Fission at intermediate neutron energies

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Abstract. In the present work, as a theoretical support to the campaign of neutron cross section measurements at the n_TOF facility at CERN[1], Monte Carlo calculations of fission induced by neutrons in the energy range from 100 MeV to 1 GeV are carried out by means of a recent version of the Liège Intranuclear Cascade Model, INCL++[6], coupled with different evaporation-fission codes, such as Gemini++[7] and ABLA07[8]. Theoretical cross sections are compared with experimental data obtained by the n_TOF collaboration and perspectives for future theoretical work are outlined.

1. Introduction

High-accuracy data of neutron-induced fission cross sections are essential to the design of Generation IV reactors and, as far as neutron intermediate energies are concerned, of accelerator-driven subcritical systems (ADS). This is the reason why fission cross sections in the unprecedented range from thermal energies up to about 1 GeV are measured at the n_TOF facility at CERN[1], exploiting the neutron beam produced by 20 GeV/c protons from the PS accelerator impinging on a lead spallation target.

Fission cross sections for natural lead and bismuth[2], forming the eutectic system that should act as a spallation target and a coolant in an ADS, as well as for actinides of the $U - Th$ cycle and minor actinides[3], have been measured relative to the $^{235}U(n,f)$ cross section, which is considered as a standard up to a neutron energy of 200 MeV, the maximum energy at which reliable data of the absolute cross section are available.

In order to obtain absolute fission cross sections of actinides and pre-actinides in the whole energy range measured at n_TOF, experimental ratios have been normalized to an evaluated $^{235}U(n,f)$ cross section, taken from the ENDF/B-VII library[4] up to 30 MeV and from the JENDL/HE-2007 library[4] from 30 MeV to 1 GeV. It is then natural to investigate whether the choice made for the normalization in the intermediate energy range, from about 100 MeV to 1 GeV, is compatible with recent absolute data of the (p,f) reaction, since it is expected that at energies well above the fission barrier neutrons and protons have a similar behaviour and the corresponding cross sections a similar energy trend. In Ref.[5], (p,f) cross sections for several pre-actinides and actinides, including, of course, ^{235}U, have been measured at nine proton energies in the range from 200 MeV to 1 GeV and are used to calibrate the fission model parameters for our (n,f) calculations.
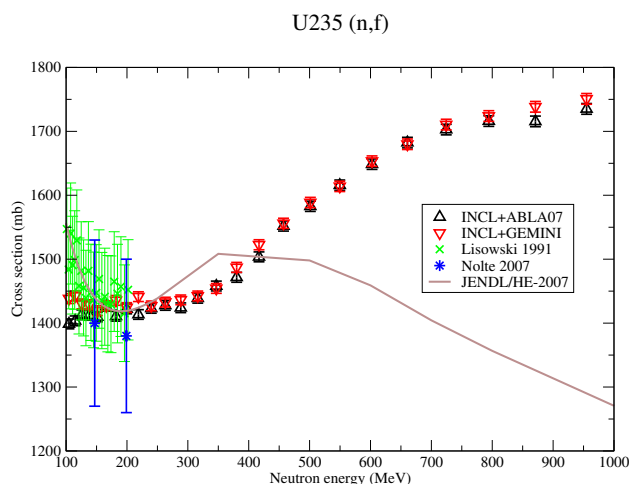
2. Cross Section Calculations

In the energy range of interest, fission induced by nucleons can be seen as a two-stage process: a fast cascade stage, initiated by the high energy projectile, and representable as a succession of two-body collisions, with emission of fast nucleons, light clusters, pions, etc, leaving an excited residual nucleus, and the slow decay stage, where the remnant decays by evaporation, fission, or other mechanisms. In our system of codes, the intranuclear cascade is described by a recent C++ version of the Liège Intranuclear Cascade Model, INCL[6], the evaporation-fission model by a C++ version of GEMINI[7] or a Fortran version of ABLA[8].

In keeping with the philosophy of the authors[6], no parameters have been modified in the INCL model, which was already optimized by reproducing a large amount of experimental data connected with the cascade stage, such as total reaction cross sections, double-differential spectra of emitted nucleons and light clusters, residue production, etc, while we have taken the freedom to adjust fission parameters in both GEMINI and ABLA. The basic parameters are essentially two: the height of the fission barrier and the level density parameter in the fission channel, a_f, or its ratio to the level density parameter in the neutron channel, a_n. In both models, the fission barrier is calculated by means of the finite-range liquid-drop model of Sierk[9], with ground-state shell and pairing corrections taken from Ref.[10], while the level density formalisms are different and cannot be discussed in this short note. The barrier height is expected to play a role only at low energy, the level density is very important in the whole energy range. Therefore, the present preliminary analysis has been carried out by adjusting only a_f on experimental (p, f) or (n, f) data.

Reproducing the experimental (p, f) cross sections of Ref.[5] already allows us to outline a a systematic trend of level density parameters, which increase with increasing fissility parameter, proportional to Z^2/A, from ^{209}Bi to ^{233}U, and decrease beyond that nucleus: for instance, GEMINI calculations suggest $a_f/a_n = 1.045$ for ^{209}Bi, 1.060 for ^{235}U and 1.020 for ^{239}Pu. The (n, f) data in the same energy range are not yet rich enough to confirm the trend.

In the case of ^{235}U we have first determined the value of a_f that permits the best reproduction of the experimental (p, f) cross section in the energy range 200 MeV -1 GeV[5] and then used it as a first guess to reproduce the experimental (n, f) cross section from 100 to 200 MeV[11][12]. Of course, for the procedure to make sense, the final value of a_f should be close to the first guess, so that (p, f) and (n, f) data are reproduced with similar model parameters.

The results of our (n, f) calculations with the INCL + GEMINI and INCL + ABLA07 chains are compared in Fig. 1 to the experimental data up to 200 MeV and to the JENDL/HE-2007 evaluation, used in Refs.[2][3] to obtain absolute (n, f) cross sections.


Figure 1. Calculated $^{235}U(n, f)$ cross section compared with the JENDL/HE-2007 evaluation[4] and experimental data[11][12].

As shown in the figure, the INCL + GEMINI and INCL + ABLA07 chains yield cross sections in close agreement in the whole energy range, which reproduce (n, f) data up to 200 MeV and are larger than the experimental (p, f) cross section at high energy, since σ_{pf} (1 GeV) = 1591 $\pm$ 113 mb[5]. At the same energy, the calculated (p, f) cross sections are 1670 mb (GEMINI) and 1700 mb (ABLA). The a_f value used in (n, f) calculations is higher by 2% than the one used in (p, f) calculations. The discrepancy might be reduced by modifying the height of the fission barrier. While our calculated cross sections increase up to 1 GeV (and start decreasing beyond that energy), the JENDL/HE-2007 evaluation steadily decreases in the same energy range.

As far as the n_TOF measurements are concerned, ^{234}U and ^{237}Np are published in Ref.[3], natural lead and ^{209}Bi in Ref.[2], while preliminary data are available for ^{232}Th and $^{233,238}U$. In the case of ^{234}U, since no (p, f) data exist in Ref.[5], we have assumed the same a_f value as for ^{235}U. Fig. 2 shows that theoretical and experimental $\sigma_{nf}(^{234}U)/\sigma_{nf}(^{235}U)$ ratios are in excellent agreement. Fig. 3 compares absolute (n, f) cross sections, which diverge at high energy, owing to the normalization to the JENDL/HE-2007 cross section of ^{235}U, adopted in Ref.[3] .
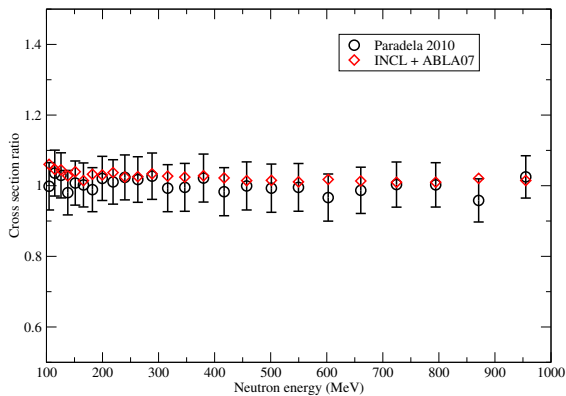
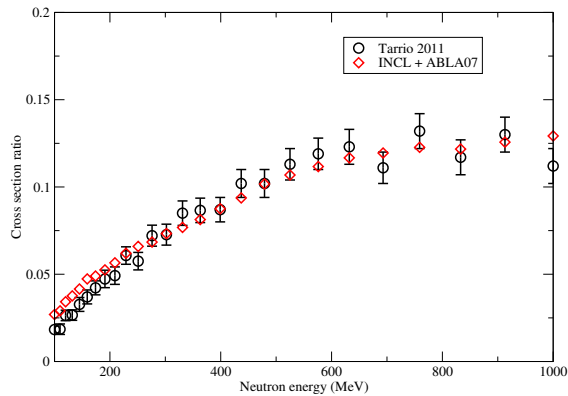**Figure 2.** Calculated *vs.* experimental $\sigma_{nf}(^{234}U)/\sigma_{nf}(^{235}U)$ ratio. Data are taken from Ref.[3].
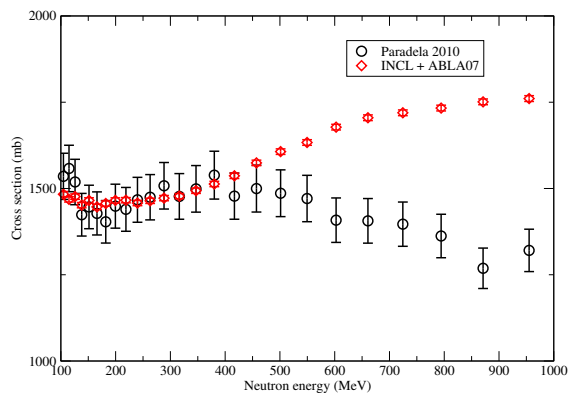
Figure 3. Calculated $\sigma_{nf}(^{234}U)$ *vs.* the experimental ratio of Fig. 2 normalized to JENDL/HE-2007[4].

In the case of ^{209}Bi, (p, f) and (n, f) data can be reproduced with the same value of a_f. Theoretical and experimental[2] ratios to $^{235}U(n, f)$ are again in excellent agreement, as shown in Fig. 4, while absolute cross sections are compared in Fig. 5; again, the normalization to the Japanese evaluation explains the disagreement at high energy.

Summing up, experimental (n, f) ratios measured at n_TOF for pre-actinides and actinides are satisfactorily reproduced by using fission model parameters that are similar, or rather close, to the ones adopted in reproducing experimental (p, f) cross sections. Absolute cross sections are larger than those obtained by the n_TOF Collaboration in the energy range from 500 MeV to 1 GeV because of different normalization.

3. Conclusions and Outlook
The preliminary calculations presented in this short note indicate that the Liège Intranuclear Cascade Model, INCL, coupled with an appropriate evaporation-fission model like GEMINI or ABLA, can reproduce the experimental data obtained at n_TOF on fission induced by intermediate energy neutrons. The fits can be improved by acting on additional fission model

Figure 4. Calculated *vs.* experimental $\sigma_{nf}(^{209}Bi)/\sigma_{nf}(^{235}U)$ ratio. Data are taken from Ref.[2].
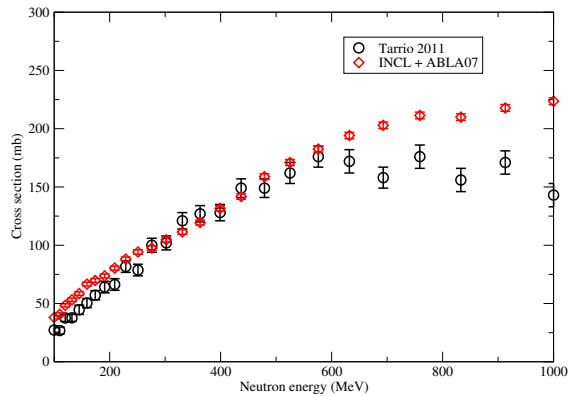
Figure 5. Calculated $\sigma_{nf}(^{209}Bi)$ *vs.* the experimental ratio of Fig. 4 normalized to JENDL/HE-2007[4].

parameters, with a view to obtaining a consistent set for the simultaneous description of (n, f) and (p, f) reactions in the same energy range. This is necessary to the derivation of absolute (n, f) cross sections from experimental ratios: on the basis of the present study, in particular, the JENDL evaluation of the $^{235}U(n, f)$ cross section adopted in Refs.[2][3] does not seem to be consistent with the experimental (p, f) cross section in the same energy range.

As a by-product of such a systematic study, it will be of interest to examine the dependence of model parameters that reproduce (n, f) data on characteristics of target nuclei, such as the fissility parameter, and check whether the trend already appearing in (p, f) data is confirmed.

Finally, it is our intention to make predictions for other isotopes whose measurements are already planned at CERN, not only of fission cross sections, but also of angular distributions of fission fragments, which are also measurable at the n_TOF facility.

Acknowledgments

References
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