BEFORE THE FALL-OUT

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TRANSWORLD
BOOKS

About the Book

Spanning fifty years, *Before the Fall-Out* tells the full story of how an exhilarating quest to unravel the secrets of the material world produced the knowledge of how to destroy it. And of how a scientific adventure shared openly between nuclear physicists from many different nations transmuted into a secretive wartime race for the ultimate weapon of mass destruction – the atom bomb.

As much as on the science, *Before the Fall-Out* focuses on the 'human chain reaction' – the intertwined lives of the many scientists of many nations whose compulsive curiosity led, however unwittingly, ultimately to Hiroshima. In her page-turning account Diana Preston reveals how individuals responded to events – from Allied scientists debating the morality of deploying the bomb, to Japanese civilians who became its first victims, and to a German chemist working on the Nazi bomb project while concealing a Jewish pianist in his Berlin apartment. Diana Preston draws on fresh material including interviews with the last living scientist to have worked with Marie Curie, the only senior scientist to have walked out on the Manhattan Project on moral grounds, and the German scientist who accompanied Werner Heisenberg on his controversial wartime visit to Niels Bohr in Copenhagen.

A Manhattan Project scientist said that the only secret of the bomb was that it could be made: once this was known, any nation could replicate it. *Before the Fall-Out* helps us make better sense of our own, dangerous world and of the threats and moral dilemmas that face our society today

CONTENTS

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The Human Chain Reaction
from Marie Curie to Hiroshima

Diana Preston

To Michael,
my husband and partner in writing

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PROLOGUE

ON 6 AUGUST 1945, the Christian Feast of the Transfiguration, the Festival of Light, a young mother, Futaba Kitayama, looked up to see ‘an airplane as pretty as a silver treasure flying from East to West in the cloudless pure blue sky’.[1] Someone standing by her said, ‘A parachute is falling.’ Then the parachute exploded into ‘an indescribable light’.

The American B-29 bomber *Enola Gay* had just dropped ‘Little Boy’, a four-ton bomb which detonated with the explosive power of 15,000 tons of TNT over the Japanese city of Hiroshima. Pilot Paul Tibbets, who had the day before named his plane after his own mother, struggled to hold the aircraft steady as the first shock waves hit. Bathed in a bright light, he looked back and saw ‘a giant purple mushroom boiling upward like something terribly alive’.[2] He switched on the intercom and announced to his shaken crew, ‘Fellows, you have just dropped the first atomic bomb in history.’

On the ground, Futaba Kitayama felt her face become strangely damp; ‘When I wiped my face the skin peeled off.’[3] Her eyes began to mist over and close as her face swelled. ‘Suddenly driven by a terror that would not permit inaction’ she staggered past writhing, flayed bodies as she tried to escape. To one doctor in the doomed city, the pervasive stench of burnt flesh was like ‘dried squid when it is grilled – the squid we like so much to eat’.[4] By December 1945, about 140,000 inhabitants of Hiroshima would be dead, either as a result of the blast and the fires that followed or of the insidious, silent effects of nuclear radiation.

When news of the bombing was announced, young Allied soldiers preparing for the invasion of Japan 'cried with relief and joy. We were going to live. We were going to grow up to adulthood after all.'[5] President Truman told a group of sailors aboard the cruiser on which he was returning from the Potsdam Conference, 'This is the greatest thing in history.'[6] Winston Churchill struck a more reflective note: 'This revelation of the secrets of nature, long mercifully withheld from man, should arouse the most solemn reflections in the mind and conscience of every human being capable of comprehension.'[7] Only three days after Hiroshima, and within days of giving birth to her second son, a New York mother wrote, 'torturing regrets that I have brought children into the world to face such a dreadful thing as this have shivered through me. It seems that it will be for them all their lives like living on a keg of dynamite which may go off at any moment.'[8]

Soon, worries were widespread that the invention of the bomb had unleashed a Frankenstein's monster capable of striking back at its creators in a wholesale and indiscriminate fashion. Although over the past sixty years such concerns have wavered in intensity and the source of the perceived threat has varied, the fear that a single plane or a single person with a suitcase can obliterate a city haunts us today.[*1]

The destructive flash that seared Hiroshima into history was the culmination of fifty years of scientific creativity and more than fifty years of political and military turmoil. Generations of scientists had contributed to that moment in physics. Yet, when they first began to tease out the secrets of matter not even future Nobel Prize winners could have predicted how their pioneering insights would combine with exterior events to produce such a defining moment in history. Like all in this story, they were only human.

For the scientists of many nations, the journey of discovery had begun in the 1890s when dedicated researchers such as Marie Curie, working alone or in small teams with rudimentary equipment, intent on achieving a fuller understanding of nature, started to identify the minute building blocks forming the world around them. Blinding discoveries were matched by blind alleys. People rushed to publish their results, not for profit nor for national prestige and power, often not even for personal glory, but rather for the pure joy of knowledge.

For a long time no-one realized their work could unlock immense energy to furnish a devastating new weapon, or, indeed, if properly harnessed, to provide a city with electricity. At the beginning of the twentieth century, radioactivity was seen as only producing benefits to health through the use of X-rays for diagnosis and the use of radioactive materials to treat many diseases including cancer. Physics was a new subject. The 1910 *Encyclopaedia Britannica* devoted fifty pages to chemistry, but physics did not feature. Around that time there were, perhaps, a thousand physicists worldwide, of whom maybe 10 per cent were engaged in the study of radioactivity. Consequently, all those involved knew one another. At a time of intense national rivalry and of competition for empire, trade and natural resources, results were pooled internationally, as further pieces in a communal jigsaw puzzle for which no-one had the master picture or pictures. Scientists studied at one another's institutes. North Americans and Japanese visited Germany; Germans came to Britain; Britons went to North America; Russians studied in France. Colleagues skied, hiked and made music together. Allegiances and rivalries stemmed from where and with whom people had studied, rather than from nationality or race.

All met at conferences, where results were shared, contacts maintained and gossip exchanged. Albert Einstein called them ‘witches’ sabbaths’.[9] Few conferences were as marked by gossip as that in Brussels in 1911, when Marie Curie was forced to withdraw as a result of an alleged affair with Paul Langevin, a close colleague and a married man. However, personalities were strong, and debate often heated. This was particularly the case when entirely novel concepts such as relativity or quantum theory were discussed, which undermined the Newtonian concept of a predictable, mechanical world whose ordered processes could be measured and whose future behaviour could be as accurately forecast as its past could be determined. Those involved were, as they recalled, undertaking ‘wholly new processes of thought beyond all the previous notions in physics’, and ‘filled with such tension that it almost took [their] breath away . . .’[10] ‘It was an heroic time . . . not the doing of any one man’ but ‘the collaboration of scores of scientists from many different countries . . . a period of patient work in the laboratory, of crucial experiments and daring action, of many false starts and many untenable conjectures . . . It was a time of creation . . .’[11]

Yet when, in 1933, despite the great advances already made, one of the world’s leading physicists, Ernest Rutherford, dismissed the idea of harnessing energy from atoms as ‘moonshine’, the physicists’ world was changing.[12] Hitler was in power. Scientists who had once travelled simply to where the best science was were now compelled to flee his and other totalitarian regimes because of their race or political views. Ernest Rutherford himself became one of those who did most to welcome them and find them work. Their knowledge and brain power were to prove vital to their hosts in the impending conflict.

In Berlin in 1939, on the eve of the long-feared war, German scientists, with considerable secret help from one of their exiled Jewish former colleagues, Lise Meitner, discovered nuclear fission – a way to unleash the power of the atom. Scientists across the world recognized that an atomic weapon might be a possibility. The personal experience of the émigrés gave added urgency to their efforts to stimulate the democracies to action so that Germany could not blackmail the world into submission by her possession of a unique and uniquely destructive weapon. The success of their advocacy meant that what had for more than forty years been an open quest for knowledge became, almost overnight, a race between belligerent nations, working in secret with large teams, for high and sinister stakes, using all available means of sabotage, espionage and disinformation to thwart their opponents.

The scientists' fears of their German colleagues' potential led one British physicist, during the 1940–1 Blitz, surreptitiously to take a Geiger counter from his laboratory to monitor bomb craters in case the enemy had mixed radioactive materials with conventional explosives to contaminate whole areas and poison their inhabitants. Allied scientists remained so concerned about what are now called 'dirty bombs' that they warned General Dwight D. Eisenhower that the Germans might well use them against the Allied troops under his command during the D-Day landings in Normandy in June 1944.

Well before D-Day, nuclear physics had become big science and big engineering. No other country was able to replicate the resources put into the American Manhattan Project. It cost $2 billion and was as big as the US car industry. The Project employed 130,000 people, from American and British scientists to security guards and process workers, not counting the military and government staff and politicians.

A fortnight after Hiroshima, an editorial in *Life* magazine commented, 'Our sole safeguard against the very real danger of a reversion to barbarism is the kind of morality which compels the individual conscience, be the group right or wrong. The individual conscience against the atomic bomb? Yes, there is no other way. No limits are set to our Promethean ingenuity provided we remember that we are not Jove.' The very success of the bomb project in its own terms retrospectively sharpened the moral searchings among those involved. To some it came to symbolize science's loss of innocence. Sound sense and acute sensibility coexisted uneasily in the character of Robert Oppenheimer, the scientific leader of the Manhattan Project. For as long as it took to complete his task, he subdued his humanist principles to achieve the most inhumane of weapons, but he would later state that 'physicists had known sin'[13] and that he, personally, was 'not completely free of a sense of guilt'.[14] Another leading scientist said that the bomb had 'killed a beautiful subject'.[15]

However, even before the bomb was dropped, a sense of individual responsibility had compelled other key staff to speak out. Joseph Rotblat, a future winner of the Nobel Prize for Peace, actually left the Manhattan Project when he realized that the weapon would become a permanent part of military arsenals which politicians were prepared to contemplate using against their then ally Russia, as well as against Germany. The Dane Niels Bohr and the Hungarian refugee Leo Szilard both argued for international co-operation and control of the discovery, and for a demonstration of the bomb's explosive power before all nations, rather than its immediate use in combat.[*2, 16]

For most of the war, the moral dilemmas posed to scientists in Axis countries and in those under German occupation, such as Denmark and France, were starker and entailed immediate personal vulnerability. The ambiguities and uncertainties of the Copenhagen meeting in 1941 between the leading German nuclear physicist Werner Heisenberg and Niels Bohr have been widely explored, but others also strove to reconcile personal conscience and patriotic sentiment. Fritz Strassmann, one of the discoverers of fission, hid a Jewish pianist in his Berlin apartment while working on nuclear calculations for the Nazi government. Before later joining the resistance and helping to liberate Paris, Marie Curie’s son-in-law, Frédéric Joliot-Curie, had to decide how far he could acquiesce in German use of his nuclear institute in Paris at a time when the prospects of Allied victory seemed remote.

The majority of Allied scientists involved would maintain that Oppenheimer’s apologia was unwarranted. Knowledge was neutral; the use to which politicians put it was the dilemma. In any case, the Allies could not have neglected the weapon’s potential when they knew that the Germans had embarked on a weapons research programme. That an Allied team had won the race on behalf of the democracies was preferable to any other outcome.

Whichever view the scientists took, the final decision to use the bomb was a political one, and one which the American and British public supported overwhelmingly on the grounds that it saved Allied lives and brought the war to a speedier end than would otherwise have been the case. With hindsight, and with distance from the feelings of individuals in war-weary nations who were apprehensive of the cost in terms of the lives of their loved ones of an invasion of Japan, historians have questioned the political judgements. They have suggested that there were alternatives to the use of the atomic bomb to end the war which would have saved Japanese lives without sacrificing Allied ones.

The moral issues that faced both the physicists in advising on the use of the bomb and the politicians in deciding upon it were, in fact, at least half a century old. Alfred Nobel, the inventor of nitroglycerine and the founder of the Nobel Prizes, not least for peace, had justified his invention as putting an end to war. In 1899, at the time of Marie Curie’s pioneering work on radium, the nations of the world met at the Hague to discuss how to avoid conflict by the creation of systems for arbitration. They also laid down in the Hague Convention rules for the conduct of war if it could not be avoided. Among them, four years before the first powered flight, was a prohibition against bombarding ‘by whatever means . . . undefended’ civilian towns or buildings, and another prohibition against the dropping of bombs from balloons ‘or other kinds of aerial vessels’.

A second conference was held at the Hague in 1907 at the instigation of President Theodore Roosevelt to review the provisions of the first. Only twenty-seven countries, including Britain and the US, supported renewal of the ban on aerial warfare. Seventeen, including Germany and Japan, did not, so the provision fell. All could agree, however, on a definition of targets permitted to be bombarded by whatever means. Civilian targets were still excluded, but aerial bombardment had gained legitimacy.[17]

The First World War brought science and warfare together in a way no other conflict had. On the evening of 22 April 1915, Germany launched the world’s first poison gas attack. The German scientist in charge of the programme defended the use of gas as a means of shortening the war and thus saving lives. After initially condemning the attacks as further breaches of the rule of civilized law by the barbarous ‘Hun’, Britain, France and later the United States, after her entry into the war, did not long delay in following suit. By the Armistice, Allied production of chemical weapons far exceeded Germany’s. The ‘Great War’ would also come to be known as the ‘Chemists’ War’. By the end of the conflict, about 5,500 scientists on all sides had worked on chemical weapons alone, and there had been a million casualties from gas attacks. Among them was Lance Corporal Adolf Hitler, who, temporarily blinded by a British gas grenade on 13 October 1918, was still in hospital the day Germany surrendered nearly a month later. Yet this ‘war to end wars’ would not do so, and the next world conflict, precipitated by that lance corporal, would be the physicists' war.

The First World War had seen the death of some ten million men, the fall of three empires, the establishment of a major communist state and the emergence of the aeroplane as a weapon. Yet, at postwar conferences, countries were lukewarm about defining further rules for the conduct of air warfare. No agreement was ever ratified. Over the years, the definition of what in the previously agreed documents was 'civilian' and thus free from attack became blurred. At the beginning of the Second World War, President Franklin Roosevelt pleaded with the belligerents to refrain from 'bombardment from the air of civilian populations or unfortified cities'. The 1940 memorandum from two émigrés to the British government arguing that an atomic bomb was feasible and urging an immediate start to a research programme suggested that the very likely high number of civilian casualties 'may make it unsuitable as a weapon for use by this country'.[18]

Yet, over the next five years of increasingly total war the Allied air forces followed the precedents set by their enemies and attacked whole cities such as Hamburg, Dresden and Tokyo, in the latter attack using the newly developed 'sticky fire' – napalm. Even before 6 August 1945 any distinction between civilians and combatants had been eliminated in practice, if not in presentation.

Today, we still experience the scientific, political and moral fall-out from 6 August 1945. Against the tumultuous background of the history of the first half of the twentieth century, *Before the Fall-Out* explains how joy in pure scientific discovery created a beautiful science which was suddenly transmuted into a wartime sprint for the ultimate weapon. Through the stories and voices of those involved it tells how individuals responded to the questions of personal responsibility posed by the results of their compulsive curiosity, and why the bomb fell on Hiroshima and its people and changed our world for ever.

CHAPTER ONE

‘BRILLIANT IN THE DARKNESS’

TOWARDS MIDNIGHT IN a Paris garden on a warm June night in 1903, attentive guests watched Pierre Curie take a phial from his pocket and hold it aloft. The radium inside shone ‘brilliant in the darkness’.[1] Curie’s gesture was a tribute to his wife, Marie, the discoverer of radium. Earlier that day this slight woman with her high-domed forehead and intense, grey-eyed gaze had become the first female in France to receive a doctorate. The occasion was an impromptu celebratory dinner party at the villa of the Curies’ friend, scientist Paul Langevin.

Marie Curie, born in 1867, was the youngest child of a progressive-minded Polish teacher of physics and mathematics, Wladislaw Sklodowski. She had left her native Warsaw, where women were barred from the university, for Paris, driven by a determination to study science and to do so in a free society. As a sovereign entity, Poland no longer existed: the three rival empires of Germany, Austro-Hungary and Russia had partitioned Marie’s homeland between them. The Sklodowskis, a close-knit, intellectual family, lived in Russian Poland where Polish culture was crudely suppressed and ‘Russianized’. In adolescence, Marie had risked prison or deportation to Siberia by studying and then teaching at the clandestine ‘Floating University’ in Warsaw – a radical Polish night-school for young women. The university’s aim was to develop a cadre of committed women capable, in turn, of educating Poland’s poor and thereby equipping them to resist Russian oppression. To avoid suspicion, the students gathered in small groups in impromptu classrooms in the cellars and attics of those bold enough to host them.

Science, particularly mathematics and chemistry, had fascinated Marie from an early age. The Floating University provided her with her first taste of working in a laboratory, albeit an illicit one, concealed from the prying eyes of the authorities in a Warsaw museum. Casting around for a suitable foreign university in which to complete her scientific education, Marie was attracted to the Sorbonne, part of the University of Paris. Not only did it have a high reputation for science, but many of Poland’s intellectual elite had settled in Paris.

However, the Sklodowskis were perennially short of money. Marie’s chances of achieving her ambition seemed remote until she identified a way of helping both her elder sister, Bronya, and herself. She would work as a governess and send all her wages to fund Bronya’s medical studies in Paris; then, as soon as she had qualified as a doctor, Bronya would send for her younger sister and, in turn, support her through her own studies. Refusing to listen to Bronya’s objections, the eighteen-year-old Marie secured a post with the Zorawski family fifty miles north of Warsaw and set out in the depths of winter for their manor house. As she later wrote, that cold, lonely journey remained ‘one of the most vivid memories of my youth’.[2] The final leg was a chilling five-hour sleigh ride across snow-covered beet fields, and she made it with a heavy heart.

Initially, though, Marie found life as a governess bearable, even pleasant. During the day she instructed her employers’ daughters and, applying the philosophy of the Floating University, also taught the local peasant children. In the evenings she pursued her own studies by candlelight. As she later recalled, ‘during these years of isolated work . . . I finally turned towards mathematics and physics, and resolutely undertook a serious preparation for future work’.[3]

She also learned 'the habit of independent work'. However, Marie's tranquillity was broken when she and the Zorawskis' eldest son, Kazimierz, fell in love when he came home on vacation from Warsaw University, where he was studying mathematics. Although his parents liked Marie, they refused to contemplate their son's talk of marriage to a woman they considered socially inferior. Eventually Marie left the Zorawskis, where, as she confessed to her brother, the 'icy atmosphere of criticism' had become intolerable.[4] She still hoped that Kazimierz would show the strength of character to defy his parents and marry her, but finally, four fruitless years after their first meeting, she accepted that he would not.

Bronya, by then qualified and married to another Polish doctor, had meanwhile been urging Marie to come to Paris. At last, in November 1891, the twenty-three-year-old Marie bought the cheapest possible train tickets for the forty-hour, thousand-mile journey to Paris, where she enrolled in the Sorbonne's Faculty of Sciences. At first she lived with Bronya, but then found lodgings in an attic room on the Left Bank, sacrificing all comforts to the one essential – solitude to study in peace. She later wrote, her room was 'very cold in winter, for it was insufficiently heated by a small stove which often lacked coal'.[5] Sometimes the temperature fell so low that the water froze in her hand basin, and 'to be able to sleep I was obliged to pile all my clothes on the bedcovers'. When that failed to warm her, she pulled towels and anything else she possessed, including a chair, on top of her. She survived on a meagre diet of tea and bread and butter supplemented by the occasional egg. One day she fainted on the street. Bronya carried her home, made her eat a large steak and lectured her on taking better care of herself, but Marie persisted in her spartan, single-minded existence.

Physical deprivation was unimportant. She had found a stimulating intellectual challenge: ‘It was like a new world opened to me, the world of science, which I was at last permitted to know in all liberty.’[6] She passed her *licence ès sciences physiques* (comparable to a bachelor of science degree) in 1893, not only top of the class but also the first woman to receive such a degree. She took her *licence ès sciences mathématiques* in 1894, coming second in her class. While she was still preparing for her mathematics exams, the Society for the Encouragement of National Industry invited her to perform a study of the magnetic properties of steels. She was eager to do so but lacked sufficient room for the necessary equipment in her laboratory at the Sorbonne. Polish friends in Paris came to her aid. They invited her to tea to meet French physicist Pierre Curie, laboratory chief of the Paris School of Physics and Chemistry. He too was working on magnetism, and they hoped that he might be able to help her.

Pierre’s background, like Marie’s, was radical and progressive. His father, a determinedly republican doctor, Eugène Curie, had tended wounded activists during the rising in 1871 of the Paris Commune – the revolutionary council formed by the workers of Paris after France’s defeat by Prussia. The Communards had gone to the barricades in defiance of the French government, which had concluded an armistice they considered shameful. The Commune lasted ten weeks before being bloodily suppressed by French government forces, leaving some twenty thousand dead. Eugène Curie sent Pierre, only twelve at the time, and his slightly older brother Jacques out into the streets to search for wounded people in need of medical care and protection from the troops.

Later, as life returned to normal, Dr Curie had encouraged his sons to explore the natural world. Both became scientific assistants at the Sorbonne where, working together in the laboratory of mineralogy, they began studying the structure of crystals. This led them to a remarkable discovery – the phenomenon of piezoelectricity[*1] whereby crystals subjected to pressure produce a current – which became the basis for the gramophone. The two young men had developed a piezoelectric quartz instrument capable of measuring the tiny voltages emitted by the crystals.

When he met Marie, Pierre Curie was thirty-five years old, introspective and unworldly. Many years before he had loved a girl whom he described in a private note as 'the tender companion of all my hours', but she had died.[7] Since then he had devoted himself to his work while striving to avoid emotional though not physical entanglements. He believed that 'a kiss given to one's mistress is less dangerous than a kiss given to one's mother, because the former can answer a purely physical need'.[8] Perhaps as a defence against intellectual engagement he claimed to believe that 'women of genius are rare' and that 'when, pushed by some mystic love, we wish to enter into a life opposed to nature, when we give all our thoughts to some work which removes us from those immediately about us, it is with women that we have to struggle . . .'[9]

After her experience with Kazimierz Zorawski, Marie was wary of relationships. Young students at the Sorbonne frequently propositioned the gamine ash blonde, excited by her combination of cool intellect and sexual charisma, but none impressed her. Pierre Curie, however, did. As she later wrote, 'his simplicity, and his smile, at once grave and youthful, inspired confidence'.[10] Tall, with cropped auburn hair and a pointed beard, he had an unconscious, loose-limbed grace. He was unable to offer Marie accommodation for her experiments, but their meeting sparked an intense relationship. They quickly discovered what Marie called 'a surprising kinship' in their ideas. Both believed science to be the world’s salvation. Both believed that they should devote their lives to make it so.

Pierre was soon broaching marriage. Marie hesitated, knowing that it would put paid to her cherished scheme of one day returning to her homeland to teach. During a visit to Poland in the summer of 1894, despite her feelings for Pierre, she actively explored the prospect of an appointment at the University of Cracow. However, Pierre knew exactly how to woo her, writing to her that, ‘It would, nevertheless, be a beautiful thing in which I hardly dare believe, to pass through life together hypnotized in our dreams; your dream for your country, our dream for humanity; our dream for science. Of all these dreams, I believe the last, alone, is legitimate.’[11] Such pleas touched Marie, as did his offer to move to Poland, a sacrifice which she told her sister Bronya she had no right to accept. On 26 July 1895 Pierre and Marie were married at a brief civil ceremony with no white dress, wedding ring or elaborate wedding breakfast. They spent their honeymoon roaming Brittany on bicycles purchased with money given as a wedding present.

By early September, the Curies were back in Paris, living in a tiny three-room apartment which Marie, impatient of domestic distractions, furnished with the bare minimum – two chairs, a table, bookshelves and a bed. Just before their wedding Pierre Curie had been appointed to a new chair of physics, created especially for him, at the Paris School of Physics and Chemistry. Marie was allowed to transfer her work on steels there from the Sorbonne. As a woman working in a laboratory she was an object of curiosity and some animosity, but this did not deter her. Neither did the birth in September 1897 of the Curies’ first daughter, Irène, whom Marie delightedly called her ‘little queen’ in letters home to Poland.[12] She completed her report on steels within three months of the birth and at once began seeking a suitable subject for her doctoral thesis. She chose a newly discovered phenomenon, Becquerel rays.

Becquerel rays owed their discovery to a phenomenon that had caught the public imagination. Two years earlier, in late 1895, Wilhelm Röntgen, a reclusive German physicist at the University of Würzburg, had been following up work by Heidelberg physicist Philipp Lenard on how electrical currents pass through gases at low pressures. Röntgen's prime piece of equipment was a three-foot-long glass tube from which most of the air had been pumped out. Inside the tube were two metal terminals – one positive, called the 'anode', and the other negative, called the 'cathode'. Fine wires passing through the glass connected the terminals to an electrical source.

Lenard had observed that, when the power was on, the negative plate produced a stream of rays which caused the tube walls to glow with a soft green light. Röntgen was prepared for this. What startled him was that, despite the black card with which he had mantled his tube to exclude exterior influences on his observations, a nearby paper screen painted with fluorescent substances (barium platinocyanide) was also glowing brightly. In fact, each time electricity pulsed through the blacked-out tube, the paper screen luminesced. Röntgen moved the screen two metres away from the tube, but still it glowed.

Lenard's experiments had demonstrated that cathode rays were stopped by quite thin barriers, so Röntgen realized that some sort of penetrating rays – hitherto unknown, and which he therefore named 'X-rays' – were escaping through the glass walls of his tube. He further deduced that these 'X-rays' were caused by the impact of the cathode rays on the tube's glass walls. He discovered that although his X-rays could penetrate thick books or decks of cards, they could not pass through denser materials such as metal so easily. When he placed his hand between the tube and the fluorescent screen, Röntgen was staggered to see the shadows of his own bones. The rays had penetrated the soft tissue but the denser bones were sharply delineated on the screen.

Röntgen tested the rays' effects using photographic plates, capturing in the world's first X-ray pictures images of everything from a compass needle in a metal case to his bones. Röntgen realized the implications: his rays could be used to identify fractures in bones and find bullets embedded in tissue. In January 1896 he announced his discovery publicly in Berlin, and before the month was out radiographs were being produced around the world. In 1901 he would become the first recipient of the Nobel Prize for Physics, introduced that year after Alfred Nobel left the bulk of his estate in trust for the annual award of five prizes for services to physics, chemistry, medicine, literature and peace. In the years ahead, the physics and chemistry awards would be dominated by those exploring the new atomic science.

As news of the miraculous rays spread and they were successfully put to work in medical diagnosis, Röntgen became a reluctant celebrity, forced to dodge newspaper reporters. Some people, though, were disturbed by his discovery. Women seriously contemplated buying 'X-ray proof underwear' to repel lascivious peeping Toms. One rhyme warned:[13]

> I hear they'll gaze
> Through cloak and gown – and even stays
> Those naughty, naughty Röntgen rays.[14]

Punch magazine quipped:

> We do not want, like Dr. Swift,
> To take our flesh off and to pose in
> Our bones, or show each little rift
> And joint for you to poke your nose in.
> We only crave to contemplate

Each other’s usual full-dress photo;
Your worse than ‘altogether’ state
Of portraiture we bar *in toto*![15]

Meanwhile, puzzled scientists struggled to explain the source of the mysterious X-rays. In Paris, physicist Professor Henri Becquerel decided to investigate whether phosphorescent and fluorescent substances produced these invisible rays.[*2] Becquerel carefully placed successive glowing materials onto photographic plates which he had previously wrapped in thick black paper to see whether rays would penetrate the paper and darken the plates. Nothing happened until he selected the powdery white salts of the rare metal uranium, luminous in sunlight. At last, there was a result. When the plates were developed Becquerel noted faint smudges – evidence of penetrating radiation. He conducted further tests, sometimes adding a coin or metal sheet and observing the faint traces of their outline.

One day he placed uranium salts together with a copper cross onto a photographic plate, but the Paris weather became overcast. Sharing the common belief that substances needed natural sunlight to luminesce, he thrust the plate into a drawer to await a brighter day. Some days later, on 1 March 1896, sheer chance or what another scientist, William Crookes – who was present and saw what happened – admiringly called ‘the unconscious pre-vision of genius’ caused Becquerel to develop the plate.[16] He found that despite being in darkness the uranium salts had emitted radiation. The image of the copper cross was ‘shining out white against the black background’.

Becquerel wrote up his results with both puzzlement and excitement. He had, in fact, discovered ‘radioactivity’ – the first new property of matter since Newton identified gravity. Although he did not appreciate the full significance of his findings, he realized that they were important and unexpected, and was therefore piqued when they attracted little comment. Röntgen’s X-rays still commanded all the attention.

Marie Curie read Becquerel’s work and was, as she later wrote, ‘much excited by this new phenomenon, and I resolved to undertake the special study of it’.[17] Since the subject was ‘entirely new’ – no-one except Becquerel had yet written about it – all she needed to do before getting started on her doctorate was to read his papers. Marie was offered a small, damp, glass-panelled storage room on the ground floor of the School of Physics as her laboratory, and on 16 December 1897 she began work.

Becquerel had noted that his rays released a light electrical charge into the air. Marie therefore decided to measure the electric current emanating from uranium salts. The Curie brothers’ piezoquartz electrometer, sensitive to the faintest trace of electrical current, was tailor-made for her purpose. She found the rays’ activity to be directly proportionate to the quantity of uranium in the specimens and that it was unaffected by light, temperature or the chemical form the uranium was in.

Wondering whether other chemical elements besides uranium might share these qualities, she plundered her colleagues’ shelves for specimens. Her careful examination of these elements revealed that, in addition to uranium, only thorium, the heaviest of the known elements after uranium, was active. Her measurements also showed that pitchblende, a heavy black ore rich in compounds of uranium, appeared nearly four times as active as pure uranium. This was not what she had expected. She repeated her meticulous tests twenty times but her results remained the same. Since she had already tested all known elements for activity, logically this could only mean one thing: the pitchblende contained a new element. She told her sister Bronya, ‘The element is there and I’ve got to find it.’[18]

Marie immersed herself completely in her work, helped by Pierre. As their younger daughter Eve later wrote, he had followed his wife's progress 'with passionate interest. Without directly taking part in Marie's work, he had frequently helped her by his remarks and advice. In view of the stupefying character of her results, he did not hesitate to abandon his study of crystals for the time being in order to join his efforts to hers in the search for the new substance.'[19] They began breaking down the pitchblende to extract the tiny fragment containing the activity, hoping thereby to solve the puzzle. They did this by extracting from the pitchblende sulphur of bismuth, a substance which, according to their measurements, was far more active than uranium. Since pure sulphur of bismuth was itself inactive, this meant that the new active ingredient had to be present in the bismuth.

It was laborious, painstaking but exciting work. As soon as they had extracted a tiny amount of active material, Marie bore it off to Eugène Demarçay, a specialist in spectrography – the science of identifying elements by the rainbow-coloured 'spectra' they display when energized by an electric current. Despite having lost an eye in a laboratory explosion, his abilities were still acute. He analysed Marie Curie's specimen and declared it was something he had never seen before.

The Curies announced their discovery of what they believed to be a new element in July 1898 in the Academy of Sciences' *Comptes Rendus,* the most influential scientific publication in France. They declared that, if proved correct, they would name it 'Polonium' in tribute to the land of Marie's birth. The title of their paper, 'On a New Radioactive Substance Contained in Pitchblende', coined a new word. The terms 'radioactive' and 'radioactivity', from the Latin word 'radius' meaning ray, were quickly taken up. So was the term 'radioelement' to define any element with this property.

After a cycling trip to the Auvergne with baby daughter Irène, whose first words 'Gogli, gogli, go' Marie recorded with as much delight as her experimental findings, they returned to Paris to resume their investigation. As they laboured, they were astonished to discover a further new radioactive element in the pitchblende. On 26 December 1898, just six months after finding polonium, they announced the likely existence of this second new element, naming it 'radium' and telling the world that its radioactivity 'must be enormous'.[20] Their paper also stated that 'one of us' (probably Marie) had shown that 'radioactivity seems to be an atomic property' – in other words, it derived from some characteristic within the atom, the tiny brick from which all matter is built.[21]

The Curies had made these startling discoveries with tremendous speed – within a year of Marie beginning her doctoral thesis. They next had to convince the many sceptics that radium and polonium were not chimera, but real. So far they had succeeded in isolating only tiny specimens of each. To prove their existence beyond dispute they needed larger samples.

It was already clear that radium was the more active of the two and therefore easier to isolate. Accordingly, Marie Curie focused on extracting pure radium – a formidable task, since radium constitutes less than a millionth part of pitchblende. She needed fifty tons of water and some six tons of chemicals to process just one ton of pitchblende from which the maximum yield would be no more than four hundred milligrams of radium – about one hundredth of an ounce. The task required facilities on an industrial scale. Instead, the School of Physics offered the Curies what Marie called a 'miserable old shed' abutting the narrow Rue Lhomond.[22] This old wooden hangar with a leaking skylight