

Surprising asymmetric nuclear fission

Physicists of the Institute for Nuclear and Radiation Physics at the K.U.Leuven and their international colleagues have observed an unexpected form of nuclear fission challenging the existing models of atomic nuclei. They studied the fission of mercury-180 and observed that this nucleus, in contrast to the conventional models, fell apart into two unequal parts.

Nuclear fission: symmetric or not?

Nuclear fission – the process by which a heavy atomic nucleus breaks up into parts – was discovered more than 70 years ago by German chemists. It was immediately clear that within this process a huge amount of energy is released. Soon, applications were found for this new source of energy, in controlled way for electricity production in nuclear reactors, but also in uncontrolled way for atomic weapons. It is, therefore, not surprising that nuclear fission was studied very thoroughly, particularly in the heaviest atomic nuclei we know on earth, like uranium and thorium.

An atomic nucleus is in many perspectives comparable with a water droplet and, thus, one thought that the fission would result into two equal parts. Often, this turns out to be right, but in the heaviest nuclei something else is observed. A uranium nucleus with 236 nuclear particles (protons and neutrons) splits into a heavy nucleus around tin-132 and a lighter fragment. This can be explained because tin-132 is a nucleus with exceptional properties: the 132 nuclear particles, 50 protons and 82 neutrons, form a unique configuration. Like the electrons revolve around the atomic nucleus in well-defined orbits and as such form shells, also the neutrons and protons move around in shells in the nucleus. Atoms with completely occupied electron shells are extra stable and have particular chemical properties: those are the noble gasses. Tin-132 is to nuclear physics what a noble gas is to atomic physics: a nucleus with completely occupied neutron and proton shells. Such a nucleus is called a double-magic nucleus, because the completely occupied shells concern both types of shells. This effect is so strong that it has an influence when the heavy uranium nucleus is about to split. For nuclei lighter than uranium, the influence of the tin-132 shell closure is less giving rise to a symmetric fission.

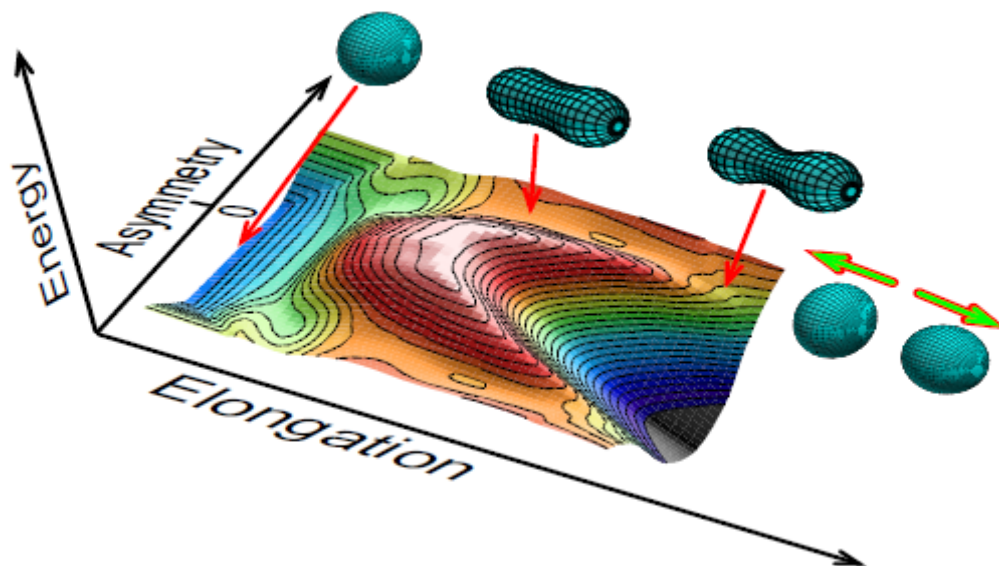
Researchers of the ISOLDE project at CERN – the European laboratory for particle physics in Geneva – who studied the decay of mercury-180 (with 80 protons and 100 neutrons in the nucleus), expected that the nucleus would split into two zirconium-90 nuclei, each with 40 protons and 50 neutrons. That result seemed by far the most probable, since 40 and 50 are ‘magic’ numbers, by which shells are exactly filled.

Mercury-180 with a nuclear surprise

ISOLDE is a setup creating pure beams of instable heavy elements, so that the reaction products can be studied. An international research team of 32 scientists consisting of experimentalists and theorists from three continents made use of a pure beam of the element thallium-180. This investigation was lead by the group of Mark Huyse and Piet Van Duppen of the Institute of Nuclear and Radiation Physics with Andrei Andreyev, ‘visiting professor’ in the group at the time, as p.i. (principal investigator). Eleven members of the team, including Master student Jytte Elseviers, are connected to the K.U.Leuven, two members are connected to the UGent.

Thallium-180 nuclei are so unstable that just a bit more than one second after their creation, half of them have decayed already. After beta decay, by which the thallium nucleus captures one electron, a mercury-180 nucleus is formed. The researchers observed that out of one billion created mercury-180 nuclei about ten split. To their surprise, it turned out mercury-180 underwent unequal fission in ruthenium-100 and krypton-80, two isotopes having no completely filled shells whatsoever like zirconium-90.

Peter Möller, a theoretician of Los Alamos National Laboratory in New Mexico, thinks to have an explanation. According to him, the key is not only to take into account the stability of the end products, but as well the 5-dimensional shape of the enclosure, which holds together mercury-180 for a little longer just during the fission. He makes use of a flood model for his description, comparable with a model predicting for instance where the water will flow to in a mountain landscape. It won't always be in a straight line to the lowest point; it depends which obstacles are present. The topology of the nuclear landscape during fission is subject to much more influences than merely the stability of the end products.

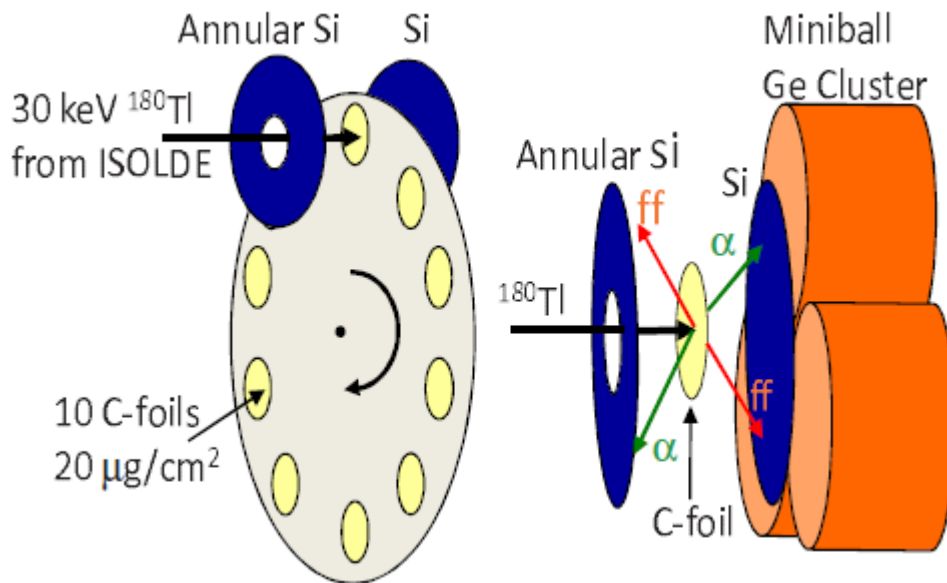


The figure shows an energy surface of the mercury-180 nucleus and the course of the fission process. Although it is energetically more favorable to split into two equal parts, the path goes through a non-symmetric valley, which is separated by a ridge from the symmetric valley. At the moment that the ridge disappears, the formation of the fission products has evolved so much that an asymmetric mass distribution is created.

Now what with the theoretical models?

This kind of information is of great value to the further fine-tuning of models describing the interactions between nuclear particles. An atomic nucleus does not split like a simple water droplet; many balances and forces are at play, which we still understand too little, also 70 years after the discovery of nuclear fission. The merit of this investigation is that the scientists have found a method to obtain very detailed information just before the fission of the nucleus, almost without perturbing the process itself. And that fission process is also relevant for a

better understanding of the nucleosynthesis: the creation of heavier nuclei, a process, which is of great importance to astrophysics and which can give an explanation for the existing abundances of elements in space, in stars, and on earth.



A schematic representation of the experimental setup. The thallium-180 nuclei are implanted in a thin carbon foil. The two fission products are detected in two silicon detectors.

The described results are published in December 2010 in the journal Physical Review Letters.