MARKUS KLUTE: Welcome back to 8.701. So we continue our discussion of nuclear physics. And in this lecture, we talk about the nuclear force. Now, in the last lecture we saw that nuclei are bound together, and we were able to calculate using an empirical model the binding energy of various nuclei.

Now, the question remains, what is actually binding those nuclei together? If you remember, I mean, in the first weeks and months of this lecture, we looked and discussed various interactions between elementary particles. We saw the electromagnetic interactions, the weak interaction, and the strong interactions. There was no discussion of the nuclear interaction or the nuclear force.

Now, what is this? We have seen that the strong force acts between quarks and hadrons. For example, we have discussed at length the pion, the pion, which is made up of an up quark and a down quark. And those are held together or bound together via the strong force. And we looked also at the structure of a proton and the structure of a neutron.

Now, the nuclear force is the residual interaction between the quarks localized in different hadrons. So the interactions between protons with this up quark here and the down quark here in a different nucleon.

You can already understand that it will be difficult to have a full understanding of the nuclear force. Why? Because there's many quarks involved, and there's many protons and neutrons involved in this process. So what we find later that we can describe this using a mean field approach, a mean field of forces between the particles involved.

So what is the experimental status? Our understanding of the nuclear force is based on various kinds of experimental information. The first comes from nucleon-nucleon (proton-proton, neutron-neutron, and proton-neutron) scattering experiments. And some of those experiments have the benefit of using spin-polarized projectiles, for example a polarized electron being used to probe the structure of a nucleus.

Nuclear binding energies, we've seen those again, and the precision measurement of masses, they give us insight, especially useful for the light nuclei. And the nuclear structure information such as energies, energy levels, spin, parities, magnetic and quadrupole moments, again, especially of the light nuclei. And there's many more to be named in more detail. But conceptually, those are the three kinds of pieces of information we have.

The experiment-- those experimental results indicate that the nuclear force depends on the distance between the interacting nucleons-- this is the radial part-- how far apart are those nucleons? And also, the spin and angular momentum of the interacting nucleon. There seems to be a spin-orbit and also a tensor part when it comes to the nuclear force.

It is also interesting to note-- and we'll talk about this more-- there doesn't seem to be any indication that the nuclear force depends on the type of nucleon, whether or not it's a proton or a neutron in the interaction. So that's charge independence.

So looking at the radial part of this, nuclear force is short range, which implies it vanishes for distances longer than about 2 femtometers. So it basically vanishes in this area here. And the nuclear force is strongly repulsive for distances shorter than about 0.5, in this area, femtometers.

You can understand the repulsiveness by the fact that you cannot really push or press an existing nucleon further than its actual radius. You cannot compress them further. This is also kind of apparent in the liquid-drop model, where we discussed, you know, the volume term, and the volume is not-- cannot be compressed further. On the other hand, you saw that there is short-range distance, in fact, because we find this linearity with the mass number in the binding energies.

Right. So here are the arguments. The binding energies per nucleus which is roughly constant, indicates that the nucleons and nuclei interact only in their immediate neighbors. Otherwise, it would have an A squared term or an A times A minus 1 term in there. And then the measurement of distances between the nuclei at which nuclear reactions start to occur, those are in the order of 1 to 2 femtometers larger than the corresponding radii.

The nuclear densities which are only slightly smaller than the nucleon densities, indicating very dense packing. So again, they are already very densely packed. You cannot push them much further.

On the spin-orbit force, here that's an area where we could go into much more detail. But for this introductory class, we don't. We will not. The scattering of spin-polarized nucleons or other spin nuclei particles allows us to understand that nuclear force has a component which depends on the spin and the angular momentum of the interaction.

Here's a fun fact. So the charge independence nuclear forces, meaning that it doesn't really-- the nuclear force doesn't really depend on whether or not there's protons and neutrons. And you can-- I could ask you, you know, would you have expected this?

Would you have expected that there is a dependence on the charge? And the answer should have been no. Because we just learned that the nuclear force is a remnant of the strong interaction, the strong interaction doesn't know about electric charges. So the answer needs to be yes.

The charge independence of nuclear force implies that electromagnetic effects are eliminated in this scattering, meaning that when you measure aspects of the nuclear force, you have to be aware of the fact that there is electromagnetic interactions, and you have to kind of try to get them out. And that can be done by, for example, comparing scatterings of protons and protons, protons and neutrons, neutrons and neutrons. If you do a comparison carefully and subtract out the electromagnetic effect, then you'll see that the force is indeed independent of the charge.

We can make use of this. So there's a lot of information behind, or experimental techniques which can make use of the fact that nuclear forces are charge independent. What you can, for example, do is study so-called mirror nuclei. Those are the ones where basically revert the N and the Z for the same A. So they're basically mirrors of themselves in terms of mirroring the protons and the neutrons.

Examples are helium-3 and tritium, for example. And those, then, allow you to study in detail those effects. So this heavy mirror nuclei inherit heavy mirror nuclei, the breaking effect-- the effect breaking charge independence of the nuclear force are strong, and the similar does not hold.

Good. One example where you can study is if, for example, one of those mirrors is radioactive or unstable nuclei. You can study the properties of the unstable nuclei by looking in detail at the mirrored nucleus. So that's one of the common and interesting ways to study radioactive nuclei, where you cannot just simply take them, excite them, and study the properties. They simply decay too fast in some cases.

Here is a table where you see this effect. You see the comparison between the nuclei, this mirror nuclei here. There's four pairs. And you see that the binding energy, the net binding energy after removing the Coulomb term, is very much the same between those groups, those mirror groups of nuclei.

And this table here or this diagram shows you excitation energies for two mirror nuclei. And you see that the energy levels are pretty much on par. Without going into any detail, they're on par between those two mirrored nuclei.