Experimental report

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Proposal: **3-07-380** **Council:** 4/2018

Title: Absolute yield and time dependenceof delayed neutron emission in 235U(n,f) and 239Pu(n,f)

Research area: Nuclear and Particle Physics

This proposal is a new proposal

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Samples:

Instrument	Requested days	Allocated days	From	To
PF1B	15	8	30/05/2018	31/05/2018
			05/09/2018	12/09/2018

Abstract:

There is currently a strong request, supported by IAEA/Coordinated Research Program, to provide new high quality data of delayed neutron (DN) yield and group constants for nuclear reactor and criticality/safety applications, as well as to validate fission models with calculations like FIFRELIN or GEF.

In this proposal, the PF1B instrument is requested to deliver a collimated cold neutron beam to an active target in the form of a flat fission chamber. The latter is surrounded by a neutron detector consisting of a cylindrical PE block, with 16 He3 tubes. A fast beam stop system will be placed prior to this device, in order to drive repeated cycles of irradation and decay phases. The DN emission will be recorded as well the prompt neutron emission, in parallel with the monitoring of the fission events from the target.
This experimental set-up is expected to provide better conditions for DN measurement at very short-time (~10 ms) compared to other reported experiments.

This proposal is part of a PhD work by D. Foligno (2016-2019). A financial support was obtained by EDF and FRAMATOME, as well as from the NEEDS/NACRE collaborative program hosted by CNRS.

“ALDEN” Experiment (n°3-07-380, from 09/05 to 09/12 2018) – Final report

Scientific context

The ALDEN (Average Lifetime of DElayed Neutrons) project aims at providing the nuclear data community with new data sets of delayed neutrons (DN) induced by thermal fission for several actinides such as ^{235}U, ^{239}Pu, ^{241}Pu, ^{233}U. The project is organized within a large collaboration (CEA/DEN, CEA/DRF, IRSN, CNRS/LPSC, CNRS/CENBG, CNRS/LPC Caen and Caen University) and is partly funded by the “Defi NEEDS” and by the I3P R&D platform, regrouping CEA, EdF and Framatome.

The ALDEN experiment, which was first set up on PF1b cold neutron beam in September 2018, was dedicated to measuring the decay of DN precursors produced by thermal fission of ^{235}U. Sufficient activity of DN precursors was built up in the actinide target by performing periodic cycles of irradiation and cool down. The major parameters of DN precursors, such as half-life, DN yield and abundance per group, could eventually be obtained from the decay curve.

Experiment principle and setup at PF1b (ILL)

A new high efficiency detector setup (LOENIEv2) was designed using TRIPOLI4 Monte Carlo code. It was based on 16 ^3He proportional counters, arranged in a polyethylene matrix in such a manner that its neutron detection efficiency is flat on the energy range of DN (0.1 – 1 MeV). Background from scattered neutrons was reduced thanks to a boron rubber shielding. A central cavity accommodated a fission chamber filled with the target material. A rotating beam shutter was also included in the setup, to allow sharply cutting the impinging neutron beam. This made it possible to acquire information on short-lived DN precursors (< 0.5 s).

The data acquisition system, designed by the ILL, was based on a VME rack including two V1724 digitizers from CAEN and one TTL acquisition card from Ioxos. Detection events issued by the neutron counters were digitized and processed, so as to record energies and time stamps. To monitor the fission rate inside the target, the signal from the fission chamber was shaped by an analog amplifier (Canberra 7820) and processed by a discriminator. The resulting TTL signals were fed into the acquisition system to get the counting rate. An ILL monitoring software (NoMad) made it possible to synchronize acquisition runs with the beam shutter motion.

Experimental campaign

The experimental campaign was split into three phases. The first day was dedicated to flux calibration (gold dosimetry), as well as various tests for setting up the neutron beam and the acquisition system’s parameters. Then, five days were spent irradiating the uranium target in various configurations. The last day was dedicated to measuring the background by replacing the active target with a dummy one.

By varying the irradiation time Δt_i and the cool down time Δt_c, the behavior of DN precursors could be modified (since the amplitude of their response depends on the ratio $\Delta t_i/\Delta t_c$) to obtain different decay curves. The irradiation time ranged from 0.25 s to 100 s and the cool down from 0.25 s to 450 s. Most of the beam time was spent on a setup with an irradiation time of 50 s and a cool down of 450 s. A typical experiment consisted in repeating many cycles of irradiation/cool-down, each run being stored in separate files (one for ^3He counters’ data and one for the fission chamber’s count rate).

The neutron beam was set so that the count rate of prompt neutron issued by the fission chamber (beam on) was ~1.7 10^5 c/s. The overall counting rate of the 16 ^3He counters was then equal to ~7.4 10^4 c/s (after background rejection and loss of counts). Detection background was satisfactory low (below 10 c/s when the beam was off), which made it possible to observe the decay of activity over a time range of around 200 s after the end of irradiation.

Because of unexpected problems with the acquisition process (due to inappropriate data processing parameters that created extra pile up in the signals), a significant amount of data was difficult to analyze afterwards. Thankfully, many acquisition parameters sets were tested and the results presented in this report were obtained from a pile up free experiment of 254 runs with 400 s of cool-down and 50 s of irradiation.

Data analysis

The first step was to process raw data to get the detection rate of DN precursors as seen by the whole system (i.e. the 16 ^3He tubes signals). This was done by applying cuts in time and energy to extract each detector’s counting rate. The 16 counting rates were then individually corrected for loss of count and summed up to get one single curve per run. The runs were synchronized in time and eventually averaged. Several physical quantities could be estimated by analyzing the experimental curve (cf. Figure 1.a), namely the number of number of DN per fission (ν_d), the average half-life of DN precursors ($T_{1/2}$) and the abundances of DN groups (a_k).

Introducing the fission rate F, the prompt neutron yield ν_p, the detection efficiencies to prompt neutrons ε_p and to DN ε_d, and the background b_i, the average counting rate during the irradiation phase is given by:

$$n_i = F\left(\nu_p\epsilon_p + \nu_d\epsilon_d\right) + b_i \qquad (1)$$

Now, let a_k, λ_k and ε_k be respectively the abundance, decay constant and detection efficiency of the k^{th} group of DN, b_d the background when the beam was off and Δt_0 some veto time window. One can write the emission rate of DN as follows:

$$n_d = F\nu_d \sum_{k=1}^{8} \epsilon_k a_k \left(1 - e^{-\lambda_k \Delta t_i}\right)\left(1 + e^{-\lambda_k \Delta t_c}\right) e^{-\lambda_k (t+\Delta t_0)} + b_d \qquad (2)$$

Note that it was necessary to introduce a veto window of 30 ms in the analysis to discard extra fissions that occurred right after the beam was cut off. This phenomenon was due to the transit time of few cold neutrons from the beam shutter to the target.

Dividing equation (2) by equation (1), it can be shown that ν_d is a factor proportional to the ratio n_i / n_d ($t=\Delta t_i$). This ratio could be experimentally determined by fitting the first 500 ms of the decay curve and then extrapolating the activity to the time were the beam was cut off ($t=\Delta t_i$). The proportionality coefficient depends only on the ratio of detection efficiencies $\varepsilon_p/\varepsilon_d$ and was obtained by simulating the detection setup with TRIPOLI4 Monte Carlo code and JEFF3.2 nuclear data library.

Fitting the equation (2) over the whole decay curve resulted in estimating the abundances of DN groups. The CEA-developed data regression tool CONRAD was used for that purpose, using a marginalization method (see details in [4]). The abundances were eventually used to calculate the average half-life of DN precursors with the following formula:

$$T_{1/2} = \ln(2) \frac{\sum_{k=1}^{8} a_k/\lambda_k}{\sum_{k=1}^{8} a_k} \qquad (3)$$

<u>Experimental results</u>

Table 1 gives an outlook of the results obtained as well as recommended values issued by the OECD/NEA WPEC-6 workgroup [3]. It is satisfactory to observe that ν_d is in close agreement with the reference value. The new estimation is also consistent within the margins of uncertainty with the most recent experiments (see Figure 1c). Also consistent with WPEC-6 recommendation, the new estimation of $T_{1/2}$ is now provided with an uncertainty reduced by a factor of three compared to the reference one.

Regarding the abundances of DN groups, one can see that the quality of fitted results is better for short-lived groups (reduced uncertainty compared to WPEC-6) than for long-lived ones (associated to uncertainties up to 60%). This comes from the fact that only one experimental curve was used to fit the 8 exponentials, whereas in the literature abundances could come from several experiments, favoring either long-lived or short-lives groups. In our case, data statistics was not sufficient to provide good estimates of the abundances of groups 6 to 8. This explains also why the correlation coefficients (see Figure 1d and Table 2) are sometimes high, especially between long-lived groups. Note that, when using the correlation matrix to calculate an integral parameter, such as the half-life $T_{1/2}$, the final uncertainty is satisfactory low in the end.

Table 1 : DN yield per fission, average half-life of DN precursors for ^{235}U from ALDEN experiment and values recommended by the OCDE/NEA WPEC-6.

	NEA/WPEC-6	Foligno *et al*. (this work)
DN per fission (ν_d)	0.0162 DN/fis.	0.01631(23) DN/fis.
Average half-life ($T_{1/2}$)	9.02(27) s	8.93(9) s
a_1	0.0328(42)	0.0364(10)
a_2	0.154(7)	0.131(4)
a_3	0.091(9)	0.115(6)
a_4	0.197(23)	0.166(8)
a_5	0.331(7)	0.355(18)
a_6	0.0903(45)	0.069(28)
a_7	0.0812(16)	0.081(40)
a_8	0.0229(95)	0.046(30)

Table 2 : Correlation matrix of DN groups' abundances.

1	-0.728	0.833	-0.466	0.462	-0.341	0.343	-0.379
-0.728	1	-0.852	0.716	-0.373	0.248	-0.052	-0.082
0.833	-0.852	1	-0.783	0.656	-0.48	0.378	-0.34
-0.466	0.716	-0.783	1	-0.814	0.652	-0.375	0.184
0.462	-0.373	0.656	-0.814	1	-0.919	0.753	-0.622
-0.341	0.248	-0.48	0.652	-0.919	1	-0.889	0.702
0.343	-0.052	0.378	-0.375	0.753	-0.889	1	-0.932
-0.379	-0.082	-0.34	0.184	-0.622	0.702		1

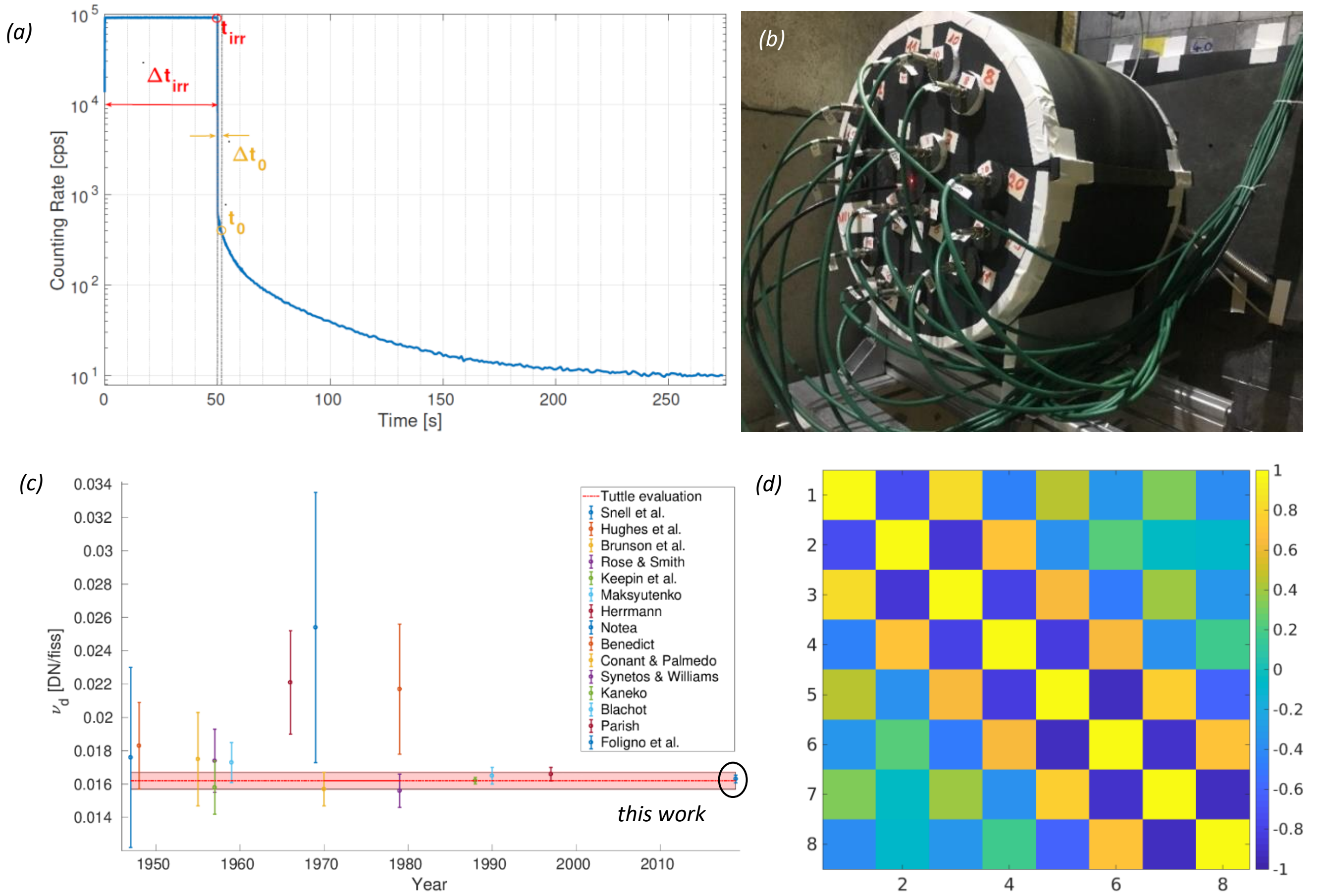

Figure 1 : Experimental curve after data processing (a). Back view of LOENIEv2 detection setup (b). ^{235}U DN yields from various experiments (c). Correlation matrix of fitted DN groups abundances (d).

Conclusions

The results of the first ALDEN experimental campaign demonstrated that, even though DN parameters associated to thermal fission of ^{235}U are well documented in the literature, it was still of high interest to produce new experimental data with reduced uncertainties. Indeed, results presented here are consistent with recommended values, like the ones issued by the OECD/NEA WPEC-6 workgroup [3]. Associated uncertainties are reduced and this is especially the case of the half-life of DN precursors $T_{1/2}$.

Upcoming experiments will be performed with other actinide targets in particular ^{239}Pu and ^{233}U. The experimental setup and data acquisition parameters will be optimized thanks to the experience acquired during the first ALDEN campaign.

References

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[4] D. Foligno, “New evaluation of delayed-neutron data and associated covariances,” PhD thesis, *to be published*.