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Prompt fission neutron emission: Problems and challenges

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Abstract. This paper presents some of the challenges ahead of us even after 75 years of the discovery of the fission process and large progress made since then. The focus is on application orientation, which requires improved measurements on fission cross-sections and neutron and γ-ray multiplicities. Experimental possibilities have vastly improved the past decade leading to developments of highly sophisticated detector systems and the use of digital data acquisition and signal processing. The development of innovative fast nuclear reactor technology needs improved respective nuclear data. Advancements in theoretical modelling also require better experimental data. Theory has made progress in calculating fission fragment distributions (i.e. GEF code) as well as prompt neutron and γ-ray emission to catch up with the improved experiments.

1. Introduction

Even after 75 years of the discovery of the fission process, it remains an active field of experimental research and theoretical challenges. Experimental investigation of the fission process has implications both on nuclear applications as well as theoretical modeling. The theoretical understanding of the fission process has made a vast improvement, however a complete and dynamical model has yet to be developed. Experimental possibilities have greatly progressed in the past decade leading to developments of highly sophisticated detector systems and the use of digital data acquisition and signal processing. The intention to go towards fast nuclear reactor technology made necessary to improve the respective nuclear data, mainly capture and fission cross sections [1]. For a better theoretical understanding of neutron and γ-ray emission in fission, more experimental prompt fission and γ-ray emission data are needed. New detectors for fission γ-ray identification make this possible [2]. More sophisticated computer codes request better input data and also hint to compensation effects.

To this end the IAEA has initiated so-called Coordinated Research Projects (CRP) on different issues like new cross section evaluations and prompt fission neutron spectra [3]. Also theory has made progress in calculating fission fragment distributions (e.g. the GEF code [4]) as well as prompt neutron and γ-ray emission [5–7] to catch up with the improved experiments mentioned above. In the following we will now look at the different challenges ahead of us.

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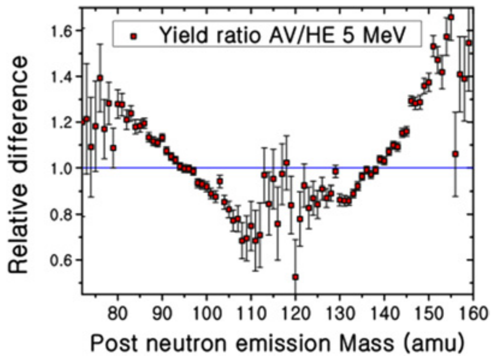

Figure 1. Relative difference between the average correction of prompt neutron multiplicity and a correction introducing higher neutron multiplicities for the heavy fragment only.

2. Prompt neutron multiplicities and spectra

Concerning prompt neutron emission there are a number of questions to be tackled in the coming years. First of all for nuclear modeling and an improved evaluation of nuclear data the knowledge of fluctuations of the prompt neutron multiplicity as a function of incident neutron energy is requested for the major actinides ^{235}U and ^{239}Pu. Fluctuations in fission fragment mass and total kinetic energy (TKE) in both isotopes have been observed in resonance neutron induced fission [8, 9]. Independently fluctuations in the number of emitted neutrons have been observed, too [10]. However in view of the fact that both neutron number and fission fragment properties has been found to vary one needs to understand to what extent the prompt neutron number is fluctuating itself or if it is only due to the observed changes in mass and TKE which leads to changing neutron multiplicities.

The prompt neutron multiplicity is also important in correcting post-neutron fission-fragment mass distributions accessible in experiments through pre-neutron mass distributions. Here, it has been brought back to the attention of both experimentalists and theoreticians that the heavy fragments emit more neutrons (see Ref. [11] and references therein). Figure 1 shows the impact of this effect on the mass distribution at incident neutron energy of 5 MeV. In the most severe cases the relative change in the mass distribution between the traditional average neutron multiplicity correction and the one attributing more neutron emission to the heavy fragments can reach up to 20–30% (see details in Ref. [11]).

Furthermore, the prompt fission neutron spectrum (PFNS) has recently again been in the highlight. As to date theory is not able to describe the experimental data, particularly in the low energy region of the outgoing neutron [12]. New measurements have been performed showing good agreement with spectral data found in literature (see Fig. 2 and details in Ref. [13]). However, as the discrepancy between theoretical description of the PFNS and the experimental result remains, a Coordinated Research Project of the IAEA in Vienna to tackle this problem on a worldwide base has commenced in 2010 [3]. Better model descriptions as well as possibilities to improve even further the measurement possibilities with as focus to the low and high (about 8 MeV) region in the PFNS are discussed. To cope with beam intensities different neutron detector arrays are presently under construction at several places (SCINTIA at JRC-IRMM [14], CHI-NU at LANL [15]).

3. Theoretical modelling

Theoretical models have seen a revival in recent years. More sophisticated models were developed which are able to calculate, based on the macroscopic-microscopic approach and on potential energy landscape calculations, many properties of fission fragments, as well as prompt neutron emission

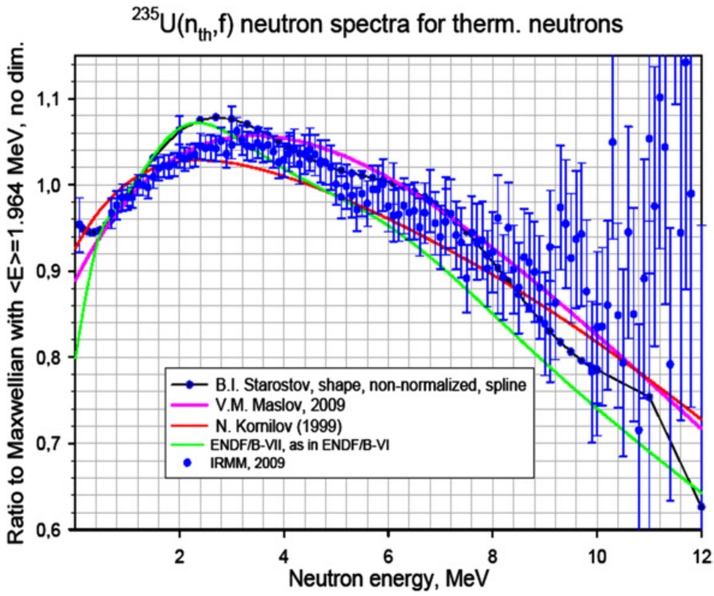

Figure 2. The most recent prompt fission neutron spectrum measurement compared to literature and relevant evaluations [13].

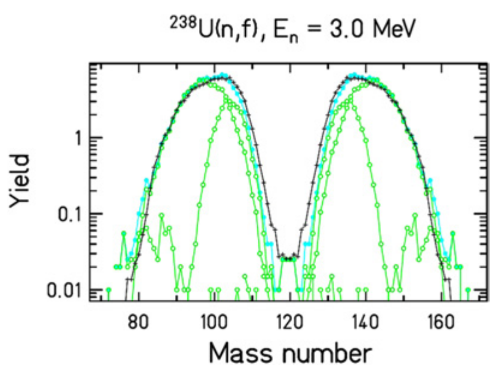

Figure 3. Mass distribution of ^{238}U (n,f) at 3 MeV incident neutron energy. Experimental data (black dots), GEF code calculation (blue dots) and mode separation (green dots).

(e.g. GEF code [4]). The agreement with experimental results for mass and charge distributions resulting from this code is really impressive over a large range of nuclides and elements in the actinide region [4] using only a limited number of parameters. Figure 3 shows one example of a result obtained with the GEF code in comparison with the experimental mass distribution for ^{238}U (n,f) at 3 MeV incident neuron energy. However many more examples can be found in Ref. [4] covering a large part of the actinides exhibiting symmetric, asymmetric and even triple humped mass distributions.

Other theoretical groups try with the Monte-Carlo approach [5–7] to determine several fission fragment properties like prompt neutron and γ-multiplicities as well as spectra. Most of those models, however, need experimental data like mass and total kinetic energy distributions as input parameters. Hence, those models are still very much dependent on high quality experimental input data.

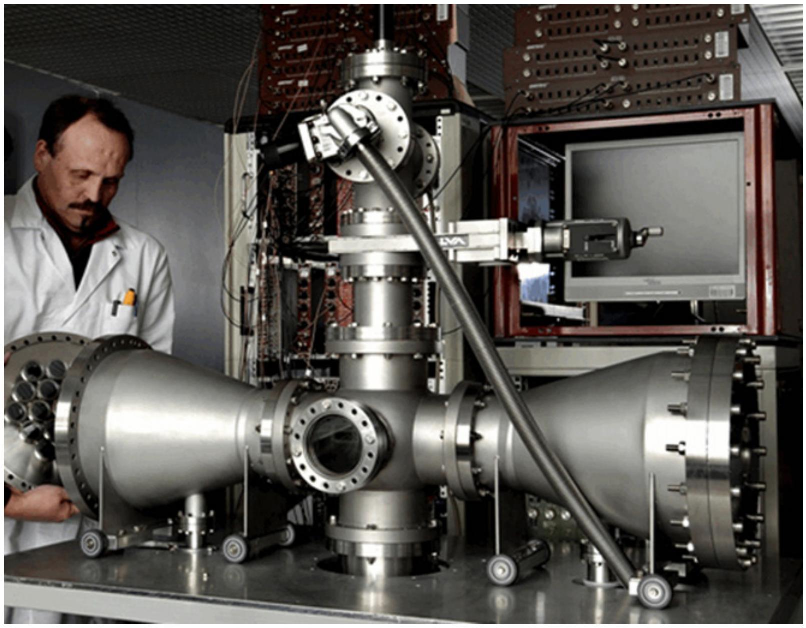

Figure 4. Photo of the VERDI 2v-2E spectrometer under construction at the Joint Research Centre -IRMM.

4. Detector developments

Improvements in detector development for fission related studies are another challenge in the coming years. Several groups are working on so-called 2v-2E detectors, which have the advantage that in this way many characteristics of the fission process like pre- and post-neutron mass yield, kinetic energy and prompt neutron multiplicity are accessible in a single experiment and event-by-event. In the US at LANL you have the SPIDER design [16] and in Europe several groups are working in this field, with the VERDI design from JRC-IRMM [17], the STEFF design at the university Manchester [18] and a design at the CEA in Saclay, FALSTAFF [19], viz. One of the major obstacles is the availability of a very fast and reliable time detector able to let the fission fragments pass with minimal energy loss. In the VERDI design tests have been performed to use chemically vapour deposited diamond based detectors, showing an intrinsic timing resolution for fission fragments better than 110 ps [20].

One challenge for fission fragment application is however the thickness of the diamond detector, which prevents the use in a real 2v-2E setup. So far successful tests have been made in a 1v-1E setup. Another promising time pick-up detector is made from micro channel plates, which have, today, a proven time resolution not far below 250 ps [21]. First tests with the STEFF detector have been presented in Ref. [18]. Also here the final proof of being able to resolve individual fission fragment masses is still to be delivered. The two other designs (SPIDER and Falstaff) have been presented at this conference and respective contributions are found in these proceedings [16, 19]. For both designs an ionization chamber will be used to determine the fission fragment mass and energy. In the case of SPIDER a new entrance window material seems to be promising [16], though still to be tested with fission fragments.

5. Conclusions

Even after 75 years of nuclear fission challenges are ahead of us. Although large progress has been made both in the theoretical understanding of the fission process as well as in the experimental investigations, a complete dynamical model with predictive power is still far away. New innovative system designs need improved nuclear data, an activity presently worldwide pursued. To this end also new detector systems are being designed to cope with the challenges ahead of us.

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