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The total neutron cross section for natural carbon in the energy range 2 to 148 keV

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Abstract. An experimental investigations of the total neutron cross section for natural carbon were done at Kyiv Research Reactor using neutron filtered beams with energies 2, 3.5, 12, 24, 55, 59, 133 and 148 keV. The intense neutron beams formed by composite neutron filters at reactor horizontal channels had the fluxes of about 10^6 - 10^7 neutron/cm^2·s at the fixed neutron energies and this enabled to measure the neutron cross sections with accuracy better than 3%. Transmission method was used in these measurements. The results are presented together with the analysis of the known previous experimental data and the evaluated nuclear data from ENDF libraries.

1 Introduction

This research is intended to the precise measurements of total neutron cross section for natural carbon. This element is well known as reactor structure material and at the same time as one of the most important scattering standards, especially at energies of less than 2 MeV, where the neutron total and elastic scattering cross sections are essentially identical. The best experimental data in the area 1 to 500 keV have the uncertainty 1 to 4% [1, 2]. However, the difference between these data and those obtained from the R-matrix analysis and used to obtain the ENDF evaluations is essential, especially in the energy range 1 to 60 keV. The use of the technique of neutron filtered beam developed at the Kyiv Research Reactor makes possible to reduce the uncertainty of the experimental data to 1% and less [3, 4]. These high precision data on natural carbon could stimulate a new run of the R-matrix analysis for carbon.

2 Experimental Set-up and Measurements

Experimental investigation of the total neutron cross section for natural carbon was made on the eighth and ninth horizontal channels (HC) at the Kyiv Research Reactor (KRR). One of these channels, having diameter 60 mm, begins in the beryllium reflector, another one, having diameter 100 mm, begins in the reactor core.

Experimental installations on horizontal reactor channels include the systems for forming of filtered neutron beams, neutron detector and counting systems, sample management systems and systems of radiation shielding.

Scheme of experimental installation on the 8-th horizontal reactor channel is shown in fig. 1. Experimental installations for total cross section measurements on the eighth and ninth HC are similar to each other, discrepancies consist in construction of the devices for sample removing (4 in fig. 1) and in construction of the radiation shielding systems (2 in fig. 1). On the both horizontal channels the radiation shielding systems are made of two boxes. The first and second boxes are separated by a shielding wall (thickness 40 cm on the 8th HC, thickness 70 cm on the 9th HC), in which the Pb collimator (internal diameter 2 cm) is placed. The outside collimator (3 in fig.1) with additional elements for beam collimation and neutron filtration and the device for

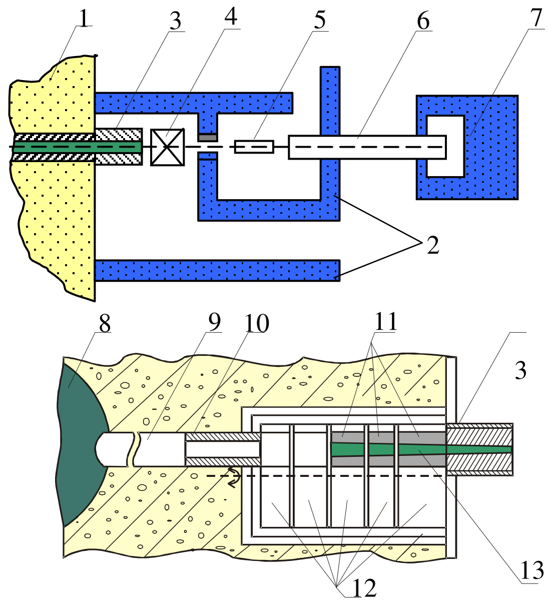

Fig. 1. Scheme of experimental installation on the 8-th horizontal reactor channel. 1 – biological shielding; 2 – radiation shielding of installation; 3– outside collimator; 4 – device for sample removing; 5 – neutron detector; 6 – tube for beam conducting up to neutron catching; 7 – neutron beam catching; 8 – beryllium reflector; 9 – horizontal reactor channel; 10 – preliminary collimators; 11 – filter-collimator assembles; 12 – beam shutter disks; 13 – filter components.

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sample removing are placed in the first boxes; detectors, their power supply electronic blocks and monitoring equipment are located in the second boxes. Walls and ceilings of boxes on the both channels were made from metal containers filled by metal scrap, water and 5-7% boric acid. Both boxes on these different channels have different sizes, disposition of entrances and thickness of walls.

The forming system includes the elements of beam collimation and neutron filtration on the way from reactor core to detector. The preliminary forming of necessary beam geometry is realized with two iron and boron carbide collimators, installed behind the shutter at the 1.5 m distance from a channel start. General length of the collimators is 600 mm (390 mm – iron, 210 mm - boron carbide). Further beam forming takes place in the first three discs of shutter and in outer collimator. In the order lead, textolite and mixture of paraffin with H_3BO_3 are used as material for these collimators. The collimation system provided beam narrowing to 12 mm/m, that corresponded to beam diameter at the sample of 10 mm.

The elements of neutron filtration system take place in the first three disks of shutter and in the outer collimator. To receive the quasi-mono-energetic beams with the average energies of 2, 3.5, 12, 24, 59, 134 and 148 keV we used the composite neutron filters that consisted of ^{10}B, ^{52}Cr, $^{58, 60}$Ni, $^{54, 56, 57}$Fe, Al, S, Co, Sc, V, Pb, Si, Ti. The filter component optimization, to obtain the largest possible intensity of the main energy line at the most optimal impurity of the parasitic energy lines in the neutron spectrum, was carried out by means of calculation using our code FILTER_L [5].

Sample management system on the 8-th HC includes centering tube, tree holders of samples, one holder of cover, holder control levers and electric motors with control blocks. Simultaneously three samples can be loaded into this system and placed in the beam. Sample management system on the 9-th HC consists of two cylindrical devices, in each of them four samples can be inserted. These devices revolve independently, so simultaneously two samples can be placed in the beam. The management systems for experimental samples provide the establishment of the samples on neutron beam with definite alternation at any sequence and combination.

The detection and neutron registration systems on the both HC include: neutron counter, electronic blocks, personal computer and communication lines about 50 m long between spectrometric installation and measuring room.

For neutron energies equal and less than 12 keV, the helium-3 detectors: a) CHM-37 (diameter - 18 mm, length - 500 mm, gas pressure – 7 atm); b) LND 2527 (diameter - 25.4 mm, length - 386.84 mm, gas pressure - 20 atm) were used. For neutron energies equal and more than 12 keV, the proportional hydrogen recoil counters: a) CHM-38 (Gas Filling - 90% H_2 + 9.56% CH_4 + 0.44% $^3He_2$, diameter – 30 mm, length – 300 mm, gas pressure - 4 atm); b) LND 281 (Gas Filling – H + CH^4 + N_2, diameter – 38.1 mm, length – 254.0 mm, gas pressure – 4.3 atm) were used. As a rule, the detectors have been installed along the neutron beam, but sometimes, when the high intensity neutron filter were used, the detectors were placed perpendicular to beam. A neutron detector and a preamplifier are combined into one construction. Signal after preamplifier through communication lines is transmitted to measuring room, where by means of amplifier БУІ-3К and CAMAC blocks it get to personal computer. Computer by means of the dedicated code ZERKIN-3 provides a measurement of preset number of neutron spectra, a sequence of their measurement and storage.

The total neutron cross sections of the carbon at the neutron filtered beams were measured on the horizontal reactor channels at KRR using transmission method. For determination of background counting rate the polyethylene samples with thickness 0.550– 4.730 g/cm^2 were used. For high statistics accuracy, the measurements were carried out during 30-40 hours for each sample. As a rule one measurement had duration about 3 – 4 hours (run for each type of sample was approximately 20 min). To remove the influence of instability factors, the samples at neutron beam were replaced every minute.

Tree type of carbon samples were used in these measurements: 1) solid samples from reactor graphite (C 99.9%); 2) powder samples, loaded into aluminum container (C 99.9%); 3) carbon discs, each of them has thickness 1 mm and diameter 30.4 mm (C 99.997 %).

The total neutron cross section for a sample with nuclear density n_x was determined as

$$\sigma_x = -\frac{1}{n_x}\ln T \,. \qquad (1)$$

Total uncertainty $\Delta\sigma_x$ included the statistical inaccuracy of measurements, sample weight and dimensions inaccuracies:

$$\Delta\sigma_x = -\frac{1}{n_x}\sqrt{\left(\frac{dT}{T}\right)^2 + (\sigma_x dn_x)^2} \,. \qquad (2)$$

2.1 Filter 2 keV

The composite neutron filter consisted of Sc, ^{60}Ni, ^{54}Fe, Al, S, Co, ^{10}B was used to receive the quasi-mono-energetic beam with the average energy 2.004 keV.

The purity of beam was about 99.92%, other additions to the main spectra were negligible: 43 keV – 0.06%, 65 keV – 0.02%. Fig. 2 shows the calculated neutron spectra with peak energy 1.937 keV for filter used in experiment. The limits of 95% response function for the 2 keV filter spectrum were defined as 1.051 to 2.710 keV.

Measurements of the total neutron cross section on carbon at the 2 keV filter carried out on the 8th HC. Six samples of reactor graphite were used in these measurements. Four of them (samples #1 - #4) were as solid ones, the rest were prepared from the same reactor graphite in powder state (samples #5 and #6). The last samples were used to test a validity of determination of the measured cross sections on thin solid carbon samples. Mistake could be appear through incorrectness of nuclear concentration determination for thin solid carbon samples because of the porosity of reactor graphite. As it is possible to see in Table 1, the results, obtained on different type of carbon samples, coincide within the experimental error.

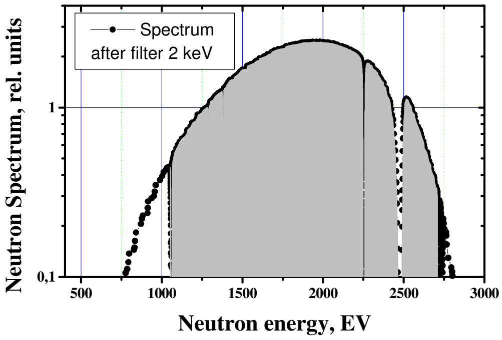

Fig. 2. Calculated neutron spectrum after filter with the average energy 2.004 keV. The shaded area corresponds to 95% response function.

Table 1. Sample thickness and experimental results, obtained on the 2 keV filter.

#	Sample thickness, atoms/b	T	ΔT, T %	σ_{tot}, barn	$\Delta\sigma_{tot}$, σ_{tot} %
		0.8116	0.25	4.675	1.18
1	0.044657	0.8071	0.12	4.799	0.60
		0.8060	0.09	4.830	0.39
2	0.047326	0.8059	0.15	4.559	0.75
		0.8070	0.17	4.531	0.88
3	0.127593	0.5501	0.13	4.684	0.32
4	0.172569	0.4461	0.31	4.677	0.53
		0.4166	0.17	4.685	0.28
5	0.186890	0.4172	0.22	4.677	0.32
		0.4179	0.22	4.668	0.32
		0.4187	0.14	4.658	0.26
		0.3163	0.25	4.648	0.30
6	0.247653	0.3154	0.25	4.659	0.30
		0.3157	0.10	4.655	0.21
Averaged on 6 samples				**4.674 ± 0.021**	**0.46**

2.2 Filter 3.5 keV

Measurements of the total neutron cross section on carbon at the 3.5 keV filter carried out on the 9th HC. The the composite neutron filter consisted of ^{60}Ni, ^{54}Fe, ^{10}B, Al, S was used to receive the quasi-mono-energetic beam with the average energy 3.267 keV.

The purity of beam was 98.7%, other additions to the main spectra were: 43 keV – 0.5%, 65 keV – 0.3%, 87 keV – 0.1%. The limits of 95% response function for the 3.5 keV filter spectrum were defined as 0.438 to 4.409 keV.

Two samples from carbon disks were used in these measurements. The sample thickness and the total neutron cross section, obtained on each sample, are presented in the Table 2.

Table 2. Sample thickness and experimental results, obtained on the 3.5 keV filter.

#	Sample thickness, atoms/b	σ_{tot}, barn	$\Delta\sigma_{tot}$, barn	$\Delta\sigma_{tot}/\sigma_{tot}$, %
1	0.00888±0.00001	4.725	0.211	4.47
2	0.02663±0.00002	4.601	0.128	2.79
Averaged on 2 samples		**4.635**	**0.110**	**2.37**

2.3 Filter 13 keV

The the composite neutron filter consisted of ^{58}Ni, ^{57}Fe, ^{10}B, Al, S, Si was used to receive the quasi-mono-energetic beam with the average energy 12.738 keV.

The purity of beam was about 98.3%, other additions to the main spectra were: (60-70) keV – 1.7%, 270 keV – 0.2%. The limits of 95% response function for the 13 keV filter spectrum were defined as 12.537 to 13.448 keV.

Measurements of the total neutron cross section on carbon at the 13 keV filter carried out on the 8th HC. One sample from reactor graphite in solid state was used in these measurements. One series from 12 runs was carried out. The total neutron cross section, averaged on these 12 measurements, is 4.714±0.046 barn (0.98%).

2.4 Filter 134 keV

We used the composite neutron filter consisted of ^{58}Cr, $^{58,60}Ni$, Al, Si and ^{10}B to obtain the quasi-mono-energetic beam with the average energy 133.59 keV.

The purity of beam was about 99.8%, other additions to the main spectra were: 13 keV – 0.01%, 60 keV – 0.02%, 155 keV – 0.02%. The limits of 95% response function for the 134 keV filter spectrum were defined as 132.206 to 135.325 keV.

Measurements of the total neutron cross section on carbon at the energy 134 keV were carried out on the 8th and 9th HC. Two samples from carbon disk was used in these measurements on the 8th HC. One of these sample (marked by*) was used in these measurements on the 9th HC, where one series from 9 runs was carried out. In Tables 3 there are characteristics of used samples and experimental results, obtained on the 8th HC.

The total neutron cross section, obtained on the 9th HC is 4.31±0.13 barn; averaged on measurements on both channels, is 4.264 ± 0.015 barn (0.35%).

Table 3. Sample thickness and experimental results, obtained on the 134 keV filter on the 8th HC.

#	Sample thickness, atoms/b	σ_{tot}, barn	$\Delta\sigma_{tot}$, barn	$\Delta\sigma_{tot}/\sigma_{tot}$, %
1*	0,00887± 0.000012	4,280	0,045	1,05
2	0,0266± 0.00026	4,263	0,015	0,35
Averaged on 2 samples		**4.265**	**0,014**	**0,33**

3 Discussion of results

Figure 3 represents our results for C-nat. total neutron cross sections at energies in the intervals 1.051 to 2.710 keV, 0.438 to 4.409 keV, 12.537 to 13.448 keV, 132.206 to 135.325 keV, obtained in this work, and in the intervals 19.3 to 25.8 keV, 51.9 to 60.2 keV, and 118.7 to 157.0 keV, obtained earlier [14], together with some experimental data from database EXFOR/CSISRS [1, 2, 6–13] and ENDF evaluations.

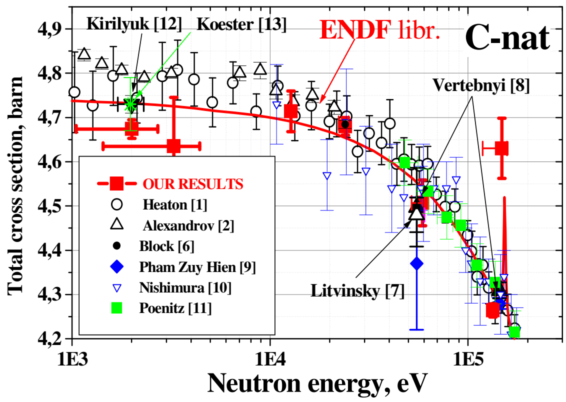

Fig. 3. Our results for C-nat. total neutron cross sections, experimental data from database EXFOR/CSISRS and ENDF libraries.

For 2 keV our result is below the data obtained in [1, 2, 12, 13] and presented in the ENDF libraries. If the discrepancies between our data and the data from [1, 2, 13] should be explained by experimental inaccuracy of the last (errors shown in fig. 3 for [1] are only statistical), that discrepancy between our result and the result obtained by Kirilyuk [12] with high accuracy - 4.73 ± 0.02 barn is not recondite. Just therefore we measured several carbon samples and tried to find all possible sources of errors in our data. As it is seen from table 1 almost for all samples and all series of measurements the cross sections lay below, so we give our result as 4.674 ± 0.021 barn.

For 3.5 keV our result is below the data obtained in [1, 2] and presented in the ENDF libraries, but its measurement accuracy is rather low - 2.4%, so one can say that our result is in a agreement with other experimental data within measurement errors.

For 13 keV our result is in a good agreement with result from [1, 2] and lies slightly higher than the ENDF evaluation.

The results, obtained at the 24, 59 and 148 keV filters, are given here without detailed explanation, as it was done in our previous paper [13]. Let remember only that at the 148 keV filter we observed dependence of total neutron cross section on sample thickness and proposed to explain it that in the energy range 118.71 to 157.01 keV is very strong resonance of the isotope ^{13}C. Its neutron width may be much more than 3.7 keV, cited in scientific literature.

For 134 keV our result lies slightly below than the data obtained in [1, 10, 11] and the ENDF evaluation. It does not contradict our assumption about strong resonance of the isotope ^{13}C at the energy about 153 keV, as the 134 keV filter extracts from reactor spectrum very narrow neutron line, on the contrary it may be explained by becoming apparent interference minimum.

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