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MEASUREMENT OF THE ENERGY DEPENDENCE OF THE NEUTRON COUNTER SENSITIVITY AT NEUTRON BEAMS OF THE ELECTROSTATIC GENERATOR

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Крылов А. Р. и др. E13-2004-20

Измерение энергетической зависимости чувствительности
нейтронных счетчиков на пучках нейтронов
электростатического генератора

Описываются измерения чувствительности нейтронных ^{3}He-счетчиков внутри полиэтиленовых замедлителей на пучках нейтронов электростатического генератора в диапазоне энергий 0,2–1,0 МэВ. Для получения моноэнергетических нейтронов использовалась реакция $p + {}^7\mathrm{Li} = n + {}^7\mathrm{Be}$. Для спектрометрии нейтронов и измерения их потока применялся образцовый ^{3}He-счетчик высокого давления. В работе изложены методики измерений и обработки экспериментальных данных. Получено хорошее согласие между результатами измерений и расчетами.

Описанная методика измерений была применена для градуировки детектора нейтронов высоких энергий (HEND) — отечественного прибора, установленного на борту американского космического аппарата «Марс–Одиссей-2001».

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Препринт Объединенного института ядерных исследований. Дубна, 2004

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Measurement of the Energy Dependence of the Neutron Counter
Sensitivity at Neutron Beams of the Electrostatic Generator

The sensitivity of the neutron ^{3}He counter within the polyethylene moderator was tested in the energy range 0.2–1.0 MeV with the neutron beam of electrostatic generator. For the monoenergetic neutron production the reaction $p + {}^7\mathrm{Li} = n + {}^7\mathrm{Be}$ was used. The high-pressure ^{3}He-filled reference counter was applied to the neutron beam spectrometry and to the neutron flux measuring. The technique of the experiment and the data processing are described. A good agreement between the experimental and calculated results is shown.

Monoenergetic neutrons were used for calibration of the High Energies Neutron Detector (HEND) — one from the set of scientific instruments, installed on board of Mars Odyssey 2001 spacecraft.

The insvestigation has been performed at the Frank Laboratory of Neutron Physics and at the Division of Radiation and Radiobiological Research, JINR.

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INTRODUCTION

It is planned to study Mars surface composition during the NASA Mars Odyssey 2001 orbital mission. The research on Martian chemical composition, especially including the search for water (the NASA strategy «Follow the Water»), is a key item of Mars exploration. Scientific equipment complex consists of Gamma-ray Spectrometer, Neutron Spectrometer (NS) with thermal neutron detector and High Energies Neutron Detector (HEND), created in the Institute for Space Research of RAS (Russia) with participation of the specialists from the Joint Institute for Nuclear Research. The set of various neutron detectors for detection of the albedo neutrons from cosmic rays interacting with the planet surface is placed on the orbiter board for the search of the Martian water-ice locations [1, 2]. HEND includes three neutron detectors on the basis of the proportional ^{3}He filled counters and the stilbene spectrometer. The ^{3}He counters with different combinations of the polyethylene moderator and the cadmium absorber are used for detection of neutrons in the energy ranges 0.4–10.0 eV, 10.0 eV–5.0 keV, and 5.0 keV–3.0 MeV. The stilbene single crystal spectrometer with CsI anticoincidence active shielding is intended for detection of fast neutrons at energies 1.0–10.0 MeV. The experimental testing of the detector sensitivity was carried out at the JINR electrostatic generator.

1. NEUTRON SOURCE

For the monoenergetic neutron production the reaction $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ with the threshold of 1881 keV was used. The detailed review of this reaction was made in [3] and neutron energies, yields, and angular distributions were calculated with laboratory differential cross sections compiled in [4]. The method of calculations offered in [5] was used in the present paper to calculate neutron yields.

Four proton energies were applied at the detector sensitivity testing: 2.000, 2.240, 2.600, and 2.707 MeV. It corresponds to neutron energies at 0°: 229.7, 506.8, 891.1 and 1030.0 keV. The neutron yield averaged within a 0.214 sr $(\pm 15^\circ)$ solid angle is given in Fig. 1. The angular dependence of the neutron energy from $^7\mathrm{Li}(p,n)^7\mathrm{Be}$ reaction at different proton energies is shown in Fig. 2. At proton energies lower than 1.921 MeV there are two branches of neutrons emitting in forward direction, so in our experiments the lowest proton energy was 2.00 MeV. Corresponding neutron energy at 0° is equal to 0.230 MeV. Starting from the proton energy 2.373 MeV $^7\mathrm{Li}(p,n\gamma)^7\mathrm{Be}^*$ reaction comes into play, but even at the highest proton energy used in our experiments — 2.707 MeV, it gives admixture of 4% of neutrons with an energy of 0.5 MeV to the main branch with an energy of 1.003 MeV. Taking into account the energy dependence of counter sensitivity, the contribution of low-energy neutrons to the detector counts could be estimated at the level less than 6%.

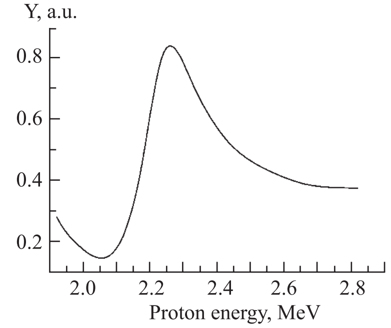

Fig. 1. Neutron yield from a thin ^{7}Li target in ^{7}Li$(p,n)^7$Be reaction at 0° averaged over a 0.214 sr solid angle

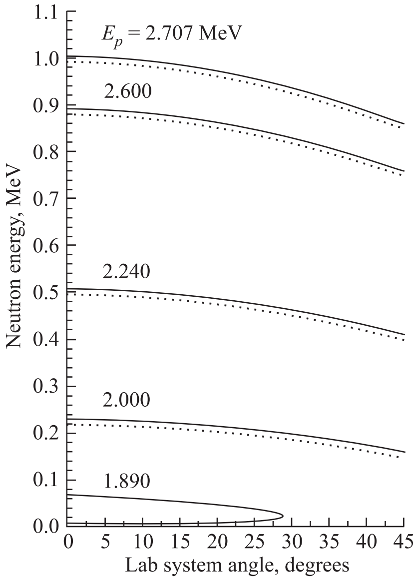

Fig. 2. Angular dependence of the neutrons emitted from a thin ^{7}Li target in the reaction ^{7}Li$(p,n)^7$Be; solid lines are for protons with energies indicated in the figure, dash-dotted lines are for protons passing through ^{7}Li target of 10 keV in thickness

The neutron-producing target was made by the natural lithium evaporation on the copper backing plate. The proton energy was stabilized with an accuracy of 0.1%. The target thickness changed from 5 to 10 keV during the experimental run. The exact thickness of the target was defined before and after the experimental run by means of measuring the neutron yield — proton energy dependencies near the threshold (Fig. 3). The change of the curves is evidence of the target

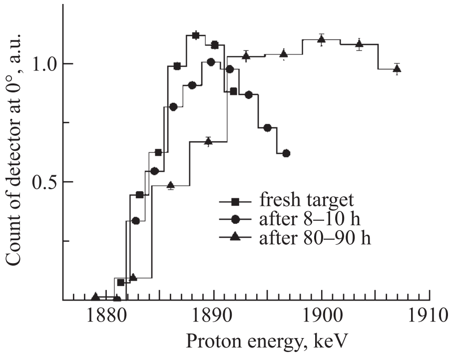

Fig. 3. Neutron detector counts vs. proton energy near the threshold of ${}^{7}\mathrm{Li}(p,n){}^{7}\mathrm{Be}$ reaction. Target thickness is determined as FWHM of the corresponding curve

variable characteristics during the run. To understand the influence of the ^{7}Li target thickness on neutron yield one needs to look at the neutron yield vs. proton energy dependence (Fig. 1). The highest variation of neutron yield takes place in the proton energy range 2.1–2.3 MeV, i.e., for proton energy 2.240 MeV in our case. The estimation at this proton energy and at the target thickness change from 5 to 10 keV gives a 0.88% decrease of the neutron yield to the end of the experimental run. For other proton energies the neutron yield variations owing to this effect are smaller. The angular range that HEND overlaps at testing (±15° maximum) and the target thickness variation during the run bring the neutron energy deviation. The maximum deviation can be estimated from Fig. 2, where the same curves shifted by 10 keV of proton energy are presented as well (by the short-dashed lines).

2. CALIBRATION

The experimental testing of the HEND sensitivity was fulfilled at the JINR electrostatic generator EG-5. The layout of the accelerator experimental hall arrangement is shown in Fig. 4. To measure the neutron flux from lithium target the SNM-16 ^{3}He-filled counter with polyethylene moderator was used (Fig. 5). Its energy response calculated by MCNP4B code at lateral irradiation is presented in Fig. 6. The comparison of the calculated counter sensitivity to the ^{252}Cf neutrons with the experimental result shows a very close agreement. In view of the counter designation it is called hereinafter as test counter (TC).

The other high-pressure ^{3}He-filled reference counter (RS-P4-0810-204) was applied to the neutron beam spectrometry and the neutron flux measuring. The precise determination of the ^{3}He content within the reference counter (RC) was

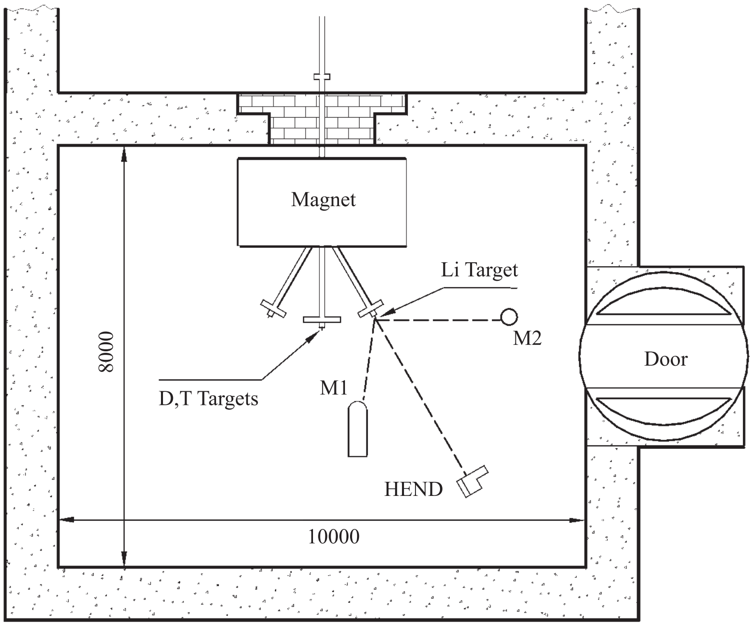

Fig. 4. EG-5 experimental hall plan view. Headroom is 5.5 m. Target height is 1.6 m over the floor

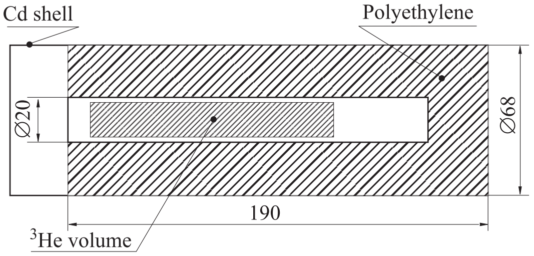

Fig. 5. Schematic desing of the TC based on SNM-16. Sensitive volume lenght is 110 mm, diameter is 17.4 mm. Cd shell thickness is 0.5 mm

preliminary done at the IBR-2 diffraction scattering neutron beam with an energy of 0.06 eV. The pressure of ^{3}He was found to be equal to 10 atm corresponding to the ratings, given by manufacturer. The density of ^{3}He at 20°C and 10 technical atm is equal to $1.2079 \cdot 10^{-3}$ g·cm^{-3}. The sensitive volume of the RC is 25.4 cm in length and 2.54 cm in diameter; the stainless steel wall thickness is 0.04 cm. The optimal voltage bias was 1250 V. The ORTEC base amplifier with 3 μs time constant was used for signal amplification. After that signal was sent to the multichannel pulse height analyzer. The condition for the counter irradiation was

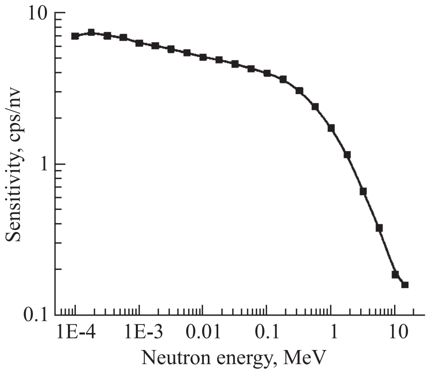

Fig. 6. The TC response function (points is calculation, curve is spline fit)

such that its counting rate did not exceed 500 imp$\cdot$s^{-1}.

The apparatus pulse-height spectrum of the ^{3}He gaseous proportional counter irradiated with the monoenergetic neutrons has the peak corresponding to the sum of the energies of the $n + {}^3\mathrm{He} \to p + {}^3\mathrm{H} + 0.764$ MeV capture reaction products. The neutron spectrometry with ^{3}He counter is based on this peak shift measurement at various neutron energies. The energy calibration of the analyzer scale must be done for these measurements. Furthermore, the neutron energy dispersion results in widening of the peak in comparison with the resolution of the thermal neutron peak. It gives the possibility to estimate the energy dispersion of the neutrons from the target. Owing to the peak asymmetry the closest estimation is realized by the examination of the right slopes of the peaks.

The RC was placed upright at a 0.5 m distance from the target under 0° to the proton beam direction. The neutrons repeatedly scattered in the experimental hall contributed significantly to the counter readings because of their closely-thermal energies and the high cross-section value of the $^3\mathrm{He}(n,p)^3\mathrm{H}$ capture reaction in this energy region. The reference counter was entirely covered with cadmium shell in order to suppress this effect. The perfect response function of the counter can be found with the thermal neutrons. In this case the peak resolution and its position are defined by the proper characteristics of the counter and electronics only. In our experiment this condition was imitated by the disposal of the thick block of polyethylene between the counter and the target. The neutron beam energy was about 200 keV. The apparatus spectrum of the RC is shown in Fig. 7. With the right half-width of the peak at the half-height (RHWHH) it was found that σ_{th} = 2.966 channels at an energy of 764 keV. This value was used as the proper resolution of the counter. The closely-thermal peak position and the ^{3}H edge effect border (191 keV) allowed the energy calibration of the analyzer scale.

Two monitors were used in the experiment: the monitor of the proton beam

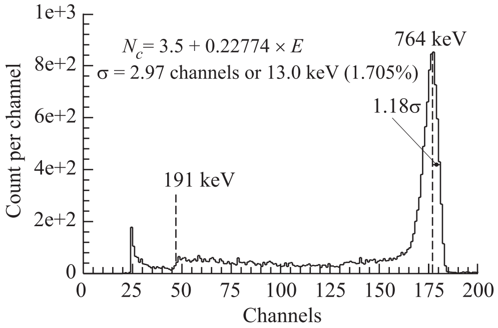

Fig. 7. The apparatus spectrum of the RC from closely-thermal neutrons

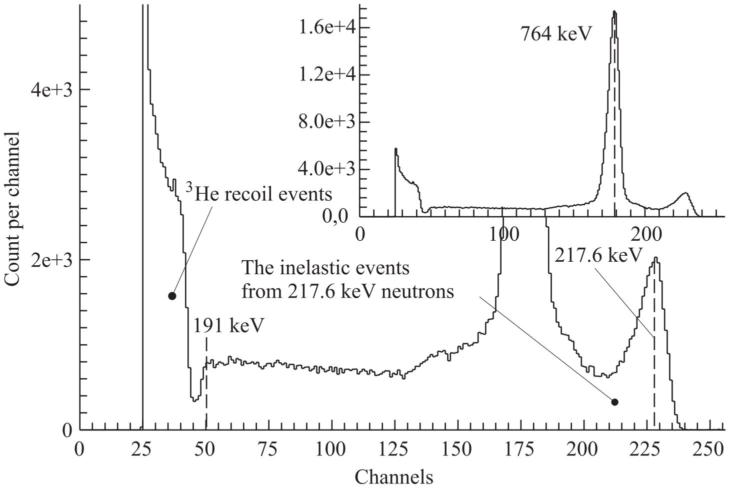

Fig. 8. The apparatus spectrum of the RC from the 217.6 keV neutrons

intensity and the monitor of the neutron yield from the target. The apparatus spectra of the RC at different neutron energies are presented in Figs. 8–11. There are two peaks in the graphs: the big peaks from the background epicadmium neutrons and on the right of them the small peaks from the beam neutrons. The small-peak maximum correlated with the value of $E + 764$ keV (E is the average energy of the beam neutrons) and E can be defined with the calibration line. The contribution of the elastic scattering process to the apparatus spectrum forming grows quickly with the increase of the neutron energy. The upper border of the elastic part of the spectrum (corresponding to $0.75E$ — neutron elastic scattering on ^{3}He) can be one more calibration point.

It was assumed as a rough approach that the energy dispersion of the beam

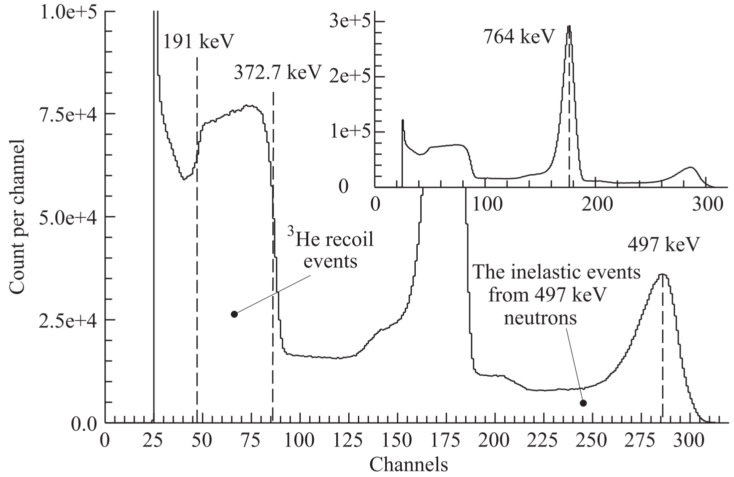

Fig. 9. The apparatus spectrum of the RC from 497 keV neutrons

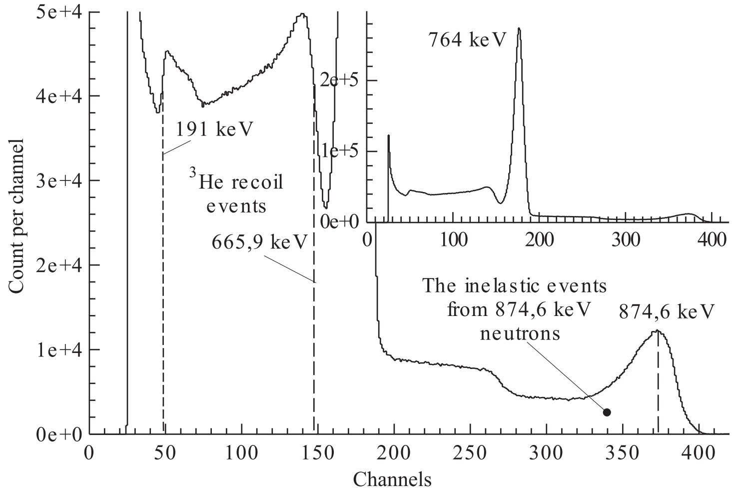

Fig. 10. The apparatus spectrum of the RC from 874.6 keV neutrons

neutrons corresponds to the normal distribution. The energy resolution of the beam neutron δ_E can be estimated in this case from $\delta_E^2\left(E\right) = \delta_\Sigma^2\left(E\right) - \delta_{\mathrm{RC}}^2\left(E\right)$, where δ_Σ is the resolution of the beam neutron peak (measured on the right slope), $\delta_{\mathrm{RC}}\left(E\right)$ is the dispersion of the peculiar counter response function at energy E. If consider $\delta_{\mathrm{RC}}^0 = \delta_{\mathrm{RC}}\left(0\right)$ — dispersion of the response function measured with thermal neutrons — and assume as the first approximation that $\delta_{\mathrm{RC}}\left(E\right) \propto E^{-0.5}$,

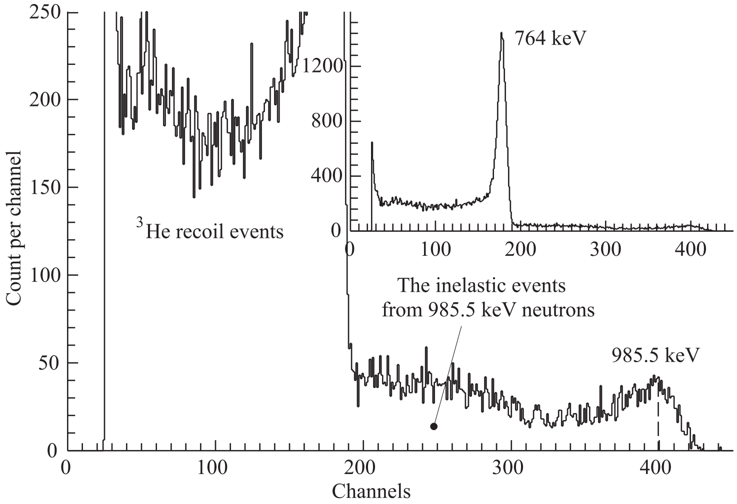

Fig. 11. The apparatus spectrum of the RC from 985.5 keV neutrons

then

$$\delta_{\mathrm{RC}}\left(E\right)=\delta_{\mathrm{RC}}^{0}\left(\frac{764+E}{764}\right)^{0.5},\quad [E]=\mathrm{keV}.$$

The conditions of the experiment and the main characteristics of the obtained neutron beams are give in Table 1.

Table 1. **The main characteristics of the neutron beams obtained with the RC.**

Exposure number	1	2	3	4
Proton energy, keV	2000	2240	2600	2707
E, keV (experiment)	229.8	489.7	868.0	973.4
E, keV (calculation)	229.5	482.6	862.2	975.0
σ_Σ, (channels)	4.24	7.54	11.38	13.36
σ'_{th} (channels)	3.37	3.80	4.33	4.47
σ_E (channels)	2.57	6.52	10.52	12.59
$\Delta E = 2.36\sigma_\Sigma/E$, %	2.72	5.47	6.77	7.54
ΔE, keV	6.24	26.79	58.76	73.41

The apparatus spectra of the RC allow estimating the average neutron flux F_{RC} during the exposure. It is possible to resolve three partial spectra in every apparatus spectrum:

1. The spectrum of events from the residual background neutrons with the peak close to 764 keV and the flat remainder down to 191 keV (energy of the residual ^{3}H in $^3\mathrm{He}(n,p)^3\mathrm{H}$ capture reaction);

2. The spectrum of events from the beam neutrons with the peak close to E + 764 keV and the flat remainder with the lower border depending on E (products of $^3\mathrm{He}(n,p)^3\mathrm{H}$ capture reaction);

3. The spectrum of events from the beam neutrons similar to rectangle with the upper border close to 0.75E (recoil nucleus from elastic n–^{3}He scattering).

The cross-sections of the $^3\mathrm{He}(n,p)^3\mathrm{H}$ capture reaction for 229.8, 489.7, 868.0, and 973.4 keV neutron energies are equal to 1219, 960.4, 825.4, and 834.5 mb according to ENDF60. The numbers of captured neutrons within the RC volume are $5.58{\cdot}10^{-4}$, $4.51{\cdot}10^{-4}$, $4.056{\cdot}10^{-4}$, and $3.987{\cdot}10^{-4}$ events per neutron for E = 229.8, 489.7, 868.0, and 973.4 keV. Hence, the number of events from the $^3\mathrm{He}(n,p)^3\mathrm{H}$ reaction in the apparatus spectra gives us estimation of the average neutron flux per monitor count. Both proton and triton can have the minimal energy losses (down to zero) owing to the edge effect at the neutron energies more than several hundreds of keV. The lower bounding channel corresponds to minimum value from

$$E_p\ (\mathrm{keV}) = 573 + 0.25E \pm 0.8664(764E)^{0.5},$$

$$E_T(\mathrm{keV}) = 191 + 0.75E \pm 0.8664(764E)^{0.5}.$$

These restrictions were taken into account at the calculations of the remainders. The monitor counts during the RC exposure were adjusted to the «living» time (t_{liv}) of the analyzer.

The numbers of the elastic events in the spectra were calculated for 489.7 and 868.0 keV only. The cross-sections of the elastic reaction for 489.7 and 868.0 keV are 1 901 and 1 926 mb and $8.96{\cdot}10^{-4}$ and $9.35{\cdot}10^{-4}$ events per neutron occur within the RC. It was assumed that all these events are spaced uniformly from zero-channel up to channel corresponding to 0.75E for the calculation of their amount. The neutron fluxes obtained with the inelastic and elastic events were similar and for 489.7 and 868.0 keV the average values were taken as the results.

To check the validity of the MCNP4B calculations for monoenergetic neutrons the measurements of the TC sensitivity were taken using the data of the RC. The measurements with the TC were carried out at three distances 0.5, 1.0, and 1.5 m for every neutron energy. The counter readings were fitted by the dependence $N/N_m = a + b/r^2$, for their correction for the background contribution. Here N and N_m are the counts of the counter and monitor (or the integrator) correspondingly, a and b are fitting coefficients. The $N'/N_m = b/r^2$ were taken as the true values of the TC readings. The average neutron fluxes (F_{TC}) through the TC during its exposures were determined with the help of F_{RC} and the monitor count ratios. The TC sensitivities (ε, imp·cm^2) were found as N'/F_{TC}. The ε accuracy is within $\pm 10\%$ limits. The results of the TC reading correction, the F_{RC} and F_{TC} calculations (both at a distance of 0.5 m), and ε measurements are presented in Table 2 and in Fig. 6. Thus, the TC was used with decision as the gauge detector during the HAND testing.

The authors are grateful to Bamblevski V. P. for the useful discussion.

Table 2. **The parameters of the TC irradiation**

Neutron energy, keV	229.8	489.7	868.0	973.4
A	4.2±0.4	4.0±0.3	3.5±0.3	3.2±0.2
b, m^2	23.5±0.5	18.3±0.4	15.0±0.3	14.4±0.3
N_m during the RC exposure, imp.	2179	2828	3303	2436
N, imp.	213102	216480	212047	146519
N', imp.	204826	207010	198180	140314
t_{liv}, s	3592	42000	51000	600
F_{RC}, cm^{-2}	$2.12 \cdot 10^6$	$7.51 \cdot 10^6$	$8.08 \cdot 10^6$	$3.96 \cdot 10^6$
N_m during the RC exposure, imp.	$7.36 \cdot 10^4$	$2.83 \cdot 10^6$	$2.68 \cdot 10^6$	$1.18 \cdot 10^4$
F_{TC}, cm^{-2}	$6.28 \cdot 10^4$	$7.50 \cdot 10^4$	$9.95 \cdot 10^4$	$8.21 \cdot 10^4$
ε (experiment), cm^2	3.26	2.76	1.99	1.71
ε (calculation), cm^2	3.41±0.49%	2.54±0.53%	1.92±0.56%	1.77±0.58%

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