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[SQUEAKING] [RUSTLING] [CLICKING]

DAVID KAISER: Today we're starting this new unit for the class. So the first main unit-- we had a kind of warm-up unit of a kind of 19th-century legacy, as you probably remember. And then we spent a good chunk of time right up until the previous class session on looking at physics really during the first 20 or 30 years or so of the 20th century-- the real focus on what were some of the kind of approaches conceptually and intellectually that physicists in many parts of the world were using to try to make sense of nature.

And that got kind of bound up with what we now call the origins of modern physics-- relativity and quantum theory in particular. We were also looking at the kinds of institutions. What kinds of settings were many of those investigations taking place in?

And so with today's class and for the next several to come, we're now looking at the next main unit, which is when physics and physicists start interacting much more directly with statecraft, with formal overt politics, with governments-- nation-state governments and even international relations.

And that, as we'll see, brings up a new host of questions, intellectual challenges, institutional relationships and all that for physicists throughout-- what we'll mostly focus on-- throughout various parts of Europe and then the United States. Although, there's lots to be said about other parts of the world too, and I'd be glad to talk about that if you have questions.

So today we're launching this next main unit of physics-- physicists and the state, meaning through governments. And we're going to start by looking actually at developments in Germany where so much of that work on what we now call modern physics had unfolded. So that's our job for today.

We have, as usual, three main parts for the class. We're going to recap or revisit some material that we actually looked rather briefly at a few sessions ago when we were talking about Einstein and the general theory of relativity and this movement that was called Deutsche Physik, which is usually translated into English as Aryan physics. A literal translation would be German. But it really meant this kind of race or racially based notion of what a proper approach to physics would be. So we'll talk about Deutsche Physik.

Then we'll pivot and talk for a good chunk of today about some developments in nuclear physics, which is quite, quite new in this period. And in particular, the ideas about nuclear fission. And as you see there, again, optional lecture notes on the course Canvas site to dig into some of that a bit more. I'll go through quickly some things, but there's some more details in the optional notes.

And the last part for today is really looking at the collision or the union of these first two topics. And we'll look at how did Werner Heisenberg himself and many of his immediate colleagues who stayed within Germany after the rise of Hitler, what did nuclear physics mean for them? And what did they think they were doing as they worked very, very hard during the war years on topics related to nuclear physics and nuclear fission?

So that's what we're going to talk about today. And then on Wednesday, we'll turn and look at some developments in Britain, and then especially in the United States around similar timescales.

OK. So this is just a reminder-- something we talked a little bit about when we talked about general relativity. As early as the spring of 1920-- I believe the very first rally was April or so of 1920-- several political opportunists within Germany took advantage of the fact that Einstein himself, as well as his general theory of relativity, had become kind of overnight sensations.

Einstein was everywhere in the news after the dramatic eclipse expedition results. He was heralded around the world as this amazing genius who had toppled Isaac Newton's physics. And so some opportunists within kind of war-ravaged Germany took advantage of Einstein's fame to get their own message out. Their message was not really about physics, so they used physics-- or the debates about some ideas in physics-- to stage what was really ultimately a kind of political movement.

So they began staging anti-relativity rallies in places like sports arenas and opera houses and music halls and so on. And the kind of public face-- the faces that were most often headlining these events-- were these two German Nobel Laureates in physics, both experimental physicists-- Johannes Stark and Philipp Lenard.

And again, there's all kinds of ironies here. Stark had actually invited Einstein back in 1907 to write a review article on Einstein's own work because Stark thought it was interesting but not getting sufficient attention. Philipp Lenard won his own Nobel Prize in 1905 for Lenard's experiments on the photoelectric effect, which of course, triggered Einstein's imagination directly. These folks had all kinds of physics interests in common in the early years of the 20th century. But by the 1920s, they had really come quite far apart.

So the rhetoric of what became known as the Deutsche Physik, or Aryan physics movement, was that of the tatmensch, the man of action, in their terms, that Newton and Galileo and Michael Faraday, according to people like Philipp Lenard, had all been Aryan. They'd all been of this what Lenard and Stark considered the kind of purest kind of racial stock, that they were just like the kinds of people the Nazis wanted to further elevate, according to Lenard, even though Newton and Galileo and Faraday themselves would certainly not have recognized that as such.

And Lenard argued that these people, unlike people like Einstein, these older heroes of physics had partaken in the same kind of active-- man of action kind of spirit as Adolf Hitler himself. Really quite striking to go back and read some of this material.

And as I mentioned in the previous time, in one of Lenard's books from the 1940s, he would include these portraits of people like Isaac Newton shown here to try to make the point that these people did not have so-called Jewish features, that even literally the shape of their face, their nose and these things proved, according to Lenard, that they were of appropriate pure racial stock, unlike the people that Lenard now was denigrating so vehemently.

And so the group began on the fringes. This was really a fringe effort starting in 1920. But just a little over a decade later, they had moved squarely into the center within Germany, especially after the Nazis achieved power in January of 1933. Again, as you may know, Adolf Hitler was elected chancellor of Germany in late January of '33. And the entire Nazi party then began to take over or be put in charge of a series of German government ministries.

And so in particular, they took over things like the Education Ministry. As you may remember from early in class, in Germany in particular, especially after there was a single unified Germany, there was one federal level, government level ministry that would place professors in basically every open slot within this kind of state-run university system.

So the adherence of Deutsche Physik, who had begun as early as 1920, were suddenly basically in charge of things like every single professorial appointment in all the universities in Germany. Of course, much beyond that as well.

So Hitler's elected in 1930-- in January of 1933. By April of that year-- very quickly-- the Nazis had begun to implement so-called civil service laws. These were basically race-based requirements for people to hold government positions. And this included things like university faculty. There were state-run universities.

So the so-called civil service laws which forbid people of non-Ayran descent, like Jews and others, from holding government jobs, this starts to trigger a very, very rapid exodus of scholars out of Germany. Either they were fired, or they were not personally fired, but were concerned about the direction things were heading, and they left in protest over the way their colleagues and students were treated.

And so this triggers about 100 physicists and mathematicians who leave Germany pretty quickly starting in around 1933. And many of them head toward both Britain and the United States. They move. Some of them move permanently. Some of them move for the duration of the wall and then relocate back to Germany. But many of them never went back.

So most famously, Einstein himself left Germany, renounced his position with the Prussian Academy of Sciences, and he moved to the Institute for Advanced Study in Princeton, New Jersey. In fact, he was the first faculty member hired there. The Institute itself was brand new. So Einstein moves to the United States.

Erwin Schrodinger, who is not Jewish, but nonetheless was very concerned very quickly at the direction of these so-called civil service laws, he resigned his position in Berlin. He moved to Oxford and then settled in Dublin for the duration of the war.

Emmy Noether, who was an immensely influential mathematical physicist from Gottingen, she left Germany and she was hired at Bryn Mawr, a women's college in Pennsylvania. Max Born also left Gottingen. He went first to Cambridge, then to Edinburgh for the duration of the war.

Younger scholars, like Hans Bethe, left positions in Germany. And he moved to Cornell and had a very, very long, long, long career at Cornell. He arrived at Cornell around 1935, and he stayed there. He was a professor there for maybe 60, or even more than 60, years. He had an enormously long career.

James Franck moved to the University of Chicago, Felix Bloch to Stanford. Viki Weisskopf eventually makes his way to MIT, first by way of Rochester and so on. It's literally 100 of these cases that have been well-documented.

And what's really important to keep in mind is that these were by no means easy transitions. For some, they were pretty easy. Einstein was welcomed immediately at the Institute for Advanced Study. It was a great boon for that new young institute. But many of these other folks who were neither so famous as Einstein, nor entering such brand new institutions, for many of these other folks it was actually not an easy move.

The United States itself, like many parts of the world, not just in Europe or North America, was deep into a Great Depression. This was already several years in. So there were many US-based scholars in this case looking for university positions, as well as all kinds of jobs. Unemployment was rampant throughout the United States.

But even beyond that, there was an entrenched, and again, by now well-documented, anti-Semitism throughout many, many US universities, including sometimes most rabidly among the most elite universities-- the Ivy League and others like that-- so that sometimes it was actually hard to place these people who were extremely eminent and already decorated in their fields. But many US universities balked or dragged their feet.

An example of that involves Robert Oppenheimer-- someone we'll be talking quite a lot about in the coming lectures. Oppenheimer was born in New York City. He wasn't someone who had to flee Germany. But when he was hired at Berkeley in 1929 before the rise of the Nazis, the department had had to work extra hard to get him hired in a department that already had something like 60 faculty-- it was a huge department-- because the department already had one other person of Jewish background in the department.

And so the department chair had to fight against the notion of having, quote unquote, "too many Jews" in a huge department by hiring this second one in. And that was even before you have this kind of exodus with the rise of the Nazis.

Likewise, at Dartmouth College-- my own alma mater, so I'm not picking on a stranger here-- again, once these outflow began in the early '30s, correspondences turned up that they were perfectly happy to bring in a refugee faculty candidate as long as the candidate, quote, "shouldn't seem too Jewish."

So there was a kind of entrenched anti-Semitism among even very, very elite, or especially very elite US universities. And that compounded the difficulties of placing some of these people, many of whom had to flee under very dire circumstances. OK. That's for the people who did leave after the rise of the Nazis. What about some who stayed behind?

So within Germany, especially once the Nazis had taken over, Nazi officials, which included the German Education Ministry and beyond, began criticizing physicists who were not themselves of Jewish background, but who seemed to demonstrate what at least the Nazi officials considered insufficient loyalty to the regime.

And one way that these folks supposedly demonstrated insufficient loyalty was that they continued to teach what was by that time branded so-called Jewish physics, which meant physics either by people who were of Jewish background, like relativity, or physics that struck some of these Deutsche Physik acolytes, like Stark or Lenard, as being somehow too mathematical, too abstract to remove from kind of proper forms of reasoning.

Often, it was actually just more crude. Was that work done by someone who was Jewish? Then it's Jewish physics. Often, it was just a simple conflation.

This reached its real apogee, the real highlight, or the highest point of this kind of attack occurred in 1937, so several years into the regime, when in fact, the acolytes of Deutsche Physik, who now had the ear of the German Education Ministry, they managed to block the appointment of Werner Heisenberg, who everyone within Germany and beyond Germany had just simply assumed would be appointed, would get a big promotion when his own main mentor retired.

So as you may remember from some lectures on so-called old quantum theory a few sessions ago, Arnold Sommerfeld was the kind of head professor, the ordinarius professor, in Munich for theoretical physics. He trained an enormous number of gifted disciples, including Heisenberg, Wolfgang Pauli, Hans Bethe-- just a huge list.

And by this point, Heisenberg was clearly Sommerfeld's most famous, most accomplished student. Heisenberg had already received the Nobel Prize by this point for his work on quantum theory. Sommerfeld retired after a long career. And everyone just assumed, including Heisenberg himself, that the central ministry would simply appoint Heisenberg as the successor.

Instead, the Deutsche Physik kind of ideologues organized a press campaign against Heisenberg labeling him what was called a white Jew. And again, that was their term. They said, we know he's not personally of Jewish background, but he behaves in too friendly a manner, in their reckoning. He was too supportive of things like Jewish physics because he kept teaching relativity, for example, in his classes. So they labeled him a white Jew and began a real kind of press smear campaign in the Gestapo-controlled press.

Things could really have gotten worse. In fact, there was a real concern that Heisenberg himself might have been sent off to a concentration camp, or certainly could have faced much worse treatment than only being denied a promotion.

And what finally stopped the attack was that Heisenberg's mother interceded directly with a close family friend, who happened to be the mother of Heinrich Himmler. Himmler's shown here in this circle. Himmler, by that point, was the chief of the SS, one of these paramilitary Nazi forces. Here's Himmler with Hitler and other Nazi officials just a few years before they kind of took over.

So it was really kind of an accident of who knows who. Heisenberg's mother calling up the mother of Himmler because they had known each other when they were each younger and basically said, can't our boys get along? It was quite extraordinary. It took that level of backroom negotiations to make sure that not worse happened to Heisenberg than only getting passed over for a fancy promotion. OK.

So that's usually seen as the kind of apogee of the power of this Deutsche Physik movement within Germany. Obviously, the Nazis weren't done in 1937. As I'm sure you know, the war dragged on until 1945. But this was really the high point of this kind of power of Deutsche Physik.

So not that the Nazis went away, but this notion of having a kind of racially pure or kind of ideological tests for physics, that begins to wane very soon after this very dramatic showdown over Heisenberg's promotion. And in fact, what many historians have come to conclude is that the regime-- the Nazis in power said, we actually could have real uses for all these physicists, at least the ones who weren't of Jewish background, that physics might not be only associated with kind of philosophy or ideology or kind of political talking points.

But there was something stirring which got even to the highest levels of the Nazi party by the late 1930s that maybe physics and physicists could be useful, could be manifestly useful to Nazi aims and not merely something to be kind of policed as a kind of thought police. And what had changed really was summed up in two words-- nuclear physics.

So let me pause there. We're going to have some questions and discussion. And then we'll look at some of the work in nuclear physics that they were talking about. Any questions about that?

Had anyone heard that story before about Heisenberg and his mother and Himmler's mother? I just find that astonishing. Talk about small world networks. No. OK. I'm happy to press on. We got a lot of juicy stuff we can talk about for nuclear physics. But if any questions come up about Deutsche Physik, of course, chime in. But if not, I think I'll press on. OK.

Obie, did you have a question? Was it-- Oh, OK. OK. Yeah, if only somebody called Hitler's mom. Yeah, exactly. Can you imagine?

Gary says, if all these remarkable physicists stayed in Germany, what would have been the result of war? Yeah. Gary, thank you. In fact, we'll be coming to that. That sets up much of the rest of today's class.

Yeah. Seeler says if only he'd been accepted at art school-- meaning Hitler, not Heisenberg. So some of you may know, Hitler was himself a kind of aspiring painter as a young person. And he felt slights at every turn, including that he was never admitted to hoped for art school. The world was out to get him, as far as he was concerned.

Alex asked a very intriguing question. Why did Heisenberg stay behind? Very good. And again, we'll talk a bit about that. But that will come up in some of the themes in the next part.

But as a preview, it's important to clarify. Heisenberg never ever joined the Nazi party. He never expressed anything like a clear sympathy with the most vile parts of the Nazi worldview. So I want to be very clear.

On the other hand, Heisenberg was very, very patriotic. He was someone who had a deep, deep pride and a longer view of German learning and German culture. And again, we'll come to that actually pretty soon.

So he was a patriotic German and not a Nazi. And he believed, as many of his colleagues did-- many, many German scientists stayed behind. He believed that the Nazi-- he hoped, in the early years-- he believed that this would be a temporary aberration, that the Nazis were so counter to what Heisenberg himself considered the kind of highest points of German learning and German philosophy and German culture, that this would be a temporary kind of fever. The fever would break. The Nazis would be run out of town soon, he hoped or believed. And therefore, there should be some kind of intellectual leaders who stayed behind to rebuild.

So he thought there would be a need for many, many smart, devoted Germans who weren't Nazis, but who were proud of the kind of longer heritage of German learning and culture. Think about all the composers and the poets, and they had this long list of which they were very, very proud.

So they thought they'd have to stick around because this Nazi thing was going to go away soon, they hoped. And then Germany would have to rebuild. And that was-- and so it was a kind of patriotism rather than Nazism per se.

But that became for many other people who did leave Germany, either because they felt they really had to for personal safety, or people like Schrodinger who were critics of the regime but were not in the same kind of personal danger-- that kind of argument didn't convince everyone. Obviously, not everyone thought this-- thought that-- some people thought Heisenberg was kind of fooling himself, or the people like Heisenberg who chose to stay.

So it was not at all obvious that this was-- even at the time, this was the best course of action or the morally appropriate one. But it was tricky. And so the short the shorter version is Heisenberg was deeply patriotic and not a Nazi. And he hoped he could help kind of rebuild the country he loved so much. And he hoped it would come soon.

That's a good question. Any other questions on that? That's actually a great segue to the next part. OK. Let's press on.

Let's see what else-- what might have helped convince even the ardent Nazis that there were other reasons to think about physics in new ways? So we're going to step back a little bit and look at some of the conceptual developments and experimental developments that have been going on really just in remarkable synchrony with the Deutsche Physik movement and the rise of the Nazis.

So throughout the late '20s and into the early '30s, several research groups really throughout-- certainly throughout Europe and beyond-- we're working on radioactivity. That dated back to the 1890s. But this group by this point, about 20 or almost 30 years in, began to suspect that there was more going on within atomic nuclei than only protons, that there might be actually a whole second kind of particle within these nuclei.

And again, to us this sounds like, no, duh. How did they know that? Well, we know that because they worked so hard to figure this out. They thought there could be an electrically neutral particle whose mass was at least pretty close to that of the proton but would not respond to the electromagnetic-- would not respond to electric attractions or repulsions the way a proton does. And they had all kinds of reasons for thinking along these lines.

Among the real kind of World leaders on that topic was a husband and wife team, or a wife and husband team, Irene and Frédéric Joliot-Curie. Irene Curie was one of the daughters of Marie and Pierre Curie. So she entered the family business. She married Frédéric, who was also a nuclear scientist. And they also set up a world-class laboratory in Paris, really kind of taking the mantle from Marie and Pierre.

And one of the things that they were especially adept at studying was something called artificial radioactivity. They really meant induced radioactivity. So Marie Curie and Pierre and members of their generation, even younger folks like Rutherford, they'd been excited about natural emitters-- substances that were radioactive without you having to do anything to them. They would emit these radiations-- alpha particles, beta particles, gamma rays on their own because of some kind of natural radioactive properties.

By this next generation, literally next generation, meaning the daughter Irene and Frédéric, they were wondering could they actually create radioactivity or induce it by taking materials that were not on their own radioactive, irradiating them-- having a radioactive source bombard them with radiation, alpha particles, beta particles whatever-- and have that new target that they shown this stuff onto, could that then become radioactive as well?

That became known as artificial. It really means induced radioactivity. And this became the next big frontier for trying to understand radioactivity in general, and by means of that, trying to get more clarity on the structure of atoms and nuclei. And so-- and as you see, Irene and Frédéric shared the 1935 Nobel Prize in Chemistry for their work. They really had already become world leaders in that.

Just a little bit before they won the prize, and they're already very clearly at the top of the game in that field, one of their colleagues, James Chadwick, who was in Britain, followed up on one of their suggestions. In fact, he basically redid an experiment that the Joliot-Curie's had done almost exactly. But he thought they weren't quite interpreting it quite right. So he wanted to zoom in on this.

So Chadwick had been a student of Ernest Rutherford's at Manchester, and by this point was himself now a more senior researcher at the Cavendish back in Cambridge. So this, again, really was an experimental design almost entirely coming from Irene and Frédéric Joliot-Curie. But Chadwick gave it a little tweak to try to clarify some things.

The idea was to take one of these natural radioactive sources-- in this case polonium. And that's what we called an alpha emitter. So all on its own polonium will be radioactive, and its form of emission is alpha particles. So then they would shine the alpha particles onto a target, a block of beryllium. And then some different kind of radiation would come out. They had now induced radioactivity. Beryllium on its own was not radioactive.

They could induce a radioactive kind of response by irradiating it with alpha particles. Some as yet unknown stuff came out. They could then-- Chadwick's idea was to shine that onto paraffin wax, a very hydrogen-rich substance, very-- each atom of which is very, very lightweight. And then protons came out. And then he could measure basically the kind of stopping power of those protons.

So what Chadwick clarified-- which one of the few times that Irene and Frédéric Joliot-Curie had not kind of just nailed it the first time, so Chadwick came in and clarified-- was this unknown radiation, the stuff that came flying out upon irradiating beryllium with alpha particles was this long suspected neutral particle, electrically neutral with a mass pretty close to that of protons.

So the way that Chadwick made sense of this reaction was that there were alpha particles coming out from the polonium and countering the beryllium that would convert into a stable carbon atom and have this unknown radiation be the neutron. And again, this is probably familiar notation for you.

The lower-- the subscript number here is what's called the atomic number. That just counts the number of protons. The placement of any of these items on the periodic table is determined by the number of protons in the nucleus. And the superscript, the raised number, is the atomic mass.

So how many basically proton masses worth did that item weigh? So an alpha particle has two units of electric charge-- twice the charge of the proton but is four times as heavy as a proton-- beryllium carbon [INAUDIBLE]. So the neutron would have had no electric charge. It had zero times the charge of a proton but had about the same mass as a proton.

And that's what Chadwick finally clarified, in part because of the paraffin here. He was able to not-- to have the particles of this unknown radiation collide-- basically have two body collisions with the very proton-rich targets in the paraffin. And then he could measure the energy with which the protons came out with a kind of stopping power, much like we saw, say, Lenard do for the photoelectric effect.

So with that, he could infer that each individual particle coming out here had a mass pretty similar to that of the protons because of the recoil pattern. And that's when the first really compelling empirical evidence for this new thing in the nucleus called the neutron, that really was introduced. And so Chadwick's work was also recognized very, very quickly.

So in the year that the Joliot-Curies shared the Nobel Prize in chemistry Chadwick won that same year the Nobel Prize in physics. This was capturing people's attention right away.

Among those people whose attention it captured right away was Enrico Fermi, another-- at this point, still pretty young-- full professor in Rome. Fermi was very eager to get the Rome group kind of on the map. Everyone was kind of jealous of Paris and the Cavendish and some of these other centers of research. And Fermi thought it was time to get his group really up to the same kind of quality.

So Fermi had just only recently been made a full professor and given a kind of research lab, well-funded group in Rome. And he realized that neutrons, unlike alpha particles because the neutrons are electrically neutral, they might be able to do even more effective induced radioactive reactions because you're not going to have a kind of electrostatic repulsion of the alpha particle with its positive charge getting repelled by the target it's trying to strike, like the positively charged nucleus of a target substance.

So the neutron, since it had no electric charge, Fermi realized, could maybe be an even better inducer of these nuclear reactions because it can somehow get perhaps even closer into the action, so to speak, without suffering that Coulomb repulsion. So he and his group were very, very methodical. And they basically tried to get purified, elemental sources of almost every single element on the periodic table starting practically with hydrogen, helium-- starting very, very early on, certainly beryllium.

And marching just one by one up every single known chemical element, or as many of them as could, they got to the very end of the known chart. They got up to uranium, which was, at the time, the heaviest known most massive element on the periodic table, the one with the largest number of protons in its nucleus-- atomic number 92.

And they would do the same trick. They would irradiate purified samples of each of these elements, including uranium, with a source of neutrons. And they would often-- not every time-- but often, they would be able to induce radioactivity much as the Joliot-Curies had been doing, and they could measure the response with Geiger counters and all the rest.

What Fermi found was they got especially strong reaction rates. They would really get this uranium start acting like a radioactive material when Fermi placed a block of paraffin, this lightweight wax, between the neutron and the uranium target. So now, with Chadwick the paraffin was to interact with the neutrons that came flying out after the neutrons had already come from a target. Now, Fermi places the paraffin wax between the source of neutrons, and in this case, say, the uranium target.

So what the Rome group assumed they were measuring-- and you can see in this one of the whole series of papers that they published-- this one by Fermi himself. Others had about five or six co-authors-- they thought they actually had made new elements. They thought they had gone beyond the then highest known atomic number.

As you see here, his paper in *Nature* was the possible production of elements of atomic number higher than 92, meaning atomic number beyond uranium. So they thought what they were doing was taking a uranium target-- so each atom which had 92 protons, a total mass of 238. They would irradiate it with neutrons. And the uranium target would do what would soon be called neutron capture. So it would absorb that incoming neutron.

So what happens then? The atomic number has not changed. This has zero proton units. So the 92 plus 0 remains 92. You still have uranium there. But the actual mass has increased by one unit. So neutron capture does not change the chemical identity of the target. It's still uranium. It still has only 92 protons in the nucleus. But you change it to a different isotope-- same number of protons, different total atomic mass. In this case, one more neutron.

And then after some time, the neutron that had been absorbed would itself undergo a radioactive decay, a so-called beta decay, where the neutron would transform into a proton-- sorry-- transform into a proton. And then a beta ray, an electron, would come flying out. It was actually Fermi who built upon suggestions by people like Wolfgang Pauli, saying that it actually it has to be more than just a beta decay to get the energy and momentum to balance, to work out.

So an electron and some as yet unseen extra particle that they eventually called the neutrino-- now we call it an antineutrino-- stuff comes flying out. The main thing is that the neutron transformed into a proton.

So now, inside that nucleus you have 92 plus 1 protons. You've actually perhaps, possibly made an element that's chemically distinct from uranium. You've actually pushed it up one place on the periodic table Because now it seems to have a total of 93 protons. And yet, since the proton and neutron have basically the same mass, the atomic mass stays the same.

So the idea was Fermi and his group were convinced they had conducted neutron capture followed by beta decay. They thought they had produced the first transuranic element. This would eventually be called neptunium. Just like in the solar system the planet Neptune is the first planet beyond Uranus, this would be the first element beyond uranium.

I actually got to see these materials the last trip I was able to make before the pandemic, although I didn't know it at the time. I actually was in Rome for a few days-- a glorious few days this past January, not quite a year ago. And I got to see in this brand new Fermi museum. On the very site of his laboratory, there's now a museum that in principle is open to the public, though it's sealed up now I'm sure.

And this was the actual lead-lined case in which they had their radioactive sources. This is the block of paraffin that Fermi used. It's like, I couldn't believe it was right there. I've been reading about this thing since I was a kid. And here are some of the examples of these purified elements-- the targets that they would irradiate with the neutrons that had gone through the paraffin wax.

And here, this is what happens if you start filming in the streets of Rome, you get pulled over by the police. So it was actually-- they're working on a documentary with NOVA about Fermi and neutrons and neutrinos, and the police didn't realize we had all the proper paperwork.

Here's Rosemary Cafferty, the production assistant, saying no, no, nice police officers. We do have the permits. Anyway. So I got to see lots of things in Rome, including Fermi's actual experiments. That was pretty awesome. OK.

So Fermi's work actually triggered a lot of reactions in the human realm and not only in the nuclear realm. So this work was, again, seen as just unbelievably interesting and important. He starts publishing this in 1934.

The main body of work comes out throughout 1935. By 1938, he again-- this work had been recognized as worthy of a Nobel Prize. Here's Fermi getting permission-- excuse me-- winning the Nobel Prize, receiving it from the King of Sweden December of 1938, just three or four years after starting that whole series of investigations.

Now, that timing is pretty remarkable. As again, many of you probably know, Italy by this point, since the '20s, had been ruled by a fascist dictator, a self-pronounced fascist dictator, Benito Mussolini. Mussolini was not in the earliest days as rabidly anti-Semitic as he would become.

But after Hitler attained power in Germany, Hitler and Mussolini made a series of pacts. And Mussolini's policies began mirroring or getting much closer to those of the overt anti-Semitism and so-called racial purity of the Nazis.

So by the early and mid-1930s, Mussolini's regime in Italy was becoming as dangerous for people of Jewish background as Hitler's was in Germany. That mattered a great deal to Fermi. Fermi himself was not Jewish, but his wife Laura was from a Jewish family.

And even though Fermi was this big fancy professor getting lots and lots of support from the central government for his research, it was becoming more and more clear that this was no-- this was not going to remain a kind of easy existence for them with a Jewish member of the family, as Mussolini began aligning policies more and more closely with those of the Nazis.

So what Fermi arranged, upon learning that he would receive the Nobel Prize, was that his entire family, his immediate family, could travel with him to Stockholm to win the prize, and they basically snuck out. So Mussolini couldn't help but let Fermi leave the country.

For Italy's grandeur, it was important to let Fermi receive the Nobel Prize. And then basically behind Mussolini's back, Fermi had arranged in secret to have his immediate family skip town, to leave almost directly from Stockholm, get on a steamboat out of, I think, the UK, and sail right to New York City.

It's a lot like-- if you've seen the famous movie, *The Sound of Music,* it's a lot [AUDIO OUT] a ceremony full of fanfare and just escaped. And so Fermi and his immediate family moved and resettled for a time in New York City.

So this is a reminder of the timing. We have this exciting new work in nuclear physics, new particles found, new kinds of nuclear transformations. The world scientists are getting very, very excited about this at just the moment when fascists are taking over many, many parts within Europe.

Now, it turns out other groups were actively working on exactly these kinds of nuclear transformations. After all, Fermi won the Nobel Prize partly because everyone-- many, many people in the field agreed this was really, really kind of hot stuff. This was important stuff.

So many groups were working on either replicating Fermi's series of experiments with this neutron capture, or trying to irradiate other sources, find other isotopes and possibly even new elements. And one of the most active in this group was a team based in Berlin.

What's really interesting about this Berlin group is that they were explicitly multidisciplinary, even more so-- certainly more so than Fermi's group. Even arguably more than the Joliot-Curies, or similar, at least, to them.

So the group included a theoretical physicist, Lise Meitner, as well as two very accomplished nuclear chemists, Otto Hahn and Fritz Strassmann. And for today's readings, we have a little-- an excerpt that's drawn from this really quite amazing biography of Meitner by Ruth Lewin Sime.

Again, for those of you who might be interested, I can't recommend this book highly enough. I just think this book is gripping and moving and beautifully written-- Sime's biography of Meitner. So I couldn't assign the whole book, but I do encourage you to read even more from Sime's biography if you have the time.

There's a little taste of an article that Ruth wrote with some colleagues in*Physics Today,* and then a kind of short piece inspired by her book by the very talented science writer Maria [INAUDIBLE]. But I think there's no substitute for this biography. Meitner, I think, is just endlessly fascinating.

So what do we learn from Sime's biography? Meitner-- Lise Meitner grew up in a Jewish family in Austria. And she was therefore only allowed to attend formal school until age 14. At that point, the rules in the late years of the Habsburg Empire, girls couldn't even finish high school. They weren't allowed to finish high school. They could go to school through age 14.

And during Meitner's kind of later teenage years, there was a series of reforms-- nationwide reforms in Austria that actually relaxed those rules. So then Meitner rushed through all the years she'd missed of the remaining years of what would have been a standard high school curriculum mostly through self-study.

She finished high school effectively in a few months. And then even more astonishing, passed the entrance exam to study physics at the very elite University of Vienna, which otherwise would never have been allowed to her until these reforms had come into place.

So she then studied very hard, and she was among the first women anywhere to earn not just an undergraduate degree, but actually, a full PhD in physics. She earned her PhD in 1905. And then she very quickly began to collaborate with Otto Hahn in Berlin. She had a few short-term kind of fellowships. And then eventually was hired-- sort of hired-- in Berlin.

She was allowed to work with him. Hahn was glad to work with her. But she was only allowed to go into the basement of this Institute in Berlin because women were literally not allowed into the main institute, not just that there weren't women's restrooms. They weren't allowed on the first, second, third floor.

So Hahn, to accommodate this very, very brilliant collaborator, colleague, agreed to work in what was essentially a kind of shop-- a kind of woodworking shop in the basement of the otherwise very fancy institute in Berlin. And that's how their collaboration started. Meitner, as a young and upcoming theoretical physicist, and Hahn, as an accomplished chemist. And here they are many years later working in their lab together in the later '30s.

So what happens is in 1933, when Hitler is elected and the so-called civil service laws go into effect by that spring, people who are of Jewish background and German citizens could no longer hold university positions or other government jobs. Lise Meitner was not a German citizen. She was an Austrian.

So it's quite astonishing that she was Jewish. Everyone knew she was Jewish. And she was able to keep her job because according to these new laws they didn't apply to her. They applied to German citizens of Jewish background.

That changed in the spring of 1938, or beginning in the spring of '38 because, again, as some of you may know, by that point, there was what is called the Anschluss, which is when Nazi [AUDIO OUT] welcomed it. But in any case, Austria became absorbed within the German-- the Nazi Reich. So now Austria, and therefore, Austrians, were subject to the kind of German laws, including these so-called civil service laws, these anti-Jewish employment laws.

So only in late spring, early summer 1938, rather than spring of 1933, was Meitner no longer entitled, according to these new laws, to keep her job. So she actually had to flee in a hurry several years after this kind of exodus had begun. So Meitner actually got a temporary position in Stockholm. She was able to flee to Sweden.

And in the meantime, Hahn and Strassmann, in their Berlin laboratory, continued these neutron bombardment experiments, again, doing just like what the Fermi group had gotten so famous for. They redid Fermi's experiments multiple times, even to the day at which Fermi was literally shaking the king's hand and receiving his Nobel Prize right throughout the month of December.

But unlike Fermi, and unlike the Nobel committee, Hahn and Strassmann concluded that neither Fermi nor are they in their own lab had actually produced these elements beyond uranium. So literally, while Fermi was receiving the prize for having made transuranic elements, Hahn and Strassmann convinced themselves that no, he didn't, and neither had they.

So this is an example of a periodic table from 1938. You can see it ends at uranium. So whereas, Fermi and the Nobel committee and all the experts-- nearly all the experts. There were a few detractors, but nearly all the experts had assumed that Fermi had nudged these nuclei up by one or maybe two places here beyond uranium.

What Hahn and Strassmann kind of grudgingly conclude using their chemist knowledge, not their not the notion as physicists, is, in fact, the uranium target had been split. It hadn't been nudged to one step larger, one step beyond uranium on the periodic table. It had actually broken into two much smaller pieces midway down the periodic table into, for example, a barium fragment and a krypton fragment, where again, the atomic number would add up.

You had 92 protons to start. You have 92 protons at the end, but not by having made one slightly larger blob of, say, neptunium or some transuranic. But, in fact, by splitting that initial target nucleus into two much smaller pieces.

And they wrote this up in December. It was published almost immediately in some Prussian Academy publications in January of 1939. And they conclude this with this very famous closing. They say, as chemists, we must actually say the new particles that result-- the products after this reaction-- behave like-- do not behave like radium, but in fact, like barium. It looks like they really had been knocked all the way down here, not in the vicinity of uranium.

So as chemists, we say we found barium. As nuclear physicists, we cannot make this conclusion, which is in conflict with all experience in nuclear physics. There was no known nuclear transformation to date after 40 years of studying such things, in which there had been that large a leap either up or down the periodic table. And I talked a bit more about this in the optional lecture notes.

All the known transformations-- alpha decay would knock you down two places. Beta decay knocked-- bring you up. You would be moving one or two places in your immediate vicinity, not halfway down the table.

So while she was now on the run-- she had just arrived at a kind of temporary position in Stockholm-- Meitner received an update from Otto Hahn about these latest experiments indicating the presence of barium, which again, to emphasize, Hahn and Strassmann as chemists knew how to do proper chemical analyzes to test for barium. And they were more and more convinced that's what was there.

So Meitner gets the update from Hahn. She has a little break with her nephew, another theoretical physicist, Otto Robert Frisch. He often went just by Robert. Frisch was actually at this point a postdoc in Copenhagen. So he was also in Scandinavia. He was able to come see his aunt. They had a few days together outside of Stockholm in a little ski vacation-- cross-country skiing.

And it's while there that Meitner had just received his letter from Hahn. Frisch comes, and they spend the day talking about how Hahn and Strassmann's results could possibly be true. And while away from any kind of workspace, while literally spending the day out in the woods-- snow-covered woods-- they work out the first ever physical model of nuclear fission. It's quite extraordinary. And again, there's plenty more in the optional notes to spell this out in more detail.

They began to argue or to convince themselves that slow neutrons were the key, that remember, Fermi was finding increased reaction rates when he put that block of paraffin, that wax between the neutrons and the target uranium. And they argue that that must have been because the paraffin was slowing down the neutrons.

There'd be enough scattering and recoil that the neutrons that made it through the paraffin would have lost a significant amount of energy from having scattered off an object of comparable size. And so they should be slowed down by their travel through that moderator, through that material that would slow down their kinetic energy.

And then Meitner and Frisch-- unlike Fermi at first-- Meitner and Frisch realized, well, if the momentum of these neutrons has been reduced, then the quantum-like behavior should have been exaggerated. If you go back to the de Broglie wavelength-- remember, we saw this inherent waviness associated quantum mechanically with any solid matter, it's proportional to Planck's constant, but inversely proportional to the momentum.

So if the neutrons are being slowed down through, say, that paraffin wax, then the velocity would be small. The waviness, the characteristic size of this quantum wave, would be enhanced.

So maybe even though this uranium nucleus is nearly 240 times bigger than-- or more massive than-- the inbound neutron, if that neutron had been slowed so that its quantum properties have been stretched-- the quantumness, so to speak-- the wavelength might be comparable in size to this entire uranium target, maybe you could set the entire target wobbling coherently to get a kind of coherent or collective response to the single bombardment by the incoming neutron.

And they began, again, working out this kind of picture that this neutron might be like a kind of liquid drop-- that was a model that Niels Bohr himself had been working out for a while-- this kind of barely stable equilibrium between a kind of surface tension keeping it together and a volume pressure that would work to-- work against the surface tension. And there might be just a balancing point when you get to very large nuclei like uranium. So once this kind of stretched-out, slow neutron encounters the nucleus, it gets the whole drop wobbling. And in fact, you could actually have this thin neck appear.

And then finally-- because this is now a very-- a dense pack of positively charged protons, this is a separate densely packed region of positive protons that can now repel each other, maybe this neck will rupture, and you'll actually get two smaller pieces. So maybe the one large nucleus could split into because it was hit by a slow-moving neutron.

They go on-- again, this part is done in much more detail in the notes. I'll just go quickly here. Still on the ski holiday while basically on a bench, or leaning against a tree, they try to wonder, would this work? Could they get a kind of order of magnitude estimate of this kind of process?

And they realize that the energy scale, the rough energies involved, if this splitting of a uranium nucleus were to hold, they could estimate by the kind of Coulomb repulsion of all the pieces-- all the protons within that nucleus. They have about 100 protons-- 92. So order of magnitude about 100 protons each with unit charge. And they're packed within a very small volume.

The average nuclear radii they knew by this point was on the order of 100th of an angstrom. And so on the order of-- oh, no, excuse me-- a 10,000th of an angstroms-- around 10 to the minus 12 centimeters.

Meanwhile, the kind typical energy scales for chemical reactions, where you're basically moving one or two electrons across distances of an atomic size, not a nuclear size. So if you take the ratio of the kind typical energy scales that seem to be involved in these nuclear transformations, compared to typical energy scales for chemical ones, the nuclear ones should be about 100 million times larger energies just from this how many charges can you-- are you moving around and what kind of volume. It's very, very kind of order of magnitude rough estimate that they're doing literally on a bench while taking a break from skiing.

Meanwhile, after splitting apart, if this really were to happen, you have two roughly equal pieces of what had once been a single nucleus, each piece will carry as they go through-- and I replicate that algebra in the notes-- each piece following splitting would carry about one third of that starting energy.

So this nuclear energy of the starting blob of roughly 100 charged particles, after splitting, each piece would only carry about a third of that. So you have two pieces. You have one third of that kind of raw energy still to account for. And that would be this energy released every time a single, large, unstable nucleus undergoes this splitting. So you have one third of this enormous energy scale available or released every time-- they estimate-- every time a single nucleus is split in this fashion.

It turns out that estimator is consistent with-- people who then fill this in within a few months-- with a different way of estimating the energy scales not based on a kind of classical Coulomb repulsion-- how many protons over here are repelling how many protons over there-- but actually, based on E equals mc squared, that the total mass of the uranium nucleus before it splits is actually greater-- is actually-- sorry-- less than the mass of the barium and the krypton.

There's a binding energy left over-- negative binding energy. And that actually is what's released when this initial thing splits, and that release times C squared gives you, again, the exact same kind of estimate as you get from this classical kind of electrostatic repulsion. That was worked out in detail by Bohr himself with another colleague.

So Frisch returns to Bohr's institute in late December. He tells Bohr all about this. Bohr was very excited about nuclear physics by this point. Frisch was Bohr's postdoc.

Frisch tells him all about Meitner's and Frisch's ideas, that maybe this big nucleus is just barely stable and could actually be split apart into two small pieces. He asks Bohr to keep it to himself. He and Meitner were going to keep working on it, maybe even perform some laboratory tests and so on, which in fact, Frisch did wind up doing.

Meanwhile, Bohr was set to leave almost practically the next day-- very soon afterwards-- to sail to the United States. He was scheduled to spend a sabbatical at Princeton-- Princeton University, right near the Institute for Advanced Study. So he does that. He sails to New York. He's actually met at the docks in New York City by Enrico Fermi, who had just fled. He had just left by way of his Nobel Prize ceremony.

Younger folks like Sam Goudsmit, whom we heard about before-- we'll hear more about soon-- Goudsmit had also fled the Netherlands and had moved to the United States some years before. Bohr basically gets off the boat and tells him, you won't believe what I've just learned. Nuclear fission is possible.

So even though Frisch had asked him to keep it quiet, Bohr basically can't help himself. He's spilling the beans to his physics colleagues practically on the docks as soon as he arrives in New York City. Then he gets to Princeton. He tells other émigré physicists like Wegner, Albert Einstein, John Wheeler, who's an American physicist, but had done his own postdoc with Bohr some years earlier. They knew each other very well.

Within days, several laboratories up and down the East Coast had actually verified this reaction. And for them, it was easy because they knew what to look for. The hard part was having these chemists, like Hahn and Strassmann, really do the kind of chemical assays to find barium. Once you know to look for barium, then even physicists, with some chemists' help, could verify that some of the fission products were, in fact, barium-- way down the periodic table, not things near uranium.

So during that sabbatical, Bohr then kept working with Wheeler. And they worked out a more detailed quantitative analysis building very directly on Meitner's and Frisch's work. By this point, Meitner and Frisch had published a few very short letters about their work that are duly cited by Wheeler and Bohr. And they work out a kind of lengthy detailed quantitative theory of this nuclear fission.

In fact, building again much on Meitner's work, it's Bohr and Wheeler who finally conclude that the fissionable, the most unstable isotope of uranium, is not the most common kind you find in the ground. That's U-238. The fissionable one, the one that's most easy to undergo this kind of splitting reaction, has a couple of fewer neutrons than the common one, U-235.

What's kind of chilling or stunning to me is their article was published in the*Physical Review* literally on the same day that the Nazis invaded Poland, which was the final kind of trigger for the start of the overt fighting of the Second World War. Again, we see the collision of these time scales.

So everyone in physics-- everyone in physics knew immediately that nuclear fission could lead to bombs. This was an enormous release of energy each time a single nucleus split. The energy scales were nothing like typical chemical scales-- chemical reaction scales. So everyone knows that.

And then their second thought was, oh, the Germans must know this, too. After all, fission had been identified in a Berlin laboratory. And as we were just saying a few minutes ago, although many researchers fled Nazi Germany, it still retained some of the world's leading experts in nuclear physics, or nuclear science, more broadly.

Heisenberg, as we said, had stayed behind. Otto Hahn, Hans Geiger, who invented the Geiger counter, Walther Bothe, Max Planck, Max von Laue-- a long list of these folks were still in Germany, let alone at the forefront of laboratory tests of these things.

So again, just to give a sense of how rapidly these things were all kind of colliding, the conceptual work, the laboratory work around these new kinds of nuclear transformations, and the headlong rush into a world-spanning war. So I mentioned the Anschluss, who were the Nazis, basically absorb Austria. That was in March of '38.

By December of '38, we have these developments of Hahn and Strassmann identifying barium, Meitner and Frisch working out the first real physical explanation. Bohr arrives in New York City. That spring, the Nazis then occupy Czechoslovakia. And Poland is what finally triggers the announcements, the declarations of war by many other countries.

So within days of the invasion of Poland, Britain, France, Australia, New Zealand, and Canada-- notably, not the United States. But many of these other countries explicitly declare war against Germany. The Soviet Union invades Poland soon after that. This is all happening at essentially the same time.

What's also happening is that in many, many of these countries on multiple sides, multiple fronts of what would become the actual warring parties, physicists are consulting with government officials to say there could be a vastly new type of weapon based on these nuclear transformations. So this is just a handful of these, again, happening with kind of lightning speed.

As we now know, as early as April 1939, barely four months after the very first indication from Hahn and Strassmann that nuclear fission could happen, the German Reich Ministry of Education started holding secret meetings on military applications of nuclear fission, meaning weapons. They could make-- they were beginning to be briefed about the possibility of nuclear bombs. And they began banning the export of uranium. They figured they need a lot of this fissionable material.

That same month-- it was much less well-known-- other historians have now by now documented it quite clearly-- the Japanese government began its own secret nuclear weapons project. It was codenamed Ni. I'm not sure what that stands for.

This, unlike the German one, was really underfunded. It was not seen as a high priority for the current war. In fact, what it turned out to be mostly was a kind of wait-- for senior physicists to keep younger physicists out of direct fighting. It was kind of like instead of being drafted, you could do some research is more or less how it functioned. But there was a formal Japanese nuclear weapons project founded as early as April 1939.

Very soon after that, Britain starts considering nuclear weapons, and they begin ramping up, especially after Robert Frisch, who then had moved-- once the Nazis took over Denmark he was no longer safe there. So he resettled in Britain, as did Rudolf Peierls, who had to leave Germany.

They compiled a top secret memo to the British government, again saying not only are nuclear weapons possible, but you only need a little bit-- comparative little bit-- of this fissionable, this rare isotope of uranium. They actually, as we now know, underestimated how little fissionable uranium you'd need. So it looked even closer to being feasible and convinced the British government to start real efforts.

And at that same time in the Soviet Union another physicist, Igor Kurchatov, starts informing the Soviet government about nuclear weapons and so on. Much like in Japan, in the Soviet Union we now know this was a low priority at first. But nonetheless, was a formal project.

And then again, perhaps most famously in the United States, Einstein himself really signed a letter. He didn't compose this letter. Some of his émigré friends and colleagues in physics wrote the letter in hopes that Einstein would sign it. And he did. They convinced him to.

He wrote a letter directly to President Franklin Roosevelt. By this point, Einstein was such a worldwide celebrity, they had channels to get this literally into the hands of the President of the United States. And you can see the letter here. You can Google it.

You can find the text where Einstein basically says, I've recently come to learn this nuclear fission thing is possible. I've also learned that Germany is now kind of hoarding uranium. This could be a very serious development. All these folks recognized very quickly that nuclear fission could have very immediate worldly effects.

So I see Obie asked do they-- how do they contain the heat of a reaction? Obie asked about the nuclear fission. Good. What's important to recognize is that these very earliest experiments were never leading to anything like what we would now call a chain reaction.

We'll talk more about this action in the next class. So they were never getting unlimited numbers of nuclei to undergo fission. Thank goodness. They would have blown up the laboratory.

So the heat released when one or two or three, a small number of nuclei fission, was not remarkable. If they had expected that, they could have maybe instrumented their laboratory to just barely maybe measure it. But I bet it was not even measurable, given the fission rates they were encountering. We'll see, of course, soon that no longer becomes true when these reactions get scaled up. And that's more-- we'll talk more about that in Wednesday's class.

Iyabo asks, why did Chadwick win the Nobel Prize for physics as opposed to chemistry? Ah, good. In the reading by Crawford, Simon, Walker, they identified one reason it was denied the Noble Prize was that radioactive was considered a chemistry project. Iyabo, thanks. It's a great point.

So I think the reason that Chadwick won the Nobel Prize in physics was because he was identifying a new physical particle. I mean, or what he was credited with. The reason they thought this work was so important was not that he-- not only that he was dealing with radioactivity, which was actually winning prizes both in physics and in chemistry. Marie Curie's first prize was actually in physics and then in chemistry or vice versa. She wound up winning in both.

But for Chadwick, it was actually identifying a new physical particle, which I think was then seen as a kind of physics domain, more or less, as opposed to the kind of chemical transmutations, or the transitions in the identities of chemical elements like what the Joliot-Curies were doing. And they, indeed, won the prize in chemistry that year.

But, I mean, your-- the question points to a-- is a good one. It points to a larger theme. There was an awfully fuzzy line then as now, but especially then. What would count as chemistry versus physics often could become kind of political.

I mean, in the sense that the very small circle of members of the Royal Swedish Academy of Sciences that decided these things, they could frankly push one way or the other based on other motives. Did they not want to give a prize to one person, or often a representative of some country?

We get very nationalistic. Don't honor this country. Do honor that. They could frankly kind of bend the rules or move that move that boundary to suit many kinds of purposes. So it's not that there were clear criteria separating, say, what would count as a physics prize versus chemistry.

And there's a lot of evidence, including from the first author of that article. Elizabeth Crawford was really immersed in the Nobel Prize archives for much of her career-- much as we learn from Crawford's work. So it's a good point.

But I think for Chadwick, the argument would have been he found a new kind of piece of matter, a new piece of nature. And that, I think, struck him as being more like the other physics prizes. Very good.

Other questions about that-- any of the nuclear physics concepts, or again this kind of amazing, we might call it a tight coupling between events in various laboratories and kind of physicist networks-- who's writing to whom, who's taking the steamer ship to where, with these kind of worldly geopolitical shifts. Amazing conjunction.

Do we know if Einstein ever spoke with FDR? He did not. Thank you, Gary. So in fact, there was a bit of a delay. FDR didn't actually receive the letter for a couple of weeks. He did read it. We know it was handed to him literally in the Oval Office, and he read it.

What's important, though, is that the myth that Einstein invented the Manhattan Project with this letter, that is just crazy, crazy, dramatically overblown. Einstein signed the letter. He didn't write it. He signed it. He thought it was important. And he was glad to have some intermediary get it to FDR, where it was delayed and had almost no impact. And so we'll talk more about this actually in Wednesday's class.

There was a little kind of study group that was put together a few months after Einstein's letter was received, not-- well, certainly, not only because of Einstein's letter. By that point other science advisors had the ear of Roosevelt and said, this really does look like it's worth paying attention to. The British were already now much more engaged as well after the Frisch-Peierls memo.

So there were many reasons for the US federal government to begin paying a little attention. We'll see they paid actually a little attention to questions about uranium and fission and weapons around the time of Einstein's letter, but not only because of Einstein's letter. And then we'll see in some more detail on Wednesday that the real kind of ramp-up came only quite a bit-- with quite a bit more of a delay.

So Einstein never spoke directly with FDR about this, and he never followed up. He wrote-- he signed the letter and then-- and that was that. So the notion that Einstein kind of jump-started the Manhattan Project, which one can still find with what I'll call lazy googling, that's really kind of totally out of proportion. Good. Any other questions on that?

Now, there's one last part I want to talk about today I think is very juicy. Let's launch into that and then some more time for discussion as well. OK.

So let's talk about Werner Heisenberg and what was going on within-- for those who stayed within Germany with this constellation of events. So by September of 1939, right around the start of the-- the overt start of the Second World War, the German army ordnance office took over the Kaiser Wilhelm Institut fur Physik, this really quite beautiful, funky building in Berlin, or just in the outskirts of Berlin-- Berlin-Dahlem-- exactly to coordinate research on nuclear fission.

They'd been briefed. They'd had these secret briefings since that spring. Fission is a thing. It could lead to weapons. So the army took over the Physics Institute-- took over control of it. A little while later, Heisenberg was actually placed in charge of it.

So Heisenberg, from the very early days, became a member of what was called the Uranverein, which is the uranium club, the little informal group of nuclear physicists and chemists who were working on fission trying to learn more. Heisenberg personally advised the military multiple times about possibilities of nuclear fission, both for weapons-- this could lead to explosive release of explosive power in a bomb-- but also for civilian power generation-- what we now call reactors.

And, again, this has been shown now in a lot of detail that Heisenberg and other from the small circle of colleagues were actively advising the army ordnance from as early as '39, '40. And like I say, within a few years, then Heisenberg himself was put in charge of the entire nuclear effort.

At the same time, Heisenberg was sent on these diplomatic missions throughout neutral countries, or especially occupied countries, including, for example, Denmark. And now this is right on the heels-- this is only two years or three years after he had been denied this promotion by the Deutsche Physik movement. So you can see how rapidly Heisenberg's star had risen yet again among leading German government officials. By 1939, '40, he was seen as actually quite useful in the context of nuclear fission.

So what he would do is basically go on diplomatic missions to basically be one of the public faces of the German government, not to proclaim pro-Nazi slogans, but rather to show off the kind of grandness of German accomplishments in higher learning. Here's this very young Nobel Laureate who knows about the atom and these mysterious things. So he'd give these very well-attended public lectures usually in places that the Nazis had just taken over and occupied, and sometimes in neutral countries.

He-- as I say, to many colleagues who heard him, colleagues who had known him for years, he sounded-- he often sounded explicitly nationalistic. He was never spouting the kind of most what I would consider grotesque or most obvious Nazi kind of speaking points, but he was certainly proudly German.

And at some points, even seemed to suggest, at least to some of these colleagues heard him, that maybe it would be good thing if Germany ruled all of Europe-- not the Nazis, but if Germany really extended its rule. Because after all, this was the high point of European culture and learning.

This is what inspires this play-- this amazing play, *Copenhagen,* which hopefully some of you are familiar with. There's a link on the Canvas site you can actually watch for free through the MIT library site, a really quite beautiful BBC production, a filmed production, of this play *Copenhagen* by Michael Frayn. It stars Daniel Craig who plays the young Heisenberg-- the same actor who would then go on to play James Bond. It's a really high-end production.

So this play is really fascinating. I encourage you to watch the film or read the play. And it swirls around one of these real life visits where Heisenberg was sent on one of these diplomatic missions, in this case, to Copenhagen very soon after the Nazis had occupied Denmark. So while he's in Copenhagen giving these fancy lectures, he visits with his own mentor, almost kind of father figure, Niels Bohr.

Now, they were afraid that by this point Bohr's house might have been bugged, might have recording devices placed in it by the Nazis. Bohr was well-known to be not at all sympathetic to the Nazis. And so Bohr and Heisenberg take these long strolls, as they always used to do, in the gardens near Bohr's house away from any inside microphones.

And what the play does I think just beautifully, very evocatively, is try to reimagine scenarios of what they possibly could have talked about away from the microphones-- sometimes with Margrethe Bohr, who we know was almost always part of Bohr's kind of conversation-- scientific, political, and otherwise.

So the play has these three characters-- Margrethe Bohr, Niels Bohr, and Werner Heisenberg. What do they think is going on with the world? What do they think the scientists' responsibility is and so on? It's a marvelous play. OK.

So we know that Heisenberg advised the German military authorities, and multiple times actually, that nuclear bombs were possible, but probably not during the present war. And that was as much because it looked like the Germans would just win very quickly. This was the period of what was called the blitzkrieg, the lightning war, where everyone expected Germany would win right away.

They invaded Poland on September 1, 1939. Everyone figured the war would be over within a year or two because it started going so well. Very few-- the Nazis suffered very few setbacks militarily once open warfare had started.

But the authorities, nonetheless, saw a future promise for this kind of weapon. They were imagining, remember, a thousand-year Reich. They had a long view.

And so they continued to fund Heisenberg's effort and also do things like seize the Belgian Congo-- the so-called Belgian Congo-- the territory within Central Africa that was known to be very rich in uranium ore. And so they wanted to get more raw uranium and fund Heisenberg's efforts and eventually install him to the head of the Kaiser Wilhelm Institut.

Members of Heisenberg's team, then, of this group, began working on what would it take to scale up these nuclear fission reactions. One member, Walther Bothe, estimated that the moderate-- the material to slow down the neutrons, like the paraffin wax in the early experiments, that to do that with carbon or graphite, you'd need kind of ultra-pure carbon. Any impurities would absorb neutrons and not slow them down. If you absorb the neutrons, you stop the fission reactions. You stop a chain reaction.

So Bothe, as we now know, overestimated how hard it would be to do this with carbon. So he advised instead that they turn to heavy water-- water that's made not with ordinary hydrogen, but with deuterium, with hydrogen atoms that have extra neutrons in the nuclei. So you have what's called heavy water.

There was this kind of amazing commando raid to blow up a heavy water plant in Norway that the Nazis wanted because they wanted to steal large amounts of heavy water. Literally, like parachuting in in cover of night-- crazy, crazy stuff.

Meanwhile, Heisenberg began on the theoretical side to estimate how much of this fissionable isotope U-235 would then need to have a runaway explosion-- the so-called critical mass. And he actually overestimated by a factor about 10 how much you'd need, at the same time, though, in ignorance of the underestimate by this Frisch-Peierls calculation.

So as the war dragged on, the bomb project gets lower and lower priority within Germany, at first because they figured they'll just win by conventional means. And later, as the war begins to really bog down, and the Nazis do get turned back militarily at various points, then the Reich needs to actually direct resources to the short-term immediate military priority. So it's a low priority at first because it looks like they'll win. It remains a low priority later because they have other short-term priorities.

So the physicist, Sam Goudsmit, who helped introduce the notion of quantum spin, he had emigrated from the Netherlands actually in the late '20s-- well before the rise of Nazism. His family stayed behind. And in fact, they later perished in Auschwitz, in Jewish background

He led the Allied reconnaissance missions inside Germany to learn about this German-- the Nazi nuclear effort, and to literally kidnap German nuclear scientists before they could flee to either the Soviets or anywhere else. This is happening before the end of the Second World War.

There's other crazy stories, that a pro baseball player named Moe Berg-- this really happened-- was basically drafted into what would become the CIA. It was the Office of Strategic Services at the time in the United States. He spoke German. He was sent to neutral countries near Germany, like Switzerland, to listen to these public lectures by Heisenberg.

The baseball player was armed with a pistol. And he was basically a amateur spy. And if it sounded like the Nazi bomb project was getting too advanced, Berg was ordered to assassinate Heisenberg. He didn't because it didn't sound like they were that close, and these amazing, pretty ridiculous or crazy stories.

Meanwhile, the Alsos mission is successful. They gather enormous documentation from the German efforts. And they also captured 10 German nuclear scientists in the spring even before Germany formally surrenders.

They capture them as basically prisoners of war, and they ferret them out of the country to Farm Hall, this quite lovely country home-- country house in rural England not too far from Cambridge University. This was called Operation Epsilon.

Once again, the house was bugged. The conversations were constantly audiotaped, transcribed, and translated. And you have an excerpt in the reader-- I'll let you read through here.

Let me just say very quickly-- I know I'm running late on time-- the first reaction upon hearing that nuclear weapons had been made and had actually been used, in this case against the city of Hiroshima by the American forces, the first reaction is utter disbelief. Heisenberg couldn't believe that anyone, let alone the bumbling Americans, could possibly have gotten so far along in this project, which his own group had made only halting progress on.

A little while later, as the transcript reveals, it's a different physicist, Carl Friedrich von Weizsacker, who says, well, we didn't make a bomb because we didn't want to. We didn't do it, as he says, on principle. If we'd wanted Germany to win the war, we would have succeeded.

And Heisenberg then says, ah. I was convinced of the possibility of making a reactor not for power, not as a weapon. But I never thought we'd make a bomb. And at the bottom of my heart, I was really glad it would be a reactor and not a bomb. They began making-- trying to make sense of what's happening so quickly around them.

Again, just to go quickly here. Sorry for the-- I'll post the slides, of course. You can see them. The idea that Heisenberg had actually purposefully resisted Hitler by dragging his feet, by slowing the project, was not a position that Heisenberg himself ever articulated. But other people began saying it on his behalf. Heisenberg said, we'd worked hard on reactors, which was true. He just chose not to emphasize they had also had ideas about weapons.

But other people speaking in some sense on behalf of Heisenberg, put together a story that Heisenberg had purposefully dragged his feet so as to deny Hitler a nuclear weapon. And we have this amazing correspondence of Heisenberg writing privately to these journalists saying, you've got it all wrong. Here's an example. I would not want this remark to be misunderstood, as saying that I myself engaged in resistance to Hitler.

And so I'll stop there. I apologize for running a bit long. I have time for a few questions. I'd be glad to stay on longer if people would like. Of course, feel free to head off to your other classes. And again, the slides are on the Canvas site.

So anyway, here's part of, again, this kind of unsteady mixture of really cutting-edge nuclear physics unfolding in real time with this kind of really fast-changing series of political and kind of military and bureaucratic maneuvers all getting wrapped up together. Any questions on that?

So I encourage you to go back to the Operation Epsilon excerpts. We do have the excerpts of the actual Farm Hall transcripts, which I put on the Canvas site, including the fateful day of August 6-- their reactions to the BBC reports of the bombing of Hiroshima and lots, lots more to talk about that as well.

We'll see some hints of this in the documentary film. We can talk more in our informal discussion next week. And in the meantime, we'll pick up this story then on Wednesday with what does some of the physicists outside of Germany do with these same set of ideas about nuclear fission and weapons prospects.

So we'll talk more about Allied efforts during the Second World War on Wednesday. So sorry for running long. Stay well. Good luck with paper two, and I'll see you soon. Bye, everyone.