THE MYSTERY OF MATTER: SEARCH FOR THE ELEMENTS

EPISODE 3 (OF 3): INTO THE ATOM
BROADCAST NATIONALLY ON PBS AUG. 19, 2015

Dmitri Mendeleev (identified on screen) works on the Periodic Table, writes down the atomic weights of the elements.

NARR: Previously on *The Mystery of Matter…*

HISTORIAN MICHAEL GORDIN VO
He figures out something rather extraordinary about the elements.

DMITRI MENDELEEV, partly in VO
The eye is immediately struck by a pattern within the horizontal rows and the vertical columns.

Mendeleev's first table morphs into the familiar modern Periodic Table.

AUTHOR ERIC SCERRI VO
He found an absolutely fundamental principle of nature.

Humphry Davy (identified on screen) performs an experiment with his voltaic pile.

HISTORIAN DAVID KNIGHT VO
Somehow the particles of matter have to be glued together to form molecules. What Davy has had is a big idea. Perhaps electricity could be this kind of glue.

Marie Curie (identified on screen) sits down at the spectroscope and peers into the eyepiece.

NARR: The spectroscope kicked off a whole new round in the discovery of elements.

The spectra of four elements appear on screen, along with their names.

PHYSICIST DAVID KAISER VO
It's almost like each element has its own bar code.

Marie and Pierre enter their lab at night and see vials of radium glowing on the shelves.

MARIE TO PIERRE
Don't light the lamps! Look!

PHYSICIST DAVID KAISER VO
Radioactivity was a sign that the atom itself was unstable. It could break apart.

Marie and Pierre look in wonder at their radiant element.

NARR: Scientists now had a pressing new question to answer: What's inside the atom?

Fade to black

Funder Credits

Episode Title: Into the Atom

Fade up to Host doing a demonstration with Geissler tubes.

HOST

In the late 1800s, tubes like this were a staple of the popular science lecture.

Host turns on the tube, and we see the beam of electricity and the crowd-pleasing glow.

HOST

When electricity was applied to the metal at this end, it would give off a glow that thrilled crowds still mystified by electricity.

Host motions to a photo of J. J. Thomson behind him.

HOST

In 1897, physicist J.J. Thomson of England's Cambridge University set out to find out what these mysterious rays were.

Host moves a magnet into place; we see the beam of electricity bend.

HOST VO

When Thomson moved a magnet near a tube modified to reveal the rays, he saw that it bent the path of that beam. Electricity, he realized, must be made up of *negatively-charged* particles – what soon came to be called "electrons."

But electrons weren't just the unit of electricity. Thomson found that even when he used different metals to generate the rays, the resulting electrons were always the same. His bold conclusion was that the electron must be a tiny piece of every atom – thousands of times smaller than the atom itself.

Animation showing size of the electron relative to the hydrogen atom – about 1/2000th the size.

PHYSICIST DAVID KAISER, partly in VO

These things were much, much smaller than anyone had ever thought a kind of physical thing could be. But over time, people began to agree that this was a piece of every atom in the universe, that all of matter had these little parts inside them.

Photo of participants in the early Solvay conferences, including Curie, Einstein and Rutherford

NARR: Now the race was on to identify the rest of the atom's pieces and understand how they fit together. This challenge drew many of the best minds in science...

Pan from vase of flowers to Moseley writing letter

NARR: … including a 22-year-old physicist from one of England's leading scientific families.

Cut to shot of mother reading the letter as VO begins.

On screen: **Words spoken by the characters in this film are drawn from their writings.**

HARRY MOSELEY VO

My dear Mother,

Two letters from you, so here a second from me …

Photo of young Moseley among his classmates at Trinity College Oxford

NARR: Henry Gwyn Jeffreys Moseley – Harry to his friends – was born with science in his blood.

Image of a Royal Society meeting

NARR: Both his grandfathers had been members of the Royal Society.

Photo of his father, Henry Nottidge Moseley

NARR: And his father was a famous naturalist and Oxford professor.

Photo of Moseley as a boy

NARR: But he died when Harry was just three ...

Photo of his mother, Amabel Gwyn Jeffreys

NARR: ... leaving him to be raised by his mother, Amabel.

Moseley continues writing the letter. Cut to shots of mother working in the garden.

HARRY MOSELEY VO

Firstly, the garden. Please occupy yourself in taking many hundreds of rose cuttings … Put them quite close together and ram the earth round them.

NARR: Harry and his mother grew very close. Together they laid out a garden alongside their country cottage. And throughout his life, his letters home were filled with instructions.

HARRY MOSELEY VO

Such Penstemons as the mole killed must be replaced … The Quamashes would like to be planted …

BIOGRAPHER JOHN HEILBRON, partly in VO

As any good gardener, he knew what he wanted planted where, and he told people what to do. He got to be very good at telling people what to do.

HARRY MOSELEY, partly in VO

… I hope the burrowing progresses and that it is being done with reference to our pretty ground plan.

Photo of young Moseley at Oxford

NARR: Moseley earned a degree in physics at Trinity College Oxford, and then elected to pursue graduate studies …

Photo of smoggy Manchester in 1910. Drawing of physics building at Owens College. Shot of the same building today.

NARR: … two hundred miles to the north, in smoggy Manchester, whose industrialists had generously endowed the local university.

NEIL TODD, MANCHESTER UNIVERSITY, partly in VO

The laboratory that Moseley came to in 1910 was, at that time, one of the most advanced physical institutes in the world.

Footage of Moseley working in the lab, then zoom to Rutherford in the center of group photo of the lab

NARR: But for Moseley, the real attraction was that it was run by the brightest star in physics – an irrepressible New Zealander named Ernest Rutherford.

Photo of Rutherford

NARR: Rutherford had leapt into the study of radioactivity as soon as Marie and Pierre Curie announced their findings.

Animation showing alpha and beta particles given off during radioactive decay

NARR: And he had already won the Nobel Prize for his discovery that radioactive atoms give off different kinds of rays and particles as they decay.

Photo of Rutherford with his instruments

PHYSICIST DAVID KAISER, partly in VO

So by 1910 he was undoubtedly among the great physical scientists, thinking hard about the nature of radioactivity, about how to understand atoms and their parts.

Moseley is working at his equipment. In the background we hear Rutherford approaching, singing "Onward Christian Soldiers" – badly. Rutherford enters the lab and comes over to speak to him.

NARR: Moseley was soon assigned a research project on radioactivity, and Rutherford kept close tabs on his progress.

ERNEST RUTHERFORD
Good morning, Moseley! Well, how's it all going?

NEIL TODD, MANCHESTER UNIVERSITY, partly in VO
He would daily make a round and visit all of the young workers where they were carrying out their experiments.

We hear bits of their conversation about a problem Moseley is having with the instrument.

HARRY MOSELEY (TO RUTHERFORD)
The tube is giving off alpha and gamma rays.

ERNEST RUTHERFORD (TO MOSELEY)
They're producing secondary electrons. Have you tried shielding?

NARR: "Papa," as they called him, would pour out advice – often seeing right to the heart of the matter.

ERNEST RUTHERFORD (TO MOSELEY)
That should do it. That should help.

Rutherford and Moseley continue discussing the problem.

PHYSICIST DAVID KAISER, partly in VO
He was constantly at the elbows and shoulders of his young students, coaxing them on, offering advice on the nitty-gritty of experimental technique. He seemed to have the magic hands to get things to work.

Rutherford claps him on the shoulder and leaves singing. Moseley returns to his work with a wry smile.

ERNEST RUTHERFORD
Carry on ... ward Christian Soldiers, marching as to war ...

NEIL TODD, MANCHESTER UNIVERSITY, partly in VO
It was a very happy atmosphere in his laboratory, because it was like a band of brothers, almost.

Photo of Rutherford's lab members in 1912. The people mentioned are highlighted.

NARR: Rutherford's band of brothers was one of the finest groups of young scientists ever assembled in one place. Among them were Hans Geiger, who would invent the radiation detector known as the Geiger counter; Charles G. Darwin, grandson of the great biologist, and James Chadwick, a future Nobel Prize winner.

Photo of young scientists at work, then shot of Manchester lab today

PHYSICIST DAVID KAISER, partly in VO

He had a very active group, of young researchers who were wondering about ultimate questions of "What is the nature of matter?" – with new discoveries practically every week.

Pull back from group lab photo

NARR: One of the most exciting discoveries came just a few months after Moseley's arrival, as Rutherford's team continued to probe the structure of the atom.

Reprise animation of electron

NARR: They knew that J.J. Thomson's tiny, negatively-charged electron was one piece of the puzzle. But that left two big unanswered questions.

PHYSICIST JIM GATES

Since atoms are generally neutral, that meant that the atom itself had to somehow have a positive charge to balance the negative charge out.

Animation with a plus sign and big question mark over the atom

NARR: But where in the atom were the positive charges needed to offset those negative electrons?

PHYSICIST DAVID KAISER

And a related question, since people knew by this point that electrons were so much less massive than the atoms themselves, where was the mass distributed?

Photo of Rutherford with Geiger

NARR: Rutherford and his students had been trying to answer these questions …

Reprise of Rutherford's radioactive decay illustration, alpha particle labeled

NARR: … with the help of the positively-charged alpha particles that poured out of radium during radioactive decay.

Animation of the gold foil experiment

NARR: They aimed a beam of alpha particles at an ultrathin sheet of gold foil.

PHYSICIST DAVID KAISER, partly in VO

Most of the time, these alpha particles would sail right through. But every now and then, some of these projectiles would actually bounce practically right back in their faces. And that was really, really unexpected.

ERNEST RUTHERFORD

It was the most incredible thing that has ever happened to me. It was almost as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you!

Shot of the lab exterior today

NARR: In late 1910, Rutherford came into the lab one day and announced he knew what this surprising result meant.

CHEMIST GREG PETSKO

It meant that the atom must be mostly empty space but have some incredibly dense, hard center.

Animation showing the atom transforming as the mass and positive charge are squashed down into the center. Red alpha particles veer off as they approach the center.

NARR: If the atom's positive charge and most of its mass were concentrated in a tiny central core, it would let most particles sail through but repel any positive charge that came near the center.

One alpha approaches the center straight on and is kicked straight back.

BIOGRAPHER JOHN HEILBRON, partly in VO

Then you can give the incoming alpha particle a real kick and sometimes turn it all the way around.

Animation reveals the new picture of the atom. The nucleus is labeled with a plus sign.

PHYSICIST DAVID KAISER, partly in VO

So with that we had this really quite, brand new vision of the structure of the atom. Almost all of its mass was concentrated very very tightly in a minute, little space, in what we would now call the nucleus. And then, separated by mostly nothing, you have these negatively charged electrons, sort of whizzing around, but at a great, great distance on the scale of the atom.

PHYSICIST JIM GATES

One of the most remarkable things about the atom is that it is mostly made of nothing!

Manchester lab group shot

PHYSICIST DAVID KAISER, partly in VO

I think the feeling in those hallways, the laboratories of Manchester, was one of great excitement. They could sense that Rutherford and his team had literally cracked open a new view of matter.

Zoom to Moseley in Manchester group photo

NARR: But while all this was going on around him, Moseley was consigned to plugging away on radioactivity research projects.

HARRY MOSELEY, partly in VO

I'm repeating someone else's experiment to please Rutherford, so the work is not very exciting. I'm hoping to be through with it soon.

Footage of Moseley working in the lab, not thrilled. He sighs.

CHEMIST RUSSELL EGDELL, partly in VO

From his correspondence, I think he found it actually slightly mundane just to be following on behind other people and not really making his own distinctive mark.

Moseley is frustrated with a broken piece of equipment. Dissolve to shot of him reading a German physics journal.

NARR: So in the spring of 1912, when a piece of his radioactivity equipment broke, Moseley seized the opportunity to strike out in a new direction.

Mother reads letter in the garden.

HARRY MOSELEY VO

My dear Mother,

I'm sorry that I didn't answer your letter sooner, but I was very busy. Last Thursday we got the result we were searching for, using the X-rays.

Moseley reads about the German work. Close-up of the article he's reading.

NARR: Moseley had turned his attention to some exciting news out of Germany.

Images of X-ray excitement from the 1890s

NARR: X-rays – the same rays that had so captivated the world 15 years earlier – had been found to have properties like those of light.

Illustration of Newton and the prism

NARR: Ever since Newton, it had been known that a prism could split light into a series of distinct colors, each with its own wavelength or frequency.

Photo of Max von Laue, animation of diffraction by crystal

NARR: What the German scientists had discovered was that X-rays could be split up, or "diffracted," in the same way … with the help of a crystal.

Image of von Laue's spots

NARR: Only the resulting image was not a rainbow but a symmetrical pattern of spots on a photographic plate.

Moseley and Darwin work together in the lab on X-rays, chattering away.

CHARLES G. DARWIN (TO MOSELEY)
Power on.

HARRY MOSELEY (TO DARWIN)
Fifteen volts and steady.

Photo of Darwin

NARR: Intrigued, Moseley asked Charles G. Darwin to join him in investigating this curious X-ray pattern.

Moseley and Darwin continue working together in the lab.

CHARLES G. DARWIN (TO MOSELEY)
220 degrees, 10 minutes.

PHYSICIST JUSTIN WARK, partly in VO
Darwin was actually a mathematician, and that's really why Moseley got hold of his services, because he knew that this was going to imply some complex mathematics.

Animation showing how planes of atoms could reflect X-rays to create the pattern of spots

NARR: Moseley and Darwin concluded that the atoms inside the crystal were neatly arrayed in rows that reflected the X-rays to create the pattern of spots.

Rutherford meets with Moseley and Darwin in the lab. Rutherford is skeptical.

NARR: Excited by this discovery, Moseley and Darwin asked Rutherford for permission to devote all their time to this new project.

ERNEST RUTHERFORD
I don't really think that we are equipped – we don't really have the supervision for this sort of thing.

BIOGRAPHER JOHN HEILBRON, partly in VO
Rutherford, who knew nothing about X-rays, was not very enthusiastic about this new departure. So he at first opposed it.

ERNEST RUTHERFORD
Are you absolutely sure this is something you want to do?

CHARLES G. DARWIN

We were fired by our interest in this unexplored field, and had no idea where it would lead. At the time, X-rays were still mysterious. We simply wanted to know what they really were.

Rutherford reluctantly assents. Moseley and Darwin exchange glances, relieved to have been given the chance to move forward.

CHARLES G. DARWIN VO

Finally, we persuaded him to let us try.

ERNEST RUTHERFORD

Okay, well, on the condition that if you run into trouble of any kind, you do ...

NEIL TODD, MANCHESTER UNIVERSITY, PARTLY IN VO

I think it was essentially their enthusiasm for the subject, which convinced Rutherford that, yeah, this was worth a shot.

ERNEST RUTHERFORD

And keep me informed all along the way.

HARRY MOSELEY

Certainly sir.

Shots of Moseley and Darwin at work in the lab. They chatter away.

CHARLES G. DARWIN (TO MOSELEY)

220 degrees, 20 minutes.

HARRY MOSELEY (TO DARWIN)

Fifteen volts and steady.

NARR: For six months, the two young researchers holed up in the laboratory.

Shot of Amabel working in the spring garden. Then back to Moseley and Darwin working together.

HARRY MOSELEY VO

I wish I were with you to see all the fresh spring, but here it’s all work. I'm like a gnome after a long winter of darkness, longing for some light.

Moseley works alone in the lab late at night.

CHARLES G. DARWIN, partly in VO

Working with Moseley is one of the most strenuous things I've ever done. He is without exception the hardest worker I’ve ever known.

ERNEST RUTHERFORD, partly in VO

I'd arrive at the laboratory in the morning and meet Moseley just as he was leaving. He'd been at it all through the night – 15 straight hours.

CHARLES G. DARWIN

Indeed, one of Moseley's skills was knowing where in Manchester you could get a meal at three in the morning.

Moseley eats fruit while he reviews the manuscript to be submitted to Nature.

HARRY MOSELEY VO

We've sent a letter off to *Nature* describing what we have found so far. But we must keep on with the work. Many others are on the same track.

Photos of two Braggs, father and son

PHYSICIST DAVID KAISER, partly in VO

Moseley was not alone in realizing this was exciting. There was some pretty steep competition, like William Bragg and his son William Lawrence Bragg, who were already working hard and fast on similar techniques.

Moseley and Darwin discuss things in the lab.

NARR: Aware of this competition and anxious to return to Rutherford's work on the atom ...

CHARLES G. DARWIN

I thought I'd come by to bid you farewell.

NARR: ... Darwin decided to leave the partnership in the summer of 1913.

HARRY MOSELEY VO

I suppose this makes sense. You were always a better theoretician than you were a lab tinkerer.

CHARLES G. DARWIN

Will you go on alone?

HARRY MOSELEY VO

Oh, certainly. I think this might lead to something.

NARR: Rather than abandoning the work ...

CHARLES G. DARWIN

Well, I wish you all the best.

They shake hands and Darwin leaves. Moseley returns to work as Darwin looks back.

NARR: ... Moseley changed his approach, leaving basic research on X-rays to others.

BIOGRAPHER JOHN HEILBRON VO

Moseley, says, "We'll, okay. I'm not quite sure what these things are, but I know perfectly well how to use them."

Moseley works alone in the lab.

NEIL TODD, MANCHESTER UNIVERSITY, partly in VO

Having done the basic work with Darwin, he decided to use the method as a tool to investigate the nature of the elements.

BIOGRAPHER JOHN HEILBRON, partly in VO

And that is when his brilliant discoveries began.

Moseley ponders an X-ray tube.

NARR: Moseley set out to learn if each element had a unique X-ray spectrum – a bar code like the ones that had been discovered a half century earlier using light. To find out, he placed a sample of an element inside an X-ray tube.

Animation of the tube in Moseley's hands shows how the X-rays are created.

NARR: When a beam of electrons struck the sample, the element gave off X-rays. Moseley could then determine the element's X-ray spectrum.

The resulting X-ray spectrum of platinum, shot of Moseley in the lab.

HARRY MOSELEY, partly in VO

The whole subject of X-rays is opening up wonderfully. When we fire electrons at a target made of platinum, we get a sharp line spectrum of five wavelengths. Tomorrow I will search for the X-ray spectra of other elements.

I believe they will prove much more important and fundamental than the ordinary light spectra.

Reprise image of light spectra

NARR: While the light spectra had been invaluable in identifying new elements, they hadn't solved certain puzzles about the *ordering* of the elements in the Periodic Table.

Pan along the Periodic Table, highlighting the increase in atomic weights

NARR: The elements were arranged in columns with similar chemical properties, but they also tended to fall in order of increasing atomic weight – the amount a single atom of an element weighed.

PHYSICIST DAVID KAISER, partly in VO

But it's not perfect. Every now and then there seemed to be anomalies, little reversals, where chemical properties seemed to suggest one kind of ordering but their weights suggested the opposite order.

CU of cobalt and nickel in the table, highlighting their inverted atomic weights.

AUTHOR ERIC SCERRI, partly in VO
For example, there was cobalt and nickel. Chemically speaking cobalt, should occur before nickel, and yet its weight is higher. And nobody knew why these inversions were happening.

In the Periodic Table, the 10 metals of Moseley's study are highlighted: 11 metals from calcium to zinc, a continuous series missing only scandium.

NARR: To find out if X-rays could solve this riddle, Moseley set out to test ten neighboring elements in the Periodic Table, including that troublesome pair, cobalt and nickel.

Moseley studies his X-ray tube, realizing he will need something different.

NARR: But Moseley quickly realized he had a problem: For each element he tested, he had to use the lab's vacuum pump to empty the tube of air.

PHYSICIST JUSTIN WARK
Vacuum pumps were jealously guarded devices. Lots of people in the lab needed a vacuum to do their research, and you had to join the queue.

Moseley begins sketching a new design.

PHYSICIST JUSTIN WARK VO
But Moseley realized that if he could put lots of these little elements at once in the same tube, then he could really make progress.

Drawing of Moseley's train, drawn from his paper. Dissolve to the actual device. Moseley has placed his metal samples at intervals along a track that has wheels. It's like a tiny freight train.

NARR: So he designed a long X-ray tube and built a tiny railroad car to carry his samples along inside it.

PHYSICIST JUSTIN WARK, partly in VO
And tied a little piece of silk fishing line to them and then tied that line to a little bobbin.

Moseley turns the bobbin to move a new element into position, then turns on the electron beam.

NARR: By turning the bobbin, Moseley could bring his samples … one after the other … into the line of fire.

PHYSICIST JUSTIN WARK, partly in VO
And so he could do all of these elements in one go, if you like, with the same vacuum tube.

Moseley places a piece of film in the film holder, covers it, closes the chamber and switches on the electron beam tube to start the generation of X-rays. An animation shows how the device works. The X-rays bounce off a crystal, creating an image on the strip of film.

NARR: As each metal was struck by the electron beam, it gave off X-rays. When diffracted by a crystal, they created a series of lines on a strip of film.

Moseley enters his dark room – a tent of black cloth behind his work station. There, in the red glow, the spectral lines appear on the film strip.

HARRY MOSELEY VO

I've worked out a simple way of finding the wavelengths of my different elements.

BIOGRAPHER JOHN HEILBRON, partly in VO

Once he got it up and running he said, "It's so easy, it's almost a sin to snatch the bread from those hungry Germans."

HARRY MOSELEY, partly in VO

In five minutes I can get a strong, sharp photograph of the x-ray spectrum.

Animation shows the spectra of the six elements he mentions.

NARR: Moseley found – just as he had hoped – that each element had a unique X-ray spectrum.

HARRY MOSELEY, partly in VO

In just four days I've got the spectrum of chromium, manganese, iron, cobalt, nickel and copper.

There is here a whole new branch of spectroscopy.

Moseley sits down and lays out his strips of film on a light table, making sure to align them properly so that they accurately reflect the wavelengths of the spectral lines.

NARR: But not even Moseley expected what he found when he compared the spectra of all ten elements in his series.

BIOGRAPHER JOHN HEILBRON

The result of these measurements was absolutely extraordinary.

Moseley continues laying out his strips of film on the light table. The staircase is traced out by a red line.

PHYSICIST JUSTIN WARK, partly in VO

He decided to simply take his photographic film and to arrange the film according to its frequency.

NARR: Each piece of film represented a different element in his series.

PHYSICIST JUSTIN WARK VO

The frequencies of the X-rays that came out had an amazingly simple relationship.

NARR: As he laid them out, one after the other, Moseley found that their dominant X-ray lines rose in frequency, step by step.

When he's through, he sees that the strips form a perfectly regular "staircase."

PHYSICIST JUSTIN WARK VO

And that produces this beautiful staircase.

JOHN HEILBRON, partly in VO

He had no idea when he started to measure these frequencies that the result, now known as Moseley's staircase, would come about. That was a great surprise.

PHYSICIST JUSTIN WARK, partly in VO

I think he must have been astonished. And I think the scientific world was astonished that it was that simple.

Moseley looks down at the staircase, realizing he has discovered something remarkable.

NARR: It would be years before scientists understood the reason for this striking pattern. But Moseley knew at once he had made a fundamental discovery.

He sits back and thinks about it.

PHYSICIST JUSTIN WARK, partly in VO

He thought, "Ah! Now I have a means, for the first time, to really tell which element is which, and to put them in a proper order."

Zoom to and highlight the cobalt and nickel steps, then reprise of their out-of-order weights in the Periodic Table

NARR: Moseley's X-ray lines showed that cobalt and nickel were just where they should be, even though their atomic weights were out of order.

Moseley looks down at the light table.

NARR: The conclusion was inescapable: The X-ray spectra of the elements didn't depend on their atomic weights but on something even simpler.

PHYSICIST DAVID KAISER, partly in VO

There was a remarkably simple relationship between the wavelength or the frequency of that X-ray that came out and something they came to call the atomic number of the element.

Periodic Table – the numbers light up one after the other, indicating an element's place in the table.

NARR: Up to now, “atomic number” had simply referred to the number of an element’s box in the Periodic Table.

CHEMIST GREG PETSKO (MOTIONING)

All the way back to Mendeleev, it’s where in the row you are. It’s counting one by one.

Pan of Periodic Table with atomic numbers highlighted

NARR: But Moseley’s results showed atomic number was much more than a convenient label.

Reprise of staircase, with atomic numbers filling in

HARRY MOSELEY, partly in VO

What we have here is proof that there's a fundamental quantity in the atom which increases by regular steps as we pass from one element to the next. This fundamental quantity can only be the charge on the central positive nucleus.

Animation: A nitrogen atom pops out of the Periodic Table. Its nucleus – an amorphous blob labeled +7 – transforms into a collection of seven positive particles. Next the oxygen atom pops out alongside it. Its nucleus contains eight positive particles. Fluorine pops out with 9 positive particles.

NARR: Moseley had discovered that the nucleus was not one big positive blob … but a collection of positively charged particles that increased in number with each heavier element. Building on Moseley’s work, Rutherford would soon discover this next piece of the atom – the proton – and show that each element in the Periodic Table is defined by the number of protons in its nucleus: its atomic number.

HARRY MOSELEY

Our experiments show that the atomic number always increases by a single unit from element to element. For hydrogen, the atomic number is 1; for helium, 2; for lithium, 3, and so on.

Periodic Table highlighting increasing atomic weight

NARR: Moseley’s discovery put the Periodic Table in a whole new light. For the most part, elements were arranged in increasing atomic weight.

PHYSICIST DAVID KAISER, partly in VO

But that’s not the real reason for that tremendous order that we find among all the elements. It really is marching along atomic number, the amount of positive electric charge on that nucleus, none of which was known in Mendeleev’s own day.

CHEMIST GREG PETSKO

Weights didn’t matter. Something fundamental that was deeper in the atom was what mattered.

ERNEST RUTHERFORD

Moseley's proof that the properties of an element are determined by its atomic *number*, not its atomic *weight*, ranks in importance with the discovery of the periodic law itself. In some respects it's even more fundamental.

HISTORIAN LAWRENCE PRINCIPE

Moseley and atomic number … that's really the crucial moment where we find out what an element really is.

Composite image of proposed new elements emerging from Moseley's X-ray device, with voicings of their unfamiliar names

NARR: Armed with his X-ray machine, Moseley could quickly sort through the dozens of supposed new elements chemists had claimed to have found, separating the real from the imagined.

PHYSICIST DAVID KAISER, partly in VO

He could distinguish between types of matter, with a brand new technique, not dependent on their chemical properties, but by measuring the atomic number based on these X-rays.

Moseley works in the lab.

NARR: Moseley's X-rays allowed him not only to rule out elements that *didn't* exist but also to predict what new elements would eventually be found.

Animated graph from Moseley's second paper showing a straight-line relationship among the elements. In the animation, we highlight the gap at 61.

NARR: In 1914, Moseley measured the X-ray spectra of 30 additional elements beyond the first ten. They, too, fell into line according to atomic number, clearly revealing where elements were missing … and where no new ones could fit.

Dissolve to Periodic Table. It is gradually filled in, as if the elements were answering a roll call. A question mark appears in box 43, which doesn't answer the roll call.

NARR: "For the first time," one scientist marveled, "it was possible to call the roll of the chemical elements – to determine how many there were and how many remained to be discovered."

BIOGRAPHER JOHN HEILBRON

The idea that somebody could know how many elements God created, that was terrific.

Wide shot of Periodic Table with all seven missing elements highlighted.

NARR: After Moseley's work, it was clear that there were seven *and only seven* elements remaining to be discovered.

HARRY MOSELEY

But since we can now predict the X-ray spectra of these elements, they should not be difficult to find.

Amabel opens a letter.

NARR: In 1914, Moseley's continuing work on the elements was interrupted when his country called.

Photo of Moseley in uniform

HARRY MOSELEY VO

My dearest Mother,

I am now a second lieutenant in the Royal Engineers …

NARR: England had been drawn into war by events in Europe.

Reprise of photo of Moseley with Trinity College classmates

NARR: Like many others of his generation, Moseley felt a duty to serve.

HARRY MOSELEY VO

… I was very lucky to get into the army so quickly because RE commissions are much in demand.

Archival photo of World War 1 troops

CHEMIST RUSSELL EGDELL, partly in VO

He had a bit of a difficulty actually getting into the army, because he wasn't an engineer and the Royal Engineers wanted engineers.

Photo of Moseley

BIOGRAPHER JOHN HEILBRON, partly in VO

He badgered the recruiting officers to allow him in.

Photo of soldiers bathing at the beach

NARR: By the summer of 1915, Moseley was stationed in Turkey.

HARRY MOSELEY VO

It gets hotter here by the day, and only cool nights and sea bathing keep life tolerable.

ERNEST RUTHERFORD, partly in VO

I had mixed feelings about the enlistment of so many young men of science – pride over their ready response to the country's call, apprehension about irreparable losses to science.

Moseley writes in the tent. On the table beside him is the latest care package from home, which includes a jar of precious Tiptree jam. His mother reads the letter in the garden.

NARR: On August 3, 1915, he wrote from Gallipoli.

HARRY MOSELEY VO

My insides returned to duty and let me once more enjoy the good things which are sent us, foremost among them your Tiptree jam.

Moseley hears a bugle call, puts on his cap, jots down a final word and leaves the tent. Image and sounds of World War I battle at Gallipoli.

NARR: One week later, as they attempted to take a ridge, Moseley's brigade was overwhelmed by Turkish troops.

Reprise photo of Moseley in uniform

NARR: The 27-year-old communications offer was shot in the head and killed.

Amabel grieves in the garden. Cut to shot of Moseley's name on a memorial list of war dead at Manchester.

NEIL TODD, MANCHESTER UNIVERSITY, partly in VO

The news of Moseley's death was a terrible shock at Manchester, because by that time it was already clear that Moseley was one of the most brilliant, young physicists of his generation.

Photo of Moseley, headline about Moseley's death: TOO VALUABLE TO DIE.

CHEMIST RUSSELL EGDELL, partly in VO

In the scientific community, there was a big sense of outrage, particularly from Rutherford, because he did feel Moseley was someone special.

ERNEST RUTHERFORD

The services he could have performed for his country … Instead they exposed him to the chances of a Turkish bullet.

Photo of Rutherford and Millikan at a Solvay Conference

NARR: Tributes poured in from around the world, none more moving than that of American physicist Robert Millikan, who had met Moseley during a visit to Rutherford's lab.

PHYSICIST ROBERT MILLIKAN

He threw open the windows through which we can glimpse the sub-atomic world with a clarity never dreamt of before.

Iconic photo of Moseley at Oxford

PHYSICIST ROBERT MILLIKAN VO

Twenty-seven years old … If the European War had done nothing worse than snuff out this one young life, that alone would make it one of most hideous crimes in history.

On a panel in the host scene, the Periodic Table fills in with all the elements Moseley predicted.

HOST

In the decades after Harry Moseley's death, chemists found all the missing elements he had left room for. By 1945, every space was filled, from the lightest element, hydrogen, to the heaviest, uranium. The Periodic Table was complete.

Except it wasn't. By this time, the next generation of element hunters had already begun a whole new chapter. They had figured how to *create new elements* – elements that didn't exist anywhere on earth.

Host steps forward to reveal photo of young Glenn Seaborg on a panel.

HOST

The central character in these events was a young American chemist named Glenn Seaborg. He set out with a simple desire to make one of these new elements.

Host steps forward again. A mushroom cloud appears on a second panel.

HOST

But he would end up changing the world forever, unleashing a force of unimaginable destructive power.

Cut to barbershop scene: A young man leafs through the January 31, 1939, issue of the San Francisco Chronicle while getting his hair cut.

NARR: The story begins in late January 1939, when a young physicist in Berkeley, California, learned of a startling discovery in an unusual way.

ERIC SEABORG, partly in VO

One of my father's colleagues, Luis Alvarez, was sitting in the barber shop getting his hair cut when he read about this in the paper.

Alvarez leaps from the chair, rips off the barber's bib and runs out of the shop.

PHYSICIST LUIS ALVAREZ, partly in VO

Buried on an inside page of the *San Francisco Chronicle* was a story from Washington. German chemists had split the uranium atom by bombarding it with neutrons. I stopped the barber, mid-snip, and ran all the way to the Radiation Laboratory to spread the word.

Photo of the Rad Lab exterior

LUIS ALVAREZ VO

The first person I saw was my graduate student, Phil Abelson.

Abelson sits at the control panel of the cyclotron. We hear the sound of running footsteps.

PHIL ABELSON, partly in VO

I was at the control console operating the cyclotron. About 9:30 a.m., I heard the sound of running footsteps outside.

Alvarez bursts into the cyclotron room and blurts out the news.

LUIS ALVAREZ

Phil, the Germans have split the uranium atom! Hahn and Strassman have done it. Uranium split in two!

PHIL ABELSON

When I heard what he had read, I was stunned.

Photo of Sather Gate at UC Berkeley in the 1930s

NARR: Word spread quickly across the University of California campus.

Photo of young Glenn Seaborg at Sather Gate

NARR: One of the first to hear the news was Glenn Seaborg, then a 26-year-old chemistry instructor.

ERIC SEABORG

He was just stunned, and he spent hours walking the streets of Berkeley thinking about it.

GLENN SEABORG

I was exhilarated at the discovery, but at the same time I felt stupid for having overlooked this possibility. I'd missed the chance for an astounding discovery.

Host enters studio. Suspended in mid-air to his left is an animation of the atom showing only red protons in the nucleus.

HOST

Many other had missed it too. In fact, the splitting of the atom – nuclear fission – was so unexpected that it forced scientists to rethink what they knew about the atom.

Camera pulls back to reveal a panel on which there is a photo of Rutherford's lab group. James Chadwick is highlighted when he's mentioned. The neutron appears in the nucleus.

HOST

To understand why, we need to step back a few years to 1932, when another of "Rutherford's Boys," James Chadwick, discovered the final piece of the atom: the neutron.

CU of the protons and neutrons together in the nucleus.

HOST

The neutron has almost the same mass as the proton, and they both occupy the nucleus. But the neutron is electrically neutral – hence its name.

Host reaches out and grabs a neutron from the nucleus. He throws it across the screen, and it enters a uranium nucleus.

HOST

Right away, scientists realized this made the neutron the perfect projectile for firing at the atom. Unlike those positive alpha particles that Rutherford and his students had been using, it would not be repelled as it approached the nucleus. It could go right in.

PHYSICIST JIM GATES

You didn't have to fight the electrical repulsion to get this object to go inside the nucleus and probe the structure there.

Photo of Enrico Fermi and his colleagues at the University of Rome in the mid-1930s

NARR: One of the first to use the neutron in this way was an Italian physicist named Enrico Fermi.

Animation illustrating Fermi's approach: A beam of neutrons fired at a sample of uranium results in a shower of fragments.

NARR: In 1934, Fermi began firing neutrons at uranium atoms, creating a shower of fragments he would then analyze.

In the animation, we now zoom in to see the interaction of a single neutron with one uranium nucleus. The neutron chips off a piece of the nucleus, and we see that the nucleus has lost two protons and two neutrons, resulting in a new element. It lands in the box for element 90, thorium, in the Periodic Table below it.

NARR: He found that a neutron sometimes chipped off a piece of the uranium nucleus, lowering its atomic number and turning it into a different element, a few spots lower in the Periodic Table.

Another fragment tries to land in the boxes from 82 (lead) to 91 (protactinium) but is rejected by all.

NARR: But some of Fermi's fragments didn't match any of the elements just below uranium. What could they be?

Photo of Fermi, then animation showing neutron absorption as he imagined it. The white neutron turns into a red proton.

NARR: Fermi concluded that sometimes an incoming neutron is *absorbed* by the uranium nucleus … and then spontaneously changes.

PHYSICIST JIM GATES

The neutron becomes a shape-shifter and changes itself into a proton!

In the animation, we again see one of the neutrons change into a proton. The number of protons in the nucleus ticks up to 93, forming a new element.

PHYSICIST JIM GATES VO

But when you change the number of protons in the atom, you change the chemistry. You have changed the identity of the atom.

Elements 93 and 94 (Ausonium – Ao – and Hesperium – Es) are added to the Periodic Table.

PHYSICIST DAVID KAISER, partly in VO

They eventually concluded, they published a paper saying they had found "transuranic elements" – elements that were even heavier than uranium. They figured they had pushed beyond the end of the Periodic Table.

Footage of Fermi accepting the Nobel Prize

NARR: For this remarkable achievement, Fermi won the Nobel Prize in December 1938. But even as he was shaking the hand of the King of Sweden, German scientists were making the discovery that would prove Fermi wrong.

Photo of grim Fermi. Push in to blackboard to reveal tiny neutron approaching huge uranium nucleus 238 times its size.

NARR: Like almost everyone else at the time, Fermi had underestimated the neutron.

PHYSICIST DAVID KAISER VO

It was very much smaller than the nucleus it was being fired at. It had no electric charge. It couldn't shove things around by electric repulsion.

Push in to the part of the Periodic Table Fermi hadn't checked

NARR: So Fermi's team hadn't checked to see if the neutron had broken the uranium nucleus in half, into much lighter elements.

PHYSICIST DAVID KAISER

They figured there's no way this tiny, little wimpy thing could bust apart something as huge, as massive, as an entire uranium nucleus.

GLENN SEABORG

Breaking a nucleus in two with a neutron would be like breaking a boulder in half by tossing a pebble at it. We all knew it was impossible for uranium atoms to break apart in that way.

Photo montage of Hahn, Strassman, Meitner and Frisch

NARR: But when the Germans repeated Fermi's experiments, they found that's exactly what happened.

Animation of the Hahn and Strassman discovery: Uranium nucleus splits in two like a water drop, the two fragments landing in the barium and krypton boxes of the Periodic Table.

PHYSICIST DAVID KAISER, partly in VO

They did not find things that looked heavier than uranium. They found well-known elements that were about half as heavy – much, much lower on the Periodic Table. The uranium nucleus had been split in two, in a way that no one had imagined possible or even worth looking for.

New York Times headline: VAST ENERGY FROM URANIUM ATOM.

NARR: The tremendous energy released when the atom split had profound implications for a world at the brink of war.

PHYSICIST DAVID KAISER, partly in VO

Across the world, physicists came to remarkably similar conclusions right away. Could the energy trapped in that nucleus be used to make an explosive unthinkably more powerful than conventional, chemical explosives?

Photo of young Seaborg in trench coat

ERIC SEABORG, partly in VO

A lot of people were thinking about the possibility of the atomic bomb. But my father, he was mostly thinking about the scientific implications.

NARR: For Seaborg, the discovery of fission presented an unexpected opportunity – a second chance to be the first to discover elements beyond uranium.

In the Periodic Table, elements 93 and 94 disappear.

ERIC SEABORG, partly in VO

Fermi had said he had discovered all these transuranium elements. Those findings just went out the window. So if there were transuranium elements to be found, well, they were still there to be discovered.

Photo of the Berkeley campus in the 1930s

NARR: And Berkeley was the perfect place to do it.

Photos of Lawrence and his 27-inch cyclotron

NARR: Under the leadership of Ernest Lawrence, Cal's Radiation Laboratory had led the world in the development of the cyclotron, a device for flinging subatomic particles at ever-greater speeds.

Animation of cyclotron

PHYSICIST JIM GATES, partly in VO

What Lawrence did was figure out that you could take a proton, or some particle that you are accelerating, and put it in a circular path, using magnetic fields to make it go in a circle.

NARR: By rapidly switching the electrical charge of the two "dees," Lawrence kept the proton chasing the ever-moving negative plate, boosting its speed on each pass.

PHYSICIST JIM GATES, partly in VO

You hit it once. When it comes around again, you hit it again, you hit it again, you hit it again. And then suddenly, you've got this really energetic tiny particle that you can then aim to your target and use it to study what's going on.

Photo of young Edwin McMillan

NARR: Just weeks after the news of fission broke, a young Berkeley physicist named Ed McMillan …

McMillan enters the cyclotron room and places his sample in front of the neutron window.

NARR: … set out to study this new phenomenon. He would repeat the Germans' experiments by bombarding uranium atoms with neutrons from the cyclotron.

Back in the lab, McMillan brushes a yellow slurry onto a small piece of white filter paper and sets it aside to dry.

NARR: To prepare his target, he applied a thin layer of uranium oxide to a piece of filter paper. His goal was to split the uranium atoms and track how far the resulting fragments flew.

PHIL ABELSON

Ed started by capturing the fission products in a stack of thin foils.

McMillan makes a stack of cigarette papers.

PHIL ABELSON VO

But eventually he found that cigarette papers worked just as well.

He puts the cigarette papers on top of the now-dry filter paper target, then places them all in a small frame. We freeze it for animation. In the animation, a beam of neutrons strikes the target, sending fragments flying.

NARR: He stacked the cigarette papers behind the uranium-coated filter paper. When this target was struck with neutrons from the cyclotron, atomic fragments would scatter in all directions.

The animation now rotates to reveal the stack of papers. We separate them to show how the fragments are caught in different layers.

NARR: Some would burrow into the stack of cigarette papers, penetrating to different depths.

McMillan loosens the frame and peels off the cigarette papers one at a time, starting with the one farthest from the filter paper. He tests each one with a Geiger counter and finds they are mildly radioactive – no surprise.

NARR: McMillan then checked the papers one at a time to see how far the radioactive fragments had traveled. As expected, he found different levels of radioactivity on each paper.

After the last cigarette paper, McMillan tests the filter paper with the Geiger counter too. To his surprise, it is much "hotter" than the cigarette papers.

NARR: The surprise came when he measured the target itself. It was much more radioactive than expected, suggesting that one product of the reaction hadn't moved at all but remained on the filter paper.

GLENN SEABORG

This lack of mobility implied that it might not be a fission product at all.

McMillan thinks about what his finding might mean.

NARR: As the possibilities raced through McMillan's mind, he quickly arrived at an explanation: This fragment had stayed put because it was much heavier than the others.

Reprise of the Fermi animation showing an incoming neutron being absorbed into the nucleus and changing into a proton.

NARR: Instead of splitting into smaller pieces, a uranium atom had *absorbed* an incoming neutron, and then that neutron had spontaneously changed into a proton, in just the way Fermi had proposed.

ERIC SEABORG

What McMillan was seeing was what Fermi thought he was seeing.

In the animation, uranium's atomic number increases by 1, becoming element 93.

NARR: If so, this would be a brand new form of matter – the *real* element 93.

Abelson and McMillan at work on chemistry experiment

NARR: But to prove it, he would need to show that its chemistry was unlike any other element … a precaution Fermi hadn't taken. For help on this, McMillan turned to an old friend – Phil Abelson, who was back in Berkeley on a short vacation.

With McMillan watching over his shoulder, Abelson performs chemical tests on McMillan's activity. A white precipitate begins to fall in the tube. Abelson and McMillan shake hands in celebration.

ERIC SEABORG VO

Phil Abelson was really taken by this activity McMillan had found. And he decided he was going to follow up on it. It was certainly a very productive vacation, because it didn't take him long – really a few days – to rule out that it was any of the other elements, 92 and down.

PHIL ABELSON

We had discovered element 93.

Animation: In close-up, neptunium takes its spot in the 1940 Periodic Table, one box to the right of uranium.

NARR: They named it neptunium, because it was beyond uranium, just as the planet Neptune is beyond Uranus.

The Periodic Table turns, and we look down the bottom row of elements as new boxes are added with question marks.

NARR: With this discovery, the search for elements had entered a whole new realm. Up to now, it had been a matter of *finding* elements that already existed in nature. But from this point on, element hunters would be *creating new elements*. There was no telling how far the Periodic Table might extend.

Photo of McMillan at blackboard

NARR: McMillan immediately set out to create element 94.

Photo of the Berkeley Faculty Club

GLENN SEABORG, partly in VO

While Ed was doing this research he lived at the Faculty Club, just down the hall from me. I kept track of his progress at breakfast, in the hallway, even in the shower.

Photo of McMillan

ERIC SEABORG VO

My father was fascinated by McMillan's search for 94, and he knew that McMillan was closing in on it. And then suddenly McMillan disappeared.

Photos of the MIT radar lab, scientists at work there

NARR: Like many other American scientists, McMillan had been called to help the country prepare for war. He had moved to the Massachusetts Institute of Technology to join the team developing radar.

ERIC SEABORG

So my father wrote to him and asked him if he could continue with this project, looking for 94 as a collaborator. And Ed McMillan very graciously said, “Yes. I would be delighted if you would do so.”

GLENN SEABORG

If Ed had left for MIT just a few months later, he certainly would have been the one to find element 94. As it was, I was in the right place at the right time. It would be the discovery that changed everything for me.

Seaborg plasters yellow uranium powder onto a piece of copper plating the same size as McMillan's cigarette papers.

NARR: As a chemist, Seaborg was thrilled at the chance to create a new element. But he conducted his research with one eye on the changes that were sweeping the world.

Headlines and war footage

NARR: In the past year, Germany had invaded Poland. France and Great Britain had declared war. Italy had sided with Germany. Fighting now raged across much of Europe and North Africa.

Photo of Einstein ca 1939

NARR: Albert Einstein, alarmed at these events and aware of Germany’s head start in nuclear research …

Copy of Einstein’s August 1939 letter to FDR, with key phrases highlighted

NARR: … had written to President Roosevelt, urging him to launch an American effort to create an atomic bomb powered by the fission of uranium.

Animation shows uranium dividing into two kinds – U-238 and U-235.

NARR: By now it was clear there are two very different kinds of uranium. Only one of them was easy to split.

PHYSICIST DAVID KAISER VO

The one that would do that most readily was a very unusual kind of uranium that had fewer neutrons in the nucleus, this very fissionable, potentially explosive kind of U-235.

ERIC SEABORG

But that is only about one percent of all the uranium. The much more common element is the uranium-238, but it doesn’t fission.

Photo of Seaborg

NARR: But Seaborg realized he might be able to turn this inactive uranium into a new element that *was* capable of splitting.

GLENN SEABORG

We knew early on that element 94 could be a big prize. If we could transform U-238 into a fissionable material, we would increase a hundredfold the amount of material usable for a bomb.

Seaborg loads the now-dry copper plate into the same metal frame McMillan had used for his cigarette papers, then exits with it.

NARR: With this goal in mind, Seaborg picked up where McMillan had left off.

Animation shows that U-238 absorbs a neutron, becoming Uranium 92-239, then decays to Neptunium 93-239. Next we see the further change Seaborg contemplates: 93-239 decays to 94-239 as a neutron becomes a proton.

NARR: He knew from McMillan's work that uranium bombarded with neutrons sometimes changed into neptunium. But neptunium itself was radioactive – spontaneously changing form. Could it be "shape-shifting" into element 94?

Joined by Arthur Wahl, Seaborg places the copper plate uranium sample in front of the cyclotron neutron window. They talk briefly.

NARR: To find out, Seaborg and graduate student Arthur Wahl used the Berkeley cyclotron to create a sample of neptunium, in the same way McMillan had.

GLENN SEABORG (TO WAHL)

Now Arthur, what we want here is the sample directly in line. You see?

Seaborg and Wahl depart.

NARR: They would then watch for signs that neutrons inside it were changing into protons, forming element 94.

As Seaborg watches, Wahl places a copper plate with a thin layer of dried yellow slurry atop a special detector with a toggle switch. Seaborg flips the switch, and the counter immediately begins crackling, indicating that element 93 is giving off beta particles (electrons) as neutrons in its nucleus turn into protons. Wahl moves the copper plate to a dish atop the lab shelf.

NARR: Sure enough, a special radiation detector showed that's exactly what was happening. But to be sure they had a new element, they'd need to create enough of it to test its chemistry.

Zoom to copper plate on dish. In animation, atoms decay into 94.

NARR: For that they'd have to wait for neptunium to break down, atom by atom, into what they hoped was element 94.

Seaborg and Wahl perform chemical tests in the lab late at night. Superimposed on the scene is a Periodic Table in which, one by one, all the known elements are eliminated.

NARR: After a month, Seaborg and Wahl had enough material to test. Mindful of Fermi's mistake, they painstakingly checked to make sure the product of their experiment was not an element that had already been discovered.

ERIC SEABORG VO

And it took them weeks to actually separate it from every other known element, but they were eventually successful in doing that.

As Seaborg adds drops to the liquid, it turns purple. This is what they are looking for. It shows that this substance behaves like no other known element.

NARR: The last possibility was finally eliminated late one night in February 1941.

In the Periodic Table graphic, the last elements to be ruled out are actinium, the 15 rare earths, and finally thorium, leaving only one possibility: Element 94. Pu takes its place alongside Neptunium.

NARR: There was then no doubt. They had discovered element 94: plutonium.

Footage of Seaborg and Wahl after their discovery

GLENN SEABORG, partly in VO

We felt like shouting our discovery from the rooftops. Under normal circumstances, we would have rushed to publish our claim to the discovery of a new element.

ERIC SEABORG

But they realized that if this was a fissionable element, it was of military importance, and there was a war going on. And so they actually had to keep it secret.

Seaborg and Wahl work in the lab.

PHYSICIST DAVID KAISER, partly in VO

Maybe for the first time ever in this history of the race to find and create new elements, Seaborg was not able to just tell anyone he knew about this very exciting new discovery. What had changed was the condition of the world.

Bombing of London footage, Japanese aggression in Asia, Hitler

NARR: By now, German planes were regularly bombing English cities … Japan had entered the war … and there were reports that Adolf Hitler had launched an effort to create an atomic bomb.

Roosevelt's response to Einstein, footage of Lyman Briggs at the blackboard at a meeting of the Uranium Committee

NARR: In response to Einstein's plea, President Roosevelt had authorized a modest research program into the possibility of a weapon fueled by the fission of uranium-235.

PHYSICIST DAVID KAISER, partly in VO

And Seaborg had realized, here is a type of material he'd made from scratch in the laboratory that might be an even more efficient fuel for that kind of weapon.

Plutonium swirls in the flask.

NARR: But was it? *Discovering* plutonium was just the first step.

Seaborg and Segre prepare uranium tubes for bombardment by the cyclotron. Photo of Segrè.

NARR: Seaborg would need to create much more of it to find out if this new element was capable of fission. Joining Seaborg to answer this critical question was Emilio Segrè, a Jewish physicist who had fled Italy amidst rising anti-Semitism.

Segre closes the box and places it in front of the cyclotron's neutron window. They exit.

NARR: They placed a two-and-a-half-pound sample of uranium next to the cyclotron and bombarded it with neutrons.

Seaborg and Segrè, wearing lead-impregnated gloves and goggles, leave the chemistry lab carrying a long pole from which a lead bucket is suspended.

ERIC SEABORG, partly in VO

During the early work of the discovery of plutonium, they were working with very small amounts, so they were not concerned about radioactivity. But to test for the fissile nature, they had to use much larger quantities. And that meant that they had to worry about radiation exposure. They were not really set up to do that kind of work, but they had to just improvise. So they would have goggles. They would have lead-lined gloves, and they ended up using buckets on poles. On looking back on it, my father said, "Gee, you know, it really seemed primitive," although they managed to do it.

Seaborg and Segrè stand behind a concrete wall with a small hole that allows them to peer through. They use a long pole with a "gripper" on the end to pour liquid from an Erlenmeyer flask into a beaker filled with yellow powder (the "irradiated uranium" that was in the tubes exposed to the cyclotron.) Later, Seaborg cranks a centrifuge.

NARR: Seaborg and Segrè separated element 93 from the rest of the reaction products … spun it to further purify the sample … and then did it all over again.

Reprise images to suggest repeating the process

GLENN SEABORG, partly in VO

We called it a night at 10 p.m., but we were back first thing in the morning to repeat the process – six cycles over the next three days. It was tedious work, but the hours flew by, because we knew we were on the verge of a discovery.

Seaborg holds up a centrifuge tube with a small amount of white material in the bottom.

NARR: The work was finally completed in March 1941.

Seaborg places the sediment from the centrifuge tube in a platinum dish the size of a dime. He spreads it smoothly over the dish, and Segrè squeezes a dab of Duco cement from a tube onto the sample. Seaborg labels it "A."

ERIC SEABORG, partly in VO

The results of all these separations was a very small amount of plutonium that they put on a small dish. And they actually covered it with Duco Cement so that it wouldn't go anywhere.

NARR: They labeled it Sample A.

The team enters the cyclotron room and places Sample A in front of the cyclotron.

GLENN SEABORG VO

Then came the moment of truth: Was this new element fissile? Was it a potential source of immense power?

Joe Kennedy arranges the detection device. Seaborg, Segrè and Wahl gather around to listen. Seaborg says: "Okay, Joe." Joe flicks the switch. We hear the sound of fission.

GLENN SEABORG VO

We placed Sample A in the path of the cyclotron's neutrons … and had our answer almost immediately. The counter registered the unmistakable kicks of fission.

The men's faces show that this is a sobering moment.

ERIC SEABORG, partly in VO

They knew immediately what the implications were. There was a large portion of uranium that could not be used in a bomb. What plutonium offered was a chance to turn all of that uranium 238 into a fissionable material.

PHYSICIST JIM GATES, partly in VO

Seaborg figured out how to take this uranium 238 and turn it into a new element, plutonium, which readily fissions.

ERIC SEABORG

And that meant there could be much more material made for bombs or for use in nuclear power.

Archival footage of car arriving, man entering building

NARR: Seaborg's discovery soon came to the attention of the leaders of the nascent American effort to create an atomic bomb …

Photo of Compton, Conant and Bush together

NARR: … including physicist Arthur Compton … and Harvard president James Bryant Conant … who met in late 1941 met to discuss Seaborg's findings.

ERIC SEABORG

That lunch where they discussed the possibility of creating a bomb was on December 6, 1941.

Photo of the Faculty Club, sound of football game on the radio

ERIC SEABORG VO

The next day, my father was home at the Faculty Club, listening to a football game on the radio, when the announcer broke in.

Footage of Pearl Harbor attack and sound of radio bulletin

RADIO ANNOUNCER

We interrupt this program to bring you a special news bulletin. The Japanese have attacked Pearl Harbor, Hawaii, by air, President Roosevelt has just announced ...

GLENN SEABORG, partly in VO

Our team had already been working hard in anticipation of war. In an instant, "the day that shall live in infamy" made work on anything else seem irrelevant.

FDR declares war before Congress, to thunderous applause.

PRESIDENT ROOSEVELT

The American people, in their righteous might, will win through to absolute victory!

War headline

NARR: With America now in the war, the atom bomb effort took on a new urgency.

Photo of Compton and Vannevar Bush in deep discussion

NARR: The leaders of the effort asked Seaborg …

Footage of University of Chicago during the war

NARR: … to report to the University of Chicago, where he would spend the next four years working on the Manhattan Project.

Photo of young Seaborg and his wife

NARR: Newly married and just 30 years old, he was put in charge of a team responsible for separating plutonium from other fission products.

Fermi highlighted in group shot of Chicago scientists

NARR: The responsibility for *creating* the plutonium fell to Enrico Fermi, who had fled fascist Italy after winning the Nobel Prize.

Footage of Fermi at work in Chicago, paintings of the Chicago Pile 1 experiment

NARR: In an abandoned squash court under the university football stands, Fermi's team built a nuclear reactor out of wood, graphite and uranium. In a historic experiment in December 1942, "Chicago Pile 1" went critical, spitting out energy and neutrons at an ever-rising rate.

PHYSICIST DAVID KAISER

Their first-ever nuclear reactor was actually creating a self-sustaining nuclear reaction.

Animation shows how the chain reaction worked.

PHYSICIST DAVID KAISER VO

Certain nuclei would split in two. That would release some neutrons as well as energy.

PHYSICIST JIM GATES, partly in VO

Those neutrons then collide with other atoms. And then you get a cascade, which we call a chain reaction.

End of animation shows the creation of plutonium.

NARR: Fermi's chain reaction not only showed an atomic bomb was possible but also provided a more efficient way to turn uranium-238 into plutonium.

Archival footage of Fermi

NARR: From Fermi's experiment emerged two distinct strategies for making an atomic bomb.

Archival photos of the Manhattan Project

NARR: One would seek to concentrate the tiny amount of natural uranium that could be split. The other would focus on making plutonium.

GLENN SEABORG

Our **challenge was to find a way to separate relatively small amounts of plutonium from tons of material so intensely radioactive that no one could come near it.**

Composite image of Met Lab chemists

NARR: As the magnitude of the challenge became clear, Seaborg would recruit more than a hundred chemists to join him in the effort.

GLENN SEABORG

"No matter what you do with the rest of your life," I said, "nothing will be as important as your work on this project. It will change the world."

Photos/footage of the huge extraction plants at Hanford

NARR: In 1943, banking on the process Seaborg's team had developed, the U.S. government began building a huge separation plant in Hanford, Washington. Here, in buildings as long as three football fields, plutonium would be made by remote control.

More Hanford images showing the size of the place

ERIC SEABORG, partly in VO

When my father got out there, he was just awestruck. And he couldn't believe that this element that he had discovered would result in these huge plants being built.

Archival footage of Los Alamos scientists preparing the test bomb known as "the gadget"

NARR: From Hanford came the pounds of plutonium that were needed for a bomb.

Alamogordo map with drawing of tower

NARR: On July 16, 1945, at a desert site near Alamogordo, New Mexico …

Archival footage: Bomb is hoisted into tower.

NARR: … scientists from nearby Los Alamos conducted the first test of an atomic bomb … with a weapon made from plutonium.

Footage of Trinity explosion

NARR: A blinding flash of light and a deafening explosion signaled the beginning of the nuclear age.

Continuing footage of the Alamogordo explosion, Hiroshima aftermath images

NARR: Just three weeks later, an American bomber dropped a uranium bomb on the city of Hiroshima, killing 100,000 Japanese.

Nagasaki aftermath images

NARR: Three days after that, a plutonium bomb destroyed the city of Nagasaki, finally bringing the war to an end.

VJ Day photo, Physical Review paper on the discovery of plutonium, finally published in 1946. CU shows names of Seaborg, McMillan, Kennedy and Wahl.

NARR: Only then could Seaborg reveal the discovery that had made this bomb possible.

Photo of McMillan. Photo of Seaborg accepting the Nobel Prize.

NARR: For their discovery of the first two elements beyond uranium, Ed McMillan and Glenn Seaborg won the Nobel Prize in Chemistry. But Seaborg wasn't content to rest on his laurels.

PHYSICIST DAVID KAISER

Seaborg had the ambition to create more new elements, to go beyond element 94, beyond plutonium.

Bottom-lit photo of Seaborg and other scientist over a vat

NARR: So even before the war ended, he and his Chicago team had resumed the hunt for new elements.

Sound up from the Nov. 11, 1945, edition of the radio show the Quiz Kids, including applause. Photo of Seaborg with the host and a little girl.

RADIO ANNOUNCER

Thank you, Bob Murphy, and good evening everyone. Well, children ...

ERIC SEABORG VO

Late in 1945 my father was on a radio program called the "Quiz Kids."

RADIO ANNOUNCER

... a most distinguished scientist, Dr. Glenn T. Seaborg.

ERIC SEABORG, partly in VO

And one of the kids asked him, as kids do, "Have you found any new elements lately?"

Photos of people listening to radio

GLENN SEABORG (ON THE RADIO)

Well yes, Dick. Recently there have been two new elements discovered – elements with atomic number 95 and 96.

ERIC SEABORG

And that's how the world came to know about americium and curium.

Photo of Albert Ghiorso with Seaborg

NARR: Back at Berkeley after the war, Seaborg and his team continued their quest …

Animation: An alpha particle is fired at an americium atom. It fuses to form berkelium.

NARR: … bombarding heavy elements with smaller ones in hopes they would fuse to form a brand new type of matter.

Photo of Seaborg at blackboard with list of elements ending in berkelium and californium

NARR: They created five new elements in the next ten years, including berkelium and californium …

Animation: The elements from 89 to 92 move to a new position below the lanthanides at the bottom of the table.

NARR: … and rearranged the Periodic Table in the process.

Photo of Seaborg and McMillan. The transuranic elements are highlighted in the modern Periodic Table.

NARR: Since Seaborg and McMillan first ventured beyond uranium, more than 25 new entries have been added to the table …

Pictures of these pioneers appear in the table in their element boxes.

NARR: … including elements named for Lawrence … Mendeleev … Fermi … Einstein … Curie … Rutherford …

Photo of Seaborg pointing to his element 106, seaborgium

NARR: … and Seaborg himself.

Photo montage of modern element hunters

NARR: Around the world today, others continue to hunt for new elements, using techniques like those Seaborg pioneered.

Wide shot of the Periodic Table. From their boxes, four elements emerge to fill four circles: potassium explodes/oxygen burns brightly/phosphorus glows in its vessel/radium glows in the dark.

NARR: So far there are 118 known elements, each with its own distinct personality. And yet all these elements – and any new ones we might find – are made up of just a few things in combination.

The Greek element animation fills the four circles, then dissolves to reveal the structure of the atom.

NARR: Not air, water, earth and fire, as the ancient Greeks believed ... but protons, neutrons and electrons.

The three particles appear in front of the host.

HOST

Amazingly, all of matter – planets and stars, plants and animals, you and me – it's all made of just these three basic parts – protons, neutrons and electrons – mixed in different ratios.

Reprise images from the series, featuring the seven major characters

NARR: We know all of this because of a long chain of people who've struggled to answer the simple question: What is the world made of?

CHEMIST GREG PETSKO, partly in VO

We're surrounded by matter. It's everything that we see and interact with. And yet, at the time this quest began, nobody understood what it was made of. Nobody understood anything about it.

HISTORIAN LARRY PRINCIPE, partly in VO

Just making one tiny step in the understanding of the natural world sometimes takes generations. There's no guide book to tell us how to do this. We have to figure it out.

AUTHOR RICHARD HOLMES, partly in VO

Nature is wonderful and mysterious, and it's hidden. But if you apply the tools of science, you can make it reveal its secrets.

Photos of the seven main characters are arrayed on panels behind the host as he walks.

HOST

It's taken centuries just to identify the elements, with each generation of scientists building on the work of those who came before. But this is just the first step.

Still to be answered are myriad questions about how these building blocks fit together to make the infinite variety of substances in nature – and how *we* can combine them in novel ways to make fantastic new materials nature never imagined. Answering those questions will take the efforts of many more scientific detectives like the ones we've met. As much as we've learned in the search for the elements, we've only begun to solve the mystery of matter.

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Banner: More from The Mystery of Matter

Photos of Seaborg and his colleagues, ending with Seaborg pointing to element 106 in the Periodic Table.

ERIC SEABORG, partly in VO

The team that discovered element 106 was trying to decide what to name this element. And they went through a long list of names until one day Al Ghiorso walked into my father's office and said, "What would you think of naming it seaborgium?" And my father was just dumbfounded and thrilled. And he said this would be the greatest honor he'd ever received, because it would be forever. As long as there were Periodic Tables, there would be seaborgium.