James Chadwick: ahead of his time

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Abstract

James Chadwick is known for his discovery of the neutron. Many of his earlier findings and ideas in the context of weak and strong nuclear forces are much less known. This biographical sketch attempts to highlight the achievements of a scientist who paved the way for contemporary subatomic physics.
1 Early years

James Chadwick was born on Oct. 20, 1891 in Bollington, Cheshire in the northwest of England, as the eldest son of John Joseph Chadwick and his wife Anne Mary. His father was a cotton spinner while his mother worked as a domestic servant. In 1895 the parents left Bollington to seek a better life in Manchester. James was left behind in the care of his grandparents, a parallel with his famous predecessor Isaac Newton who also grew up with his grandmother. It might be an interesting topic for sociologists of science to find out whether there is a correlation between children educated by their grandmothers and future scientific geniuses.

James attended Bollington Cross School. He was very attached to his grandmother, much less to his parents. Nevertheless, he joined his parents in Manchester around 1902 but found it difficult to adjust to the new environment. The family felt they could not afford to send James to Manchester Grammar School although he had been offered a scholarship. Instead, he attended the less prestigious Central Grammar School where the teaching was actually very good, as Chadwick later emphasised.

Chadwick’s modest background did not prevent him from receiving an excellent general education. Especially his mathematics teacher encouraged him and finally persuaded him to enter a competition for a scholarship at Manchester University, which he won at the age of sixteen [1].

2 University studies

In May 1907, Ernest Rutherford moved from McGill University in Canada to Manchester University. He inherited from his predecessor a modern and well-equipped department with one major deficiency: there was no radium. The problem was solved by Stefan Meyer from the Radium Institute in Vienna with a generous gift of some 300 milligrams of radium chloride. The Manchester School of radioactivity under Rutherford’s leadership soon produced results that would revolutionise science.

In the fall of 1908, Chadwick came to the university for a preliminary interview. Although he intended to take up mathematics, he ended up being interviewed by a lecturer from the physics department. Chadwick was too shy to admit his mistake and thus started his life as a physicist by accident. He was not too impressed by his first-year courses but things changed substantially when in his second year he attended lectures on electricity and magnetism delivered by Rutherford, “the first stimulating lectures I had ever had in physics” [2].

At the end of the second year, there was no more formal education in physics. Instead, the few remaining honours students in physics were assigned specific research projects by Rutherford. As Chadwick later remarked [2]: “I had half an education in physics. There were whole aspects of physics I knew little about.”
At that time, there were no generally accepted units for radioactivity. At an international congress in Brussels in September 1910 it was agreed that the amount of radioactivity released by a gram of radium would serve as the standard unit, later to be known as a curie. The third-year research project assigned to Chadwick was a highly topical one. He was instructed to investigate a method initially devised by Rutherford to compare different radium sources. When Chadwick became aware of a small problem in Rutherford’s original setup he did not dare to mention it to the master, risking rather to disappoint Rutherford who noticed the problem after the first measurements. The approach was applied to a comparison of the two standard radium sources available at the time, one initially provided by Marie Curie and the other by Stefan Meyer. The comparison was completely convincing, leading at one hand to the acceptance of an agreed world standard and, on the other hand, to Chadwick’s first published paper together with Rutherford [3].

In the summer of 1911, Chadwick graduated with first class honours although the final exam was by no means straightforward. The written part presented no problems. On the other hand, Chadwick found out only shortly before the exam that he also had to undergo a practical examination, with J.J. Thomson as external examiner. Chadwick claims that he was terrified by Thomson’s charisma and could hardly say a word [2]. In any case, Rutherford was convinced of Chadwick’s talents and accepted him as a graduate student. As a demonstrator he received his first salary, modest enough but sufficient for regular lunches after three years as an impoverished undergraduate. The growing impact of the Manchester School attracted many visitors, among them Niels Bohr who came in March 1912 as a postdoctoral fellow and made friends with Chadwick. The most prominent result of Bohr’s stay was his atomic model, which dominated the physicists’ view of the atom till the emergence of quantum mechanics and beyond.

The next project of Chadwick was a thorough investigation of $\gamma$-ray absorption in gases. Until that time all information on $\gamma$-ray absorption coefficients had been indirect. Using simple but ingenious techniques, Chadwick was able to measure these coefficients with uncertainties of only a few percent. This research definitely established Chadwick as an imaginative experimenter. Moreover, in addition to obtaining precise results he was able to draw concise and far-reaching conclusions in the ensuing publications. In the present case, his first paper as sole author [4], he pointed out that the high concentration of ions found in the upper atmosphere could not be wholly due to radiation from the radioactive material in the earth and, therefore, must be the result of radiation from outer space. In the same year 1912 the Austrian physicist Viktor Hess established the existence of cosmic rays after ionization measurements on a series of seven balloon flights [5].

Chadwick received his M.Sc. in the summer of 1912. In the following year, the university nominated him for a prestigious 1851 Exhibition Science Research Scholarship. Rutherford wanted Chadwick to spend at least one year of this scholarship in his group in Manchester but the terms of the scholarship foresaw that the recipient would have to work at an institute other than the nominating university. Despite Rutherford’s interventions, the scholarship commissioners remained adamant: take it or leave it. It was finally agreed that Chadwick would spend the first year of tenure either in Berlin with Rutherford’s former
collaborator Hans Geiger or at the University of Vienna. No one, least the scholarship commissioners, could foresee that Chadwick was about to embark on one of his life’s great adventures [1].

3 First World War

In the fall of 1913, Chadwick arrived in Berlin to spend the first year of his stipend in Geiger’s laboratory at the Physikalisch-Technische Reichsanstalt in Charlottenburg, a suburb of Berlin. Geiger had returned from Manchester to Germany in 1912 after performing seminal experiments with his student Ernest Marsden that established Rutherford’s atomic model. He gave Chadwick a warm welcome and introduced him to other colleagues such as Otto Hahn and Lise Meitner from the Kaiser Wilhelm Institute for Chemistry. After quickly obtaining a working knowledge of German and getting used to German bureaucracy [2], Chadwick soon enjoyed the friendly atmosphere and Geiger’s helpful guidance. His chosen area of work was β radiation. He could not anticipate that this topic would remain a crucial and much debated subject in the development of subatomic physics for at least another twenty years. Nor could he anticipate that his contribution, although completely correct, would remain contested for almost fifteen years.

3.1 Beta decay

During the first decade of the 20th century it was established that α particles are helium nuclei and β particles are electrons. It was also found that in a given α decay the emitted α particles all had the same energy corresponding to the mass difference between initial and final nuclei. It was natural to assume the same behaviour for the emitted electrons in β decay. But by 1913, researchers from both the Manchester School and Hahn’s laboratory had discarded the hypothesis that the β spectrum was monochromatic. Instead, the experiments seemed to show that β spectra consisted of several discrete lines. To that date, the weak point of all experiments was the detection of the emitted electrons on photographic plates. When Chadwick entered the game he had the advantage of employing instead of a photographic plate a particle counter that had just been developed by Geiger and that has been carrying his name ever since. After initial doubts about his results he convinced himself that the line spectrum was actually an artefact of the photographic detection. In the publication [6], a hallmark of modern physics that is unfortunately difficult to access (the original publication was probably translated into German by Geiger [1]), he made it absolutely clear that the accepted picture of Rutherford, Hahn and others was incorrect and that the β spectrum was actually continuous. While Rutherford immediately accepted Chadwick’s results, many others like Meitner remained sceptical.

After the war, Rutherford suggested to Charles Ellis, a young member of the Manchester group (see also Subsec. 3.3), to reexamine the issue of the β spectrum. Ellis not only confirmed Chadwick’s findings of 1914 but he also explained the occurrence of discrete lines
superimposed on the continuous spectrum as being due to internal conversion involving electrons in the atomic shell \[7\]. Lise Meitner was not convinced and insisted \[8\] that the primary electrons in $\beta$ decay must all have the same energy because of energy conservation. Although her reasoning was theoretically correct she could not explain the continuous spectrum found by Chadwick and Ellis blaming it on problems with their experimental setups. Since Chadwick’s original result was called into question by Meitner he teamed up with Ellis for a measurement of the intensity distributions of electrons in the $\beta$ decays of $^{214}_{82}Pb$ (radium B) and $^{214}_{83}Bi$ (radium C) by an ionisation method. They summarised their results as follows \[9\]: “Firstly, the continuous spectrum has a real existence which is not dependent on the experimental arrangement and any explanation of it as due to secondary causes is untenable . . .” Due to her theoretical “prejudice”, Meitner was still not convinced. It took another five years of hard work by Ellis and collaborators before the matter was finally settled. In 1927, Ellis and Wooster undertook an absolute measurement \[10\] of the heat produced by the total absorption of the electrons emitted in the $\beta$ decay of $^{210}_{83}Bi$. They demonstrated that the average energy released per individual $\beta$ decay was equal to the mean energy of the continuous spectrum and that secondary processes, as called for by Meitner, did not exist. In a follow-up experiment, Meitner and her colleague Orthmann not only confirmed \[11\] the results of Ellis and Wooster but they arrived at an even stronger conclusion. Ellis and Wooster had speculated that some continuous $\gamma$ spectra could save energy conservation because $\gamma$ rays could not be observed in their calorimeter. But Meitner and Orthmann showed employing special counters that such a continuous $\gamma$-ray spectrum did not exist.

The experimental situation was now settled but the theoretical dilemma became even worse. As the results appeared to contradict the sacrosanct conservation of energy, Bohr speculated\[11\] at the end of the 1920s that in the microcosm energy conservation might only hold on average, but that an individual decay could violate the energy balance. But there was also a problem with the conservation of angular momentum if the electron with its spin $1/2$ were the only decay product in addition to the final nucleus. Moreover, there were also problems with quantum statistics. According to the general picture of the nucleus at the time, the nucleus of the nitrogen isotope $^{14}_{7}N$ should contain fourteen protons and seven electrons. Because of the odd number of particles with spin $1/2$ the nitrogen nucleus would have half-integer spin and should satisfy Fermi-Dirac statistics. But experiment actually showed that the $^{14}_{7}N$ nucleus had integer spin and was therefore a boson. Finally, it was difficult to reconcile with quantum mechanics and in particular with the uncertainty relation that particles as light as electrons could be confined in such a small volume as an atomic nucleus.

In December 1930, Pauli broke the Gordian knot in his famous letter to the “radioactive ladies and gentlemen” who gathered for a meeting in Tübingen. He proposed as a solution of the various problems that the electron in $\beta$ decay is accompanied by an additional particle that would have to be electrically neutral and have spin $1/2$. Pauli named the postulated particle neutron but soon the name neutrino (the small neutron) proposed by Enrico Fermi

\[ ^{1} \text{Actually, Bohr upheld his view at least until 1932.} \]
was generally accepted (see also Sec. 5). In the presence of this neutrino, the conservation of both energy and angular momentum would be restored. The mass difference between initial and final nuclei determines the total energy of the decay products. This energy is now shared between electron and neutrino, hence the continuous energy spectrum of the electron. Because the neutrino has spin 1/2 the conservation of angular momentum is also guaranteed. Pauli wrote in his letter that he did not dare to publish his idea for the time being. Proposing a particle that could possibly never be detected experimentally was too daring at that time. Three years later, after the discovery of the neutron by Chadwick (Sec. 5), Fermi formulated the first quantum field theory of $\beta$ decay [12].

3.2 Particle-wave duality

Back in 1914, Chadwick started a project scattering $\beta$ particles on a thin gold foil, in analogy to the famous experiments of Geiger and Marsden with $\alpha$ particles. In the course of that work he suggested to Geiger [2] “that perhaps electrons might be scattered from a crystal surface in much the same way as X rays. Geiger said there was nothing in it, it was rather a silly suggestion to make.” Nine years later, a certain Louis de Broglie had the same idea [13], inspiring in particular Erwin Schrödinger to set up his wave mechanics. In this case, the relevant experiments were indeed performed [14, 15], demonstrating wave-particle duality also for matter particles. Once again, Chadwick was ahead of his time but the following events would have prevented him anyway from actively pursuing his idea.

3.3 Science in an internment camp

Chadwick’s career came to an abrupt end in August 1914 when the First World War broke out. After the invasion of Belgium by the German army Great Britain declared war on Germany and the situation became precarious for a British citizen in Berlin. Although his German colleagues in the laboratory were very helpful as Chadwick later acknowledged gratefully he was arrested in November 1914 as an enemy alien. Together with hundreds of other British civilians, he was interned in a camp (Engländerlager) in Ruhleben near Spandau west of Berlin. Initial hopes that the war would be over by Christmas soon faded and four years full of privation followed.

This period is described in much detail in Brown’s biography [1]. Here, I confine myself to the remarkable social activities in the camp, in particular in the form of an Arts and Science Union where Chadwick played a prominent role. For instance, he delivered regular lectures on electricity and magnetism and even on radioactivity that were well received by the participants. One of them was Charles Ellis who as a cadet of the Royal Military Academy had the bad luck of spending his summer holidays together with colleagues in Germany at the outbreak of the war. All of them were interned in Ruhleben.

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2Wave-particle duality was already well established for photons at that time.
Ellis developed a strong interest in science and soon became Chadwick’s favourite student. After the war, the two men continued to work together in Cambridge where Ellis became a world authority for the physics of $\beta$ and $\gamma$ rays (see Subsec. 3.1). While in the camp, Chadwick managed to organise a small laboratory where they performed several experiments mainly in chemistry. He was even given for inspection some radioactive toothpaste that became popular in Germany at that time. For getting both equipment and scientific literature the camp authorities were remarkably cooperative. Chadwick was even allowed to leave the camp for visiting the prominent German scientists Heinrich Rubens, Walther Nernst and Emil Warburg who all offered help.

The general living conditions were less agreeable. By 1917 the blockade of the British Navy on merchant ships had a devastating effect on food supplies to Germany in general and to the inmates of the Ruhleben camp in particular. Chadwick was severely undernourished and had serious digestive problems that would accompany him for the rest of his life. After the armistice in November 1918 all internees were released. After a long journey via the Baltic and the North Sea, Chadwick finally arrived at his parents’ home in Manchester.

4 Strong interaction

As early as 1815, the English chemist William Prout suspected on the basis of existing measurements of atomic masses that all atoms are built up of hydrogen atoms (Prout’s hypothesis). Scattering $\alpha$ particles on light atoms, in particular on nitrogen, Rutherford demonstrated that the hydrogen nucleus (denoted proton by him in 1920) does indeed occur in all nuclei [16]. But Rutherford also recognised that additional, electrically neutral constituents must be contained in the nuclei in order to explain nuclear masses. He called these constituents neutrons and he pictured them as bound states of protons and electrons. Two reasons seemed to support such a picture. The mass of these neutrons was comparable with the proton mass and the negatively charged electrons would compensate the electrostatic repulsion between the protons at least to some extent.

Scattering $\alpha$ particles on protons, Rutherford found deviations from the Coulomb law (electrostatic repulsion between $\alpha$ and $p$) [17]: “…not inconsistent with the view that the forces between colliding atoms augment rapidly for values of $d < 3.5 \cdot 10^{-13}$ cm.” He associated the deviations with the complex nature of $\alpha$ particles as bound states of four protons and two electrons. With an improved experimental setup, Chadwick repeated the experiment, first as part of his doctoral thesis at Cambridge and then more thoroughly together with a young colleague, the Swiss-born Canadian Etienne Bieler. Their results confirmed Rutherford’s findings but their conclusions went beyond. Investigating the differential cross section for various scattering angles, they observed agreement with expectations for slow $\alpha$ particles (low energies). On the other hand, the measured numbers of scattered protons greatly exceeded the expectations for fast $\alpha$ particles (high energies), in one case 100 times as large, with only the Coulomb force between point charges. In the latter case also the
angular distribution of the scattered protons was different. Their main conclusion [18] was hailed by Abraham Pais [19] as marking the birth of the strong interactions: “...no system of four H nuclei (i.e. protons) and two electrons united by inverse square law forces could give a field of force of such intensity over so large an extent ...It is our task to find some field of force which will reproduce these effects ...The present experiments do not seem to throw any light on the nature or the law of variation of the forces at the seat of an electric charge, but merely show that the forces are of very great intensity.”

During the following years, the Cambridge group extended their studies by scattering α particles on heavier atoms, more specifically on helium, magnesium and aluminium. These attempts were reviewed in the classic monograph of Rutherford, Chadwick and Ellis in 1930 [20]. The results for α α scattering were similar to those from α p scattering [21]. Extending the experiments to the heavier atoms magnesium and aluminium did not clarify the situation. One reason was that the lever arm for distinguishing between the Coulomb force and any additional force is smaller for heavier atoms. From his results, Bieler [22] concluded that the additional force was attractive and seemed to vary with distance as $r^{-4}$ although a dependence as $r^{-3}$ could not be ruled out either. On the other hand, Debye and Hardmeier claimed that a force varying as $r^{-5}$ would also describe the data by assuming that the incoming α particle strongly polarises the heavy nuclei [23]. However, as emphasised in Ref. [20], it did not seem possible to explain the collisions with hydrogen or helium nuclei in the same way.

At the end of the 1920s, the situation was as unclear as at the beginning of the decade. Once again, Chadwick and his colleagues were some fifteen years ahead of their time. For an understanding of the experimental results two fundamental theoretical developments were necessary, the quantum mechanical scattering theory and the Yukawa potential with the pion mass setting the scale for the onset of the new force [24].

From 1935 on, significant progress was made in the understanding of the strong interactions of nucleons and mesons. Mainly on the basis of nonrelativistic potential models involving mesons, it became possible to explain nuclear structure and nuclear reactions. However, these achievements were restricted to reactions where nucleons have small relative velocities. The developments leading to the formulation of a relativistic quantum field theory of the strong interactions (quantum chromodynamics) and its incorporation in the Standard Model of the fundamental interactions can for instance be found in Ref. [25].

5 Discovery of the neutron

Asked by Charles Weiner whether he had thought that his work done on the neutron might be of Nobel Prize calibre, Chadwick answered [2]: “The award of a Prize, it seems to me, to be not so much a question of luck but a question of being there at the right time.” In 1932, Chadwick was indeed right on time. In consequence, he was ennobled by the Nobel Foundation in 1935 and by the English King in 1945 where the second knighthood also acknowledged his role in the Manhattan Project.
Chadwick’s discovery of the neutron thus differed from many of his earlier achievements where he happened to be ahead of his time. Since the neutron discovery is described in much detail in many books [11] and articles [26], I will confine myself here to a brief summary of events for completeness.

Rutherford had introduced the notion of a neutron as bound state of proton and electron already in 1920 in order to understand nuclear masses. Especially after the advent of quantum theory, the difficulties of this picture became more and more acute. As already mentioned in Subsec. 3.1, a serious discrepancy with experiment had to do with quantum statistics. In Rutherford’s model the nucleus of the nitrogen isotope $^{14}_7$N contained fourteen protons and seven electrons. Because of the odd number of particles with spin 1/2 the nitrogen nucleus would have half-integer spin and should satisfy Fermi-Dirac statistics, contradicting experimental evidence. In addition, while a bound state of proton and electron was well understood in the form of the hydrogen atom, it was difficult to reconcile with the uncertainty relation that particles as light as electrons could be confined in such small volumes as atomic nuclei.

Already in 1930, Walther Bothe and Herbert Becker [27] had scattered energetic α particles from a polonium source on several light elements such as $^9_4$Be. They observed a very penetrating radiation that was not deflected by an electric field and was therefore interpreted as γ rays. Two years later, Irène and Frédéric Joliot-Curie repeated the experiment [28]. When the unknown radiation was directed at some hydrogen-containing material such as paraffin wax, it released high-energy protons. Therefore, the process was interpreted as proton Compton scattering. The problem was that this would have required γ rays with unrealistically high energy (50 MeV). The Italian theorist Ettore Majorana commented sarcastically [29]: “What fools, they have discovered the neutral proton and they do not recognize it.”

Neither Chadwick nor his mentor Rutherford believed the interpretation as proton Compton scattering. Chadwick immediately set to work and within three strenuous weeks not only repeated the French experiment but also scattered the radiation on various atoms other than hydrogen. He found that the new radiation consisted not of γ rays, but of uncharged particles with about the same mass as the proton. The last sentence in his Nature article [30] is crystal clear: “Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis (i.e. the γ-ray hypothesis) can only be upheld if the conservation of energy and momentum is relinquished at some point.”

One may ask the question why Chadwick was more successful than the Joliot-Curies, both experienced scientists who would receive the Nobel Prize in chemistry in 1935 for their discovery of artificial radioactivity. A plausible answer is that Chadwick was not only right on time but he was also in the right surroundings. While there was a general consensus that atomic nuclei consisted of protons and electrons, the idea of a neutron as bound state of proton and electron was rather specific to the Cavendish Laboratory. This is for instance spelled out by Joliot [31] when commenting on Chadwick’s discovery: “The

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3 The same problem existed for the $^9_3$Li nucleus.
word neutron had already been used by the genius Rutherford in 1923 (actually 1920), at a conference, to denote a hypothetical neutral particle which, together with protons, made up the nucleus. This hypothesis had escaped the attention of most physicists, including ourselves. But it was still present in the atmosphere of the Cavendish Laboratory where Chadwick worked and it was natural – and just – that the final discovery of the neutron should have been made there.” Another indication is that Pauli in his letter of December 1930 to the “radioactive ladies and gentlemen” proposed to call his hypothetical particle “neutron” as if he had never heard of Rutherford’s neutron. Fortunately, Fermi came to the rescue and renamed Pauli’s particle neutrino to avoid confusion.

Whether the neutron is a bound state of proton and electron or not was still an open question for some time. The neutron mass is a crucial parameter to answer this question. If

$$m_n > m_p + m_e,$$  \hspace{1cm} (5.1)

the neutron cannot be a bound state and it would be as elementary a particle as the proton. The precise measurement of the neutron mass turned out to be very demanding. Several measurements of the neutron mass published by different groups were not conclusive and allowed for both possibilities. Initially, Chadwick favoured the bound-state nature of the neutron \[32\]: “It is, of course, possible to suppose that the neutron may be an elementary particle. This view has little to recommend it at present, except the possibility of explaining the statistics of such nuclei as \(^{14}\text{N}\).”

In 1933 Maurice Goldhaber, a young refugee from Nazi-Germany, was offered a research position at the Cavendish by Rutherford. At some point, he suggested to Chadwick that the deuteron (usually called diplon at the time) might be a good candidate for a precise measurement of the neutron mass if it could be split by bombarding it with \(\gamma\) rays:

$$\gamma + ^2\text{H} \rightarrow p + n.$$  \hspace{1cm} (5.2)

Their experiment \[33\] produced a precise value for the neutron mass showing that the neutron cannot be a bound state. Electrons were banished from atomic nuclei, which consist of protons and neutrons only.

### 6 Later years

In the fall of 1935, shortly before receiving the Nobel Prize, Chadwick moved to Liverpool University. He refurbished the old-fashioned laboratories and initiated the construction of a cyclotron, making Liverpool one of the European centers of nuclear physics. As leading expert on neutron physics, he was chosen to write the final draft of the so-called MAUD Report, the basis of American-British collaboration in the Manhattan Project. His presence at the Trinity nuclear test was characterised by a science journalist associated to the Manhattan Project \[34\]: “Never before in history had any man lived to see his own discovery materialize itself with such telling effect on the destiny of man.” In 1948, Chadwick moved
back to Cambridge to become Master of Gonville and Caius College, where he had been a research student in the early 1920s. He retired at the end of 1958 and moved to North Wales with his wife. Ten years later they once more moved back to Cambridge to be near their daughters. James Chadwick died in his sleep on July 24, 1974.

Acknowledgements  I have made extensive use of the excellent biography of Andrew Brown [1] and of the interviews recorded by Charles Weiner [2]. For more detailed studies of Chadwick’s biography, especially also of his personality, I very much recommend these two references. For suggestions, corrections and other help, I thank Walter Grimus, Helmut Neufeld, Maria Probst, Michael Springer and Brigitte Strohmaier.

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