10 From Heisenberg to Yukawa

Our last five remarkable physicists were born in the seven years between 1901 and 1907. They came from Austria, England, Germany, Japan and America.

Werner Heisenberg (1901–1976)

In the great revolution of fundamental physics which started with the ideas of Planck and culminated with the impressive breakthrough of the 1920s, and in the completed framework of quantum mechanics, Heisenberg made many important contributions. Among these there were two, the basic treatment of quantum transitions and the formulation of the uncertainty principle, that were so original and impressive that they came close to the popular image, so often unrealistic, of great new concepts growing out of the thoughts of a single individual of genius. In the two years from 1925 to 1927, which saw the emergence of a new set of principles of physics, which have since then been refined and widely applied but not fundamentally changed, the steps taken by Heisenberg were large and decisive.

Werner Karl Heisenberg was born on December 5, 1901 in the elegant Würzburg suburb of Sanderau. The family moved to Munich in 1910 and he came to regard it as his home town, retaining throughout his life an intense affection for the city. His father August, the son of a master locksmith, was a domineering man of great vigour. Werner had a younger brother, Karl, who later emigrated to America and became wealthy, as well as three sisters and an elder brother, Erwin, who became an industrial chemist. August himself held the chair of mediaeval and modern Greek philology at the university and later became professor of Byzantine studies. We know little about his wife Anna (née Wecklein), except that her father, a Greek scholar, was headmaster of the renowned Maximilian Gymnasium in Munich, the school that her son Werner attended.

Disabling allergies and illnesses recurred throughout Werner's life; at the age of five he nearly died of a pulmonary infection. He was a sensitive youth, who sought security in mathematics and in other formal subjects such as grammar and science. He distinguished himself early at school, particularly in mathematics: none of the work seemed to cause him any great

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effort. He showed an early interest in physics and was particularly fascinated by the possibility of applying mathematics to practical situations. When the First World War began, his father August, being a reserve officer, was called up; after a brief experience of combat at the front he was transferred to garrison duty in Munich. The gymnasium building was commandeered and the students spent much of their time on paramilitary training, leaving them with little time for schoolwork. In the spring of 1918 boys as young as sixteen were drafted for auxiliary service, and Werner was sent to work on a farm. This involved long hours of manual labour, which left him too tired to read at night the books he had brought with him, such as the philosophical works of Kant.

When the First World War ended in November 1918, conditions in Germany were chaotic, with political authority passing back and forth between different factions. At one point Heisenberg and other boys worked as messengers for a group that was trying to restore law and order in the city. The duties were not onerous and he was able to make progress with his reading, in which philosophy played an important part. More than did the farmwork, this provided many contacts and later friendships with young men of a similar age, with whom he had many earnest discussions. The youth movement in Germany included various such groups of young

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people who were dissatisfied with what their elders had made of the world and who were impatient with old customs and old prejudices. They felt an emotional need for a new leader who would restore Germany's greatness, to whom they would give total commitment. In his autobiographical writings Heisenberg is studiously vague about which particular group he belonged to, but it was probably the Weisser Ritter, a group that was strongly antagonistic towards science, especially physics. Thus Heisenberg had to choose between two extremes, both of which seem to have attracted him.

After graduating from the gymnasium in 1920, Heisenberg matriculated at the University of Munich. During the first two years there, he submitted four promising research papers on physics. His mathematical background was uneven; he knew a lot about number theory but had only just encountered calculus. When he came across Weyl's book *Raum–Zeit–Materie*, he was both attracted and repelled by the sophistication of the mathematical arguments and the underlying physical concepts. With the idea of becoming a mathematician, he went to ask Ferdinand von Lindemann, the old-fashioned professor of mathematics, for permission to attend his seminar, even though he was a mere freshman. As soon as he mentioned having read Weyl's book, von Lindemann turned him down.

After this rebuff Heisenberg applied to Sommerfeld, a friend of his father's, and was immediately accepted. Sommerfeld was not only a great theoretical physicist with extensive experience in all parts of the subject and an intimate knowledge of its frontiers, but also probably its greatest teacher. His seminars and colloquia attracted students and young scholars from far afield, even from America, and helped to make Munich a world centre for theoretical physics. Often before or after a colloquium Sommerfeld could be seen at the Hofgarten cafe discussing problems with members of the audience and covering the marble tables with formulae. Sometimes he would invite them to join a skiing party on the Südenfeld, two hours by train from Munich, where he was part owner of a ski-hut. In the evenings, after a simple meal, the talk would turn to mathematical physics; and this was when receptive students might learn what he was currently thinking about. The forbidding martial impression made by Sommerfeld initially very soon gave way to a feeling of benevolence and helpful authority. He trained nearly a third of Germany's professors of physics; four of his former students were awarded Nobel prizes. Theoretical physics is a subject that attracts youngsters with a philosophical mind who speculate about the highest principles without sufficient foundations. It was just this type of beginner that he knew how to handle, leading them step by step to a realization of their lack of actual knowledge and providing them with the skill necessary for fertile research.

As soon as Heisenberg became a student at Sommerfeld's institute he met the brilliant Wolfgang Pauli, another student, who was somewhat senior to him and became his mentor. Their close friendship, during which they frequently exchanged views about major mathematical, physical and philosophical problems, lasted until the death of Pauli in 1958. Despite having completed an able thesis on hydrodynamics, Heisenberg only just succeeded in passing his doctoral examination, because his strengths on the theoretical side of physics were offset by a poor performance on the experimental side.

Sommerfeld took Heisenberg to the Georgia Augusta to listen to a two-week series of seminar talks by Bohr, who made a deep impression on Heisenberg. When Sommerfeld went for the winter semester 1922/3 to the University of Wisconsin as a visiting professor, he arranged for Heisenberg to spend this period with Max Born at Göttingen. Born was enthusiastic about the young man and before long they were collaborating on research. 'Heisenberg is at least as talented as Pauli', Born reported to his friend Einstein, 'but personally more pleasant and delightful. He also plays the piano very well.' 'I have grown very fond of Heisenberg', he confided to Sommerfeld, 'he is liked and esteemed by us all. His talents are extraordinary, but his friendly, modest attitude, his good spirits, his eagerness and enthusiasm are especially pleasing.' He described Heisenberg as looking like a simple peasant boy, with short fair hair, clear bright eyes and a charming expression.

The next year, after habilitating at Göttingen at the unusually early age of twenty-two, Heisenberg spent the summer vacation with friends from the youth movement on a walking tour and then went to Copenhagen as a research associate. He already knew how deeply Bohr understood the problems of physics, and how much he could learn from him. Their discussions, often conducted on walks in the countryside, also ranged over many other fields of human life and affairs, and here Bohr's wisdom and warmth made a deep impression on his young disciple. They went on a walking tour of Sjaelland, the island on which the Danish capital is situated. When he returned the following year, Bohr wrote that 'he is as congenial as he is talented' and 'in spite of his youth he has succeeded in realizing hopes of which earlier we hardly dared dream . . . in addition his vigorous and harmonious personality makes it a daily joy to work together with him towards common goals.' Heisenberg later said that in Göttingen he learned mathematics, in Copenhagen physics. The affection and mutual respect he and Bohr felt for each other continued to deepen over the next fifteen years.

In 1925, at the age of twenty-three, Heisenberg wrote the paper that laid the foundations of quantum mechanics on which subsequent generations have built. This was not just an extension or elaboration of the work of others, but an unexpected, radical new departure, which abandoned the basic notions of the old classical physics, such as electrons moving in orbits, replacing them by a much more abstract description. Less than a year later Schrödinger, as we know, published his theory of wave mechanics, which at first appeared to be an alternative theory to Heisenberg's. However, the two theories turned out to be essentially the same. Schrödinger's mathematics is in many ways easier to handle, but both points of view are needed in order to develop a real understanding of the physical world.

In 1927 Heisenberg was offered chairs in both the Universities of Leipzig and Zürich; he chose the former and became the youngest full professor in Germany. At his first seminar he had an audience of two, but soon students and other collaborators were attracted, and frequently senior visitors attended. His duties were not light. It was then normal for the professor to give the main undergraduate lectures in theoretical physics, usually on a four- or six-semester cycle, and to set examinations on the course-work, which he had to mark. There were also the usual faculty and committee meetings, but, in spite of these demands on his time, Heisenberg was always accessible to his students. He remained as before – informal and cheerful in manner, almost boyish, with a modesty that verged on shyness. His weekly seminar was preceded by tea, and for this he would go out to a nearby bakery for some pastries. After a strenuous discussion, and during other free periods, the whole group would descend to the basement and play table tennis. Heisenberg was a very good player and could beat everyone else, until a Chinese physicist arrived, who was equally skilful, if not more so.

Problems, difficulties and new ideas in physics were debated very intensely. Heisenberg was able to help his students particularly through his powerful intuition. Usually he did not pay too much attention to the mathematical details of their work, as long as they could see where they were going, but he needed to grasp the physics of their problem himself. Once he had done so, he was usually able to guess the answer, and he was usually right. Naturally Heisenberg's own output of papers during this period did not match the pace of previous years; a further distraction was a lecture tour of the USA in 1929. Quantum mechanics was now essentially complete, and the next task was to work out its consequences and to see how it would explain the many mysteries, paradoxes and contradictions in atomic physics. He found that it was an exhilarating experience to see how easily the solutions to the old puzzles fell into place.

When Hitler seized power in Germany and the Nazi ideology took hold in the universities, Heisenberg, like many other academics, was deeply shocked by the anti-intellectual attitude of the regime. In a book of reminiscences, published in 1969, he describes an imaginary conversation with a student who is a leader of the Hitler Youth. One feels that, while formally maintaining his refusal to have anything to do with Nazi gatherings and other activities, he can see something to admire in the ideas of his companion. The student himself deplores the anti-Semitism and other destructive features of the movement, but insists that its essential aim is to create a better world, to fight corruption and dishonesty, and to restore respect for Germany.

However, the disastrous aspects of Nazi policies began to dominate to such an extent that Heisenberg and a few colleagues soon started to talk of resignation. He went to see Planck about this; his advice was to remain. However many professors resigned, he said, it would not affect Nazi policy. Heisenberg would have to emigrate, Planck went on, and while undoubtedly he would find a position abroad, he would be taking it away from someone else who was being forced to leave Germany. The present regime was bound to end in disaster, Planck concluded, and after that happened people like Heisenberg would be needed as leaders.

Many German physicists faced the same problem as Heisenberg; other than those dismissed or expecting to be dismissed, hardly any decided to leave. Of those who remained, von Laue was outstanding for his uncompromising stand, his proud aloofness and his refusal to cooperate with the regime. To have taken that position was not in Heisenberg's character. In referring to his attraction to military service, which involved annual training as a reservist, he remarked that 'it is nice not to have to think, for a change, but only to obey'. He tried to carry on as before, to maintain the old atmosphere, in spite of the loss of his Jewish colleagues; he commented that he rather envied them, since they had no choice. This was not the only occasion when he displayed amazing insensitivity to the effects of Nazi persecution on individuals.

In 1933 Heisenberg was awarded the prestigious Max Planck medal of the German Physical Society. No Nobel prize for physics had been awarded in 1931; the 1932 prize had been deferred and now it was announced that this had been awarded to Heisenberg. Meanwhile the grip of the Nazis on German science was steadily tightening. Visits by German scientists to foreign countries required official approval, likewise visits by foreign scientists to Germany. Although the Nazis had reservations about Heisenberg's political attitudes, his prestige was such that he was seldom if ever refused permission to travel. Mainly through visits to Copenhagen, he kept in touch with the latest ideas in physics.

In 1935 Heisenberg was proposed for the chair in Munich in succession to Sommerfeld, who was retiring. This was an attractive opportunity, both because it meant succeeding his respected teacher and particularly because of his fondness for the city. However, the proposal was attacked by those who opposed relativity and quantum theory as 'Jewish physics'. The authorities ruled against his appointment in favour of a nonentity. After this personal attacks on Heisenberg became more virulent, until eventually instructions from a high party level put an end to them and Heisenberg was appointed after all.

By this time Heisenberg had found added strength and support; in January 1937 he had made the acquaintance of Elisabeth Schumacher, daughter of the great Berlin economist, and they were married three months later. Although it was a successful marriage, Heisenberg always put his career first. Twins, a son Wolfgang and a daughter Anna Maria, were born in 1938; eventually there were to be seven children, all of whom shared their parents' love of music. Of the twins, Anna Maria Hirsch became a physiologist while Wolfgang, a lawyer by training, worked for a foundation concerned with science and politics. Jochen became an experimental physicist at MIT while Martin became a professor of biogenetics. Barbara Blum married a physicist. Christine Mann became a teacher and her husband a physiologist. The youngest, Verena, became a technician in a physiology laboratory.

By the summer of 1939, when it was clear that war was inevitable, Heisenberg purchased a country house at Urfeld, in the Bavarian Alps, as a refuge for his family (there were at this stage three children) in case of need. He revisited the USA and lectured at the universities of Michigan and Chicago, where many of his old friends and colleagues tried to persuade him to leave Germany because of the impending disaster, in which his presence could not achieve anything. However, Heisenberg did not agree; above all, he believed that leaving would be disloyal to the young people in his research group, who would rely on him for guidance in keeping science going and whose responsibility it would be to rebuild science after the war. These young people could not find positions abroad as easily as he could, and he would feel that he was taking an unfair advantage.

When the war came, Heisenberg was appointed chief technical consultant for research on nuclear fission after being excused normal military service on medical grounds. For the next five and a half years this took up most of his time and energy. He developed the theory of a nuclear reactor. Experiments indicated that a system of uranium metal and heavy water of suitable size could sustain a chain reaction. A successful experimental reactor could have been constructed, but much more time would have been needed to produce anything of practical value. The type of reactor the American physicists constructed had been dismissed as impracticable because Heisenberg had miscalculated the critical mass required; since atomic research was everywhere top secret by this time, mistakes were liable to remain uncorrected. It has been suggested that Heisenberg deliberately made the production of an atomic bomb appear impracticable, because he did not want the Nazis to have such a weapon, but the evidence for this is unconvincing. As regards atomic energy, for Germany this was a long-term project and unlikely to affect the outcome of the war.

Heisenberg had reported as early as December 1939 that, although energy could be generated from ordinary uranium if it were used in conjunction with heavy water or graphite to slow down the neutrons, it would be necessary to use enriched uranium-235 to produce an explosive. These two lines of attack became the chief objectives of the German atomic-energy programme and for a year or two progress was remarkably rapid, in spite of rather lukewarm official backing. Heisenberg was at first a consultant to the Kaiser Wilhelm Institute for physics in Berlin-Dahlem, where much of the research was being done, and during that time he continued to live in Leipzig, where some unrelated work was being done at the physics institute. The Kaiser Wilhelm Institute had been placed under military control but, after reorganization, in 1942 it was returned to the Kaiser Wilhelm Gesellschaft and Heisenberg was appointed Director. He was also appointed full professor at the University of Berlin and elected to the Berlin Academy. When he moved to the German capital in the spring of 1943, his family went to live in their country house in Urfeld, but later that year, when the air raids became more intense, the laboratory was evacuated to Tailfingen.

Several reactor experiments were set up but none actually achieved criticality; indeed, the final experiment under Heisenberg's control was carried out only a few weeks before the arrival of Allied troops. It came close to being critical and it became clear that a small increase in scale would achieve that state, but time was running out; the end of the war was near and there could be no chance of practical results before then. It was not known in Germany that Fermi had already achieved a chain reaction in Chicago three years earlier.

As soon as Germany had fallen to the Allied forces, an Anglo-American team searched Heisenberg's office and other places where work on the nuclear project might have been carried out, and concluded that the Germans had got nowhere near producing a bomb. However, to avoid the risk that the German nuclear physicists might be taken to the Soviet Union, ten of them, including Hahn and Heisenberg, were rounded up and escorted to Britain, where they were interned in Farm Hall, a pleasant manor house in the Cambridgeshire village of Godmanchester. Although they were still under guard, the internees enjoyed a good deal of freedom. Their rooms were bugged and it was hoped to learn from their conversations something about secret research in Germany, especially research into atomic energy. It was there that they heard in August 1945 the news of the atomic bomb used against Japan and realized that the Americans were far ahead. The German scientists were not only amazed that this revolutionary weapon of destruction had been produced but also mystified as to how it had been possible.

Why did Heisenberg work for his country on atomic energy, and why was the total achievement of the German project so slight? As regards the first question, Heisenberg was a patriot, technically in the army, and wanted Germany to win the war. It might have been different if the work had come close to making an atomic bomb, but it did not. He wrote 'We knew then that one could in principle make atomic bombs, and knew a realizable process, but we regarded the necessary technical effort as rather greater than in fact it was.' As regards the other question, the basic reason for the slow progress was that the work was not pursued with urgency. The authorities never instructed their scientists to make an all-out effort and did not give them the support and services such an effort would have required. Even the USA, with far greater industrial resources, without serious shortages and without interruption by air raids, was not able to make atomic bombs until after the end of the war in Europe. Also, to generate electricity by atomic energy was hardly a top priority in war-time. Moreover, there were errors, misjudgements and omissions, both in the scientific work and in the organization and planning

Although the subsequent German work on atomic energy was not in the short term aimed at producing weapons, Heisenberg and his colleagues were aware of the fact that they were working on a programme that

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could lead to that result. For example, a nuclear reactor, intended to produce power, could be converted into an explosive device. They decided to consult Niels Bohr, and in October 1941 Heisenberg went to Copenhagen; by this time Denmark was under German occupation, and the visit was by no means welcome. Just what was said is disputed, but it seems clear that they parted with Bohr so angry that he never forgave Heisenberg.

After the war, Heisenberg cited the meeting as evidence of his reluctance to help Hitler create the ultimate weapon of mass destruction. The purpose of his visit to Copenhagen, he suggested, was to share his qualms over nuclear weapons. In Bohr's recollection, on the other hand, Heisenberg said that 'There was no need to talk about details, since you were completely familiar with them and had spent the past two years working more or less exclusively on such preparations.' He concluded that under Heisenberg everything was being done in Germany to develop atomic weapons.

Either account could be inaccurate. Bohr was known as being better at talking than listening, and he could have misunderstood what Heisenberg said to him. Of course, Bohr was a citizen of a peaceful country, occupied without provocation by the armies of a hateful regime, and Heisenberg, although an old friend and disciple, was also a citizen of the occupying power. Soon after Heisenberg's visit the Germans occupied the Bohr Institute and, as we know, the Jewish or partly Jewish members, including Bohr himself, fled the country. There was a plan to appoint Heisenberg as director and staff it with German scientists, so as to coerce the remaining Danish scientists into contributing to the German war-effort. Heisenberg succeeded in preventing this happening.

In the autumn of 1943 Heisenberg visited occupied Holland. During the visit he took a walk with an old friend and colleague from Copenhagen, in which Heisenberg began to talk about history and world politics. He explained that 'It had always been the historical mission of Germany to defend the West and its culture against the onslaught of eastern hordes and the present conflict was one more example. Neither France nor England would have been sufficiently determined and sufficiently strong to play a leading role in such a defence, and so, perhaps, a Europe under German leadership might be the lesser evil.'

At the end of the war in Europe, German scientists were dispersed, laboratories were closed and many of the cities in which they were located were severely damaged. The Allied armies which had occupied the country were trying to get life back to normal. In the British zone, at least, the policy was to encourage the leading German scientists to resume their research and teaching. With their agreement, Göttingen was chosen as the best place to serve as the centre for the rebuilding of scientific research. They gathered there, under the auspices of what was now the Max Planck Gesellschaft. At first this functioned only in the British zone, but after a time it was able to extend its activities over the whole of Western Germany.

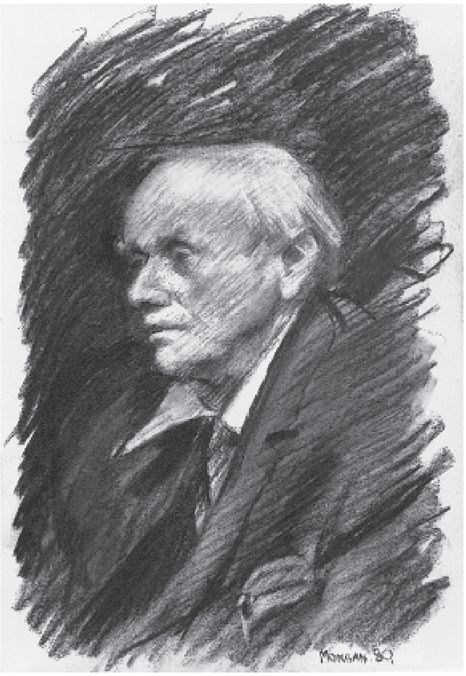
During the Göttingen period Heisenberg devoted much of his time and energy to questions of the future organization of science in the Federal Republic. He made a major contribution to the decision to start a nuclear-reactor programme. Whereas he pleaded strongly in favour of nuclear power, he opposed, equally strongly, any suggestion that Germany should make or acquire atomic bombs. In the autumn of 1958 the Max Planck Institute for physics and astrophysics, which Heisenberg had directed in Göttingen, moved to Munich and he was able to return to the city he had always loved. He remained director of the institute until his retirement in 1970. After that most of his writings were reviews or essays of a general nature; his reputation outside Germany was clouded by his failure to explain his war-time record satisfactorily. Five years later his health began to decline, and he died of cancer on February 1, 1976, at the age of seventy-four.

Heisenberg was undoubtedly a great physicist, the creator of quantum mechanics. Nevertheless, the account he gave of his work during the war, and his justification for it, are open to question; the whole truth may never be known, but there is considerable evidence to suggest that he would have regarded it as his patriotic duty to organize the production of atomic weapons, which might have affected the outcome of the war. When it was clear that Germany was going to be defeated, he told a Swiss colleague that 'It would have been so sweet if we had won.'

Paul Dirac (1902–1984)

Paul Dirac was a theoretical physicist in the same class as the best in Europe; according to Bohr he had the purest soul of them all. He contributed as much as anyone to the establishment of the new science of quantum mechanics. Between the ages of twenty-three and thirty-one he unveiled an original and powerful formulation of the theory, a primitive but important version of quantum electrodynamics, the relativistic wave equation of the electron, the idea of antiparticles and a theory of magnetic monopoles.

The future physicist was born on August 8, 1902 in Bishopston, a suburb of the city of Bristol. His mother Florence (née Hilton), the daughter of a ship's captain, came from Liskeard in Cornwall. His father Charles was brought up in the French-speaking Valais region of Switzerland but



emigrated to England in the 1880s and supported himself by giving French lessons. They had three children, the eldest being Reginald, who was two years older than Paul, and the youngest Beatrice, four years younger. All three were registered at birth as Swiss citizens, but they and their father relinquished Swiss citizenship and became British in 1919. Although he had lost touch with his own parents, who were originally French, Charles wished his children to speak French at home and speak it correctly. 'My father made the rule that I should only speak to him in French', recalled Paul later on. 'He thought it would be good for me to learn French in that way. However, since I found I couldn't express myself in French, it was better for me to stay silent than talk in English. So I became very silent at that time – that started very early.' His mother, who had worked in the library of Bristol University before marriage, could hardly speak French at all and so she usually took meals separately with the other children.

From 1896 Charles had been teaching in the Merchant Venturers Technical College in Bristol; after this was taken over by Bristol University, part of it was hived off to become a secondary school, which was where Charles now taught French. He had the reputation of being exceptionally strict in class. He was an outstanding linguist, able to speak eight or nine

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languages, and an enthusiast for Esperanto. Although he cared about his children and their future careers, he succeeded in alienating his sons. Reginald, the elder, wanted to be a doctor; his father Charles made him study mechanical engineering. After graduating from Bristol University with a third-class degree, Reginald took a job as a draughtsman at an engineering works, but gave it up and three months later committed suicide at the age of twenty-four.

Paul's relations with his father were always chilly. After he grew up they had little personal contact, although Charles was proud of his son's success and tried to understand what he did. When Paul was awarded the Nobel prize and was told that he could invite his parents to attend the ceremony in Stockholm, he chose to invite only his mother. He rarely visited Switzerland, because he associated it so much with his father. As a young man Paul never had a girl-friend and seems to have had a rather platonic conception of the opposite sex for some time. He confided to a friend: 'I never saw a woman naked, either in childhood or in youth . . . The first time I saw a woman naked was in 1927, when I went to Russia with Peter Kapitza. She was a child, an adolescent. I was taken to a girls' swimming pool, and they bathed without swimming suits. I thought they looked nice.'

Paul's mathematical ability became apparent even at primary school. He went on from there to the college where his father taught, at the age of twelve. Although the academic standards there were high, the teaching had a vocational orientation. Modern languages were taught for use, metal work was in the syllabus, as was shorthand, but classics and literature were not. However, the school was particularly strong in mathematics and science. Paul was soon so far ahead of his class in mathematics that he was allowed to work largely on his own. He was recognized as a boy of exceptional intelligence; Paul's schoolfellows remember him as silent and aloof.

After leaving school in 1918, Dirac entered Bristol University, where he studied electrical engineering. In 1921, after graduating, he looked without success for work as an engineer. He won an exhibition to St John's College, Cambridge, but did not take it up because he could not afford the additional expense of being a Cambridge undergraduate. Then he was offered two years' free tuition by Bristol University to return and study mathematics, where, unlike at Cambridge, he would be able to economize by living at home. This he accepted and, after a brilliant performance in the final examination, was awarded a government grant that enabled him to go up to Cambridge as a graduate student. Two years later he was given a more generous award from the Commissioners for the 1851 Exhibition. At Cambridge his research supervisor was Rutherford's son-in-law Ralph Fowler, who recognized in Dirac a student of exceptional ability. Before long Dirac was publishing research, first on statistical mechanics and then on quantum mechanics. At that time the Bohr–Sommerfeld quantum theory was the best available theory of atomic phenomena, but it had many shortcomings and contradictions. He attempted to find ways of improving it, but without success.

Dirac first met Bohr in May 1925 when the latter gave a talk in Cambridge on the fundamental problems and difficulties of quantum theory. He said later that 'people here were pretty much spell-bound by what Bohr said . . . while I was very much impressed by him his arguments were mainly of a qualitative nature, and I was not able really to pinpoint the facts behind them. What I wanted was statements which could be expressed in terms of equations, and Bohr's work very seldom provided such statements.' In the summer of 1925 Heisenberg came to address the Kapitza Club, which had become the unofficial Cambridge forum for discussing modern physics. Afterwards Dirac said that he did not remember him talking about the new ideas in his great paper that laid the foundations of quantum mechanics; the subject of his talk was something less exciting. However, when Fowler received the proofs of the paper on quantum mechanics and showed them to Dirac, he soon realized its revolutionary significance.

Dirac's first paper on quantum mechanics, the basis for his Ph.D. thesis of 1926, paralleled much of what was being done at the same time elsewhere, but he followed it up with more innovative work that immediately attracted the attention of theoreticians everywhere. Born was about to leave on a visit to America when 'The day before I left there appeared a parcel of papers by Dirac, whose name I had never heard . . . Never have I been so astonished in my life: that a completely unknown and apparently young man could write such a perfect paper.' Fowler arranged for Dirac to spend some time first in Copenhagen and then in Göttingen and Leiden. He enjoyed the informal and friendly atmosphere of the Bohr institute and had many long conversations with the Great Dane: 'I admired Bohr very much. We had long talks together, very long talks in which Bohr did practically all of the talking.' While respecting Bohr greatly for his depth of thought, he said he did not know that Bohr had any influence on his own work because Bohr tended to argue qualitatively, while Dirac was more mathematical. At

Göttingen he got to know Robert Oppenheimer, at the time a Ph.D. student, while at Leiden he mainly worked with Ehrenfest.

In 1927 St John's elected Dirac to a fellowship, after which he lived and worked in college. In the same year he was invited to the sixth Solvay conference, where he made important contributions to the discussion and had the opportunity of meeting Einstein and Lorentz. In 1930 he was elected to the Royal Society at the unusually young age of twenty-eight. He spent much of the following year at the Institute for Advanced Study in Princeton and, soon after returning to Cambridge, he was elected Lucasian Professor of mathematics; his teacher Fowler had been elected Plumerian Professor of mathematical physics the previous year. Sadly, his extreme rationalism now led Dirac into sterile byways after his amazingly successful early years. Few of his later contributions to physics had lasting value, and none had the revolutionary character of his earlier work.

In 1933 Dirac and Schrödinger shared the Nobel prize for physics 'for the discovery of new productive forms of atomic theory'. At first Dirac was inclined to refuse it because he so hated publicity, but changed his mind when Rutherford warned him that a refusal would attract even greater publicity. At the seventh Solvay conference Dirac gave a talk on 'Structure and Properties of Atomic Nuclei'. He liked to travel, and often went to the Soviet Union to see his friend Kapitza. In the academic year 1934/5, when he was on leave from Cambridge, Dirac returned to Princeton, mainly to revise his classic textbook *The Principles of Quantum Mechanics* for a second edition. There he developed a close friendship with Eugene Wigner, whose sister Margit Balasz was visiting from Budapest at the time. Her temperament was quite unlike Dirac's, spontaneous and impulsive, with strong likes and dislikes. There was an attraction of opposites, and in January 1937 they were married in London. From then until he retired in 1969 the Diracs lived in a house in Cavendish Avenue, Cambridge. The household included two children, a son and a daughter, from Margit's first marriage, both of whom took the name of Dirac, and two daughters from the second marriage; later Dirac's mother Florence came to live with them.

There are many stories about Dirac's personality, usually related to his taciturnity, for which he was inclined to blame his father, perhaps unfairly. Heisenberg, who knew Dirac well, recalled that 'We were on the steamer from America to Japan and I liked to take part in the social life on the steamer and so, for instance, I took part in the dances in the evening. Paul, somehow, didn't like that too much but he would sit in a chair and look at the dances. Once I came back from a dance and took a chair beside him and he asked me "Heisenberg, why do you dance?" I said "Well, when there are nice girls it is a pleasure to dance." He thought for a long time about it and after about five minutes he said "Heisenberg, how do you know *beforehand* that the girls are nice?"'.

Although he was not much interested in teaching, Dirac seems to have had some success as a research supervisor. Among the doctoral students who were supervised by him, the mathematician Harish-Chandra stands out. As for Dirac's lectures, one who attended his regular course on quantum theory recalled that 'The delivery was always exceptionally clear and one was carried along in the unfolding of an argument which seemed as majestic and inevitable as the development of a Bach fugue.' Dirac was an inveterate traveller and, although not a serious mountaineer, he climbed some high mountains, notably Mount Elbruz in Turkey, which brought on an attack of altitude sickness.

Until he retired Dirac based himself in Cambridge, except for extended visits to the Institute for Advanced Study in Princeton, the Tata Institute for Fundamental Research in Bombay and Moscow State University. Although he had attractive offers from elsewhere, he chose to remain in England, so as to give a lead to young British theoreticians, until in 1972 he crossed the Atlantic and took on a new lease of life at the Tallahassee campus of Florida State University. In Cambridge he tended to work mainly at home and went to the university only for classes and seminars; in Tallahassee he was on the campus all day. He published prolifically, over sixty papers during the last twelve years of his life, although they were not research papers. Gradually his health failed and he died at Tallahassee on October 20, 1984.

Dirac refused all honorary degrees, but among the honours he accepted, apart from the Nobel prize, perhaps the Copley and Royal medals of the Royal Society and the Order of Merit should be singled out. There are several paintings of him and several portrait busts. 'Dirac was tall, gaunt, awkward and extremely taciturn', wrote a German scientist after his death, 'he has succeeded in throwing everything he has into one dominant interest. He was a man, then, of towering magnitude in one field, but with little interest and competence left for other human activities. In other words he was the prototype of the superior mathematical mind; but while in others this has coexisted with a multitude of interests, in Dirac's case everything went into the performance of his great historical mission, the establishment of the new science quantum mechanics, to which he probably contributed as much as any other man.'

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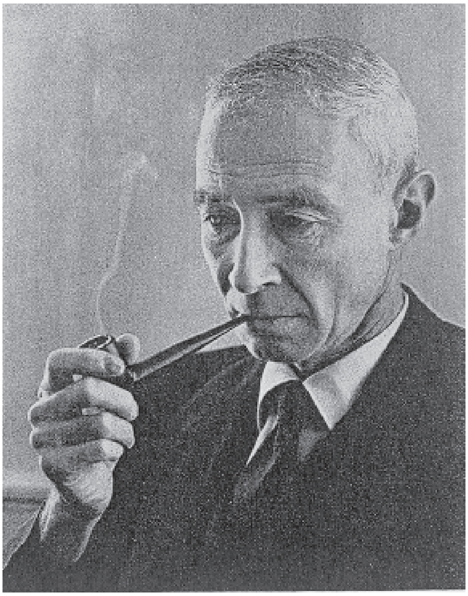

J. Robert Oppenheimer (1904–1967)

In America the study of physics was slow to develop. There were outstanding individuals at times, such as Henry, Gibbs and Millikan, but it was not until after the Second World War that the USA became the world leader in physical research, with immigrants from Europe and elsewhere setting the standard for native-born Americans to attain. More than anyone else it was Oppenheimer who was responsible for raising American theoretical physics from the state of being little more than a provincial adjunct of Europe to world leadership.

J. Robert Oppenheimer was born on April 22, 1904 in New York; the letter J. in his full name may refer to his father Julius, who had come to the USA from Germany at the age of seventeen and developed a prosperous business importing textiles. Oppenheimer's mother Ella (née Friedman) came from Baltimore. She was said to have been unusually sensitive, and had studied painting in Paris. Robert had one younger brother, Frank Friedman Oppenheimer, born in 1912, who became professor of experimental physics at the University of Colorado: he also had another brother who died in infancy. The family was well-off, with a sumptuous apartment on Riverside Drive in Manhattan, furnished with post-impressionist paintings, and an estate on Long Island, where they kept a yacht. They were non-observant Jews, much interested in art and music.

In 1911 the young Oppenheimer entered the non-sectarian School of Ethical Culture, one of the best in the city of New York, where he joined a large number of other Jewish boys who were excluded from private schools through the rigid quota system. He received an education in what, for those days, were advanced liberal concepts of social justice, racial equality and intellectual freedom. Being very shy, he was much bullied and, rather than mixing with other boys, immersed himself in his schoolwork, in poetry and in science, particularly physics and chemistry. When he was only five he had started collecting mineralogical specimens, some of which came from his grandfather in Germany. By the time he was eleven his collection was so good and his knowledge so extensive that he was admitted to membership of the Mineralogical Club of New York.

After graduating from school in 1921, Oppenheimer made a trip to Europe, but became sick with colitis. He entered Harvard the next year, just after the university had introduced its quota system for admitting Jewish students, the intention being to restrict them to the same proportion as obtained in the population as a whole. Originally he had intended to major in chemistry, but soon switched to physics. It was characteristic of him not to abandon a subject in which he had once been interested; familiarity with chemistry was to be very useful to him later on in his career. At Harvard he was strongly influenced by Percy Williams Bridgeman, a distinguished and unconventional experimental physicist. Apart from this, he kept very much to himself and devoured knowledge avidly. 'I had a real chance to learn', he said, 'I loved it. I almost came alive. I took more courses than I was supposed to, lived in the library stacks and just raided the place intellectually'. In addition to studying physics and chemistry, he learned Latin and Greek and graduated *summa cum laude* in 1925, having taken three years to complete the normal four-year course. He retained a lifetime affection for Harvard, serving as a member of the Board of Overseers from 1949 to 1955.

After graduation from Harvard, Oppenheimer spent four years studying at the great European centres of physics. First he spent the academic year 1925/6 as a member of Christ's College, Cambridge. After having been turned down by Rutherford, he was assigned a rather uninspiring research project and altogether he was generally unimpressed by Cambridge. His parents came over to see him, having heard that he was having treatment for depression. It was rather a disappointing year, but at least he reached the conclusion that he preferred theoretical physics to experimental physics and decided that he would do his doctoral work at Göttingen, under Born. While at Cambridge he had begun a thesis on the application of quantum theory to transitions in the continuous spectrum, which he completed so rapidly that it was ready for submission early in 1927. At the same time he was building up his knowledge of the revolutionary new developments in theoretical physics.

Next Oppenheimer was awarded a Rockefeller-funded fellowship by the American National Research Council, later the National Science Foundation. He held it first at Harvard and then at the California Institute of Technology, presided over by Millikan. In the year 1928/9 he held a fellowship from the International Education Board and used it to visit Ehrenfest in Leiden and to see Bohr's disciple Kramers in Utrecht. In the first half of 1929 he went on to the ETH in Zürich, where he worked with Pauli, another influence on his scientific development.

On his return to the USA in 1929, Oppenheimer received many offers of academic positions. He accepted two of them, becoming assistant professor of physics concurrently at the California Institute of Technology and at the Berkeley campus of the University of California. In the ensuing thirteen years he divided his time between the two institutions, spending the autumn and winter in Berkeley, the rest of the year in Pasadena. The majority of the best American theoretical physicists who matured in those years were trained by him at one stage or another in their careers. His teaching, his style and his example influenced them all.

Oppenheimer was fortunate to enter physics in 1925, just when modern quantum physics came into being. Although he was too young to take part in its formulation, he was one of the first to use it for the exploration of problems that had defeated the old quantum theory. Probably the most important ingredient he brought to his teaching was his ability to choose the most interesting problems. Although his lectures were difficult, they conveyed so well the beauty of the subject that almost every student repeated his course, which was based on the survey by Pauli in the *Handbuch der Physik*. He was interested in almost everything, but principally quantum-field theory, cosmic rays and nuclear physics.

The magnetism and force of Oppenheimer's personality was such that his students tended to copy his gestures and mannerisms; he had exquisite manners, a marvellous command of language and a ready wit. In those days students were generally short of money; he entertained them generously, to concerts, dinners and other social events. Among his many friends in the Berkeley faculty were not only scientists but also classicists, artists and so on. Most of the time he was indifferent to the events taking place around him. He never read a newspaper or listened to the radio; he never

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used the telephone. However, he had a passion for fast cars and particularly enjoyed racing trains when the railroad track ran alongside the highway. He was described as having titanic ambition but was tortured by self-doubt. In 1936 he was promoted to full professor at both of the institutions where he worked. The following year his father died; his mother had died six years earlier. In 1941 he was elected to the National Academy of Sciences. In 1940 he married the divorcée Katherine (Kitty) Harrison; they had one son, Peter, and one daughter, Katherine.

In 1942, after America had entered the Second World War, Oppenheimer was appointed leader of the theoretical side of the effort to design and build an atomic bomb. Research in England had made it seem very likely that the concept was viable. The chemical firm Dupont was contracted to build a production reactor, and it was time to prepare for the assembly of an atomic weapon. A permanent laboratory was needed for the work, somewhere remote because of the need for secrecy. For many years Oppenheimer and his brother had rented a ranch in the high country of the state of New Mexico, where they loved to spend their summers horseback riding. The government established its laboratory on a beautiful mesa nearby, called Los Alamos. Oppenheimer, as director of the enterprise, set about recruiting his team. Many of the best physicists were already involved in war work and disinclined to move, but he was very persuasive and those who came to join him found it an unforgettable experience.

The task they were faced with was formidable. Initially not much more was known than the fundamental theory behind a chain reaction. The details of the fission process had to be fully understood, but no fissionable material was yet available. Nuclear physicists found themselves dealing with unfamiliar subjects, like hydrodynamics, but Oppenheimer kept morale high and not only led the physicists but also argued against the tendency of the military to impose security measures the scientists regarded as excessive; for example, they had to use false names. The preparatory work was completed in 1945, at just about the time that a sufficient amount of the isotope uranium-235 became available. In 1946, at the end of it all, Oppenheimer was awarded the Medal of Merit by President Truman, 'for his great scientific experience and ability, his inexhaustible energy, his rare capacity as an organizer and executive, his initiative and resourcefulness, and his unswerving devotion to duty'.

It was obvious that a community like Los Alamos would be deeply concerned with the ominous implications of the atomic bomb. Oppenheimer was one of those most concerned, and had many discussions about this problem with Bohr amongst others. Bohr had come to the USA in 1944 as a consultant on the project, but his main interest was in talking to statesmen and trying to persuade them that international control was the only way to avoid a pernicious arms race or worse, atomic war. Bohr did not get far with the statesmen but he greatly impressed Oppenheimer and through him other scientists. In 1949, after the Soviet Union had exploded its first atomic bomb, the chances of any international agreement receded, and the scientists had little influence on the arms race which then developed.

In 1945 Oppenheimer resigned as director of the Los Alamos laboratory while remaining on a number of major national and international committees concerned with atomic energy. He returned to California briefly to resume his professorships. In 1948 he was president of the American Physical Society, and the following year he was appointed as both professor of physics and director of the Institute for Advanced Study in Princeton. Not all the permanent members of the institute supported his appointment, and he was not universally popular. He arrived with an armed guard carrying a large safe containing secret documents, and much of his time and energy was spent working in Washington.

During the Cold War a notorious witch-hunt took place in the USA, when many prominent people were accused, rightly or wrongly, of being Communists or crypto-Communists and therefore not to be trusted with secret information. Oppenheimer was a known left-winger. Although his brother and sister-in-law both joined the Communist Party, apparently he never did so himself. Nevertheless, at the end of 1953 President Eisenhower ordered that his clearance for secret government work should be suspended. The ensuing protracted security investigation became a *cause célèbre*. Many of his fellow-scientists came out in his defence, but he had made powerful enemies who testified against him. The decision was upheld, and it was not until eight years later that the American government made amends. When President Johnson, carrying out a decision made by the late President Kennedy, presented him with the prestigious Enrico Fermi award at the White House, Oppenheimer commented: ‘I think it is just possible, Mr President, that it had taken some charity and some courage for you to make this award today.’

Under Oppenheimer theoretical physics at the Institute for Advanced Study was strengthened, to some extent at the expense of mathematics. The institute faculty had always included prominent physicists; Einstein as a permanent member, Bohr, Dirac and Pauli, amongst others, as visitors, but now younger physicists were increasingly encouraged to visit, as well as those who were already eminent. Although he was never quite in the top rank of researchers himself, Oppenheimer could still conduct a lively seminar and play a leading and often critical role in the vigorous discussion which usually followed the talk. His own writings and lectures, after the war, were more concerned with the problems of the human race than with physics as such; increasingly he performed the twin roles of public symbol and interpreter of modern physics. Among the many foreign honours he received were membership of the Legion of Honour and the fellowship of the Royal Society. A heavy smoker, Oppenheimer died of throat cancer in Princeton on February 18, 1967, after having taken early retirement the previous year.

Maria Goeppert-Mayer (1906–1972)

Regrettably, only three of my remarkable physicists are women. The handicaps that Marie Curie and Lise Meitner faced have already been described; those that Maria Goeppert had to deal with, several decades later, were different but equally discouraging. Maria Gertrude Kate Goeppert was the only child of well-educated upper-middle-class parents. She was born on July 28, 1906, in what was then the German city of Kattowitz in Upper Silesia, and

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is now the Polish city of Katowice. Her mother Maria (née Wolff) taught French and music before her marriage. Her father, Friedrich Goeppert, who was professor of medicine at the university with a special interest in paediatrics, took special pride in being the sixth straight generation in a family of university professors; later his daughter would be proud to have continued the family tradition. Friedrich Goeppert encouraged his daughter's natural curiosity and adventurousness, and made it clear that he would like her to be more than simply a housewife. She later said that she found her scientific father more interesting than her mother, yet she was devoted to her mother, who delighted to entertain faculty members at lavish dinner parties and to provide a home filled with flowers and music for her only daughter.

Maria Goeppert was blond, with blue eyes, very earnest and unguarded in her expression, who learned the importance of duty while young and presented a reserved, somewhat aristocratic bearing as an adult. As a child she was described as active, adventurous and tense. She suffered from severe headaches and minor illnesses during childhood, perhaps exacerbated by her parents' high expectations. In 1910, when she was four, the family moved to Göttingen, where her father had been appointed professor of paediatrics at the Georgia Augusta. They had Hilbert as a neighbour, and their social circle included many of the scientists of the great university. The public schools of Göttingen had very good teachers; she excelled at languages and mathematics. To prepare for the *Abitur* she completed her school education at the *Frauenstudium*, a small private school run by suffragettes to prepare girls for higher education: unfortunately, before she could finish the three-year course it was closed due to hyperinflation. Rather than change schools again, she chose to take the *Abitur* a year earlier than normal. After passing this successfully, she entered the Georgia Augusta in 1924 to major in mathematics. Like most of the women students, she began by studying for the teaching certificate, but found the classes uninteresting. She considered medicine, but her father argued against it, fearing that she would suffer too much distress whenever a patient died.

The Georgia Augusta had long been famous for mathematics and was becoming so for theoretical physics as well. In 1927, inspired by the lectures of Max Born, Maria Goeppert switched to physics. That year her father, whom she idolized, died unexpectedly and, knowing what he would have wished, she honoured his memory by resolving to complete her doctorate, as a student of Born. She also spent a term in Cambridge, at Girton College, primarily to learn English, but she was also able to meet the Rutherfords. She was described as the prettiest girl in Göttingen, rather short and plump, with blue eyes and a fine-grained complexion. Her widowed mother, in accordance with a Göttingen tradition, began taking young people from the university as boarders in her substantial house: one was a post-doctoral student in chemistry from California named Joseph Mayer, the son of an Austrian-born engineer and an American schoolteacher. He and Maria became great friends and in 1930 they married. The same year she completed her doctoral dissertation 'On Elemental Processes with Two Quantum Jumps'. This was a theoretical treatment of two-photon processes, which she later used to determine the probability of double beta decay.

Meanwhile her husband had obtained a position as assistant professor of chemistry at Johns Hopkins University and so the couple moved to Baltimore. At that time universities were rather hesitant to hire women for academic positions. Prejudice against women scientists began to recede as the twentieth century progressed, but prejudice remained. In America many universities had 'anti-nepotism' rules, preventing husband and wife both holding academic positions in the same institution, and Johns Hopkins was one of these; there was no chance of an academic post for her there. Since no-one was working on quantum mechanics at Johns Hopkins, on Born's recommendation she collaborated in research with the physical chemist Karl Herzfeld, who was working on energy transfer and the liquid phase, and published some papers with him and with her husband. However, physical chemistry was not her chosen field and during the summers she returned to Göttingen, where she wrote several papers with Max Born on beta-ray decay.

She found it difficult to adjust to life in America and was homesick for Germany. By marrying an American she had forfeited her German nationality and become for a time stateless, which created various bureaucratic problems. In the spring of 1933 she took out American citizenship, calling herself Maria Goeppert-Mayer professionally, Maria Mayer otherwise. Her first child, Maria Ann, was born that year, the second, Peter Conrad, five years later. Although both children initially studied science in college, they did not pursue it further. The family lived in a large house, with an attractive garden, where they entertained streams of German visitors. Before their son was born her husband was appointed to a much-better-paid position as associate professor of chemistry at Columbia University and so they moved to New York, where she collaborated with him on a textbook, *Statistical Mechanics*, published in 1940, which became a classic. Unfortunately, it was assumed that her husband had done most of the work on this, so she did not receive her due credit, a common experience for married women. Until the USA entered the Second World War she was never on the payroll of an American university. Later she worked for the Manhattan project and participated actively in efforts to help the German refugee scientists. Her feelings about the war were ambivalent, due to her German roots and love of family, friends and colleagues in the land of her birth. She told her children that the war was against the Nazis, not the German people. Some of the other German scientists in exile felt differently about the homeland which had rejected them, but she continued to love Germany and the Germans and to insist that Hitler was an aberration.

At the end of 1941 Goeppert-Mayer took a part-time teaching position at Sarah Lawrence College in Bronxville, New York, where she developed a unified science course. A few months later she joined the secret project to separate the isotope uranium-235 from uranium-238, and she also worked with Edward Teller on nuclear fusion. When the first atomic bombs were dropped on Japan, with such devastating results, she was relieved that her part in their development had been very minor. After the war Joseph Mayer moved to the University of Chicago, where she was offered an associate professorship but without salary, due to anti-nepotism rules, and she joined the research group at the Argonne National Laboratory as senior physicist, the first time she held a normal scientific post. The Mayers lived in a handsome old house on the South Side of the city, ideal for entertaining. Like her mother she had a flair for this. She filled their house with flowers, often from their own garden. She specialized in cultivating orchids in a greenhouse on the top floor of their house.

Her collaboration with Teller on the origin of the chemical elements led to considerations of their relative abundance. She noticed that the most stable elements contained particular numbers of either protons or neutrons, later called the 'magic numbers'. Shell models for the nucleus had been considered and discarded earlier, but Goeppert-Mayer believed that new evidence strongly supported this concept. In 1948 she published a paper that set out the evidence but without a theory. A chance remark by Fermi, who was keenly interested in her work, triggered the insight that enabled her to solve the theoretical problem. By assuming the occurrence of spin–orbit coupling, she was able to calculate the energy levels that matched the magic numbers. Always impeccably correct in her behaviour towards others, she delayed publishing her results because she had heard that several other physicists were working on shell models in the USA. As it turned out, it was a group in Heidelberg that published a similar interpretation to hers, at about the same time as she did; later she co-authored a book on the subject with one of them, Hans Jensen, a 'dear gentle man' but rather inclined to procrastinate. It is said that through Bohr he provided information about

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the progress of German research into atomic weapons that was useful to the Allies.

During the war Goeppert-Mayer, an inveterate chain-smoker, began to experience health problems. In 1956 she lost most of the hearing in one ear. In 1959 both she and her husband were appointed to full professorships at the new San Diego campus of the University of California, although they were under pressure to remain in Chicago. A stroke in 1960, not long after the move to La Jolla where the campus is located, left her partly paralysed, but she continued to carry on as best she could. It was there in 1963 that the news arrived that she was to become a Nobel laureate. She and Jensen shared half the prize in theoretical physics for their discoveries concerning nuclear shell structure; the other half went to Wigner for contributing to the theory of the atomic nucleus and the elementary particles. Election to the National Academy of Sciences and several honorary doctorates soon followed, but her health gradually declined and she died of heart failure on February 20, 1972.

Goeppert-Mayer dealt with the obstacles she faced in her career partly by identifying with men at an early age and by disregarding the expectations of the society in which she lived. Like some other successful women scientists, she received much encouragement from key men in her life, beginning with her father, 'a gentle bear of a man', who wanted her to make something of her gifts. Many of her colleagues, including Born and Fermi, were supportive, but, perhaps partly because she worked so long without recognition, she was unduly modest about her work and abilities. Some of the difficulties Goeppert-Mayer experienced turned to her advantage. Unable to determine her own career path, she seized the opportunities which arose as she followed her husband's career. Although she had been educated as a mathematical physicist and was equipped with great facility in the Born–Heisenberg matrix formulation of quantum theory, she turned to physical chemistry when she went to America. The combination of theoretical and practical knowledge was important for her later work on nuclear structure. What was undertaken from expedience led to a deeper appreciation of experiment and understanding of a new field. She learned about nuclear physics, another new field to her, from Teller and from Fermi while at Columbia and Chicago. The varied strands in her background, both the planned and the unplanned, eventually converged in the studies that earned her the Nobel prize for the shell model of the nucleus. In the first century of the prizes, only two women have been awarded a Nobel prize in physics.

Hideki Yukawa (1907–1981)

Hantarō Nagaoka, who studied under Boltzmann, was the first Japanese physicist to participate fully in the competitive world of theoretical and experimental physics. Some young Japanese scientists studied in Germany, others in Britain, a few in France. They encountered language and other cultural difficulties. For example, several young professors of the faculty of science of the Imperial University who went to study at the University of Berlin heard an address glorifying the progress of German science in which the dean of the faculty said 'In order to study science in Germany, there come to this country many foreigners, Americans and so on, and lately even Japanese. In future, no doubt, even apes will be coming . . .'

Until around 1935 the contribution of the Japanese nation to world physics was very limited. By the end of the Second World War, however, Japan had become a significant contributor to theoretical physics, with an impressive number of first-rate research workers. Initially by far the largest volume of Japanese research was on the most modern aspect of the subject: elementary particles and fields. The new Japanese school was essentially the school of Hideki Yukawa and his friend and contemporary Sin-itiro Tomonaga. Both were Nobel laureates in physics. Both of them wrote

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autobiographies that have been translated into English, but Yukawa is more informative about his early years, and for that reason I choose him as the main subject for this profile. Of the two, Tomonaga had a more open and engaging personality; he remarked that 'Yukawa's eyes look inward, mine look outward.'

The man known to the scientific world as Hideki Yukawa was born in the Azabu district of Tokyo on January 23, 1907, during the fortieth year of the Meiji era. The child was the middle one of five brothers, the fifth of seven children altogether. Their parents were Takuji Ogawa and his wife Koyuki. Until his marriage to Sumi Yukawa in 1932, when he was adopted into his wife's family, the future physicist's name was Hideki Ogawa. Hideki's father's name had been changed from Asai to Ogawa for a similar reason. For a few months after Hideki's birth his father remained on the staff of the Geological Survey Bureau in Tokyo but in 1908 he became professor of geography at the University of Kyoto. Thus Hideki regarded Kyoto, the former capital city of Japan, as his home town; he spent almost all his life there.

Both the Asai family and the Ogawa family could look back on generations of scholars steeped in the tradition of Chinese as well as Japanese culture. Hideki's grandfather was a Confucian scholar and teacher of Chinese classics. His son Takuji, brought up in the same tradition, was well-versed in Chinese religion and philosophy, collected antiques and maintained an active interest in the history of ancient China and Japan throughout his life. He was associated with the Institute of Oriental Culture, under whose auspices he frequently visited China to participate in archaeological surveys and expeditions.

Like his brothers, Hideki was exposed to ancient traditions in childhood and adolescence. He recalled that, even before he entered primary school, he had studied various Chinese classics: 'In practice this meant that I repeated aloud after my grandfather a version of the Chinese texts converted into Japanese. At first, of course, I had no idea of the sense of it at all. Yet oddly enough I gradually began to understand without being told.'

In his autobiography Ogawa, as Yukawa was called in his youth, says that he was afraid of the stormy temperament of his unpredictable father and tried to avoid him; the influence of the boy's mother and grandparents on his upbringing seems to have been dominant. We learn from Ogawa himself that as a boy he was clumsy and ill at ease in his relations with other people. 'I never did develop socially', he recalled, 'often I think human relationships are tiresome, even among Japanese. Relating to foreigners simply wears out my nerves.'

At school Ogawa consistently obtained good marks, but when asked a question would often remain silent when he knew the answer perfectly well. When the time to choose a speciality arrived, he found it difficult to make a decision. His difficulty in interacting with people was linked, so he relates, to a complete lack of interest in human problems, so that all fields within the sphere of social science in the broad sense had no appeal whatsoever. Although literature and philosophy interested him, mathematics was his favourite subject. Indeed, the latter field seemed for a time to be the most likely choice of specialization, even though he had some doubts about devoting himself to a study that seemed to be so unrelated to the natural world.

Ogawa, when young, lived in a world of his own and made his own decisions. An avid and catholic reader, at the age of thirteen he entered high school, where he discovered in its library a series of books in Japanese explaining modern physics at a level he found accessible, at least in part. Ogawa related that he found the ideas of relativity comprehensible and exciting. On the other hand, in commenting on an introduction to quantum theory, he recalled that 'however much I read it, it made no sense to me . . . so I thought it might be a good idea to study it'. He appears to have kept to this resolution with remarkable tenacity.

Ogawa relates that, while he was at high school, he took very little notice of the normal run of student life around him, feeling an aversion to the bohemian life-style of his contemporaries. He was supposed to attend a class in economics and law but relates that these lectures went in one ear and out the other. Even so, his natural ability and methodical habits seemed to carry him safely over all examination hurdles. While he was at school a well-publicized visit to Japan by Einstein in 1922 had opened up the new world of ideas in physics to the Japanese. Ogawa taught himself some German and, when browsing in a bookshop, picked up the first volume of Planck's *Einführung in die theoretische Physik*. He relates with great warmth how he found the work both intelligible and fascinating, and as a result he decided to study at the physics department of the University of Kyoto.

The year of his entry was 1926, just after the discovery of the new quantum mechanics in the west. Whatever of the older quantum theory was included in the course he was offered – and it seems that there was very little – the new ideas had certainly not penetrated far. The account he

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gave of his studies is entirely about his private reading: learning the older quantum theory from an English translation of Reich's *Quantentheorie* and then, just as the first news of quantum mechanics was reaching Japan, being inspired by Born's *Probleme der Atomdynamik*. From then on it was a matter of studying new papers as they became available. As with so many other workers of the day, Schrödinger's version of quantum mechanics – wave mechanics – came as a revelation. He found it so much easier to understand than the Heisenberg matrix mechanics that had preceded it. Ogawa persuaded his teacher to agree to his choosing the new theory as his main subject for graduation. It seems that the only outside stimulus during these studies was from his friendship with his classmate Tomonaga.

Like Ogawa, Sin-itiro Tomonaga came from a family of culture, renowned for its literary scholarship. He was born in 1906, the eldest son of Sanjuro Tomonaga, who in turn was of Nagasaki samurai descent. Sanjuro had studied philosophy and history of philosophy at Tokyo Imperial University and at the time of Sin-itiro's birth was professor of philosophy at Shinshu University (later known as Otani University) in Tokyo. The following year he took up the position of associate professor at Kyoto University and in 1909 went to Europe for further study, leaving his wife and child with relatives in Tokyo. When he returned after an absence of four years, the family went to live in Kyoto, where he had been appointed professor.

Also like Ogawa, Sin-itiro Tomonaga gained admission to the faculty of science at Kyoto University in 1926 and elected to specialize in physics. He was greatly disappointed at the level of the lectures, especially in physics: moreover, the laboratories provided were dark, dirty and old-fashioned. More advanced work was being done in the laboratory of Professor Kajuro Tamaki, whose speciality was fluid dynamics and whose interests extended to relativity but not quantum theory. Soon Ogawa, Tomonaga and a few other ambitious students were studying western publications together. They saw that in atomic physics one major problem after another was rapidly being resolved, often by young researchers such as Heisenberg, Dirac, Pauli and Fermi.

Ogawa realized that quite basic questions remained unanswered in the context of relativistic quantum theory, in the quantum theory of fields and in the description of the atomic nucleus. He made the bold decision to concentrate on these even newer problems. As his graduation thesis he chose to offer some investigations on the properties of Dirac's equation. While there is no record of what went into this work, it was sufficiently impressive to enable him to graduate in 1929 and, although Tamaki did not accept research students, he and Tomonaga were allowed to remain in the laboratory as unpaid assistants. That year both Heisenberg and Dirac visited Kyoto, as did also the physicist Yoshio Nishina, who had just returned from seven years in Europe, most of the time spent studying with Bohr in Copenhagen. Nishina was impressed by the two young researchers and invited Tomonaga to join him in Tokyo.

In 1932 Ogawa married the classical Japanese dancer Sumi Yukawa and, as we have seen, adopted her family name, replacing the name of Ogawa. He was also appointed instructor in physics at his *alma mater*, where he lectured on quantum mechanics, using Dirac's textbook. One of his students described his voice as being 'gentle as a lullaby, an ideal invitation to sleep'. The following year he began speculating about the nature of the proton–neutron force. Before the moment of breakthrough Yukawa was given the chance to move from the peaceful atmosphere of Kyoto to the much livelier surroundings of the industrial city of Osaka, where a new university was being built up with a strong physics department, including a large experimental group provided with modern accelerator equipment. In this stimulating environment Yukawa's ideas came to fruition and his famous first paper was published, predicting the existence of a new fundamental particle, the meson.

After 1937 Yukawa was increasingly seen as a leader of theoretical physics in Japan. Already he could attract many research students, and his appointment to a chair was not long delayed. He was happy that this should be at his *alma mater*, soon to be internationally recognized as a major centre for theoretical physics. His first visit to the west included attendance at the eighth Solvay conference in Brussels in 1939. The arrangements for this were disrupted by the outbreak of the Second World War, but Yukawa was able to take the opportunity to establish personal contact with European and American physicists.

After the war, when Yukawa's own interest was beginning to turn away from the particular topic of meson theory to more general unsolved problems, the experimental discovery of the pion further enhanced his reputation. In 1948 he accepted Oppenheimer's invitation to work at the Institute for Advanced Study in Princeton, which was followed by appointment to a chair at Columbia University in New York. He remained at Columbia until 1953, when he was offered the directorship of a new inter-university research institute in Kyoto, housed in a building to be named in his honour. Yukawa remained in the old capital for the rest of his life. After reaching the age of seventy-four he became gravely ill and died from pneumonia on

September 8, 1981, survived by his widow Sumi and two sons, Harumi and Takai. He had received the Nobel prize in 1949, and many other honours as well.

In conclusion, something should also be said about the later career of Yukawa's friend Tomonaga, a quiet person of great charm. After a period of studying nuclear theory at Leipzig University under Heisenberg from June 1937 to August 1939, Tomonaga returned to Japan and received his D.Sc. from Tokyo Imperial University. In 1941 he was appointed professor at the Tokyo University of Science and Literature. Two years later Tomonaga was mobilized with other Japanese physicists to undertake research on magnetrons and ultra-short-wave circuits at the laboratory of the Naval Research Institute at Shimada. In addition he was a part-time lecturer at Tokyo University. Because of the intense air raids on Tokyo, he sent his family to live in the country while he remained in the city. During a raid on April 13, 1945 the district to the west of the campus where many professors lived was destroyed, including the house of Tomonaga.

After the war his seminar became a Mecca for young physicists. In 1948 he was elected to the Science Council of Japan. The following year he visited the Institute for Advanced Study in Princeton. In 1965 he shared the Nobel prize in physics with Richard Feynman and Julian Schwinger for contributions to quantum electrodynamics. Tomonaga's theory of 1943 had been developed quite independently of the American one, of which he did not become aware until the war was over. Like his friend Yukawa, he was awarded the prestigious Cultural medal of Japan, and numerous other scientific honours.

Much more than Yukawa, Tomonaga took on responsibility for nuclear physics and science policy generally in Japan. Scientists had long been perceived as left-wing agitators, opposed to big business and keen to distance themselves from the bureaucracy; Tomonaga attempted to break down this stereotype. The two Nobel laureates attended the first Pugwash conference held in Canada in 1957 and put their prestige behind the movement to ban atomic and hydrogen bombs. Tomonaga's health was poor in later years, and he died on July 8, 1979. Today Japanese workers contribute significantly to many branches of physics, both experimental and theoretical, following the lead of the two pioneers.