webinar 9: synchrotron methods

(automated transcription)

Today we have a live stream again in contrast to last week and this week it will be about synchrotron radiation methods, a sister technique if you want of Mössbauer spectroscopy, but I noticed that there was one question in the forum that I did not see last week, a question to Mössbauer spectroscopy, so let me first step back to last week and answer that question. It's a question about the concept of line width and what happens with resonant absorption or emission in an atom. So we had the atom with a given mass, we had a visible light photon of a few eV, we calculated the line width which was 2 times 10 to the power minus 11 eV, sorry we calculated the recoil energy 2 times 10 to the power minus 11 and we reasoned that the line width would be something like 10 to the power minus 9 to 10 to the power minus 12 and somebody was confused that the recoil energy is within that line width and that this was the good feature. So that made me realize that maybe not all of you understood what I meant with this picture, so let me tell this once again. It is the case that all excited levels of atoms and also of nuclei, they have a finite lifetime and therefore a non-zero line width and resonant scattering in the normal sense of the word takes advantage of that. Even if there is recoil, recoil is unavoidable, you loose some energy due to recoil or in the absorption process you have to compensate for some energy that will be given to the recoil, so even though you have this energy that has to be spent to recoil somehow, because that recoil energy is smaller than the line width, even if you do spend that extra energy, you can still make the excitation. You take away a bit of energy E0 in this diagram, so you take away a bit of the energy E0 if you emit the photon, but the remaining E0 is still within the uncertainty that is allowed by the line width and therefore that photon with reduced energy can still get absorbed by an identical atom. So therefore if you discuss scattering of light on atoms and resonant absorption of light by atoms, you will usually not discuss recoil. It is there, but you hardly notice it. It is only in the case of gamma rays and nuclei where recoil is much larger than the line width, there it suddenly starts to matter. So I guess that this point was not fully understood by the people who asked this question. And there was a related question, still about line width. I read, for the same amount of energy input from an absorbed photon, an atom can reach different total energy levels. Not really, it is still the case, so this line width is typically smaller than the distance between different levels, but, and the question continues with something like energy bookkeeping, the energy bookkeeping is not that strict as you would think if you work with levels that have no line width at all. If there is no line width, then you need to have exactly this energy to make the transition, thanks to line width, there is some slack on that. If you have a little bit less or a little bit more energy, you can still make the transition. And that is happening all the time, but these differences are usually small. We will come back to this in the story about synchrotron radiation, because also there line width plays its role. So with that, and let me first verify YouTube, the stream is still indicated as slow. Well, I hope for the people who try to watch live that it is not too much of a problem. So the topic of today is then synchrotron radiation methods with the concept of forward scattering, which is a method of class 3. And we have three steps that we will deal in this webinar, and the first one is synchrotron radiation facilities. If you google for synchrotron radiation facilities for some images, you will find maps like this, and the purpose of that first part was to understand what is shown on these maps. And the first aspect of this is synchrotron. The first question we have to answer is, what is a synchrotron? I asked you to describe a synchrotron in your own words, and these are the answers I got. We will not read all of them, but I will search for keywords in these answers. And the first keyword that appears in many answers is that a synchrotron is an accelerator, a particle accelerator, and in the situations where we will meet it, even more precisely, an electron accelerator. That's one aspect of a synchrotron. The second aspect is that there is something related to bending, circular, ring, curved. A synchrotron is not a linear accelerator, a synchrotron is a curved accelerator. And how do you keep a charged particle,

say an electron, on a circular or curved track? You need a magnetic field for that. And the third aspect, these are the three concepts that play a role in a synchrotron. You can add more detail, because strictly spoken, all of this would also apply to a cyclotron, which is a different type of circular particle accelerator with magnetic fields. A synchrotron is a variant of that which is more powerful, because it synchronizes the switching of the magnetic field with the relativistic mass of the particle. Some of you have mentioned that, but let's not step into that detail here. The key part is, a synchrotron is a circular electron accelerator with a variable magnetic field, and with circular we really mean the electrons move with the fixed radius, independent of their speed, they move with a fixed radius. The variable magnetic field makes sure that they stay on that circular track. So that's synchrotron. Where do we see the synchrotron in these pictures? That's here, this inner ring, that is the synchrotron. It's not the most visible part of a synchrotron radiation facility, it's not the thing where you make a synchrotron radiation facility for, but the synchrotron is indispensable. Let me also emphasize that the synchrotron as such, that's an accelerator and that's not a source of electromagnetic waves or a source of photons. So I repeat one of your answers, that starts as a synchrotron is a type of particle accelerator, yes, that produces highly intense beams of electromagnetic radiation, no, that is not what the synchrotron does, it happens elsewhere, we will come to that. After the synchrotron, the next concept is synchrotron radiation. What is that? I asked you, you gave a set of answers, and let's look at the keywords, synchrotron radiation is electromagnetic radiation, these are photons of some range of frequencies, you can make synchrotron radiation of any frequency, the concept itself does not limit the frequency of the photon. The second keyword, it's radiation that is emitted by a charged particle, in our case it will be electrons, that emit electrons emit the synchrotron radiation. And when does an electron or any charged particle emit synchrotron radiation? When it is on a curved track, if it is accelerated perpendicular to its linear movement, so if it makes a curve in the path, then it will emit synchrotron radiation. Can you understand why? Well, yes, but not in this course, we take this as a given. A charged particle on a curved track loses energy by emitting radiation, electromagnetic radiation. That was, as one of you remarked, that was a nuisance to people who were building the first particle accelerators, because if you make a circular accelerator, you keep increasing the speed of your particles, but they are on a circular track, so they continuously emit synchrotron radiation, and therefore they lose energy. So part of the energy you put into speeding up the particles is lost again, because they emit the synchrotron radiation. In the devices that we are discussing today, we will try to maximize this effect instead, and to harvest this radiation. So the short summary of what is synchrotron radiation is electromagnetic radiation emitted by charged particles that are on a curved path. And then the next one, okay, ah, I inserted this slide, yeah, how does that synchrotron radiation look like? If you look from the point of view of the charged particle, you are an observer who sits on the charged particle, who travels with the charged particle on this curved track, then you see a type of dipole pattern. An observer who is looking at this from a lab frame, sees something different due to the Lorentz transformation. If this would be a very slowly moving particle, then the distribution pattern of the photons would be for this external observer similar to the pattern seen by the travelling observer. But if the particle is moving near the speed of light, as will happen in our devices, then this pattern is totally warped by the Lorentz transformation. And the photons are emitted in more or less one single direction. The opening angle is of the order of magnitude of 1 over gamma, where gamma is this relativistic enhancement factor. So if v approaches the speed of light, then this becomes really small. So this will be an advantage. Spontaneously, naturally, this radiation emitted by high speed particles will be collimated into a beam. We don't have to do something special for this. So now we can make the last step and go to synchrotron radiation facilities. What are these? Again, your answers and some highlights. So synchrotron radiation facilities are scientific research facilities that are built for producing and using synchrotron radiation. A synchrotron radiation facility, in short version, produces synchrotron radiation and delivers it to a diverse set of experimental setups. So where does that production of synchrotron radiation happen? Not in the synchrotron. The synchrotron is meant to bring the electrons to some speed. And once they have reached their maximal speed,

then the electrons are put into this outer ring, the storage ring, where they keep circulating. Whenever they pass a measurement station, there is something that produces the synchrotron radiation. We will see this in more detail, or you have seen this in more detail, but we will come back to it. At every measurement station, synchrotron radiation is produced. So then I ask you to look up some words, and by the collection of all these words, we will have now the final view on how the map of a synchrotron radiation facility looks like. So first you have the linac, the linear accelerator, and that is the accelerator where the electrons get their first acceleration. So that is this linear part here. You start from electrons that are basically at speed zero, and by a series of potential differences that are one after the other, you accelerate the electrons until they have a speed that matches with the synchrotron. So if you would start using a synchrotron with electrons that are at zero speed, that would not work. You have to inject them at some minimal speed, and only then the synchrotron can start operating on them. So the linac, the synchrotron, the synchrotron speeds up the electrons until they reach their maximal speed, and then they are deposited in the storage ring. I put here one of your answers and I highlighted some important sentences. The particles are injected in the storage ring, but at that point they have already been accelerated to their final energy. So the storage ring itself is not an accelerator anymore. The electrons keep orbiting at their maximal speed in the storage ring. It is really storage. However, you cannot say that there is no acceleration happening at all in the storage ring, because at every measurement station, synchrotron radiation will be emitted. And even everywhere along this curved path, some synchrotron radiation will be emitted. So the electrons continuously lose energy, and after a while they would not be going fast enough anymore to stay on this circular track. So after every measurement station, after every emission of synchrotron radiation, there is a small post-acceleration stage where the lost energy is compensated. The electron loses energy by synchrotron radiation and is then sped up again until it reaches again the original speed. And then this process is repeated in every measurement station. What is the word bunch? That's a name for the little packets of electrons that are circulating along the loop. So this is not a continuous stream of electrons. They are kept in bunches. Many electrons together, that travel together. And this is here another cartoon version of this. Say you have one measurement station here, and in this case you have five bunches in the ring. So that means that if the time difference between two bunches is 200 nanoseconds, that means that every 200 nanoseconds in this measurement station, a flash of synchrotron radiation is delivered. The undulator, that was another keyword. What is the undulator? That is now the device that will really produce the synchrotron radiation. Remember, when do we have synchrotron radiation? When is it emitted? Well, at the moment when an electron is on a curved track. It's always on a curved track in the storage ring. But that curved track is deliberately kept rather straight. So these are rings with diameters of several hundreds of meters. So this curvature is not very strong. But whenever we come near a measurement station, we put there a composition of magnets, static magnets, that are made in such a way, a cartoon version is here, an alternation of north-south, south-north, such that the electron that enters in this undulator, the path is strongly curved in alternating directions. So here you maximize the curvature. You force the electron to make many sharp turns, many wiggles, and at every sharp turn such a bunch of collimated synchrotron radiation is emitted, and all these bunches add, and you get this powerful flash of synchrotron radiation at the undulator, at every measurement station. Beamline, that's another keyword. What is the beamline? That's a name for whatever is after the undulator in one particular measurement station. So synchrotron scientists will not use the word measurement station, they will say beamline. I'm doing this experiment at beamline with that name in this synchrotron radiation facility. And depending on what the beamline is meant for, the detectors for instance that are in the beamline will be different, or even the undulator will be different, because not for all beamlines the same initial synchrotron radiation will be delivered. Brilliance is another word, and okay, I see that now the stream status finally is healthy again, good. So brilliance is another keyword. Brilliance is a measure for how good the synchrotron is, how many useful photons will it deliver to my experiment. And you can imagine that this will depend on the intensity, the number of photons per second, but that's not

enough, there is more that matters. In which solid angle are these photons delivered? It makes a difference whether you're after the undulator, whether all your photons are emitted into a narrow solid angle, or into a larger solid angle. The smaller this solid angle can be kept, the better. And also on to which area they are delivered. If you put your sample very close to the undulator, then you will keep on the surface area of your sample, you will accept all photons that are produced. If you put the sample farther away for the same solid angle, you will have less photons on the area of your sample. And finally there is the useful line width. You are usually interested in photons of a particular frequency, and you allow for some margin. So how many photons are there within a small margin around your target frequency? All these numbers together, all these features together, they combine into one number, which is the brilliance of your synchrotron, or of the beamline of your synchrotron, of the brilliance accepted by a particular beamline in your synchrotron. Well, with this you are ready to answer the confidence statement. Can you explain the concept synchrotron, synchrotron radiation, and synchrotron radiation facilities? With the answers you have given, and with the discussion we just have had, I hope you will be able to answer confidently on this. And the second one, I can explain the meaning of the major ingredients of a synchrotron radiation facility, the linac, the storage ring, the undulator, and so on. So these are the things we just have discussed, and I hope that the people who had some troubles with this will also move to the confident side. That was our first item for today. The second one, nuclear resonance scattering. And here, I offered you here some information, and asked to write, based on this information, a short Wikipedia article about what is nuclear resonance scattering. And I admit that it was a bit annoying that still these conference talks are not available. As I told you last week in the previous webinar, this is not within my control, that I asked again to the people who can change this. And from yesterday afternoon onwards, at least some of the conference presentations are there again, and today we will do another step. There was a complication, but after today, they should all be available again, at least if that complication can be solved in the right way. So I hope that the annoying fact of these videos not being there, that this will soon be solved. Okay, before looking at this Wikipedia article, let's look at what was discussed in the video, this paper about the basics of nuclear resonance scattering, of synchrotron radiation, by Schlage and Rulsberger. And in that paper they discuss a typical experiment, where you have these bunches traveling with a distance of 200 nanoseconds. You have a flash delivered every 200 nanoseconds, and now you are going to do a time-dependent measurement in this interval of 200 nanoseconds. That's an important feature of synchrotron radiation methods. You need a time interval here, where no new flash is delivered, where you have some time to measure. And this is not what all users of the synchrotron want. There are some users who are doing time-independent measurements and they are just interested in statistics, in intensity. So for these users it would be much better if, say, every 20 nanoseconds a bunch would pass. So you would have your storage ring filled with many more bunches and have many more flashes. So that would be very bad for synchrotron radiation methods, but that would be very good for, say, X-ray diffraction at a synchrotron. And that shows already that there will be a competition at synchrotrons. Some days of the year they will fill the storage ring in this way, as on this cartoon. And these are the days when the forward scattering people can do their measurements. And there are more days, many more days of the year, when more packages are put in the storage ring. And these are the days when, say, the X-ray diffraction people can do their measurements. Now, what happens when a photon hits a quantum system? And I put this in general a quantum system, so this can be an atom or a nucleus. What happens when a photon hits a quantum system? Scattering. And this is a classical cartoon of scattering. So some of the photons will travel through, but some of the photons will interact with the sample and the result will be a final photon, a scattered photon, that travels in a different direction. We can quantify the amount of scattering by classical properties, the scattering cross-section or the scattering length. And what are these? These are, well, if you consider this as a classical process, how large should my target be, how large should my quantum system be in order to produce this observed amount of scattering? The larger the target in linear size, so if you put a disk there with some area, or if you put a sphere there with some radius, the

larger that area, the larger the radius of that sphere, the more scattering there will be. And we know that if you have an incoming photon that matches an excitation energy of your quantum system, that then you will have a resonance, a strongly increased interaction between the photon and the quantum system, which can be represented by a strongly increased scattering length or scattering cross-section. This is illustrated in the paper by Schwage and Reusberger by an iron atom. So we first look at the situation where our quantum system is an iron atom, I stress atom, and we have a photon energy that is around 7 keV, which is an energy that matches with a k-edge transition in the iron atom. So this can excite an electron from the iron atom. And in the red line of the picture you will see on the next slide, a picture from the paper, that is the scattering length in Bohr radii that is observed. So what do we see on this picture? This is a measurement at a synchrotron, where you tune the energy of the synchrotron, you let the energy evolve from 6 to 12 keV, and every time the amount of scattering expressed by the scattering length is measured. And you see this scale here, which is around 7 keV, this on this scale, this is represented now in deviation from the resonance energy. So it's 0 at resonance and then minus at the left, plus at the right. You see that if you reach resonance, that then the scattering length is strongly increased. It looks like, at resonance, it looks like you have here a classical disk with a radius of 8 Bohr radii. So the iron atom can be represented by a classical disk of 8 Bohr radii with radius. Which is the conclusion that is printed there. I draw your attention to the width of this resonance. So this is here expressed in eV, so the width of this resonance is roughly 40 eV. So as soon as you are within 10, 20, 30, up to 40 eV from the resonance, you will start to see this strongly increased scattering. So far so good, now we will repeat the story, but we will do this now with an energy that is not 7 keV, but about 14 keV. And our quantum system will not be the iron atom, but an iron-57 nucleus. And 14.4 keV, you might remember this from the Musbauer chapter, 14.4 keV, that is the transition energy, the Musbauer transition energy in the iron-57 nucleus. So that is a resonance as well, but now a resonance in the nuclear system. What happens if we dare do the experiment? You keep increasing the photon energy by tuning the synchrotron. At about 14.4 keV you observe strongly increased scattering. Here you have again the blow-up, the red line is the scattering length. And look at it now, this is still in the same units of Bohr radii, you go up to 200. So the iron nucleus, although it is much smaller than the iron atom, behaves as a classical disk with a radius of 200 Bohr radii, compared to only 8 Bohr radii for the atom. Although the nucleus is much smaller, it behaves as a much stronger scatterer. Furthermore, the width here, this scale, is in nanoelectron volt. So the width here is about 40 nanoelectron volt, a billion times smaller than the width here. Which is why on this overall picture, where you have a scale of keV, here you can see some width, but here this is just one vertical line. So you have a much stronger scatterer with a much sharper resonance line. That's for the interaction between the photon and the quantum system, be it an atom or a nucleus. Now let's look at the photon. If we have a radioactive atom, say an excited iron-57 isotope, that decays and that emits a photon, then we discussed last time in the Mossbauer chapter, that due to the lifetime of that excited level, the photon will have some line width. Now the lifetimes of these Mossbauer levels, they are typically of the order of hours, days, so that line width here will be small. A synchrotron however, there the flashes are produced at very sharp moments, picoseconds with a picosecond resolution. You can say, my bunch, my flash has a duration of less than a picosecond. And due to the uncertainty principle, energy-time, that means that the line width of these photons will be much larger, millielectron volts. What does that mean? It doesn't mean that in these bunch of photons that come from the synchrotron, that there will be a few photons with a bit of a smaller energy and a few photons with a bit of a larger energy and most of the photons with an energy here in the middle. No, that is not what happens. This line width means that every photon has all these energies available. There is an uncertainty in the energy of the photon, not because you don't know, but because the photon intrinsically does have all these energies simultaneously. And I go back to the question from last week that we dealt with in the beginning. The question where it was said, what does that mean, this line width, these energy levels? It's weird energy bookkeeping if you can trade off a bit of energy in the transition. So, yes, and if you were confused there, you will probably be even more confused now. And you must

be confused. There is no other reaction possible on such statements than being confused. Photons do not have one specific energy. They intrinsically have a spread of energies. And usually we don't notice that because this spread is so narrow that we don't notice it. We don't experience the consequences. But for a photon produced by a synchrotron, that spread is relatively large and we really have photons that have a milli-EV range of energies available to them. Then, let's see where can we put, we know that synchrotrons have a spread of energies and synchrotron radiation methods, forward resonance scattering, that this is a method of class 3. So, we should be able to put it on our very important picture. And I asked you a confidence question about that. But the distribution was not to the right, so to say. So, let me show you where we can recognize our very important picture number 2. This is the picture from Schlage and Roelsberger. I will show you that what you see there at the left hand side, that this is something we have seen in the very important picture number 2. Because that's these green lines. So, the ground state level split in two by the hyperfine interaction for spin 1 half and the ground state level with the excited nucleus with spin 3 halves split in four. Well, exactly that situation was drawn here. So, what Schlage and Roelsberger discuss is just a subset of our very important picture number 2. And these transition lines here, these are the transitions of type 3. Now, I emphasized a few minutes ago that every photon has these energies within a milli-EV range at once. And that means that if such a photon interacts with the ground state level at once, and if there are a few hyperfine transitions possible, what was the energy difference between these different hyperfine transitions? They are hyperfine transitions. So, the energy differences are of the order of micro-EV. This line has a transition of transition energy that is only a few micro-EV different from this line. And the photon has a range of energies available within one milli-EV. That's enormously much more. So, that means that this photon can excite all these transitions at once. We do have again quantum superposition. You have a process with multiple paths. My photon can make this excitation, can make this excitation, can make this excitation. We don't know which one, we don't observe which one. And if we cannot observe which one, then we must say they all happen at once. We have to sum the amplitudes of all these processes. And if we want to know the intensity, we have to take the modulus squared of this sum of amplitudes. See the Maas-Bauer topic. Not as we would classically do, sum the different intensities. So, this was the picture that we used one week ago for the double-slit experiment. There, the two processes were that the photon could go through two different slits. And because we don't observe through which slit, we have to sum the amplitudes and the intensity pattern that we see on the screen. And that will have this interference term. Exactly the same will happen in forward scattering of synchrotron radiation. We will have interference. In the paper of Schlage and Roelsberger, I would say it's explained in a bit a misleading way. They say, well, my photon excites all frequencies, either this one or another one. And these two photons are re-emitted at slightly different times due to the lifetime of your excited state. So, not everyone will decay at the same time. And therefore, these photons will, they start with slightly different frequencies at slightly different times. And that will give rise to an interference in time. That's not what happens. It's really the quantum interference. It's like here. You have a process with multiple possibilities, multiple paths. And therefore, you have to sum the amplitudes and the interference you see here on the screen and here as a function of time. That is this quantum interference. Quantum beats is also the word that people use in this context. More explicitly, if there would be no hyperfine interaction in my sample, what would you then see? Exponential decay. There is only one energy transition possible. So, the incoming photon excites the system. After some time, the system de-excites. And what you measure in your detector is the de-excitation as a function of time. I will come back to this a bit later. There was a question related to that. But so far, let's take the semi-classical approach. It's just decays. And you observe the exponential decay in a log plot, a linear line, for the number of decays as a function of time. Look at this 150 nanoseconds. We can only measure up to the next bunch, which will come at 200 nanoseconds. So, you measure during that short time interval. But you do this again and again and again. So, that's how you can build statistics here. If there is a hyperfine interaction, then you have this multiple paths. You have the interference. And the interference here is seen as a modulation of your time spectrum. So, not a linear line, but a

line with a lot of oscillations. So, the signature of the hyperfine interaction in your nuclear forward scattering experiment is this modulation. You literally see the quantum interference. So, that's the method forward scattering of synchrotron radiation. There were some questions related to that. Somebody asked, is this forward resonance scattering just what we saw for Mossbauer spectroscopy? Or is this forward method something else? Yes, in a way it is what we saw for Mossbauer spectroscopy, but it is also different. So, remember, for Mossbauer spectroscopy, we had this very narrow line width of the photons. For synchrotron radiation, the photons have a very broad line width. Mossbauer photons, they can excite only one resonance at once. And therefore, you need that Doppler shift to tune the energy in order to screen the different resonances. With synchrotron photon, the energy is much broader. You excite all transitions simultaneously. And that's why you see this interference pattern. So, in that respect, there is a difference. There is also a difference in the type of measurement you do. You measure as a function of energy, as a function of Doppler shift with Mossbauer. You measure as a function of time with synchrotron radiation. However, the fundamental aspects that you see quantum interference, that is the same in both. And I think I have some slides, some of the slides of the Mossbauer chapter here, related to another question that I will come to in a minute. But we shortly discussed one week ago that the correct way to look at the Mossbauer experiment is that also here you have two paths in the forward direction. You have the path of a photon that does not interact with the sample and the path of a photon that is absorbed and re-emitted. If you look in the forward direction, then you don't see the difference between these two. So that means that you have to sum the amplitudes of these paths. And because there is a phase shift in the absorption and re-emission process, something we did not discuss in detail, this product term will get a negative sign. And the majority of the photons does not interact with the sample, so this I0 is very large. The intensity of the non-interacting photons is very large. The intensity of the interacting photons is very small, negligibly small. So you would not see this if Mossbauer spectroscopy would be a classical experiment. Your detector would not notice that some of the photons have interacted. In contrast to what the classical explanation of Mossbauer spectroscopy would be, they say that these absorbed photons are re-emitted in all directions, so therefore you lose this intensity I1. And that's the dip you see in your detector. But that intensity I1 is way too small to be observed. But what you do observe is this negative term, which is the product between the modulus of the amplitude of the non-interaction and the amplitude of the interaction. And this A0 is large, A1 is small, but a product of something that is large and small is still reasonable. So you notice that you subtract this from I0. That is the dip in your Mossbauer spectrum. So why am I telling this again? Because here you see that in Mossbauer spectroscopy you have quantum interference between the forward path that is non-interacting and interacting. And in forward scattering at a synchrotron you also have this quantum interference, but now between different interacting paths. That is the difference between the methods. But the fact that you do have forward scattering and that this is a quantum process, that is the same in Mossbauer and in synchrotron forward scattering. So let me then come to the question you see here on the slide that I didn't deal with yet. If Mossbauer spectroscopy sees fewer photons at resonance frequencies associated with these specific energy transitions because the photons have been scattered away from the detector. That is the classical explanation. Although I remember that this was not the best explanation. Yes, because we had this quantum explanation. How are the measurements of the emitted photons taken in nuclear resonance scattering at a synchrotron? Why would a detector at a synchrotron don't see this effect and a conventional detector does not see this effect either? So why don't you observe the dips here? Well, you do observe the dips, but they are, well, let me say it in another way. In Mossbauer spectroscopy the quantum interference shows itself as a dip in the energy domain or velocity domain. And this in forward scattering of synchrotron radiation, the quantum interference shows itself as oscillations in the time domain. So what would be a dip at a synchrotron? You would need to integrate all the events you see within these 200 nanoseconds and somehow correlate that to energies. So you work at a fixed energy, at the resonance energy of the photon. You select your photons such that they have the resonance energy of your quantum system with

the unavoidable millielectron volt distribution. So it's a very different type of measurement. You measure something differently in a different domain. That's why we said one measurement is the Fourier transform of the other measurement in a way. So I don't know whether that is really a clear answer to this question, but you don't attempt to measure a dip in a synchrotron experiment. If you still struggle with that, or if you can rephrase your actual problem more precisely, then please try again and we can see next week whether I have a better answer to that. And that's it. Another question that someone asked, a request to deal in the webinar with the advantages and disadvantages of nuclear resonance scattering at a synchrotron compared to Mössbauer spectroscopy. Well, some of the advantages of using the synchrotron method, that is the block that is listed here in the beginning, in a way it's simpler than Mössbauer spectroscopy, because you don't need that reference sample on a vibrating drive, although that reference sample is a well-known and easy system, so this is a minor advantage, and building such a drive is a bit less involved than building a synchrotron radiation facility. A more important example is that the energy of the photons that the synchrotron can produce is tunable, and therefore you can study many more isotopes. Mössbauer spectroscopy is almost exclusively done with iron-57 and tin-119, because you have so many requirements on the parent activity and the features of the isotope itself, that these are the only two that are practically useful. With a synchrotron you don't have this parent, you don't have the requirements on the parent activity. You can take whatever isotope and the only thing that matters is, is there a transition available from the ground state to some excited state that is within the reach of the energies that your synchrotron can deliver, and because you can tune that energy in quite a large range, you can study many more isotopes. There is of course the higher intensity of your synchrotron beam, therefore you can collect your spectrum in a much shorter time. Maybe it takes you several days or a couple of weeks to collect a Mössbauer spectrum in a lab, and at a synchrotron you could do the same experiment in seconds. Or you can take a sample that is so small that in the lab you would never get enough statistics, but in a synchrotron you can. And something we didn't discuss, the radiation, the photons from a synchrotron are polarized, and that gives you an extra degree of freedom. You can play with the polarization and therefore extract even more information from your spectrum. Disadvantages of using the synchrotron is, you can't just go there and do your experiment. You need to submit a proposal, compete with other people who want to use the precious time of the synchrotron, and only when your proposal is accepted, you know, okay, I will have so many time slots, say six months from now, when I can do my experiment. That's a practical barrier. And also the spectra you get, all these oscillations, they look much more complex than a Mössbauer spectrum. A Mössbauer spectrum you can take and say, okay, I see by the naked eye that this is a quadrupole interaction. With synchrotron spectrum, no, that's not possible. Of course you have software to do this analysis, so that is less of a problem, but if you have a complex spectrum with many interactions that are happening simultaneously, it might not be obvious how to start analyzing that. And then sometimes people do a separate Mössbauer spectrum on the same sample, with perhaps less statistics, but to have at least an idea, maybe this looks like there are five different sites in my sample with five different types of hyperfine interaction, let's try to fit my synchrotron spectrum with this initial assumption. So it's not one or the other, it very much depends on the situation you are in. Good, time is going fast, but well, let's see where we get. I then asked you, as in synthesis of the forward scattering of synchrotron radiation, to write a short Wikipedia article about this method, and I flash here two of these proposals that are both quite okay, I don't have specific comments to make to them. And rather I would use the next few minutes to discuss an example that was also presented in that paper by Schlage and Reusberger, to have a bit more insight on how a synchrotron experiment looks like, and which information we can extract from this. So the example is done for a very specific sample, and it's a sample where you have a substrate of iron-platinum, which is a hard magnet, meaning that the magnetization of this material will be along a specific direction, a specific crystallographic direction, and is not easily changed. On top of that iron-platinum you deposit 11 atomic layers of iron, plain iron, so BCC crystal structure, and you wonder what will be the magnetization of iron in every layer. If you

wouldn't do anything, then iron, which is a soft magnet, where the magnetization can easily be changed with respect to the crystallographic directions, because this is a soft magnet, the magnetization will adopt the underlying magnetization of the substrate. But now you put an external magnetic field perpendicular to the magnetization of the substrate, and you wonder how will this evolve throughout the 11 layers. Probably the layer closest to the substrate will want to take the orientation of the substrate, and the layer most far away from the substrate will rather follow the magnetization dictated by the external field. Interesting question, but how the hell do you measure that? And this is where synchrotron radiation will be useful. They make a very specific sample where the iron-platinum is made by iron with only isotope 56, which is the most dominant isotope in iron, I think some 97% of all iron nuclei are iron-56, but you use a source of iron that is cleaned, isotopically cleaned, you have removed all iron-57, and you make this iron-platinum with that isotope. That is not an isotope for which, well, if you work with synchrotron radiation of this 14.4 keV, that is not a transition in iron-56, so you will be blind for the substrate. Also this 11 layers of BCC iron are made with iron-56, you are blind for everything except for the atoms that are here along this black line. So this thin layer that is under an angle with the substrate, this thin layer is made with iron-57. And then the 11 layers are completed again with iron-56. That means that your synchrotron experiment is only sensitive to the iron atoms in the substrate. And that means that you have to measure every atom in this layer. And because you can position the spot of the synchrotron beam so precisely, you can first shoot at this region, and then this region, and so on, so you can step by step go through the sample, collect a spectrum every time, and by going from left to right it basically means that you measure a different spectrum. And this gives all these hard to interpret spectra with many beads, but you see that a continuous line is drawn through them, so a fit of these spectra, and that fit is analysed in terms of the rotation angle, and you see that if you apply an external field of 116 millitesla, then even the layer closest to the iron-platinum hesitates, should I follow iron-platinum or should I follow the external field. The layer at the surface follows the external field, if you increase the field, then you get more and more alignment along the field, even for the closest layer. So you can really follow with atomic layer resolution what these magnetizations do. That would be impossible without a synchrotron. Good, we have a few minutes left for the last topic, nuclear inelastic scattering, and this is something where there were two videos about that, and also a text, so you had to do this just with the text, but I hope now the videos will be working again. These are the two snapshots from the videos with the slide that explains the method, and I asked you to explain the method nuclear inelastic scattering, or nuclear resonant vibration spectroscopy, to explain that method in your own words, based on either the videos or the text, and I hope that you will do that. So let me go through one of these explanations and I put the screenshot from the video next to it, such that we can see what happens. So this nuclear inelastic scattering is a method used to measure the vibrations of crystals or molecules. So this is an important difference with the nuclear forward scattering that we just saw. That was a method to detect hyperfine interactions, and to extract from this information of your sample. Nuclear inelastic scattering is a method that is meant to measure vibrations. It doesn't measure hyperfine interactions, it measures vibrations, so the phonons in your molecule or crystal. It works by using synchrotron radiation, which produces intense beams of electromagnetic photons, so the undulator delivers a beam of photons, there is some collimation to select only the frequency that you are interested in, and then you have a sample. For our experiments where you have nuclear transitions with very narrow line widths, you even have to filter the frequency more precisely, so you go through a high resolution monochromator to select really a photon with this millielectron volt distribution around a very specific frequency, that one interacts with your sample, and when these photons interact with the nuclei in the sample, then there is this resonant excitation. Not, as is given in this answer, that the photon makes the nuclei to vibrate. No, the nuclei vibrate and the nuclei are already vibrating, because that is a property of your sample material. If this is a particular crystal at room temperature, then there will be several vibrational modes thermally excited, and the nuclei will be vibrating according to these vibrational modes, unavoidable. Now, that means that if you have a

crystal with a very high resolution, and if you have this very precise photon that is entering and that wants to create the nuclear transition, with that line width that is rather small, well, if there would be no vibrations, you would just see this central peak. If you are around energy zero, the transition energy, then you will have resonant absorption. But it could be that some of the vibrational modes that are present will contribute. If you have a photon that is entering with an energy that is a bit less, millielectron volts less, so this is really tuning the energy of the synchrotron photon. Every synchrotron photon has a width of 1 millieV, so if you are 20 millieV away from the resonance, you cannot cover this by the line width of the photon, it is really a different photon. But if now, at the moment when the photon interacts with the sample, if now a phonon is used, the energy of a phonon, the energy of a specific vibrational mode is used to compensate for the missing energy, then absorption is possible as well. The system, the nucleus is excited by absorbing a photon and by distributing the energy of the photon by destroying a phonon and using that vibrational energy to cover the missing part of the transition. And simultaneously, if the decay, the decay can happen for photons with a higher energy. If you use most of the energy for the decay itself and the excess energy to create a phonon, you will measure a vibration. In this way you will measure not a single peak, but a much more structured spectrum and that structured spectrum, that tells you at which energies do I have phonon modes available. So you measure part of the vibrational spectrum of your sample. That is what nuclear inelastic scattering does. So I hope that with this you can be more confident about nuclear inelastic scattering and once again I agree, this year it was particularly hard because these videos were missing. And I also hope that with this explicit explanation you can see more the difference between these two types of synchrotron methods. The part of synchrotron Mössbauer spectroscopy at extreme conditions, that part I don't discuss in this webinar, that was an optional part anyway and that video was missing as well. But if you have some time left and if you are interested in a really fascinating talk about using Mössbauer spectroscopy at a synchrotron, then I can recommend that one. Okay, with this we have reached the end of this webinar. And even not excessively much over time. I did not see questions appearing in the chat. I checked one last time. No, they are not there. So I think we can close here and you can tackle the next module and we see each other here, same place, same time in one week from now. Bye-bye.