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One experiment maps multiple isotopes exhibiting pygmy excitations

In a single experiment, physicists have measured the 'excess' emission of high-energy gamma rays from more than a dozen heavy, unstable atomic nuclei. Mapping the gamma-ray emissions of so many isotopes produced in nuclear fission marks an important step towards a better understanding of one of the key phenomena in modern nuclear physics: the fission process itself.

Why do excited heavy nuclei produced in fission appear to emit excessive amounts of particularly energetic gamma radiation? New clues to this long-standing question have emerged from an international experiment carried out at the GANIL accelerator facility in Caen, northern France. Here, a beryllium-9 target was bombarded with uranium-238 ions, producing unstable curium-247 nuclei that rapidly underwent fission into two lighter fragments. By combining unique experimental techniques, researchers were able – for the first time within a single experiment – to collect data on high-energy gamma-ray emissions from more than a dozen heavy, unstable isotopes. The first results of the experiment, to which the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow made a significant contribution, have just been published in *Physics Letters B*.

"Observing the excited nuclei produced in the fission of curium was crucial for our project, it gave us access to heavy nuclei that had never before been investigated using comparable methods," says Dr. Michał Ciemala (IFJ PAN). *"GANIL is home to the excellent stationary magnetic spectrometer VAMOS++. Our comprehensive measurements became possible by combining its capabilities with those of the mobile PARIS gamma-ray spectrometer."*

The PARIS spectrometer is an array of state-of-the-art scintillation detectors arranged in clusters and designed to record high-energy gamma rays within extremely short time intervals. Originally proposed by Prof. Adam Maj, the instrument has been under development for more than a decade by an international scientific consortium coordinated by IFJ PAN, with a substantial part of the work carried out using the technical and research infrastructure of the Bronowice Cyclotron Centre, a division of IFJ PAN.

"VAMOS++ allowed us to determine precisely the masses and charges of the nuclei produced in the fission of excited curium, while PARIS recorded the gamma radiation emitted by those nuclei," explains Dr. Ciemala. *"Since excited curium can fission into many different isotopes, our two-week measurement campaign enabled us to become the first team to record high-energy gamma emissions from an entire family of neutron-rich nuclei located far from the well-explored valley of stability."*

The valley of stability refers to atomic nuclei that do not undergo rapid spontaneous radioactive decay. Stable nuclei possess energetically favorable configurations of protons and neutrons. For light nuclei, stability is generally associated with similar numbers of protons and neutrons, whereas heavy nuclei require an excess of neutrons to remain stable.

Using the combined data from the PARIS and VAMOS++ spectrometers, the experimental team identified the specific unstable nuclei produced in the fission of curium and assigned the observed gamma-ray emissions to each isotope. Theoretical calculations subsequently performed by re-

searchers in France for these individual isotopes suggest that at least part of the observed high-energy gamma radiation originates from pygmy resonances.

Pygmy resonances are associated with collective vibrations occurring in heavy nuclei that contain substantially more neutrons than protons. The excess neutrons tend to accumulate near the nuclear surface, forming a layer known as the neutron skin. When such a nucleus is excited – for example, by the impact of another particle – the neutrons in the outer layer begin to oscillate collectively relative to the protons in the nuclear core. At the same time, the excess neutrons themselves can undergo additional vibrational modes. As these neutron oscillations lose energy, they emit particularly energetic gamma rays. Because this radiation is considerably weaker than that associated with the collective oscillation of the neutron skin, these excitation modes are referred to as pygmy resonances.

The group of isotopes whose gamma-emission properties are reported in the study includes more than a dozen unstable nuclei located in the vicinity of the doubly magic isotope tin-132 (in nuclear physics, magic numbers correspond to completely filled proton or neutron shells; a doubly magic nucleus has both proton and neutron numbers equal to magic values).

“Until now, measurements of high-energy gamma-ray emissions had to be performed in painstaking, long-term experiments designed specifically for individual isotopes. In a single experiment, we mapped many nuclei that had never before been studied from this perspective. Not only did we obtain data for an entire range of isotopes, but all measurements were performed under the same experimental conditions and with the same systematic uncertainties. This gives our results a major advantage: they enable exceptionally reliable comparisons of gamma-ray emissions across different isotopes,” says Dr. Ciemala.

The new dataset collected in the experiment will help nuclear theorists improve the calibration of modern models describing the fission process, leading to a better understanding of its dynamics. Such advances may eventually contribute to the design of next-generation nuclear power plants that are more efficient and safer, but also produce smaller quantities of long-lived radioactive waste. The results are also expected to benefit astrophysics. More accurate knowledge of fission processes and the properties of excited heavy nuclei will improve studies of how the chemical elements are synthesized in the Universe, refine models of neutron-star mergers, and contribute to more accurate estimates of black-hole lifetimes.

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The Henryk Niewodniczański Institute of Nuclear Physics (IFJ PAN) is currently one of the largest research institutes of the Polish Academy of Sciences. A wide range of research carried out at IFJ PAN covers basic and applied studies, from particle physics and astrophysics, through hadron physics, high-, medium-, and low-energy nuclear physics, condensed matter physics (including materials engineering), to various applications of nuclear physics in interdisciplinary research, covering medical physics, dosimetry, radiation and environmental biology, environmental protection, and other related disciplines. The average yearly publication output of IFJ PAN includes over 600 scientific papers in high-impact international journals. Each year the Institute hosts about 20 international and national scientific conferences. One of the most important establishments of the Institute is the Bronowice Cyclotron Centre (CCB), which is an infrastructure unique in Central Europe, serving as a clinical and research centre in the field of medical and nuclear physics. In addition, IFJ PAN runs four accredited research and measurement laboratories. IFJ PAN is a member of the Marian Smoluchowski Kraków Research Consortium: “Matter-Energy-Future”, which in 2012-2017 enjoyed the status of the Leading National Research Centre (KNOW) in physics. In 2017, the European Commission granted the Institute the HR Excellence in Research award. As a result of the categorization of the Ministry of Education and Science, the Institute has been classified into the A+ category (the highest scientific category in Poland) in the field of physical sciences.

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SCIENTIFIC PUBLICATIONS:

“First experimental isotopic mapping of the fission “γ-bump” and its connection to the Pygmy dipole resonance”
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LINKS:

<http://www.ifj.edu.pl/>

The website of the Institute of Nuclear Physics, Polish Academy of Sciences.

<http://press.ifj.edu.pl/>

Press releases of the Institute of Nuclear Physics, Polish Academy of Sciences.

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Artistic visualization of gamma radiation emissions by the pygmy neutron skin resonances of excited atomic nuclei produced in curium fission. (Source: IFJ PAN)