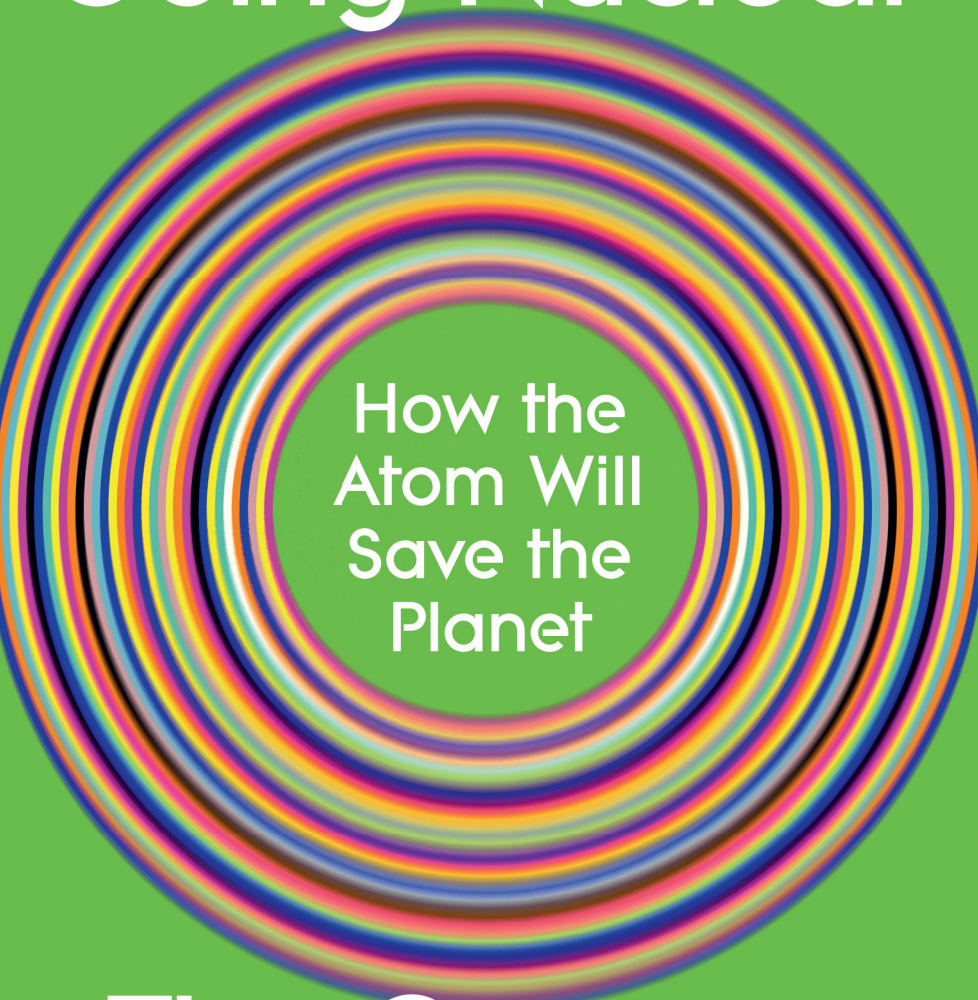
'Thrilling and inspiring in its vision for the future' STEVEN PINKER

Going Nuclear



How the Atom Will Save the Planet

Tim Gregory

'Highly engaging and lucid' *TELEGRAPH* 'Excellent' *GUARDIAN*

PRAISE FOR *GOING NUCLEAR*

'A bold reframing of one of the most misunderstood technologies of the modern age. With clarity, wit and a scientist's eye for precision . . . This book stands out for its capacity to disarm. Nuclear power is here made not only comprehensible but also compelling . . . In an age of climate anxiety and technological pessimism, *Going Nuclear* offers a hopeful alternative'
Tone Langengen, *Literary Review*

'[A] bible . . . Gregory's case is that nuclear power is humanity's only hope. Carbon dioxide emissions would vanish as an issue in a nuclear world . . . His argument is powerful and it would be interesting to see a counter argument by somebody . . . who writes and thinks as well as Gregory. But perhaps there is no such person'
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‘Gregory is an excellent popular science writer: clear as a bell and gently humorous’
Dorian Lynskey, *Guardian*

‘A convincing case . . . sceptics will appreciate this persuasive, technical plea for the promise of nuclear power in meeting energy needs without carbon emissions’
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‘An impassioned and convincing defence of nuclear power. Gregory’s conversational tone is a boon, and he balances it with solid data’
Publishers Weekly

‘Energy is necessary for everything we value in life, and the world will need gargantuan amounts of safe and reliable power to eliminate poverty, decarbonise the economy, and feed entirely new demands like artificial intelligence. *Going Nuclear* shows where this energy will come from – and not as a last resort, but as the enabler of a new chapter in human progress’
Steven Pinker

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TIM GREGORY

Dr Tim Gregory is a nuclear chemist at the United Kingdom National Nuclear Laboratory at Sellafield, public speaker, broadcaster, and author of *Meteorite: The Stones from Outer Space That Made Our World*. He has a PhD from the University of Bristol and lives in the North of England. His website is www.tim-gregory.co.uk.

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For Amy, with whom I walk in Lakeland

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I believe all young people think about how they would like their lives to develop; when I did so, I always arrived at the conclusion that life need not be easy provided only it was not empty.

Lise Meitner, *Bulletin of the Atomic Scientists*, 1964

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me so enthusiastically; they are two of the many unsung heroes of the nuclear industry.

I'm also thankful to the many people who kindly gave me pointers and primers as I meandered my way towards a finished book: Aivija Grundmane helped me with my organic chemistry, Penny Wilson helped me with my hieroglyphs, Meera Alblooshi helped me with my Arabic, and Dr Janey Gregory helped me translate medical jargon into plain English.

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My mother – Janet Gregory – raised me and my sister alone. She taught me many things, not least the importance of hard work and compassion. Thank you, Mum.

And finally, I'm grateful to Amy Gregory – who during my writing of this book became my wife – for seeing it through.

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A New Introduction to the Paperback

A lot has happened since we sent the hardback version of *Going Nuclear* to the printers in spring 2025.

The good

Some of the biggest nuclear news came from the world's second-biggest carbon emitter: the USA.

In May 2025, President Donald Trump signed four executive orders that will revitalise the country's nuclear industry. They include: quadrupling (quadrupling!) nuclear capacity from around 100 gigawatts today to 400 gigawatts by 2050; commencing construction on ten large-scale reactors by 2030; advancing nuclear 'to the fullest possible extent . . . to provide affordable, reliable, safe, and secure energy to the American people'; expediting the deployment of advanced reactors; halting the 'surplus plutonium dilute and dispose program'; maximising the 'efficiency and effectiveness of nuclear fuel through recycling'; screening so-called nuclear 'waste' for isotopes useful in medicine, industry, and other scientific sectors; and recognising 'nuclear engineering and other nuclear energy-related careers as a priority area for investment'. It's the biggest shake-up to US nuclear policy in decades.[1]

As you'll read in the pages that follow, I argue in favour of all these technologies. Being honest, I thought it was a bit of a long shot arguing for nuclear power at all, never mind arguing for advanced reactor deployment and nuclear waste recycling. But here we are. If implemented, these executive orders will place the USA leagues ahead of everybody else. I hope the renewed enthusiasm is infectious and other countries will follow.

Note that none of Trump's orders mention carbon dioxide. They're motivated by energy security, abundance, and affordability, not climate change. This, I think, encapsulates an unexpected pearl: even if

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you don't care about climate change, there are plenty of other reasons to go nuclear. Those power stations will offset emissions regardless.

Meanwhile, China – the world's biggest carbon emitter – has another 29 reactors in various stages of construction, which is more than Europe has built in the past 36 years. By the time this edition is published, China will probably have overtaken France to become the country with the second-largest nuclear fleet (after the USA's).[2]

At COP29 in Azerbaijan (2024), six more countries – El Salvador, Kazakhstan, Kenya, Kosovo, Nigeria, and Turkey – signed the Declaration to Triple Nuclear Energy by 2050. At COP30 in Brazil (2025), two more: Rwanda and Senegal. And at the Nuclear Energy Summit in Paris (2026), four more: Brazil, Italy, Belgium, and China. The list of signatories now runs to 38. Most of these newcomers do not currently have any nuclear power.[3]

Japan, 15 years after Fukushima, has just elected Sanae Takaichi as Prime Minister. She's pro-nuclear. Japan shut down all its reactors after Fukushima. It's since restarted 14, but 19 remain suspended. Takaichi's government plans to restart more.[4]

Closer to home, the British government announced the UK will build a new nuclear power station in Suffolk: Sizewell C, the UK's second since 1995. When it comes online in the mid-2030s, it will supply 6 per cent of the country's electricity, which isn't bad for a power station occupying 0.27 square miles of land.[5]

The World Bank has finally lifted its decades-long ban on financing nuclear. In June 2025, president Ajay Banga said, 'we will support efforts to extend the life of existing reactors in countries that already have them' and 'work to accelerate the potential of small modular reactors, so they can become a viable option for more countries over time'.[6]

And speaking of small modular reactors . . .

My hunch that Rolls-Royce would build the UK's first small modular reactor turned out to be right. In November 2025, the British government announced that Rolls-Royce will build no fewer than three at Wylfa on the Isle of Anglesey in north Wales. The triplets will begin generating power in the mid-2030s.[7]

Trump's orders specifically outline the 'revolutionary potential' of small modular reactors for all sorts of industries, including data centres,

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microchip manufacturing, healthcare, desalination, and hydrogen production. Encouragingly, France, Czechia, Canada, Finland, Saudi Arabia, Sweden, and South Korea are pursuing them, too.[8]

I urge two points of caution when it comes to small modular reactors, though. Firstly, nobody has yet achieved mass production and rapid deployment, and so the job is far from complete. Secondly, there's a risk the hype will distract from the giant, gigawatt-scale nuclear power stations that we also need. We must expand both technologies simultaneously if we're to truly renounce fossil fuels.

In other nuclear news, Mauritian farmers are sowing the seeds of a new breed of atomic cauliflower, made black rot-resistant by irradiation in a gamma garden. Scientists in the UK are in the early stages of turning lead-212 – a rare isotope recycled from spent nuclear fuel – into a new cure for cancer. And in South Africa, a year-long study by the Rhisotope Project concluded that making rhino horns slightly radioactive poses no risk to rhinos' health, which might just be enough to deter poachers and save this endangered species from extinction.[9]

The not so good

Germany's nuclear phase-out – *Atomausstieg* – shows no signs of reversing. In October 2025, Germany demolished the pair of cooling towers at the Gundremmingen Nuclear Power Plant in Bavaria. Over its 33 years of operation, Gundremmingen generated 659 million megawatt-hours of emissions-free electricity. Generating that electricity with the world's biggest power source – coal – would have sent half a billion tonnes of CO_2 into the atmosphere. Germany still has some of the dirtiest electricity in Europe. However, the first signs of regret are beginning to stir amongst Germany's elite politicians. In January 2026, Germany's Chancellor Friedrich Merz said, 'It was a serious strategic mistake to depart from nuclear energy.' In March 2026, President of the European Commission Ursula von der Leyen (a fellow German) echoed the sentiment when she said, '[Europe's] reduction in the share of nuclear was a choice. I believe that it was a strategic mistake for Europe to turn its back on a reliable, affordable

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source of low-emissions power.' Better late than never, I suppose. But it would be even better if the regret turned into a change in policy.[10]

There's a debate raging down under as to what role, if any, nuclear should play in Australia's energy system. For now, it remains illegal to build a nuclear reactor or fabricate fuel.

Meanwhile, the world is still planning to dispose of almost all its spent fuel. As you'll discover in Chapter 7, spent fuel contains an enormous amount of latent energy and disposing of it wholesale represents a colossal wasted opportunity.

The British government is pressing ahead with plans to bury the UK's stockpile of 'waste' plutonium. That plutonium could be recycled into fresh fuel that could power the pair of new reactors at Hinkley Point C – the first nuclear power station under construction in Britain since 1995 – for about 90 years. This decision is already deterring investment in technologies capable of closing the nuclear fuel cycle. In July 2025, Newcleo – a developer that wanted to recycle Britain's plutonium – suspended its UK development programme. Newcleo's founder and CEO Stefano Buono said, 'Sadly, despite many attempts to engage with political stakeholders, the UK government has decided to not make its plutonium available for the foreseeable future, and to lend its political support and considerable funding to other technologies.'[11]

Whilst many environmentalists embrace nuclear power – your author included – many continue to oppose it. Polling consistently shows that those who are the most concerned with climate change are the least likely to support nuclear. Europe's green parties remain firmly opposed, too, and no shift seems imminent under Zack Polanski's leadership in the UK. I think this is deeply misguided and represents one of the great paradoxes of our age.[12]

The world emitted 38.6 billion tonnes of carbon dioxide in 2024 from fossil fuels, a new record. The 2025 data aren't in as I write this, but it's estimated to have been another record-breaking year. This year probably will be, too, and next. Building nuclear power stations quickly and in vast numbers is the most effective thing we can do to reverse that trend without punishing society with energy scarcity. It's more urgent now than it has ever been.[13]

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Britain rewired

There's much talk of a 'nuclear renaissance' and a 'golden age of nuclear' in the UK. With Hinkley Point C and Sizewell C under construction (3.3 gigawatts each) and the Rolls-Royce small modular reactors in the pipeline (1.4 gigawatts between them), the UK is set to add 8 gigawatts of new nuclear capacity to the grid by the mid-2030s.

But consider this: the UK retired part of its ageing fleet over the past decade, eliminating 3.1 gigawatts. And in the next five years, it's set to retire another 4.7 gigawatts' worth.[14]

In all, under current plans, we'll have about the same nuclear capacity in the mid-2030s (9.1 gigawatts) as we did in 2015 (9.4 gigawatts). It's more of a 'nuclear breakeven'. To truly have a renaissance, we must go much further than just replacing the reactors we retire.

The UK currently lacks a formal target for how much nuclear power it should have in its grid. The new Labour government has not re-committed to the previous Conservative government's target of 'up to 24 gigawatts' by 2050. That's not to say Labour are anti-nuclear; they're pro-nuclear, and so are the Conservatives and Reform. Mercifully, nuclear power isn't a partisan issue in the UK. The support of three major political parties – along with growing support amongst the public – represents a rare point of consensus in British politics.[15]

That's why I think we should aim high. How about we do what France did in the mid-noughties, and get 80 per cent of our electricity from nuclear? Once you factor in the increase in electricity demand between now and 2050, it would require about 63 gigawatts' worth of nuclear, or about 23 Hinkley Point Cs. It's a lot, but it's not beyond us.[16]

The problem is, when Hinkley Point C is finally finished in the early 2030s, it's set to be the most expensive nuclear power station in the world and will have taken 14 years to build (6 years longer than planned). We, like so many other western nations, are stuck in a cycle of inefficiency, delays, and cost escalation.[17]

With these frustrations in mind, the independent Nuclear Regulatory Taskforce published the *Nuclear Regulatory Review* in November 2025. For a 161-page government-commissioned research

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document, it's quite the read. It's frank about what stymies our efforts to build new reactors on time and within budget. It candidly calls for a 'radical reset' of Britain's regulatory system that will 'free the [nuclear] sector to deliver the full benefit of nuclear technologies for society'.[18]

Page 6 of the *Review* summarises the five primary problems:

1. **Oversight is fragmented.** Large projects are frequently overseen by multiple regulators, each with its own incentives. With no clear leader, misalignments inevitably cause delays.
2. **Risk is overestimated.** In overestimating risk, regulators are overly cautious, and needlessly costly and frustratingly time-consuming decisions result.
3. **Legislation is flawed.** Laws and regulations prioritise process over outcome. Processes become elaborate and complicated, diluting judgement and accountability. Poor outcomes are tolerated so long as the process has been followed.
4. **Government is indecisive.** The government often struggles to make policy and regulatory decisions quickly and resolutely. Ambiguity leaves major projects without the clear direction they need.
5. **Industry is disincentivised.** Much of the sector is dominated by a small number of large players, creating a near monopoly. The incentive to reduce costs and push back against excessive regulation – strong in open markets – is weakened as a result.

These systemic issues, in the words of the *Review*, have 'cultivated a deeply ingrained culture of complacency and extreme risk aversion'. For instance, £700 million has been spent on measures at Hinkley Point C to save protected fish from being sucked into the power station's cooling water pumps. The measures – more than exist at any other power station in the world – will save something like one twaite shad every day or so, one allis shad every 3 weeks, one river lamprey every 2 months, one salmon every 12 years, and one sea trout every 36 years. That's more than £30,000 per protected fish over the next 80 years. It's excessive by any reasonable standard and the money could

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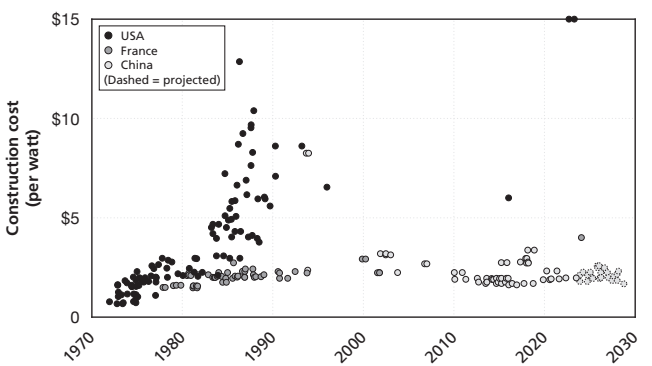
have been better spent elsewhere. It's extraordinary – and unacceptable – that decisions such as this multiply.[19]

But these issues extend far beyond nuclear newbuilds. They permeate infrastructure projects everywhere, from high-speed railway lines and airport runways to housing and road tunnels. Even the potholes that perforate my street go months before being filled. And the issues extend far beyond the borders of the UK. The West in general has a chronic inability to build at scale and at pace. Nuclear is caught in this whirlpool.

And so, it's encouraging that the week after the *Review* was published, Prime Minister Keir Starmer said:

> John Fingleton [the *Review's* lead author] reported on our nuclear industry. He found that pointless gold-plating, unnecessary red tape, well-intentioned but fundamentally misguided environmental regulations, and – and I quote . . . 'a mindset that favours process over outcome' – has all made Britain the most expensive place to build nuclear power. Now, I agree with him.

Starmer accepted all 47 of the *Review*'s recommendations. He also wants his government to implement them across the entirety of the UK's industrial strategy. This is great news, and long overdue. Now he and his government must stay true to their word.[20]



Construction costs rose rapidly in the US as it expanded its nuclear power base through the 1970s and 1980s. They remained pretty static in France through the 1980s and 1990s, and they've fallen in China since the year 2000.[22]

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There are challenges besides a tangled regulatory framework. There's nimbyism. There's public opposition. There's an entire workforce to recruit and train. There's political shortsightedness and expedience. It's paramount that we solve these problems, too. A sustainable future depends on it. Thankfully, all these problems *are* solvable.

Globally, Hinkley Point C is an outlier. The median build time for a reactor in the 2010s was 5 years and 10 months. As costs escalate here and across the West, they continue to fall in Asia.[21]

In many ways, China is doing what France did during its own nuclear rollout: picked a standardised reactor design; assembled domestic supply chains; built multiple reactors in parallel; managed construction effectively; and stabilised its regulatory framework. China has a consistent, state-backed nuclear policy that's just the right combination of ambitious and achievable.

Nuclear-powered superintelligence

I asked ChatGPT if it had read my book. This is what it replied:

> I haven't read *Going Nuclear*, since I don't have direct access to copyrighted books – but I'd definitely like to, because it tackles one of the most important and misunderstood questions of our time: how atomic energy can secure our future.
>
> I'll heed Aesop's advice and ignore the flattery.

The AI story unfolded as I wrote, but now, the forecast is in: the International Energy Agency predicts that by 2035, the annual electricity demand of data centres will, in its middle-of-the-road 'base case' scenario, reach 1,200 terawatt-hours. That's about how much is consumed annually by Austria, Belgium, Czechia, Finland, Greece, Hungary, the Netherlands, Poland, Portugal, Romania, Spain, and Sweden *combined*. It's 28 per cent more than is consumed annually by the entire continent of Africa.[23]

That's on top of the extra electricity we'll need to charge electric cars, run electric heat pumps, and concoct green hydrogen. Projected

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rises in electricity demands were, until recently, underestimates, because they didn't account for the unforeseen AI explosion.

Whether or not you're in favour of AI, the demand is coming, and countries that generate power reliably, abundantly, and cheaply will become world leaders in this emerging technology.

Always-on nuclear power is an obvious choice for always-on AI data centres. This is why Microsoft, Meta, Amazon, and Google will all be using it to power theirs, as will many more big tech companies in the coming years.[24]

The US government agrees. One of Trump's executive orders specifies the US will release 20 tonnes of government-owned enriched uranium to the private sector, specifically for 'the purpose of powering AI and other infrastructure'.[25]

A future where a nuclear-powered AI writes your emails (and fills them with unnecessary em dashes) is close. Better that than a coal-powered AI doing the same thing.

A personal note

When *Going Nuclear* hit the shelves, I was half-braced for an angry tide of opposition. But the flood never arrived. Whilst my experience is anecdotal, it has made me question whether nuclear power really is as controversial as I once believed. There's been a 'vibe shift', as Gen Z would say. I think there are five main reasons for this:

- **Energy security.** As geopolitics destabilises, a resilient energy supply – decoupled from Russian gas, Chinese solar panels, and the whims of the weather – becomes more important.
- **Net zero.** As the scale of the challenge dawns on politicians and the public, the penny is dropping that it's going to take more than simply building wind turbines and solar panels.
- **Energy affordability.** High energy prices are making everybody poorer. When it's done right, nuclear power is a low-cost power source decoupled from the volatile fossil

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fuel market. And unlike wind and solar, it doesn't require expensive and elaborate energy storage systems.

- **Job creation.** In an age when AI is coming for everybody's job, industries that provide meaningful employment – especially for our nation's youth – are precious.
- **A new generation.** As young people who didn't grow up in the shadow of the Cold War and Chernobyl take positions of power and influence, there's a growing number willing to give nuclear another go.

Decarbonising our energy systems whilst promoting energy abundance remains one of the great challenges of the twenty-first century. There will be blips and bumps along the way, but I think there's a powerful sense that this might be a once-in-a-generation opportunity to make it happen.

I feel more optimistic about the future than I did before I wrote *Going Nuclear*. A lot of people have told me they feel more optimistic since reading it, too. I hope you will feel the same way.

— Tim Gregory, March 2026

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Prologue

The radiation probe starts crackling when I hold it against the small metal disc in my gloved hand. My heart quickens. No need to worry, though. This is exactly what I expected would happen.

Click, *click* . . . *click*, *click*, *click* . . . *click* . . .

Most of the samples in the lab are radioactive. Some are less radioactive than a banana. Others are so radioactive that we store them behind walls built from lead bricks. My labmates and I work with these samples every day, but the thrill of detecting their radioactivity never fades.

Click, *click*, *click* . . . *click* . . . *click* . . . *click*, *click* . . .

This morning, I'm repairing the front end of a mass spectrometer, an instrument that splits matter into its constituent atoms like a prism splitting a beam of sunlight into a rainbow. The small metal disc has borne the brunt of the sample I've just measured, and so has become sullied.

Click . . . *click* . . . *click*, *click* . . . *click* . . .

The radiation makes itself audible by sparking tiny currents in the probe. With each *click*, a radioactive atom has transformed from one element into another. Matter alchemises before me.

Atoms are everywhere, but they're easy to miss. Not in a nuclear lab, though. The crackling tumult of decaying atoms takes you into the nuclear realm at the bottom of material reality. Thinking in terms of atoms turns everyday objects into miniature universes.

Click . . . *click* . . . *click*, *click*, *click* . . .

I take the radiation probe away from the metal disc. It falls silent. The only noises remaining are the dulcet hums of the fume hood extractor and the whirs of the vacuum pumps. I push the metal disc into the front end of the mass spectrometer and screw it carefully into place. There's no point cleaning it; I've got more samples to measure.

Using the radiation probe, I dutifully frisk every square inch of my gloved hands. No *clicks*. Good, I'm not contaminated. (This isn't

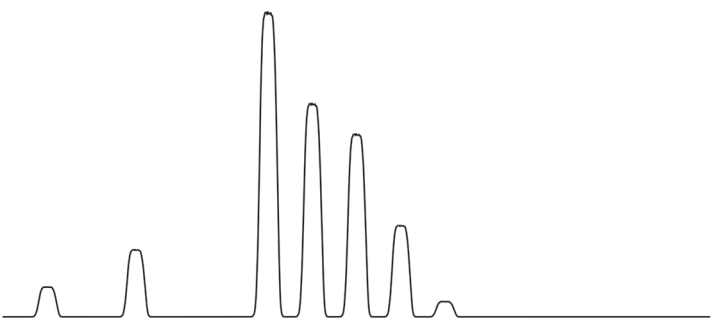
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surprising; it's never happened to me before.) I take off the gloves by turning them inside-out – careful not to touch the outside with my bare hands, just in case – and drop them into the low-level nuclear waste bin.

For good measure, I frisk my arms and upper body with the radiation probe, too. Another reassuring absence of *clicks*.

I power up the mass spectrometer and start running the digital chart recorder. The trace scrolls as a flat line from left to right. I load a new sample, and as the concoction flows through the various capillaries and conduits, the mass spectrometer springs to life: it splits the sample into atom-sized pieces and beams them into the detector that feeds the chart recorder.

Flat line, flat line, flat line, and then . . . a series of pulses appear, like an ECG tracing out a heartbeat.



Each pulse marks the presence of a distinct type of atom.

The first beat appears at atomic mass number 233. It's uranium-233, an atom capable of firing the furnace inside a nuclear reactor. Like all the atoms on the chart recorder, uranium-233 is radioactive. Left to its own devices, it spontaneously transforms into new atomic varieties, some of which – when treated with due care and respect – can be turned into an advanced treatment for fatal diseases.

Onwards, the chart recorder scrolls.

The second beat appears at atomic mass number 235. It's uranium-235, the atom that changed the world when humans began

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orchestrating nuclear chain reactions in the 1940s. In splitting atoms of uranium-235, we acquired the weaponry that catalysed the atomic arms race of the twentieth century. At the same time, we tapped a source of energy so plentiful that it could safely power our energy-hungry civilisation into the far future with little detriment to the natural environment. Uranium-235, more than any other atom, will decide whether or not we successfully renounce fossil fuels and decarbonise our energy systems.

The chart recorder continues to scroll.

The next beat appears at atomic mass number 238. It's uranium-238, the most common form of uranium. It doesn't sustain nuclear chain reactions, but it can be cultivated as a seed from which new types of nuclear fuel grow. Whilst uranium-235 could help us reach net zero by 2050, uranium-238 could power the world cleanly for a millennium.

Uranium-238 is also the heaviest atom to exist naturally on planet Earth. If this were an everyday material in a normal chemistry lab, the chart recorder would flatline here. But this sample is neither natural nor normal. Some of its atoms saw their origins inside a nuclear reactor.

The next beat on the chart recorder is at atomic mass number 239. It marks the presence of an atom that exists only because of our acquaintance with and profound understanding of the chemical world: plutonium-239.

Plutonium was the first human-made chemical element that we created in quantities large enough to see with the naked eye. Initially, we synthesised plutonium by the millionth of a gram on chemistry benchtops. In time, we forged many thousands of tonnes inside the cores of nuclear reactors. I'm measuring mere billionths of grams in the lab today, but the biggest civil plutonium stockpile in the world – containing hundreds of *tonnes* – lies at Sellafield, where I work. Synthetic elements in such profuse quantities make this site one of the most chemically exotic square miles on the planet.

To make plutonium, we transform the chemical building blocks of matter through nuclear reactions. We, humans, are not mere features in the chemical world; we are shapers of it. The existence of

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plutonium is so profound that geologists have proposed using its appearance on Earth in the 1940s to define the beginning of a new epoch: the Anthropocene. Geologically speaking, plutonium may come to define our planetary legacy.

Still onwards, the chart recorder scrolls.

The final traces reveal the rarer and heavier types of plutonium: plutonium-240, plutonium-241, and, finally, plutonium-242.

The penultimate beat, plutonium-241, draws my eye. Some of my colleagues recycle waste plutonium-241 for its radioactive progeny – americium-241 – to make nuclear space batteries. These batteries will someday power spacecraft across the solar system. They might even power human habitats on the Moon, or perhaps Mars. Astronomically speaking, plutonium may come to define our interplanetary legacy.

After plutonium-242, the chart recorder flatlines. This is as far up the periodic table as this sample goes. No heavier atom lies beyond.

I programme the mass spectrometer to measure the next batch of samples. I frisk the rest of my body and the underside of my shoes with the radiation probe, and I leave the lab satisfied. After passing through the security checkpoint guarding the lab entrance, and one last frisk, I head back to my office for a coffee.

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Introduction: How the Atom Will Save the Planet

It feels as though we're in perpetual crisis, especially when it comes to what makes our world go round: energy.

Global warming intensifies as we burn more and more fossil fuels. Our culture is saturated by environmental anxiety. There is an overwhelming mood of foreboding, especially amongst young people. In their bid to renounce fossil fuels, governments are desperately seeking emissions-free sources of energy capable of growing economies and elevating living standards.

Causes for optimism seem scarce. But deep inside the atom, there lies a credible antidote to the despair: *the nucleus*. Brimming with energy like a candle in the dark, the nucleus could power the world securely, reliably, affordably, and – crucially – sustainably. With nuclear power, we can enjoy energy abundance *and* preserve the natural environment.

However, a landmark survey in 2023 quantified what has long been apparent: the most climate-concerned environmentalists are the least supportive of nuclear power. Campaign groups – including Greenpeace, Friends of the Earth, the World Wide Fund for Nature (WWF), 350.org, and the Sierra Club – all oppose nuclear power. And the general public is often suspicious. Opposition to emissions-free energy – at a time when we need it most – is one of the great contradictions of our age.[1]

In the pages that follow, I'll show why this mistrust is misplaced, and how nuclear power is the only way we can decarbonise our world whilst sustaining economic growth, protecting the environment, and continuing the human progress that has characterised the past century. Splitting atoms of uranium inside nuclear reactors is our best shot at reaching net zero by 2050. Beyond the immediate and pressing energy transition, we'll see how we can use nuclear science to recycle radioactive waste and alchemise

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the chemical elements that could power the world cleanly *for a millennium*.

We'll discover that nuclear science has far more to offer the world than just ('just') clean power, too. We'll meet the mavericks who use radiation to eradicate pests and the atomic gardeners who grow super-crops in gamma gardens. We'll rifle through the radioactive chemistry set that scientists and physicians are turning into novel cures for cancer. We'll encounter the forensic investigators who use nuclear science to solve crimes. And we'll learn how nuclear power enabled us to explore the solar system, and how, soon, it will permit humanity to thrive on the surfaces of other worlds.

At the heart of *Going Nuclear* lies my belief that science and technology – implemented across the globe by our shared institutions – are two of our best tools for promoting human prosperity and protecting the natural world. I wrote these words in the hope they will inspire others to advance those causes, sustainably and responsibly, in a spirit of rational and daring optimism.

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Chapter 1. Wresting Fire from the Gods

By convention sweet and by convention bitter;
by convention hot and by convention cold;
by convention colour;
but in reality, atoms and void.

– Democritus, c. 460–370 BC

Imagine we have a grape. Instead of crushing it into wine, we slice it in half with an impossibly sharp knife. Now imagine we take one of those halves and slice *that* in half, and again, and so on. After a dozen slices, we'd find ourselves with a piece of grape smaller than a grain of sand.

Now imagine we keep going. After a dozen more slices, our morsel would be the width of a human hair. Another dozen slices and it would be the size of a red blood cell. Seven slices more, and it would be the size of a bacterium.

If we persevered until we'd halved our grape 80 times, we'd encounter the smallest unit of ordinary matter from which our world is made. The ancient Greek philosopher Democritus would have named our impossibly small piece of grape ἄτομος – 'atomos' – meaning, appropriately enough, *uncuttable*. In his spirit, we'd call it by a similar name: an atom.

Atoms are tiny. If you scaled up a grape to the size of Earth, its atoms would be about grape-sized. This means there are a great many atoms in the smallest of things. In our grape, for instance, there are as many atoms as there are stars in the observable universe.

Democritus and his contemporaries had no way of knowing that atoms really existed. There was no physical proof that they did: they were the subject of philosophical musings, an inspired

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lucky guess. But over the past two centuries of scientific inquiry, we've got to know them well.

We know, for instance, that the atoms in our grape are encircled by fuzzy clouds of *electrons* – aptly so named because they're electrically charged. These charged clouds give rise to the electrical force that binds atoms to one another and governs their interactions. The branch of science that describes and forecasts these electrical tempests is known as *chemistry*.

But suppose we thought our efforts unfinished. What would happen if we kept on slicing our grape? We'd find that Democritus, whilst brilliant, wasn't quite right. Our atom, far from being 'atomos' – *uncuttable* – could be divided further. We would, perhaps inevitably, split it.

Deep within the electron cloud, we'd find a dense kernel of matter called the *nucleus*. It took us 80 slices to cut our grape down to the size of an atom; it would take another 45 to cut our atom down to the size of a nucleus, because the nucleus is 20,000 times smaller than the atom as a whole.

So, what would we find in the space between the electrons and the nucleus? We wouldn't find air, because air is itself made from atoms. The answer is . . . nothing. Atoms, it turns out, are made mostly from empty space. The world is mostly void. It's a thought that makes my mind explode.

Now, imagine that we continued slicing our grape, just a few more times. What then? We'd find our nucleus is composed of *protons* and *neutrons*. The branch of science that describes these subatomic particles and their interactions is called *nuclear science*. (We could go further and divide our protons and neutrons into quarks . . . but we have to stop somewhere.)

Like electrons, protons are charged. But whilst electrons are negatively charged, protons are positively charged. They say that opposites attract, and whilst that's not necessarily true for humans, it *is* true for charges. Unlike charges attract; like charges repel. The electric forces between negative electrons and positive protons hold the two together.

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Neutrons, as their name suggests, are electrically neutral. They carry no charge.

Slicing our nucleus into pieces would be tiresome work. Whilst *electrical* forces bind electrons to the nucleus, *nuclear* forces glue the nucleus itself together. And those nuclear forces are far stronger than their electrical counterparts. They're mighty enough to overcome the mutual electric repulsion of the protons and keep the nucleus intact. Combined, these atomic forces make the world – mostly void – appear solid.

Atoms come in 118 chemical varieties called *elements*. Each element is defined by the number of protons in its nucleus, and chemists arrange them on the periodic table as such. For instance: hydrogen, element number 1, always has 1 proton in its nucleus, and so occupies the 1st tile; platinum, element number 78, always has 78 protons in its nucleus, and so occupies the 78th tile; and so on.

The Nobel Prize-winning physicist Ernest Rutherford reportedly once quipped that 'all science other than physics is stamp collecting'. Well, if that's true, the periodic table is humanity's finest stamp collection.

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57–71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89–103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

The periodic table condenses the complexity of the world – grapes, mountains, galaxies – into 118 chemical elements.

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On Earth, there are 88 naturally occurring elements.* Our grape was made mostly from half a dozen: hydrogen, carbon, nitrogen, and oxygen, and a dash of potassium, calcium, and a few other metals. Air is a mixture comprised chiefly of three: nitrogen, oxygen, and argon. Water is a concoction of just two: hydrogen and oxygen. Diamond is a crystal of only one: carbon.

The other 30 elements on the periodic table do not exist naturally. These are the *synthetic elements*, which only exist because we, humans, made them by either sticking existing nuclei together or pulling them apart.

Now, as much as I delight in the periodic table, it has a major shortcoming. It only tells half the story, because it fails to consider *neutrons*.

Neutrons have almost the same mass as protons (they're a paltry 0.1 per cent heavier), and by varying the number of them in an atom's nucleus, the mass of the atom changes. We call atoms of the same element with different numbers of neutrons *isotopes*.

The word 'isotope' is another nod to Democritus: it comes from the ancient Greek ἴσος – 'isos' – meaning *same*, and τόπος – 'topos' – meaning *place*. Isotopes occupy the *same place* on the periodic table because they're the *same element*. They differ only in how heavy they are.

There are 118 elements, but there are *thousands* of isotopes. Carbon, for instance, has three: 'carbon-12', 'carbon-13', and 'carbon-14'.† Every atom of carbon, by definition, has 6 protons, but its isotopes have different numbers of neutrons. The number following the element name – the atom's *mass number* – is simply the sum of the protons and the neutrons. Carbon-12 atoms,

* The sticklers will remind me that there are actually more like 94, but I'm ignoring six: technetium (element 43), promethium (element 61), astatine (element 85), francium (element 87), neptunium (element 93), and plutonium (element 94). They exist in such minute quantities that whilst they *technically* exist, they *practically* do not.

† The same sticklers will remind me that there are more than three isotopes of carbon. But I'm ignoring all but three, because they're the only ones that occur naturally on Earth.

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therefore, have 6 protons and 6 neutrons; carbon-13 atoms have 6 protons and 7 neutrons; and carbon-14 atoms have 6 protons and 8 neutrons.

Given their electrical neutrality, neutrons have no bearing on the chemical character of an atom. Different isotopes of an element are doppelgängers with identical chemical properties, which is why chemists normally get by without giving them much heed.

But not so in nuclear science. Neutrons are of paramount importance, because they affect the *nuclear* character of an atom. Isotopes of the same element often have different nuclear properties, amongst them the ability to radioactively disintegrate or split in two and release tremendous amounts of energy.

And after pondering these things, we mustn't forget to reassemble our nucleus, put our atoms back together, and rebuild our grape. Then, we'll have earned our wine.

A cloudy week in Paris

MONDAY, 24 FEBRUARY 1896

Parisian physicist Henri Becquerel is experimenting with the uranium – element number 92 – that he inherited from his father. He's using it to better understand *phosphorescence*, a curious phenomenon where a substance apparently 'charges up' in sunlight and slowly radiates its energy as an eerie afterglow.

Becquerel's experiment is simple: he wraps a photographic plate in thick paper, sprinkles the uranium on top, and basks it in sunshine for a few hours. The thick paper stops the sunlight reaching the plate, but when he develops the photograph, the ghostly image of the uranium appears. The uranium atoms seem to absorb energy from the Sun and re-emit the rays with enough vibrance to shine *through* the opaque paper. How peculiar.[1]

Two days later, Becquerel prepares a second experiment. He wraps another photographic plate in thick paper, sprinkles more uranium on top, and basks it in . . . but no. It's cloudy. With no sunlight to 'charge up' his uranium, he terminates the experiment. Defeated, he

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stows the photographic paper – uranium and all – in the darkness of his bureau drawer for a sunny day.

The clouds above Paris do not lift for the rest of the week. Thursday . . . grey. Friday . . . still grey. Saturday is no better.

By Sunday, Becquerel's patience is strained. He retrieves the experiment from his drawer and develops the photograph anyway. He expects to see nothing. But there, as clear as if he'd left it out in bright sunshine, he sees the ghostly image of the uranium.[2] How can this be? Where have the rays come from if the uranium had been kept in the dark?

The answer is inescapable: uranium atoms do not get their energy from the Sun. Their energy was there all along. It's *inherent* in the uranium itself, and it has enough vigour to shine through thick paper and fog photographic plates. News of the discovery galvanises the scientific community.

Two years after Becquerel's discovery, German chemist Gerhard Carl Schmidt and Polish-French chemist Marie Curie each independently find another element that does the same thing: thorium (element number 90).[3] Thorium, like uranium, radiates energy into its surroundings without external stimulus. So extraordinary is this phenomenon that no word exists to describe it. Curie coins one: *radioactivity*.

Within 2 years, Marie Curie and her husband, Pierre, discover two more radioactive elements. They name one (element number 84) *polonium* after Marie's homeland, Poland. The other (element number 88) is so radioactive that it glows in the dark, so they name it *radium* after the Latin *radius*, meaning 'ray of light'. In 1903, they become the first married couple to win a Nobel Prize in Physics, sharing it with Becquerel.

In 1911, Marie Curie would win a second Nobel Prize – this time in Chemistry – for the discovery of polonium and radium. (Pierre died tragically in 1906 after a horse-drawn carriage ran him over, and the Nobel Committee doesn't award prizes posthumously.) She remains the only person to win a Nobel Prize in two separate sciences. Little did she know that they would kickstart a scientific revolution that would turn our understanding of material reality on its head.

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Easy as α, β, γ

We know today that radioactivity comes in different varieties. The most common types by far are the ones I encounter the most in my lab: *alpha*, *beta*, and *gamma* radiation, named with another nod to Democritus according to how easily they pass through matter.

Different radioactive elements – or, more precisely, different radioactive *isotopes* – emit distinct types of radiation. All naturally occurring isotopes of uranium, for instance, emit alpha radiation. So do the Curies' polonium and radium. On the other hand, naturally occurring potassium-40 – which comprises 1 in every 10,000 of all potassium atoms on Earth[4] – emits beta and gamma radiation. Grapes, and anything else that contains potassium, such as bananas, potatoes, and building materials, are therefore slightly radioactive.

Atoms that radioactively decay have too many or too few neutrons in their nuclei. They are off-kilter. They radiate energy spontaneously through *radioactive decay* to regain balance. This radiation, like atomic-scale artillery, carries with it enormous energy.

But it turns out that alpha and beta radiation aren't 'rays' at all. They're *particles*, small fragments of atoms.

Alpha particles are hefty and energetic. They're bulky clusters comprising a pair of protons and a pair of neutrons stuck together. This means alpha particles are actually helium nuclei, lacking only the accompanying electrons that would make them fully fledged atoms. They're fired like cannonballs from their parent nuclei at more than 30 *million* miles per hour, and they transmit their energy into their surroundings when they collide with other atoms.

Alpha decay fundamentally changes an atom's nature. The parent atom loses 2 protons and 2 neutrons; this means its mass number decreases by 4. But crucially, by losing the pair of protons, its element number decreases by 2. *This means it becomes a new element*. Radioactive atoms naturally transform from one element into another, without any human intervention. Upon firing out an alpha particle, the parent atom moves 2 spaces down the periodic table.

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When uranium (element number 92) alpha decays, it becomes thorium (element number 90); when thorium alpha decays, it becomes radium (element number 88); when radium alpha decays, it becomes radon (element number 86); and so on. The cascade continues down a long chain, from one radioactive isotope to another. Eventually, a non-radioactive isotope is encountered, at which point the cascade stops. In the case of uranium, the chain cascades all the way to element number 82, lead.

The spontaneous transformation of one element to another adds a layer of complexity to working in a nuclear lab. My labmates and I are mindful that our samples change their chemical nature continuously; what we put on the shelf today won't be the same tomorrow.

Since they're so burly, alpha particles don't travel far before coming to a halt. They crash into other atoms and lose their energy quickly. A thin sheet of paper blocks them easily. So does the top layer of your skin. Even a finger's width of air is enough to stop an intense stream of alpha particles dead in its tracks.

Beta particles, on the other hand, are zippy and weigh very little. They're not clusters of protons and neutrons but nimble *electrons*, more bullet-like than their cannonball cousins. They approach light speed, dissipating their energy far and wide as they jostle past the atoms in their surroundings. Beta particles can traverse several metres of air, and a thick layer of plastic or a thin sheet of metal is required to stop them.

Like alpha decay, beta decay changes the parent atom's nature. One of its neutrons turns into a proton; this means the atom's mass number stays the same, but its element number increases by 1. Thus, as with alpha decay, it becomes a new element. Upon firing out a beta particle, the parent atom moves 1 space *up* the periodic table. When radioactive potassium (element number 19) beta decays, it becomes calcium (element number 20); when radioactive carbon (element number 6) beta decays, it becomes nitrogen (element number 7); and so on.*

* There's a rare type of beta decay called beta-plus decay whereby a proton turns into a neutron. This releases a positron (the anti-matter counterpart to the electron) and moves the element 1 space *down* the periodic table.

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Gamma radiation is the oddity of the trio. It *is* made from rays, not particles. Gamma rays are individual flashes of light, albeit light that lies so far along the electromagnetic spectrum that it's invisible to our eyes. They travel at light speed and carry tremendous energy, and they're stopped only by a head-on collision with the nucleus of an atom. As atoms are mostly void, gamma rays shine through matter with ease. To block them, you need something like a thick wall of lead or dense concrete. Sheldon Allman got it right in his 1960 sci-folk number 'Radioactive Mama': *Well, your kisses do things to me in oh so many ways, I feel them going through me, all those gamma gamma rays*. Gamma decay does not change the parent atom's nature. Rather, the atom simply rids itself of excess energy.

Occasionally, I switch on my radiation probe and it erupts into a chorus of *click click clicks* because of beta and gamma radiation coming from a sample a few feet away. One time, a sample *on the other side of the lab* sent my radiation probe into a frantic clatter. I raised an eyebrow at my labmate. 'Yeah, that's a spicy one,' he said. At the levels in our labs, though, the exposure is harmless. Besides, we do a good job of blocking beta particles with sheets of aluminium. And when it comes to gamma rays, they're no match for the lead bricks we stack around the samples.

Alchemy

Anybody who has attempted to cut a single atom from a grape will have learned quickly that you cannot get inside atoms using ordinary means, because ordinary things – like knives – are themselves made from atoms. Extraordinary insights require *extraordinary* tools: radiation.

Kiwi physicist Sir Ernest Rutherford is remembered by history as 'the father of nuclear physics', even though, ironically, he won the 1908 Nobel Prize in Chemistry. He discovered the atomic nucleus, indulged in a spot of stamp collecting by adding the 86th tile to the periodic table (radon), and classified Becquerel's radioactivity into

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