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Monte-Carlo Evaluations of Low-Energy Neutron Radiative Capture in ^{93}Nb-Targets and γ-Quanta Forward-Backward Asymmetry Caused by Geometry and Kinematics

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1. Introduction

In order to ascertain the values of forward-backward asymmetry of γ-quanta emitted at the radiative decay of nuclei with middle weights A~100 after capture of neutrons with energies near low-energy p-wave resonances, the experiment already started by the time-of-flight method at 10-m flight-path of the IREN facility (FLNP, JINR) with ^{93}Nb-targets. A considerable interest in the development of these experiments is preserved due to the fact that a correct determination of γ-quanta forward-backward asymmetry in the energy region of p-wave resonance allows obtaining its parameters – the neutron $\Gamma_{n1/2}$ and $\Gamma_{n3/2}$ partial widths.

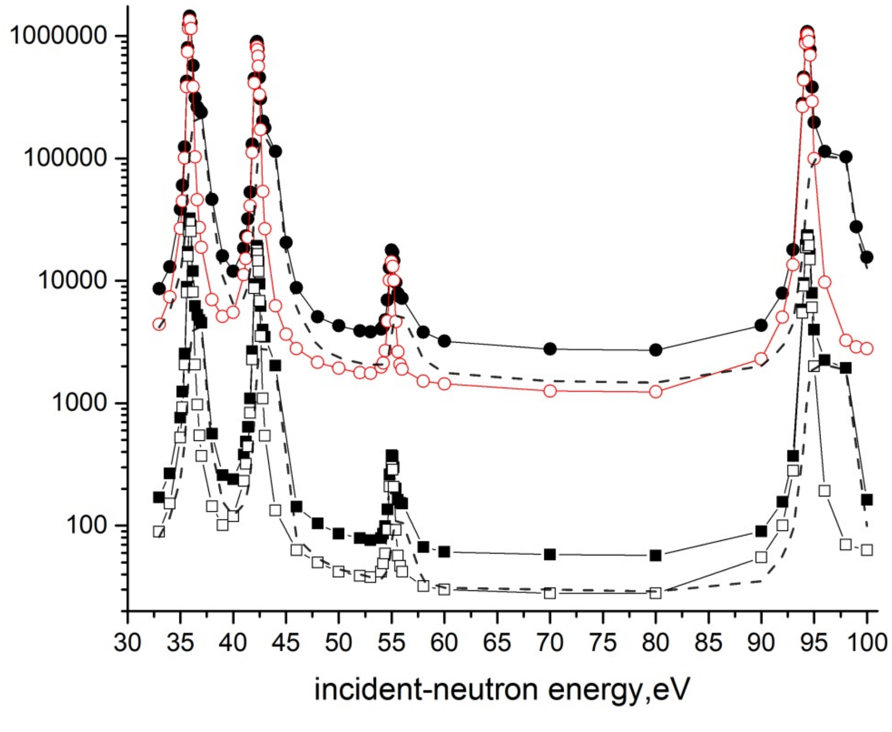

Fig.1a. Calculations of number of neutrons captured in ^{93}Nb-targets with 4×4 cm cross sizes and thicknesses of 0.004 cm (squares of the bottom spectra) and 0.2 cm (circles of the upper spectra): closed points and squares – total-captured neutrons, open points and squares – neutrons captured without scattering in the targets, dashed curves – neutrons captured after multiple scattering.

In order to obtain the statistically significant value of the experimental forward-backward anisotropy of gammas, it is need to evaluate taking into account contribution of the asymmetries which distort the spatial γ-quanta anisotropy. To evaluate the inevitable distortion of the required γ-anisotropy by the asymmetry of γ-quanta detection caused by kinematics and geometry, the Monte-Carlo calculations were performed with ^{93}Nb-targets of different thicknesses.

2. Calculations of neutron capture in the targets

A multiple scattering of neutrons in the target before their capture always distorts the shape of neutron-capture resonances measured with the time-of-flight technique. An increase in the target thickness leads to enlargement of neutron capture and, consequently, number of gammas rises, but neutron multiple scattering also rises and distorts the required spatial anisotropy. So the target must be thick enough (for desirable high yield of gammas) and, at the same time, it must be as thin as possible (for minimization of an undesirable γ-detection asymmetry due to geometry and kinematics). It might be as well to choose a target thickness, which provides an absolute advantage of capture of neutrons without their scattering.

Calculations of neutron capture by ^{93}Nb-targets have been made at 10^7 of neutrons, which run into the target with given initial energy. In order to evaluate a contribution of multiple-scattered neutrons into the total capture, three niobium samples of the same 4×4 cm cross size were considered as targets: two plates with thicknesses of 2 and 6 mm, and 400 mcm foil. Capture and total cross sections of ^{93}Nb were taken from JENDL-5 library of JAEA NDC data [2], where Doppler broadening was already taken into account (the library data were extrapolated linearly to required neutron energy after each neutron-nuclear collision).

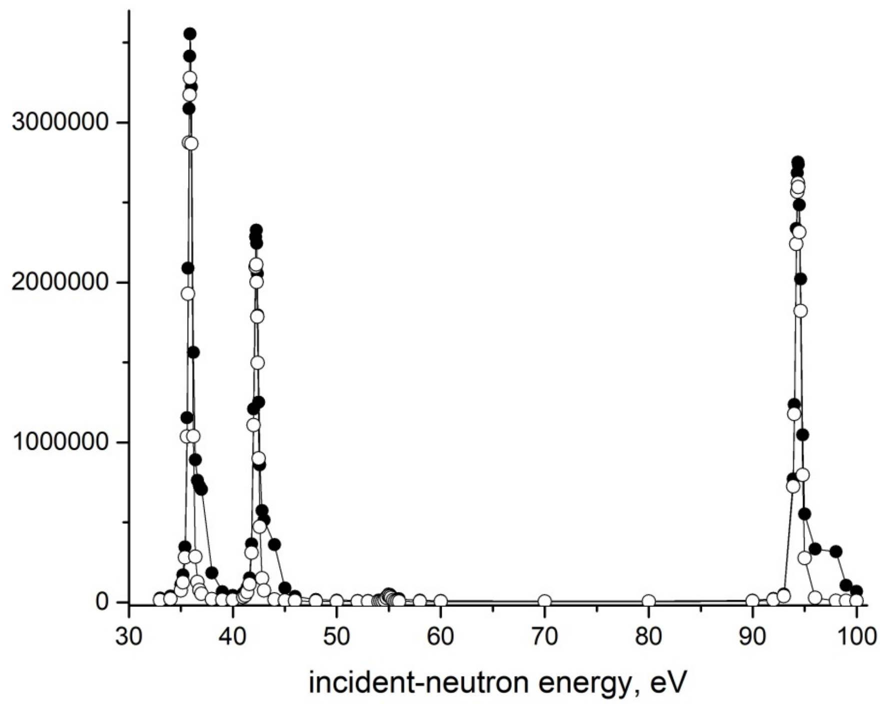

Fig.1b. Number of neutrons captured by ^{93}Nb target with 4×4 cm cross size and thicknesses of 0.6 cm: closed points – total capture of neutron, open points – neutrons captured without scattering in the targets.

In Fig.1a the calculated spectra of neutrons, which are captured in ^{93}Nb targets with thicknesses of 0.004 and 0.2 cm are shown in the incident-neutron energy interval near studied p-wave resonances (35.8, 42.3 and 94.3 eV) in logarithmic scale. And Fig.1b shows analogous spectrum at incident-neutron energies up to 100 eV for target thickness of 0.6 cm in linear scale. Total spectra of captured neutrons are presented by closed points and squares, and open points and squares denote neutrons captured without scattering in the targets. In both Figs.1 there is a noticeable asymmetry of the calculated peaks of total-captured neutrons. Contributions of neutrons captured in the targets after their scattering (in Figs.1a they are shown by dashed curves) are evident in the studied p-wave resonances as bumps from the side of incident-neutron energies bigger than resonance-maxima energies. The bumps appear due to growing in number of captured neutrons, as energy loss of scattered neutron reduces its energy to the maximum of resonance. In linear scale the resonance at the neutron energy of 55 eV, which exist in the data-base [2], is barely noticeable, and it is doubtful if it will be observed in the experiment.

Monte-Carlo calculations show that there is an advantage of captured unscattered and single-scattered neutrons in the targets of considered thicknesses. In spite of there is quite a number of single-scattered neutrons in 2 mm- thickness target, multiple scattering of neutrons is practically absent and can be neglected, but in 6 mm-target contribution of neutrons captured after multiple scattering is not negligible. The contributions of both single-scattered and multiple scattered neutrons to the total capture are considerable from the side of neutron energies more than resonances' maxima.

However, at the energies of maxima of considered p-wave resonances in the target with thickness of 2 mm a majority of incident neutrons pass without capture or scattering (81% at the 35.8 eV peak energy, 87% at 42.3 eV and 83% at 94,3 eV), in 6 mm-target there are more than a half of such neutrons (53%, 65% and 58%, correspondingly), and only (0.3–0.4)% of incident neutrons are captured or scattered in the 400 mcm-foil at the energy of resonances' maxima.

3. Evaluation of kinematic and geometrical asymmetry of γ-quanta recording

Gamma-quanta of radiative capture, emitted from the point of neutron capture in the target with finite sizes, were recorded by two forward and two backward detectors. The X-Z vertical view of geometry for Monte-Carlo calculations is presented in Fig.2. The detectors are placed at R=20 cm distance from the center of the target at the angles 45^{o}, 135^{o}, 225^{o} and 315^{o}. The sizes of the entry windows of all detectors were the same – 6.5 cm in width and 7.6 cm in height (Y axis-size), the targets were 4×4 cm plates with different thicknesses (Z axis-size).

In order to evaluate γ-quanta forward-backward asymmetry, caused by real geometry of the experiment (variations of solid angles of the windows of the detectors) and by energy losses of multiple-scattered before capture neutrons, calculations were made under an assumption of isotropic emission of only one γ-quantum in the point of neutron capture in the target. The ratio obtained the required asymmetry is calculated as in [1]:

$$\mathrm{eff}(E) = \frac{N_{1f}(E) + N_{2f}(E) - N_{1b}(E) - N_{2b}(E)}{N_{1f}(E) + N_{2f}(E) + N_{1b}(E) + N_{2b}(E)}, \qquad (1)$$

where $N_{1f}(E)$ and $N_{2f}(E)$ are numbers of γ-quanta recorded by forward detectors, $N_{1b}(E)$ and $N_{2b}(E)$ are numbers of gammas recorded by backward detector, correspondingly.

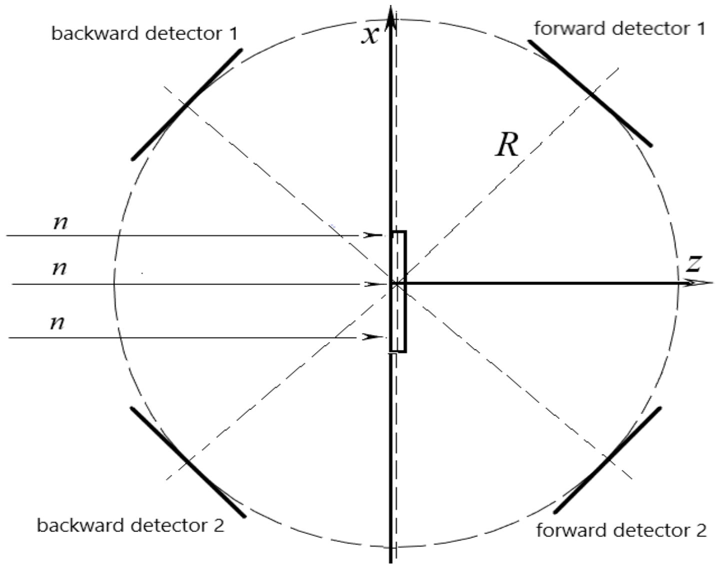

Fig.2. The X-Z plane view for Monte-Carlo calculations of gammas recorded by forward and backward detectors.

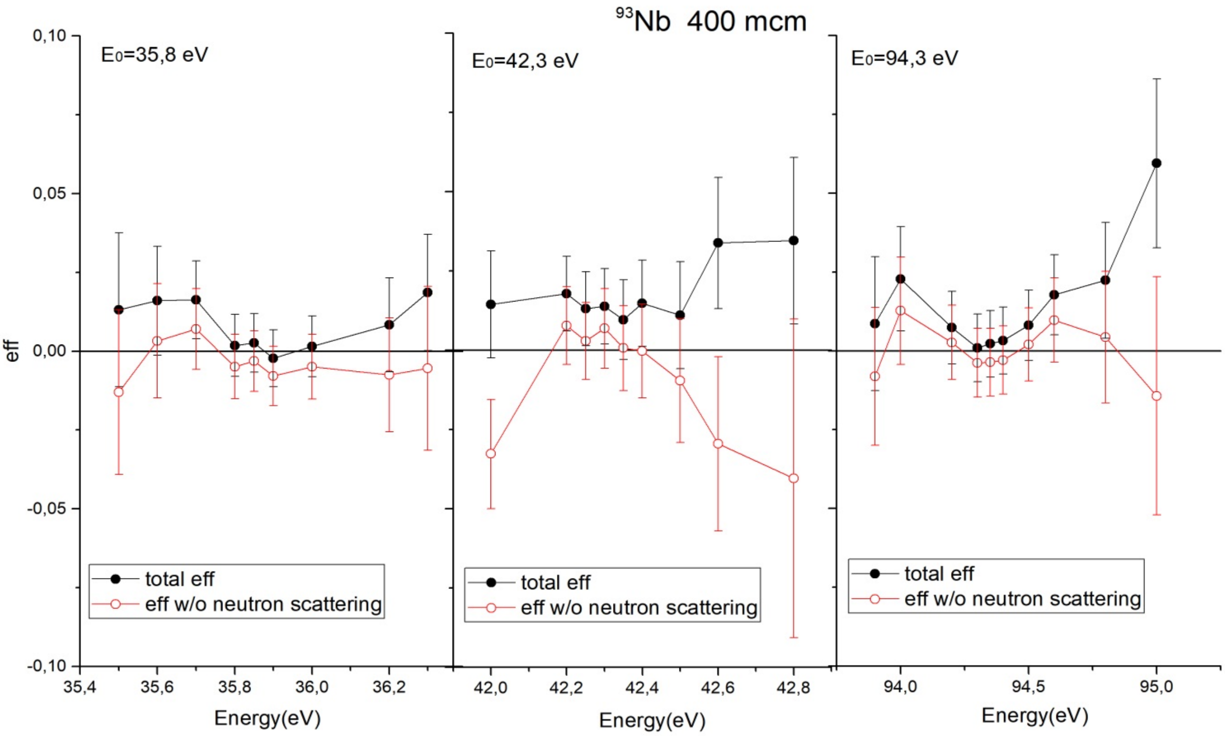

Fig.3a. Calculations of asymmetry, eff(E), of forward-backward γ-detection near p-wave resonances of ^{93}Nb at the neutron energies 35.8, 42.3 and 94.3 eV. The target is niobium foil

of 0.004 cm thicknesses and 4×4 cm cross size. Closed points – the total asymmetry effect (for γ-quanta emitted after total neutron capture), open points – for γ-quanta, which recorded if neutrons are captured without scattering in the target.

To obtain numbers of γ-quanta, which arrive at the windows of the forward and backward detectors, calculations have been made for 10^8 of incoming neutrons of given initial energy. The energy dependences of the ratios (1) of differences in γ-quanta numbers (the geometry and kinematics asymmetry effect, eff(E)) for the target thicknesses 400 mcm, 2 mm and 6 mm are shown in Figs. 3a, 3b and 3c, correspondingly. The total effect (calculated for gammas emitted after total neutron capture in the target) is shown by closed points, and open points show the effect for γ-quanta, which recorded if neutrons are captured without scattering in the target. The absolute uncertainties of foregoing ratio (1) were determined taking into account statistical errors of detectors counts [1]:

$$\Delta \mathrm{eff}(E) = \\ = \mathrm{eff}(E)\sqrt{\frac{1}{N_{1f}(E)+N_{2f}(E)+N_{1b}(E)+N_{2b}(E)}+\frac{N_{1f}(E)+N_{2f}(E)+N_{1b}(E)+N_{2b}(E)}{\left(N_{1f}(E)+N_{2f}(E)-N_{1b}(E)-N_{2b}(E)\right)^2}}.$$

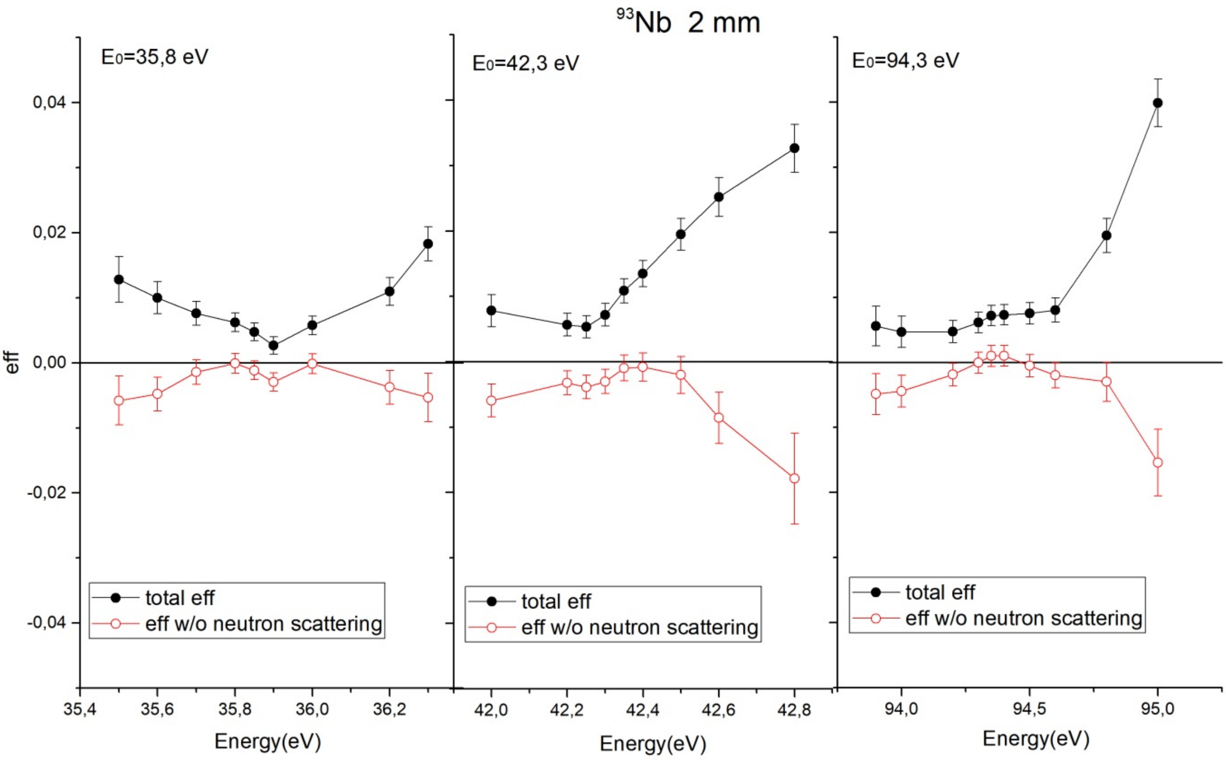

Fig.3b. Calculations of asymmetry of forward-backward γ-detection near p-wave resonances of ^{93}Nb at the neutron energies below 100 eV. The target is niobium plate of 0.2 cm thicknesses and 4×4 cm cross size. Closed points – the total asymmetry effect (for γ-quanta

emitted after total neutron capture), open points – for γ-quanta, which recorded if neutrons are captured without scattering in the target.

The part of neutrons, which are scattered in the target and leave it without capture, was also evaluated. Calculations of numbers of lost neutrons, as well as of γ-quanta, which leave the target but not hit the detectors windows, are presented in Fig.4 for thicknesses of 2 and 6 mm (at statistics of 10^7 events for each point of incident-neutron energy). Fig.4 shows that there is a great deal of scattered neutrons, which go out of the target without capture (the number of lost neutrons with initial energies between the resonances is more than 99% of all scattered neutrons), and number of unrecorded gammas is greatly more than ones recorded by the detectors.

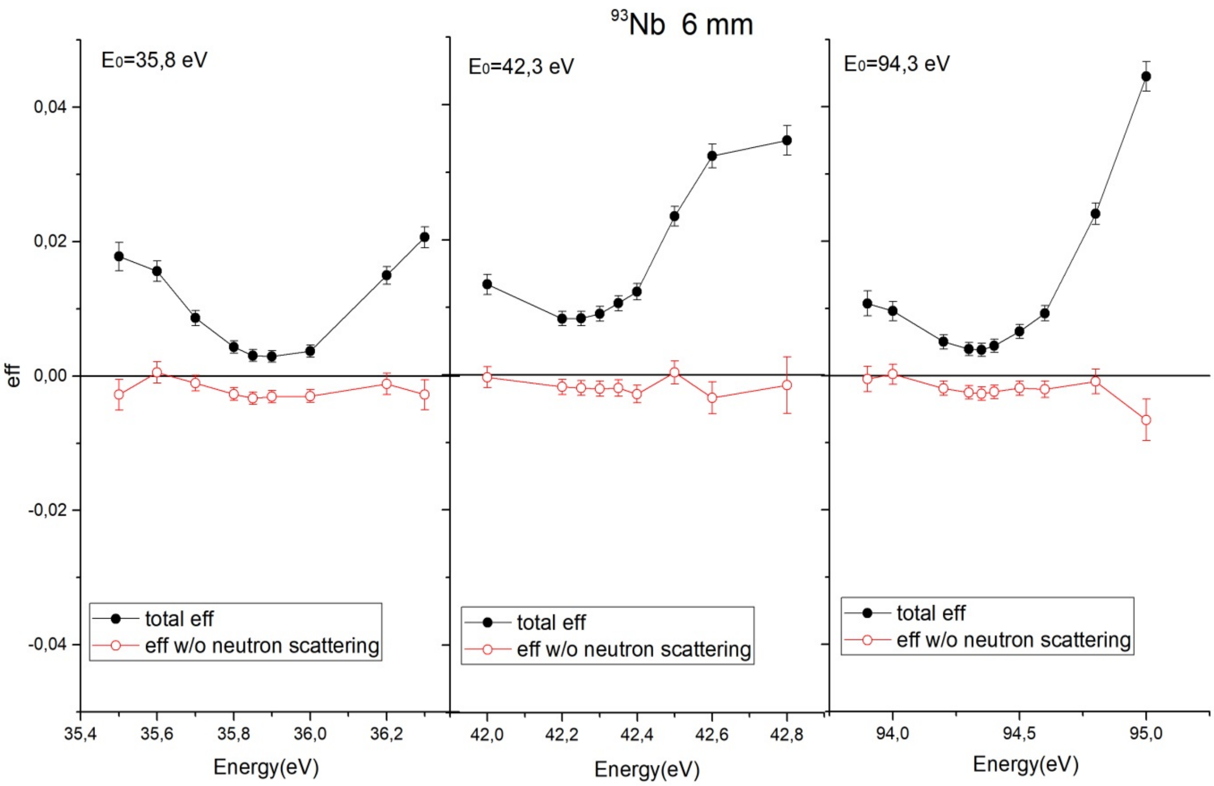

Fig.3c. Calculations of asymmetry of forward-backward γ-detection near p-wave resonances of ^{93}Nb below 100 eV. The target is niobium plate of 0.6 cm thicknesses and 4×4 cm cross size. Closed points – the total asymmetry effect (for γ-quanta emitted after total neutron capture), open points – for γ-quanta, which recorded if neutrons are captured without scattering in the target.

4. Conclusion

As it was made clear from the Monte-Carlo calculations, the statistically significant forward-backward γ-detection asymmetry cannot be obtained with 400 mcm ^{93}Nb target, in the target with thickness of 2 mm multiple scattering of captured neutrons is practically absent, and even for 6 mm-target a part of multiple-scattered neutrons in total capture is small in comparison with contribution of single-scattered neutrons (~3–4 %). As Figs. 1a and 1b show, the peaks of investigated resonances of ^{93}Nb nucleus from the side of smaller (relative to the maxima) neutron energies are practically not distorted by contributions of capture of neutrons witch are scattered in the targets.

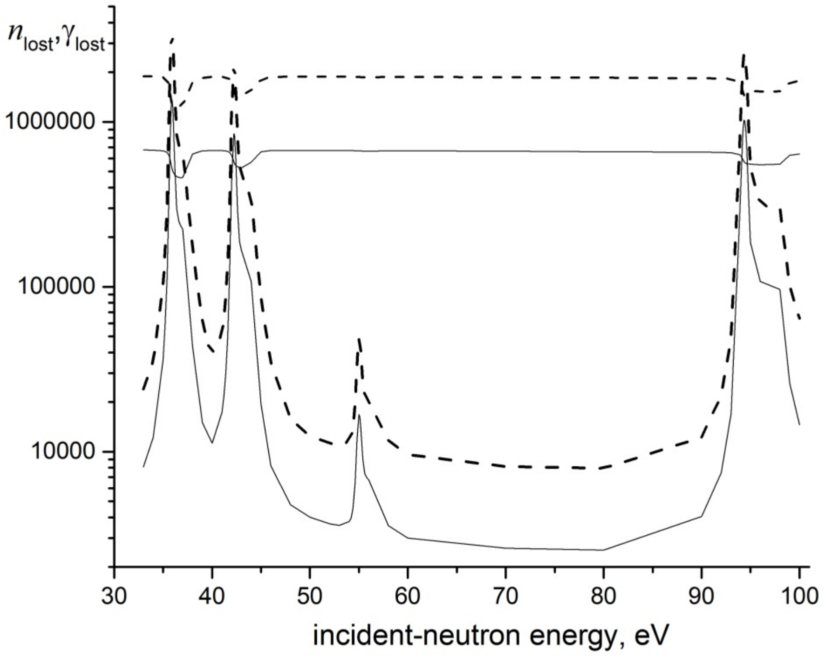

Fig.4. Numbers of lost neutrons, which are scattered and leave the target without capture (lines with dips at the resonance energies), and lost gammas unrecorded by detectors (curves with peaks at the resonance energies) for ^{93}Nb-targets (ordinate axis) relative to 10^7 of incident neutrons in each point of neutron energy (abscissa axis): solid curves– calculations for target thickness of 2 mm, dashed curves– for target thickness of 6 mm.

Thus, Monte-Carlo calculations under condition of isotropic γ-emission from ^{93}Nb(n,γ) reaction show that

1) the considered ^{93}Nb-target thicknesses are not quite thick in order that a major portion of incident neutrons were not pass through them without capture or scattering, even at the maxima energies of the investigated resonances;
2) there is an advantage of captured unscattered and single-scattered neutrons in the targets of considered thicknesses;
3) in the energy regions near low-energy p-wave resonances under study, a “mistaken” forward-backward asymmetry of γ-quanta detection caused by kinematics and geometry is less than 5% for all given target thicknesses.

References

1. Kuznetsov V.L., Mitsyna L.V., Rebrova N.V., Sedyshev P.V., *Evaluation of a Mistaken Asymmetry in the Projected Experimental Search of Spatial Anisotropy of Gammas*

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2. JAEA Nuclear Data Center JENDL-5, https://wwwndc.jaea.go.jp/jendl/j5/j5.html