The atomic nucleus – Probing the building blocks of matter

One of the central themes throughout the history of scientific research has been to understand the very building blocks of our physical world, and that means being able to understand the structure and behaviour of the atomic nucleus. As a theorist, that involves developing mathematical models that can account for the properties of nuclei in terms of the behaviour of their individual components.

But it's not an easy job. The atomic nucleus - that tiny dense core of protons and neutrons at the centre of an atom – is an incredibly complex object, whose behaviour is governed by the rules of quantum mechanics. In fact the forces that operate between its proton and neutron constituents, known collectively as nucleons, are so complex that the mathematical equations describing them can only be solved exactly for the very simplest of nuclei, containing just a few particles. To describe the structure of nuclei that can contain up to several hundreds of nucleons, we need to make approximations to model the way these tiny objects behave and interact with each other.

The force that binds nucleons together to form a nucleus is called the strong force and our understanding of some of its key components has been gained through studying even the most basic properties of nuclei that exist in everyday life.

The fact that nuclei exist at all tells us that the attraction between nucleons must be strong enough to overcome the electromagnetic repulsion between the positive charges of the protons.

We observe that nuclei containing certain 'magic' numbers of protons or neutrons are more stable than their surrounding neighbours and this is evidence for a quantum shell structure within the nucleus. This means that we can imagine the nucleons to fill shells within a nucleus, much like the way electrons are arranged in shells around the nucleus within atoms. When the number of protons or neutrons reaches a magic number, that means the shell is completely filled and it would require a large amount of energy to remove a nucleon, giving the nucleus extra stability against radioactive decay.

The fact that many nuclei are unstable is a result of the fact that the strong force only has a short range. This means that we can't just keep adding nucleons to make bigger and bigger nuclei because the forces holding them together die away rapidly with distance, setting a limit to nuclear existence.

Some of the key questions we would like our models to be able to reliably answer are just where are these limits of existence for nuclei, what is the heaviest element we can make and what are the most exotic nuclei, with the most extreme ratios of protons and neutrons that can exist?

By building up our knowledge of the underlying nuclear forces, we can begin to construct theoretical models based around approximating a mathematical function that represents them.

We can also create a shopping list for ourselves of the essential nuclear properties that our models must be able to successfully describe over a wide range of nuclei.

At the most basic level this will include the trends in nuclear size and shape, as well as the total amount of energy that holds the nucleus together. We also want to calculate the precise shell structure within the nucleus, as the distribution of shells is crucial for determining the magic numbers and therefore the stability of nuclei. Only then can we even consider trying to answer these questions.

Currently, one of the most successful nuclear models for describing properties across the full range of nuclei is borrowed from atomic theory and says that the structure of a nucleus can be calculated from the force felt by a single nucleon due to the average interaction of all the other nucleons. This average interaction is called a mean-field and is derived directly from our underlying knowledge about the strong nuclear between nucleons.

Mean-field models have enjoyed a great deal of success over the years, however, the recent improvements in experimental techniques have led to a few surprises that provide new challenges for nuclear theory and our current models.

If you take a look at this picture, it shows all the possible combinations of protons and neutrons within the nuclear landscape. You have proton number, which determines the chemical element along here and neutron number, which indicates the isotope of a particular element along here.

The black squares indicate the stable nuclei; about 250 of them and the intersecting red lines show the magic numbers for protons and neutrons, which give the nuclei situated along these lines extra stability due to their filled shells.

All of the nuclei in the shaded areas are unstable against radioactive decay, where the yellow bits are nuclei that have been produced and studied in experiments, and the green areas are nuclei that are predicted by our nuclear models to exist, but haven't been studied in experiments yet.

Our ability to probe the internal structure of the most exotic nuclei that we can currently produce has uncovered some unexpected features that even the most sophisticated nuclear models can't reproduce, suggesting that our understanding of the nuclear forces is incomplete.

One of these features is the discovery that as you move away from the stable nuclei, the arrangement of the nucleons within shells starts to change. This means that as we move into the more exotic regions of this landscape the numbers of protons and neutrons we associate with magic numbers start to disappear, and new ones start to emerge.

This is really surprising since it was previously thought that magic numbers were constant over the full landscape, but it turns out not to be the case.

I work on developing and improving the mean-field models I mentioned earlier, and one of the ways we can do this is to make improvements to the nuclear forces that are used based on our ever growing knowledge about the complex interactions between nucleons.

There is one component of the nuclear force that has been neglected from many models in the past. It is called the tensor force and it depends on the positions and orientation of the spins of the individual nucleons. It has been shown to have a strong influence on the arrangements of the nucleons in the more exotic regions and it's inclusion within mean-field models in recent studies has revised our understanding of shell structure and therefore the magic numbers within exotic nuclei, going some way to explaining the differences between experimental data and model calculations.

I study the role of this particular force within the mean-field model on the predicted properties of nuclei out at the very extremes of nuclear existence and I'm just going to show you very quickly one example of a calculation I have made for a region called the superheavy elements.

If you look at this picture once more, you can see that way up here, disconnected from everything else there is this little island of nuclei that are predicted to be extra stable in comparison to everything around it. Now, we can't reach these nuclei in experiments yet and although all models predict it to be there, they tend to disagree on exactly what the next magic numbers will be for protons and neutrons up here.

So the question is, does inclusion of the tensor force within mean-field models change the predicted location of these stable superheavy nuclei? This links in with one of those questions I mentioned earlier about where the limits of existence are.

This graph shows the calculated energies of the individual shells within nuclei that have a set number of protons, and the number of neutrons is varied across the bottom here. Where you see the larger gaps between shells is evidence, although not conclusive, for a magic number. This one on the left is the predicted shell structure before the tensor force is included into the model and you can see that although there is a slight gap here, which is for 114 protons, there is also a gap of around the same size for 126 protons, so we can't really distinguish between them.

If we then add in the contribution from the tensor force, you can start to see that these shell levels shift up and down a bit and actually a clearer gap starts to open up at proton number 114 across a range of nuclei. This picture actually now shows closer agreement with the predictions of some other types of model, so it's quite exciting to see that the tensor force does have an influence and in fact we can start to reconcile some of the discrepancies not only experiment and theory, but also between different types of model.

Of course this is not the whole story, but as our understanding of the complex forces between nucleons continues to grow, we can keep improving our models by incorporating more detail into the forces, in particular making mean-field models powerful and versatile tools for making reliable predictions about not just the structural properties of nuclei, but also the way the behave when they are exited, or when they collide together, bringing us closer to answering of some of the most fundamental questions about the world we live in.

Thank you.