Abstract

A brief review is given of selected highlights in scientific developments from the birth of modern nuclear physics at the end of the 19th century to the discovery of the neutron in 1932. This is followed by some important milestones in neutron and reactor physics that have led to our current understanding and implementation of nuclear technologies. The beginnings can be traced back to the discovery of X-rays by Roentgen, the identification of natural radioactivity by Becquerel and the discovery of the electron by Thomson, towards the end of the 19th Century. Rutherford was a key figure in experimental physics who determined the structure of the atom and who inspired his students at McGill, Manchester and Cambridge Universities (many of whom would become Nobel laureates) in the pursuit of their physics research.

One of Rutherford's students, James Chadwick, had studied the work carried out by Bothe and Becker on alpha particle-induced disintegration of light elements which had led to their observation of high energy penetrating radiation that neither they nor the Joliot-Curies could identify. Chadwick knew that the only possible explanation was the emission of a neutron in the nuclear reaction. He carried out tests in the Cavendish Laboratory and submitted his now classical paper identifying the neutron to the periodical Nature in 1932.

The discovery of the neutron and of nuclear fission in 1939 opened up new areas for scientific investigation, in, for example, astrophysics, geology, neutron and nuclear physics. The prospects for nuclear power in particular appeared to be unlimited and both civil and military applications have been actively pursued.

Many new experimental facilities have been designed and built to provide intense sources of neutrons for research purposes. Work carried out in such centres is included in the programme of the 7th International Topical Meeting on Neutron Radiography, an important forum for discussion of the latest research work of this ever-growing scientific community.

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1. The beginnings of modern nuclear physics

The first half of the last century was marked by the dramatic political upheavals created by two world wars. These events had a significant influence on the pace and direction of scientific discovery during the whole period and for much of the latter half of that century.

1.1. The early days

What perhaps was the dawn of modern atomic and nuclear physics began with the important scientific discoveries made at the end of the 19th century. Wilhelm Röntgen had observed and identified X-ray radiation in 1895 (for which he was awarded the first Nobel Prize in Physics in 1901). The natural radioactivity present in uranium compounds was discovered by Henri Becquerel (1896) and JJ Thomson identified the electron as a fundamental particle of matter in 1897. These discoveries were crucial for starting a transformation in the scientific understanding of natural phenomena [1].

A key experimental physicist at this time was Ernest Rutherford who became a professor of physics at McGill University (1899-1907). With Frederick Soddy, he identified and named the alpha and beta particles, determined the radioactive changes in the radium, thorium and actinium series and derived the exponential nature of radioactive decay. The term gamma ray was separately proposed by Andre-Louis Debierne (the discoverer of the element actinium) who was working as an assistant to Pierre and Marie Curie in Paris.

1.2. Physics in Manchester

After becoming professor of physics at the University of Manchester (1907-1919), Rutherford continued with his research activities into radioactivity, inspiring and stimulating many capable research students in experimental techniques. Under his leadership, Manchester University Physics Department became the most important centre in Britain for studies in atomic and nuclear physics.

In 1913, a series of classic experiments on the scattering of alpha particles by gold foil was carried out by Hans Geiger and Ernest Marsden which led Rutherford to deduce that the atom contained a heavy positively charged central nucleus [2].

Hantaro Nagaoka had earlier proposed a nuclear model of a central nucleus with rings of orbiting electrons (in 1904), but this was not an acceptable theory to most scientists because the electrons would be expected to lose energy and collapse into the central nucleus under classical electromagnetic theory.

In 1919, Rutherford discovered that light elements such as nitrogen disintegrated under alpha particle irradiation and a proton emitted. This was later proven to be the transmutation of nitrogen into oxygen in cloud chamber measurements carried out by Patrick Blackett at Cambridge University.

1.3. James Chadwick at Manchester University

James Chadwick was born near Manchester of a poor family. He was a hard worker at school and obtained a scholarship to attend university. Preliminary interviews were held at Manchester University with physics and mathematics entrants being interviewed in the same building but he got in the wrong line and found himself answering questions from a physics department lecturer. As he was too shy to admit that he wanted to study mathematics but because he also liked the enthusiasm of his interviewer, he ended up going to university in 1908 to study physics. Chadwick therefore started life unexpectedly as a physicist at Manchester University.
His qualities were recognised by Rutherford who gave him, as his final year project, the test of a method for accurate inter-comparison of different radium sources. This needed to be first proven as a method and then established as a working technique following a meeting of the International Congress of Radiology and Electricity in Brussels in 1910 at which the proposal had been adopted to define the Curie as the amount of radiation released by a gram of radium. Mme Marie Curie had agreed to prepare a pure source of about 20 milligrams for use in comparative measurements [3].

After graduating, Chadwick continued with post-graduate work on radioactivity under Rutherford and obtained his M.Sc. As one of the outstanding students, Chadwick was then nominated by the university for a research scholarship in 1913. Under the terms of this scholarship, he had to spend part of the time at another university. There was no way that Rutherford could get this requirement relaxed and therefore Chadwick chose to work in Geiger's laboratory in Berlin. However, when war was declared in 1914, he was interned and had to remain in Germany until the armistice in November, 1918. Geiger himself, like many scientists on both sides, went to fight on one of the war fronts. Henry Moseley who, at Manchester University, had studied characteristic X-ray line spectra emitted by the different elements and showed that the X-ray energy increased with atomic number, was one of those killed, at the Dardanelles in 1915. At the end of the war and on his return to Britain, Chadwick re-joined Rutherford at Manchester University.

Niels Bohr, who had visited Manchester as a post-doc in order to work with Rutherford and who became a Reader in physics (1914-1916), applied the quantum theory that had been proposed by Max Planck (in 1900) to Rutherford's model of the atom and published in 1913 that atomic electrons could only occupy certain discrete orbits around a nucleus with each level at a certain energy. Bohr later made another very important contribution to nuclear physics with the concept of the compound nucleus (1936).

In this same year (1936), Gregory Breit and Eugene Wigner determined the cross-section for the formation of the compound nucleus [4]. This equation provides an illustration of Werner Heisenberg's uncertainty principle for energy and lifetime.

1.1. The Cavendish Laboratory

Rutherford became professor of physics at the Cavendish Laboratory at Cambridge University in 1919, returning to the university from which he had completed his postgraduate studies in 1898 under Thomson. He asked Chadwick to go to Cambridge with him [5]. Figure 1 shows a photograph of the Staff and Research Students of the Cavendish Laboratory in 1933 and includes six Nobel Laureates.
Among the research students at the Cavendish Laboratory with Chadwick was Wilfrid Lewis who was an expert in electronics. After completing his PhD, he continued at the Cavendish Laboratory as a member of staff before working in a senior scientific role at the UK government’s Telecommunications Research Establishment during World War II. He was later appointed as the Director of the National Research Council of Canada’s Atomic Energy Division, now known as AECL and was instrumental in pushing forward development of the heavy water-natural uranium power reactor project, coming to be regarded as the father of the CANDU reactor. He became a professor of physics at Queen’s University, Kingston in 1974.

Chadwick (Figure 2) eventually became Assistant Director of the Laboratory and was Rutherford’s closest colleague, acting in effect as his deputy in supervising research students and in handling questions of administration. He would make a daily tour of the laboratory to discuss projects with the research students.

The stream of experimental discoveries from the different laboratories stimulated the development of theoretical atomic physics by among others, Bohr in Copenhagen, Lois de Broglie in Paris who had proposed the wave theory of matter in 1924 and Heisenberg in Göttingen who proposed the new quantum physics in 1925 based on the mathematical description of observable quantities. In 1926, Schrödinger announced his new wave mechanics principles [1].

1.2. The discovery of the neutron

Polonium-210, a radioactive material, which emits alpha particles but no gamma rays and which had been discovered by Marie Curie in 1898, was becoming available in increasing quantities to scientists. This source was being used by Walther Bothe and Herbert Becker to investigate the disintegration of light elements by alpha particles and with it they had detected the emission of gamma radiation. They found penetrating radiation from both lithium and beryllium, but that from beryllium was of particularly high energy. Irène and Frédéric Joliot-Curie repeated Bothe and Becker’s experiment and confirmed their results. They also noted that, when they passed the radiation produced through paraffin wax, the intensity increased and this they explained by the knock-on protons produced entering the ionization chamber being used for measurements. After reading their paper published in 1931, Chadwick immediately realised that, if energy and momentum were to be conserved, this was clearly the result of a heavy neutral particle being emitted from the beryllium. Within one month he had repeated the experiment, carried out the analysis and submitted the letter to Nature [6] identifying the neutron (in February 1932).
Rutherford in the 1920s had proposed the existence of a neutral particle and first used the name "neutron".

The Joliot-Curies continued with their alpha particle irradiation experiments and reported the discovery of induced artificial radioactivity in 1934, which earned them the 1935 Nobel prize in Chemistry.

It has been said that Ettore Majorana, who had worked with both Bohr and Heisenberg, had reviewed the Joliot-Curies' experiments and had also come to the conclusion that the only explanation was the generation of a neutral particle. Enrico Fermi had told him to publish his conclusions, but he did not do so.

1.3. The first particle accelerator

The limited range of particle energies available from natural radioactive sources led Rutherford (with urging from Chadwick) to encourage the development of high voltage sources for the acceleration of particles to high energy. In the same year as the neutron's discovery, John Cockcroft and Ernest Walton demonstrated nuclear transmutation in the Cavendish Laboratory by artificially accelerating protons at 125 kV in a linear accelerator on to a lithium target using a zinc sulphide screen to detect the alpha particles produced [5]. This work was the starting point in development of high voltage accelerators and soon many different configurations were being studied. The first cyclotron was constructed by Ernest Lawrence in Berkeley, California in 1938.

In addition to the accelerators that have been constructed in large national and international laboratories for high energy nuclear physics research, many others, accelerating particles to energies of between 100 kV and 1 GeV or more, have been designed and built for use as neutron sources.

1.4. Neutron stars

The identification of the neutron was to have important ramifications in the field of astrophysics. Two years after Chadwick's discovery, Walther Baade and Fritz Zwicky proposed the formation of neutron stars in supernovae [7]. They had been the first to describe a supernova the previous year.
In 1967, Jocelyn Bell and Anthony Hewish detected regular radio pulse emission from a distant source and this pulsar was later identified by Thomas Gold (1968) as an isolated, rotating neutron star. The neutron and its properties, in particular its lifetime, mass and magnetic dipole moment were, therefore, important for theoretical modelling of different stellar processes [7].

Chadwick and Maurice Goldhaber made the first precise determination of the neutron mass in 1935 and predicted that the neutron would be beta-active, decaying spontaneously into a proton, electron and neutrino [8].

1.5. False physics

In a different vein, it is interesting to remember the apparent discovery of what were called n-rays at the beginning of the 20th century. This new form of radiation with its remarkable properties had been announced by Prof. René Blondlot of the University of Nancy (in 1903). These powerful rays were claimed to be emitted spontaneously by many metals, could be refracted by aluminium and they could increase the ability of the human eye to detect light. Many papers were published in Comptes Rendus by Blondlot (a member of the French Academy) and others, including Jean Becquerel (son of Henri). Among the many sceptical scientists was Prof. Heinrich Rubens of Berlin who was very aggrieved because the Kaiser had commanded him to demonstrate the rays to him and after attempting this over a period of two weeks, he could not duplicate Blondlot's results. It was agreed by a group of scientists that Prof. Robert Wood, a renowned optical physics investigator, would go to Nancy to investigate. Wood was shown the experimental procedure by Blondlot, who had set up an aluminium prism in front of a narrow slit in a darkened room and measured the refractive index for the several different components of the N-rays using a thin strip of phosphorescent paint. After a number of experiments, Wood secretly removed the aluminium prism, but this did not affect the results that Blondlot then read out. Wood's report was published in Nature in 1904 and this effectively closed down this episode [9].

1.6. Neutron chain reaction

In 1933, Leo Szilard realised that a neutron would more easily interact with a nucleus than would an alpha particle and if a reaction involving a neutron with a nucleus could result in two or more neutrons being produced, this might make a chain reaction possible. He had been an avid reader of H.G.Wells' books and had recently read "The World Set Free" written in 1913 which had described the liberation of atomic energy on a large scale for industrial purposes, the development of atomic bombs and a world war resulting in mass destruction by nuclear forces [10].

1.7. Neutron fission

Studies of neutron reactions with different materials were being pursued by many scientists who were attempting to understand the processes taking place. A notable milestone was Otto Hahn and Fritz Strassman's skillful detection of barium in the break up of uranium nuclei by neutrons in 1939 [10]. This process was described as a fission process by Otto Frisch and Lise Meitner in the same year.

Following the dramatic discovery of the fission of uranium, the realisation that this could lead to generation of large amounts of energy stimulated intense activity in research laboratories in Europe and America. Ludwik Kowalski and Frederik Joliot-Curie in Paris measured the number of neutrons emitted in the fission of uranium-235. By 1940, Joliot-Curie had taken out a patent for a heavy water moderated reactor and was actively investigating the design of an atomic bomb. The French had obtained 200 kg of
heavy water from Norway but, with the fall of France imminent, this material was removed from Joliot-Curie's laboratory to be shipped to Britain. The Earl of Suffolk, a scientist from Edinburgh University was working as a government representative in Paris. He lived the high life - surrounded by beautiful women and drinking champagne - but at the same time, he helped French scientists and engineers to get out of the country. He obtained a large quantity of industrial diamonds at gunpoint from diamond merchants in Antwerp and commandeered a British coal transport ship to transfer the cargo. The 26 cans of heavy water plus about 25 French scientists (including Hans von Halban and Kowarski, who worked in Joliot-Curie's laboratory and had co-authored an important paper on nuclear fission in 1939 with him) sailed to Britain in June 1940. Joliot-Curie himself did not want to leave France. The heavy water was transported to Wormwood Scrubbs, a prison in London before being moved to the Library at Windsor Castle. The French representatives thought that Britain would be invaded and they decided to send Halban and Kowarski to North America with the heavy water to continue their work there [10]. Who needs James Bond with real-life tales like this?

Fermi's work with slow thermal neutrons in 1934 showing that neutrons at a lower energy were more likely to interact with matter had led to the discovery of fission and later to the construction of the first thermal neutron reactor in a squash court at Chicago University. Intense efforts would then follow to make use of nuclear power for military purposes and also for electrical power generation. Power reactors were developed that were optimised to produce Pu for military use and later, commercial reactors were adding to the Pu stockpile.

1.8. Nuclear cross-section data

In order that accurate theoretical models of neutron interactions in multiplying or moderating media could be derived, it was essential that good quality experimental data on neutron cross-sections be obtained. Nuclear data relevant to the fission process was accumulated mainly in great secret by each country. Eventually, at the 1955 Geneva Conference on Peaceful Uses of Atomic Energy, much basic data of use in the nuclear energy field was released and this marked a new era of international data exchange and global cooperation became possible. New reactor and accelerator source facilities were constructed around the world to improve on data acquisition.

To handle and distribute the new data, four compilation centres were created: the National Nuclear Data Centre (Brookhaven Laboratory, USA), the Nuclear Data Bank (OECD, Paris, France), the Nuclear Data Section (IAEA, Vienna, Austria) and the Centre for Nuclear Data (Obninsk, Russia).

Important basic neutron cross-section data, both integral and differential and obtained since the discovery of the neutron, have been collected from measurements over the world at accelerator and reactor neutron sources. Results were first collated by Donald Hughes and John Harvey (1955) to produce best fit data and published as BNL-325 (the BARN book).

One of the pioneers in the use of thermal neutrons to study structural, dynamical and magnetic aspects of condensed matter and also to obtain cross-section data was Bertram Brockhouse. At Chalk River, he developed sophisticated thermal neutron-scattering equipment and experimental methods. In particular, he invented the triple-axis crystal spectrometer, which is now widely used in neutron-scattering research laboratories. He became a professor of physics at McMaster University and was awarded the Nobel prize in 1994 for his work on neutron scattering and the development of neutron spectroscopy. The co-winner of the Nobel prize in this year was Clifford Shull, who had started his pioneering work on the neutron diffraction technique in 1946 at the Oak Ridge National Laboratory.

The evaluated nuclear reaction databases, ENDF and others are now collected, compiled and disseminated digitally by the international network of Nuclear Reaction Data Centres (NRDC) - a world-
wide co-operation of nuclear data centres under the auspices of the IAEA. The libraries accessible include:

- ENDF/B-VII.1 (USA 2011)
- JEFF-3.1 (Europe 2005)
- JENDL-4.0 (Japan 2010)
- CENDL-3.1 (China 2009)
- ROSFOND (Russia 2010)

All data are stored in the internationally adopted format ENDF-6 maintained by the Cross Section Evaluation Working Group (CSEWG), which is a cooperative effort between the organisations (national laboratories, industry and universities) in the USA and Canada that are responsible for the production of the U.S. Evaluated Nuclear Data File ENDF/B.

One useful table of cross-section data for thermal neutron reactor physics calculations was devised by Carl Westcott. He was one of Rutherford's last Ph.D. students, receiving his Ph.D. degree in 1936 for studies of the processes involved in neutron interactions with matter. In 1944, he transferred to the joint British/Canadian Atomic Energy Project at the National Research Laboratories in Montreal and then to the Chalk River Nuclear Laboratory. After a period at the University of Birmingham, Westcott moved first to McGill University in Montreal and then joined the staff of the Chalk River Nuclear Laboratory in 1954 where he specialised in nuclear data acquisition and use. In this field, he developed the "Westcott Convention" for easily and accurately estimating neutron reaction rates in thermal fission reactors using his tabulated g and r cross-section functions for different activation materials at different neutron temperatures. It was particularly useful for determining reaction rates including cadmium ratios and for calculating neutron temperatures using thin activation foils where the thermal neutron flux was described by a Maxwell-Boltzmann distribution.

In order to obtain accurate data for use in reactor physics computer codes, models for the scattering of neutrons on the molecules of different moderator and other materials were derived by a number of laboratories. One example is Mark Nelkin's water model, which was incorporated into computer programs for the physics calculations of light water moderated reactors. Software programs were developed to characterise neutron behaviour in multiplying and non-multiplying media e.g. MUFT and SOFOCATE (Westinghouse) using the method of spherical harmonics (P_N method) and the Carlson D_N method for solving the transport equation. Monte Carlo methods were also being developed (e.g. the MCNP program) and with the dramatic leap in computing power these have now become a routine method of calculation [4].

1.9. Neutron sources and neutron radiography

High neutron flux research reactors and accelerators had been built with multiple beam lines to provide for the high demands of experimental neutron physics programmes. Many of those first generation accelerator and reactor sources have now been de-commissioned. Today, very diverse neutron physics experiments are carried out mainly at spallation neutron source centres or at high flux reactors and these large-scale facilities incorporate a wide range of beam line facilities for researchers.

If we look at developments of the neutron radiography technique from the early beginnings, the very first neutron radiographs were obtained using radioisotope sources. These were produced by H. Kallmann and H. Kuhn in Berlin in the 1930s, followed by O. Peter in 1946. A review of the development work
carried out in Germany from 1935 to 1944 was given by Carl-Otto Fischer at the San Francisco 4th World Conference on Neutron Radiography in 1992 [11].

The first reactor-based neutron radiographs were made at Harwell by J. Thewlis and R. Derbyshire in 1956. A concise review of developments was published by Harry Berger in his book on neutron radiography [12]. Berger began his well-documented studies at the Argonne National Laboratory in 1960 whilst, in the U.K., John Barton started work on NR projects at the University of Birmingham in 1961. These latter two modern pioneers of neutron radiography together with Prof. Hisao Kobayashi from Rikkyo University, were granted Honorary Membership of the International Society for Neutron Radiography (ISNR) at the 9th World Conference of Neutron Radiography, held at Kwa-Maritane, South Africa in 2010 [13].

The whole field of neutron radiography using steady-state/pulsed, reactor- and accelerator-based sources is well reviewed in numerous series of meetings, including the ITMNR, the World Conferences on Neutron Radiography and, more recently, the specialist Neuwave meetings. The present ITMNR, the 7th in the series, promises another programme of fascinating and stimulating scientific papers and discussions.

The fundamental particles of nuclear physics have been used in many research applications as probes into the structure of matter. The role of neutrons, in particular, illustrates the diversity and usefulness of such techniques in improving our understanding of the world about us.

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