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Measurements of Gamma-Ray Production Cross Sections and Spectra in Inelastic Interaction of 14 MeV Neutrons with Nuclei C, O, Mg, Al, Fe, Cu, Zr, Mo, W and Pb

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The results of new measurements of gamma-ray production cross sections and spectra in inelastic interaction of 14 MeV neutrons with nuclei C, O, Mg, Al, Fe, Cu, Zr, Mo, W, Pb are discussed. The measurements were carried out for the gamma-ray energy interval of 0.5-14 MeV using the pulsed neutron source and scintillation gamma-spectrometer combined with the time-of-flight technique. Parameters of the used samples, the geometry and conditions of measurements are described. The corrections connected with the multiple scattering of neutrons and gamma-rays in samples and the contribution of gamma-rays from the neutron target are taken into consideration.

The total and differential gamma-ray production cross sections are given for all samples together with their uncertainties. The estimated uncertainty of the total production cross sections is about 9% for the confidence probability level of 0.95.

KEYWORDS: gamma-ray spectrum, 14 MeV neutrons, time-of-flight technique, pulsed neutron generator, T(d,n)^{4}He-reaction, gamma-ray production cross sections, NaI detector, response function, multiple scattering of neutrons and gamma-rays, unfolding of gamma-spectrum.

I. Introduction

Experimental data on the gamma-ray production cross sections and spectra are rather numerous for thermal and resonance neutrons, but they are more rare for fast neutrons. However, the data for fast neutrons are very important for many applications related to the radiation shielding problems. A special interest evokes the gamma-ray production data for 14 MeV neutrons, which are important for development of various fusion applications. The available evaluated data on the corresponding cross sections are contradictory for many nuclei and more reliable experimental data are required for most important structure materials.

It was noted in the previous publications[1, 2] that the experimental data could be essential improved by means of a more careful choice of the experiment geometry, by using a more intensive stabilized neutron source and applying the modern verified Monte-Carlo codes for estimation of the gamma-spectrometer response function and the analysis of corrections on the multiple scattering of gamma-rays and neutrons. As the main shortcomings responsible for big methodical uncertainties of previous experimental data were clarified we try to eliminate them in new measurements, which were supported by the ISTC Project 731-97.

In the present report the measurement method is briefly described in section II, the electronic equipment is considered in section III, the data processing is discussed in section IV, and the gamma-ray production cross sections and spectra obtained are presented in section V.

II. Measurements

In the measurements reported below the following upgrades were made:

1. Parameters of the neutron pulse were improved: the pulsed component of neutron yield was increased up to 93-95 % that allows to increase the ratio effect/background for the hard part of gamma-ray spectra.

2. The response function of gamma-spectrometer was estimated up to the gamma-ray energies of 14 MeV. Due to this the dimension of the matrix was increased up to 56x56 elements that made possible to represent the gamma-ray spectrum more precisely in the range of gamma-ray energies above 8 MeV.

3. Reconstruction of the gamma-ray spectra from the pulse-height distributions measured was carried out by several iteration steps until a fit of the gamma-spectrum with the applied response functions of spectrometer coincides with the pulse-height distribution obtained within the limit of several percents. It allowed at the first time to evaluate the methodical uncertainties of differential cross section determinations for the whole range of gamma-ray energies from 0.5 to 14 MeV.

The measurement method is based on the use of the scintillation spectrometer with a large crystal of NaI(Tl) ∅150x100 mm and the time-of-flight technique[2] in the geometry shown in **Fig. 1**.

The neutron generator was placed in the hall behind a concrete wall of 3m thickness out of the detector sight. Neutrons were produced from the T(d,n)^{4}He reaction with the deuteron beam bombarded the titanium-tritium target at the energy of 130 keV. The pulsed mode[3] was achieved by a periodical

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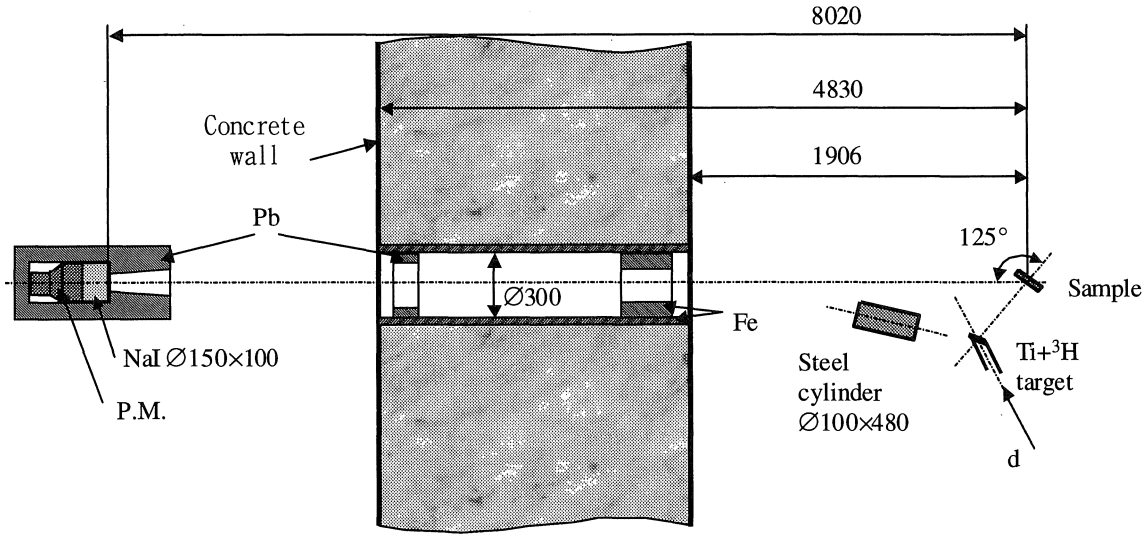

Fig. 1 Experimental arrangement

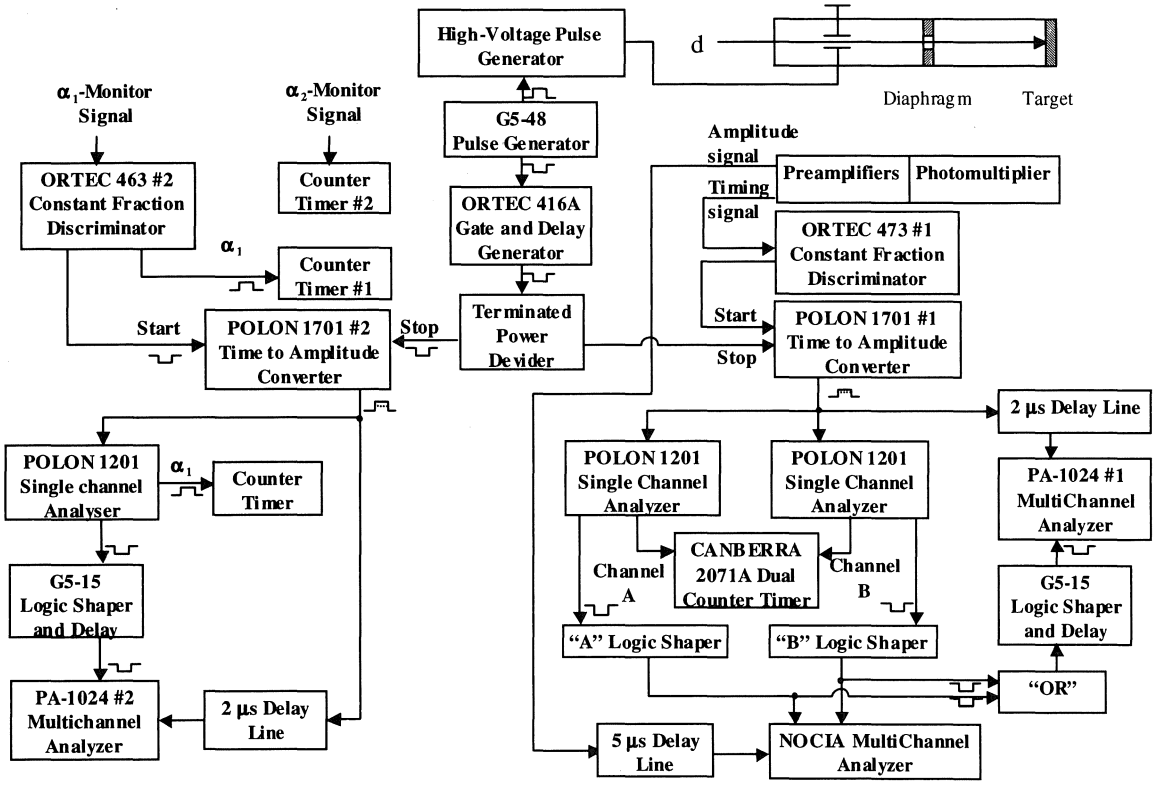

Fig. 2 The electronic setup

displacement of the deuteron flux with a protective diaphragm relative to the axis of the deuteron drift tube by high-voltage pulses in the interval of τ=25 ns. The pulse repetition rate was 500 kHz. The average neutron yield from the target was $\approx 2\text{-}5\times10^8$ n/s.

The detector enclosed in a lead shield with a conical collimator was located in the measurement hall at the flight path of 8 m. To reduce the background from the concrete collimator walls a steel cylinder overlapped a direct flux of neutrons. The gamma-rays were registered at the angle of 125° to the direction of the neutron beam incident on a sample. The effective neutron energy was 14.3 MeV.

The neutron yield from the target was monitored by two scintillation α-counters installed in the deuteron drift tube, which recorded α-particles accompanying the T(d,n)^4 He reaction. The relation between the neutron flux on the sample

and the integral neutron yield from the target at the corresponding solid angle was determined by means of calibration experiments. In the place of samples the certified proton telescope was located, the counting sensitivity of which to 14 MeV neutrons was defined with the accuracy of ±1.5% for the confidence probability level of 0.95[4]. Accounts of the α-counters and the proton telescope determine universal relation between the α-monitor and the neutron flux on the sample. Using this relation the effective integral neutron yield was determined from the counts of the α-monitor, and the pulse yield – from the number of counts of the same monitor under the regime of coincidences with pulses from the starting generator.

The samples under research with the natural isotopic composition were located at the distance of 20 cm from the target center and were manufactured as the disks of 150 mm diameter and the thickness from 3.96 mm for Pb to 19.35 mm for water. The sample masses cover the range from 342 g for water to 831.4 g for molybdenum. In the measurements with H_2O and a powder of W the samples were enclosed in plastic containers with masses of 39.1 and 32.8 g respectively.

III. A Diagram of the Electronics

The scheme of electronics is illustrated in **Fig. 2**. The starting generator G5-48 initiates all the equipment and the generator of high-voltage deflecting pulses. All functional units were synchronized in time by the adjustment of appropriate delays.

The core of the scheme is the time-to-amplitude converter of 1701 type produced by the POLON (#1) operating according to the principle "Start-Stop". The output pulses from the converter were transferred to two single-channel analyzers of 1201 type (POLON), one of which cuts a working "gate" (Channel A) from the converter in a time distribution, and the second - the background one (Channel B). The double timers of 2071A type (CANBERRA) calculated number of pulses in «gates».

Pulses from the outputs of single-channel analyzers "gave a permission" to conduct the amplitude analysis of the operating detector pulses through logical shaping amplifiers A and B.

As an analyzer of pulses the spectrum analyzer LP-4900B (NOKIA) was used. A signal was transferred to the analyzer input from the 10-th dynode of the photomultiplier via a preamplifier and a delay line. The amplitudes were analyzed in the mode of splitting by planes. On one plane the amplitude distribution of the working "gate" was recorded, and on another – the background one.

Distribution of amplitudes in time "gates" was recorded by a multi-channel pulse height analyzer PA-1024 (#1) in the mode of coincidence with pulses of the logical shapers A and B.

To monitor the integral neutron yield from the a-monitors the "Counter Timers" (#1 and #2) were used. Besides, the counts of α_1-monitor corresponding to the pulsed neutron yield were marked out from the overall counts by the time-to-amplitude converter #2 of 1701 type (POLON). The converter was turned on similarly to the converter #1. A time distribution of pulses from α_1-monitor was recorded by the multi-channel analyzer PA-1024 (#2).

To improve the time resolution the time signals from the photomultiplier and from the α_1-monitor were delivered to converters via the modules #1 and #2, respectively, of the time correctors 473 and 463 (ORTEC).

The time stability of spectrometric channels was controlled during the measurements regarding to the full energy peak location of the gamma-ray sources. If it was necessary, the full energy peak location was corrected by changing the high voltage for the detector.

To take into account a contribution of gamma-rays produced in the air volume viewed by the detector and in the containers (30-40g) that used within some samples, the measurements without samples were performed.

A pure events from the sample were deduced according to the following relation:

$$N_{effect}=(N_{effect+background} - N_{background})^{\text{with the sample}} - (N_{effect+background} - N_{background})^{\text{without the sample}} \quad (1)$$

Figures 3 and **4** illustrate the typical time distributions for signal and background gates in one of measurements with the presence and absence of the sample, respectively.

Figures 5 and **6** illustrate the typical pulse height distributions for these measurements.

IV. Determination of Cross Sections

The differential gamma-ray production cross sections in i-th energy interval are determined from the following relation:

$$\left(\frac{d\sigma}{d\Omega}\right)_i = \frac{N_i^{\gamma} \cdot \sigma_{tot}}{\Delta\Omega \cdot n_{col.} \cdot N_0 \cdot K_{att.i} \cdot K_{mult.i} \cdot K_a}, \quad (2)$$

where σ_{tot} is the total cross section of neutron interaction with sample nucleus under research; N_i^{γ} is the number of gamma-rays in the i-th energy interval obtained by unfolding the gamma-ray pulse height distribution; $\Delta\Omega$ is the solid angle from the sample to the detector used for determination of the efficiency and response function of the spectrometer; N_0 is the integral effective pulse neutron yield from the target into 4p; $n_{col.}$ is the number of primary collisions of neutrons with nuclei of the sample under research per one effective neutron emitted from the target; $K_{att.i}$ is the coefficient of gamma-ray attenuation of i-th energy interval at the time-of-flight base (8 m); $K_{mult.i}$ is the connection factor for contribution of multiple neutron and gamma-ray interactions in i-th energy interval; K_a is the connection factor for annihilation radiation from the sample under its interaction with gamma-rays from the neutron target.

For the geometry of measurements (the differential cross section is measured at the angle of 125°) the total gamma-ray production cross section into the i-th energy interval is defined as follows:

$$\sigma_i = 4\pi \cdot \left(\frac{d\sigma}{d\Omega}\right)_i, \quad (3)$$

and the integral gamma-ray production cross section in the whole energy interval is defined as

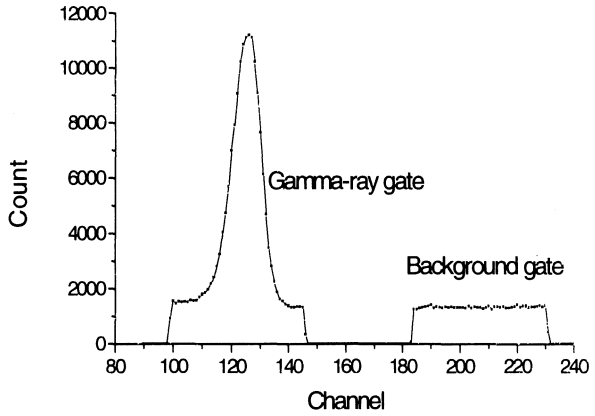

Fig. 3 Time distribution of detector pulses in measurements with Al sample

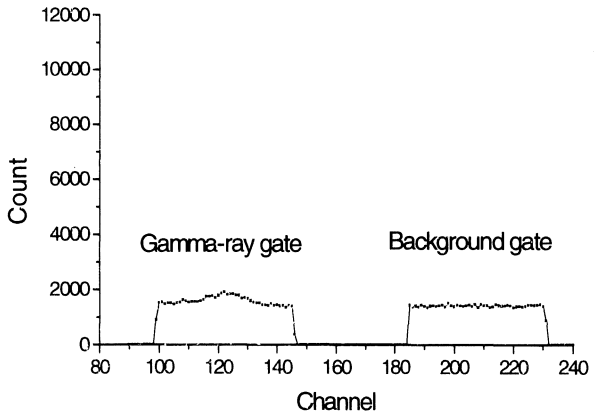

Fig. 4 Time distribution of detector pulses in measurements without a sample

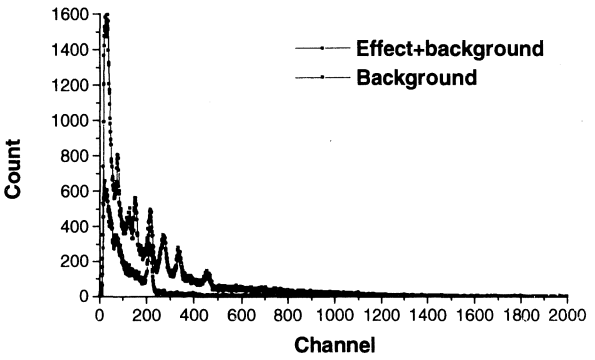

Fig. 5 Pulse-height distribution in measurements with Al sample

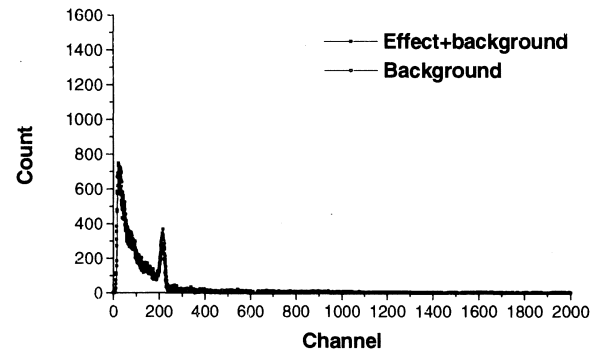

Fig. 6 Pulse-height distribution in measurements without a sample

$$\sigma = 4\pi \cdot \sum_i \left(\frac{d\sigma}{d\Omega}\right)_i = \sum_i \sigma_i \qquad (4)$$

The uncertainties were estimated by analyzing the errors of each coefficient in Eq. (2). In the analysis the errors of $\Delta\Omega$, $K_{att.i}$, K_a were neglected since each of these coefficients is known with an accuracy better than 1%. The uncertainty of σ_{tot} does not effect the results obtained since the ratio $\sigma_{tot}/n_{col.}$ is practically independent from the constants used. For other coefficients the uncertainties were estimated as the following:

1. Error in the determination of N_0 is 3%
2. Error of $K_{mult.}$ is ± 5%
3. Error of $n_{col.}$ is ± 4.5%
4. Error of N^g_i is ± 5%

Thus, the total methodical error of integral gamma-ray production cross sections is estimated as 9% for the confidence probability of 0.95.

In evaluations of the differential cross section errors the additional components of uncertainties were taken into account related to errors of the unfolding procedure and statistical errors of the original experimental pulse-height distributions.

V. Results

The results obtained for the differential and total gamma-ray production cross sections in the 15-group energy scale are given in **Table 1**.

The values of differential cross section errors varies with the energy interval. For the interval of 0.5-1.0 MeV the main contribution to the uncertainties relates to the coefficient $K_{mult.}$ responsible for the multiple scattering of neutrons and gamma-rays. To improve the accuracy of data at this interval we plan to perform the additional measurements with thin samples, for which the multiple scattering effects should be much smaller than for samples used in the present measurements.

On the other hand, in high-energy parts of spectra the statistical errors of experimental pulse-height distributions are responsible mainly for the resulting errors of data. Improvement of data accuracy for these energies relates completely to the

Table 1 Differential and total gamma-ray production cross sections, mb

E_γ, MeV	C	O	Mg	Al	Fe	Cu	Zr	Mo	W	Pb
0.50 - 0.75		22±5	57±10	36±12	123±53	354±51	323±74	1013±118	823±111	1368±127
0.75 - 1.00			74±8	129±14	945±88	432±41	472±44	1588±150	687±67	935±91
1.00 - 1.50		11±8	519±50	168±18	808±75	1082±100	537±53	1079±110	1152±107	640±67
1.50 - 2.00			157±16	310±29	267±28	355±34	455±46	534±52	881±85	634±61
2.00 - 2.50			78±8	260±24	197±20	189±19	606±61	305±29	649±63	357±39
2.50 - 3.00		159±18	125±13	142±14	190±20	124±14	185±20	182±19	453±47	504±50
3.00 - 4.00			138±14	194±19	279±28	183±19	262±28	190±20	472±53	242±29
4.00 - 5.00	218±25	7±4	145±15	119±13	150±18	123±16	133±17	98±11	137±43	180±24
5.00 - 6.00			72±8	86±10	122±18	73±13	84±13	41±7	35±14	40±16
6.00 - 7.00		200±34	54±6	56±7	91±16	54±13	56±14	22±5	21±20	13^{+21}_{-13}
7.00 - 8.00			50±7	45±6	73±13	24±10	34±10	12±4	10^{+16}_{-10}	6^{+10}_{-6}
8.00 - 9.00		2^{+4}_{-2}	27±6	25±6	38±9	11±8	21±9	4±4	3^{+10}_{-3}	3^{+6}_{-3}
9.00 –10.0			26±4	9±3	21±7	2^{+7}_{-2}	7^{+10}_{-7}	3^{+10}_{-3}	2±2	
10.0 –12.0			8^{+9}_{-8}	4^{+5}_{-4}	9±9	1^{+5}_{-1}	4^{+6}_{-4}	2^{+5}_{-2}		
12.0 –14.0										
Total	218±25	401±36	1530±138	1583±142	3313±298	3007±271	3179±286	5073±457	5325±479	4922±443

increase of a number of counts for the experimental pulse-height distributions. It can be achieved in additional measurements by the increased of sample masses. We hope to perform such experiments for the most important structure materials in the nearest future.

In the middle part of spectra the differential cross section errors correspond practically to the methodical uncertainty. So any improvements are possible only after development of new more precision methods of measurements.

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