Paul Dirac

Paul Adrien Maurice Dirac (/dɪˈræk/ *dih-RAK*; 8 August 1902 – 20 October 1984) was an English mathematical and theoretical physicist who is considered to be one of the founders of quantum mechanics.[6][7] Dirac laid the foundations for both quantum electrodynamics and quantum field theory.[8][9][10][11] He was the Lucasian Professor of Mathematics at the University of Cambridge, a professor of physics at Florida State University and a 1933 Nobel Prize in Physics recipient.

Dirac graduated from the University of Bristol with a first class honours Bachelor of Science degree in electrical engineering in 1921, and a first class honours Bachelor of Arts degree in mathematics in 1923.[12] Dirac then graduated from the University of Cambridge with a PhD in physics in 1926, writing the first ever thesis on quantum mechanics.[13]

Dirac made fundamental contributions to the early development of both quantum mechanics and quantum electrodynamics, coining the latter term.[10] Among other discoveries, he formulated the Dirac equation in 1928, which describes the behaviour of fermions and predicted the existence of antimatter,[14] which is one of the most important equations in physics,[8] and is regarded by some physicists as the "real seed of modern physics".[15] He wrote a famous paper in 1931,[16] which further predicted the existence of antimatter.[17][18][14] Dirac shared the 1933 Nobel Prize in Physics with Erwin Schrödinger for "the discovery of new productive forms of atomic theory".[19] He was the youngest ever theoretician to win the prize, at the age of 31, until T. D. Lee in 1957.[20] Dirac also contributed greatly to the reconciliation of general relativity with quantum mechanics. His 1930 monograph, *The Principles of Quantum Mechanics*, is one of the most influential texts on quantum mechanics.[21]

Paul Dirac	
OM FRS	
Dirac in 1933	
Born	Paul Adrien Maurice Dirac 8 August 1902 Bristol, England
Died	20 October 1984 (aged 82) Tallahassee, Florida, U.S.
Alma mater	University of Bristol (BS, 1921; BA, 1923) University of Cambridge (PhD, 1926)
Known for	- Introducing Fermi–Dirac statistics (1926) - Founding quantum electrodynamics (1927) - Formulating the Dirac equation (1928) - Postulating the positron (1928)

Dirac's contributions were not restricted to quantum mechanics. He contributed to the Tube Alloys project, the British programme to research and construct atomic bombs during World War II.[22][23] Dirac made fundamental contributions to the process of uranium enrichment and the gas centrifuge,[24][25][26][23] and whose work was deemed to be "probably the most important theoretical result in centrifuge technology".[27] He also contributed to cosmology, putting forth his large numbers hypothesis.[28][29][30][31] Dirac also anticipated string theory well before its inception, with work such as the Dirac membrane and Dirac–Born–Infeld action, along with other contributions important to modern-day string and gauge theories.[32][33][34][35]

Dirac was regarded by his friends and colleagues as unusual in character. In a 1926 letter to Paul Ehrenfest, Albert Einstein wrote of a Dirac paper, "I am toiling over Dirac. This balancing on the dizzying path between genius and madness is awful." In another letter concerning the Compton effect he wrote, "I don't understand the details of Dirac at all."[36] In 1987, Abdus Salam declared that "Dirac was undoubtedly one of the greatest physicists of this or any century . . . No man except Einstein has had such a decisive influence, in so short a time, on the course of physics in this century."[37] In 1995, Stephen Hawking stated that "Dirac has done more than anyone this century, with the exception of Einstein, to advance physics and change our picture of the universe".[38] Antonino Zichichi asserted that Dirac had a greater impact on modern physics than Einstein,[15] while Stanley Deser remarked that "We all stand on Dirac's shoulders."[39] Dirac is widely considered to be on par with Sir Isaac Newton, James Clerk Maxwell, and Einstein.[40][41][42]

Personal life

Early years

Paul Adrien Maurice Dirac was born at his parents' home in Bristol, England, on 8 August 1902,[43] and grew up in the Bishopston area of the city.[44] His father, Charles Adrien Ladislas Dirac, was an immigrant from Saint-Maurice, Switzerland, of French descent,[45] who worked in Bristol as a French teacher. His mother, Florence Hannah Dirac, née Holten, was born to a Cornish Methodist family in

	▪ Postulating the magnetic monopole (1931) ▪ Introducing the bra–ket notation (1939)
Spouse	Margit Wigner (m. 1937)
Children	2
Relatives	Eugene Wigner (brother-in-law)
Awards	FRS (1930) Nobel Prize in Physics (1933) Royal Medal (1939) Copley Medal (1952) Max Planck Medal (1952)
Honours	Order of Merit (1973)
Scientific career	
Fields	Theoretical physics
Institutions	University of Cambridge
Thesis	*Quantum Mechanics (http://www.worldcat.org/oclc/15668650)* (1926)
Doctoral advisor	Ralph H. Fowler
Doctoral students	Homi J. Bhabha[1] Harish-Chandra[2] Dennis Sciama Fred Hoyle[3] Behram Kurşunoğlu[4] John Polkinghorne[5] C. J. Eliezer
15th Lucasian Professor of Mathematics	
In office 1932–1969	
Preceded by	Joseph Larmor
Succeeded by	James Lighthill

Liskeard, Cornwall.[46][47] She was named after Florence Nightingale by her father, a ship's captain, who had met Nightingale while he was a soldier during the Crimean war.[48] His mother moved to Bristol as a young woman, where she worked as a librarian at the Bristol Central Library; despite this she still considered her identity to be Cornish rather than English.[49] Paul had a younger sister, Béatrice Isabelle Marguerite, known as Betty, and an older brother, Reginald Charles Félix, known as Felix,[50][51] who died by suicide in March 1925.[52] Dirac later recalled: "My parents were terribly distressed. I didn't know they cared so much ... I never knew that parents were supposed to care for their children, but from then on I knew."[53]

Portrait of Paul Dirac by Clara Ewald, 1939

Charles and the children were officially Swiss nationals until they became naturalised on 22 October 1919.[54] Dirac's father was strict and authoritarian, although he disapproved of corporal punishment.[55] Dirac had a strained relationship with his father, so much so that after his father's death, Dirac wrote, "I feel much freer now, and I am my own man." Charles forced his children to speak to him only in French so that they might learn the language. When Dirac found that he could not express what he wanted to say in French, he chose to remain silent.[56][57]

Education

Dirac was educated first at Bishop Road Primary School[58] and then at the all-boys Merchant Venturers' Technical College (later Cotham School), where his father was a French teacher.[59] The school was an institution attached to the University of Bristol, which shared grounds and staff.[60] It emphasised technical subjects like bricklaying, shoemaking and metalwork, and modern languages.[61] This was unusual at a time when secondary education in Britain was still dedicated largely to the classics, and something for which Dirac would later express his gratitude.[60]

Dirac studied electrical engineering on a City of Bristol University Scholarship at the University of Bristol's engineering faculty, which was co-located with the Merchant Venturers' Technical College.[62] Shortly before he completed his degree in 1921, he sat for the entrance examination for St John's College, Cambridge. He passed and was awarded a £70 scholarship, but this fell short of the amount of money required to live and study at Cambridge. Despite having graduated with a first class honours Bachelor of Science degree in electrical engineering, the economic climate of the post-war depression was such that he was unable to find work as an engineer. Instead, he took up an offer to study for a Bachelor of Arts degree in mathematics at the University of Bristol free of charge. He was permitted to skip the first year of the course owing to his engineering degree.[63] Under the influence of Peter Fraser, whom Dirac called the best mathematics teacher, he had the most interest in projective geometry, and began applying it to the geometrical version of relativity Minkowski developed.[64]

In 1923, Dirac graduated, once again with first class honours, and received a £140 scholarship from the Department of Scientific and Industrial Research.[65] Along with his £70 scholarship from St John's College, this was enough to live at Cambridge. There, Dirac pursued his interests in the theory of general relativity, an interest he had gained earlier as a student in Bristol, and in the nascent field of quantum physics, under the supervision of Ralph Fowler.[66] From 1925 to 1928 he held an 1851 Research Fellowship from the Royal Commission for the Exhibition of 1851.[67] He completed his PhD in June

1926 with the first thesis on quantum mechanics to be submitted anywhere.[68] He then continued his research in Copenhagen and Göttingen.[67] In the spring of 1929, he was a visiting professor at the University of Wisconsin–Madison.[69][70]

Family

In 1937, Dirac married[71] Margit Wigner, a sister of physicist Eugene Wigner[72] and a divorcee.[73] Dirac raised Margit's two children, Judith and Gabriel, as if they were his own.[74] Paul and Margit Dirac also had two daughters together, Mary Elizabeth and Florence Monica.[75]

Margit, known as Manci, had visited her brother in 1934 in Princeton, New Jersey, from their native Hungary and, while at dinner at the Annex Restaurant, met the "lonely-looking man at the next table". This account from a Korean physicist, Y. S. Kim, who met and was influenced by Dirac, also says: "It is quite fortunate for the physics community that Manci took good care of our respected Paul A. M. Dirac. Dirac published eleven papers during the period 1939–46. Dirac was able to maintain his normal research productivity only because Manci was in charge of everything else".[76]

Paul and Manci Dirac in Copenhagen, July 1963

Personality

Dirac was known among his colleagues for his precise and taciturn nature. His colleagues in Cambridge jokingly defined a unit called a "dirac", which was one word per hour.[77] When Niels Bohr complained that he did not know how to finish a sentence in a scientific article he was writing, Dirac replied, "I was taught at school never to start a sentence without knowing the end of it."[78] He criticised the physicist J. Robert Oppenheimer's interest in poetry: "The aim of science is to make difficult things understandable in a simpler way; the aim of poetry is to state simple things in an incomprehensible way. The two are incompatible."[79]

Dirac himself wrote in his diary during his postgraduate years that he concentrated solely on his research, and stopped only on Sunday when he took long strolls alone.[80]

An anecdote recounted in a review of the 2009 biography tells of Werner Heisenberg and Dirac sailing on an ocean liner to a conference in Japan in August 1929. "Both still in their twenties, and unmarried, they made an odd couple. Heisenberg was a ladies' man who constantly flirted and danced, while Dirac—'an Edwardian geek', as biographer Graham Farmelo puts it—suffered agonies if forced into any kind of socializing or small talk. 'Why do you dance?' Dirac asked his companion. 'When there are nice girls, it is a pleasure,' Heisenberg replied. Dirac pondered this notion, then blurted out: 'But, Heisenberg, how do you know beforehand that the girls are nice?' "[81]

Margit Dirac told both George Gamow and Anton Capri in the 1960s that her husband had said to a house visitor, "Allow me to present Wigner's sister, who is now my wife."[82][83]

Another story told of Dirac is that when he first met the young Richard Feynman at a conference, he said after a long silence, "I have an equation. Do you have one too?"[84]

After he presented a lecture at a conference, one colleague raised his hand and said: "I don't understand the equation on the top-right-hand corner of the blackboard". After a long silence, the moderator asked Dirac if he wanted to answer the question, to which Dirac replied: "That was not a question, it was a comment."[85][86]

Dirac was also noted for his personal modesty. He called the equation for the time evolution of a quantum-mechanical operator, which he was the first to write down, the "Heisenberg equation of motion". Most physicists speak of Fermi–Dirac statistics for half-integer-spin particles and Bose–Einstein statistics for integer-spin particles. While lecturing later in life, Dirac always insisted on calling the former "Fermi statistics". He referred to the latter as "Bose statistics" for reasons, he explained, of "symmetry".[87]

Views on religion

Heisenberg recollected a conversation among young participants at the 1927 Solvay Conference about Einstein and Planck's views on religion between Wolfgang Pauli, Heisenberg and Dirac. Dirac's contribution was a criticism of the political purpose of religion, which Bohr regarded as quite lucid when hearing it from Heisenberg later.[88] Among other things, Heisenberg imagined that Dirac might say:

> I don't know why we are discussing religion. If we are honest—and scientists have to be— we must admit that religion is a jumble of false assertions, with no basis in reality. The very idea of God is a product of the human imagination. It is quite understandable why primitive people, who were so much more exposed to the overpowering forces of nature than we are today, should have personified these forces in fear and trembling. But nowadays, when we understand so many natural processes, we have no need for such solutions. I can't for the life of me see how the postulate of an Almighty God helps us in any way. What I do see is that this assumption leads to such unproductive questions as to why God allows so much misery and injustice, the exploitation of the poor by the rich, and all the other horrors He might have prevented. If religion is still being taught, it is by no means because its ideas still convince us, but simply because some of us want to keep the lower classes quiet. Quiet people are much easier to govern than clamorous and dissatisfied ones. They are also much easier to exploit. Religion is a kind of opium that allows a nation to lull itself into wishful dreams and so forget the injustices that are being perpetrated against the people. Hence the close alliance between those two great political forces, the State and the Church. Both need the illusion that a kindly God rewards—in heaven if not on earth—all those who have not risen up against injustice, who have done their duty quietly and uncomplainingly. That is precisely why the honest assertion that God is a mere product of the human imagination is branded as the worst of all mortal sins.[89]

Heisenberg's view was tolerant. Pauli, raised as a Catholic, had kept silent after some initial remarks, but when finally he was asked for his opinion, said: "Well, our friend Dirac has got a religion and its guiding principle is 'There is no God, and Paul Dirac is His prophet.'" Everybody, including Dirac, burst into laughter.[90][91]

Later in life, Dirac wrote an article mentioning God that appeared in the May 1963 edition of *Scientific American*, Dirac wrote:

It seems to be one of the fundamental features of nature that fundamental physical laws are described in terms of a mathematical theory of great beauty and power, needing quite a high standard of mathematics for one to understand it. You may wonder: Why is nature constructed along these lines? One can only answer that our present knowledge seems to show that nature is so constructed. We simply have to accept it. One could perhaps describe the situation by saying that God is a mathematician of a very high order, and He used very advanced mathematics in constructing the universe. Our feeble attempts at mathematics enable us to understand a bit of the universe, and as we proceed to develop higher and higher mathematics we can hope to understand the universe better.[92]

In 1971, at a conference meeting, Dirac expressed his views on the existence of God.[93] Dirac explained that the existence of God could be justified only if an improbable event were to have taken place in the past:

It could be that it is extremely difficult to start life. It might be that it is so difficult to start a life that it has happened only once among all the planets... Let us consider, just as a conjecture, that the chance of life starting when we have got suitable physical conditions is 10^{-100}. I don't have any logical reason for proposing this figure, I just want you to consider it as a possibility. Under those conditions ... it is almost certain that life would not have started. And I feel that under those conditions it will be necessary to assume the existence of a god to start off life. I would like, therefore, to set up this connection between the existence of a god and the physical laws: if physical laws are such that to start off life involves an excessively small chance so that it will not be reasonable to suppose that life would have started just by blind chance, then there must be a god, and such a god would probably be showing his influence in the quantum jumps which are taking place later on. On the other hand, if life can start very easily and does not need any divine influence, then I will say that there is no god.[94]

Dirac did not commit himself to any definite view, but he described the possibilities for scientifically answering the question of God.[94]

Career

Dirac discovered the relativistic equation for the electron, which now bears his name. The remarkable notion of an antiparticle to each fermion particle – e.g. the positron as antiparticle to the electron – stems from his equation. He is credited as being the one to create quantum field theory, which underlies all theoretical work on sub-atomic or "elementary" particles today, work that is fundamental to our understanding of the forces of nature, alongside creating quantum electrodynamics and coining the term.[9][11] He proposed and investigated the concept of a magnetic monopole, an object not yet known empirically, as a means of bringing even greater symmetry to James Clerk Maxwell's equations of electromagnetism. Dirac also coined the terms "fermion" and "boson".[95]

Throughout his career, Dirac was motivated by the principles of mathematical beauty,[96] with Peter Goddard stating that "Dirac cited mathematical beauty as the ultimate criterion for selecting the way forward in theoretical physics".[97] Dirac was recognised for being mathematically gifted, as during his

time in university, academics had affirmed that Dirac had an "ability of the highest order in mathematical physics",[98] with Ebenezer Cunningham stating that Dirac was "quite the most original student I have met in the subject of mathematical physics".[99] Therefore, Dirac was known for his "astounding physical intuition combined with the ability to invent new mathematics to create new physics".[17] During his career, Dirac made numerous important contributions to mathematical subjects, including the Dirac delta function, Dirac algebra and the Dirac operator.

The 1927 Solvay Conference in Brussels, a gathering of the world's top physicists. Dirac is in the centre of the middle row, seated behind Albert Einstein.

Quantum theory

Dirac's first step into a new quantum theory was taken late in September 1925. Ralph Fowler, his research supervisor, had received a proof copy of an exploratory paper by Werner Heisenberg in the framework of the old quantum theory of Bohr and Sommerfeld. Heisenberg leaned heavily on Bohr's correspondence principle but changed the equations so that they involved directly observable quantities, leading to the matrix formulation of quantum mechanics. Fowler sent Heisenberg's paper on to Dirac, who was on vacation in Bristol, asking him to look into this paper carefully.[100]

Dirac's attention was drawn to a mysterious mathematical relationship, at first sight unintelligible, that Heisenberg had established. Several weeks later, back in Cambridge, Dirac suddenly recognised that this mathematical form had the same structure as the Poisson brackets that occur in the classical

Dirac (front row 3rd from left), next to Éamon de Valera (front row 4th from left), Erwin Schrödinger (front row 2nd from right) at Dublin Institute for Advanced Studies in 1942

dynamics of particle motion.[100] At the time, his memory of Poisson brackets was rather vague, but he found E. T. Whittaker's *Analytical Dynamics of Particles and Rigid Bodies* illuminating.[101] From his new understanding, he developed a quantum theory based on non-commuting dynamical variables. This led him to the most profound and significant general formulation of quantum mechanics to date.[102] His novel formulation using Dirac brackets allowed him to obtain the quantisation rules in a novel and more illuminating manner. For this work,[103] published in 1926, Dirac received a PhD from Cambridge. This formed the basis for Fermi–Dirac statistics that applies to systems consisting of many identical spin 1/2 particles (i.e. that obey the Pauli exclusion principle), e.g. electrons in solids and liquids, and importantly to the field of conduction in semi-conductors.

Dirac was famously not bothered by issues of interpretation in quantum theory. In fact, in a paper published in a book in his honour, he wrote: "The interpretation of quantum mechanics has been dealt with by many authors, and I do not want to discuss it here. I want to deal with more fundamental things."[104] However, in 1964 he wrote a short article about the interpretation of quantum field theory when based on the Heisenberg picture of quantum theory; his primary point in the article was that the Schrödinger model does not work for this purpose.[105]

The Dirac equation

In 1928, building on 2×2 spin matrices which he purported to have discovered independently of Wolfgang Pauli's work on non-relativistic spin systems (Dirac told Abraham Pais, "I believe I got these [matrices] independently of Pauli and possibly Pauli got these independently of me."),[106] he proposed the Dirac equation as a relativistic equation of motion for the wave function of the electron.[107] This work led Dirac to predict the existence of the positron, the electron's antiparticle, which he interpreted in terms of what came to be called the *Dirac sea*.[108] The positron was observed by Carl Anderson in 1932. Dirac's equation also contributed to explaining the origin of quantum spin as a relativistic phenomenon.

The necessity of fermions (matter) being created and destroyed in Enrico Fermi's 1934 theory of beta decay led to a reinterpretation of Dirac's equation as a "classical" field equation for any point particle of spin $\hbar/2$, itself subject to quantisation conditions involving anti-commutators. Thus reinterpreted, in 1934 by Werner Heisenberg, as a (quantum) field equation accurately describing all elementary matter particles – today quarks and leptons – this Dirac field equation is as central to theoretical physics as the Maxwell, Yang–Mills and Einstein field equations. Dirac is regarded as the founder of quantum electrodynamics, being the first to use that term. He also introduced the idea of vacuum polarisation in the early 1930s. This work was key to the development of quantum mechanics by the next generation of theorists, in particular Schwinger, Feynman, Sin-Itiro Tomonaga and Dyson in their formulation of quantum electrodynamics.

Dirac's *The Principles of Quantum Mechanics*, published in 1930, is a landmark in the history of science. It quickly became one of the standard textbooks on the subject and is still used today. In that book, Dirac incorporated the previous work of Werner Heisenberg on matrix mechanics and of Erwin Schrödinger on wave mechanics into a single mathematical formalism that associates measurable quantities to operators acting on the Hilbert space of vectors that describe the state of a physical system. The book also introduced the Dirac delta function. Following his 1939 article,[109] he also included the bra–ket notation in the third edition of his book,[110] thereby contributing to its universal use nowadays.

Magnetic monopoles

In 1931, Dirac proposed that the existence of a single magnetic monopole in the universe would suffice to explain the quantisation of electrical charge.[111] No such monopole has been detected, despite numerous attempts and preliminary claims.[112] (see also Searches for magnetic monopoles).

Gravity

Dirac quantised the gravitational field.[46][113] His work laid the foundations for canonical quantum gravity.[114] In his 1959 lecture at the Lindau Meetings, Dirac discussed why gravitational waves have "physical significance".[115] Dirac predicted gravitational waves would have well defined energy density in 1964.[113] Dirac reintroduced the term "graviton" in a number of lectures in 1959, noting that the energy of the gravitational field should come in quanta.[116][117]

String theory

Dirac is seen as having anticipated string theory, with his work on the Dirac membrane and Dirac–Born–Infeld action, both of which he proposed in a 1962 paper,[118][119] along with other contributions.[32][33] He also developed a general theory of the quantum field with dynamical constraints,[120][121][32] which

forms the basis of the gauge theories and superstring theories of today.[32][46][122]

Significant and influential work

Shortly after Wolfgang Pauli proposed his Pauli exclusion principle that two electrons cannot occupy the same quantum energy level, Enrico Fermi and Dirac[103] both realized the principle would dramatically alter the statistical mechanics of electron systems. This work became the basis for Fermi–Dirac statistics.[123]:488

Dirac wrote an influential paper in 1933 regarding the Lagrangian in quantum mechanics.[124] The paper served as the basis for Julian Schwinger and his quantum action principle,[125] and laid the foundations for Richard Feynman's development of a completely new approach to quantum mechanics, the path integral formulation.[113][126]

In a 1963 paper,[127] Dirac initiated the study of field theory on anti-de Sitter space (AdS).[128] The paper contains the mathematics of combining special relativity with the quantum mechanics of quarks inside hadrons, and lays the foundations of two-mode squeezed states that are essential to modern quantum optics, though Dirac did not realize it at the time.[129] Dirac previously worked on AdS during the 1930s,[130] publishing a paper in 1935.[131]

In 1930, Victor Weisskopf and Eugene Wigner published their famous and now standard calculation of spontaneous radiation emission in atomic and molecular physics.[132] Remarkably, in a letter to Niels Bohr in February 1927, Dirac had come to the same calculation,[133] but he did not publish it.[134]

In 1938,[135] Dirac renormalized the mass in the theory of Abraham-Lorentz electron, leading to the Abraham–Lorentz–Dirac force, which is the relativistic-classical electron model; however, this model has solutions that suggest force increase exponentially with time.[136]

Fermi's golden rule, the formula for computing quantum transitions in time dependent systems, declared a "golden rule" by Enrico Fermi, was derived by Dirac.[137] Dirac was the one to initiate the development of time-dependent perturbation theory in his early work on semi-classical atoms interacting with an electromagnetic field. Dirac, with Werner Heisenberg, John Archibald Wheeler, Richard Feynman, and Freeman Dyson ultimately developed this concept into an invaluable tool for modern physics, used in the calculation of the properties of any physical system and a wide array of phenomena.[138]

University of Cambridge

Dirac was the Lucasian Professor of Mathematics at the University of Cambridge from 1932 to 1969. He conceived the Helikon vortex isotope separation process in 1934.[139][140] In 1937, he proposed a speculative cosmological model based on the large numbers hypothesis. During World War II, he conducted important theoretical work on uranium enrichment by gas centrifuge.[141] He introduced the separative work unit (SWU) in 1941.[142] He contributed to the Tube Alloys project, the British programme to research and construct atomic bombs during World War II.[143][23]

Dirac's quantum electrodynamics (QED) included terms with infinite self-energy. A workaround known as renormalisation was developed, but Dirac never accepted this. "I must say that I am very dissatisfied with the situation", he said in 1975, "because this so-called 'good theory' does involve neglecting infinities which appear in its equations, neglecting them in an arbitrary way. This is just not sensible

mathematics. Sensible mathematics involves neglecting a quantity when it is small – not neglecting it just because it is infinitely great and you do not want it!"[144] His refusal to accept renormalisation resulted in his work on the subject moving increasingly out of the mainstream. Shin'ichirō Tomonaga, Schwinger and Feynman mastered this approach, producing a QED with unprecedented accuracy, resulting formal recognition by an award of the Nobel Prize for physics.[145]

In the 1950s in his search for a better QED, Paul Dirac developed the Hamiltonian theory of constraints[146][147] based on lectures that he delivered at the 1949 International Mathematical Congress in Canada. Dirac had also solved the problem of putting the Schwinger–Tomonaga equation into the Schrödinger representation[148] and given explicit expressions for the scalar meson field (spin zero pion or pseudoscalar meson), the vector meson field (spin one rho meson), and the electromagnetic field (spin one massless boson, photon).

The Hamiltonian of constrained systems is one of Dirac's many masterpieces. It is a powerful generalisation of Hamiltonian theory that remains valid for curved spacetime. The equations for the Hamiltonian involve only six degrees of freedom described by g_{rs}, p^{rs} for each point of the surface on which the state is considered. The g_{m0} (m = 0, 1, 2, 3) appear in the theory only through the variables g^{r0}, $(-g^{00})^{-1/2}$ which occur as arbitrary coefficients in the equations of motion. There are four constraints or weak equations for each point of the surface x^0 = constant. Three of them H_r form the four vector density in the surface. The fourth H_L is a 3-dimensional scalar density in the surface $H_L \approx 0$; $H_r \approx 0$ (r = 1, 2, 3)

In the late 1950s, he applied the Hamiltonian methods he had developed to cast Einstein's general relativity in Hamiltonian form[149][150] and to bring to a technical completion the quantisation problem of gravitation and bring it also closer to the rest of physics according to Salam and DeWitt. In 1959 he also gave an invited talk on "Energy of the Gravitational Field" at the New York Meeting of the American Physical Society.[151] In 1964 he published his *Lectures on Quantum Mechanics* (London: Academic) which deals with constrained dynamics of nonlinear dynamical systems including quantisation of curved spacetime. He also published a paper entitled "Quantization of the Gravitational Field" in the 1967 ICTP/IAEA Trieste Symposium on Contemporary Physics.

The 1963–1964 lectures Dirac gave on quantum field theory at Yeshiva University were published in 1966 as the Belfer Graduate School of Science, Monograph Series Number, 3.
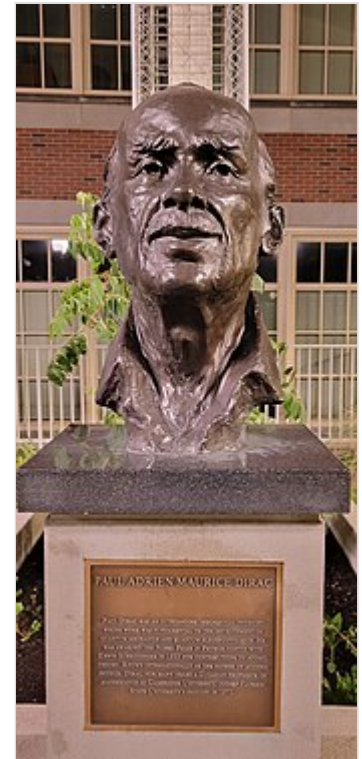
Florida State University and University of Miami

In 1969, Dirac was forced to retire from his chair at Cambridge, due to his age (67).[152] Before his retirement he was offered a visiting position at the University of Miami in Coral Gables, Florida; he accepted, joining its newly formed Center for Theoretical Studies.[153] In September 1970 he also accepted a visiting professor position at Florida State University in Tallahassee, Florida, and moved his family to Tallahassee. He accepted a position at FSU as a full professor in 1972.[96][154]

Contemporary accounts of his time in Tallahassee describe it as happy, except that he apparently found the summer heat oppressive and liked to escape from it to Cambridge.[155] He would walk about a mile to work each day and was fond of swimming in one of the two nearby lakes (Silver Lake and Lost Lake),

and was also more sociable than he had been at the University of Cambridge, where he mostly worked at home apart from giving classes and seminars. At Florida State, he would usually eat lunch with his colleagues before taking a nap.[156]

Dirac published over 60 papers at FSU during those last twelve years of his life, including a short book on general relativity.[157] His last paper (1984), entitled "The inadequacies of quantum field theory," contains his final judgment on quantum field theory: "These rules of renormalisation give surprisingly, excessively good agreement with experiments. Most physicists say that these working rules are, therefore, correct. I feel that is not an adequate reason. Just because the results happen to be in agreement with observation does not prove that one's theory is correct." The paper ends with the words: "I have spent many years searching for a Hamiltonian to bring into the theory and have not yet found it. I shall continue to work on it as long as I can and other people, I hope, will follow along such lines."[158]

In 1975, Dirac gave a series of five lectures at the University of New South Wales which were subsequently published as a book, *Directions in Physics* (1978). He donated the royalties from this book to the university for the establishment of Dirac Lecture Series. The Silver Dirac Medal for the Advancement of Theoretical Physics is awarded by the University of New South Wales to commemorate the lecture.[159]

A bust of Paul Dirac at Florida State University

Students

Amongst his many students[3][160] were Homi J. Bhabha,[1] Fred Hoyle, John Polkinghorne[5] and Freeman Dyson.[161] Polkinghorne recalls that Dirac "was once asked what was his fundamental belief. He strode to a blackboard and wrote that the laws of nature should be expressed in beautiful equations."[162]

Honours

Dirac shared the 1933 Nobel Prize for physics with Erwin Schrödinger "for the discovery of new productive forms of atomic theory".[19] Dirac was also awarded the Royal Medal in 1939 and both the Copley Medal and the Max Planck Medal in 1952. He was elected a Fellow of the Royal Society in 1930,[163][45] a member of the American Philosophical Society in 1938,[164] an Honorary Fellow of the American Physical Society in 1948, a member of the United States National Academy of Sciences in 1949,[165] a member of the American Academy of Arts and Sciences in 1950,[166] and an Honorary Fellow of the Institute of Physics, London in 1971. He received the inaugural J. Robert Oppenheimer Memorial Prize in 1969.[167][168] Dirac became a member of the Order of Merit in 1973, having previously turned down a knighthood as he did not want to be addressed by his first name.[81][169]

In Lev Landau's logarithmic scale of physicists from 0 to 5 based off productivity and genius, he ranked Dirac a 1, along with other fathers of quantum mechanics, such as Werner Heisenberg and Erwin Schrödinger.[170]

Death

In 1984, Dirac died in Tallahassee, Florida, and was buried at Tallahassee's Roselawn Cemetery.[171] Dirac's childhood home in Bishopston, Bristol is commemorated with a blue plaque,[172] and the nearby Dirac Road is named in recognition of his links with the city of Bristol. A commemorative stone was erected in a garden in Saint-Maurice, Switzerland, the town of origin of his father's family, on 1 August 1991. On 13 November 1995 a commemorative marker, made from Burlington green slate and inscribed with the Dirac equation, was unveiled in Westminster Abbey.[171][173] The Dean of Westminster, Edward Carpenter, had initially refused permission for the memorial, thinking Dirac to be anti-Christian, but was eventually (over a five-year period) persuaded to relent.[174]

The tombstone of Dirac and his wife in Roselawn Cemetery, Tallahassee, Florida. Their daughter Mary Elizabeth Dirac, who died 20 January 2007, is buried next to them.

Legacy

On the occasion of the 100th anniversary of Dirac's birth, Richard Dalitz wrote "The influence and importance of Dirac's work have increased with the decades, and physicists use daily the concepts and equations that he developed."[46]

After his death, two organisations of professional physicists established annual awards in Dirac's memory. The Institute of Physics, the United Kingdom's professional body for physicists, awards the Paul Dirac Medal for "outstanding contributions to theoretical (including mathematical and computational) physics".[175] The first three recipients were Stephen Hawking (1987), John Stewart Bell (1988), and Roger Penrose (1989). Since 1985, the International Centre for Theoretical Physics awards the Dirac Medal of the ICTP each year on Dirac's birthday (8 August).[176]

The commemorative marker in Westminster Abbey

The Dirac-Hellman Award at Florida State University was endowed by Bruce P. Hellman in 1997 to reward outstanding work in theoretical physics by FSU researchers.[177] The Paul A.M. Dirac Science Library at Florida State University, which Manci opened in December 1989,[178] is named in his honour, and his papers are held there.[179] Outside is a statue of him by Gabriella Bollobás.[180] The street on which the National High Magnetic Field Laboratory in Innovation Park of Tallahassee, Florida, is located is named Paul Dirac Drive. As well as in his hometown of Bristol, there is also a road named after him, Dirac Place, in Didcot, Oxfordshire.[181] The Dirac-Higgs Science Centre in Bristol is also named in his honour.[182]

The BBC named a video codec, Dirac, in his honour. An asteroid discovered in 1983 was named after Dirac.[183] The Distributed Research utilising Advanced Computing (DiRAC) and Dirac software are named in his honour.

Publications

- *The Principles of Quantum Mechanics* (1930): This book summarises the ideas of quantum mechanics using the modern formalism that was largely developed by Dirac himself. Towards the end of the book, he also discusses the relativistic theory of the electron (the Dirac equation), which was also pioneered by him. This work does not refer to any other writings then available on quantum mechanics.
- *Lectures on Quantum Mechanics* (1966): Much of this book deals with quantum mechanics in curved space-time.
- *Lectures on Quantum Field Theory* (1966): This book lays down the foundations of quantum field theory using the Hamiltonian formalism.
- *Spinors in Hilbert Space* (1974): This book based on lectures given in 1969 at the University of Miami deals with the basic aspects of spinors starting with a real Hilbert space formalism. Dirac concludes with the prophetic words "We have boson variables appearing automatically in a theory that starts with only fermion variables, provided the number of fermion variables is infinite. There must be such boson variables connected with electrons..."
- *General Theory of Relativity* (1975): This 69-page work summarises Einstein's general theory of relativity.

References

Citations

1. Bhabha, Homi Jehangir (1935). *On cosmic radiation and the creation and annihilation of positrons and electrons* (https://www.repository.cam.ac.uk/handle/1810/250819) (PhD thesis). University of Cambridge. EThOS uk.bl.ethos.727546 (https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.727546).
2. Harish-Chandra (http://mathshistory.st-andrews.ac.uk/Biographies/Harish-Chandra.html), School of Mathematics and Statistics, University of St Andrews.
3. Paul Dirac (https://mathgenealogy.org/id.php?id=18524) at the Mathematics Genealogy Project
4. DeWitt, C. M., & Rickles, D., eds., *The Role of Gravitation in Physics: Report from the 1957 Chapel Hill Conference* (Berlin: Edition Open Access, 2011), p. 30.
5. Polkinghorne, John Charlton (1955). *Contributions to quantum field theory* (http://idiscover.lib.cam.ac.uk/primo-explore/fulldisplay?docid=44CAM_ALMA21428195830003606&context=L&vid=44CAM_PROD&search_scope=SCOP_CAM_ALL&tab=cam_lib_coll&lang=en_US) (PhD thesis). University of Cambridge. EThOS uk.bl.ethos.727138 (https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.727138).
6. Simmons, John (1997). *The Scientific 100: A Ranking of the Most Influential Scientists, Past and Present* (https://archive.org/details/100mostinfluenti0000simm). Secaucus, New Jersey: Carol Publishing Group. pp. 104–108. ISBN 978-0806517490.
7. Mukunda, N., *Images of Twentieth Century Physics* (Bangalore: Jawaharlal Nehru Centre for Advanced Scientific Research, 2000), p. 9 (https://books.google.com/books?id=YFGJ2PAEUmwC&pg=PP9).
8. Berry, Michael (1 February 1998). "Paul Dirac: the purest soul in physics" (https://physicsworld.com/paul-dirac-the-purest-soul-in-physics/). *Physics World*. Retrieved 16 October 2023.

9. Duck, Ian; Sudarshan, E. C. G. (1998). "Chapter 6: Dirac's Invention of Quantum Field Theory". *Pauli and the Spin-Statistics Theorem* (https://archive.org/details/paulispinstatist0000unse/mode/2up). World Scientific Publishing. pp. 149–167. ISBN 978-9810231149.

10. "Quantum Field Theory > The History of QFT (Stanford Encyclopedia of Philosophy)" (https://plato.stanford.edu/entries/quantum-field-theory/qft-history.html). *plato.stanford.edu*. Retrieved 22 October 2023.

11. Bhaumik, Mani L. (2022). "How Dirac's Seminal Contributions Pave the Way for Comprehending Nature's Deeper Designs". *Quanta*. **8** (1): 88–100. arXiv:2209.03937 (https://arxiv.org/abs/2209.03937). doi:10.12743/quanta.v8i1.96 (https://doi.org/10.12743%2Fquanta.v8i1.96). S2CID 212835814 (https://api.semanticscholar.org/CorpusID:212835814).

12. Schmitz, Kenneth S. (2018). *Physical Chemistry: Multidisciplinary Applications in Society* (https://books.google.com/books?id=4WGdBgAAQBAJ&dq=Paul+Dirac+bachelor+applied+mathematics&pg=PA310). Elsevier. p. 310. ISBN 978-0-12-800513-2.

13. Gordin, Michael D. (6 February 2017). "Dr. Strange" (https://www.americanscientist.org/article/dr-strange). *American Scientist*. Retrieved 29 May 2024.

14. "Discovering the positron" (https://timeline.web.cern.ch/timeline-header/142#416). *timeline.web.cern.ch*. Retrieved 23 October 2023.

15. Zichichi, Antonino (2 March 2000). "Dirac, Einstein and physics" (https://physicsworld.com/a/dirac-einstein-and-physics/). *Physics World*. Retrieved 22 October 2023.

16. Dirac, Paul (1931). "Quantised singularities in the electromagnetic field" (https://royalsocietypublishing.org/doi/10.1098/rspa.1931.0130). *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*. **133** (821): 60–72. Bibcode:1931RSPSA.133...60D (https://ui.adsabs.harvard.edu/abs/1931RSPSA.133...60D). doi:10.1098/rspa.1931.0130 (https://doi.org/10.1098%2Frspa.1931.0130). ISSN 0950-1207 (https://search.worldcat.org/issn/0950-1207).

17. Gottfried, Kurt (2011). "P. A. M. Dirac and the discovery of quantum mechanics" (https://pubs.aip.org/aapt/ajp/article-abstract/79/3/261/398648/P-A-M-Dirac-and-the-discovery-of-quantum-mechanics?redirectedFrom=fulltext). *American Journal of Physics*. **79** (3): 2, 10. arXiv:1006.4610 (https://arxiv.org/abs/1006.4610). Bibcode:2011AmJPh..79..261G (https://ui.adsabs.harvard.edu/abs/2011AmJPh..79..261G). doi:10.1119/1.3536639 (https://doi.org/10.1119%2F1.3536639). S2CID 18229595 (https://api.semanticscholar.org/CorpusID:18229595).

18. Kragh, Helge (10 September 2013), "Paul Dirac and The Principles of Quantum Mechanics" (https://mprl-series.mpg.de/studies/2/11/index.html), *Research and Pedagogy: A History of Quantum Physics through Its Textbooks*, MPRL – Studies, Berlin: Max-Planck-Gesellschaft zur Förderung der Wissenschaften, ISBN 978-3-945561-24-9, retrieved 23 October 2023

19. "The Nobel Prize in Physics 1933" (https://www.nobelprize.org/nobel_prizes/physics/laureates/1933/). The Nobel Foundation. Retrieved 4 April 2013.

20. Farmelo, Graham (2008). "Paul Dirac: The Mozart of Science" (https://www.ias.edu/ideas/2008/farmelo-on-dirac). *www.ias.edu*. Retrieved 8 May 2024.

21. Brown, Laurie M. (2006). "Paul A. M. Dirac's Principles of Quantum Mechanics" (https://faculty.washington.edu/seattle/physics441/online/about%20Dirac.pdf) (PDF). *Physics in Perspective*. **8** (4): 381–407. Bibcode:2006PhP.....8..381B (https://ui.adsabs.harvard.edu/abs/2006PhP.....8..381B). doi:10.1007/s00016-006-0276-4 (https://doi.org/10.1007%2Fs00016-006-0276-4). S2CID 120303937 (https://api.semanticscholar.org/CorpusID:120303937).

22. Cathcart, Brian (25 May 2006). "Tube Alloys directorate (act. 1941–1945)" (https://www.oxforddnb.com/display/10.1093/ref:odnb/9780198614128.001.0001/odnb-9780198614128-e-93791). *Oxford Dictionary of National Biography* (online ed.). Oxford University Press. doi:10.1093/ref:odnb/93791 (https://doi.org/10.1093%2Fref%3Aodnb%2F93791). Retrieved 25 October 2023. (Subscription or UK public library membership (https://www.oxforddnb.com/help/subscribe#public) required.)

23. Vrobel, Daniel P. (2020). *Paul Dirac: The Atomic Centrifuge and the Tube Alloys Project* (http s://diginole.lib.fsu.edu/islandora/object/fsu:770703/datastream/PDF/view) (Master thesis). Florida State University.

24. McKie, Robin (31 January 2009). "Anti-matter and madness" (https://www.theguardian.com/ books/2009/feb/01/strangest-man-paul-dirac-review). *amp.theguardian.com*. Retrieved 24 October 2023.

25. Kemp, R. Scott (26 June 2009). "Gas Centrifuge Theory and Development: A Review of U.S. Programs" (https://doi.org/10.1080%2F08929880802335816). *Science & Global Security*. **17** (1): 1–19. Bibcode:2009S&GS...17....1K (https://ui.adsabs.harvard.edu/abs/200 9S&GS...17....1K). doi:10.1080/08929880802335816 (https://doi.org/10.1080%2F08929880 802335816). ISSN 0892-9882 (https://search.worldcat.org/issn/0892-9882).

26. Gilinsky, Victor (2010). "Remembrances of Dirac" (https://doi.org/10.1063%2F1.3431338). *Physics Today*. **63** (5): 59. Bibcode:2010PhT....63e..59G (https://ui.adsabs.harvard.edu/abs/ 2010PhT....63e..59G). doi:10.1063/1.3431338 (https://doi.org/10.1063%2F1.3431338).

27. Kragh 1990, p. 158

28. Dirac, Paul Adrien Maurice (5 April 1938). "A new basis for cosmology" (https://royalsocietyp ublishing.org/doi/10.1098/rspa.1938.0053). *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*. **165** (921): 199–208. Bibcode:1938RSPSA.165..199D (https://ui.adsabs.harvard.edu/abs/1938RSPSA.165..199 D). doi:10.1098/rspa.1938.0053 (https://doi.org/10.1098%2Frspa.1938.0053). ISSN 0080-4630 (https://search.worldcat.org/issn/0080-4630). S2CID 121069801 (https://api.semantics cholar.org/CorpusID:121069801).

29. Kragh, Helge (2014). "Paul Dirac and the Magic of Large Numbers" (https://academic.oup.c om/book/4223/chapter-abstract/146058250?redirectedFrom=fulltext). *Masters of the Universe: Conversations with Cosmologists of the Past*: 217–237. doi:10.1093/acprof:oso/9780198722892.003.0012 (https://doi.org/10.1093%2Facprof%3Aos o%2F9780198722892.003.0012). ISBN 978-0-19-872289-2 – via Oxford Academic.

30. Saibal, Ray; Mukhopadhyay, Utpal; Ray, Soham; Bhattacharjee, Arjak (2019). "Dirac's large number hypothesis: A journey from concept to implication" (https://www.worldscientific.com/ doi/10.1142/S0218271819300143). *International Journal of Modern Physics D*. **28** (8): 1930014–1930096. Bibcode:2019IJMPD..2830014R (https://ui.adsabs.harvard.edu/abs/201 9IJMPD..2830014R). doi:10.1142/S0218271819300143 (https://doi.org/10.1142%2FS02182 71819300143). S2CID 127899548 (https://api.semanticscholar.org/CorpusID:127899548) – via World Scientific.

31. Dubois, Eve-Aline; Füzfa, André; Lambert, Dominique (2022). "The large numbers hypothesis in cosmology" (https://www.worldscientific.com/doi/10.1142/9789811258251_02 59). *The Fifteenth Marcel Grossmann Meeting*. WORLD SCIENTIFIC: 1741–1744. Bibcode:2022mgm..conf.1741D (https://ui.adsabs.harvard.edu/abs/2022mgm..conf.1741D). doi:10.1142/9789811258251_0259 (https://doi.org/10.1142%2F9789811258251_0259). ISBN 978-981-12-5824-4. S2CID 225097737 (https://api.semanticscholar.org/CorpusID:225 097737).

32. Kragh 1990, pp. 198, 348

33. Sanyuk, Valerii I.; Sukhanov, Alexander D. (1 September 2003). "Dirac in 20th century physics: a centenary assessment" (https://ufn.ru/en/articles/2003/9/c/). *Physics-Uspekhi*. **46** (9): 937–956. doi:10.1070/PU2003v046n09ABEH001165 (https://doi.org/10.1070%2FPU20 03v046n09ABEH001165). ISSN 1063-7869 (https://search.worldcat.org/issn/1063-7869). S2CID 250754932 (https://api.semanticscholar.org/CorpusID:250754932).

34. Han, Xiaosen (1 April 2016). "The Born–Infeld vortices induced from a generalized Higgs mechanism" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4892282). *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*. **472** (2188): 20160012. Bibcode:2016RSPSA.47260012H (https://ui.adsabs.harvard.edu/abs/2016RSPSA.47260012H). doi:10.1098/rspa.2016.0012 (https://doi.org/10.1098%2Frspa.2016.0012). ISSN 1364-5021 (https://search.worldcat.org/issn/1364-5021). PMC 4892282 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4892282). PMID 27274694 (https://pubmed.ncbi.nlm.nih.gov/27274694).
35. "Biographical and Research Highlights" (https://www.damtp.cam.ac.uk/events/dirac/dirac/highlights.html). *Department of Applied Mathematics and Theoretical Physics (DAMTP)*. Retrieved 21 June 2024.
36. Kragh 1990, p. 82] "Dirac verstehe ich im Einzelnen überhaupt nicht (Compton-Effekt)"
37. Kursunoglu, Behram N.; Wigner, Eugene P. (1987). *Paul Adrien Maurice Dirac: Reminiscences about a Great Physicist* (https://archive.org/details/pauladrienmauric0000unse). Cambridge University Press. p. 262. ISBN 9780521340137.
38. "The Strangest Man: The Hidden Life of Paul Dirac, Quantum Genius" (https://cerncourier.com/a/the-strangest-man-the-hidden-life-of-paul-dirac-quantum-genius/). *CERN Courier*. 25 August 2009. Retrieved 22 October 2023.
39. Deser, Stanley (2004). "P.A.M. Dirac and the Development of Modern General Relativity" (https://www.worldscientific.com/doi/abs/10.1142/S0217751X04018622). *International Journal of Modern Physics A*. **19** (supp01): 99–105. Bibcode:2004IJMPA..19S..99D (https://ui.adsabs.harvard.edu/abs/2004IJMPA..19S..99D). doi:10.1142/S0217751X04018622 (https://doi.org/10.1142%2FS0217751X04018622). ISSN 0217-751X (https://search.worldcat.org/issn/0217-751X).
40. Hey, Tony; Walters, Patrick (1987). *The Quantum Universe* (https://archive.org/details/quantumuniverse0000heya/mode/1up). Cambridge University Press. p. 124. ISBN 978-0521267441.
41. Close, Frank (20 May 2009). "Paul Dirac: a physicist of few words" (https://doi.org/10.1038%2F459326a). *Nature*. **459** (7245): 326–327. Bibcode:2009Natur.459..326C (https://ui.adsabs.harvard.edu/abs/2009Natur.459..326C). doi:10.1038/459326a (https://doi.org/10.1038%2F459326a). ISSN 1476-4687 (https://search.worldcat.org/issn/1476-4687).
42. Kragh 1990, pp. ix, 12.
43. Farmelo 2009, p. 10 (https://books.google.com/books?id=-TT_z4llWoIC&pg=PA10)
44. Farmelo 2009, pp. 18–19 (https://books.google.com/books?id=-TT_z4llWoIC&pg=PA18)
45. Dalitz, R. H.; Peierls, R. (1986). "Paul Adrien Maurice Dirac. 8 August 1902 – 20 October 1984" (https://doi.org/10.1098%2Frsbm.1986.0006). *Biographical Memoirs of Fellows of the Royal Society*. **32**: 137–185. doi:10.1098/rsbm.1986.0006 (https://doi.org/10.1098%2Frsbm.1986.0006). JSTOR 770111 (https://www.jstor.org/stable/770111).
46. "Paul Dirac: a genius in the history of physics" (http://cerncourier.com/cws/article/cern/28693). *Cern Courier*. 15 August 2002. Retrieved 4 February 2022.
47. Farmelo 2009, pp. 8, 441
48. Farmelo 2009, pp. 8
49. Farmelo 2009, pp. 441
50. Kragh 1990, p. 1
51. Farmelo 2009, pp. 10–11
52. Farmelo 2009, pp. 77–78 (https://books.google.com/books?id=-TT_z4llWoIC&pg=PA77)
53. Farmelo 2009, p. 79 (https://books.google.com/books?id=-TT_z4llWoIC&pg=PA79)
54. Farmelo 2009, p. 34
55. Farmelo 2009, p. 22
56. Mehra 1972, p. 17

57. Kragh 1990, p. 2

58. Farmelo 2009, pp. 13–17

59. Farmelo 2009, pp. 20–21

60. Mehra 1972, p. 18

61. Farmelo 2009, p. 23

62. Farmelo 2009, p. 28

63. Farmelo 2009, pp. 46–47

64. Galison, Peter (2000). "The Suppressed Drawing: Paul Dirac's Hidden Geometry" (https://w ww.jstor.org/stable/2902912). *Representations* (72): 145–166. doi:10.2307/2902912 (https:// doi.org/10.2307%2F2902912). ISSN 0734-6018 (https://search.worldcat.org/issn/0734-601 8). JSTOR 2902912 (https://www.jstor.org/stable/2902912).

65. Farmelo 2009, p. 53

66. Farmelo 2009, pp. 52–53

67. 1851 Royal Commission Archives

68. Farmelo 2009, p. 101

69. Kursunoglu, Behram N.; Wigner, Eugene Paul, eds. (1990). *Paul Adrien Maurice Dirac: Reminiscences about a Great Physicist* (https://books.google.com/books?id=1Pg7t9a_AX4 C&q=paul+dirac+university+of+wisconsin+1929&pg=PA132). Cambridge University Press. p. 132. ISBN 0521386888. Retrieved 30 September 2020.

70. "Paul Adrien Maurice Dirac" (https://pages.hep.wisc.edu/~ldurand/715html/courseinfo/biogra phies/dirac.html). University of Wisconsin-Madison. Retrieved 30 September 2020.

71. Farmelo 2009, p. 284

72. Farmelo 2009, p. 253

73. Farmelo 2009, p. 256

74. Farmelo 2009, p. 288

75. Farmelo 2009, pp. 305, 323

76. Kim, Young Suh (1995). "Wigner's Sisters" (https://web.archive.org/web/20080303112257/ht tps://ysfine.com/dirac/wigsis.html). Archived from the original (http://ysfine.com/dirac/wigsis. html) on 3 March 2008.

77. Farmelo 2009, p. 89

78. "Paul Adrien Maurice Dirac" (http://www-history.mcs.st-and.ac.uk/Printonly/Dirac.html). University of St. Andrews. Retrieved 4 April 2013.

79. Mehra 1972, pp. 17–59 (https://books.google.com/books?id=CpJiqUFkHGoC&pg=PA17)

80. Kragh 1990, p. 17

81. McKie, Rob (1 February 2009). "Anti-matter and madness" (https://www.theguardian.com/bo oks/2009/feb/01/strangest-man-paul-dirac-review). *The Guardian*. Retrieved 4 April 2013.

82. Gamow 1966, p. 121

83. Capri 2007, p. 148

84. Zee 2010, p. 105

85. Raymo, Chet (17 October 2009). "A quantum leap into oddness" (https://www.theglobeandm ail.com/arts/books-and-media/review-the-strangest-man-by-graham-farmelo/article428949 4/). *The Globe and Mail*. (Review of Farmelo's *The Strangest Man*.)

86. Farmelo 2009, pp. 161–162, who attributes the story to Niels Bohr.

87. Mehra, Jagdish; Rechenberg, Helmut (2001). *The Historical Development of Quantum Theory* (https://books.google.com/books?id=-pL56OcVubgC&q=Paul+Dirac+Einstein+statist ics+Symmetry&pg=PA746). Springer Science & Business Media. p. 746. ISBN 9780387951805.

88. Pais, A., *Niels Bohr's Times: In Physics, Philosophy, and Polity* (Oxford: Clarendon Press, 1991), p. 320 (https://archive.org/details/nielsbohrstimesi0000pais/page/320).

89. Heisenberg 1971, pp. 85–86

90. Heisenberg 1971, p. 87

91. Farmelo 2009, p. 138 (https://books.google.com/books?id=-TT_z4llWoIC&pg=PA138), who says this was an old joke, pointing out a *Punch* footnote in the 1850s that "There is no God, and Harriet Martineau is her prophet."

92. Dirac, Paul (May 1963). "The Evolution of the Physicist's Picture of Nature" (http://blogs.scie ntificamerican.com/guest-blog/2010/06/25/the-evolution-of-the-physicists-picture-of-nature/). *Scientific American*. Retrieved 4 April 2013.

93. Kragh 1990, pp. 256–257

94. Kragh 1990

95. Farmelo 2009, pp. 331

96. "Paul Dirac - Biography" (https://mathshistory.st-andrews.ac.uk/Biographies/Dirac/). *Maths History*. Retrieved 31 December 2023.

97. Goddard, Peter (1998). *Paul Dirac: The Man and his Work* (https://archive.org/details/isbn_0 521583829). Cambridge University Press. pp. x. ISBN 978-0521583824.

98. Farmelo 2009, pp. 82

99. Farmelo 2009, pp. 76

100. Farmelo 2009, pp. 83–88

101. Coutinho, S. C. (1 May 2014). "Whittaker's analytical dynamics: a biography" (https://doi.org/ 10.1007/s00407-013-0133-1). *Archive for History of Exact Sciences*. **68** (3): 355–407. doi:10.1007/s00407-013-0133-1 (https://doi.org/10.1007%2Fs00407-013-0133-1). ISSN 1432-0657 (https://search.worldcat.org/issn/1432-0657). S2CID 122266762 (https://ap i.semanticscholar.org/CorpusID:122266762).

102. "Paul Dirac: a genius in the history of physics" (http://cerncourier.com/cws/article/cern/2869 3). *Cern Courier*. 15 August 2002. Retrieved 13 May 2013.

103. Dirac, Paul A. M. (1926). "On the Theory of Quantum Mechanics" (https://doi.org/10.1098%2 Frspa.1926.0133). *Proceedings of the Royal Society A*. **112** (762): 661–77. Bibcode:1926RSPSA.112..661D (https://ui.adsabs.harvard.edu/abs/1926RSPSA.112..661 D). doi:10.1098/rspa.1926.0133 (https://doi.org/10.1098%2Frspa.1926.0133). JSTOR 94692 (https://www.jstor.org/stable/94692).

104. Dirac, "The inadequacies of quantum field theory", in B. N. Kursunoglu & E. P. Wigner, eds., *Paul Adrien Maurice Dirac* (https://books.google.com/books?id=1Pg7t9a_AX4C) (Cambridge: Cambridge University Press, 1987), p. 194.

105. Dirac, P. A. M. (July 1964). "Foundations of Quantum Mechanics" (https://www.nature.com/a rticles/203115a0). *Nature*. **203** (4941): 115–116. Bibcode:1964Natur.203..115D (https://ui.ad sabs.harvard.edu/abs/1964Natur.203..115D). doi:10.1038/203115a0 (https://doi.org/10.103 8%2F203115a0). ISSN 0028-0836 (https://search.worldcat.org/issn/0028-0836). S2CID 34171325 (https://api.semanticscholar.org/CorpusID:34171325).

106. Behram N. Kurşunoğlu; Eugene Paul Wigner (eds.). *Reminiscences about a Great Physicist*. Cambridge University Press. p. 98 (https://books.google.com/books?id=1Pg7t9a_ AX4C&pg=PA98).

107. Dirac, P. A. M. (1 February 1928). "The Quantum Theory of the Electron" (https://doi.org/10. 1098%2Frspa.1928.0023). *Proceedings of the Royal Society of London A*. **117** (778): 610– 24. Bibcode:1928RSPSA.117..610D (https://ui.adsabs.harvard.edu/abs/1928RSPSA.117..6 10D). doi:10.1098/rspa.1928.0023 (https://doi.org/10.1098%2Frspa.1928.0023).

108. Paul Dirac (https://www.nobelprize.org/laureate/40) on Nobelprize.org with his Nobel Lecture, 12 December 1933 *Theory of Electrons and Positrons*

109. P. A. M. Dirac (1939). "A New Notation for Quantum Mechanics". *Proceedings of the Cambridge Philosophical Society*. **35** (3): 416. Bibcode:1939PCPS...35..416D (https://ui.ads abs.harvard.edu/abs/1939PCPS...35..416D). doi:10.1017/S0305004100021162 (https://doi. org/10.1017%2FS0305004100021162). S2CID 121466183 (https://api.semanticscholar.org/ CorpusID:121466183).

110. Gieres (2000). "Mathematical surprises and Dirac's formalism in quantum mechanics". *Reports on Progress in Physics*. **63** (12): 1893. arXiv:quant-ph/9907069 (https://arxiv.org/ab s/quant-ph/9907069). Bibcode:2000RPPh...63.1893G (https://ui.adsabs.harvard.edu/abs/20 00RPPh...63.1893G). doi:10.1088/0034-4885/63/12/201 (https://doi.org/10.1088%2F0034-4 885%2F63%2F12%2F201). S2CID 10854218 (https://api.semanticscholar.org/CorpusID:10 854218).

111. Dirac, P. A. M. (1931). "Quantised Singularities in the Electromagnetic Field" (https://doi.org/ 10.1098%2Frspa.1931.0130). *Proceedings of the Royal Society A*. **133** (821): 60–72. Bibcode:1931RSPSA.133...60D (https://ui.adsabs.harvard.edu/abs/1931RSPSA.133...60D). doi:10.1098/rspa.1931.0130 (https://doi.org/10.1098%2Frspa.1931.0130).

112. Patrizii, L.; Spurio, M. (19 October 2015). "Status of Searches for Magnetic Monopoles" (htt ps://www.annualreviews.org/doi/10.1146/annurev-nucl-102014-022137). *Annual Review of Nuclear and Particle Science*. **65** (1): 279–302. arXiv:1510.07125 (https://arxiv.org/abs/151 0.07125). Bibcode:2015ARNPS..65..279P (https://ui.adsabs.harvard.edu/abs/2015ARNPS.. 65..279P). doi:10.1146/annurev-nucl-102014-022137 (https://doi.org/10.1146%2Fannurev-n ucl-102014-022137). ISSN 0163-8998 (https://search.worldcat.org/issn/0163-8998).

113. Debnath, Lokenath (2013). "A short biography of Paul A. M. Dirac and historical development of Dirac delta function" (http://www.tandfonline.com/doi/abs/10.1080/0020739 X.2013.770091). *International Journal of Mathematical Education in Science and Technology*. **44** (8): 1201–1223. Bibcode:2013IJMES..44.1201D (https://ui.adsabs.harvard.e du/abs/2013IJMES..44.1201D). doi:10.1080/0020739X.2013.770091 (https://doi.org/10.108 0%2F0020739X.2013.770091). ISSN 0020-739X (https://search.worldcat.org/issn/0020-739 X). S2CID 121423215 (https://api.semanticscholar.org/CorpusID:121423215).

114. Schick, Michael (2021). *Canonical Quantum Gravity* (https://www.imperial.ac.uk/media/impe rial-college/research-centres-and-groups/theoretical-physics/msc/dissertations/2021/Michael -Schick-Dissertation.pdf) (PDF) (Thesis). Imperial College London.

115. Skuse, Ben (1 September 2022). "Black Holes - Topic | Lindau Mediatheque" (https://mediat heque.lindau-nobel.org/topics/black-holes). *Lindau Nobel Mediatheque*. Retrieved 2 November 2023.

116. Farmelo 2009, pp. 367–368

117. Debnath, Lokenath (2013). "A short biography of Paul A. M. Dirac and historical development of Dirac delta function" (http://www.tandfonline.com/doi/abs/10.1080/0020739 X.2013.770091). *International Journal of Mathematical Education in Science and Technology*. **44** (8): 1201–1223. Bibcode:2013IJMES..44.1201D (https://ui.adsabs.harvard.e du/abs/2013IJMES..44.1201D). doi:10.1080/0020739X.2013.770091 (https://doi.org/10.108 0%2F0020739X.2013.770091). ISSN 0020-739X (https://search.worldcat.org/issn/0020-739 X). S2CID 121423215 (https://api.semanticscholar.org/CorpusID:121423215).

118. Dirac, P. A. M. (19 June 1962). "An extensible model of the electron" (https://royalsocietypub lishing.org/doi/10.1098/rspa.1962.0124). *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*. **268** (1332): 57–67. Bibcode:1962RSPSA.268...57D (https://ui.adsabs.harvard.edu/abs/1962RSPSA.268...57D). doi:10.1098/rspa.1962.0124 (https://doi.org/10.1098%2Frspa.1962.0124). ISSN 0080-4630 (https://search.worldcat.org/issn/0080-4630).

119. "membrane in nLab" (https://ncatlab.org/nlab/show/membrane). *ncatlab.org*. Retrieved 19 June 2024.

120. Dirac, P. A. M. (1950). "Generalized Hamiltonian Dynamics" (https://doi.org/10.4153%2FCJM-1950-012-1). *Canadian Journal of Mathematics*. **2**: 129–148. doi:10.4153/CJM-1950-012-1 (https://doi.org/10.4153%2FCJM-1950-012-1). ISSN 0008-414X (https://search.worldcat.org/issn/0008-414X).

121. Dirac, P. A. M. (1951). "The Hamiltonian Form of Field Dynamics" (https://doi.org/10.4153%2FCJM-1951-001-2). *Canadian Journal of Mathematics*. **3**: 1–23. doi:10.4153/CJM-1951-001-2 (https://doi.org/10.4153%2FCJM-1951-001-2). ISSN 0008-414X (https://search.worldcat.org/issn/0008-414X).

122. Misha, S., *Quantum Field Theory II* (Singapore: World Scientific, 2019), p. 287 (https://books.google.com/books?id=EbySDwAAQBAJ&pg=PA287).

123. Domb, Cyril (2003). "Some Observations on the Early History of Equilibrium Statistical Mechanics" (http://link.springer.com/10.1023/A:1022139230789). *Journal of Statistical Physics*. **110** (3/6): 475–496. Bibcode:2003JSP...110..475D (https://ui.adsabs.harvard.edu/abs/2003JSP...110..475D). doi:10.1023/A:1022139230789 (https://doi.org/10.1023%2FA%3A1022139230789).

124. Dirac's paper "THE LAGRANGIAN IN QUANTUM MECHANICS" is reprinted in Feynman & Brown 2005

125. Schweber 1994, pp. 354, 573.

126. Baulieu, Laurent; Iliopoulos, John; Sénéor, Roland (2017). *From Classical to Quantum Fields* (1st ed.). Oxford University Press. p. 164. ISBN 978-0-19-878839-3.

127. Dirac, Paul (1963). "A Remarkable Representation of the 3 + 2 de Sitter Group" (https://pubs.aip.org/aip/jmp/article-abstract/4/7/901/230214/A-Remarkable-Representation-of-the-3-2-de-Sitter?redirectedFrom=fulltext). *Journal of Mathematical Physics*. **4** (7). AIP Publishing: 901–909. Bibcode:1963JMP.....4..901D (https://ui.adsabs.harvard.edu/abs/1963JMP.....4..901D). doi:10.1063/1.1704016 (https://doi.org/10.1063%2F1.1704016).

128. Mezincescu, Luca; Townsend, Paul K. (2020). "DBI in the IR" (https://dx.doi.org/10.1088/1751-8121/ab5eab). *Journal of Physics A: Mathematical and Theoretical*. **53** (4): 044002. arXiv:1907.06036 (https://arxiv.org/abs/1907.06036). Bibcode:2020JPhA...53d4002M (https://ui.adsabs.harvard.edu/abs/2020JPhA...53d4002M). doi:10.1088/1751-8121/ab5eab (https://doi.org/10.1088%2F1751-8121%2Fab5eab). ISSN 1751-8121 (https://search.worldcat.org/issn/1751-8121).

129. Kim, Y S; Noz, Marilyn E (1 December 2005). "Coupled oscillators, entangled oscillators, and Lorentz-covariant harmonic oscillators" (https://iopscience.iop.org/article/10.1088/1464-4266/7/12/005). *Journal of Optics B: Quantum and Semiclassical Optics*. **7** (12): S458 – S467. arXiv:quant-ph/0502096 (https://arxiv.org/abs/quant-ph/0502096). Bibcode:2005JOptB...7..458K (https://ui.adsabs.harvard.edu/abs/2005JOptB...7..458K). doi:10.1088/1464-4266/7/12/005 (https://doi.org/10.1088%2F1464-4266%2F7%2F12%2F005). ISSN 1464-4266 (https://search.worldcat.org/issn/1464-4266).

130. de Wit, Bernard; Herger, Ivan (2000). "Anti-de Sitter Supersymmetry" (https://link.springer.com/chapter/10.1007/3-540-46634-7_4). In Kowalski-Glikman, Jerzy (ed.). *Towards Quantum Gravity*. Lecture Notes in Physics. Vol. 541. Berlin, Heidelberg: Springer. pp. 79–100. doi:10.1007/3-540-46634-7_4 (https://doi.org/10.1007%2F3-540-46634-7_4). ISBN 978-3-540-46634-5.

131. Dirac, P. A. M. (1935). "The Electron Wave Equation in De-Sitter Space" (https://www.jstor.org/stable/1968649). *Annals of Mathematics*. **36** (3): 657–669. doi:10.2307/1968649 (https://doi.org/10.2307%2F1968649). ISSN 0003-486X (https://search.worldcat.org/issn/0003-486X). JSTOR 1968649 (https://www.jstor.org/stable/1968649).

132. Stenholm, Stig Torsten; Suominen, Kalle-Antti (27 April 1998). "Weisskopf-Wigner decay of excited oscillator states" (https://opg.optica.org/oe/abstract.cfm?uri=oe-2-9-378). *Optics Express*. **2** (9): 378–390. Bibcode:1998OExpr...2..378S (https://ui.adsabs.harvard.edu/abs/1998OExpr...2..378S). doi:10.1364/OE.2.000378 (https://doi.org/10.1364%2FOE.2.000378). ISSN 1094-4087 (https://search.worldcat.org/issn/1094-4087). PMID 19381205 (https://pubmed.ncbi.nlm.nih.gov/19381205).

133. Schweber 1994, pp. 31–32.

134. Kragh 1990, p. 125

135. Dirac, P. A. M. (5 August 1938). "Classical Theory of Radiating Electrons" (https://royalsocietypublishing.org/doi/10.1098/rspa.1938.0124). *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*. **167** (929): 148–169. Bibcode:1938RSPSA.167..148D (https://ui.adsabs.harvard.edu/abs/1938RSPSA.167..148D). doi:10.1098/rspa.1938.0124 (https://doi.org/10.1098%2Frspa.1938.0124). ISSN 0080-4630 (https://search.worldcat.org/issn/0080-4630).

136. Seto, K.; Zhang, S.; Koga, J.; Nagatomo, H.; Nakai, M.; Mima, K. (1 April 2014). "Stabilization of radiation reaction with vacuum polarization" (https://doi.org/10.1093/ptep/ptu031). *Progress of Theoretical and Experimental Physics*. **2014** (4): 43A01–0. arXiv:1310.6646 (https://arxiv.org/abs/1310.6646). doi:10.1093/ptep/ptu031 (https://doi.org/10.1093%2Fptep%2Fptu031). ISSN 2050-3911 (https://search.worldcat.org/issn/2050-3911).

137. Jena, Debdeep (26 May 2022). *Fermi's Golden Rule* (https://academic.oup.com/book/43800/chapter/370780511) (1 ed.). Oxford University PressOxford. pp. 461–480. doi:10.1093/oso/9780198856849.003.0020 (https://doi.org/10.1093%2Foso%2F9780198856849.003.0020). ISBN 978-0-19-885684-9.

138. Geddes, Chris D.; Lakowicz, Joseph R. (2006). *Reviews in Fluorescence 2006* (https://books.google.com/books?id=WJUrPL4FZsAC&dq=Fermi%27s+golden+rule+dirac&pg=PA38). Boston, MA: Springer Science+Business Media, Inc. Springer e-books. ISBN 978-0-387-33016-7.

139. Kaufmann, André (2022), Kaufmann, André (ed.), "Useful Applications of the RHVT" (https://doi.org/10.1007/978-3-030-89766-6_6), *The Ranque Hilsch Vortex Tube Demystified: Understanding the Working Principles of the Vortex Tube*, Cham: Springer International Publishing, p. 69, doi:10.1007/978-3-030-89766-6_6 (https://doi.org/10.1007%2F978-3-030-89766-6_6), ISBN 978-3-030-89766-6, retrieved 11 January 2024

140. Farmelo 2009, pp. 248–249 (https://books.google.com/books?id=-TT_z4llWoIC&pg=PA248) quote=During a visit to Cambridge in May 1934, Wigner saw the apparatus and asked Dirac questions about it,

141. Kemp, R. S., "Gas Centrifuge Theory and Development: A Review of US Programs" (https://www.researchgate.net/publication/228424622_Gas_Centrifuge_Theory_and_Development_A_Review_of_US_Programs), *Science and Global Security*, June 2009.

142. Bernstein, Jeremy (13 June 2009). "SWU for You and Me". arXiv:0906.2505 (https://arxiv.org/abs/0906.2505) [physics.hist-ph (https://arxiv.org/archive/physics.hist-ph)].

143. Cathcart, Brian (25 May 2006). "Tube Alloys directorate (act. 1941–1945)" (https://www.oxforddnb.com/display/10.1093/ref:odnb/9780198614128.001.0001/odnb-9780198614128-e-93791). *Oxford Dictionary of National Biography* (online ed.). Oxford University Press. doi:10.1093/ref:odnb/93791 (https://doi.org/10.1093%2Fref%3Aodnb%2F93791). Retrieved 25 October 2023. (Subscription or UK public library membership (https://www.oxforddnb.com/help/subscribe#public) required.)

144. Kragh 1990, p. 184

145. Schweber 1994

146. Dirac, P. a. M. (1950). "Generalized Hamiltonian Dynamics" (https://www.cambridge.org/core/journals/canadian-journal-of-mathematics/article/generalized-hamiltonian-dynamics/F4C30A59B59BEE09E9CB6F07377B8BD3). *Canadian Journal of Mathematics*. **2**: 129–148. doi:10.4153/CJM-1950-012-1 (https://doi.org/10.4153%2FCJM-1950-012-1). ISSN 0008-414X (https://search.worldcat.org/issn/0008-414X).

147. Dirac, P. a. M. (1951). "The Hamiltonian Form of Field Dynamics" (https://www.cambridge.org/core/journals/canadian-journal-of-mathematics/article/hamiltonian-form-of-field-dynamics/E17F213F85E3377BC2EBB3A1E0876BC8). *Canadian Journal of Mathematics*. **3**: 1–23. doi:10.4153/CJM-1951-001-2 (https://doi.org/10.4153%2FCJM-1951-001-2). ISSN 0008-414X (https://search.worldcat.org/issn/0008-414X).

148. Phillips R. J. N. 1987 *Tributes to Dirac* p31 London: Adam Hilger

149. Dirac, P. A. M. (19 August 1958). "The theory of gravitation in Hamiltonian form" (https://royalsocietypublishing.org/doi/10.1098/rspa.1958.0142). *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*. **246** (1246): 333–343. Bibcode:1958RSPSA.246..333D (https://ui.adsabs.harvard.edu/abs/1958RSPSA.246..333D). doi:10.1098/rspa.1958.0142 (https://doi.org/10.1098%2Frspa.1958.0142). ISSN 0080-4630 (https://search.worldcat.org/issn/0080-4630).

150. Dirac, P. A. M. (1 May 1959). "Fixation of Coordinates in the Hamiltonian Theory of Gravitation" (https://journals.aps.org/pr/abstract/10.1103/PhysRev.114.924). *Physical Review*. **114** (3): 924. Bibcode:1959PhRv..114..924D (https://ui.adsabs.harvard.edu/abs/1959PhRv..114..924D). doi:10.1103/PhysRev.114.924 (https://doi.org/10.1103%2FPhysRev.114.924). Retrieved 16 October 2020.

151. Dirac, P. A. M., "Energy of the Gravitational Field" (https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.2.368), *Physical Review Letters*, Vol. 2, Nr. 8, 20 March 1959, pp. 368–371.

152. Kragh, Helge (2016). *Simply Dirac* (https://pressbooks.pub/simplydirac/) (ebook ed.). Simply Charly (published 29 April 2016). ISBN 978-1-943657-00-1.

153. "Dirac Receives Miami Center Oppenheimer Memorial Prize" (https://pubs.aip.org/physicstoday/article-abstract/22/4/127/426774/Dirac-Receives-Miami-Center-Oppenheimer-Memorial). *Physics Today*. **22** (4): 127–128. April 1969. doi:10.1063/1.3035512 (https://doi.org/10.1063%2F1.3035512).

154. Klopfenstein, Kelsey (3 April 2024). "How Paul Dirac's legacy brought a student from Nepal to FSU" (https://news.fsu.edu/news/fsuglobal/2024/04/03/how-paul-diracs-legacy-brought-a-student-from-nepal-to-fsu/). *Florida State University News*. Retrieved 29 July 2024.

155. "Paul Dirac" (https://www.famousscientists.org/paul-dirac/). *Famous Scientists*. 13 October 2021.

156. Pais, Abraham (2009). *Paul Dirac: The Man and His Work* (https://books.google.com/books?id=Hm22wB0wGFcC). Cambridge University Press. p. 27. ISBN 978-0-511-56431-4. OCLC 958553083 (https://search.worldcat.org/oclc/958553083) – via Google Books.

157. Baer, H. A., & Belyaev, A., eds., *Proceedings of the Dirac Centennial Symposium* (Singapore: World Scientific, 2003), p. 3 (https://books.google.com/books?id=9RvJCgAAQBAJ&pg=PA3).

158. Pais, Abraham (2009). *Paul Dirac: The Man and His Work* (https://books.google.com/books?id=Hm22wB0wGFcC). Cambridge University Press. p. 28. ISBN 978-0-511-56431-4. OCLC 958553083 (https://search.worldcat.org/oclc/958553083) – via Google Books.

159. "Dirac Medal awards" (https://web.archive.org/web/20130412032421/http://www.phys.unsw.edu.au/ANNUAL_REPORTS/2004/school7.html). University of New South Wales. Archived from the original (http://www.phys.unsw.edu.au/ANNUAL_REPORTS/2004/school7.html) on 12 April 2013. Retrieved 4 April 2013.

160. O'Connor, John J.; Robertson, Edmund F., "Paul Dirac" (https://mathshistory.st-andrews.ac.uk/Biographies/Dirac.html), *MacTutor History of Mathematics Archive*, University of St Andrews

161. Sandberg, L., "Freeman J. Dyson (1923–2020), Scientist and Writer, Who Dreamt Among the Stars, Dies at 96" (https://www.ias.edu/press-releases/2020/freeman-j-dyson-1923–2020), IAS, 28 February 2020.

162. John Polkinghorne. 'Belief in God in an Age of Science' p 2

163. "Nobel Bio" (https://www.nobelprize.org/nobel_prizes/physics/laureates/1933/dirac-bio.html). Nobel Foundation. Retrieved 27 January 2014.

164. "APS Member History" (https://search.amphilsoc.org/memhist/search?creator=Paul+Dirac&title=&subject=&subdiv=&mem=&year=&year-max=&dead=&keyword=&smode=advanced). *search.amphilsoc.org*. Retrieved 16 May 2023.

165. "Paul A. Dirac" (http://www.nasonline.org/member-directory/deceased-members/46802.html). *www.nasonline.org*. Retrieved 16 May 2023.

166. "Paul Adrien Maurice Dirac" (https://www.amacad.org/person/paul-adrien-maurice-dirac). *American Academy of Arts & Sciences*. 9 February 2023. Retrieved 16 May 2023.

167. Walter, Claire (1982). *Winners, the blue ribbon encyclopedia of awards* (https://archive.org/details/winnersblueribbo0000walt). Facts on File Inc. p. 438 (https://archive.org/details/winnersblueribbo0000walt/page/438). ISBN 9780871963864.

168. "Dirac Receives Miami Center Oppenheimer Memorial Prize". *Physics Today*. **22** (4): 127. April 1969. doi:10.1063/1.3035512 (https://doi.org/10.1063%2F1.3035512).

169. Farmelo 2009, pp. 403–404

170. Li, Jichao; Yin, Yian; Fortunato, Santo; Wang, Dashun (18 April 2019). "Nobel laureates are almost the same as us" (https://www.nature.com/articles/s42254-019-0057-z). *Nature Reviews Physics*. **1** (5): 301–303. Bibcode:2019NatRP...1..301L (https://ui.adsabs.harvard.edu/abs/2019NatRP...1..301L). doi:10.1038/s42254-019-0057-z (https://doi.org/10.1038%2Fs42254-019-0057-z). ISSN 2522-5820 (https://search.worldcat.org/issn/2522-5820).

171. "Dirac takes his place next to Isaac Newton" (https://web.archive.org/web/19970427191316/http://www.fsu.edu/~fstime/FS-Times/Volume1/Issue1/Dirac.html). Florida State University. Archived from the original (http://www.fsu.edu/~fstime/FS-Times/Volume1/Issue1/Dirac.html) on 27 April 1997. Retrieved 4 April 2013.

172. Fells, M., *Bristol Plaques* (Cheltenham: The History Press, 2016), p. 40 (https://books.google.com/books?id=ezJIDAAAQBAJ&pg=PT40).

173. "Paul Dirac" (http://www.dirac.ch/PaulDirac.html). Gisela Dirac. Retrieved 4 April 2013.

174. Farmelo 2009, pp. 414–415 (https://books.google.com/books?id=-TT_z4llWoIC&pg=PA414).

175. "The Dirac Medal" (http://www.iop.org/about/awards/gold/dirac/page_38427.html). Institute of Physics. Retrieved 24 November 2007.

176. "The Dirac Medal" (http://www.ictp.it/about-ictp/prizes-awards/the-dirac-medal.aspx). International Centre for Theoretical Physics. Retrieved 4 April 2013.

177. "Undergraduate Awards" (https://web.archive.org/web/20130412191942/http://www.physics.fsu.edu/undergrads/UndergraduateAwards.htm). Florida State University. Archived from the original (http://www.physics.fsu.edu/undergrads/UndergraduateAwards.htm) on 12 April 2013. Retrieved 4 April 2013.

178. "Remodelled Dirac Science Library Opened at FSU" (http://grahamfarmelo.com/remodelled-dirac-science-library-formally-opened-at-fsu/). Graham Farmelo. 22 February 2015. Retrieved 12 October 2015.

179. "Paul A.M. Dirac Papers" (http://purl.fcla.edu/fsu/MSS_1989-009). Florida State University. Retrieved 18 March 2021.

180. Farmelo 2009, p. 417

181. "Dirac Place, Didcot OX11 8TL" (https://www.google.co.uk/maps/place/Dirac+Pl,+Didcot+OX11+8TL/@51.6019901,-1.2359636,17z/data=!3m1!4b1!4m5!3m4!1s0x4876beade0b4889f:0xa7b8fb34ab4aaa78!8m2!3d51.6019901!4d-1.2337749). Google Maps.

182. Weale, Sally (29 January 2015). "Bristol's Cotham school scores exam results to outshine famous alumni" (https://www.theguardian.com/education/2015/jan/29/bristol-cotham-school-scores-exam-results-famous-alumni-peter-higgs-paul-dirac). *The Guardian*.
183. "5997 Dirac (1983 TH)" (https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=5997+Dirac). Jet Propulsion Laboratory. Retrieved 9 January 2015.

General sources

- Capri, Anton Z. (2007). *Quips, Quotes, and Quanta: An Anecdotal History of Physics* (https://books.google.com/books?id=GfmR0mHxeZkC&pg=PA148). Hackensack, New Jersey: World Scientific. ISBN 978-981-270-919-6. OCLC 214286147 (https://search.worldcat.org/oclc/214286147).
- Crease, Robert P.; Mann, Charles C. (1986). *The Second Creation: Makers of the Revolution in Twentieth Century Physics* (https://archive.org/details/secondcreationma00crea). New York City: Macmillan Publishing. ISBN 978-0-02-521440-8. OCLC 13008048 (https://search.worldcat.org/oclc/13008048).
- Farmelo, Graham (2009). *The Strangest Man: The Hidden Life of Paul Dirac, Quantum Genius*. London: Faber and Faber. ISBN 978-0-571-22278-0. [Published in the United States as *The Strangest Man: The Hidden Life of Paul Dirac, Mystic of the Atom*. ISBN 978-0-465-01827-7.]
- Feynman, Richard P.; Brown, Laurie M. (2005). *Feynman's thesis: a new approach to quantum theory* (https://www.worldcat.org/title/ocm62332166). Hackensack, NJ: World Scientific. ISBN 978-981-256-366-8. OCLC 62332166 (https://search.worldcat.org/oclc/62332166).
- Gamow, George (1966). *Thirty Years That Shook Physics: The Story of Quantum Theory* (https://books.google.com/books?id=L90_wY1VCW0C&pg=PA121). Garden City, New York: Doubleday. ISBN 978-0-486-24895-0. OCLC 11970045 (https://search.worldcat.org/oclc/11970045).
- Heisenberg, Werner (1971). *Physics and Beyond: Encounters and Conversations* (https://archive.org/details/physicsbeyondenc00heis). New York City: Harper & Row. ISBN 978-0-06-131622-7. OCLC 115992 (https://search.worldcat.org/oclc/115992).
- Kragh, Helge (1990). *Dirac: A Scientific Biography* (https://archive.org/details/diracscientificb0000krag). Cambridge: Cambridge University Press. ISBN 978-0-521-38089-8. OCLC 20013981 (https://search.worldcat.org/oclc/20013981).
- Mehra, Jagdish (1972). "The Golden Age of Theoretical Physics: P. A. M. Dirac's Scientific Works from 1924–1933". In Wigner, Eugene Paul; Salam, Abdus (eds.). *Aspects of Quantum Theory*. Cambridge: University Press. pp. 17–59. ISBN 978-0-521-08600-4. OCLC 532357 (https://search.worldcat.org/oclc/532357).
- Schweber, Silvan S. (1994). *QED and the men who made it: Dyson, Feynman, Schwinger, and Tomonaga* (https://archive.org/details/qedmenwhomadeitd0000schw). Princeton, New Jersey: Princeton University Press. ISBN 978-0-691-03685-4. OCLC 28966591 (https://search.worldcat.org/oclc/28966591).
- Zee, Anthony (2010). *Quantum Field Theory in a Nutshell* (https://archive.org/details/isbn_9780691140346). Princeton, New Jersey: Princeton University Press. ISBN 978-1-4008-3532-4. OCLC 318585662 (https://search.worldcat.org/oclc/318585662).

Further reading

- Brown, Helen (24 January 2009). "The Strangest Man: The Hidden Life of Paul Dirac by Graham Farmelo – review [print version: The man behind the maths]" (https://web.archive.org/web/20090202082203/http://www.telegraph.co.uk/culture/books/bookreviews/4316309/Th

e-Strangest-Man-the-Hidden-Life-of-Paul-Dirac-by-Graham-Farmelo---review.html). *The Daily Telegraph (Review)*. p. 20. Archived from the original (https://www.telegraph.co.uk/culture/books/bookreviews/4316309/The-Strangest-Man-the-Hidden-Life-of-Paul-Dirac-by-Graham-Farmelo---review.html) on 2 February 2009. Retrieved 11 April 2011..

- Gilder, Louisa (13 September 2009). "Quantum Leap – Review of 'The Strangest Man: The Hidden Life of Paul Dirac by Graham Farmelo' " (https://www.nytimes.com/2009/09/13/books/review/Gilder-t.html). *The New York Times*. Retrieved 11 April 2011. Review.
- Mukunda, N. (1987) "The life and work of P.A.M. Dirac", pages 260 to 282 in *Recent Developments in Theoretical Physics*, World Scientific MR935624 (https://mathscinet.ams.org/mathscinet-getitem?mr=935624)

External links

- Oral history interview transcript with P. A. M. Dirac on 1 April 1962, American Institute of Physics, Niels Bohr Library & Archives (https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-1) - Session I
- Oral history interview transcript with P. A. M. Dirac on 6 May 1963, American Institute of Physics, Niels Bohr Library & Archives (https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-2) - Session II
- Oral history interview transcript with P. A. M. Dirac on 7 Mary 1963, American Institute of Physics, Niels Bohr Library & Archives (https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-3) - Session III
- Oral history interview transcript with P. A. M. Dirac on 10 May 1963, American Institute of Physics, Niels Bohr Library & Archives (https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-4) - Session IV
- Oral history interview transcript with P. A. M. Dirac on 14 May 1963, American Institute of Physics, Niels Bohr Library & Archives (https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-5) - V
- Free online access to Dirac's classic 1920s papers from Royal Society's Proceedings A (https://royalsocietypublishing.org/action/doSearch?field1=Contrib&text1=Dirac&ConceptID=&ConceptID=&publication=&Ppub=&access=on)
- Annotated bibliography for Paul Dirac from the Alsos Digital Library for Nuclear Issues (https://web.archive.org/web/20190502044245/http://alsos.wlu.edu/qsearch.aspx?browse=people%2FDirac%2C+Paul)
- The Paul Dirac Collection at Florida State University (http://purl.fcla.edu/fsu/MSS_1989-009)
- The Papers of Professor Paul Dirac (https://archivesearch.lib.cam.ac.uk/repositories/9/resources/1531) at Churchill Archives Centre
- Oral history interview with Steve Edwards and Joe Lannutti on Dirac's appointment at Florida State University (https://www.youtube.com/watch?v=fWo010EsiYk)