MARKUS KLUTE: Welcome back to 8.701. So in this lecture, we talk about nuclear fusion. And what we mean by fusion is the energy production by two light nuclei fusing together to produce a heavier one which is more tightly bound. And again, we can understand this from the empirical mass formula, OK?

So the difficulty in nuclear fusion is that we now have to overcome the Coulomb barrier from the other side. So we have to bring two light nuclei together, have to overcome the Coulomb barrier in order to form this heavier and more tightly bound state. You might think that you can just take a two beams of protons like we do at the LHC, bombard them, and create heavier nuclei. But the problem is that most of the nuclei will scatter elastically, and will not lead to a new-bound state.

So the practical way to overcome the Coulomb barrier is by creating a confined mixture and supplying heat, such that the thermal energy is enough to overcome the Coulomb barrier. You can estimate how much energy is needed. If you, for example, assume a Coulomb barrier of about 5 MeV, this implies temperatures of 5 times 10 to the 10 Kelvin. OK, so that's really, really hot, right? If you compare this to typical temperatures within stars, you'll find that those are only 10 to the 8 Kelvin.

So now you ask, why does it still work? Why do we see fusion within a stellar medium? And the answer to this is, again, quantum tunneling, and to some degree, it's also the fact that when we have a medium of a specific temperature, the kinetic energy of the particle involved follows a mixture of energy distribution. So you find some particles which have enough energy to overcome the Coulomb potential. Even so, the mean value would be below.

The processes within the sun, they are dominated by so-called proton-proton cycle, or PPI cycle. And this happens in a number of steps. You start with hydrogen or protons-- the core of the sun is basically a plasma. So we can forget about electrons in this context. So we have two protons fusing together to a deuteron, which is a proton and a neutron, via the weak interaction. Here, you find for the first time, again, the neutrinos being produced in the sun.

Then, you supply the deuterium again. And together with the proton, you are able to produce the helium. And then the helium, again, is being used to supply the third step in this. Helium-3 is supplied to produce helium-4. So this then-- the end product is a helium-4 here, and energy. You combine all of those three steps, you find that you start with four protons. You produce helium-4 plus positrons, neutrinos, photons, and energy. In fact, as I was just saying, this all happens within the hot plasma. The positrons are basically annihilated with electrons, which are part of the plasma, adding another MeV of energy to this.

All right, this is one, and the dominant energy production mechanism within the sun. But it's not the only one. Also quite interesting is the so-called carbon cycle. It's contributing about 3% to the sun's energy output. So here, carbon basically works as a catalyst. So you have a carbon and, again, a proton producing nitrogen. The nitrogen produces carbon-13, carbon-13 together with a proton nitrogen-14, 14, nitrogen-14 with a proton oxygen-15, and oxygen-15, nitrogen-15, and then, last but not least, nitrogen-15 together with a proton produces carbon-12 again, and helium.

So you see that the carbon-12 is the catalyst here, which is used to produce helium and energy. So if you produce this cycle, that you combine this cycle, you find that, again, from four protons or four hydrogen atoms, you produce helium, positrons, again, neutrinos, photons, and energy-- very similar, it's visible, to this combined chain, with the exception that there is one additional photon. And again, here, the positrons supply additional energy and they annihilate with electrons.

Great, so we have seen that we do two things. We create heavier forms of metal starting from hydrogen, and we produce energy. And so this is the energy production mechanism within the sun. This is nice. You produce-- you start with hydrogen or deuterium. Those are two elements which are very abundant. And you produce energy. So the question comes up whether or not you can actually use this on Earth, in a controlled environment, in order to produce energy and solve many of the ongoing issues we have on this planet.

There are several efforts underway. And this goes back all the way to the '50s of the last century. The most prominent one currently is the so-called ITER project, which is international collaboration, and a project where one tries to build a fusion reactor in France.

I can already tell you that the next stage for this is in about five years to complete the project, or complete the production of-- construction of the project, and produce energy for the first time with this project in this controlled environment. It will take another 10, 15 years on this road map of research in order to produce, or be able to produce, nuclear power reactors-- nuclear fusion power reactors which can be used in some sort of commercial way. There's a few other interesting projects which use different magnet technologies which might have a more faster pathway to success.

But coming back to the story here, so you could start with protons again in a proton-proton reaction. But it turns out that this is a rather slow process, and not very promising for a controlled reaction. But deuterium or tritium are also very promising. Note that, for deuterium here, you have to overcome the same Coulomb barrier, right? The charges involved are the very same. But the cross sections are higher. And therefore, the likelihood for the process to occur is higher. And therefore, this can happen much faster. Deuterium is-- again, as I was saying before-- very abundant. You can just extract it from water. Tritium is a little bit more difficult to deal with-- to produce and to control because it's radioactive and has some really not so good features.

But this is a model picture of ITER. Again, this is an international project. It has a rather bad reputation these days. It's by far the most expensive scientific endeavor. But again, I mean, I think this is investment to the future of this planet. And hopefully it will succeed in the next years with this project, and in the long run with having nuclear fission-- fusion avail-- sorry, nuclear fusion available for energy creation.

What you see here is-- the key feature of this reactor is toroidal magnets which confine the plasma. And also, electric fields are used in order to heat the plasma up first. So you have to provide heat to a point that the heat being produced in the fusion process is sufficient to self-sustain. And so confining the plasma and providing enough energy, and the radiation in this and so on, this is all very difficult problems to solve.