die in der Theorie der Elementarteilchen auftretende universelle Länge," *Annalen der Physik 32,* 20–33.
(1968), "Theory, criticism and a philosophy," pp. 32–46 in *From a Life in Physics,* Vienna: IEAE.
(1971A), *Physics and Beyond,* New York: Harper & Row.
(1971B), "Die Bedeutung des Schönes in der exakten Naturwissenschaft," pp. 288–305 in *Schritte über Grenzen,* Munich: R. Piper & Co.

(1972), "Indefinite metric in state space," pp. 129–36 in Salam and Wigner, eds. (1972).
(1973), "Development of concepts in the history of quantum theory," pp. 264–75 in Mehra, ed. (1973).
Heisenberg, W. and Pauli, W. (1929), "Zur Quantendynamik der Wellenfelder," *Zeitschrift für Physik 56*, 1–61.
(1930), "Zur Quantendynamik der Wellenfelder, II," *Zeitschrift für Physik 59*, 168–90.
Heller, M. (1979), "Questions to infallible oracle," pp. 199–210 in M. Demianski, ed., *Physics of the Expanding Universe*, Berlin: Springer.
Hendry, J. (1981), "Bohr–Kramers–Slater: a virtual theory of virtual oscillators and its role in the history of quantum mechanics, *Centaurus 25*, 189–221.
(1983), "Monopoles before Dirac," *Studies in the History and Philosophy of Science 14*, 81–7.
(1984A), *The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue*, Dordrecht: Reidel.
(1984B), *Cambridge Physics in the Thirties*, Bristol: Adam Hilger.
Hirosige, T. (1966), "Electrodynamics before the theory of relativity, 1890–1905," *Japanese Studies in History of Science 5*, 1–49.
Hoddeson, L., and Baym, G. (1980), "The development of the quantum mechanical electron theory of metals: 1900–28," *Proceedings of the Royal Society of London A371*, 8–23.
Hoddeson, L., Baym, G., and Eckert, M. (1987), "The development of the quantum-mechanical theory of metals, 1928–1933," *Review of Modern Physics 59*, 287–327.
Holton, G. (1978), *The Scientific Imagination*, Cambridge: Cambridge University Press.
Houston, W. V., and Hsieh, Y. M. (1934), "The fine structure of the Balmer lines," *Physical Review 45*, 263–72.
Howarth, T. (1978), *Cambridge between Two Wars*, London: Collins.
Hoyle, F. (1948), "A new model for the expanding universe," *Monthly Notices of the Royal Astronomical Society 108*, 372–82.
(1980), *Steady-State Cosmology Re-Visited*, Cardiff: University College Cardiff Press.
(1986), *The Small World of Fred Hoyle. An Autobiography*, London: Michael Joseph.
Huntley, H. E. (1970), *The Divine Proportion. A Study in Mathematical Beauty*, New York: Dover Books.
Infeld, L. (1978), *Why I Left Canada*, Montreal: McGill-Queen's Univeristy Press.
(1980), *Quest. An Autobiography*, 2nd edn., New York: Chelsea Publ. Co.
Iwanenko, D., and Ambarzumian, V. (1930), "Les électrons inobservables et les rayons $\beta$," *Comptes Rendus 190*, 582–4.
Iwanenko, D., and Landau, L. (1928), "Zur Theorie des magnetischen Elektrons," *Zeitschrift für Physik 48*, 340–8.
Jacobsen, J. C. (1936), "Correlation between scattering and recoil in the Compton effect," *Nature 138*, 25.

Jammer, M. (1966), *The Conceptual Development of Quantum Mechanics*, New York: McGraw-Hill.
Jeans, J. (1930), *The Mysterious Universe*, London: Cambridge University Press.
(1931), "The annihilation of matter," *Nature 128*, 103–10.
Joffe, A. F. (1967), *Begegnungen mit Physikern*, Leipzig: Teubner.
Jordan, P. (1924), "Zur Theorie der Quantenstrahlung," *Zeitschrift für Physik 30*, 297–319.
(1927A), "Ueber eine neue Begründung der Quantenmechanik," *Zeitschrift für Physik 40*, 809–38.
(1927B), "Zur Quantenmechanik der Gasentartung," *Zeitschrift für Physik 44*, 473–80.
(1928), "Die Lichtquantentheorie," *Ergebnisse der Exakten Naturwissenschaften 7*, 158–208.
(1929), "Der gegenwärtige Stand der Quantenelektrodynamik," *Physikalische Zeitschrift 30*, 700–12.
(1932), "Zur Methode der zweiten Quantelung," *Zeitschrift für Physik 75*, 648–53.
(1935), "Zur Quantenelektrodynamik, III. Eichinvariante Quantelung und Diracsche Magnetpole," *Zeitschrift für Physik 97*, 535–7.
(1936), *Anschauliche Quantentheorie*, Berlin: Springer.
(1937), "Die physikalischen Weltkonstanten," *Die Naturwissenschaften 25*, 513–17.
(1938), "Ueber die Diracschen Magnetpole," *Annalen der Physik 32*, 66–70.
(1939), "Bermerkungen zur Kosmologie," *Annalen der Physik 36*, 64–70.
(1952), *Schwerkraft und Weltall*, Braunschweig: Vieweg.
Jordan, P., and Klein, O. (1927), "Zum Mehrkörperproblem der Quantentheorie," *Zeitschrift für Physik 45*, 751–65.
Jordan, P., and Pauli, W. (1928), "Zur Quantenelektrodynamik," *Zeitschrift für Physik 47*, 151–73.
Jordan, P., and Wigner, E. (1928), "Ueber das Paulische Aequivalenzverbot," *Zeitschrift für Physik 47*, 631–51.
Josephson, P. R. (1988), "Physics and Soviet-Western relations in the 1920s and 1930s," *Physics Today*, September, 54–61.
Jost, R. (1972), "Foundation of quantum field theory," pp. 61–78 in Salam and Wigner, eds. (1972).
Jungk, R. (1958), *Brighter than a Thousand Suns: A Personal History of the Atomic Scientists*, New York: Harcourt Brace.
Kedrov, B. M. ed. (1979), *Das Neutron*, Berlin (GDR): Akademie-Verlag.
Kedrov, F. B. (1984), *Kapitza: Life and Discoveries*, Moscow: MIR Publishers.
Kerber, G., et al. (1987), *Erwin Schrödinger*, Vienna: Fassbaender.
Klein, O. (1927), "Elektrodynamik und Wellenmechanik vom Standpunkt des Korrespondenzprinzips," *Zeitschrift für Physik 41*, 407–42.
(1929), "Die Reflexion von Elektronen an einem Potentialsprung nach der relativistischen Dynamik von Dirac," *Zeitschrift für Physik 53*, 57–65.
(1973), "Ur mitt Liv i Fysiken," *Svensk Naturvetenskap 1973*, 159–72.
Klein, O., and Nishina, Y. (1929), "Ueber die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac," *Zeitschrift für Physik 52*, 853–68.

Kostro, L. (1986), "Einstein's conception of the ether and its up-to-date applications in the relativistic wave mechanics," pp. 435–50 in W. M. Honig et al., eds. *Quantum Uncertainties*, New York: Plenum Press.

Kragh, H. (1981A), "The genesis of Dirac's relativistic theory of electrons," *Archive for History of Exact Sciences 24*, 31–67.

(1981B), "The concept of the monopole: a historical and analytical case-study," *Studies in the History and Philosopy of Science 12*, 141–72.

(1982A), "Cosmo-physics in the thirties: towards a historiography of Dirac cosmology," *Historical Studies in the Physical Sciences 13*, 69–108.

(1982B), "Erwin Schrödinger and the wave equation: the crucial phase," *Centaurus 26*, 154–97.

(1984), "Equation with many fathers: the Klein–Gordon equation in 1926," *American Journal of Physics 52*, 1024–33.

(1985), "The fine structure of hydrogen and the gross structure of the physics community, 1916–26," *Historical Studies in the Physical Sciences 15*, 67–126.

Krajcik, R. A., and Nieto, M. M. (1977), "Historical developmet of the Bhabha first-order relativistic wave equations for arbitrary spin," *American Journal of Physics 45*, 818–22.

Kramers, H. A. (1925), "Eenige opmerkingen over de quantenmechanica van Heisenberg," *Physica 5*, 369–76.

(1934), "On the classical theory of the spinning electron," *Physica 1*, 825–8.

(1957), *Quantum Mechanics*, Amsterdam: North-Holland.

Kramers, H. A., and Heisenberg, W. (1925), "Ueber die Streuung von Strahlen durch Atome," *Zeitschrift für Physik 31*, 681–708.

Kursunoglu, B. N., and Wigner, E. P., eds. (1987), *Paul Adrien Maurice Dirac. Reminiscences about a Great Physicist*, Cambridge: Cambridge University Press.

Lamb, W. (1983), "The fine structure of hydrogen," pp. 311–28 in Brown and Hoddeson, eds. (1983).

Lanczos, K. (1926), "Ueber eine feldmässige Darstellung der neuen Quantenmechanik," *Zeitschrift für Physik 35*, 812–36.

Landau, L., and Peierls, R. (1931), "Erweiterung des Unbestimmtheitsprinzips für die relativistische Quantentheorie," *Zeitschrift für Physik 69*, 56–66.

Langer, R. M. (1932), "The fundamental particles," *Science, 76*, 294–5.

Langevin, A. (1966), "Paul Langevin et les congrès de physique Solvay," *La Pensée*, no. 129, 3–32, and no. 130, 89–104.

Larmor, J. (1894), "A dynamical theory of the electric and luminiferous medium," *Philosophical Transactions of the Royal Society 185*, 719–822.

Lees, A. (1935) "The electric moment of an electron," *Proceedings of the Cambridge Philosophical Society 31*, 94–7.

(1939), "The electron in classical general relativity theory," *Philosophical Magazine 28*, 385–95.

Lenard, P. (1909), "Ueber Lichtemission und deren Erregung," *Sitzungsberichte Heidelberger Akademie*, dritte Abhandlung.

Lewis, T. (1945), "Some criticism of the theory of point electrons," *Philosophical Magazine 36*, 533–41.

Lipschitz, R. (1884), *Untersuchungen über Summen von Quadraten*, Bonn: F. Cohen.
Lodge, O. (1906), *Electrons*, London: Bell and Sons.
(1922), "Speculation concerning the positive electron," *Nature 110*, 696–7.
(1925), *Ether and Reality*, New York: George Doran Co.
London, F. (1950), *Superfluids. Macroscopic Theory of Superconductivity*, New York: Wiley.
Lovejoy, A. O. (1976), *The Great Chain of Being*, Cambridge, Mass.: Harvard University Press (1st edn. 1936).
Lützen, J. (1982), *The Prehistory of the Theory of Distributions*, Berlin: Springer.
MacKinnon, E. M. (1974), "Ontic commitments of quantum mechanics," pp. 225–308 in R. S. Cohen and M. W. Wartofsky, eds., *Logic and Epistemological Studies in Contemporary Physics*, Dordrecht: Reidel.
(1982), *Scientific Explanation and Atomic Physics*, Chicago: University of Chicago Press.
Mandel, H. (1930), "Einige vergleichende Bemerkungen zur Quantentheorie des Elektrons," *Zeitschrift für Physik 60*, 782–94.
Margenau, H. (1933), *Mathematical Gazette 17*, 493.
(1935), "Methodology of modern physics," pp. 52–89 in Margenau, *Physics and Philosophy: Selected Essays*, Dordrecht: Reidel, 1978 (first published in *Philosophy of Science 2*, 1935, 48–72, 164–87).
Maxwell, J. C. (1891), *Treatise on Electricity and Magnetism*, 3rd edn., Oxford: Clarendon Press.
Mehra, J. (1972), "The golden age of theoretical physics: P. A. M. Dirac's scientific works from 1924–1933," pp. 17–59 in Salam and Wigner, eds. (1972).
ed. (1973), *The Physicist's Conception of Nature*, Dordrecht: Reidel.
Mehra, J., and Rechenberg, H. (1982+), *The Historical Development of Quantum Theory*, 5 vols., Berlin: Springer.
Merriell, D. (1981), "On the idea of beauty," pp. 184–223 in *The Great Ideas Today*, Chicago: Encyclopedia Britannica.
Merton, R. K., and Zuckerman, H. (1973), "Age, aging, and age structure in science," pp. 497–559 in R. K. Merton, *Sociology of Science*, Chicago: University of Chicago Press.
Milne, E. A. (1935), *Relativity, Gravitation and World-Structure*, Oxford: Oxford University Press.
Minkowski, H. (1915), "Das Relativitätsprinzip," *Annalen der Physik 47*, 927–38.
Mituo, T. (1974), "Methodological approaches in the development of the meson theory of Yukawa in Japan," pp. 24–38 in S. Nakayama et al., eds., *Science and Society in Modern Japan*, Cambridge, Mass.: MIT Press.
Mohorovicic, S. (1934), "Möglichkeit neuer Elemente und ihre Bedeutung für die Astrophysik," *Astronomische Nachrichten 253*, 93–108.
Møller, C. (1963), "Nogle erindringer fra livet på Bohrs institut i sidste halvdel af tyverne," pp. 54–64 in *Niels Bohr, et Mindeskrift*, Copenhagen: Gjellerup. Special issue of *Fysisk Tidsskrift 60*.
Morrison, M. (1986), "More on the relationship between technically good and conceptually important experiments: a case study," *British Journal for Philosophy of Science 37*, 101–22.

Mott, N. (1986), *A Life in Science*, London: Taylor & Francis.
(1987), "Reminiscences of Paul Dirac," pp. 231–4 in Kursunoglu and Wigner, eds. (1987).
Moyer, D. F. (1981A), "Origins of Dirac's electron, 1925–1928," *American Journal of Physics 49*, 944–9.
(1981B), "Evaluation of Dirac's electron," *American Journal of Physics 49*, 1055–62.
(1981C), "Vindication of Dirac's electron," *American Journal of Physics 49*, 1120–5.
Nernst, W. (1907), *Theoretische Chemie*, 5th edn., Stuttgart: Ferdinand Enke.
Newton, I. (1729), *Principia Mathematica*, London, Trans. by A. Motte, Ed. by F. Cajori, Berkeley: University of California Press, 1946.
Nikolsky, K. (1932), "The interaction of charges in Dirac's theory," *Physikalische Zeitschrift der Sowietunion 2*, 447–52.
Oppenheimer, J. R. (1930A), "Note on the theory of the interaction of field and matter," *Physical Review 35*, 461–77.
(1930B), "On the theory of electrons and protons," *Physical Review 35*, 562.
(1930C), "Two notes on the probability of radiative transitions," *Physical Review 35*, 939–47.
(1931), [review of Dirac, *Principles of Quantum Mechanics*], *Physical Review 37*, 97.
(1934), "Are the formulae for the absorption of high energy radiations valid?" *Physical Review 47*, 44–52.
Oppenheimer, J. R., and Carlson, J. F. (1932), "The impacts of fast electrons and magnetic neutrons," *Physical Review 41*, 763–92.
Oppenheimer, J. R., and Furry, W. H. (1934), "On the theory of the electron, negative and positive," *Physical Review, 45*, 245–62.
Pais, A. (1972), "The early history of the theory of the electron: 1897–1947," pp. 79–93 in Salam and Wigner, eds. (1972).
(1982), *'Subtle is the Lord . . .': The Science and the Life of Albert Einstein*, Oxford: Oxford University Press.
(1986), *Inward Bound. Of Matter and Forces in the Physical World*, Oxford: Clarendon Press.
(1987), "Playing with equations, the Dirac way," pp. 93–116 in Kursunoglu and Wigner, eds. (1987).
Pauli, W. (1919A), "Mercurperihelbewegung und Strahlenablenkung in Weyls Gravitationstheorie," *Verhandlungen der Deutschen Physikalischen Gesellschaft 21*, 742–50.
(1919B), "Zur Theorie der Gravitation und der Elektrizität von Herman Weyl," *Physikalische Zeitschrift 20*, 457–67.
(1921), *Theory of Relativity*, Oxford: Pergamon Press, 1958 (trans. of "Relativitätstheorie," *Encyklopädie der mathematischen Wissenschaften*, vol. V19, Leipzig: Teubner, 1921).
(1923), "Ueber das thermische Gleichgewicht zwischen Strahlung und freien Elektronen," *Zeitschrift für Physik 18*, 272–86.
(1927), "Zur Quantenmechanik des magnetischen Elektrons," *Zeitschrift für Physik 43*, 601–23.

(1931), [review of Dirac, *The Principles of Quantum Mechanics*] *Die Naturwissenschaften 19,* 188–9.
(1933), "Die allgemeinen Prinzipien der Wellenmechanik," pp. 771–938 in *Handbuch der Physik* 24/1, Berlin: Springer.
(1943), "On Dirac's new method of field quantization," *Review of Modern Physics 15,* 175–207.
(1946), "Dirac's Feldquantizierung und Emission von Photonen kleiner Frequenzen," *Helvetica Physica Acta 19,* 234–7.
(1964), "Exclusion principle and quantum mechanics," Nobel Lecture delivered December 13, 1946, in Stockholm; pp. 27–43 in *Nobel Lectures, Physics 1942–1962,* Amsterdam: Elsevier.
(1979), *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a.,* eds. K. von Meyenn, A. Hermann, and V. F. Weisskopf, vol. 1 (1919–29), Berlin: Springer.
(1985), *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a.,* ed. K. von Meyenn, vol. 2 (1930–9), Berlin: Springer.
Pauli, W., and Solomon, J. (1932), "La théorie unitaire d'Einstein et Mayer et les équations de Dirac," *Journal de Physique et Radium* (7), *3,* 452–63, 582–9.
Pauli, W. and Weisskopf, V. F. (1934), "Ueber die Quantisierung der skalaren relativistischen Wellengleichung," *Helvetica Physica Acta 7,* 709–31.
Pearson, K. (1891), "Ether squirts," *American Journal of Mathematics 13,* 309–70.
Peierls, R. (1936), "Interpretation of Shankland's experiment," *Nature 137,* 904.
(1985), *Bird of Passage. Recollections of a Physicist,* Princeton: Princeton University Press.
(1987), "Address to Dirac Memorial Meeting, Cambridge," pp. 35–7 in Taylor, ed. (1987).
Penrose, R. (1979), Interview, pp. 34–50 in P. Buckley and F. D. Peat, eds., *A Question of Physics: Conversations in Physics and Biology,* London: Routledge & Kegan Paul.
Petiau, G. (1936), "Contribution à la théorie des équations d'ondes corpusculaire," *Memoires de l'Académie Science Royale de Belgique 16,* 1–116.
Petroni, C., and Vigier, J. P. (1983), "Dirac's aether in relativistic quantum mechanics," *Foundations of Physics 13,* 253–86.
Pickering, A. (1981), "Constraints on controversy: the case of the magnetic monopole," *Social Studies in Science 11,* 63–93.
Placintéanu, J. J. (1933), "Considérations théoriques sur la constitution des neutrons, électrons positifs et photons. Existence des protons négatifs," *Comptes Rendus 197,* 549–52.
Poincaré, H. (1896), "Remarques sur une expérience de M. Birkeland," *Comptes Rendus 123,* 530–3.
(1960), *Science and Method,* New York: Dover Books (first published in Paris in 1908).
Pokrowski, G. I. (1929), "Ueber die Wahrscheinlichkeitsgesetz bei dem Zerfall radioaktiver Stoffe sehr kleiner Konzentrations," *Zeitschrift für Physik 58,* 706–9.
Popper, K. R. (1959), *The Logic of Scientific Discovery,* New York: Basic Books.

Proca, A. (1936), "Sur la théorie ondulatoire des électrons positifs et negatifs," *Comptes Rendus 7*, 347–53.
Przibram, K., ed., (1963), *Briefe zur Wellenmechanik*, Vienna: Springer-Verlag.
Pyenson, L. (1977), "Herman Minkowski and Einstein's special theory of relativity," *Archive for History of Exact Sciences 17*, 71–95.
Richardson, O. W. (1931), "Isolated quantised magnetic poles," *Nature 128*, 582.
Rohrlich, F. (1965), *Classical Charged Particles*, Reading, Mass.: Addison-Wesley.
(1973), "The electron: development of the first elementary particle theory," pp. 331–69 in Mehra, ed. (1973).
Rosenfeld, L. (1932), "Ueber eine mögliche Fassung der Diracschen Programms zur Quantenelektrodynamik und deren formalen Zusammenhang mit der Heisenberg-Paulischen Theorie," *Zeitschrift für Physik 76*, 729–34.
(1967), "Niels Bohr in the thirties," pp. 114–36 in S. Rozental, ed., *Niels Bohr. His Life and Work as Seen by His Friends and Colleagues*, New York: Wiley.
Rosenthal-Schneider, I. (1949), "Presuppositions and anticipations in Einstein's physics," pp. 131–46 in P. Schilpp, ed., *Albert Einstein: Philosopher–Scientist*, New York: Tudor Publ. Co.
Rüger, A. (1988), "Atomism from cosmology: Erwin Schrödinger's work on wave mechanics and space–time structure," *Historical Studies in the Physical Sciences 18*, 377–401.
Rydberg, J. R. (1906), *Elektron. Der erste Grundstoff*, Lund: Håkan Ohlsson.
Saha, M. N. (1936), "On the origin of mass in neutrons and protons," *Indian Journal of Physics 10*, 141–53.
(1948), "Note on Dirac's theory of magnetic poles," *Physical Review 75*, 1968.
Salam, A., and Wigner, E. P., eds. (1972), *Aspects of Quantum Theory*, Cambridge: Cambridge University Press.
Salaman, E., and Salaman, M. (1986), "Remembering Paul Dirac," *Endeavour*, May, 66–70.
Sambursky, S. (1937), "Static universe and nebular red shift," *Physical Review 52*, 335–8.
Sánchez-Ron, J. M. (1983), "The problems of interaction: on the history of the action-at-a-distance concept in physics," *Fundamenta Scientiae 4*, 55–76.
Schrödinger, E. (1926A), "Quantisierung als Eigenwertproblem (erste Mitteilung)," *Annalen der Physik 79*, 361–76.
(1926B), "Quantisierung als Eigenwertproblem (vierte Mitteilung)," *Annalen der Physik 81*, 109–40.
(1931A), "Zur Quantendynamik des Elektrons," *Sitzungsberichte Preussischen Akademie der Wissenschaften 3*, 63–72.
(1931B), "Spezielle Relativitätstheorie und Quantenmechanik," *Sitzungsberichte Preussischen Akademie der Wissenschaften 3*, 238–47.
(1940), "Maxwell's and Dirac's equations in the expanding universe," *Proceedings of the Royal Irish Academy, Section A 46A*, 25–47.
(1956), *Science, Theory and Man*, London: Allen & Unwin.
Schuster, A. (1898), "Potential matter – a holiday dream," *Nature 58*, 367.

Schweber, S. S. (1986A), "Shelter Island, Pocono, and Oldstone: the emergence of American quantum electrodynamics after World War II," *Osiris 2*, 265–302.
(1986B), "The empiricist temper regnant: theoretical physics in the United States 1920–1950," *Historical Studies in the Physical Sciences 17*, 55–98.
(1986C), "Feynman and the visualization of space–time processes," *Review of Modern Physics 58*, 449–508.
Schwinger, J., ed. (1958), *Selected Papers on Quantum Electrodynamics*, New York: Dover Books.
(1969), "A magnetic model of matter," *Science 165*, 757–61.
Shankland, R. (1936), "An apparent failure in the photon theory of scattering," *Physical Review 49*, 8–13.
Shanmugadhasan, S. (1987), "Dirac as a supervisor and other remembrances," pp. 48–57 in Taylor, ed. (1987).
Singh, J. (1970), *Great Ideas and Theories of Modern Cosmology*, New York: Dover.
Slater, J. C. (1927), "Radiation and absorption on Schrödinger's theory," *Proceedings of the National Academy of Sciences 13*, 7–12.
(1929), "The theory of complex spectra," *Physical Review 34*, 1293–322.
(1967), "Quantum physics in America between the wars," *International Journal of Quantum Chemistry 1*, 1–23.
(1975), *Solid-State and Molecular Theory: A Scientific Biography*, New York: John Wiley & Sons.
Small H., ed. (1981), *Physics Citation Index 1920–1929*, Philadelphia: Institute for Scientific Information.
(1986), "Recapturing physics in the 1920s through citation analysis," *Czechoslovachian Journal of Physics B36*, 142–7.
Smith, A. C., and Weiner, C., eds. (1980), *Robert Oppenheimer, Letters and Recollections*, Cambridge, Mass.: Harvard University Press.
Snow, C. P. (1934), *The Search*, New York: Charles Scribner's Sons.
(1981), *The Physicists*, London: Macmillan.
Stöckler, M. (1984), *Philosophische Probleme der Relativistischen Quantenmechanik*, Berlin: Duncker & Humblot.
Strachan, C., ed. (1969), *The Theory of Beta-Decay*, Oxford: Pergamon.
Stuewer, R. H. (1983), "The nuclear electron hypothesis," pp. 19–68 in W. R. Shea, ed., *Otto Hahn and the Rise of Nuclear Physics*, Dordrecht: Reidel.
Sudarshan, E. C. G., Mukunda, N., and Chiang, C. C. (1982), "Dirac's new relativistic wave equation in interaction with an electromagnetic field," *Proceedings of the Royal Society of London A379*, 103–7.
Sutherland, W. (1898), "Cathode, Lenard, and Röntgen rays," *Philosophical Magazine 47*, 269–84.
Tamm, I. (1930), "Ueber die Wechselwirkung der Freien Elektronen nach der Diracschen Theorie des Elektrons und nach der Quantenelektrodynamik," *Zeitschrift für Physik 62*, 545–68.
(1931), "Die verallgemeinerten Kugelfunktionen und die Wellenfunktionen im Feld eines Magnetpoles," *Zeitschrift für Physik 71*, 141–50.

Taylor, J. G. (1987A), "Constrained dynamics," pp. 114–23 in Taylor, ed. (1987B).
ed. (1987B), *Tributes to Paul Dirac*, Bristol: Adam Hilger.
Teller, E. (1948), "On the change of physical constants," *Physical Review 73*, 801–2.
Thomson, J. J. (1900), *Elements of the Mathematical Theory of Electricity and Magnetism*, Cambridge: Cambridge University Press.
(1907), *The Corpuscular Theory of Matter*, London: Constable and Co.
Tolman, R. C. (1930), "Discussion of various treatments which have been given to the non-static line-element for the universe," *Proceedings of the National Academy of Sciences 16*, 582–94.
Tomonaga, S.-I. (1973), "Development of quantum electrodynamics," pp. 404–12 in Mehra, ed. (1973); reprint of Nobel Lecture, 1966.
Tuve, M. A. (1933), "Search by deflection-experiments for the Dirac isolated magnetic pole," *Physical Review 43*, 770–1.
Van der Waerden, B. L., ed. (1967), *Sources of Quantum Mechanics*, New York: Dover Books.
Van Vleck, J. H. (1932), *The Theory of Electric and Magnetic Susceptibilities*, Oxford: Oxford University Press.
(1934A), "A new method of calculating the mean value of $1/r^2$ for Keplerian systems in quantum mechanics," *Proceedings of the Royal Society of London A143*, 679–81.
(1934B), "The Dirac vector model in complex spectra," *Physical Review 45*, 405–19.
(1968), "My Swiss visits of 1906, 1926, and 1930," *Helvetica Physica Acta 41*, 1234–7.
(1972), "Travels with Dirac in the Rockies," pp. 7–16 in Salam and Wigner, eds. (1972).
Villard, P. (1905), "Les rayons magnétocathodiques," *Revue Générale des Sciences 16*, 405–7.
Vogel, H. (1968), *Physik und Philosophie bei Max Born*, Berlin (GDR): Akademie-Verlag.
Walker, C. T., and Slack, G. A. (1970), "Who named the −ON's?" *American Journal of Physics 38*, 1380–9.
Waller, I. (1930), "Bemerkungen über die Rolle der Eigenenergie des Elektrons in der Quantentheorie der Strahlung," *Zeitschrift für Physik 62*, 673–6.
Weart, S. R., And Szilard, G. W. (1978), *Leo Szilard: His Verson of the Facts*, Cambridge, Mass.: Harvard University Press.
Wechsler, J., ed. (1978), *On Aesthetics in Science*, Cambridge, Mass.: MIT Press.
Weinberg, S. (1977), "The search for unity: notes for a history of quantum field theory," *Dædalus 106*, Fall 1977, 17–35.
Weiner, C., ed. (1972), *Exploring the History of Nuclear Physics*, New York: American Institute of Physics.
Weisskopf, V. F. (1934), "Ueber die Selbstenergie des Elektrons," *Zeitschrift für Physik 89*, 27–39.
(1972), *Physics in the Twentieth Century: Selected Essays*, Cambridge, Mass.: MIT Press.

(1973), "My life as a physicist," pp. 983–97 in A. Zichichi, ed., *Properties of the Fundamental Interactions*, Bologna: Editrice Compositori.
(1983), "Growing up with field theory: the development of quantum electrodynamics," pp. 56–81 in Brown and Hoddeson, eds. (1983).
Weisskopf, V. F., and Wigner, E. (1930), "Berechnung der natürlichen Linienbreite auf Grund der Diracschen Lichttheorie," *Zeitschrift für Physik 63*, 54–73.
Wentzel, G. (1926), "Die mehrfach periodischen Systeme in der Quantenmechanik," *Zeitschrift für Physik 37*, 80–94.
(1933), "Ueber die Eigenkräfte der Elementarteilchen," *Zeitschrift für Physik 86*, 479–94, 635–45.
(1960), "Quantum theory of fields (until 1947)," pp. 48–77 in M. Fierz and W. F. Weisskopf, eds., *Theoretical Physics in the Twentieth Century*, New York: Interscience.
(1966), "Comments on Dirac's theory of magnetic monopoles," *Progress in Theoretical Physics, Suppl.*, nos. 37–8, 163–74.
Werskey, G. (1979), *The Visible College: A Collective Biography of British Scientists and Socialists of the 1930s*, London: Allen Lane.
Wesson, P. S. (1978), *Cosmology and Geophysics*, Bristol: Adam Hilger.
Weyl, H. (1918), "Gravitation and Elektrizität," *Sitzungsberichte der Preussischen Akademie der Wissenschaften*, 1918, 465–78.
(1921), *Raum, Zeit, Materie*, 4th edn., Berlin: Springer.
(1929A), "Gravitation and the electron," *Proceedings of the National Academy of Sciences 15*, 323–34.
(1929B), "Elektron und Gravitation," *Zeitschrift für Physik 56*, 330–52.
(1931), *The Theory of Groups and Quantum Mechanics*, New York: Dover Books (German edn. 1928).
(1932), *The Open World. Three Lectures on the Metaphysical Implications of Science*, New Haven: Yale University Press.
Wheeler, J. A. (1985), "Physics in Copenhagen in 1934 and 1935," pp. 221–6 in A. P. French and P. J. Kennedy, eds., *Niels Bohr. A Centenary Volume*, Cambridge, Mass.: Harvard University Press.
Whitley, S. (1984), "Review of the gas centrifuge until 1962," *Review of Modern Physics 56*, 41–98.
Whittaker, E. T. (1917), *A Treatise on the Analytical Dynamics of Particles and Rigid Bodies*, 2nd edn., Cambridge: Cambridge University Press.
(1921), "On tubes of electromagnetic force," *Proceedings of the Royal Society of Edinburgh 42*, 1–23.
(1949), *From Euclid to Eddington*, Cambridge: Cambridge University Press.
(1960), *A History of the Theories of Aether and Electricity*, vol. 2, New York: Harper.
Wick, G. C. (1934), "Induced radioactivity," *Rendiconti Lincei 19*, 319–24.
Wien, W. (1930), *Aus dem Leben und Wirken eines Physikers*, Leipzig: Teubner.
Wigner, E. P. (1928), "Ueber die Erhaltungssätze in der Quantenmechanik," *Nachrichten von der Kgl. Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, 1928, 375–81.

(1932), "Ueber die Operation der Zeitumkehr in der Quantenmechanik," *Nachrichten von der Kgl. Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, 1932, 546–59.
(1939), "On unitary representations of the inhomogeneous Lorentz group," *Annals of Mathematics 40*, 149–204.
(1947), *Physical Science and Human Values*, Princeton: Princeton University Press.
(1969), "The unreasonable effectiveness of mathematics in the natural sciences," pp. 123–40 in T. L. Saaty and F. J. Weyl, eds., *The Spirit and the Uses of Mathematical Sciences*, New York: McGraw-Hill.
(1973), "Relativistic equations in quantum mechanics," pp. 320–31 in Mehra, ed. (1973).
(1984), "Interview de Eugene P. Wigner sur sa vie scientifique," *Archive Internationale d'Histoire des Sciences 34*, 177–217.
Williams, E. J. (1935), "Correlation of certain collision problems with radiation theory," *Kongelige Danske Videnskabernes Selskab, Matematisk-Fysiske Meddelelser, 13*, no. 1, 1–50.
(1936), "Conservation of energy and momentum in atomic processes," *Nature 137*, 614–15.
Williamson, R., ed. (1987), *The Making of Physicists*, Bristol: Adam Hilger.
Wood, R. W. (1908), "On the existence of positive electrons in the sodium atom," *Philosophical Magazine 15*, 274–9.
Yourgrau, W. (1961), "Some problems concerning fundamental constants in physics," pp. 319–41 in H. Feigl and G. Maxwell, eds., *Current Issues in the Philosophy of Science*, New York: Holt, Rinehart & Winston.
Yukawa, H., and Sakata, S. (1937), "Note on Dirac's generalized wave equations," *Proceedings of the Mathematical-Physical Society of Japan 19*, 91–5.

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