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WELL KNOWN AND NEW NEUTRON FILTERS AND EMPLOYMENT OF THEM FOR FUNDAMENTAL AND APPLIED INVESTIGATIONS

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This is a short review of the neutron filtered beam technique developed in Neutron Physics Department (NPD) at Kyiv Research Reactor (KRR) by now. The ways for search of new neutron filters and improving of known ones are described. A short information about characteristics of the existing filters is presented. This review may be useful for users who wish to use the existing filtered beams at KRR or to develop neutron filtered beam technique at their installations.

***Keywords:** research reactor, neutron filtered beam technique, ENDF/B libraries.*

BASIC PRINCIPLES OF NEUTRON FILTERS DEVELOPMENT

The main idea of neutron filter development is the use of large quantities of matter which nuclei have the deep interference minima in their total neutron cross sections. By transmitting reactor neutrons through thick layer of such material, one can obtain the quasi-mono-energetic neutron lines instead of white reactor spectrum. To get only one quasi-mono-energetic neutron line it is possible to use the two ways:

1) to take so thick layer of this material that only neutrons, corresponding to the most deep interference minimum, would be able to pass through it;

2) to use additional materials, for which resonance maximima in their total neutron cross sections coincide with interference minima for filter material, with the exception of the most deep interference minimum energy.

The first way is very easy for modeling, but in general it is unacceptable in practice, as to depress all parasitic lines it is necessary to take so mach quantity of the filter material that an intensity of main energy line becomes very low. For example, if we use as a filter material scandium with thickness about of 170g/cm^2, we obtain the very known 2 keV filter [1]. For this filter ratio of intensities of the main neutron line and the higher energetic parasitic lines (this ratio is called a purity of filter) will be approximately equal to 75%. To get the 95% purity of this filter it is necessary to take scandium five times more, but thus intensity of the main 2 keV line diminishes by a factor of 16. If we use the second way, i.e. for getting of the 95% purity 2 keV filter, we take as additional materials Co, Ti and ^{10}B, intensity of the main line diminishes only by a factor of 2.

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Selection of the suitable composite materials and their thickness by means of visual examination of the total neutron cross sections is unreal (see Fig. 1, in which the total neutron cross sections for all materials of the 2 keV composite filter are presented). The selection by means of experimental investigations can demand a lot of reactor time. Therefore the best way to optimize a filter composition is execution of preliminary modeling calculations, with subsequent test of this calculated filter by experiment. Methods, realized for this aim in the NPD, will be describe below.

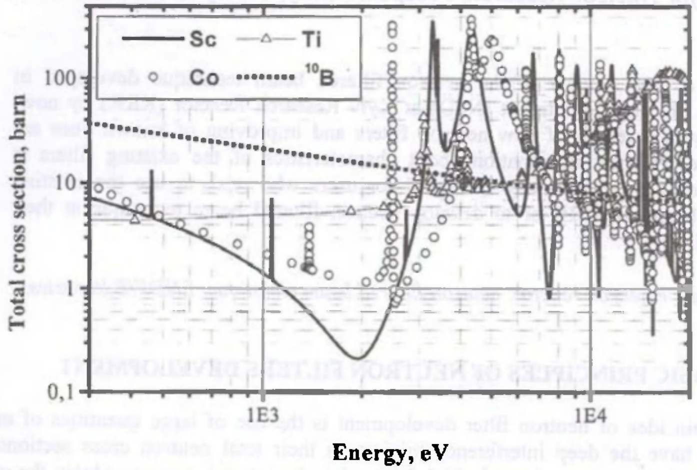

Fig. 1. Total neutron cross sections for Sc, Ti, Co, and ^{10}B in the energy range from 0.3 to 20 keV (JENDL-3.3 library).

Now let formulate the basic demands to neutron filters:

1. The purity of the main energy line in neutron spectrum has to be as much close to 100% as possible.
2. Neutron intensity has to be the most possible value, sufficient to obtain the necessary accuracy in experiment.
3. Construction and composition have to provide the minimal possible gamma-background.
4. In necessary case construction and composition have to allow to increase or to reduce the width of base line without essential worsening of filter quality.
5. The amount of enriched isotopes in filter components has to be minimum necessary.
6. Filter components have to provide the energy range of filtered neutrons up to 1 MeV and more.

THE MAIN TASKS FOR SCIENTIFIC RESEARCH, WHERE THE FILTERED NEUTRON BEAMS ARE USED

1. High precision measurements (0.1 – 0.01 %) of total neutron cross sections for fundamental neutron-nuclear investigations.
2. Precise measurements (to 1 %) of neutron cross sections, the getting of averaged nuclear parameters (σ_t, σ_s, σ_γ, σ_f, S_o, S_1, S_2, R_o, R_1, D, $<\Gamma_\gamma>$).
3. Measurements of neutron capture gamma-spectra.
4. Measurements of σ_{inel} for the first exited levels of heavy nuclides.
5. Measurements of activation cross sections.
6. Isomeric ratio investigations.
7. Investigations of Doppler-effect.
8. The use in time of flight method for precise cross section measurements of σ_t, σ_γ, σ_{inel}
9. Research of radiation damage energy dependence in materials.
10. Neutron radiography and tomography.
11. Bio-medical investigations.
12. Neutron and boron neutron capture therapy (BNCT).
13. Prompt Gamma-ray Activation Analysis (PGAA).
14. Development of standard fluxes for neutron-dosimetry purposes.
15. Energy calibration of proton recoil counters.

NEUTRON FILTERS AT THE KYIV REASEARCH REACTOR

The KRR is a tank-type reactor with beryllium reflector and light water both as moderator and coolant. The core is an assembly of fuel rods, which are 36% enriched with uranium-235. The nominal thermal power is 10 MW. Neutron flux in the core is about 10^{14} n/cm^{2}s. The KRR has ten horizontal tubes, which are used for nuclear physics investigations, solid state and material structure study and applied works. Now three of these ten horizontal tubes are employed in experimental investigations with using of the neutron filtered beam technique. The typical construction of forming system of filtered neutron beam at the KRR is presented in Fig. 2.

The forming system of filtered neutron beam 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 beginning. General length of the collimators are 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. By turns lead, textolite and mixture of paraffin with H_3BO_3 are used as material for these collimators. The collimation system provides beam narrowing to 12 mm/m, that correspondes to beam diameter at the sample in 10 mm. The elements of neutron filtration system take place in the first three disks of shutter and in outer collimator.

The wide set of natural elements and enriched isotopes are used as components for neutron filters in NPD at KRR:

- Natural elements: Si, Al, V, Sc, S, Mn, Fe, Ti, Mg, Co, Ce, Cr, Rh, Cu, B, Cd, LiF.
- Enriched isotopes: ^{52}Cr (99.3%), ^{54}Fe (99.92%), ^{56}Fe (99.5%), ^{57}Fe (99.1%), ^{58}Ni (99.3%), ^{60}Ni (92.8% – 99.8%), ^{62}Ni (98.04%), ^{80}Se (99.2%), ^{10}B (85%), ^{7}Li (90%).

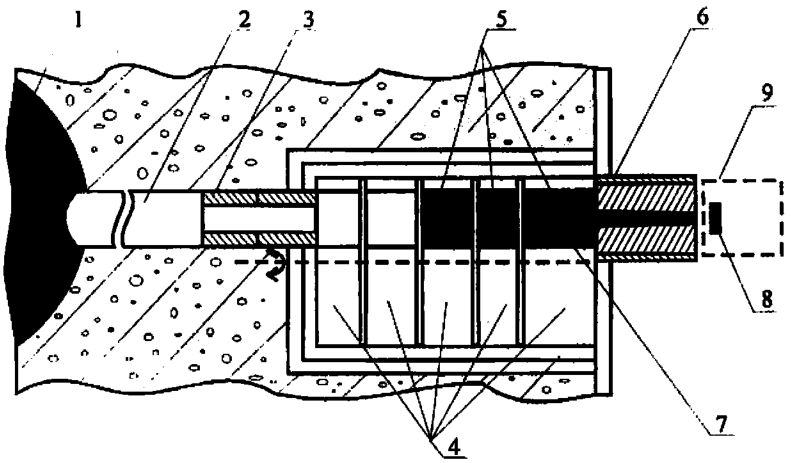

Fig. 2. Construction of forming system of filtered neutron beam on the KRR to obtain the quasi-mono-energetic neutron line. 1 – beryllium reflector; 2 – horizontal channel tube; 3 – preliminary collimator; 4 – beam shutter disks; 5 – filter-collimator assembles; 6 – outside collimator; 7 – filter components; 8 – sample for activation; 9 – device for samples removing.

Availability of such wide set of materials, especially enriched isotopes, allowed to create in NPD the unique set of neutron filters, providing more than ten neutron lines in the energy range from thermal energy to several hundred kilo-electron-volts, intensity of such lines may reach 10^6 – 10^8 n/cm^{2}s [2], and this is much more than any other method (time of flight or others) can ensure. The wide set of filter materials also allows us to modify filter parameters (purity, intensity, width, etc.) subject to the given research task. Through expensiveness of high enriched isotopes, the natural elements or enriched isotopes available in NPD are usually considered as components of new or improved filters.

The filter component optimization procedure intended for getting the most possible intensity of the main energy line at the most possible low intensity of the parasitic energy lines in filtered neutron spectrum includes the following three main steps:

1-th step:
modeling calculation of neutron filtered spectra;
2-nd step:
creation of filter with calculated amount of the chosen components;
3-rd step:
experimental testing of the created filter.

If it is necessary the sequence of these steps is repeated. If desired quality of filter is attained, its characteristics are determined.

Modeling calculation of neutron filtered spectra

For modeling calculation of neutron spectra formed by filters, there were developed the special computer code using FORTRAN language. This code FILTER allows to put into calculation practically any material and isotope combination, that are used to get the filtered neutron spectrum with necessary energy.

This code FILTER (version 5) allows obtaining the two energy dependent values which image the filtered neutron spectrum:

1. Neutron transmission T(E) multiplied by incident reactor neutron spectrum $\Phi(E)$:

$$F1(E) = T(E) * \Phi(E) = \exp[-\sum n_i * \sigma_i(E)] * \Phi(E), \qquad (1)$$

where n_i – nuclear thickness of the i-th filter component; $\sigma_i(E)$ – total neutron cross section of the i-th nuclide.

2. Neutron transmission T(E) multiplied by incident reactor neutron spectrum $\Phi(E)$ and multiplied by an energy dependent cross section of the reaction, which used for neutron detection $\sigma_{react}(E)$, i.e. it allows to take into account an efficiency of the used neutron detector:

$$F2(E) = T(E) * \Phi(E) * \sigma_{react}(E). \qquad (2)$$

The incident reactor neutron spectrum $\Phi(E)$ is taken as function composed of 3 parts: Maxwellian, 1/E – dependence and fission spectrum. This spectrum was normalized to unit: $\int\Phi(E)dE = 1$ in the limits from 10^{-5} eV to 20 MeV.

The total neutron cross sections for nuclides $\sigma_i(E)$ were obtained from ENDF libraries in the energy range from 10^{-5} eV to 20 MeV in point-wise form at the temperature 300K using the PREPRO2002 [3] and NJOY99 [4] codes. JENDL-3.3, ENDF/B-6 libraries were taken as the basis for forming this special library. Today it consists of 65 files, each of them includes the total neutron cross section for one nuclide. That structure of the cross section library allows to realize in the FILTER code a selection as filter component any nuclide by name of its file, combination them in any sequence, and, if it is necessary to add new files with needed cross sections.

The pportunity of using these simple expressions for determination of a neutron spectrum shape after filter is due to a strict collimation of neutron filtration system, otherwise it would be necessary to calculate a neutron transport from core to sample place taking into account all processes (scattering, absorption, etc.). Correctness of this statement was tested by calculation of a neutron spectrum shape after the 24 keV filter using MCNP4c code [5]. The MCNP4c results were similar to those obtained by means our code FILTER.

Creation of filter with calculated amount of the chosen components

As a rule, when we create a new filter (or improve an existing one) with energy different from thermal, the first filter component, having location on the beginning of the third beam shutter disk (the most close to core, see Fig. 3), is boron-10, to avoid excessive activation of the rest filter components. Also in the first three shutter disks the main components of filter are inserted. The filter components, which are planed to alter, are placed, if it is possible, in outside collimator. To lighten and to quicken the procedure of filter changing, special containers for filter were made. These containers are tubes from stainless steel, length of them are equal to length of beam shutter disks. Collimation materials (ordinarily paraffin with H_3BO_3 and lead, taking turns) and filter components are inserted in these tubes. One of the real filters is presented in Fig. 4, as an example.

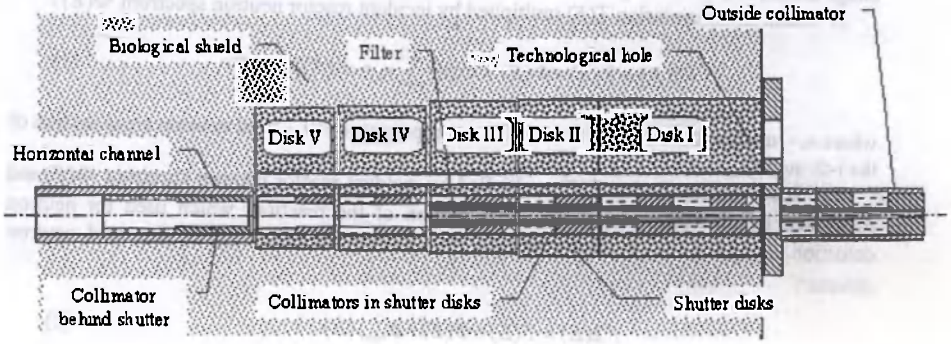

Fig. 3. Location of filter in horizontal rector channel.

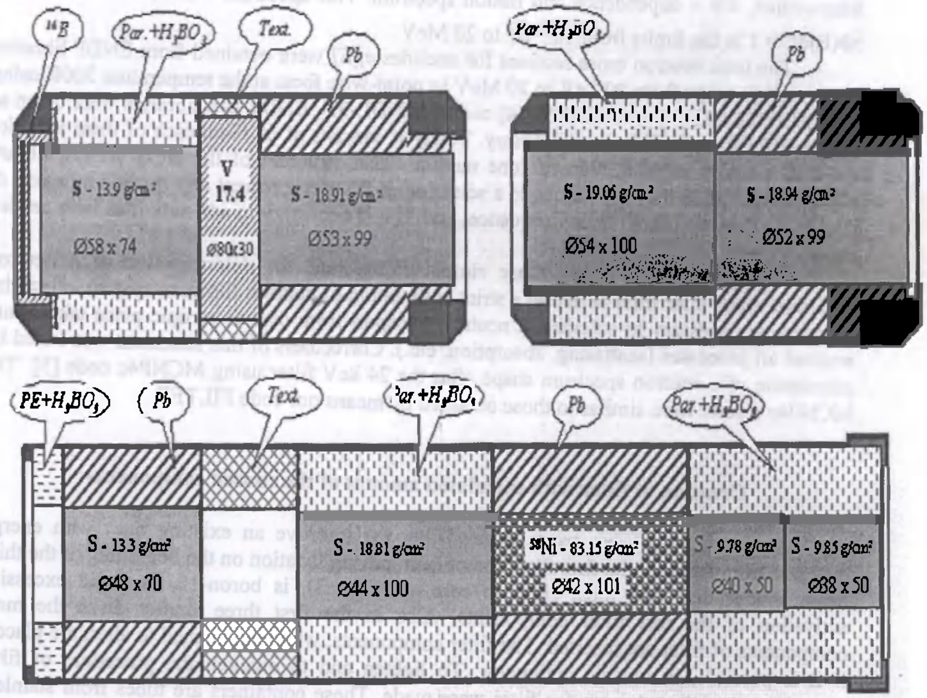

Fig. 4. The 59 keV filter. Top picture – the III and II shutter discs (from left to right), lower picture – the I shutter disc.

Experimental testing of the created filter

To demonstrate procedure of experimental testing of the created filter let us consider the filter, main components of which are S, ^{58}Ni, V, ^{10}B, and Al. Resuts of calculation with the code FILTER show that if we take ^{10}B - 0.281 g/cm^2, ^{58}Ni - 83.15 g/cm^2, V - 17.4 g/cm^2, S - 122.55 g/cm^2, Al - 5.4 g/cm^2, we can obtain a neuron filter with energy 59 keV and the purity of this filter will be better than 99%, other additions to the main spectra will be negligible – each of lines is less than 0.2%. This filter was arranged (just it is shown in Fig. 4; Al was placed in outer collimator) and a neutron spectrum after them was measured by means proton recoil counter. The experimental results are shown in Fig. 5. On the lower part of this figure the shape of neutron filtered beam spectrum obtained by differentiation of previous curve is presented. As it can be seen, contribution of the parasitic higher energy lines is negligible.

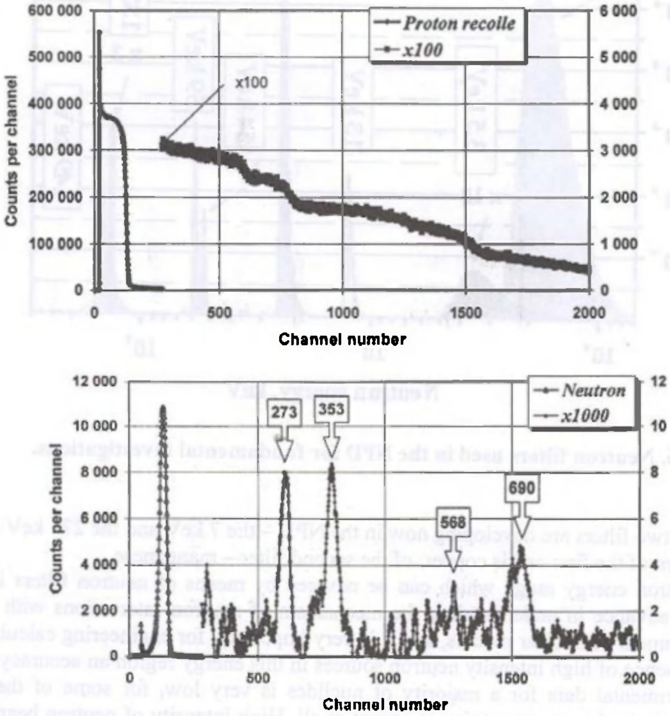

Fig. 5. Instrumental spectrum from proton recoil counter after neutron filter with energy 59 keV (top picture), and the shape of neutron filtered beam spectrum obtained by differentiation of previous curve (lower picture).

FILTERS AND EMPLOYMENT OF THEM FOR FUNDAMENTAL AND APPLIED INVESTIGATIONS IN THE NPD

As a result of this activity characteristics of the whole series of neutron filters were improved and today these filters are used for fundamental investigations, carried out in the NPD. Their energies and comparative intensity are shown in Fig. 6. Energy region, which they cover, is from thermal energy (this filter is not presented in figure) to 149 keV.

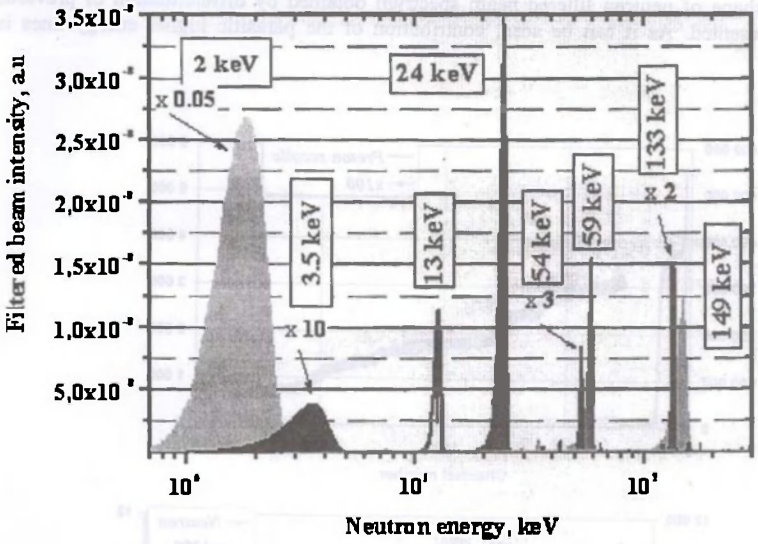

Fig. 6. **Neutron filters used in the NPD for fundamental investigations.**

Another two filters are developing now in the NPD – the 7 keV and the 275 keV filters. Main component of the first one is copper, of the second filter – manganese.

The neutron energy range which can be covered by means of neutron filters is very interesting for advance in understanding the mechanism of neutron interactions with nuclei and for development of nuclear models, and it is very important for engineering calculations, but through absence of high intensity neutron sources in this energy region an accuracy of the available experimental data for a majority of nuclides is very low, for some of them the experimental data in this energy region is absent at all. High intensity of neutron beams and experimental methods developed in the NPD, made it possible to carry out the measurements with high accuracy, for example, for total neutron cross section with accuracy better than 1%.

The illustration of such investigation on the neutron filtered beams may be our results of measurements of the carbon neutron cross section, presented in [6] or the effective neutron cross sections and resonance factors for cromium-52 [7]. In this paper a part of these results are presented in Fig. 7 and Fig. 8, as an example.

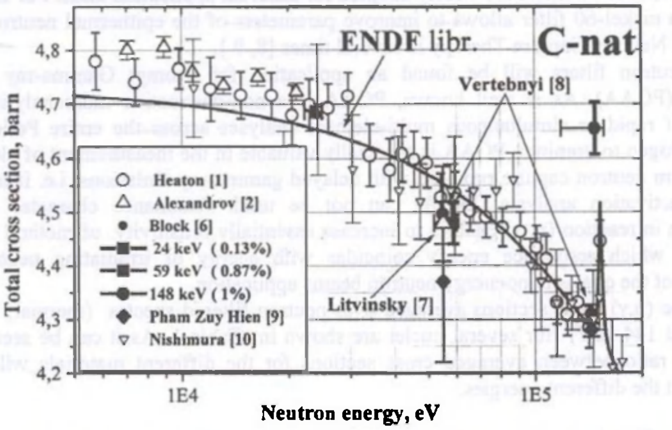

Fig. 7. Experimental results for the carbon total neutron cross section, obtained in NPD on the neutron filtered beams 24, 59 and 148 keV using transmission method [6] and data from ENDFB/6 and EXFOR libraries.

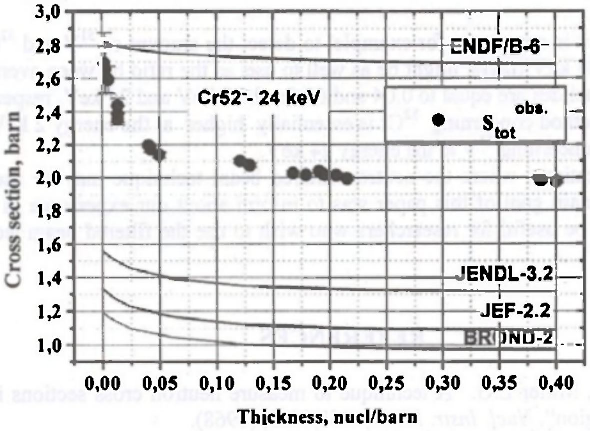

Fig. 8. Experimental total neutron cross sections for ^{52}Cr, measured on the 24 keV filtered beam using transmission method [7] and data from ENDF/B libraries.

The neutron filtered beam technique is very successfully employed in the NPD for measurements of the total neutron scattering cross sections, the angle distribution of scattering neutrons, etc. (results of the cross section measurements for the reaction ^{181}Ta(n, γ)$^{182\ m2}$Ta are presented at this conference).

Also, neutron filters are widely adopted for different application tasks. For example, the using of a nickel-60 filter allows to improve parameters of the epithermal neutron beam for the Boron Neutron Capture Therapy in several times [8, 9].

Neutron filters will be found an application for Prompt Gamma-ray Activation Analysis (PGAA). As is well known, PGAA is a non-destructive radioanalytical method capable of rapid or simultaneous multi-element analyses across the entire Periodic Table, from hydrogen to uranium. PGAA is especially valuable in the measurement of elements that do not form neutron capture products with delayed gamma-ray emissions, i.e. if instrumental neutron activation analysis (INAA) can not be used. Resonance character of neutron absorption in reaction (n, γ) enables to increase essentially sensitivity of method concerning elements, which resonance energy coincides with energy of irradiating neutrons under condition of the quasi-monoenergy neutron beams application.

The (n,γ) cross sections averaged over neutron filtered spectra (thermal, 2 , 3.5, 24, 54, 59 and 144 keV) for several nuclei are shown in Table 1. As it can be seen from this table, the ratio between averaged cross sections for the different materials will be rather different at the different energies.

Table 1. The (n,γ) cross sections averaged over neutron filtered spectra (in barns).

E_n,keV	Thermal	2.0	3.5	24	54	59	144
Cl-35	41.8	0.006	0.027	0.0014	0.0072	0.0083	0.0043
V-51	4.92	0.0350	0.223	0.0183	0.0273	0.0058	0.0073
Cr-52	0.8	0.9400	0.0010	0.0003	0.0013	0.0189	0.0084
Co-59	16.5	0.0040	0.0110	0.0260	0.0093	0.0070	0.0074

Therefore, if it is necessary, for example, to detect the amount of ^{51}V and ^{52}Cr in their mixture, the 2 and 24 keV filters might be as well to use, as the ratio between averaged cross sections for these nuclides are equal to 0.04 and 61 for the 2 keV and 24 keV, respectively. So sensitivity of the method concerning ^{52}Cr is essentially higher at the energy 2 keV, and it is essentially higher concerning ^{51}V at the energy 24 keV.

List of applications, where the neutron filtered beam technique may be used, can be continued, but the main goal of this paper was to inform about our experience in this field, and we hope it will be useful for researchers who wish to use the filtered beam technique in their work.

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