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How inelastic scattering stimulates nonlinear reactor core parameter behaviour

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ABSTRACT

Nonlinear and skewed distributions for safety-related parameters of a realistic Pressurized Water Reactor (PWR) are observed due to the current limited knowledge of the inelastic scattering of neutrons on ^{238}U. The current knowledge of this cross section, about 20% uncertainty, does not lead to normally distributed core parameters, thus increasing the probability of rare events. In this paper, it is demonstrated how the simulations of 14 years of PWR operation with realistic history and fuel loading pattern induce non-Normal distributions for 3-dimensional peaking quantities and why a reduction of the ^{238}U inelastic cross section uncertainty by a factor 2 is desirable.

1. Introduction

It is generally accepted that the current knowledge on nuclear physics quantities is adequate for the safe operation of existing Light Water Reactors (LWR) (Rochman et al., 2017). This is, on the one hand, due to the large accumulated practical experience in power plant operation over the last decades, and, on the other hand, thanks to the use of mock-up systems to support safe LWR operations. Nowadays, as such downsized reactor replicates represent a non-negligeable cost, computer simulations in decision-making process tend to slowly take a precedence over experiments, therefore increasing the need for reliable calculations of the reactor behaviour, under almost any circumstances. One necessity for "reliable calculations" is naturally a correct assessment of all sources of uncertainties, for instance coming from model simplifications, theoretical limitations, or from the assumptions on input parameters. In this context, one important component in such simulations is the so-called nuclear data (*e.g.* cross sections). More precisely, quantities such as energy released per fission, cross sections, emission probabilities and angular distributions are generally perceived to be known with enough accuracy so that the behaviour of a typical LWR core can be simulated with sufficient precision from the neutronics point-of-view (additionally, continuous experimental efforts are being made to improve the fundamental knowledge of these nuclear data for current and future systems (Colonna et al., 2010)). Of course such a statement starts to be less true in the case of advanced reactors, transient behaviour, or even atypical LWR core configurations (*e.g.* with new types of fuel, high burn-up rates or high enrichments). But even in these cases, it is often the combination of the neutronics with the other sources of uncertainties, such as from thermal–hydraulics or fuel behaviour, which can lead to unexpected local behaviour.

As an example of the growing importance of simulations, neutronics calculations for reactor full core are performed almost everyday and impact the operation of power plants. In the case of current reactor operations, any change in the core is first checked by one, two, or three independent institutions, again based on their simulation capabilities: the reactor operator, the fuel vendor, the safety authority, and possibly a technical support organization. For instance, a reloading fuel pattern for a new reactor cycle is designed by the fuel vendors (contracted by the reactor operator), checked by the national safety authority, which can be advised by a local expert group. Such multiplication of simulations is performed to minimize the risks of errors through multiple independent checking. This being said, such checking is indeed independent as long as the methodologies used by the organizations are different, and even in this case, such simulation tools often rely on the same set of nuclear data (or cross sections). Being aware of this potential flaw, different organizations are nowadays pushing towards the so-called "*best estimates plus uncertainties*" approach,

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or BEPU (D'Auria et al., 2012), which basically requires a complete assessment of the uncertainties associated to a calculated core parameter.

One can see in the previous example the increasing needs of reliable nuclear physics data, which was not the case 20 years ago for LWR systems. Whereas the nominal cross sections are empirically well-adjusted to minimize biases between simulations and measurements, their uncertainties can be large enough to induce substantial spread in calculations. This is naturally not the case for the fission cross section of ^{235}U, or the capture cross section of ^{238}U, but other quantities such as the inelastic scattering can strongly affect core calculations. In short, the BEPU approach is shining a light on where the nuclear physics knowledge needs improvement; this can be considered as an opportunity to perform more precise measurements, in turn leading to smaller uncertainties, higher safety for the environment protection and cost saving. In this paper, we are going to show how the current knowledge of the inelastic scattering of ^{238}U (the most abundant isotope in the reactor fuel) is poor enough to induce relative large uncertainties on dedicated core parameters with an important impact on core design and safety related calculations. Indeed, if sufficiently changed, this cross section can in fact impact reactor core behaviour because the fast neutron population is affected by the inelastic scattering in the fuel. We will also show how these predicted safety related parameters depart from a Gaussian distribution, and how their distributions are linked in a nonlinear manner to the inelastic scattering distributions.

Such asymmetric and nonlinear behaviour typically increases the probability of rare events (compared to an assumed normal distribution) and can either raise safety concerns or call for an increase of safety margins (and cost). Such a dilemma cannot be solved by more precise calculations and only better knowledge of such cross sections (reduced experimental uncertainties for differential inelastic scattering) can increase the confidence in calculated quantities. To achieve this goal, we will place ourselves in the simplified case where only the uncertainties due to nuclear data are considered.

In the following, we will first present the type of systems considered and the method used to calculate probability density functions (pdf) for core parameters. Then the link between such core parameters and the cross section knowledge will be established with examples of skewed distributions and nonlinearity due to the current knowledge of nuclear data. Finally, we will recommend what a maximum amount of acceptable uncertainty for the ^{238}U inelastic cross sections would be, so that nonlinearities and skewed distributions disappear.

This way, the present study is an example of more reliable simulations of nuclear reactor core by making the link between basic nuclear physics knowledge and large-scale system behaviour more tangible.

2. Realistic systems and knowledge

One of the goals of this work is to study conditions under which the actual nuclear data knowledge can lead to skewed pdf and nonlinearity for a realistic full-size reactor system. It has already been demonstrated that excessive cross section variations can induce nonlinear behaviour for parameters of a large-scale system (Koning et al., 2008). It was also demonstrated that the current knowledge of many cross sections is not adequate for future energy systems (Generation-IV and fusion) (Aliberti et al., 2006; Colonna et al., 2010). But it has not yet been proven that the existing knowledge on nuclear data (from realistic covariance matrices) can induce variations in current LWR core parameters which depart from the usual linear expectations.

2.1. Current knowledge on nuclear data

The generic term of "nuclear data" is employed here instead of cross sections, energy spectra and neutron emission probabilities, induced by an incident neutron on a specific nucleus, generally from 0 to 10 or 20 MeV. They vary as a function of the incident neutron energy and such energy dependence can be considered in specific energy groups by simulation codes. Some energy regions are more important than others: the thermal range (where the majority of fission and capture events happen), and also the 0.1 to 5 MeV range, being the energy range where most of the fission neutrons are emitted. Of course the loss of energy by scattering below 0.1 MeV is also important. Such quantities are at the heart of the reactor physics calculations performed every day to check new core configurations and by online core surveillance systems. Examples of such nuclear data are the fission cross section of ^{235}U, or the inelastic scattering on ^{238}U. Their nominal (or their best estimate) values are often first adjusted to match differential data, and then possibly again adjusted to reproduce integral data (*e.g.* from experimental configurations). Their uncertainties, often provided in terms of covariance matrices (uncertainties and energy correlations) are, on the contrary, often only adjusted based on differential measurements and current theoretical knowledge of nuclear reactions. One can immediately notice a possible disagreement between the observed integral uncertainties (for instance on the boron concentration) and the calculated uncertainties based on covariance matrices from differential measurements: generally, the calculated uncertainties are typically larger than the observed ones for integral quantities, leading to interesting discussions between the reactor and nuclear data communities.

In this work, the nuclear data from the American library ENDF/B-VII.1 (Chadwick et al., 2011) are used. Such a library provides good performances in terms of C/E (Calculated over Experiment ratios) once included in assembly and core simulators, and also comes with a large collection of covariance data. This last remark is important for this work, as the largest number of sources of uncertainties need to be included, if one wants to obtain comprehensive uncertainties on core parameters from nuclear data, as required by the BEPU approach. The other alternative libraries, such as the European JEFF-3.2 or Japanese JENDL-4.0 (Shibata et al., 2011) libraries do not contain covariance matrices for a sufficient number of the important isotopes/reactions. The TENDL-2015 library (Koning et al., 2012) could also be selected, but as demonstrated later, the ENDF/B-VII.1 nuclear data also present the advantage of being used in the nominal calculation scheme employed in this study.

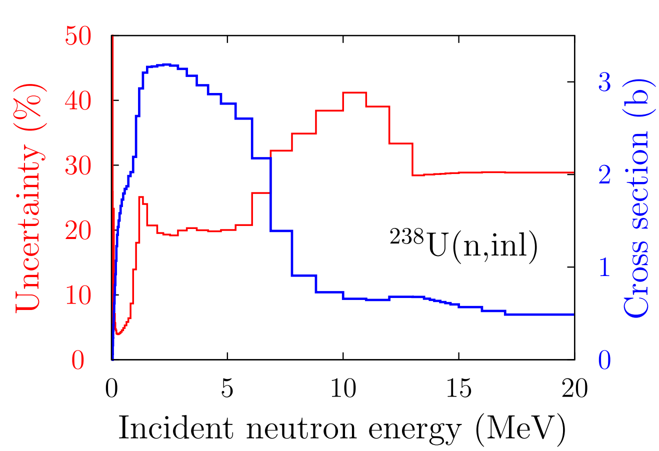

Fig. 1. Inelastic cross section and uncertainties for ^{238}U from the ENDF/B-VII.1 library. Left Y-axis: uncertainties, right Y-axis: cross section.