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Exploiting correlations in gamma ray detection to non-invasively monitor nuclear reactors

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Autonomous monitoring of nuclear reactors is a challenging task, yet a crucial component of the International Atomic Energy Agency‘s (IAEA) efforts to ensure compliance with the non-proliferation treaty. At EPFL, we recently demonstrated that so called ‚gamma noise‘, i.e., correlations in gamma detection events, can be used to reliably monitor a research reactor from meters away, a distance to the reactor core much higher than expected [1] or commonly performed using neutrons only. This newly gained flexibility could enable new inspection tools for the IAEA, but could also aid in the monitoring of spent reactor fuel or damaged reactors.

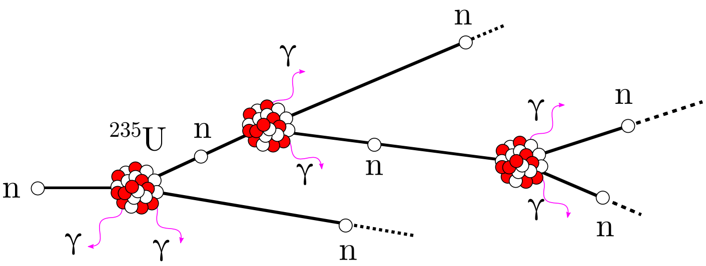

Figure 1: A fission chain in time: An initial neutron causes a heavy nucleus, e.g. Uranium-235, to fission, releasing energy, neutrons, and gamma rays. The newly liberated neutrons can subsequently induce another fission, causing a chain reaction.

Nuclear energy and the IAEA

Climate crisis scenarios, such as those outlined by the UN IPCC [2], suggest that nuclear energy could play a critical role in providing low-emission electricity to reduce global reliance on fossil fuels. The World Energy Council’s 2019 World Energy Scenarios report [3] projects an overall increase in the absolute amount of installed nuclear power across various plausible pathways until 2060.

However, nuclear energy remains a strategically sensitive technology due to the potential availability of special nuclear material (SNM) from the fuel cycle. The International Atomic Energy Agency (IAEA) leads non-proliferation efforts to ensure the peaceful use of nuclear energy, which includes controlled technology transfer to non-nuclear states, treaty facilitation and verification, as well as inspections and monitoring of nuclear facilities worldwide.

Given the anticipated growth in nuclear power installations, there will be a corresponding need to improve safeguard efforts. As part of its R&D plans [4], the IAEA seeks to improve existing safeguard technologies to effectively address emerging technological trends, particularly in the context of inspections and reactor monitoring. This includes novel approaches for non-proliferation monitoring tailored to small modular reactors (SMRs), which, due to their smaller size and design, present unique challenges. Often, safeguarding measures require inspectors to manually verify the declared inventory of a facility through item identification and counting. Autonomous monitoring of nuclear reactors using radiation signatures is therefore a key area of development.

Methods for reactor monitoring

Common radiation signatures used to monitor nuclear reactors include neutrons, gamma rays, and antineutrinos. Recent studies showed that large-area neutron detectors placed at stand-off distances (i.e., beyond the reactor vessel) can track a reactor’s power evolution [5]. These methods only provide simple information (reactor on/off, and approximate power level), and the signal may be vulnerable to tampering through deliberate source positioning. Similarly, antineutrino detectors have been shown to be able to track a reactor’s power evolution, with the added advantage of providing information about the antineutrino spectrum [6]. Antineutrino measurements are, however, still subject to significant uncertainties, and provide information only on the order of weeks, typically applicable to power systems above 100 MW_{th}. Moreover, detector volumes of 3’000 liters or more are necessary to achieve significant detection rates, posing challenges in terms of cost and mobility. Consequently, both neutron and antineutrino detectors are currently inadequate for detecting fuel composition changes that occur on a timescale shorter than a week, potentially allowing time for secondary use activities and signal tampering in smaller and lower-power facilities.

To address the need for real-time measurement of both the reactor’s current state and changes in fuel composition, so called ”noise measurements” may offer a viable method. By exploiting the temporal correlation between subsequent detector counts, it is possible to directly observe a reactor’s fission chain propagation (see infobox). A common approach in noise analysis involves measuring the excess variance caused by temporal correlation, as compared to a strictly Poisson random process where variance equals the mean.

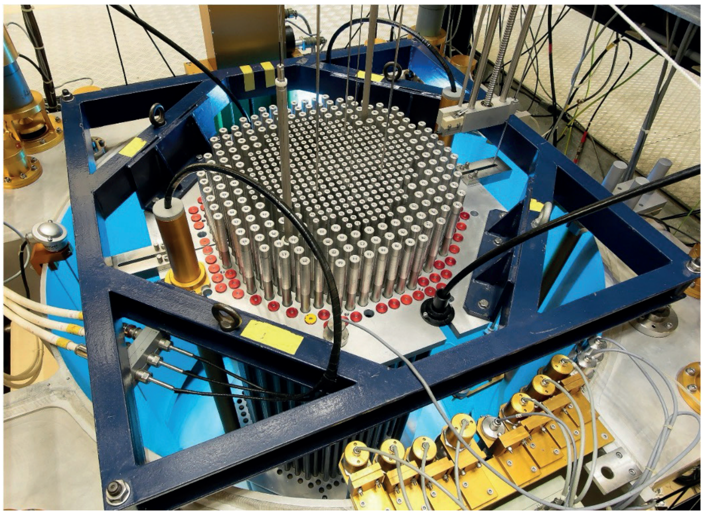

Figure 2: The CROCUS reactor at EPFL. The blue light stems from a lamp, as with a maximum power of 100 W, the Cerenkov radiation is not intense enough to be visible.

Correlations in detection events

Observing a standard radioactive sample, the detection events in time are randomly distributed. This is due to a special property of radioactive decay: it is spontaneous and has a constant probability in time. Measuring a source for some amount of time would therefore yield a Poisson distribution in the events detected per interval of time. This translates into the variance of detection events per time interval being equal to the mean value. However, in a nuclear reactor, events in time are potentially correlated: each fission releases 2-3 neutrons and 3-7 gamma rays on average, and thus successive detection events could stem from successive fission events. The thereby induced correlation in the detector signal causes the variance of the detection events per time interval to increase with larger time intervals. The correlation is directly related to the time-dependent behavior of the system. This behavior was initially described by R. Feynman in 1956 when describing the neutron population of the LOPO 'water boiler' reactor at Los Alamos National Laboratory [7].

In 1956, Feynman et al. [7] demonstrated that the shape of this excess variance over an arbitrary time bin size can be represented by an analytical function. By fitting this function to detector signals, the "prompt decay constant" α of the system can be determined, which reflects the average length of prompt fission chains. This measurement can then be compared to previous data or code predictions of α to assess reactor operation, schedule compliance, or potential changes in fuel composition.

Previous noise experiments conducted in CROCUS using high-efficiency neutron detectors indicated that correlations from fission chains are statistically indiscernible from background beyond 20 cm from the fuel [8]. This observation was interpreted as an intrinsic limitation of neutron noise, limiting the applications of the noise method to research.

The CROCUS reactor at EPFL

CROCUS is a uranium-fueled and light water-moderated reactor, which was previously used mainly for teaching purposes. With a maximum allowed power of 100 W (i.e. a maximum total neutron flux of about 2.5×10^9 cm$^{-2} \cdot$ s^{-1}), it belongs to the category of zero-power reactors, where pure neutronics are studied without thermal feedbacks induced by power. After its moving from Avenue de Cours in Lausanne, it reached its first divergence with its current design on the EPFL campus in 1983. From an education point of view, which remains its primary motivation, it is continuously employed for EPFL students in Physics in their second and third year of Bachelor, as well as for students in the joint EPFL/ETH Zurich Swiss Master programme in Nuclear engineering since 2008, in close collaboration with the Paul Scherrer Institute (PSI). It also hosts internships, Master semester projects and Master theses.

Research programmes in CROCUS were rejuvenated in 2014, following the appointment of a new professor, and the assembling of a new team. Over the past decade, an expertise and a unique set of experimental results were obtained, along and thanks to developments in nuclear instrumentation. The core consists in two interlocked fuel zones with different fuel and pitches which, despite being an additional complexity, are also a challenge of interest for deterministic codes, towards their experimental validation. Although CROCUS lacks flexibility in fuel type and configuration, its low technological uncertainties, operation precision and stability, reflector and interpin space, and general accessibility, revealed it to be a perfect candidate for reference, but also atypical experimental endeavours.

Gamma-ray noise for novel reactor monitoring

Our research indicates that gamma-ray noise methods offer a more affordable, compact, and simple monitoring tool, providing direct information on fission chain propagation. For noise measurements, the detectors do not require calibration beyond a simple visual inspection of oscilloscope signals, as the relevant information is encoded in the timing between pulses, allowing for a relatively fast setup.

A significant limitation of applying fission chain correlation analysis to reactor monitoring is the potential for thermal-hydraulic noise (i.e., mechanical vibrations due to coolant flow) to overpower the fission correlation signals. Consequently, the proposed technique may not provide useful information for reactors operating above 100 kW, although this remains to be tested in the future.

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