

## INVESTIGATION OF THE SCATTERING CROSS SECTIONS OF NEUTRONS ON CARBON NUCLEI AT THE REACTOR FILTERED BEAMS

Olena Gritzay<sup>1</sup>, Mykola Gnidak<sup>1</sup>, Volodymyr Koloty<sup>1</sup>, Oleksandr Korol<sup>1</sup>, Volodymyr Razbudey<sup>1</sup>, Vitalij Venedyktov<sup>1</sup>, Jeffery Richardson<sup>2</sup>, Kenneth Sale<sup>2</sup>

<sup>1</sup>*Institute for Nuclear Research, National Academy of Sciences of Ukraine Kyiv, Ukraine*

<sup>2</sup>*Lawrence Livermore National Laboratory, Livermore, CA, USA*

Natural carbon is well known as reactor structure material and at the same time as one of the most important neutron scattering standards, especially at energies less than 2 MeV, where the neutron total and neutron scattering cross sections are essentially identical. The best neutron total cross section experimental data for natural carbon in the range 1 - 500 keV has uncertainties of 1 - 4 %. However, the difference between these data and those based on R-matrix analysis and used in the ENDF libraries is evident; especially in the energy range 1 - 60 keV. Experimental data for total scattering neutron cross sections for this element in the energy range 1 - 200 keV are scanty. The use of the technique of neutron filtered beams developed at the Kyiv Research Reactor makes it possible to reduce the uncertainty of the experimental data and to measure the neutron scattering cross sections on natural carbon in the energy range 2 - 149 keV with accuracies of 3 - 6 %. Investigations of the neutron scattering cross section on carbon were carried out using 5 filters with energies 2, 3.5, 24, 54 and 133 keV. The neutron scattering cross sections were measured using a detector system covering nearly  $2\pi$ . The detector consisting of <sup>3</sup>He counters (58 units), was located just above the carbon samples. The <sup>3</sup>He counters (CHM-37, 7 atm, diameter = 18 mm, L = 50 cm) are placed in five layers (12 or 11 in each layer). To determine the neutron scattering cross section on carbon the relative method of measurement was used. The isotope <sup>208</sup>Pb was used as the standard. The normalization factor, which is a function of detector efficiency, thickness of the carbon samples, thickness of the <sup>208</sup>Pb sample, geometry, etc., for each sample and for each filter energy has been obtained through Monte Carlo calculations by means of the MCNP4C code. The results of measurements of the neutron scattering cross sections at reactor neutron filtered beams with energies in the range 2-133 keV on carbon samples together with the known experimental data from database EXFOR/CSISRS and ENDF libraries are presented.

### Introduction

Though natural carbon was considered for many years as a scattering standard, the elastic scattering cross section is determined ambiguously. The recent ENDF libraries (ENDF/B-6, JEFF-3.0, JENDL-3.3, BROND-2) contain information about the elastic scattering cross section for natural carbon. According to the methods used for representation of these cross sections in the ENDF libraries, they may be subdivided into two groups. The first group consists of ENDF/B-6, JEFF-3.0, and BROND-2, where the elastic scattering cross sections in the energy range 1.E-5 eV to 4.81 MeV were estimated using R-Matrix analysis. The JENDL-3.3 belongs to the second group, where at the neutron energies above 10 eV, the elastic scattering cross section was obtained by subtracting the reaction cross section from the total cross section.

The experimental data for the elastic scattering cross section of natural carbon in the neutron energy range 1 - 500 keV are scanty; only two papers [1, 2] have these values. The first work was carried out for the 60 - 1.782 keV region, but information about accuracy of the measured data is absent. The 1.5 - 442 keV region was investigated by [2], the accuracy of the obtained elastic scattering cross section lies within 5 - 10 %.

The technique of neutron filtered beams developed at the Kyiv Research Reactor (KRR) makes it possible to reduce the uncertainty of the experimental data and to measure the neutron scattering cross sections on natural carbon in the energy range 2 - 149 keV with accuracy 3 - 6 %. Investigations of the elastic scattering cross section on carbon were carried out using 5 neutron filters with energies 2, 3.5, 24, 54 and 133 keV.

### Experimental set-up

Experimental investigation of the elastic scattering cross section for natural carbon was made on the ninth horizontal channel (HC) at the KRR. Experimental installations on the HC include the systems for forming filtered neutron beams, systems of radiation shielding, sample management systems, detection and neutron counting systems. The experimental layout is shown schematically in Fig. 1 (not to scale).

The neutron beam forming system includes the elements of beam collimation and neutron filtration on the way from the reactor core to the investigated sample. The preliminary forming of the necessary beam geometry

is realized with two iron and boron carbide collimators (C1 in Fig. 1). Further beam forming takes place in the first three discs of the shutter and in outer collimators (F, C2, C3 in Fig. 1). The collimator materials are lead, textolite and a combination of paraffin with  $H_3BO_3$  in that order. The collimation system provided a beam narrowed to 20 mm, corresponding to a beam diameter at the investigated sample of 25 mm.

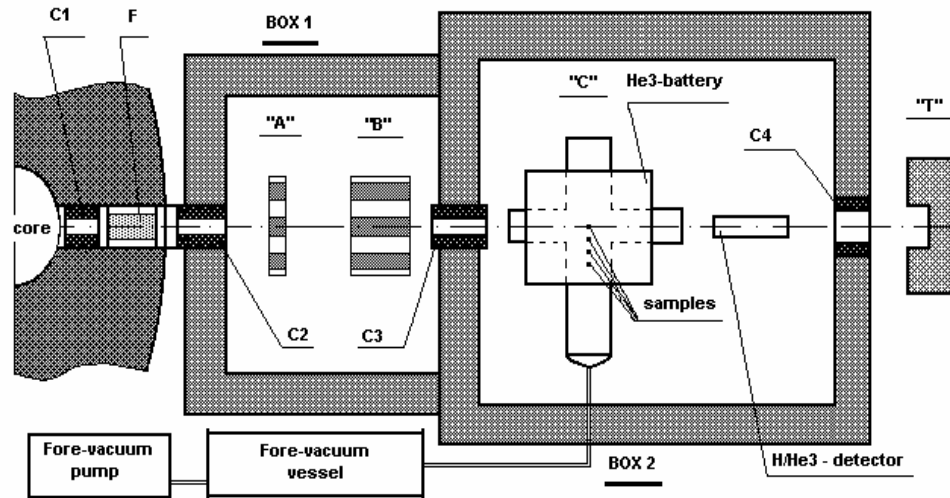


Fig. 1. The experimental layout on the 9<sup>th</sup> HC (not to scale). C1, C2, C3 and C4 – collimators; F - filters; “A”, “B”, “C” – devices for placement of samples.

The elements of the neutron filtration system take place in the first three disks of the shutter and in the outer collimator (Fig. 2). To produce quasi-mono-energetic beams with average energies of 2, 3.5, 24, 54 and 133 keV we used composite neutron filters, the components of which are presented in Table 1. The filter component optimization was calculated using our code FILTER\_L [3] 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.

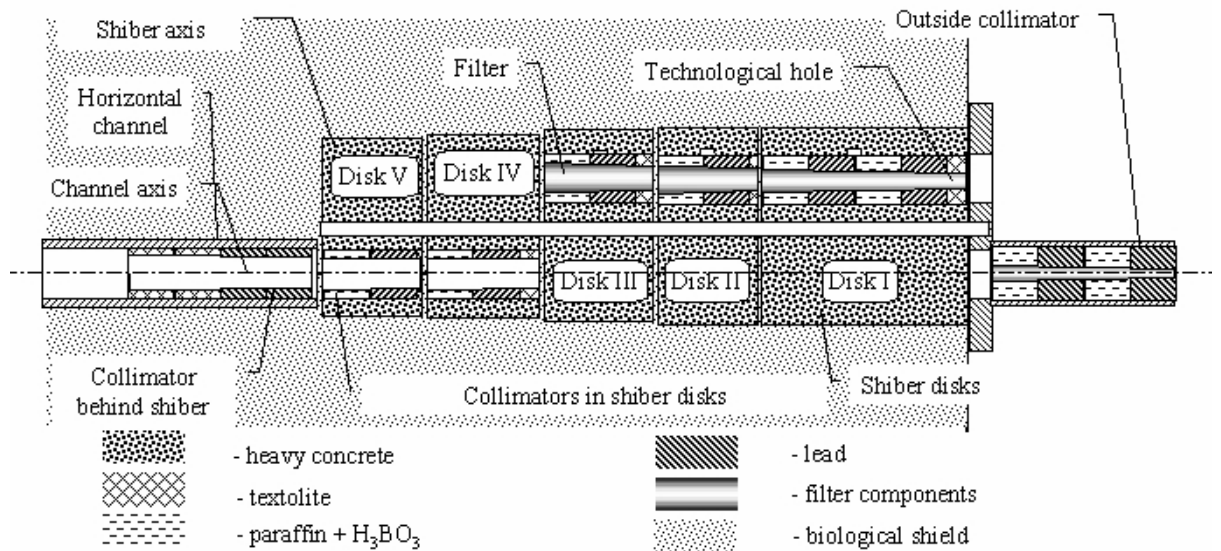


Fig. 2. The elements of neutron filtration system in horizontal reactor channel.

Systems of radiation shielding are made of two boxes. The first and second boxes are separated by a shielding wall (thickness 70 cm), in which the Pb collimator (internal diameter 20 mm, C3 in Figure 1) is placed. Walls and ceilings of boxes were made from metal containers filled by metal scrap, water and 5 - 7 % boric acid.

The outside collimator C2 and two devices (“A” and “B”) for placement of samples are located in the first box; detectors, their power supply electronic blocks and monitoring equipment are located in the second box.

Table 1. The filter components (g/cm<sup>2</sup>) used for the forming of the filtered neutron beams

2 keV filter						
<sup>10</sup> B (85 %)	<sup>45</sup> Sc	<sup>60</sup> Ni	<sup>54</sup> Fe	S	<sup>59</sup> Co	<sup>27</sup> Al
0.2	104.6	80.2	39.35	56.0	26.7	0.54
3.5 keV filter						
<sup>10</sup> B (85 %)	<sup>54</sup> Fe	<sup>60</sup> Ni	S	Cd	<sup>27</sup> Al	
3.15	170.7	146.2	36.7	0.865	1.349	
24 keV filter						
<sup>10</sup> B (85 %)	S	Fe	<sup>27</sup> Al			
0.95	16.35	236.1	99.86			
54 keV filter						
<sup>10</sup> B (85 %)	Si	S	<sup>27</sup> Al			
0.2	144.926	36.7	10.796			
133 keV filter						
<sup>10</sup> B (85 %)	<sup>52</sup> Cr	<sup>58</sup> Ni	<sup>60</sup> Ni	Si	<sup>27</sup> Al	
0.2	95.94	194.06	3.1157	93.08	0.54	

The sample management system consists of three devices “A”, “B” and “C”, which run independently. Devices “A” and “B” are usually used in the total cross section measurements and they are described in detail in [4]. In elastic scattering measurements, one of these devices (“A” or “B”) was used for location of polyethylene sample to cover a neutron beam. Measurements with polyethylene sample are necessary to determine background counting rate. Device “C” was constructed specially for these elastic scattering measurements. It looks like a cross made of two tubes. The diameter of the tube, located along the neutron beam, is 60 mm; the diameter of the tube perpendicular to beam is 100 mm. In this tube five sample holders are placed. The sample holder is a thin-walled tube (without top and bottom), made from aluminum alloy, set in thin rod. The inner diameter of the holder is 30.45 mm, so solid samples have a diameter 30.40 mm. The stand with holders (samples) moves perpendicular to the beam, installing a measured sample in the centre of beam. The sample position is fixed with an accuracy of 0.1mm and checked by the control system of the device “C”. To reduce scattering on air, vacuum about 0.01 Torr is maintained inside of “C”.

The detection and neutron counting systems included: neutron detector, electronic blocks, personal computer and communication lines about 50 m long between the spectrometric installation and the measuring room. The neutron detector, consisted of the <sup>3</sup>He counters (58 units), was located just above the carbon samples. The He-3 counters (CHM-37, 7 atm, diameter = 18 mm, L = 50 cm) were placed in five layers (12 or 11 in each layer). The detector was covered by cadmium sheet with thickness 0.5 mm; it was protected then by borated polyethylene bricks.

Cleaner pictures of the experimental facility, relating to the scattering chamber, and samples (device “C”) and the neutron detection system (assembly of the <sup>3</sup>He counters with radiation shielding), can be seen in Figure 3, in which part of the MCNP simulation is shown.

### Measurements and results

Measurements of the elastic scattering cross section on carbon were carried out at 5 neutron energies in the range 2 to 133 keV. From two to four carbon samples were used for measurements at each energy. The samples are a set of carbon disks (from one to four units), each with a thickness of 1mm and a diameter of 30.4 mm (C 99.997 %). These carbon disks were made by GoodFellow Cambridge Limited Company (England).

To determine the elastic scattering cross section on carbon, the relative method of measurement was used. The isotope <sup>208</sup>Pb was used as the standard. The choice of this standard was based on the following: 1) Values of the total neutron cross section and elastic neutron cross section for the <sup>208</sup>Pb are well known; 2) Resonances in the <sup>208</sup>Pb cross sections are absent in the energy regions that are covered by the neutron filters used in these measurements. The thickness of the <sup>208</sup>Pb sample was  $0,00616 \pm 1E-05$  nucl/barn (enrichment of <sup>208</sup>Pb to 98.3 %, chemical purity 99.98 %).

The order of execution of the elastic scattering cross section measurements on carbon was the following:

- 1 – holder of sample (direct beam);
- 2 – the 1<sup>st</sup> investigated carbon sample (placed in holder);
- 3 – sample of <sup>208</sup>Pb (standard, placed in holder);
- 4 – the 2<sup>nd</sup> investigated carbon sample (placed in holder).

This sequence was repeated, with the neutron beam covered by a polyethylene sample inserted in the device “A” or “B”. For the determination of the background counting rate polyethylene samples with thickness 4.730 to 0.550 g/cm<sup>2</sup> were used.

To remove the influence of instability factors, each of these 8 positions was replaced every minute. As a rule one measurement had 20 such cycles, so the duration of one measurement was about 3 hours. For high statistical accuracy the measurements were carried out for 18 - 120 hours for each energy.

For each measurement and for each carbon sample the experimental value of the ratio  $N_{\text{exp}}^C/N_{\text{exp}}^{Pb}$  was calculated with formula

$$\frac{N_{\text{exp}}^C}{N_{\text{exp}}^{Pb}} = \frac{(N_{\text{smpl}}^C - N_{\text{holder}}) - (N_{\text{smpl}+PE}^C - N_{\text{holder}+PE})}{(N_{\text{Pb}}^{Pb} - N_{\text{holder}}) - (N_{PE}^{Pb} - N_{\text{holder}+PE})}, \quad (1)$$

where on the right side the symbol N with different indexes labels sum from the first to the last channels of the analysis region in different spectra, namely:  $N_{\text{smpl}}^C$  – the carbon sample is on the beam;  $N_{\text{smpl}+PE}^C$  – the carbon sample is on the beam, covered by polyethylene sample;  $N_{\text{holder}}$  and  $N_{\text{holder}+PE}$  – the sample holder is on the beam and it is on the beam, covered by polyethylene sample;  $N_{\text{Pb}}^{Pb}$  and  $N_{PE}^{Pb}$  – the <sup>208</sup>Pb sample is on the beam and on the beam, covered by polyethylene sample.

Then all  $N_{\text{exp}}^C/N_{\text{exp}}^{Pb}$  values, obtained for this investigated carbon sample, were averaged over all its measurements, and this averaged value was used for the determination of the elastic scattering cross section. Analysis of the measured spectra was performed by our C\_SG-W7 code.

To determine the elastic scattering cross section on carbon ( $\sigma_s^C$ )<sub>exp</sub> the following expression has been used:

$$(\sigma_s^C)_{\text{exp}} = \alpha \frac{N_{\text{exp}}^C}{N_{\text{exp}}^{Pb}}, \quad (2)$$

$\alpha$  is a function of detector efficiency, thickness of the carbon samples, thickness of the <sup>208</sup>Pb sample, geometry, etc. For each sample and for each filter energy the  $\alpha$  value has been obtained through Monte Carlo calculation by means of the MCNP4C code [5].

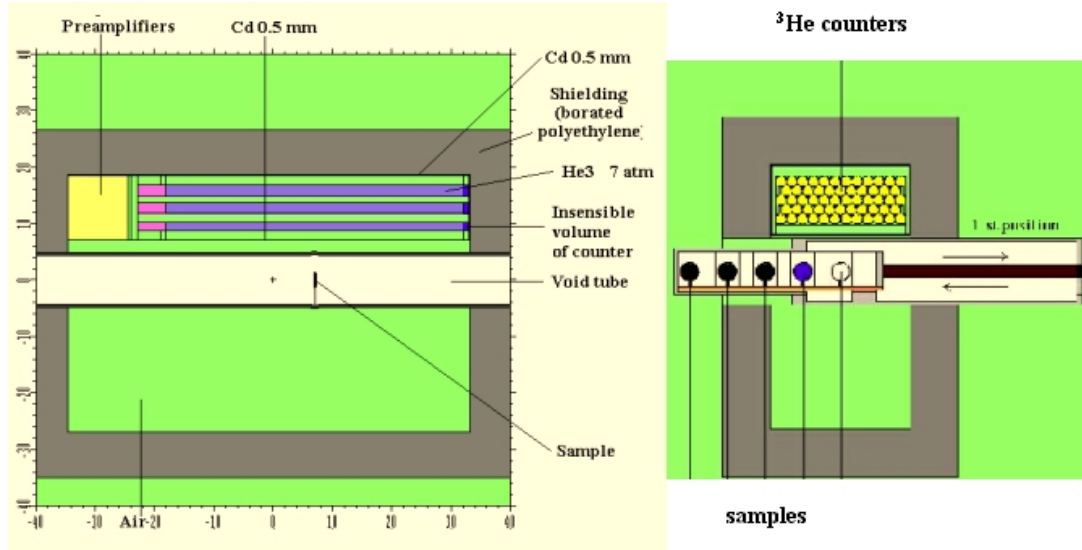


Fig. 3. Disposition of the He-3 counters and samples (vertical cross section).  
In the left - along neutron beam, in the right - perpendicular to beam.

The Monte-Carlo calculation model took into account almost all of the experimental facility details, including: 1) the scattering chamber with two investigated samples in their holders (carbon disks), standard sample (<sup>208</sup>Pb), empty holder and duplicate position for one more sample (unused); 2) the gear for automatic replacement of samples; 3) the neutron detector (58 <sup>3</sup>He counters placed in 5 layers) with all assembly components and preamplifier module; 4) radiation shielding blocks for both the detector and the whole facility (Fig. 3). The chemical compositions corresponded to real materials of the facility. The neutron beam was represented by mono directional source with a circular cross section (diameter 27 mm), located on the right end of the third collimator (C3 in Fig. 1, it is not displayed in Fig. 3). The energy spectrum of the

source was taken to be the spectrum calculated by the FILTER\_L code, using as components the real composition of each filter.

The neutron spectrum after the filter has one main quasi-mono-energetic line and one or more parasitic energy lines. As for scattering measurements the intensity of filtered beam has to be higher because some of the used filters were not very pure. So, the 54 keV filter had purity about 75 % (the purity of the rest of them was better – about 98 % - 99 %). To estimate the influence of the parasitic energy lines on the results, MCNP calculations were carried out with a neutron spectrum having only one main line and with the real spectrum.

Analysis of the results of these MCNP calculations show that the presence of the parasitic energy lines in the filtered neutron spectrum may make changes in values of the determined elastic scattering cross section of not more than 2 %, if the parasitic energy lines amount to 25 % (the 54 keV filter). If they amount to 1 or 2 % (the rest filters), these changes may reach a maximum of 0.12 % for the 1mm carbon sample at the 133 keV filter. All experimental and calculated results, corrected for the presence of the parasitic energy lines in the filtered neutron spectra, are presented in Table 2.

The results of measurements of the elastic scattering cross sections on carbon samples at reactor neutron filtered beams with energies 2, 3.5, 24, 54 and 133 keV together with the known experimental data from database EXFOR/CSISRS and ENDF libraries are presented in Fig. 4.

Table 2. The experimental and calculated results

#	Thickness, atoms/barn	$\alpha$ , barn	$\Delta\alpha$ , barn	$\frac{N_{exp}^C}{N_{exp}^{Pb}}$	$\Delta \frac{N_{exp}^C}{N_{exp}^{Pb}}$	$(\sigma_s^C)_{exp}$ , barn	$\Delta(\sigma_s^C)_{exp}$ , barn
2 keV filter							
1	0.008877±1.2E-05	7.739	0.019	0.6096	0.0003	4.7175	0.0118
2	0.017753±2.4E-05	3.952	0.008	1.1961	0.0008	4.7271	0.0100
3	0.02663±3.6E-05	2.687	0.005	1.7419	0.0001	4.6807	0.0088
4	0.035507±4.8E-05	2.061	0.004	2.2849	0.0001	4.7094	0.0084
Average on 4 carbon samples						4.7063	0.0102 (0.22 %)
3.5 keV filter							
3	0.008877±1.2E-05	7.5798	0.0184	0.6278	0.0190	4.7586	0.1445
4	0.02663±3.6E-05	2.6339	0.0048	1.8192	0.0530	4.7916	0.1399
Average on 2 carbon samples						4.7756	0.1005 (2.10 %)
24 keV filter							
1	0.017753±2.4E-05	3.7711	0.0101	1.239	0.036	4.6716	0.0185
2	0.02663±3.6E-05	2.5642	0.0057	1.825	0.084	4.6802	0.0239
Average on 2 carbon samples						4.6748	0.015 (0.31 %)
54 keV filter							
1	0.008877±1.2E-05	7.183	0.021	0.6252	0.0008	4.4906	0.0146
2	0.008877±1.2E-05	7.170	0.021	0.6324	0.0015	4.5344	0.0173
3	0.017753±2.4E-05	3.663	0.009	1.2292	0.0022	4.5031	0.0135
4	0.017753±2.4E-05	3.658	0.009	1.2378	0.0019	4.5273	0.0129
5	0.02663±3.6E-05	2.493	0.006	1.8497	0.0051	4.6113	0.0164
6	0.02663±3.6E-05	2.489	0.006	1.8211	0.0042	4.5325	0.0146
Average on all carbon samples						4.5293	0.0134 (0.30 %)
133 keV filter							
1	0.008877±1.2E-05	6.1740	0.0212	0.6815	0.0029	4.2076	0.0230
2	0.008877±1.2E-05	6.1590	0.0211	0.6937	0.0037	4.2725	0.0271
3	0.017753±2.4E-05	3.1522	0.0090	1.3263	0.0051	4.1808	0.0200
4	0.017753±2.4E-05	3.1462	0.0090	1.3735	0.0037	4.3214	0.0169
5	0.02663±3.6E-05	2.1384	0.0057	1.9375	0.0070	4.1432	0.0186
6	0.02663±3.6E-05	2.1346	0.0057	2.0230	0.0093	4.3184	0.0230
Average on all carbon samples						4.2392	0.0234 (0.55 %)

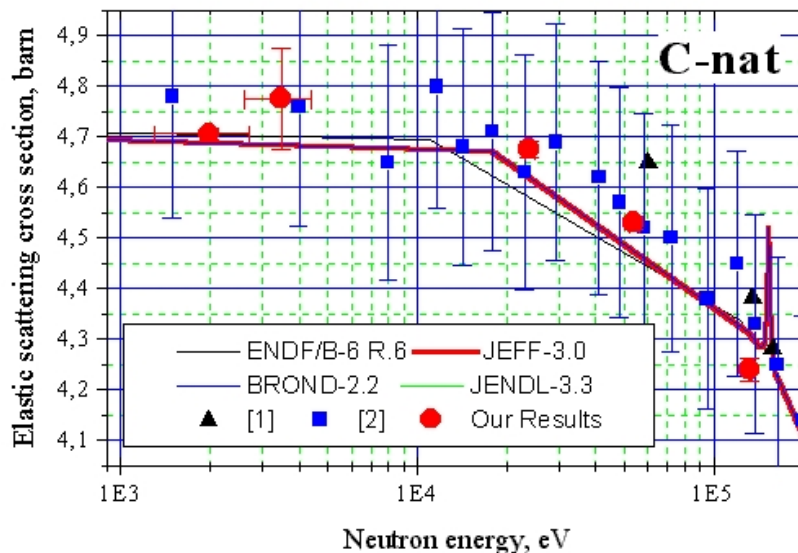


Fig. 4. Results of the elastic scattering cross sections for natural carbon in the neutron energy range 2 -133 keV, the known experimental data from database EXFOR/CSISRS and ENDF libraries.

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#### ИССЛЕДОВАНИЕ СЕЧЕНИЙ РАССЕЯНИЯ НЕЙТРОНОВ ЯДРАМИ УГЛЕРОДА НА НЕЙТРОННЫХ ПУЧКАХ АТОМНОГО РЕАКТОРА

**Елена Грицай, Николай Гнидак, Владимир Колотый, Александр Король, Владимир Разбудей, Виталий Венедиктов, Джефри Ричардсон, Кеннет Сейл**

Природный углерод известен как структурный реакторный материал. В то же время он является одним из наиболее важных стандартов рассеяния нейтронов, особенно при энергиях ниже 2 МэВ, где полные нейтронные сечения и сечения рассеяния почти равны. Лучшие экспериментальные данные по полным сечениям для природного углерода в диапазоне 1 – 500 кэВ имеют неопределенности 1 – 4 %. Однако имеет место очевидное расхождение между этими данными и данными, основанными на R-матричном анализе, которые использовались в ENDF-библиотеках, особенно в интервале 1 – 60 кэВ. Экспериментальные данные для углерода в интервале 1 – 200 кэВ довольно скудны. Использование техники фильтрованных пучков, развитой на Киевском исследовательском реакторе, сделало возможным уменьшить неопределенности экспериментальных данных и измерить сечения рассеяния нейтронов на природном углероде в интервале 2 – 149 кэВ с точностью 3 – 6 %. Исследования были выполнены с использованием пяти фильтров с энергиями 2, 3.5, 24, 54 и 133 кэВ. Сечения рассеяния были измерены с помощью детекторной системы, близкой к 2л. Детектор, который представлял собой батарею из 58 <sup>3</sup>He-счетчиков, был расположен непосредственно над образцами углерода. <sup>3</sup>He-счетчики (СНМ-37, 7 атм, диаметр 18 мм, длина 50 см) были размещены пятью слоями (11 или 12 в каждом слое). Для определения сечения рассеяния нейтронов на углероде был использован относительный метод измерения. В качестве стандарта использовался изотоп <sup>208</sup>Pb. Множители нормализации, которые зависят от эффективности детектора, толщин образцов углерода и <sup>208</sup>Pb, геометрии и др., были получены расчетами Монте-Карло для каждого образца и каждой энергии фильтра с помощью программы MCNP-4C. Результаты измерений сечений рассеяния нейтронов образцами углерода представлены совместно с экспериментальными данными из баз данных EXFOR/CSISRS и ENDF.

## ДОСЛІДЖЕННЯ ПЕРЕРІЗІВ РОЗСІЮВАННЯ НЕЙТРОНІВ ЯДРАМИ ВУГЛЕЦЮ НА НЕЙТРОННИХ ПУЧКАХ АТОМНОГО РЕАКТОРА

**Олена Грицай, Микола Гнідак, Володимир Колотий, Олександр Король,  
Володимир Разбудей, Віталій Венедиктов, Джефрі Річардсон, Кеннет Сейл**

Природний вуглець відомий як структурний реакторний матеріал. У той же час він є одним з найбільш важливих стандартів розсіювання нейтронів, особливо при енергіях нижче 2 МеВ, де повні нейтронні перерізи та перерізи розсіювання майже ідентичні. Кращі експериментальні дані по повних перерізах для природного вуглецю в діапазоні 1 – 500 кеВ мають невизначеності 1 – 4 %. Проте існують очевидні розходження між цими даними та даними, основаними на R-матричному аналізі, що були використані в ENDF-бібліотеках, особливо в інтервалі 1 – 60 кеВ. Експериментальні дані для вуглецю в інтервалі 1 – 200 кеВ досить нечисленні. Використання техніки фільтрованих пучків, розвинутої на Київському дослідницькому реакторі, зробило можливим зменшити невизначеність експериментальних даних і виміряти перерізи розсіювання нейтронів на природному вуглецю в інтервалі 2 – 149 кеВ з точністю 3 – 6 %. Дослідження було виконано з використанням п'яти фільтрів з енергіями 2, 3.5, 24, 54 и 133 кеВ. Перерізи розсіювання було виміряно за допомогою детекторної системи, з розмірами близькими до 2л. Детектор, що являв собою батарею з 58 <sup>3</sup>He-лічильників, було розташовано безпосередньо над зразками вуглецю. <sup>3</sup>He-лічильники (СНМ-37, 7 атм, діаметр 18 мм, довжина 50 см) було розташовано п'ятьма шарами (11 чи 12 в кожному шарі). Для визначення перерізів розсіювання нейтронів на вуглеці було використано відносний метод вимірювання. Як стандарт використано ізотоп <sup>208</sup>Pb. Множники нормалізації, які залежать від ефективності детектора, товщин зразків вуглецю та <sup>208</sup>Pb, геометрії та ін., було одержано за розрахунками Монте-Карло для кожного зразка і кожної енергії фільтра з використанням програми MCNP-4C. Результати вимірів перерізів розсіювання нейтронів зразками вуглецю представлено сумісно з експериментальними даними з баз даних EXFOR/CSISRS та ENDF.