KEEPING AN EYE

Prof. Michał Kowal heads the Department of Theoretical Physics at the Polish National Centre for Nuclear Research (NCBJ). His research focuses on the heaviest atomic nuclei, including stability analysis, basic nuclear properties and isomers.

michal.kowal@ncbj.gov.pl

PROF. MICHAŁ KOWAL

ON THE ELEMENTS

JAKUB OSTAŁOWSKI

Prof. Michał Kowal (National Centre for Nuclear Research, NCBJ) talks about the complexities of theoretical work, long-lived and excited nuclear states, and the frontier of our knowledge about superheavy atomic nuclei.

ACADEMIA: **What are chemical elements, and how many of them are there?**

MICHAŁ KOWAL: Today we know of 118 chemical elements. The heaviest ones were synthesized at the Joint Institute for Nuclear Research in Dubna, Russia, and were recently named by the International Union of Pure and Applied Chemistry (IUPAC). The heaviest element has 118 protons in its nucleus and is called oganesson. This is the second time in the history of physics and chemistry that a chemical element has been named after a living person, in this case the Russian physicist Yuri Oganessian. Oganesson (Og) is predicted to be a member of group 18 in the periodic table, which comprises the so-called noble gases including helium, neon, argon, krypton, xenon or radon. However, this prediction has yet to be verified.

A chemical element is defined by the number of protons in its atomic nucleus. But nuclei can also contain neutrons, and depending on the number of neutrons in the nucleus, one and the same element can take on many different forms, called isotopes. We currently know of some 3,000 isotopes; however, only just over one hundred of those are stable, long-lived isotopes. As a rule, atoms of the heaviest elements exist for mere milliseconds before decaying. This short period is enough for us to be able to detect them, and their half-lives can be estimated indirectly. But because they are so short-lived, we currently don't know how to do chemical research on superheavy isotopes. With the atomic number of 112, copernicium (Cn, discovered by Sigurd Hoffman) is the heaviest element to have been analyzed chemically, if we can even speak of chemical analysis in this case. The recently discovered elements have brought the existing periodic table to completion.

You mean the period table of the elements, which arranges them into a regular pattern of recurring properties?

Absolutely. Up until recently the periodic table taught in schools still had some gaps – those have now all been filled. The question remains, can we perhaps synthesize an element that's even heavier than oganesson, with an atomic number of Z = 119 or higher? Which group in the periodic table would it be a member of? Those are not trivial questions. With so many protons in the nucleus, the relativistic effects that deform the electron orbitals are too strong for us to accurately predict the arrangement of orbitals in a superheavy atom. With lighter elements, this a lot more straightforward.

The heaviest elements (Z = 114, 115, 116, 117 and 118) were synthesized in Dubna, Russia, through so-called hot fusion reactions. Somewhat lighter elements, such as darmstadtium (110), roentgenium (111) and copernicium (112), were synthesized in the GSI Helmholtz Centre for Heavy Ion Research in Germany through a different kind of reaction known as cold fusion.

Hot fusion, i.e. the reaction used to synthesize the heaviest elements, is a highly sophisticated method involving heavily radioactive targets used over a period of weeks or even months. Obviously, even the preparation of such a target is a highly complex chemical process and requires special permits to handle the highly radioactive materials. A fast-rotating target is then collided with another heavy ion – a projectile. Ions of Calcium-48 happen to make the best projectiles for synthesizing superheavy nuclei in hot fusion reactions. We don't fully understand why that is the case, but that particular calcium isotope seems special, even a little bit "magical" in that respect. No other projectile has produced comparable success in hot fusion reactions. Currently, attempts are being made at RIKEN in Japan to synthesize an atom with an atomic number of 119 using a vanadium projectile. We'll see how that works out...

When successful, hot fusion creates a heavy nucleus in a highly excited state that rapidly emits two, three or four fast neutrons, each removing seven or eight MeV of energy from the system, whereby it "cools down." At every stage of this emission the neutrons compete with the fission processes that lead to nucleus decay. Crucially, this means that the nucleus generated through hot fusion must be resistant to nuclear fission. The so-called fission barrier is the main parameter in this respect. What we do in Warsaw is calculate the fission barriers and other fundamental properties for the heaviest nuclear systems.

Is your work experiment-based?

Absolutely not. We specialize in theory. From the theoretical perspective, the first difficulty is that superheavy nuclei are exceptionally unstable systems. They are so short-lived that it's hard to predict how long they might exist, and the probability of synthesizing a nucleus of this kind is extremely small to begin with. This is why for some time now we have been looking for metastable states of short-lived elements, often referred to as isomers. Isomers are nuclear configurations with low excitation which for certain reasons appear to have far more stability than corresponding ground states. If a nucleus finds itself in such a metastable state it will usually have extreme properties – it will decay in unusual ways or be unusually long-lived, which is precisely what we want to achieve.

Recently we've been able to find many possible states that produce metastable systems, what we call K-isomers. If synthesized, such isomers might live tens of thousands of times longer than their extremely short-lived ground states. In that case they'd probably be easier to study by chemical means: instead of testing the chemical properties of elusive ground state nuclei we might be looking at the chemical properties of their metastable isomers. In fact, it is entirely possible that some excited states have already been synthesized in laboratories but went undetected and unrecorded. Detectors are typically calibrated to detect nuclei with lives measured in milliseconds. Some metastable isomers may have been synthesized, but then nobody waited the seconds or minutes needed to detect them.

We offer an explanation for the mechanism that underlies this stability in our most recent article. A metastable isomer is a low-lying in energy high-spin state. The structure of this isomer state will differ from the ground state, meaning that it cannot easily decay to the ground state – this process would involve considerable restructuring, which is not easily achieved in nuclear decay. So, on the face of it we appear to be dealing with the same kind of nucleus with the same atomic number and the same number of nucleons – but because the nucleons are arranged in a different way and would need to get rearranged, the decay is much slower. In the case of high-spin isomers, alpha decay is additionally hindered by the so-called centrifugal barrier that's related to changes in angular momentum. Decay being strongly hindered for those two reasons, the nucleus spends a long time in a metastable state before decaying to a state with a similar structure, which is also excited relative to the ground state. This time, however, alpha decay occurs without any change to centrifugal barrier, which on the one hand radically facilitates the decay process, but on the other hand the required energy cost is connected with the fact that the state in the descendant nucleus is usually a high energy one. This effect reduces the available decay energy and slows the process down. As a result, virtually all the potential channels for alpha decay are hindered, meaning that a nucleus in an isomer state has increased stability. Those being high-energy reactions, generating such states should not be too difficult.

How did you identify this mechanism?

In Warsaw we have a long tradition of research into superheavy elements, owing in no small part to Prof. Adam Sobiczewski, the doyen of our research group, who recently passed away. The publications I am referring to were written in close collaboration with my colleague Janusz Skalski (Polish National Centre for Nuclear Research) and Piotr Jachimowicz (University of Zielona Góra). Our recent interest in K-isomers stems from the fact that they seem to have a potential for finding long-lived states thanks to their unusual structure. This in itself is exciting enough, and we were motivated to pursue this research angle. We wrote our first publication about potentially long-lived high-spin states already three years ago. That publication was about odd nuclei. Nuclei with an odd number of nucleons (especially both protons and neutrons) are notoriously tricky to study both theoretically and experimentally. When studying odd nuclei, we found our first candidates for long-lived states (which in this case may often include ground states as well). The hindering mechanism works slightly differently in odd nuclei. We found some unusual ground states with high spin in odd nuclei; as a result, the decay of the ground state in such nuclei is inherently blocked because the structure of the nucleus differs from the structure of the "daughter" nucleus it decays to. Odd nuclei include isotopes such as ^{272}Mt (an atom of meitnerium with 109 protons and 163 neutrons). ^{272}Mt has never been synthesized, but once created, our calculations suggest it could live millions of times longer than most of the superheavy elements we know today.

How can this be verified by empirical means?

We work with the theory: we make predictions and estimate possible outcomes. In each case we make it clear which model was used for our calculations and we state our assumptions. The calculations are time-consuming and quite advanced, requiring powerful computing capabilities. Luckily, we can now work with a supercomputer, namely the high-power computer cluster at the National Centre for Nuclear Research at the Computing Centre in Świerk (CIŚ). Still, at the end of the day physics is an experimental science. It's the experimenters at Dubna, GSI or other laboratories who win accolades as "discoverers." We do theoretical prediction work, modelling the possible properties of such elements before they are even synthesized. This is a complex, nontrivial process, and our calculations must be treated with caution. Our findings invite further tests, but only experiments can produce fully reliable results.

Do you ever visit laboratories were such experiments take place?

Yes, I try to collaborate closely with the GANIL facility in Normandy where a highly sophisticated S3 separator is about to be put into operation. High-spin states will be a major research angle when that happens. With good separation and detection, it will be possible to study the structure of heavy nuclei in considerable detail. K-isomers are also studied at the Argonne laboratory in the United States. Other facilities include Jyväskylä in Finland and obviously Dubna in Russia. In Poland, there is a growing pressure for modernizing our existing old cyclotron at the Heavy Ion Laboratory in Warsaw (ŚLCJ). That would make it possible to do more efficient research into the structure of heavy nuclei, and potentially also superheavy nuclei in the future.

INTERVIEWED BY ANNA ZAWADZKA