PREFACE

By Way of Explanation

Until about 10.30 a.m. on Wednesday, 10 May 2017, I would never have written this book. Pinned to the noticeboard in my study is a black enamel lapel badge stamped with the silver crow's foot of the Campaign for Nuclear Disarmament. When I joined CND in 1980, the Cold War was at its most glacial, and I'd seen enough of the world through the eyes of a young doctor to realise that there could only be losers – hundreds of millions of them – in a nuclear war. Even when a busy career and family life pushed it down the list of things to worry about, the nightmare of watching a mushroom cloud boiling up into the sky above the rooftops still haunted me. Like everyone else, I breathed a sigh of relief when a near-miraculous thaw in East–West relations ended the Cold War in late 1991. I stopped wearing my CND badge but didn't cancel my membership. The planet seemed a safer place, but the visceral fear of nuclear weapons never left me and never will.

On that morning in May 2017, I was dipping into a treasure trove – the index of holdings in the archives of Churchill College, Cambridge. I was researching a book about DNA and had come to sift through the papers of Sir John Randall FRS, who may have thrown away the Nobel Prize for discovering the double helix because he engineered a conflict between Rosalind Franklin and Maurice Wilkins (who, with James Watson and Francis Crick, went on to win the Prize in 1962). If I'd stuck to my brief, you wouldn't be reading this. However, my gaze wandered past 'RANDALL' and was caught by 'TUBE ALLOYS'. These seemingly meaningless words rang a vague bell: something that Wilkins had done during the war? On impulse, I asked to see the material.

A heavy cardboard filing box arrived containing several bound volumes like old-fashioned desk diaries, their covers embossed in gilt capitals – 'MINUTES OF TUBE ALLOYS TECHNICAL COMMITTEE – TOP SECRET' – and each carrying a gummed paper label: *DECLASSIFIED 04/06/2007.* Leafing through the close-typed foolscap pages, I recognised a couple of Nobel Prize winners: James Chadwick, discoverer of the neutron, and John Cockcroft, who split the atom. The other names meant nothing to me. Mark Oliphant. A trio who sounded oddly German: Otto Frisch, Rudolf Peierls and Franz Simon. Two enigmatic chaps – Mr Akers and Mr Perrin – who apparently ran the show. The committee first met on 6 November 1941, at the 'Tube Alloys Directorate Office' in Old Queen Street, London SW. The minutes provided vivid snapshots of frantic activity, excitement, frustration and danger, against the backdrop of Britain at war. Tube Alloys had taken over from an earlier committee cryptically named 'M.A.U.D.', and its purpose was to build an atomic bomb. Five minutes in, the story had become a thriller and I was hooked. I put John Randall on hold and spent all day and the following morning trying and failing to work out where Tube Alloys fitted into the time-honoured saga of how America made the bombs that were dropped on Hiroshima and Nagasaki in August 1945.

The book about DNA stayed on my desk for another couple of years. In August 2019, I dug out my notes to see if Tube Alloys had lost its excitement. It hadn't. Soon after, I found myself listening to a gripping story from an intelligent, articulate man. Before the chance encounter in the Churchill College archives, I would never have talked to him because I'd despised what he did; while working at the Atomic Weapons Establishment in Aldermaston, he'd helped to perfect Britain's hydrogen bombs. He surprised me with occasional flashes of bitterness – which were triggered, I realised, by the same two words that had caught my eye in the archive index. Tube Alloys.

Why was the man from Aldermaston so bitter? Because, he said, everyone knows about the Manhattan Project but very few have even heard of M.A.U.D. or Tube Alloys. He believed that the Americans

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deliberately airbrushed British scientists and their contributions from accounts of 'the race to build the bomb', leaving the impression – still prevalent today – that the bomb was an all-American invention created from nothing in the USA. Then he told me that America alone couldn't have produced a workable nuclear weapon until after the war had ended; without those forgotten British scientists, the atomic devastation of Hiroshima or Nagasaki could never have happened.

Seeing my surprise, he showed me his own archive of books, articles and cuttings that he'd gathered over fifty years and challenged me to find out if he was right. We shook hands on it, and that's how this book came to be written.

1

SETTING THE SCENE

1595–1918

Where to begin? The story of how the atomic bomb was invented reaches its climax in the summer of 1945, but its roots go back much earlier. We could start with the discoveries of uranium, radioactivity, the neutron, nuclear fission or plutonium; or the births of James Chadwick, Otto Frisch, Rudi Peierls or Robert Oppenheimer; or the Nazification of science which hounded Jewish physicists out of Germany; or the establishment of the M.A.U.D. Committee in Britain or the Manhattan Project in America. In fact, the story opens in the Ore Mountains that today straddle the frontier between Germany and the Czech Republic – and, to begin at the beginning, we have to step back over 500 years to the silver rush which brought vast wealth to the Kingdom of Bohemia.

An Element of Little Importance

The pitch-black mineral discovered in 1595 near the silver-mining town of St Joachimsthal (Map 1) was a disappointment from the start. It was as heavy as the real thing but yielded no silver, so the miners gave it the derisory name *Pechblende* – from the German words for 'pitch' and 'deceiver' – and left it in the ground.[1] *Pechblende* became 'pitchblende' in English but was otherwise ignored for almost two centuries until, in 1789, Martin Heinrich Klaproth showed that pitchblende contained a new element which he named after the recently discovered planet Uranus.[2] It took another half-century to isolate uranium, which turned out to be a silvery grey metal, as heavy as gold and hard as steel. By then, massive deposits of uranium ore had been found in Canada, the Urals and the Congo, but its only commercial use was in colouring the vivid yellow and green 'uranium glass' which was a passing fad during the 1860s.[3] Scientists were similarly unexcited. Dimitri Mendeleyev, the wild-haired Russian architect of the periodic table of the elements, initially gave uranium an atomic weight of 116, less than half the correct value.[4]

The first hint that uranium possessed properties which set it apart from other elements came in 1857, when the French photography pioneer Claude Niepce de Saint-Victor reported that uranium salts poured out invisible rays which exposed a photographic plate. Niepce missed the full significance of his observations, and his work was actively suppressed by a jealous rival and former collaborator. Nonetheless, the 'uranic rays' went on to win a Nobel Prize, albeit for someone else and thirty years after Niepce's death. The lucky recipient of the prize – for Physics, in 1903 – was Henri Becquerel, honoured for having discovered his 'rays of genius'. Becquerel never acknowledged Niepce's prior discovery, even though he must have known all about it: he was the son of Edmond Becquerel, President of the all-powerful Academy of Science in Paris and the collaborator turned jealous rival who had pushed Niepce into oblivion. Niepce died bitter about 'certain people' (Becquerel père) who had robbed him of his reputation, but he wasn't totally forgotten; forty years later, Henri Becquerel's son ranted about the 'bastards' who had resurrected Niepce's claim to the discovery of radioactivity.[5]

Becquerel's uranic rays were feeble – they took days to burn a decent image on a photographic plate – and quickly lost their magic after his flurry of papers in spring 1896. They were eclipsed initially by X-rays, the all-seeing invisible radiation which Konrad Roentgen in Würzburg had discovered a few months earlier. X-rays thrilled everyone, scientific or not; Roentgen's name was effectively stamped on the first Nobel Prize in Physics (as yet unborn) when he passed his hand in front of his X-ray tube and the bones inside his fingers appeared on the detector screen. Becquerel's radiation was just a ten-paper sideshow beside the thousands of articles and numerous books devoted to the miraculous X-rays, which peered inside the living body, cured skin cancer and even drove sales of lead-lined knickers to protect ladies' modesty from the 'naughty Roentgen rays'.[6] Before long, Becquerel himself lost interest. His uranic rays could well have been forgotten – just like Niepce's – but for an extraordinary stroke of luck which assured his place in history.

Becquerel's saviour was a thirty-year-old Polish woman, already displaying academic brilliance and her 'will of iron and maniacal taste for perfection' – and who would later become legendary for weathering personal tragedy ('the saddest eyes I have ever seen,' according to an American benefactress) and for wearing the same simple black dress to accept both her Nobel Prizes. Marya Skłodowska grew up in the Old Quarter of Warsaw under Russian oppression. She watched the Russians sack her father, a physics teacher, and sat through the night with a schoolfriend whose brother was to be hanged at dawn; it was no wonder that she always spat on the monument to the tsar and danced for joy when he was assassinated. Marya excelled at school but Warsaw University only admitted men, so she educated herself from textbooks in Polish, French and German and risked imprisonment by attending the 'Floating University', a fugitive night school banned by the Russians. Aged twenty-four, she bought a fourth-class train ticket to Paris and registered at the Sorbonne as Marie Skłodowska to study physics and mathematics. Paris embodied both heaven and hell: heaven, soaking up knowledge at the feet of France's greatest scientists and in the library until it closed at 10 p.m.; then home to hell, a tiny attic cubicle where water froze in the jug beside her bed.[7]

She came top of the class and was introduced to a tall and eccentric 'scientist of genius' named Pierre Curie. They hit it off immediately, and she began working in his lab on her first research project. In 1895, they took a few days away from the lab bench to get married; their first daughter was born in 1897.[8] Next came a doctorate, the first in France for a woman. Marie Curie chose a high-risk topic – the 'astonishing uranic rays', now abandoned by Becquerel and everyone else. She worked in a derelict storeroom that 'sweated with damp', and scrounged samples of uranium compounds from colleagues and mineral collectors. Pierre built her an exquisitely sensitive instrument which measured the strength of radiation by its ability to make air conduct electricity. With the 'Curie electrometer', Marie quickly proved that the intensity of the radiation emitted by a sample was proportional to its uranium content, confirming that the rays came from the uranium atom itself. Next, she found that thorium was the only other of the eighty known elements to emit radiation. Her tour de force was to show that some pitchblende samples poured out far more radiation than their uranium content would have predicted, and to deduce that these must contain an even more powerful source of radiation. It wasn't thorium, the only other known candidate, and so must be a new element.

Pierre now dropped his own research and became his wife's full-time scientific collaborator. To cut short a long story (hundreds of tons of pitchblende delivered by lorry from St Joachimsthal, thousands of litres of concentrated acid and four years of 'the most desperate and arid effort'), the Curies eventually isolated tiny samples of two new active elements, both present at less than one part in 1,000,000,000 of pitchblende. They named them 'polonium' ('after the country of origin of one of us') and 'radium', which blasted out 'enormous radiation' that lit up solutions of its salts with a beautiful pale blue glow. And Marie invented a new word: '*radioactivité*', short for *activité radiante*, which rolled beautifully off the tongue in French and was immediately snapped up by other languages.[9]

Radium made the Curies world famous, not only for their brilliance, dedication and hard work, but also for their oddness and naivety. Marie was regarded with both admiration and suspicion as 'the rarest of animals: a woman physicist'. With radium trading at fifty times the price of gold, they could have been millionaires; instead, they handed all their intellectual property to industrialists, who gave them nothing in return.[10] And while radium cursed Marie and Pierre with the misery of unwanted celebrity, it was remarkably kind to Henri Becquerel. The 1903 Nobel Prize in Physics was shared between him (50 per cent) for discovering radioactivity, and the Curies (25 per cent each) for their research into Becquerel's 'radiation phenomena'. Marie wouldn't have figured at all if Pierre hadn't made a fuss after discovering that the Academy of Science in Paris had only nominated Becquerel and himself.[11] The Curies didn't attend the prize ceremony in Stockholm. They stayed in Paris to honour 'commitments' including the heavy teaching burdens which paid their bills; their Nobel awards were accepted on their behalf by a French minister.[12]

Radium, the spinoff product of uranium research whose existence Becquerel had never even suspected, now pushed uranium into the shade. Everything about radium had charisma: the brilliance, self-sacrifice and modesty of its discoverers, and its own power and potential to transform the future. Radium rays were millions of times stronger than those from uranium, so intense that you could scribble a message on a photographic plate with a radium-tipped stylus. The radiation also created ozone from oxygen and turned diamonds green, while *Curiethérapie* (radium therapy) made skin cancers and even internal tumours shrivel away.[13]

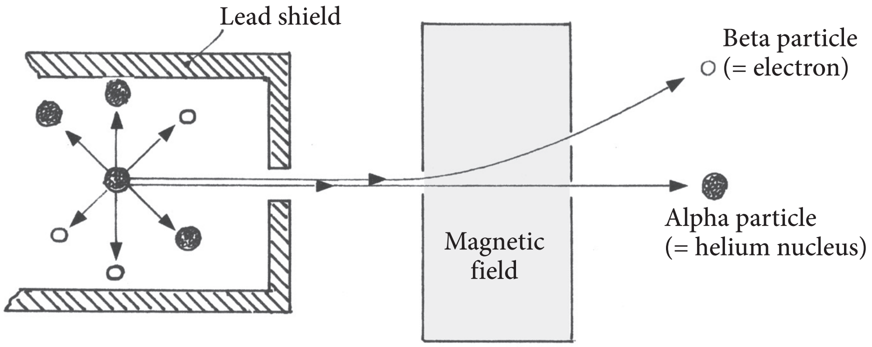
The Curies' new element also turned the spotlight on one of the impenetrable black boxes of physics – the inner working of the atom. Radium ignited a chain reaction of research that threw up cutting-edge questions: the nature of radioactivity and how it was generated; whether uranium, radium and other radioactive elements might be related; and what atoms looked like inside.

And the notion that vast, potentially explosive amounts of energy were somehow locked away inside the atom, waiting to be liberated.

Alpha Male

Henri Becquerel had started to unravel the 'very complicated phenomenon' of radioactivity by firing a narrow beam of radium rays across a photographic plate straddled by a powerful magnet. Switching on the magnet split the beam into two components: one continued straight ahead, while the other was pulled sideways. Becquerel deduced that both components consisted of tiny particles, but with contrasting properties. The ones deflected by the magnetic field were negatively charged, virtually weightless and travelled almost as fast as light, while their undeflected companions were much slower and heavier (Figure 1). He also dissected the radiation from the other radioactive elements. Like radium, thorium sprayed out both types. Uranium emitted only the lightweight, negatively charged particles, and polonium only the heavy, slower ones.[14]

The two particles were fleshed out by Ernest Rutherford, the new Professor of Physics at McGill University in Montreal. Growing up in New Zealand, Rutherford displayed 'unusual powers of concentration' and narrowly survived a swimming accident that killed his two brothers. He won a scholarship to Trinity College, Cambridge, becoming J.J. Thomson's first research student at the famed Cavendish Laboratory. On arrival at McGill, he was twenty-eight years old, tall, blue-eyed, confident and with 'volcanic energy and an immense capacity for work'.[15] He showed that the slow, heavy radiation particles – which he called 'alpha' – travelled at one-tenth of the speed of light and weighed as much as an atom of the second element, helium (atomic weight 4). Alpha-particles were positively charged, but so massive that they were only deflected by an extremely powerful magnetic field; they could be stopped dead by thin aluminium foil or 4 inches of air. Rutherford named the speed-of-light, negatively charged particles 'beta'. These turned out to be electrons, whose discovery J.J. Thomson had recently reported to the Royal Institution in London. Weighing only 1/8,000th of an alpha-particle, beta-particles were high-velocity bullets that could slice through an aluminium block.[16]



1. Components of ionising radiation: alpha- and beta-particles.

The alpha-particles, as heavy as helium, led Rutherford to make an extraordinary leap in lateral thinking. While investigating a transient radioactivity that sometimes wrecked experiments on radium, he found the culprit to be a dense, intensely radioactive gas that could be boiled off solutions of radium salts and dispersed by a puff of air. This 'emanation' (later renamed 'radon') was released slowly and steadily by radium; it blasted out alpha-particles even more powerfully than its parent and accounted for most of the radioactivity attributed to radium. Its atomic weight turned out to be 222, four less than its parent element radium. Noting that this difference was exactly the weight of an alpha-particle, Rutherford suggested that radium generated an atom of emanation whenever it fired off an alpha-particle.[17] This made him wonder whether uranium might similarly break down into other radioactive products. At this point, Rutherford hired a chemist – a wise decision, as his own knowledge of the subject was notoriously sketchy. Frederick Soddy, twenty-three years old and with a First in Chemistry from Oxford and an 'outstandingly strong personality', joined him in 1900 to begin the four-year crusade to map out the process that they called 'radioactive decay'.[18]

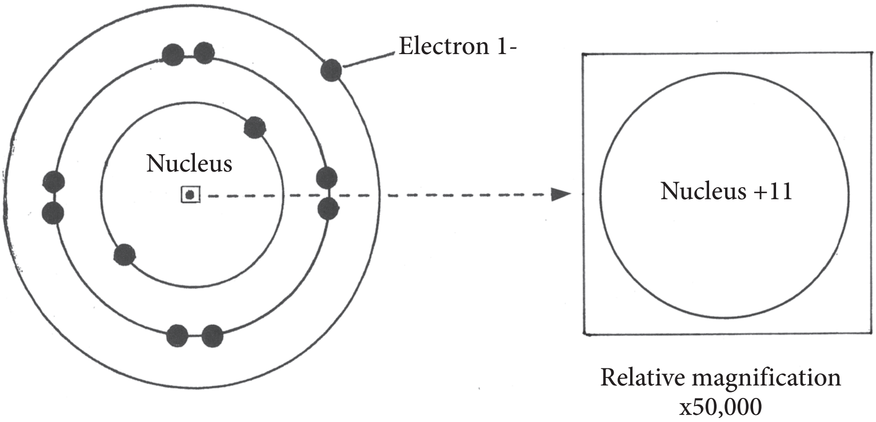
The emanation, the offspring of radium, turned out to be the parent of a new radioactive element (which they called 'Radium A', atomic weight 218), created by emitting an alpha-particle. Radium A wasn't the end of the road, as it popped out an alpha-particle and a beta-particle to yield another new element ('Radium B'). And so it went on. Soddy and Rutherford showed that the cascade of radioactive decay began with uranium (with its top atomic weight of 238) and ended with lead, which is non-radioactive because its ancestors have spat out every radioactive particle at their disposal. The process involved begetting on a biblical scale: radium was the great-great-great-grandchild of uranium, and there were another nine generations after that. Some barely existed, whereas others hung around for ever. As they were all created continually, a sample of pitchblende was a snapshot of a never-ending family party that embraced fourteen generations.[19]

Alpha-particles were also responsible for Rutherford's next coup, after moving from McGill to Manchester University. As a student, he'd been taught that the atom was solid like a billiard ball – 'a nice hard fellow, red or grey in colour, according to taste' – but one afternoon in April 1911 found him standing in the doorway of his lab, looking smug and telling everyone that he knew what the atom really looked like. He had reanalysed experiments done by two students, Hans Geiger and Ernest Marsden, who had shot alpha-particles at gold foil. Most passed straight through as if the foil contained more holes than gold – but about one in 100,000 bounced back. As alpha-particles are high-energy projectiles, Rutherford found these ricochets 'astonishing . . . as if someone had fired a 15-inch shell at a piece of tissue paper and it had come back and hit him.'[20]

Rutherford envisaged the nucleus as unbelievably tiny but carrying essentially all its mass and a number of positive charges; the rest of the atom was a relatively vast emptiness through which whirled the correct number of negatively charged electrons to balance the positive charges in the nucleus. This structure explained why alpha-particles fired at gold foil collided so rarely against something with enough mass and positive charge to sling them back in their tracks. And the billiard ball had shrunk in the wash. Rutherford calculated that the nucleus was 1/100,000th of the diameter of the atom, equivalent to a real billiard ball centred on a circle of green baize twice the size of the Wembley Stadium. Rutherford's revolutionary structure of the atom was published in May 1911.[21] The model has subsequently been tweaked but Rutherford's basic vision has stood the test of time (Figure 2). Like gold foil, everything consists of over 99.9999 per cent nothingness.

Same Outside, Different Inside

In 1904, Frederick Soddy moved to the University of Glasgow and continued to work on radioactive decay. He became famous for his public lectures and jaw-dropping demonstrations on radioactivity. His star turn was to puff the radium emanation over pieces of willemite, a zinc mineral that blazes with jade-green fluorescence when bombarded by alpha-particles. 'One of the most beautiful sights I know,' Soddy told the entranced crowd, as the darkened auditorium filled with the magical glow.[22]



2. The atom, as envisaged by Ernest Rutherford and modified by Niels Bohr.

In 1910, Soddy made a far-reaching discovery that even Rutherford had missed. It had been assumed that each element had sole occupancy of its cell in the periodic table, but Soddy realised that some cells had to accommodate squatters which were chemically identical but had different atomic weights and radioactive signatures. For example, 'mesothorium-1' (atomic weight 228) was chemically indistinguishable from radium (atomic weight 226); the two could stand in for each other in chemical reactions. Soddy summed it up neatly – 'the same on the outside, different inside' – and proposed a snappy new name for chemically identical variants with different atomic weights: 'isotopes', from the Greek meaning 'same place' (the term was actually coined at a dinner party by a friend of Soddy's wife).[23]

The idea was heresy, but Soddy trampled over criticism and laid out the evidence. Many cells in the periodic table were overcrowded: for example, thorium (atomic weight 232) shared its chemistry with four others whose atomic weights ranged from 227 to 234. Soddy pointed out that the squatters' existence would never have been suspected if they hadn't been radioactive, and suggested that non-radioactive elements also had isotopes. Proof soon followed from precise measurements of atomic weight in 'ordinary' lead (207) and 'radio-lead', associated with pitchblende and derived from the decay of uranium (206). Furthermore, ordinary air contained minute amounts of neon with an atomic weight of 22, two more than 'ordinary' neon.[24]

For now, though, there was no hint of isotopes at the beginning or end of the periodic table. Hydrogen (atomic number 1, atomic weight 1) and uranium (atomic number 92, atomic weight 238) each appeared to be alone in its cell.

The year 1913 ended with an accolade for Frederick Soddy that would be noted around the globe. A much-anticipated book, soon to be published, was dedicated to him because it 'owed long passages' to *The Interpretation of Radium*, the anthology of Soddy's public lectures in Glasgow.[25] The author was H.G. Wells, zoology graduate and world-famous father of science fiction. Wells's bestsellers such as *The Time Machine*, *The Invisible Man* and *The War of the Worlds* were all rattling good yarns that implanted futuristic science into Edwardian drawing rooms. His new book was classic Wells: a clairvoyant, credible nightmare.

Wells's imagination had been seized by Soddy's account of how radium had revealed the huge amount of energy stored in the atom. Pierre Curie first observed that radium samples were always warm, and calculated that the element generated enough heat to turn its own weight of ice into steam in just forty-five minutes. On a grander scale, unexpected hot spots along the Simplon Tunnel under the Alps were related to radium-rich rock strata. But how could radium pour out radiation and heat year after year – 'like Aladdin's lamp', Soddy said – when an unbreakable law of physics states that energy cannot be created from nothing? Uranium contained even more energy than radium: Soddy's lecture demonstration jar contained just 1 lb of uranium oxide, but the same energy as 160 tons of coal. Harnessing that energy, if ever achievable, could 'transform a desert continent, thaw the frozen poles and make the whole world one smiling Garden of Eden' – or even enable mankind to 'explore the outer reaches of space and emigrate to more favourable worlds'.[26]

In *The World Set Free*, Wells envisaged civilisation transformed by cheap and unlimited energy from radioactivity – but with a twist that Soddy hadn't predicted. First, humanity had to be purified by fire, also the product of radioactivity. Wells invented a new term for the horrific weapon which engulfed Paris and Berlin in manmade infernos. He called it the atomic bomb.[27]