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Measurement of the average energy and multiplicity of prompt-fission neutrons from ^{238}U(n,f) and ^{237}Np(n,f) from 1 to 200 MeV

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Abstract. Taking advantage of the neutron source of the LANCSE, it has been possible to obtain a measure of the velocity distribution and the number of prompt-neutrons emitted in the neutron-induced fission of ^{238}U and ^{237}Np over a broad incident neutron energy range. The mean kinetic energy was extracted and is shown as a function of the incident-neutron energy. We confirm here the observation, for both reactions, of a dip around the second-chance fission which is explained by the lower kinetic energy of the pre-fission neutrons. Such a observation is reproduced by Los Alamos model as implemented at Bruyères-le-Châtel and by the Maslov model. As far as the neutron multiplicity is concerned, a similar dip is observed.

1 Introduction

For power applications, a precise knowledge of prompt-fission neutron properties is of major importance for simulating nuclear reactors. Indeed, the number of neutrons emitted during the fission process, as well as their spectra, have been studied theoretically and experimentally for 60 years. These studies mainly concern a few actinides of importance in commonly exploited nuclear systems. The forthcoming generation of nuclear reactors (GEN4) will probably run, taking advantage of a fast neutron spectrum to incinerate minor actinides like ^{237}Np or various americium and curium isotopes. Moreover, high-energy neutron induced fission must be specially modelled in the so-called accelerator-driven systems (ADS) which are currently being designed. The latter may be used in the future to incinerate specific waste in dedicated facilities. On the other side, new knowledge on properties of neutrons produced in fission of actinides at moderate excitation energies contributes for instance to the understanding of the competition between neutron and Light Charged Particle statistical emission. Several groups (refs. [1,2]) have pursued some efforts to develop theoretical descriptions in order to estimate the fission prompt-neutron properties. Those descriptions are based on the energy conservation considerations and statistical calculations for estimating the competition between the open deexcitation channels.

Our collaboration already published (see refs. [3,4]) recent experimental results concerning prompt fission neutron spectra (PFNS) emerging from the neutron induced fission of ^{238}U and ^{235}U. Those results have been obtained taking advantage of a similar experimental set-up. We decided to measure, with an improved set up, fission neutron properties for neutron induced fission of ^{238}U and study in addition the fission of ^{237}Np.

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2 The experiment

2.1 The set-up

The experiment was performed at the LANSCE using the fast neutrons produced by the WNR spallation source. The 800 MeV proton beam impinges on a tungsten target producing high-energy neutrons. Even if most of the neutrons are produced in the 1–10 MeV range, the high energy tail allows the study of neutron induced reactions up to 300 MeV incident energy. The proton-beam structure consists of 300 ps pulses spaced every 1.8 μs.

The FIGARO experimental set-up (see ref. [5] for an extensive description of the set-up) is located 22 m from the spallation target allowing a precise determination of the kinetic energy of the incoming neutrons in measuring their time-of-flight (ToF). A time signal is provided by a 10 cm long ionisation chamber containing 94 plates where 380 mg of pure actinide (resp. ^{238}U or ^{237}Np) were deposited. The neutrons emitted in coincidence with the detection of fission fragment were detected thanks to 20 scintillation neutron detectors located 1 meter from the fission chamber covering angles ranging from 45 to 135 degrees. A pulse-shape analysis permitted fully separating gammas from neutrons. In the previously reported experiment (refs. [3] and [4]), only 3 neutron detectors were available. This improvement made possible a better angular coverage and allowed for higher statistics. Thus, an additional ToF signal was recorded, the start signal being given by the fission chamber as the stop was obtained from the neutron detector. The kinetic energy of the fission neutrons were consequently recorded providing us with the prompt fission neutron spectra (PFNS). The ToF resolution of the fission chamber was 6 ns. The energy resolution of the latter allowed for disentangling alpha emission from real fission events. The 20 EJ301-type neutron detectors were made of cylindrical cells filled with scintillating liquid.

2.2 Data reduction

The main issue is here to determine the efficiency of the neutron detectors. The efficiency strongly varies with the kinetic energy of the detected neutrons. It is 0 below 0.5 MeV and increases to reach a plateau around 2 MeV. Then, it slowly decreases. We calibrated individually all 20 detectors using the ^{238}U run. Boykov et al. (ref. [6]) measured accurately the PFNS in the 2.9 MeV neutron induced fission of ^{238}U. Therefore, we gated on the incident neutron spectrum to select only 2.9 ± 0.1 MeV neutrons and obtained with that condition raw fission neutron spectra for all neutron detectors. The raw spectra were divided energy bin per energy bin by the Boykov spectrum to get the efficiency function for every detector. The neutron detectors were used solely in the 0.7–7 MeV range. Below 0.7 MeV, their response was too poor to correct properly for it. Above 7 MeV, we acquired too few events to get a reasonable statistical uncertainty. All PFNS were therefore truncated due to the lack of efficiency of the neutron detectors below 0.7 MeV and above 7 MeV. Consequently, we had to fit the measured spectra by a Watt function to recover the missing parts. The integration of the latter amounts to 21 ± 1% of the entire PFNS.

The overall efficiency of the neutron detectors was estimated in a similar way. The neutron multiplicity was also precisely determined in the Boykov paper. We again gated on the kinetic energy of the incoming neutrons in the range 2.9 ± 0.1 MeV, fitted the corrected PFNS by a Watt spectrum and finally estimated the overall efficiency of every neutron detector assuming a 2.76 neutron multiplicity.

The incoming neutron energy spectrum was divided into 41 energy bins from 1 MeV to 200 MeV. The fission cross-section being low for neutron energies below 1 MeV, no reliable result could be obtained. Above 200 MeV, the incident neutron flux was too little to allow for an accurate measurement.

3 Results and discussion

We produce here consecutively the results for ^{238}U and ^{237}Np neutron induced fission. We fitted the PFNS by Watt spectra (see equation (1)) accounting for the non-measured low-energy part and high-energy tail of the spectra.

$$N_w(E) = Amp \times \frac{2A^{2/3}}{\sqrt{\pi B}} \exp\left(-\frac{B}{4A}\right) \exp(-AE) \times \sinh(BE)^{1/2}. \quad (1)$$

Where Amp stands for the amplitude of the fitted distribution, $A = 1/T$, the inverse of the temperature of the emitting fragments. $B = 4E_f/T$, where E_f is the recoil energy of the fragments.

The mean kinetic energy of the neutrons is given by equation (2)

$$\langle E \rangle = \frac{3}{2}T + E_f. \quad (2)$$

The results of the measurement are given in the following section. They are still preliminary. They are subject to improvement, especially concerning the estimation of the error bars. The experimental set-up did not permit measurement of the high energy neutrons which could emerge from pre-equilibrium emission or direct interaction. Such a component is peaked in the forward direction where no detector was positioned. It should be negligible below 10 MeV incident energy. Above 10 MeV, the lack of detection of forward-peaked high energy neutrons introduces a bias mainly on the estimated mean kinetic energy of the emitted neutrons. The measured multiplicity is affected to a lesser extent. The reader should keep in mind that all evaporated neutrons were accounted for, the high energy neutrons being undetected.

3.1 ^{238}U results

We chose to measure again ^{238}U in order to test our new set-up, so that we could compare our new measurement with other experimental results.

3.1.1 Mean kinetic energy

The mean value of the measured PFNS is shown in figure 1 as a function of the kinetic energy of the incoming neutron. All available other experimental results are also plotted on the same graph. The uncertainty is currently estimated to be about 2%.

The amount of new experimental data provided by our recent measurement strongly contrasts with the sparse experimental results available until now. Our data allows extending the measured domain from 20 to 200 MeV.

The kinetic energy of the emitted neutrons vary moderately over the full dynamics, ranging from 1.8 to 2.3 MeV. Above 20 MeV, we observe a slow increase of the kinetic energy. The latter seems to stabilize above 150 MeV. However, some fluctuations are observed below 20 MeV. A detail of the low energy part of the distribution is also shown in figure 1. We observe very good agreement (within error bars) with all other measurements except the low energy Japanese data (see Miura

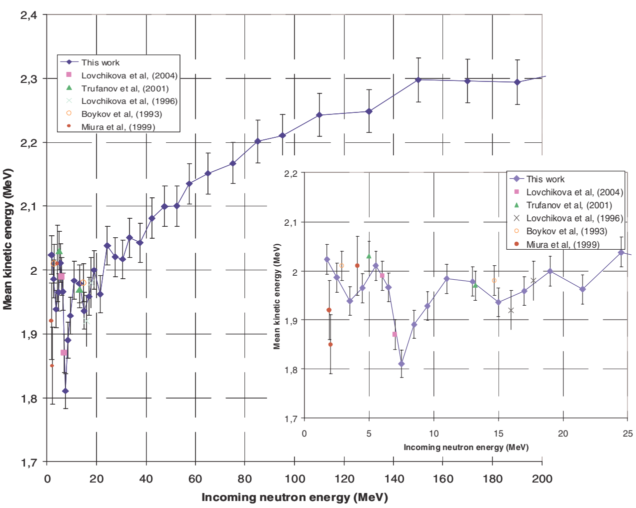

Fig. 1. Mean value of the PFNS in the ^{238}U(n,f) reaction as a function of the neutron energy. Other experimental results are also shown.

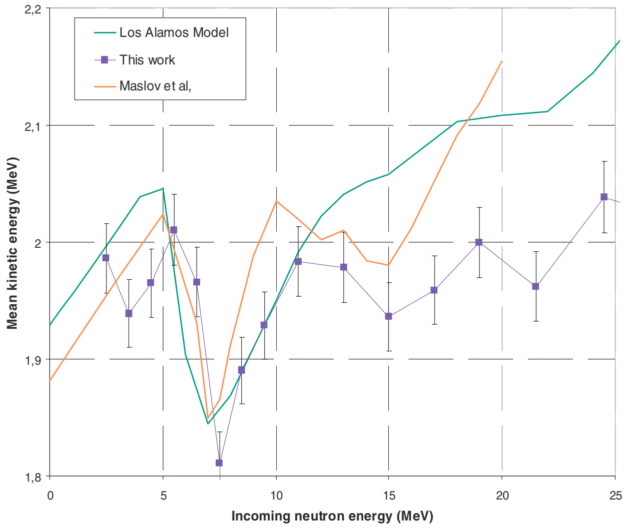

Fig. 2. Our data compared to the Los Alamos model as implemented at Bruyères-le-Châtel and to the Maslov model (preliminary).

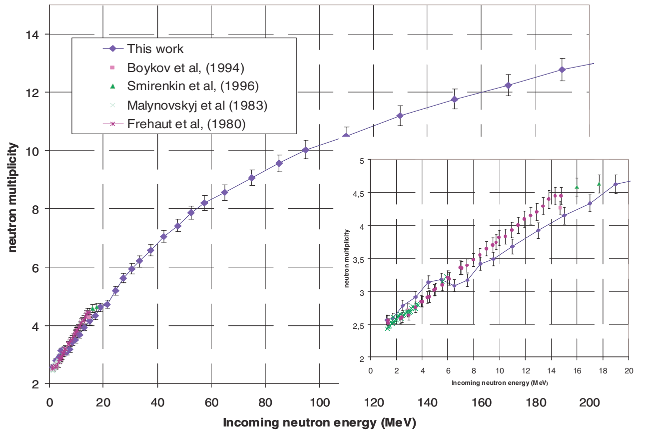

Fig. 3. Neutron multiplicity as a function of the kinetic energy of the neutron. Previously measured data are also shown.

et al. (ref. [7], 1996) at 1.9 and 2 MeV which are not consistent with the other experimental data. We observe a pronounced dip around 7 MeV. That dip is nicely described with 5 coherent experimental data points between 6.5 and 11 MeV.

This dip could be explained by the weight of the pre-fission neutrons. Indeed, when the (n,nf) channel opens around 7 MeV, neutrons can be emitted prior to fission. Those neutrons exhibit a lower kinetic energy than the post-fission neutrons because they don't receive the fission boost.

Our data together with the results of other groups give an indication of the presence of a smaller second dip around 15 MeV.

The figure 2 shows the comparison of our data with the results of two models (see ref. [1,2]). Both models reproduce the dip around 7 MeV. The Maslov model seems to describe more accurately the slope below and above the minimum. Moreover, the Maslov model predicts a second drop between 10 and 15 MeV. Such a slope is qualitatively observed in our data. Above 10 MeV for the Los Alamos model and 15 MeV for the Maslov one, the mean kinetic energy seems overestimated by both models.

3.1.2 Neutron multiplicity

The integration of the fitted Watt spectra allowed us to extract the fission neutron multiplicity.

The neutron multiplicity measured in the neutron induced fission of ^{238}U is plotted figure 3. Other recent and older experimental data are also plotted on the same graph. Our data exhibit a constant increase up to 200 MeV. There are no fluctuations in our data. The uncertainty is estimated to be about 3%. We observe a change of slope in our data around 7 MeV. Such behaviour is not seen in Fréhaut's data. We don't have any clear explanation for such a disagreement at the moment. However, our data seem to be in good agreement (within error bars) with the other experimental results even if our data are systematically higher than other measurements below 8 MeV and lower above 8 MeV.

3.2 ^{237}Np results

^{238}U was extensively measured during the last 30 years, but few measurements exist for ^{237}Np. We only found 2 recent measurements for PFNS. We report here for the first time a new measurement of both PFNS and multiplicity on the neutron-induced fission of ^{237}Np over a broad energy range. The statistical uncertainty on the ^{237}Np data is higher than what we obtained for the ^{238}U run. The measurement time was shorter.

3.2.1 Mean kinetic energy

The mean kinetic energy obtained from the PFNS measurement is plotted as a function of the neutron energy in figure 4. Only 2 sets of other experimental data were found in the literature. Both measurements as well as the Maslov model are also plotted in figure 4. It's impressive to see how close our data are to the Maslov simulation below 15 MeV. Actually, the model is in better agreement with our results than the other experimental data. Especially Lovchikova's data give between 5 and 10% higher mean kinetic energy. Boykov's data are however in agreement within uncertainties. Again, we observe a pronounced dip around 7 MeV. It fits nicely with the increase of the 2nd chance fission cross-section. The presence of a second dip around 13 MeV, thus corresponding to the 3rd chance fission, seems to be confirmed by these new data.

Again, the predicted very fast increase of the mean kinetic energy above 15 MeV is clearly not seen in our experimental results.

3.2.2 Neutron multiplicity

The neutron multiplicity in the neutron induced fission of ^{237}Np is plotted in figure 5. Experimental results obtained by

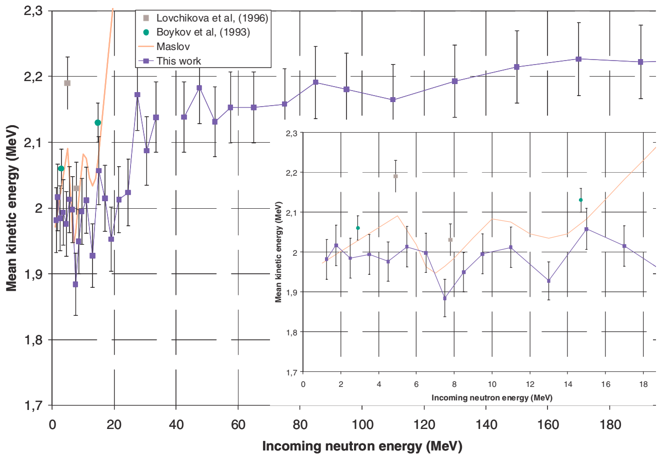

Fig. 4. Measured mean kinetic energy compared to other data and the Maslov model.

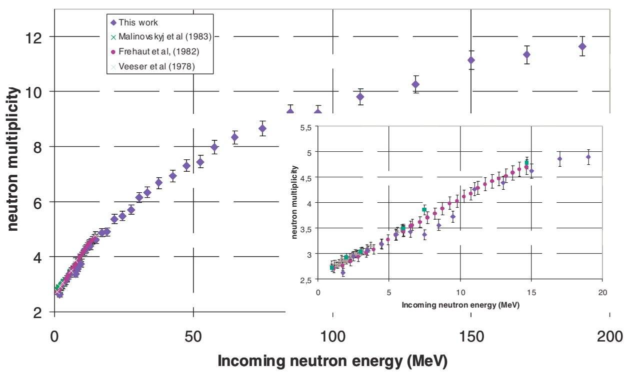

Fig. 5. Neutron multiplicity as a function of the kinetic energy of the neutron. Previously measured data are also shown.

other groups are also shown. Fréhaut's data provide the more complete set of comparable data since they cover the full 1–15 MeV range. The agreement between our data and all others is rather good. They are only 3 data points which are not compatible with Fréhaut's results. They appear to be in same region as for ^{238}U. It seems that our data may suffer from a systematic underestimation from 7 to 10 MeV.

Nevertheless, for all other experimental points, we observe an impressive agreement, the discrepancy being often as low as 1%.

4 Conclusion

We performed an extensive measurement of the Prompt-Fission Neutron Spectra in the neutron-induced fission of ^{238}U and ^{237}Np. We took advantage of the secondary neutron source available on FIGARO, at the LANSCE facility. The results are still preliminary; however, we already got promising data on neutron multiplicity and mean kinetic energy. As far as the uranium experiment is concerned, we obtained an impressive agreement with previously measured mean kinetic energies. The latter seems to vanish around the second chance fission. Such a behaviour was predicted by various simulations. The measured multiplicity differs slightly more from the previous experimental studies, especially when compared to Fréhaut's data. The ^{237}Np data exhibit a lower statistics. Nevertheless, our measured mean kinetic energy is in good agreement with Maslov simulation as it is systematically lower than Lovchikova's data. We observe a 8% discrepancy in the second chance fission region as the agreement with other measurements is rather good for all other neutron energies. The origin of that discrepancy will be investigated.

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