Paul Adrien Maurice Dirac – An Appreciation

Of the two major revolutions in physics in the twentieth century – the relativity theories and quantum theory – in many ways the latter was the more profound. Its discovery was the work of many hands, an essentially European effort, and the entire development lasted a quarter of a century. It consisted of two distinct phases – the period of the Old Quantum Theory, from 1900 up to about 1923-24, was the first phase, with the major contributions coming from Planck, Einstein, Bohr and Sommerfeld. The second phase was inaugurated by Heisenberg's discovery of matrix mechanics in summer 1925 and culminated in the completion of quantum mechanics more or less as we know it today by 1926-27. In this phase the dominating figures were Heisenberg, Dirac, Schrödinger, Pauli, de Broglie and Max Born. In particular the actual creation of quantum mechanics was the result of the work of the trio – Heisenberg, Dirac and Schrödinger. Thus Dirac belongs to the period of the construction and consolidation of the new quantum mechanics.

This issue of *Resonance* celebrates the life and work of Dirac, through this life-sketch and several articles describing his many remarkable achievements.

Paul Adrien Maurice Dirac – hereafter Dirac – was born on 8 August 1902 in Bristol in England. His father Charles Adrien Ladislas Dirac was originally from Monthey in Switzerland, and had come to Bristol in the early 1890's to work as a French tutor, later becoming French lecturer at the Merchant Venturers Technical College. His mother Florence Hannah (née Holten) came from Liskeard in Cornwall in England. Dirac had two siblings, an elder brother Reginald Charles Felix born in 1900 and a younger sister Beatrice Isabelle Marguerite born in 1906.

Dirac attended elementary and secondary schools in Bristol and in 1918 became a student of electrical engineering at the University. In 1921 he obtained the BSc degree, and also competed for a scholarship to enter St.John's College in Cambridge. He won an Open Exhibition but due to lack of finances could not take it up. He could not find a job as an electrical engineer, but was permitted by the Mathematics Department at Bristol University to attend lectures there without payment of fees. Finally two years later in 1923 he was awarded a research studentship which enabled him to go to St.John's College in Cambridge. The association with St.John's continued for the rest of his life.

At Cambridge Dirac worked under the guidance of R H Fowler (son-in-law of Ernest Rutherford), initially on problems of relativistic statistical mechanics and the old quantum theory. (Incidentally Fowler was PhD guide for Homi Bhabha and Subrahmanyan Chandrasekhar later on). His major break came in August 1925. Heisenberg had visited Cambridge in July 1925 and told Fowler about his work earlier that summer. After his return to Göttingen, Heisenberg sent Fowler a proof copy of his work on matrix mechanics, which Fowler passed on to Dirac. While initially unimpressed by Heisenberg's work, after a few weeks Dirac realized that Heisenberg had actually solved the problem of the construction of a new mechanics. In particular Dirac saw that the failure of commutativity of multiplication, which Heisenberg had regarded as a possible flaw in his theory, was in fact vitally important and a key

feature of the new theory. Ignited by this spark, Dirac went on to create his own version of the new quantum mechanics with many original and essential ideas. His discovery of the link between commutators in quantum mechanics and Poisson brackets in classical mechanics is a beautiful expression of Bohr's Correspondence Principle and gave particular pleasure to Dirac. His explorations into the structure of the new quantum mechanics led to the concepts of q-numbers and c-numbers, the development of the transformation theory, the invention and use of the delta function, the analysis of symmetry properties of wave functions for identical particles and the link to their Bose or Fermi statistics, and somewhat later on the invention of the famous bra and ket notation. All these and more have become part and parcel of every physicist's training since several decades.

I will return to a survey of some of Dirac's many original ideas and achievements later, after a brief look at important events in his life.

Dirac's 1926 PhD thesis of about 140 pages was titled 'Quantum Mechanics' and consisted of his own remarkable contributions to its foundations. He was elected Fellow of St.John's College in 1927. In 1932 he succeeded Joseph Larmor as Lucasian Professor of Mathematics, a position he held till 1969. He was elected Fellow of the Royal Society in 1930. In 1933 Dirac shared the Physics Nobel Prize with Schrödinger, being cited for his 'discovery of new fertile forms of the theory of atoms and for its applications'. Soon after completing the PhD, Dirac made important visits to the Bohr Institute in Copenhagen, as well as to Max Born's school in Göttingen. In the ensuing years he made many trips to the erstwhile Soviet Union, to the USA and to Japan. In 1954-55 he spent several months at the Tata Institute of Fundamental Research in Bombay at the invitation of Homi Bhabha.

In 1937 Dirac married Margit Balasz (née Wigner), sister of the well-known physicist Eugene Paul Wigner. They had two daughters, Mary Elizabeth born in 1940 and Florence Monica born in 1942. After retirement from Cambridge in 1969, he moved to Florida, USA becoming Research Professor at Florida State University, Tallahassee in 1971. He was awarded the first Oppenheimer Prize in 1969, and the Order of Merit in 1973.

Dirac's relationship with his father was not a happy one. At home Charles strictly enforced the rule that the children should only speak in French or not at all. Dirac took the option of speaking very little – "so I became very silent at that time– that started very early" – a trait he retained throughout his life. He was always a man of very few but well-chosen words. His brother Reginald committed suicide in 1924. And as his biographer Kragh records: "He could not forget the traumatic experiences of his childhood, for which he blamed his father, with whom he came to want to have as little contact as possible". When his father died in 1936 Dirac wrote to Margit "I feel much freer now".

Coming back to his everlasting contributions to physics, he inaugurated quantum field theory in 1927 by performing the quantisation of the electromagnetic field. This brought to a conclusion the glorious chapter of modern physics starting with Planck's discovery of the radiation law in 1900, Einstein's photon concept of 1905, Ein-

stein's A and B coefficients and the ideas of spontaneous and stimulated emission and absorption of radiation by matter from 1916, and finally Bose's discovery of the new quantum statistics in 1924. In the next year, 1928, Dirac discovered the relativistic wave equation for the electron. The key idea was the introduction of spinors into physics, and it led to the first successful union of special relativity with quantum mechanics. Tomonaga records that the basic ideas came to Dirac while he was staring at a fire place at St.John's College! This discovery led to the explanation of many puzzling features of the electron – its intrinsic spin, its magnetic moment, the fine structure of the spectrum of hydrogen, and finally the prediction of the positron and the general concept of antimatter. In 1930 he completed his masterly exposition of the new mechanics titled *Principles of Quantum Mechanics* which has become a classic. It appears that Einstein always carried around a copy, and he spoke admiringly of "Dirac to whom in my opinion we owe the most logically perfect presentation of quantum mechanics". This book was revised four times, with Dirac making important improvements of notation in successive editions.

His work on the prediction of the positron and the remarkable properties of magnetic monopoles in the framework of quantum mechanics dates from 1931. In 1933 he examined the role of the Lagrangian of classical mechanics in the quantum context. This seminal paper of Dirac inspired Feynman a few years later to create his own Path Integral formulation of quantum mechanics, a third form comparable in significance to Heisenberg's original matrix mechanics and Schrödinger's later wave mechanics. In the mid 30's he did some work on wave equations for particles of higher spin. The paper on the Large Numbers hypothesis dates from 1937, and the work on the classical theory of the electron from 1938. In 1942 he suggested the use of an indefinite metric in Hilbert space of quantum mechanics and in 1945 he inaugurated the field of unitary representations of noncompact Lie groups by working out such representations for the Lorentz group. This was carried forward by his student Harish-Chandra from India.

Another major contribution of Dirac is to the classical mechanics of so-called singular systems. These are cases where the usual textbook recipes for passing from the Lagrangian to a Hamiltonian formulation, as a prelude to quantisation, fail. To handle such systems Dirac created concepts and methods of great elegance and depth. He applied them himself to the case of Einstein's general relativity. These methods were first presented in a series of lectures at the Canadian Mathematical Congress in Vancouver in 1949, and later appeared as a beautiful book of lectures given at Yeshiva University in 1964.

There are several other important ideas of Dirac one might recount, but it is time to say something about his personality. Dirac was a shy and genuinely modest person who readily acknowledged his debt to others. Bohr said of him: "of all physicists, Dirac has the purest soul". While introducing Heisenberg at a lecture in 1972 he said that they were both research students at the same time working on the same problem, and Heisenberg succeeded where he himself failed.

Dirac was a great believer in beauty in the mathematical formulation of physical laws. In a 1939 lecture he said: "Mathematical beauty cannot be

defined any more than beauty in art can be defined, but which people who study mathematics usually have no difficulty in appreciating". And on another occasion: "It seems that if one is working from the point of view of getting beauty in one's equations, and if one has a really sound insight, one is on a sure line of progress".

In his younger days Dirac was quite atheistic in his thinking. During a conversation in 1927 involving Dirac, Heisenberg, Pauli and others, Dirac is reported to have said: "... 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". To which Pauli retorted: "There is no God and Dirac is his prophet". But he presumably changed his attitude somewhat in later years, going by a letter from Margit to Abraham Pais, in which she said: "Paul was no atheist. Many times did we kneel side by side in chapel, praying. We all know he was no hypocrite". Dirac's lifestyle was ascetic, he was indifferent to discomfort or food, and neither smoked nor touched alcohol – making N F Mott compare him to Gandhi.

Dirac had a great insight into nature's laws, and an unequalled combination of mathematical inventiveness and elegance in expression. On the occasion of Dirac's 80th birthday Harish-Chandra wrote: "I have often pondered over the roles of knowledge or experience on the one hand and imagination or intuition on the other, in the process of discovery. I believe that there is a certain fundamental conflict between the two, and knowledge, by advocating caution, tends to inhibit the flight of imagination. Therefore, a certain naïvete, unburdened by conventional wisdom, can sometimes be a positive asset. I regard Dirac's discovery of the relativistic equation of the electron as a shining example of such a case... . Within a few years, nature conferred her approval on Dirac's marvelous insight by the discovery of the positron".

Dirac died in Florida on 20 October 1984. That was the passing of the last of the founders of quantum mechanics, who in his life had shown, again in Harish-Chandra's words, "... profound originality of thought and purity and gentleness of spirit".

N Mukunda
Centre for Theoretical Studies
Indian Institute of Science
Bangalore 560012, India.

"Whenever Dirac sends me a manuscript, the writing is so neat and free of corrections that merely looking at it is an aesthetic pleasure. If I suggest even minor changes, Paul becomes unhappy and generally changes nothing at all"

– Niels Bohr on Dirac