1 Paul Dirac: aspects of his life and work[1]

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'Of all physicists, Dirac has the purest soul.'
Niels Bohr

In the year 1902, the literary world witnessed the death of Zola, the birth of John Steinbeck, and the first publications of *The Hound of the Baskervilles*, *The Immoralist*, *Three Sisters*, and *The Varieties of Religious Experience*. Monet painted *Waterloo Bridge*, and Elgar composed *Pomp and Circumstance*, Caruso made his first phonograph recording and the Irish Channel was crossed for the first time by balloon. In the world of science, Heaviside postulated the Heaviside layer, Rutherford and Soddy published their transformation theory of radioactive elements, Einstein started working as a clerk in the patent office in Berne, and, on August 8, Paul Adrien Maurice Dirac was born in Bristol, one of the children of Charles

Dirac (1866–1936), a native of Monthey in the Swiss canton of Valais, and Florence Holten (1878–1941), daughter of a British sea captain. There was also a brother two years older, Reginald, whose life ended in suicide, in 1924, and Beatrice, a sister four years younger. About his father Dirac has recalled:

> My father made the rule that I should only talk to him in French. He thought it would be good for me to learn French in that way. Since I found that I couldn't express myself in French, it was better for me to stay silent than to talk in English. So I became very silent at that time – that started very early.[2]

The first edition of Dirac's book, *The Principles of Quantum Mechanics*, has stood on my shelves since my graduate days in Holland. Learning from it the beauty and power of that compact little Dirac equation was a thrill I shall never forget. Years later, in January 1946, I first met Dirac and his wife on a brief visit to their home at 7 Cavendish Avenue in Cambridge. I saw much more of him in the autumn of that year when we met at the Institute for Advanced Study in Princeton. He had spent the academic year 1934–5 there, and also, during my own time at the Institute, the fall term of 1946, and academic years 1947–8, 1958–9, and 1962–3. In the course of all these visits to Princeton I came to know Dirac quite well. A friendship developed. In the course of joint talks and walks and wood chopping expeditions, I developed a good grasp of his views on physics. I also met him elsewhere, especially in Tallahassee where, in 1972, at age 70, he had started a new career: Professor of Physics at the Florida State University.

I shall presently tell of those encounters with Dirac, and of my impressions of his personality. First, however, I should like to speak of his career prior to the time of my personal contacts with him.

Young Paul first attended the Bishop Road primary school, then, at age 12, the secondary school at the Merchant Venturer's

Technical College, both in Bristol, where his father taught French. Much later he has recalled that

> [This] was an excellent school for science and modern languages. There was no Latin or Greek, something of which I was rather glad, because I did not appreciate the value of old cultures . . . I played soccer and cricket . . . and never had much success. But all through my schooldays, my interest in science was encouraged and stimulated.[3]

At the suggestion of his father, Dirac started in 1918 to study at the electrical engineering department of the University of Bristol, from which he graduated with first-class honours in 1921. Forty years later he wrote:

> I would like to try to explain the effect of this engineering training on me. I did not make any further use of the detailed applications of this work, but it did change my whole outlook to a very large extent. Previously, I was interested only in exact equations. Well, the engineering training which I received did teach me to tolerate approximations, and I was able to see that even theories based on approximations could sometimes have a considerable amount of beauty in them . . . I think that if I had not had this engineering training, I should not have had any success with the kind of work that I did later on . . . I continued in my later work to use mostly the nonrigorous mathematics of the engineers, and I think that you will find that most of my later writings do involve nonrigorous mathematics . . . The pure mathematician who wants to set up all of his work with absolute accuracy is not likely to get very far in physics.[4, 5]

During those years as an engineering student,

> A wonderful thing happened. Relativity burst on the world . . . It is easy to see the reason for this tremendous impact. We had just been living through a terrible and very serious war . . . Everyone

> wanted to forget it. And then relativity came along . . . It was an escape from the war.
>
> Previously, as a schoolboy I had been much interested in the relations of space and time. I had thought about them a great deal, and it had become apparent to me that time was very much like another dimension, and the possibility had occurred to me that perhaps there was some connection between space and time, and that we ought to consider them from a general four-dimensional point of view. However, at that time the only geometry that I knew was Euclidean geometry.[4]

In 1921, Dirac looked without success for an engineering job. Then, to his luck, he was offered free tuition for two years to study mathematics at the University of Bristol.

Those years conclude what one may call the prelude to Dirac's scientific career.

In the autumn of 1923, Dirac enrolled at Cambridge with a maintenance grant from the Department of Scientific and Industrial Research. Nine years later he would succeed Joseph Larmor (1857–1942) to the Lucasian Chair of Mathematics, once held by Newton.[6] It was Ralph Fowler (1889–1944) who, in Cambridge, introduced Dirac to the old quantum theory, and it was from him that he first learned of the atom of Rutherford, Bohr, and Sommerfeld.

Dirac first met Bohr in May 1925 when the latter gave a talk in Cambridge on the fundamental problems and difficulties of the quantum theory. Of that occasion Dirac said later:

> People were pretty well spellbound by what Bohr said . . . While I was very much impressed by [him], his arguments were mainly of a qualitative nature, and I was not able to really pinpoint the facts behind them. What I wanted was statements which could be expressed in terms of equations, and Bohr's work very seldom

provided such statements. I am really not sure how much my later work was influenced by these lectures of Bohr's . . . He certainly did not have a direct influence, because he did not stimulate one to think of new equations.[4]

In July 1925 Dirac first met Heisenberg, also in Cambridge. In that month, Heisenberg's first paper on quantum mechanics had come out.

I learned about this theory of Heisenberg in September, and it was very difficult for me to appreciate it at first. It took two weeks; then I suddenly realized that the noncommutation was actually the most important idea that was introduced by Heisenberg.[7]

The result was Dirac's first paper on quantum mechanics.[8] Prior to that time he had already published seven respectable papers which had not caused any particular response. Number eight caused a stir, however. It contained the relation $pq - qp = h/2\pi i$, independently derived shortly before by Born and Jordan. The respective authors were unaware of one another's results. Born has described his reaction upon receiving Dirac's paper:

This was – I remember well – one of the greatest surprises of my scientific life. For the name Dirac was completely unknown to me, the author appeared to be a youngster, yet everything was perfect in its way and admirable.[9]

In those days, Dirac invented several notations which are now part of our language: *q*-numbers, where '*q* stands for quantum or maybe queer'; *c*-numbers, where '*c* stands for classical or maybe commuting.'[4] He has described his work habits in those years: 'Intense thinking about those problems during the week and relaxing on Sunday, going for a walk in the country alone.'[4] Dirac was forever much attracted by the beauty of nature, particularly of mountain areas. He liked to climb mountains, for which he practiced by climbing trees on the Gog–Magog hills outside

Cambridge, even then wearing his perennial dark suit. He avoided technical climbs but nevertheless ascended impressive peaks, in the Rockies, the Alps, and the Caucasus. In 1936, accompanied by Igor Tamm (1895–1971), he managed to reach the 5640 m high top of the Elbruz, Europe's highest mountain, but collapsed at a high altitude, where he had to rest for 24 hours before completing the descent.[10]

In May 1926, Dirac received his Ph.D. on a thesis entitled 'Quantum Mechanics.'[11] Meanwhile Schrödinger's papers on wave mechanics had appeared, to which Dirac reacted with initial hostility, then with enthusiasm. He quickly applied the theory to systems of identical particles.[12] At almost the same time, that problem also attracted Heisenberg,[13] whose main focus, on a few particle systems, resulted in his theory of the helium atom.[14] Dirac's paper[12] (August 1926), on the other hand, will be remembered as the first in which quantum mechanics is brought to bear on statistical mechanics. Recall that the earliest work on quantum statistics, by Bose and by Einstein, predates quantum mechanics. Also, Fermi's introduction of the exclusion principle in statistical problems, though published[15] after the arrival of quantum mechanics, is still executed in the context of the 'old' quantum theory.[16] All these contributions were given their quantum mechanical underpinnings by Dirac, who was, in fact, the first to give the correct justification of Planck's law, which started it all: 'Symmetrical eigenfunctions . . . give just the Einstein–Bose statistical mechanics . . . (which) leads to Planck's law of black-body radiation.'[12]

It is edifying to remember that it took some time before it was sorted out when Bose–Einstein and Fermi–Dirac statistics respectively apply. Dirac in August 1926:

> The solution with anti-symmetric eigenfunctions (F.D. statistics) . . . is probably the correct one for gas molecules, since it

> is known to be the correct one for electrons in an atom, and one would expect molecules to resemble electrons more closely than light-quanta.[12]

Other great men were not at once clear either about this issue, Einstein, Fermi, Heisenberg, and Pauli among them.[16]

Having obtained his doctorate, Dirac was free to travel and, in September 1926, he went to Copenhagen. 'I admired Bohr very much. We had long talks together, long talks in which Bohr did practically all the talking.'[4] It was there that he worked out the theory of canonical transformations in quantum mechanics, since known as the transformation theory.[17] 'I think that is the piece of work which has most pleased me of all the works that I've done in my life . . . The transformation theory (became) my darling.'[7] In this paper, Dirac introduced an important tool of modern physics, the δ-function, about which he remarked right away:

> Strictly, of course, $\delta(x)$ is not a proper function of x, but can be regarded as the limit of a certain sequence of functions. All the same, one can use $\delta(x)$ as though it were a proper function for practically all the purposes of quantum mechanics without getting incorrect results.[18]

Dirac's stay in Copenhagen – lasting till February 1927 – is also highly memorable, because it was there that he completed the first[19] of two papers in which he laid the foundations of quantum electrodynamics.The sequel[20] was written in Goettingen, the next important stop on his journey.

Preceding these two papers, Dirac had already given[12] a theory of induced radiative transitions by treating atoms quantum mechanically but still considering the Maxwell field as a classical system.[21] However, 'one cannot take spontaneous emission into account without a more elaborate theory.'[12] Here, Dirac echoed Einstein who, already in 1917, still the days of the old quantum theory, had stressed that spontaneous emission 'make[s] it almost inevitable to formulate a truly quantized theory of radiation.'[22] In his Copenhagen paper,[19] Dirac did just that. He proceeded to quantize the electromagnetic field, thereby giving the first rational description of light quanta, and then derived from first principles Einstein's phenomenological coefficient of spontaneous emission.[23]

The theory was not yet complete, however: 'Radiative processes . . . in which more than one light quantum take(s) part simultaneously are not allowed on the present theory.'[19] How young quantum mechanics still was. Early in 1927, Dirac did not yet know that these processes are perfectly well included in his theory. All one had to do was extend perturbation theory from first order (used by him in the treatment of spontaneous emission) to second order. So, in his Goettingen paper,[20] he developed[24] second order perturbation theory, which enabled him to give the quantum theory of dispersion.[25] He further noted[26] that the theory could now also be applied to the Compton effect, a subject that had interested him earlier.[27]

In Goettingen Dirac met Robert Oppenheimer (1904–67), who lived in the same pension and with whom he became close friends. Dirac found the catholic interests of Oppenheimer, who spent much time reading Dante in the original, very difficult to understand. It is said that Dirac once asked him: 'How can you do both physics and poetry? In physics we try to explain in simple terms something that nobody knew before. In poetry it is the exact opposite.'

In the year 1927, of which I speak, Dirac was elected Fellow of St John's College in Cambridge and began lecturing on quantum mechanics. In 1929 he was nominated Praelector in mathematics and physics, a post with only nominal duties. In 1930 he was elected Fellow of the Royal Society. As of September 30, 1932, he became the Lucasian Professor, a post he was to hold until 1969. Out of his lectures to students grew his book on quantum mechanics, the first edition of which appeared in 1930. I may note here that in all he published about 200 papers.

Dirac devoted only a small part of his duties to teaching and almost none to administration. He preferred to work by himself and created no school. It has been written of him that he was one of the few scientists who could work even on a deserted island.[28] While it lay therefore not in his nature to seek out research students, he nevertheless delivered a fair number of Ph.Ds.[29]

When Dirac wrote an article or gave a lecture he considered it unnecessary to change his carefully chosen phrases. When somebody in the audience asked him to explain a point he had not understood, Dirac would repeat exactly what he had said before, using the very same words.[30] Be that as it may, his style of lecturing was admirable, as I have been privileged to notice frequently. Some of his students have put it well:

> The delivery was always exceptionally clear and one was carried along in the unfolding of an argument which seemed as majestic and inevitable as the development of a Bach fugue.[31]

Nevertheless I tend to agree with Sir Nevill Mott (1905–96), who has said:

> I think I have to say his influence was not very great as a teacher . . . He never would advise a student to examine the experimental evidence and see what it means . . . He would never, between his great discoveries, do any sort of bread-and-butter problem. He would not be interested at all.[32]

I return to the year 1927, when I left Dirac in Goettingen. From there he went to Leiden and concluded his travels of that year by attending the Solvay conference in Brussels (in October), where he met Einstein for the first time. From discussions with Dirac, I know that he admired Einstein. The respect was mutual ('. . . Dirac, to whom, in my opinion, we owe the most logically perfect presentation of (quantum mechanics)'[33]). Yet, the contact between the two men remained minimal, largely, I would think, because it was not in Dirac's personality to seek father figures.

That 1927 Solvay conference marks the beginning of the well-known debate between Bohr and Einstein on the interpretation of quantum mechanics. Fifty years later Dirac said: 'This problem of getting the interpretation proved to be rather more difficult than just working out the equations.'[7] As time went by he expressed reservations not only regarding quantum field theory but also, though less strongly, in relation to ordinary quantum mechanics,[34,35] but never more clearly than in 1979 when he and I were both in Jerusalem to attend the Einstein centennial celebrations:

> In this discussion at the Solvay conference [of 1927] between Einstein and Bohr, I did not take much part. I listened to their arguments, but I did not join in them, essentially because I was not very much interested. I was more interested in getting the correct equations. It seemed to me that the foundation of the work of a mathematical physicist is to get the correct equations, that the interpretation of those equations was only of secondary importance . . . It seems clear that the present quantum mechanics is not in its final form . . . I think it is very likely, or at any rate quite possible, that in the long run Einstein will turn out to be correct, even though for the time being physicists have to accept the Bohr probability interpretation, especially if they have examinations in front of them.[36]

Later I shall comment further on Dirac's position.

Dirac has recalled a conversation with Bohr during the 1927 Solvay conference. Bohr: 'What are you working on?' Dirac: 'I'm