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Method of interpretation of measurements of delayed neutrons in the DET-12 device

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Abstract

DET-12 is a device to measure delayed neutrons from fissions in fissionable material samples which were activated in the primary neutron flux from D-T or D-D reactions in hot plasma of big fusion devices (tokamaks, stellarators). In the paper, a method is outlined how to interpret the registered time decay of delayed neutrons in order to obtain information on intensity of the primary neutron flux. The method combines a restoration of the decay function (multi-exponential) from the data stored in a multiscaler regime and a Monte Carlo calculation of a basic approximation of the neutron energy spectrum.

1. Introduction

Activation of fissionable elements by neutrons is considered as a possible diagnostics of D-D and D-T fusion plasmas. Fission of some nuclei, caused by fusion neutrons leads up to emission of secondary neutrons: prompt and delayed. Proper interpretation of the time decay function of the delayed neutrons enables an assessment of the parameters of the primary neutron flux density which induced fission.

In the Institute of Nuclear Physics PAN, a dedicated measuring set-up was composed. A measuring chamber was designed, optimized with use of Monte Carlo simulations, and constructed [1], [2]. The device (called DET-12) was equipped in neutron detectors and a relevant system of data acquisition. Substantial test of neutron counting were performed with use of a neutron isotopic source [2]. Here, an interpretation method of the collected data (numbers of counts decaying in time) is presented to obtain information on the value of the primary neutron flux.

2. Detection of delayed neutrons

2.1. Principle of the detection

Activation of fissionable elements by neutrons has been considered as a possible diagnostics of D-D and D-T fusion plasma. Fission caused by fusion neutrons leads up to emission of secondary neutrons: prompt and delayed. Proper interpretation of the time decay function of delayed neutrons enables an assessment of the parameters of the primary neutron flux density inducing fission.

The decay of delayed neutrons from an individual isotope can be depicted as a sum of exponentials, characterized by decay constants of its precursors:

$$S(t) = r_f \sum_{i=1}^{m} a_i \lambda_i \, \mathrm{e}^{-\lambda_i t} \quad , \tag{1}$$

where r_f is the number of fission reactions in the sample, m is the number of delayed neutron groups, a_i is the absolute yield fraction of the i-th group delayed neutron precursor and λ_i is the effective decay constant of the corresponding group. The relative and absolute yield fractions of delayed neutron precursor depends on the fissile/fissionable material and the neutron energy spectrum causing the fission. The decay of fission products during irradiation time is omitted in the above equation and this report. The influence of irradiation time is not taken into account, all equations are valid for pulse neutron experiments only.

Among a variety of possible mathematical representations of the delayed neutrons decay a six-group model has been commonly used, where the values of both the relative yield and the decay constants are free parameters, *i.e.*, calculated by the least square fit of six exponential expressions.

2.2. Measuring set-up

Fig.1 shows a general view of the DET-12 device built in IFJ PAN for measurements of the time decay of delayed neutrons from fissionable samples. Components of the device are specified in Fig.2. A chamber for measuring emission of delayed neutrons from the sample is surrounded by a bismuth layer which prevents the accompanied γ radiation entering the detectors. The next layer is made of polyethylene and contains neutron detectors. Fast neutrons are slowed down in polyethylene and thermal neutrons are recorded by the twelve ^{3}He detectors. This part of the device is surrounded, in turn, by layers which prevent outside background neutrons entering the detectors. Looking from the outside, it consists of cadmium, and a B_4C layer. Polyethylene slows down external fast neutrons. Thermal neutrons are absorbed by cadmium and finally in the layer of boron carbide (Fig. 2). Details of the device and the data acquisition system have been already described in [2].

Fig. 1. View of the DET-12 device.

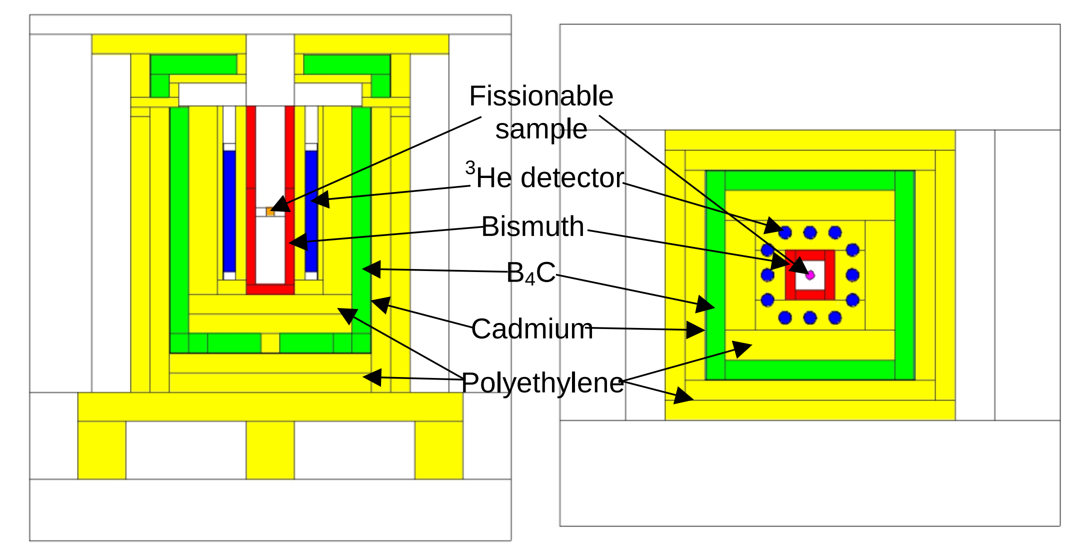

Fig. 2. Diagram of DET-12 (vertical and horizontal cross sections).
Helium detectors are drawn in navy blue. A measured sample is situated in the centre.

2.3. Principle of the measurement

The effective decay half-lives of delayed neutron precursors (groups) vary from 0.2 s up to 56 s. In order to record the delayed neutrons a quick transport method, e.g. pneumatic rabbit system, needs to be applied.

The following procedure is assumed. A sample of fissionable or fissile material is irradiated in the investigated neutron field and then quickly transported (e.g. by means of the rabbit system) to the measuring position in DET-12. The sample is placed in the middle of measuring chamber and twelve ^{3}He detectors are used to detect delayed neutrons. Pulses from the detectors are recorded in certain time intervals (realized by a computer card type of multiscaler). The data acquisition system was described in [2]. Monte Carlo simulations of the time distributions of the emitted delayed neutrons and recorded signals were made [3]. The time dependent recorded signal is the subject of the further analysis.

3. Analysis of the stored data

3.1. Theoretical background

Mathematical model of the number of events recorded in the detector in time between t_j and $t_j + \Delta t_j$ can be written as follows:

$$N\left(t_j\right) = N_b + \varepsilon\, r_f \sum_{i=1}^{m} a_i \lambda_i \int_{t_j}^{t_j+\Delta t_j} \mathrm{e}^{-\lambda_i t'}\, dt' + e_j \tag{2}$$

where:

N_b – the number of background counts, ε – detection efficiency, e_j – random element.

After integration performed in Eq.(2):

$$N\left(t_j\right) = N_b + \varepsilon r_f \sum_{i=1}^{m} a_i\, \mathrm{e}^{-\lambda_i t_j}\left(1-\mathrm{e}^{-\lambda_i \Delta t_j}\right) + e_j\,. \tag{3}$$

Let us denote:

$$\alpha_{ij} = \varepsilon\, r_f\, a_i\left(1-\mathrm{e}^{-\lambda_i \Delta t_j}\right), \qquad x_{ij} = \mathrm{e}^{-\lambda_i \Delta t_j}, \qquad \text{and} \quad N_j = N(t_j)\ . \tag{4}$$

Then:

$$N_j = N_b + \sum_{i=1}^{m} \alpha_{ij} x_{ij} + e_j\,. \tag{5}$$

The number of groups of delayed neutron precursors and the decay constants of each group are known. The issue concerning decomposition of delayed neutrons decay curve comes down to assessing the values of parameters α_{ij}. In such a case the fitting problem can be reduced to linear regression model [4].

It has been proved that even based on limited number of counts it is possible to restore some parameters of the original time-dependent decay function .For instance, if relative yield fraction of delayed neutron precursor is known, then the number of fission events can always be determined based on recorded time-dependent neutron counts, even if the only one delayed neutron group was being recorded. The number of fission reactions in the irradiated sample can be calculated using formula:

$$r_f = \frac{\alpha_{ij}}{\varepsilon a_i \left(1 - e^{-\lambda_i \Delta t_j}\right)} \quad . \tag{6}$$

The uncertainty of the number of fission reactions comes from the uncertainty of the values of parameters α_{ij}.

3.2. Assessment of feasibility to restore the decay-function based on the recorded count numbers

In the further analysis it is assumed that due to the used sample transport system the counting of delayed neutrons starts 10 s after the irradiation. This determines the number of delayed neutron groups which could be recorded. Moreover, it is assumed that energy spectrum of primary neutrons causing fission is known and, accordingly, the relative and absolute yield fractions of delayed neutron precursors are known as well.

The following fissionable materials have been already investigated: ^{235}U, ^{238}U, ^{232}Th. The fission caused by thermal, 500 keV, 2.5 MeV and 14 MeV neutrons have been considered [3]. The yield fractions of delayed neutron precursors differ for different fissionable materials and slightly depend on the energy of neutron causing the fission. The parameters of delayed neutrons are collected in Tables 1–4.

The fraction of the total fission neutrons that are delayed is:

$$\beta = \frac{\nu_d}{\nu} , \tag{7}$$

where:

ν – the total yield of neutrons per fission,

ν_d – the total yield of delayed neutrons per fission.

Then:

$$a_i = \nu_d \cdot \frac{\beta_i}{\beta} . \tag{8}$$

Table 1. Delayed neutron parameters for ^{235}U fission by thermal neutrons [5], $\nu_d = 0.01668$, $\beta = 0.0067$

Group	Decay constant λ_i [s^{-1}]	Relative yield β_i/β
1	0.0124	0.033
2	0.0305	0.219
3	0.111	0.196
4	0.301	0.395
5	1.14	0.115
6	3.01	0.042

Table 2. Delayed neutron parameters for ^{235}U fission by fast neutrons [5], $\nu_d = 0.01673$, $\beta = 0.0064$

Group	Decay constant λ_i [s^{-1}]	Relative yield β_i/β
1	0.0127	0.038
2	0.0317	0.213
3	0.115	0.188
4	0.311	0.407
5	1.40	0.128
6	3.87	0.026

Table 3. Delayed neutron parameters for ^{238}U fission by fast neutrons [5], $\nu_d = 0.0460$, $\beta = 0.0164$

Group	Decay constant λ_i [s^{-1}]	Relative yield β_i/β
1	0.0132	0.013
2	0.0321	0.137
3	0.139	0.162
4	0.358	0.388
5	1.41	0.225
6	4.02	0.075

Table 4. Delayed neutron parameters for ^{232}Th fission by fast neutrons [5], $\nu_d = 0.0531$, $\beta = 0.0203$

Group	Decay constant λ_i [s^{-1}]	Relative yield β_i/β
1	0.0124	0.034
2	0.0334	0.150
3	0.121	0.155
4	0.321	0.446
5	1.21	0.172
6	3.29	0.043

In order to restore the decay function only the parameters of the first two groups are sufficient to adjust to the measurement data if the delayed neutron counting starts 10 s after the irradiation. Then the following expression should be minimized:

$$F(\alpha_{1j}, \alpha_{2j}) = \sum_j \frac{\left(N_j - N_b - \alpha_{1j} x_{1j} - \alpha_{2j} x_{2j}\right)^2}{\left(\delta N_j\right)^2}\ , \tag{9}$$

where $\delta N_j = \sqrt{N_j}$ is the uncertainty of the measurement of the number of counts in the *j*-th time interval. Thus the values of α_{ij} can be calculated from the following system of equations:

$$\frac{\partial F}{\partial \alpha_{1j}} = 0\,, \qquad (10a)$$

$$\frac{\partial F}{\partial \alpha_{2j}} = 0\,. \qquad (10b)$$

The uncertainty $\delta\alpha_{ij}$ of the α_{ij} comes from the uncertainty of the measured values only, so the formula is:

$$(\delta\alpha_{ij})^2 = \sum_j \left(\delta N_j \frac{\partial \alpha_{ij}}{\partial N_j}\right)^2 . \qquad (11)$$

4. Determination of the primary neutron flux

The obtained α_{1j} and α_{2j} values can be used to determine the number of fission reactions, r_f, caused by investigated neutrons in the irradiated sample. The uncertainty of r_f depends linearly on uncertainty of the α_{ij} parameters.

The detection efficiency of the DET-12 system (ε in Eq. (2)) has been experimentally assessed to 18.8 % [2].

On the other hand, the number of fission reactions in the irradiated sample can be expressed as follows:

$$r_f = N_f \int_0^\infty \sigma_f(E)\,\varphi(E)\,\mathrm{d}E\,, \qquad (12)$$

where

N_f – the number of fissile/fissionable atoms,

$\sigma_f(E)$ – fission reaction cross section,

$\varphi(E)$ – neutron flux density as a function energy (the spectrum).

Therefore the calculated number of fission reaction allows determining flux density of neutrons causing fission when they energy spectrum is known.

If the neutron energy spectrum (say, φ_0) is already calculated, e.g. by means of the MCNP radiation transport code [6], and normalized:

$$\int_0^\infty \varphi_0(E)\,\mathrm{d}E \equiv 1\,, \qquad (13)$$

then the fission reaction rate per normalized flux density can be calculated:

$$R_f = \int_0^\infty \sigma_f(E)\,\varphi_0(E)\,\mathrm{d}E \ . \qquad (14)$$

Thus, the actual flux density of neutrons causing fission can be determined using number of fission reaction (r_f) estimated by fitting the experimental data due to the following relation:

$$\phi = \frac{\int_0^\infty \sigma_f(E)\,\varphi(E)\,dE}{\int_0^\infty \sigma_f(E)\,\varphi_0(E)\,dE} = \frac{\frac{r_f}{N_f}}{R_f} \ . \qquad (15)$$

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