A Lifelong Quantum Quest

Rajaram Nityananda

John Wheeler's work over his entire working life coming under the broad heading of quantum mechanics is described – it ranges over very practical issues relating to atomic and nuclear physics (particularly nuclear fission), a far-reaching conceptual framework such as the scattering matrix, and deep foundational issues. His inspiration enabled his students to make outstanding contributions as well.

Rajaram Nityananda worked at the Raman Research Institute in Bangalore and the National Centre for Radio Astrophysics in Pune, and has now started teaching at the Indian Institute for Science Education and Research, Pune. He has worked on problems in optics, dynamics, and statistical physics, often applied to astronomy. The role of puzzles, paradoxes, physical arguments and connections/analogies between different areas are a significant preoccupation.

1. Introduction

John Wheeler is most remembered today for his contributions to gravitation, which are described in Jayant Narlikar's article (p.22) in this issue of *Resonance*. The present article is devoted to his work in quantum mechanics – the theme with which he started his research career. Perhaps the most famous of his papers in this area is with the legendary Niels Bohr, in 1939, on the mechanism of nuclear fission. Another major contribution is the invention of the S-matrix (explained below), a standard tool of today's quantum physicist. In the nineteen sixties, his student Hugh Everett came up with a remarkable – and still controversial – interpretation of quantum mechanics. And another student, Jakob Bekenstein, was the first to apply quantum ideas to black holes, in the nineteen seventies. This inspired none other than Stephen Hawking to take the idea further, and raised questions which are still not answered.

Fortunately, we have a rather detailed account from Wheeler's own perspective, in his own words – an extensive interview, (conducted over 22 sessions!) by his own former student, Kenneth Ford, and now available in the archives of the *American Physical Society* [1], and

Keywords
Wheeler, quantum mechanics, fission.

Today, we talk of an 'integrated PhD' in our institutions, where it is combined with a master's degree. It appears that Wheeler's PhD, in 1933, was actually integrated with his bachelor's and master's, and took six years in all, starting from high school!

the present article draws on this source in addition to the original scientific papers.

2. Doctoral and Postdoctoral Work

Wheeler's introduction to quantum physics – and indeed physics research – came at Johns Hopkins University, which had the reputation of being the first university in the US focused primarily on research. Today, we talk of an 'integrated PhD' in our institutions, where it is combined with a master's degree. It appears that Wheeler's PhD, in 1933, was actually integrated with his bachelor's and master's, and took six years in all, starting from high school! The young Wheeler was introduced to quantum theory by his thesis adviser, Karl Herzfeld, who was a student of Arnold Sommerfeld, and had moved from Germany, as had many other scientists during this period. Another member of the group was Maria Goeppert, herself later a Nobel Prize winner for the shell model of the nucleus, and a student of Max Born, a founder of quantum mechanics. He took up atomic spectroscopy to start with. An important theme which he learnt was the idea of dispersion, which is taught in all high school physics textbooks as the variation of refractive index of a transparent medium like glass, blue light being more bent than red. What is not so often taught is that this can be traced to a 'resonance' – that there is one (or more) frequency of light of still shorter wavelength, which glass can absorb. The relation is quantitative – given the absorption, one can calculate the dispersion, and vice versa. Sometimes, the absorption is simpler to describe – we need to know the excited states to which the system can go under the influence of the light.

Wheeler's postdoctoral work, with the nuclear physicist Gregory Breit in New York, pushed this theme further. Breit, with Eugene Wigner, had derived a basic formula which extended this idea of dispersion to nuclear physics, and Wheeler plunged into this new field, wrestling with how to describe the bewildering variety of reactions which were being discovered and studied in the realm of atomic nuclei.

3. The S-Matrix

In his first job, at the University of North Carolina, Wheeler proposed what he called the 'method of resonating groups', a term he borrowed from Linus Pauling's concept of resonance in chemistry – a molecule (benzene is a famous example) behaving with a split personality, needing two, or more structures to describe it! This kind of split – called 'superposition' – is a characteristic feature of quantum mechanics. Because not much was known about the forces between neutrons and protons making up the nucleus, he proposed a model in which it could simultaneously be in a superposition of many configurations – in one configuration, two of the protons and two of the neutrons would assemble to look like an alpha particle, in others they could be separate, etc.

This paper is unusual for its mixture of styles. It starts with a a very concrete idea – a scheme, even a numerical scheme – for coping with all these configurations. But it then moves to a deep, abstract idea picking out what could be said in general terms, independently of details.

This paper is unusual for its mixture of styles. It starts with a a very concrete idea – a scheme, even a numerical scheme – for coping with all these configurations. But it then moves to a deep, abstract idea picking out what could be said in general terms, independently of details, but at the same time useful to experimenters. It turns out that the other form of resonance, which Breit and Wigner pioneered, also played a role in his thinking and his mathematics. The result was what we now call the scattering or S-matrix. In mathematics, a matrix is a set of numbers arranged in rows and columns. In Wheeler's paper, each row refers to one initial state. The numbers in all the columns are complex, but can be squared to give the probabilities of going from this initial state to each of the final states. For example, the initial state could be a neutron and a proton and the final state could

Wheeler had the opportunity to spend a year at the Mecca of theoretical physics at that time – Niels Bohr's group at Copenhagen, Denmark, which had been humming with international activity in atomic and nuclear physics from 1921.

be the same particles, but also a nucleus of deuterium plus a photon. At high energies even more particles could be produced.

Today, the S-matrix is recognized as a standard tool for describing processes in nuclear and particle physics. But Wheeler's contribution is not so well known, for an interesting reason (see *Box* 1). Incidentally, Wheeler's two famous textbooks – *Gravitation* with Charles W Misner and Kip S Thorne, and *Spacetime Physics* with Edwin F Taylor – are full of boxes, very much part of his style!

After working with Breit, Wheeler was looking for a permanent academic position, but also wanted to spend time in some of the schools where exciting work was going on. He had the opportunity to spend a year at the Mecca of theoretical physics at that time – Niels Bohr's group at Copenhagen, Denmark, which had been humming with international activity in atomic and nuclear physics from 1921. Bohr's style involved intense and critical discussions with many younger people, particularly of basic conceptual issues, of which there was no shortage in this phase of the development of physics. From Wheeler's own account, he got to know many people and learnt many things there, but did not complete a major piece of work. However, it laid the foundations for the fundamental paper [2] that he wrote in 1939 with Bohr who was visiting the US, at Princeton.

4. Nuclear Fission

The phenomenon of nuclear fission had been discovered a few years earlier – nuclei of uranium broke into two fragment nuclei of elements with lower atomic number when bombarded by neutrons. Data regarding this process – how it depended on neutron energy, what were the fragments, how more neutrons could escape from the reaction, how other nuclei also might be 'fissionable' – were accumulating in laboratories all over the world. Wheeler was well prepared to work in this area, and

Box 1

To give a small flavour of what an S-matrix looks like, to those familiar with basic matrices and complex numbers, we give the example of a half-silvered mirror. Light can fall from the left l or from down d, and go either up u or right r (see *Figure* A). The outgoing amplitudes are connected with the incoming amplitudes by the two equations,

$$r = Tl + Rd\,; \quad u = Rl + Td\,.$$

Physically, T and R are complex numbers which give the transmitted and reflected amplitudes when a unit amplitude is incident on the mirror. These equations can also be written in a matrix form

$$\begin{bmatrix} r \\ u \end{bmatrix} = \begin{bmatrix} T & R \\ R & T \end{bmatrix} \begin{bmatrix} l \\ d \end{bmatrix}.$$

The energy in the light beam is proportional to the square of the absolute amplitude; so conservation of energy will place restrictions on the complex numbers T and R. These are $|R|^2 + |T|^2 = 1$ and $R = \pm i\sqrt{1 - |T|^2}$. You can derive the first one by applying conservation to a case when $l = 1, d = 0$; and the second one by considering a case when $l = d = 1/\sqrt{2}$. For quantum mechanical S-matrices, it is the probability which is conserved, and much more progress is made by exploiting other nice mathematical properties.

A few years after Wheeler, Werner Heisenberg, in Germany, possibly unaware of Wheeler's work (the second world war was being fought and they were on opposite sides) came up with the same concept, in greater generality, and perhaps his work was more influential, given his towering stature in twentieth century physics. To Heisenberg the S-(now for *Streuung*, meaning scattering in German!) matrix was fundamental. He came to the view that one should only deal with observables – a view which served him so well when he discovered the uncertainty principle in 1933. But now, in 1941, he viewed the S-matrix as the escape from the many technical difficulties of calculating physical processes in the quantum theory of electrons and photons, known as field theory, which he had himself pioneered. As mentioned in Vasant Natarajan's article in this issue, these difficulties were tamed to a large extent by Wheeler's student, Feynman, along with others. Wheeler himself took a more practical view of the S-matrix. But, under Heisenberg's influence many others too gave up 'field theory' and pursued the S-matrix as an end in itself. Starting from the 1970's, field theory has bounced back and S-matrix theory is regarded as useful and interesting but not fundamental.

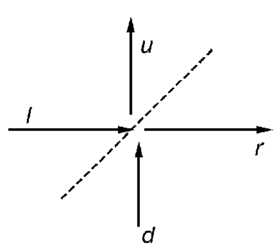

Figure A. Illustrating the S-matrix of a half-silvered mirror, which transforms two incident amplitudes *l* and *d* into two outgoing amplitudes *u* and *r*.

this paper undertook to place the whole field in a single framework. It is usually remembered for using the analogy of a liquid drop – normally such a drop needs energy to break into two, because the surface area increases. But if it is charged, then one gains energy in the division by moving like charges further apart. The delicate balance of these two governs the basic fission process. But this is a simplification of their analysis, which actually went into considerable detail, and used quantum mechanics in very innovative ways to make predictions which were in good agreement, given how complex the phenomenon was. In fact, the very complexity of the nucleus was exploited by using the 'statistical model' and 'compound nucleus model' both of which had been developed by Bohr and others. The basic idea is that with the entry of the neutron, the nucleus is able to access all configurations which are energetically feasible, leading to fission as well as other forms of decay. The two vital numbers were the energy release – enormously more than the energy of the neutron which triggered the fission – and the fact that more neutrons were released than went in. A chain reaction in which fission of one nucleus triggers the fission of more nuclei in the vicinity and continuously releases energy thus became possible. Thus this paper laid the foundation for the harnessing of nuclear energy, both in reactors and in nuclear weapons. Bohr himself came back to the US as a refugee from the German invasion of Denmark in 1943 and joined the atomic bomb project, and Wheeler became a key figure in the effort to produce plutonium in the first large-scale reactor during the war. His knowledge of nuclear physics and indeed many other fields made him invaluable to the war effort, and this continued into the post-war project in the US to build the fusion (also known as hydrogen) bomb.

Thus this paper laid the foundation for the harnessing of nuclear energy, both in reactors and in nuclear weapons.

5. Back to Fundamental Research

It is interesting that Wheeler himself confesses that, during this period, he pursued two ideas which did not work and he gave up. One was to try and make electrons and positrons as fundamental building blocks of matter, and the other to abandon field theory in favour of action at a distance (Vasant Natarajan's article, p.39). This did have a useful by-product, however. Legend has it that he telephoned his research student, Richard Feynman, whom he told that he had found why all electrons in the universe had the same mass and charge. The reason? Because there is only one electron! (see *Figure* 1). This picture proved very useful to Feynman when he constructed quantum electrodynamics. In his later years, Wheeler stated that he would not stop until he had a pictorial representation of any idea he was pursuing.

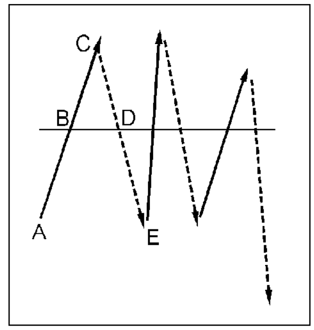

Figure 1. Wheeler's picture of a single particle manifesting in many places at a given time (horizontal line BD...). The solid lines like ABC represent electrons, while dashed lines like CDE are positrons, positively charged particles. The incoming photons at A which produce the pair, and outgoing photons at C which result from the pair annihilating, are not shown. This is only a picture and its value is that it led Feynman to a concrete way of calculating processes involving electrons and photons.

Wheeler's work in gravitation (Jayant Narlikar's article) was not unconnected with his quantum interests. Although he chose to work with Bohr rather than Robert Oppenheimer in 1937, he saw the significance of Oppenheimer's work which seemed to show that neutron stars were possible and needed the application of general relativity, but also nuclear physics at high density to give a realistic description, since Oppenheimer had assumed neutrons with no strong interactions between them. It is interesting that the Russian physicist Yakov Zel'dovich (*Resonance*, Vol.16, No.5, 2011) followed a very parallel track, having worked on reactors, the fusion bomb, and then moved to gravitation. In fact, Wheeler was proud that Zel'dovich had his own book with Harrison, Thorne, and Wakano translated from the Russian. Later, Thorne returned the compliment by overseeing the translation of the Zel'dovich–Novikov volumes on *Relativistic Astrophysics* into English.

This period, which continued in some sense till the end of Wheeler's life, was marked by a style worthy of Bohr himself –attracting the brightest and the best young people and inspiring them to do great things.

This period, which continued in some sense till the end of Wheeler's life, was marked by a style worthy of Bohr himself – attracting the brightest and the best young people and inspiring them to do great things.

6. Foundations of Quantum Theory

Wheeler's ability to think very originally on quantum matters is nicely demonstrated in his famous proposal of a 'delayed choice' experiment (*Box* 2). Two other examples concerned with quantum mechanics are worth citing. Wheeler had a deep conviction that gravity had to come under the framework of quantum mechanics, and on the smallest scale, even the basic notion of spacetime would be replaced by some kind of 'foam'. But according to none other than Niels Bohr, the wave function of quantum mechanics only describes what an external

Box 2. Delayed Choice: A Wheeler Special

A very good example of Wheeler's ability to bring fresh insight into a well-worn subject is his 'delayed choice' proposal in the context of the two-slit experiment. It is well known that when particles like electrons pass through the double slit, the overall distribution of arrivals on the screen shows an interference pattern, and this is usually described as demonstrating the 'wave nature' of the electron. From the earliest days of quantum theory – the debate between Bohr and Einstein in 1927 – the question of how we get interference effects even when only one electron at a time passes through the system has intrigued physicists. The classic, 'complementary' view is that we get interference whenever we do not observe which slit the electron passes through. Any attempt to determine this destroys the interference pattern. This point of view is eloquently described in the very first chapter of Volume III of Feynman's *Lectures on Physics* (1964). Yet there was one aspect of this that had not been explicitly realized and stated, which Wheeler brought into sharp focus as late as 1978. In his proposal, one observes which slit the particle (in his case, the photon) passes through, exercising the option of using, as an alternative to the usual screen, a telescope at the same location. This does not violate the uncertainty principle – it is easy to check that in order to have enough resolving power to separate the two slits, the diameter of the telescope has to be bigger than the size of the fringes, so that one does not get an interference pattern in the detected photons. One has to choose, as before, whether to see interference or to see which slit the particle passed through. However, the real punch comes later – one can, in principle, make this choice after the particle has passed the slit. Wheeler, never one for half measures, suggested that – again in principle! – this could be applied to two images of an astronomical source produced by a 'gravitational lens', so one would have billions of years to make up one's mind as to what to measure! (See *Figure* A). Thus the discussions by Bohr, or Feynman, which emphasize doing something at the slits to determine the WW ('which way' in English, *welcher weg* in German!) information is not the whole story.

Box 2. Continued

Box 2. Continued

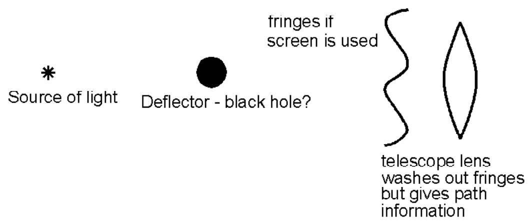

Figure A. Wheeler's cosmic version of the delayed choice experiment. A photon from an astronomical source (left) encounters a large gravitating mass (deflector, centre) and hence can reach the observer (right) by two paths. The observer has the choice of inserting a screen and observing fringes (wavy lines) or using a telescope lens (extreme right) to determine which path the photon took. (The reader should note that there are many factors which would make the cosmic version impractical – the finite range of wavelengths and the finite size of the source both limit the 'coherence', i.e., the ability to form fringes).

Experimenters in quantum optics took up the challenge. In the laboratory one had only a few tens of nanoseconds, the time for light to travel a few meters, to make up one's mind, but that was enough. A particularly 'clean' version was carried out in 2007 (Vincent Jacques, *et al.*, Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment, *Science*, Vol.315, pp.966–968, 2007; arXiv:quant-ph/0610241v1). This paper which gives references to earlier work, confirmed the expectation from quantum theory. It does contradict naive interpretations in which we think of the particle as having a definite state after it passed the slits, even though we did not do anything to measure it. The overall moral seems to be that quantum states come wrapped in a sealed black box labelled 'Fragile: handle with care'! The experiment is yet another warning that we should use quantum mechanics to make experimental predictions about the entire system, in which case it does well. When we use mental pictures about parts of the system, not based on measurement, (in this case, a statement like 'the photon has passed the slit and surely it knows whether it has gone through one or both') we run into trouble. Of course, the dilemma of the state–observer split remains, as discussed in the main article.

observer knows about the system, and undergoes 'collapse' as that knowledge changes. This orthodoxy is in fact known fact known as the 'Copenhagen' interpretation in honour of Bohr. This is problematic even for human observers, but particularly so when one talks, as Wheeler did, about the wave function of the whole universe – who is observing it from the outside? His student, Hugh Everett, came up with the 'relative state' interpretation of quantum mechanics in which no classical observer is needed, the observer is also part of the wave function, and hence is not in a definite state. Put crudely, we may think that the wave function has collapsed in a particular way, because of our observation, but this is only one of many terms in the wave function,

In his later years, Wheeler was fascinated by the notion of information as the fundamental building block of the world, and characteristically coined the slogan "it from bit" (i.e., all entities are informational in Nature).

and it has other terms in which different alternatives (which quantum mechanics allows) are realized. Everett was able to derive the basic rules of computation in quantum theory from his relative state idea. This did not attract much attention initially, and Everett himself went on to work in other areas. But some years later, under the catchy name 'many worlds' given by Bryce deWitt, this idea has won attention again. Characteristically, Wheeler himself gave it up later, but it is still being pursued by others.

Another of Wheeler's students, Jakob Bekenstein, came up with a major new idea in 1973. Three of the most eminent practitioners of general relativity – James Bar- deen, Brandon Carter, and Stephen Hawking – had come up with three laws for black holes which were remarkably parallel to the laws of thermodynamics, but concluded that this was merely an analogy and should not be taken more seriously. Bekenstein disagreed with them – he introduced Planck's constant and gave formulae for the entropy and temperature of black holes which were meant to be taken literally, contradicting the wisdom of the experts, but laying the foundations for a flourishing industry which continues to this day. Work in this field has to address fundamental questions. In every other area we know of, entropy counts the number of microscopic states but for black holes, states of what? Empty spacetime? Answers abound but there is no single accepted answer.

In his later years, Wheeler was fascinated by the notion of information as the fundamental building block of the world, and characteristically coined the slogan "it from bit" (i.e., all entities are informational in Nature). This is of course just an idea, like spacetime foam. It is clear that quantum mechanics ran like a thread through his entire career, both the practical applications and the foundations. Truly a long quantum journey of eighty years – from his early days as a student in Johns Hopkins (1928) till the end (2008).

Suggested Reading

[1] **The long interview with Wheeler:www.aip.org/history/ohilist/4958.html**

[2] **N Bohr and J A Wheeler, The mechanism of nuclear fission, *Phys. Rev.*, Vol.56, pp.426–450, 1939.**

Address for Correspondence
Rajaram Nityananda
NCRA-TIFR
Pune 411007, India.
Email:
rajaram.nityananda@gmail.com