

Measurements of the Temporal Characteristics of Delayed Neutrons from Neutron Induced Fission of ^{241}Am in the Energy Range from 14.2 to 18 MeV

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Abstract

Analysis of existing database on the relative abundances of delayed neutrons and half-lives of their precursors measured for neutron induced fission of heavy nuclei in the energy range above 14 MeV shows that such data are not available for many nuclides which are important for nuclear fuel cycle. In the present work for the first time the time dependence of delayed neutron activity for the neutron-induced fission of ^{241}Am in the energy range from 14.2 to 18 MeV.

Introduction

In the recent years efforts to purification of nuclear physics database on delayed neutrons was substantially referred to analysis of delayed neutron characteristics for neutron induced fission of ^{235}U , ^{238}U , ^{239}Pu in energy range from thermal values to several MeV [1]. Nuclides and energy range used in this work have been determined first of all by needs of power engineering.

At the same time the energy range of primary neutrons exists for which physical characteristics of delayed neutrons are known significantly worse. First of all, it belongs to energy range above 14 MeV. This energy range is interesting for practical applications related to the development of nondestructive methods used for analysis of fissile materials which is based on delayed neutron registration.

The neutron source

The reaction $\text{T}(d,n)^4\text{He}$ was used to generate neutrons in energy range from 14.2 to 18 MeV. Solid tritium target was irradiated by the beam of the accelerated deuterons from cascade generator CG-2.5 SSC RF-IPPE. Energy of accelerated deuterons was varied from 0.5 to 2 MeV. Interruption of the beam was made using a Faraday cup. Energy dependence of neutrons generated in the $\text{T}(d,n)^4\text{He}$ reaction on incident deuteron energy is shown in Fig. 1.

Beams of neutrons emitted at the angle 0 and 90 degrees against the deuterons beam direction were used. This allowed us to study temporal characteristics of delayed neutrons in the energy range from 14.2 to 18 MeV.

Experimental method and preliminary analysis of the obtained data

The experimental method used in present experiments based on cyclic irradiation of the fissile sample in a well-known neutron flux and consequent measurement of the time dependence of delayed neutron activity. For that, the guide tube of pneumatic transport system with the sample under investigation was placed between two ionization fission chambers near the target of the electrostatic generator CG-2.5.

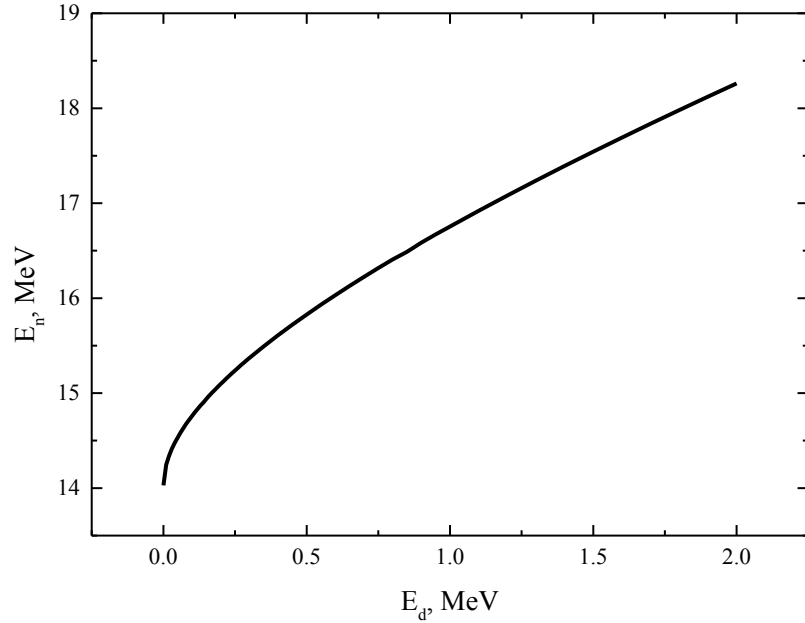


Fig. 1. Energy dependence of neutrons generated in the $T(d,n)^4He$ reaction on the incident deuteron energy.

Experimental set-up used in the present work was placed on the beams of electrostatic accelerator CG-2.5 of SSC RF-IPPE. The basic components of the set-up are shown in Fig. 2.

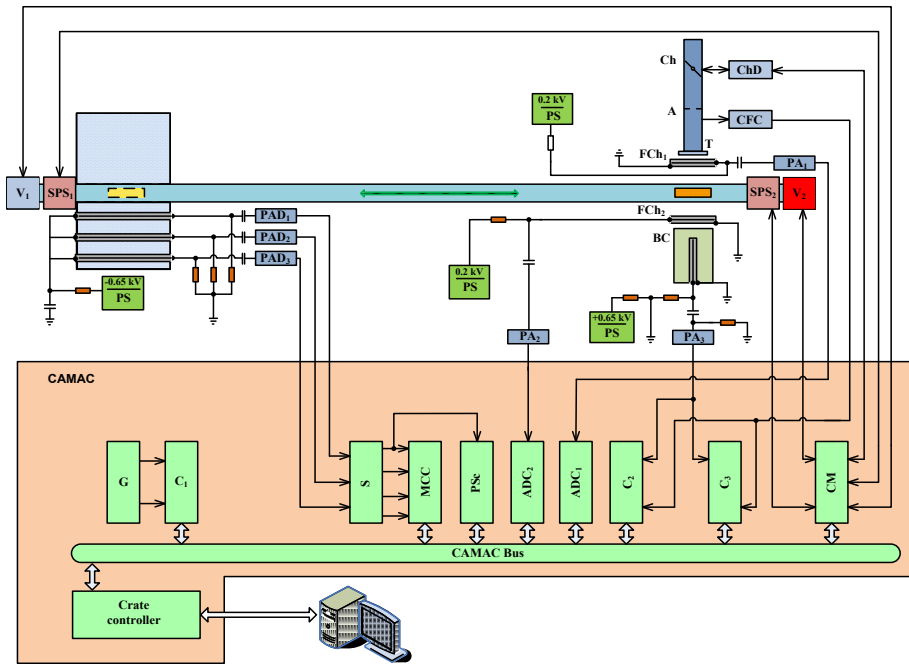


Fig. 2. Block diagram of the experimental setup: (PAD) preamplifier, amplifier, and discriminator; (S) summator; (PA) preamplifier and amplifier; (V) electromagnetic valve; (SPS) sample position sensor; (CM) controlled unit; (CFC) current-to-frequency converter; (ADC) analog-to-digital converter; (PSc) preset-scaler; (MCC) multichannel counter; (G) quartz generator of pulses; (PS) power source; (Ch) chopper; (ChD) magnetic chopper drive; (A) ion guide aperture; (T) accelerator target; (FCh) fission chamber; (BC) boron counter of neutrons; (C1) counter with a preset exposure time; (C2) counter of total counts from the CFC and BC; and (C3) counter of the CFC and BC counts within preset time intervals.

Boron counters SNM-11 were chosen the main element of the registration of detector, because of their low sensitivity to γ -rays. Detector presents the assay of 30 counters, distributed in polyethylene moderator. It consists of three concentric circles, which have radiuses 53, 80 and 110 mm. Inner ring consists of 6 boron counters, medium and outer rings consist of 12 counters each. Outer diameter of moderator was equal to 400 mm, length – 300 mm. The counters were operating in proportional mode at bias voltage 650 V [2]. There was an opening $\varnothing 36$ mm in the center of detector for seen for installation of investigated fissile sample. The detector was shielded with boron carbide, cadmium and borated polyethelene.

Short transportation time of the sample (~ 100 -150 ms) from the irradiation position to the detector was accomplished by the fast pneumatic system. It enabled allowed us to measure delayed neutron yields of short-lived precursors. Sample transport tube was a thin-walled stainless steel tube with an outer diameter 10 and a wall thickness of 0.3 mm. Two electromagnetic valves controled the supply of compressed air into the guide tube. The position of the sample in the neutron detector was fixed with a plug with a hole in the center for controlling the discharge of excess pressure in front of a moving sample and mitigate the impact of the sample. Information on the status of the sample was obtained from the two photodiodes and light sources mounted on the guide tube on the irradiation position and neutron detector.

Preliminary processing of the experimental data consisted in the summation of delayed neutron decay curves obtained in the separate measurement cycles. The summed curves was analyzed using the iterative least squares method with the purpose to estimate the relative abundances of delayed neutrons a_i and half-lives of their precursors T_i . The information on correlation coefficients of group parameters a_i, T_i under estimation, which was later used for averaging of group parameters sets corresponding to the definite energy of initial neutrons was obtained.

Experimental control and acquisition of experimental information was performed by the data acquisition and storage system based on the CAMAC standard with a personal computer connected to the CAMAC crate using the controller FK-4410.

Experimental conditions and additional experiments

It should be noted that specific features of the $T(d,n)^4\text{He}$ reaction, concerned with high intensity and high energy of generated neutrons beams essentially complicated the processing procedure of measured data, which is usually used for the work with neutron sources based on $T(p,n)^3\text{He}$ and $D(d,n)^3\text{He}$ reactions. Additional experiments was made to estimate the magnitude of the effect, concerned with blocking of the neutron detector being in the intensive neutron flux and the effect of the concomitant source ($D(d,n)^3\text{He}$ reaction), appearing as a result of deuteron implantation into the backing of the tritium target.

Processing of the experimental data

The number of counts of delayed neutron detector $N(t_k)$, registered in the k -channel of time analyzer t_k with duration Δt_k after the sample irradiation using the neutrons from $T(d,n)^4\text{He}$ and $D(d,n)^3\text{He}$ reactions can be represented as follows

$$N_l(t_k) = A_l \cdot \sum_{i=1}^n F_{li} \cdot \frac{a_{li}}{\lambda_{li}} \cdot \exp(-\lambda_{li} \cdot t_k) \cdot (1 - \exp(-\lambda_{li} \cdot \Delta t_k)) + B_l(t_k) \cdot \Delta t_k, l = (T, D), k = (1, \dots, m), \quad (1)$$

Where T and D related to the measurements using $T(d,n)^4\text{He}$ and $D(d,n)^3\text{He}$ reactions correspondingly, a_{li} and λ_{li} – relative abundance and decay constant of i th delayed neutron group, $B_f(t_k)$ – intensity of neutrons background, A_l – saturation activity,

$$F_{li} = (1 - \exp(-\lambda_{li} \cdot t_{ir})) \cdot \left(\frac{N}{1 - \exp(-\lambda_{li} \cdot T)} - \exp(-\lambda_{li} \cdot T) \cdot \left(\frac{1 - \exp(-n \cdot \lambda_{li} \cdot T)}{(1 - \exp(-\lambda_{li} \cdot T))^2} \right) \right) \quad (2)$$

Presents the expression considering the irradiation history of the sample and registration of accumulated activity, which includes the following experimental parameters: N – the number of irradiation cycles, T – duration of the one measurement cycle, which consisted of irradiation time in one cycle t_{ir} , transportation time of the sample to the neutron detector and the count time of delayed neutron activity [3].

Results

Time dependences of neutron activity after neutron induced fission of ^{241}Am in the energy range from 14.2 to 18 MeV obtained in the present work considering the blocking effect and effect of concomitant source (filled squares, open squares, circles, triangles) are shown on figure 3. The discrepancy of the experimental data is a consequence of few statistics. Data obtained as result of estimation of delayed neutrons parameters represented by continuous curves. Estimation of the parameters A, B, a_i, λ_i ($i = 1, \dots, n$) on the observed values of time dependence $N(t_k)$ ($k=1, \dots, m$) (eq. 1, 2) was made within the 6-group representation using the iteration least squares method.

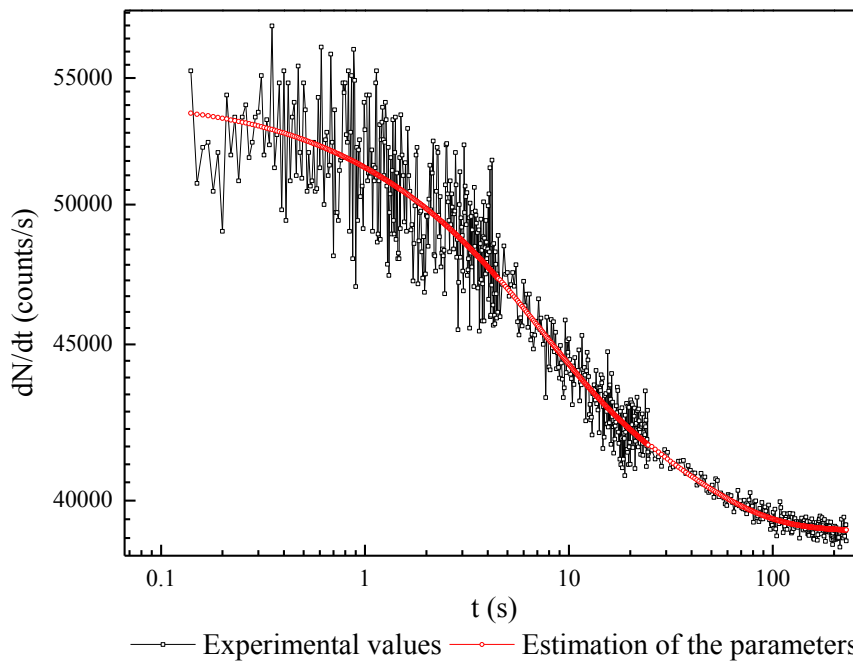


Fig. 3 – Time dependence of ^{241}Am sample activity. Irradiation time 180 s. Black squares – experimental data including the corrections on the blocking effect and effect of concomitant source; red circles curve – data obtained as result of estimation of delayed neutrons parameters.

The obtained results on energy dependence of relative abundances of the separate delayed neutron group a_i and half-lives of their precursors T_i for neutron induced fission of ^{241}Am in the energy range from 14.2 to 18 MeV are presented in the Table 1. Values of group parameters (a_i, T_i) shown in the Table 1 in a six-group representation was obtained by

averaging of these parameters of several series of the measurements, corresponding to the similar energy of the primary neutrons. The average half-life was calculated for each energy using the following formula

$$\langle T \rangle = \frac{\sum_i a_i T_i}{\sum_i a_i}, \quad (3)$$

Where a_i – the relative abundances of the i th delayed neutron group; T_i – the half-life of the i th delayed neutron group.

Table 1. Relative abundances and half-lives for neutron induced fission of the ^{241}Am in the energy range from 14.2 to 18 MeV.

$E_n, \text{ MeV}$	Group number							Average half-life, s
	i	1	2	3	4	5	6	
14,23±0,20	a_i	0,0382 ±0,0008	0,224 ±0,005	0,461 ±0,010	0,195 ±0,004	0,063 ±0,001	0,019 ±0,004	9,20 ± 0,14
	T_i	56,0 ±1,2	12,1 ±0,2	7,47 ±0,14	4,46 ±0,09	0,44 ±0,01	0,174 ±0,004	
15,84±0,20	a_i	0,0420 ±0,0003	0,229 ±0,002	0,427 ±0,003	0,215 ±0,002	0,067 ±0,001	0,019 ±0,002	10,81 ± 0,08
	T_i	55,1 ±0,5	24,1 ±0,2	5,26 ±0,04	3,23 ±0,03	0,49 ±0,004	0,175 ±0,002	
16,20±0,20	a_i	0,0399 ±0,0008	0,258 ±0,005	0,388 ±0,008	0,221 ±0,005	0,073 ±0,002	0,020 ±0,004	11,47 ± 0,19
	T_i	55,6 ±1,2	24,4 ±0,4	5,76 ±0,11	3,12 ±0,07	0,47 ±0,01	0,177 ±0,004	
16,70±0,20	a_i	0,0394 ±0,0008	0,274 ±0,002	0,367 ±0,008	0,226 ±0,005	0,075 ±0,002	0,020 ±0,004	11,19± 0,20
	T_i	54,7 ±1,2	23,2 ±0,5	5,50 ±0,11	2,77 ±0,06	0,48 ±0,01	0,178 ±0,004	
17,98±0,20	a_i	0,0399 ±0,0007	0,257 ±0,004	0,372 ±0,006	0,234 ±0,004	0,077 ±0,001	0,020 ±0,003	10,74± 0,16
	T_i	54,4 ±0,9	23,5 ±0,4	4,99 ±0,08	2,69 ±0,05	0,49 ±0,008	0,178 ±0,003	

Figure 4 represents the energy dependence of the average half-life of delayed neutron precursors for neutron induced fission of the ^{241}Am in neutrons energy range from 14.2 to 18 MeV. Each energy point has been obtained by averaging of the $\langle T \rangle$ values from the separate series of the measurements. For each energy point the correlation matrix of the delayed neutron parameters has been obtained. Summation method was used to obtain the value of the average half-life using the following expression

$$\langle T_{1/2} \rangle = \frac{\sum_i P_{ni} \cdot CY_i \cdot T_{1/2}^i}{\sum_i P_{ni} \cdot CY_i}, \quad (4)$$

where CY_i – the cumulative yield of i th precursor, P_{ni} and $T_{1/2}^i$ – the delayed neutron emission probability and the half-life of i th precursor, respectively. Summation was made over 368 precursors. The data on cumulative yields from *ENDF/B-VII.1* library was used for the present calculation [4]. The data on probabilities of delayed neutron emission and half-lives of delayed neutron precursors were used from *Abriola et al, 2013*[5].

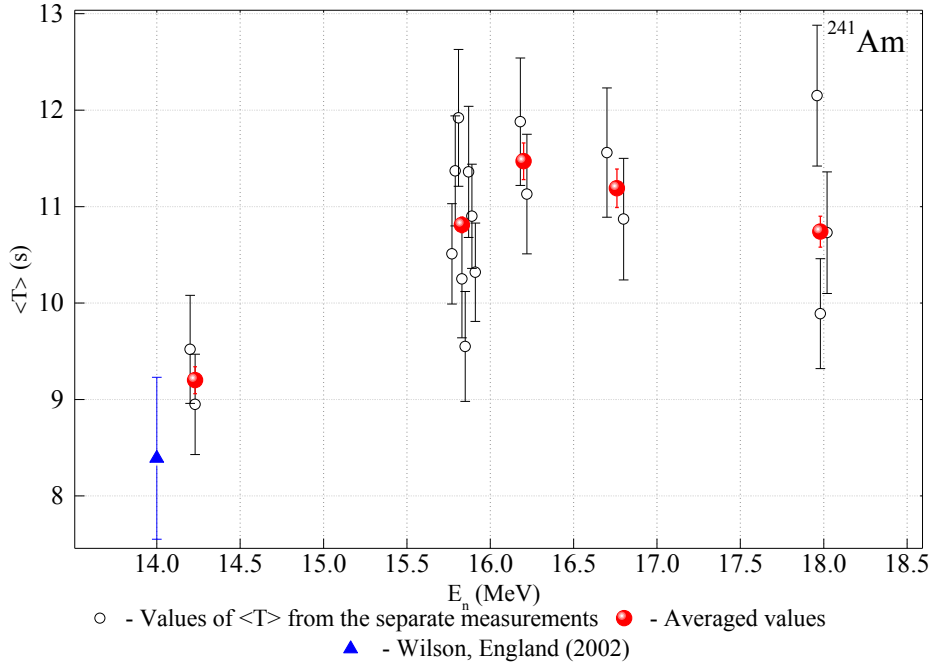


Fig. 4. Energy dependence of the average half-life of delayed neutron precursors for neutron induced fission of the ^{241}Am in the energy range from 14,2 to 18 MeV. Open circles – the values of the average half-life from the separate series of experiments; filled red circles – the values of the average half-life averaged from the experimental series, filled blue triangle – average half-life of delayed neutron precursors obtained using summation method.

Table2 – Correlation matrix of group parameters obtained for the case of neutron induced fission of ^{241}Am by neutrons with energy of 17.9 MeV

	$a1$	$T1$	$a2$	$T2$	$a3$	$T3$	$a4$	$T4$	$a5$	$T5$	$a6$	$T6$
$a1$	1											
$T1$	-0.32	1										
$a2$	0	0	1									
$T2$	0.06	-0.11	0	1								
$a3$	-0.2	-0.06	0	0.01	1							
$T3$	-0.03	-0.26	0	0	-0.11	1						
$a4$	0	0.09	0	0.01	0.06	0.11	1					
$T4$	-0.35	0.05	0	0.02	-0.08	-0.01	0.02	1				
$a5$	0.09	0.05	0	0	0.05	0.07	-0.03	0.05	1			
$T5$	-0.19	0.04	0	0	-0.01	0.01	0	-0.09	0.01	1		
$a6$	0.1	0	0	0	0.01	0.01	0	0.02	0	0.01	1	
$T6$	-0.03	0	0	0	0	0	0	0.01	0	0	0	1

Correlation matrix of delayed neutron parameters was obtained for each energy of incident neutrons. Correlation matrix of estimated group parameters obtained for the case of neutron induced fission of ^{241}Am by neutrons with energy of 17.98 MeV represented in the Table 2.

Conclusion

Measurements of the temporal dependence of neutron activity for the case of neutron induced fission of the ^{241}Am in energy range from 14.2 to 18 MeV have been made for the first time. The obtained decay curves were processed with considering the effect of additional source and blocking effect, inevitably arising when $T(d,n)^4\text{He}$ reaction is used as a neutron source. Values of the group parameters based on the processed decay curves have been obtained for each incident neutrons energy, which in turn have been used for calculation of the average half-lives of delayed neutron precursors. Data on energy dependence of relative abundances and half-lives of their precursors for neutron induced fission of the ^{241}Am in the energy range from 14.2 to 18 MeV are presented in numerical form.

Reference list

1. D'Angelo. An international cooperation to improve delayed neutron data. Progress in Nuclear Energy, Vol. **41**, No. 1–4, pp. 1–3, 2002.
2. <http://www.ortec-online.com/download/428.pdf> (16.05.16)
3. Piksaikin V.M., Kazakov L.E., Isaev S.G., Tarasko M.Z., Roshchenko V.A., Tertychnyi R.G., Springs G.D., Campbell J.M. Energy dependence of relative abundances and periods of delayed neutrons from neutron-induced fission of ^{235}U , ^{238}U , ^{239}Pu in 6- and 8-group model representation. Prog. Nucl. Energy **41** (1–4), 203-222,2002a.
4. JANIS Database. URL: <http://www.oecd-nea.org/janis/> (16.05.16).
5. Abriola D., Singh B., Dillmann I. Beta-delayed neutron emission evaluation. IAEA Report INDC(NDS)-0599/BN, G, ND. – IAEA, Vienna, Austria. – 2011.