CHARACTERIZATION OF THE HEND STILBENE SPECTROMETER

[3]Martinkovic J., [2]Kozyrev A., [2]Litvak M., [2]Mitrofanov I., [1]Timoshenko G., [*1]Shvetsov V.

[1]Joint Institute for Nuclear Research, 141980, Dubna, Moscow region, Russia.
[2]Institute for Space Research of RAS, Moscow, Russia.
[3]Comenius University, Bratislava, Slovak Republic

Abstract

The HEND (High Energy Neutron Detector) is the Russian instrument intended for search of planetary water that is mounted on the board of the "2001 Mars Odyssey" spacecraft. HEND is a set of four neutron counters for detection of epithermal, resonance and fast neutrons. The neutron spectrometer on the basis of stilbene detector is used for the detection of neutrons with energies above 0.5 MeV. The detector is surrounded by veto counter from CsI(Tl) for charged particles rejection. The characterization of the stilbene spectrometer with the gamma-ray and neutron sources is described. The neutrons of ^{252}Cf and from ^{7}Li(p, n)^{7}Be reaction were used for the characterization and verification of the sensitivity calculation. The influence of the veto counter on the spectrometer sensitivity was determined as well.

Introduction

The High Energy Neutron Detector (HEND) was developed in the Space Research Institute (Moscow, Russia) with the assistance of Joint Institute for Nuclear Research (Dubna, Russia). Mounting of HEND on the spacecraft "2001 Mars Odyssey" has been performed in accordance with Implementation Agreement between Rosaviakosmos and NASA.

Three types of scientific equipments were placed on the spacecraft board for study of element distribution at the Martian surface and search for water: GRS (HPG Gamma-Ray Spectrometer, USA), NS (Neutron Spectrometer, USA) and HEND.

The main goal of the GRS is constructing the global map of gamma radiation of the Mars' surface. Nuclear gamma-lines of primary elements of planetary matter are emitted as results of inelastic collisions and capture of secondary neutrons produced by cosmic rays. The water is the most widespread substance contained the hydrogen. The presence of powerful hydrogen gamma-line (2.225 MeV) in gammas spectrum can be the evidence of the water existence under the spacecraft.

The NS and HEND are intended for scanning of albedo neutrons from the Mars' surface in a wide energy range from thermal energy up to tens of MeV. The relation between thermal neutrons and neutrons with energies above ~ 0.1 eV depends significantly on the content of light nuclei (hydrogen nuclei first of all) in the subsurface layer of the Mars [1]. Hence, the increasing of the thermal/fast neutron fluxes ratio allows assuming the presence of water ice or permafrost in some area of the surface under the spacecraft. NS is developed for detection of thermal and epithermal neutrons. HEND is designed for detection of epithermal, intermediate and fast neutrons and is the assembly of four instruments. HAND has three ^{3}He-filled proportional counters with different moderators of polyethylene and cadmium cans:

1. Small detector (SD) that is the most sensitive for the neutrons at the energy range 0.4 eV – 10 eV;
2. Medium detector (MD) that is the most sensitive for the neutrons at the energy range 10 eV – 1 keV;
3. Large detector (LD) that is the most sensitive for the neutrons at the energy range 10 keV – 1 MeV.

Fourth instrument is the neutron stilbene spectrometer with two scintillators. The stilbene crystal has 32 mm in diameter and 40 mm in height. The crystal is coupled with Hamamatsu PMT R1924. The veto-counter on the base of CsI(Tl) scintillator with Hamamatsu PMT R1840 surrounding the stilbene crystal is used for anti-coincidence rejection of the outer charged particles. The special electronic circuit is applied for the recoil protons and gamma rays signals separation ob the basis of signal shape. The concept design of the stilbene spectrometer is shown in Fig. 1.

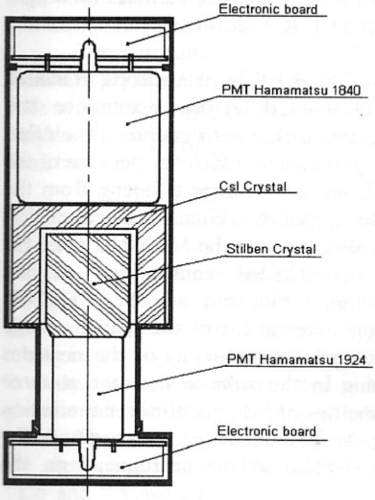

Fig. 1. The concept design of the HEND stilbene spectrometer

The non-linear scale of the spectrometer's analyzer has 16 channels only. The channel widths vary approximately exponentially depending on the channel number. The lover border of the first channel is determined the threshold of the signal registration. The three practically identical patterns of the HEND were produced: KDI (control and diagnostic unit) and FU-1 (flight unit) for the testing and FU-2 for the flight. The testing of every pattern HEND's sensors were done by the ^{252}Cf reference neutron source and by the neutron beams of the JINR electrostatic generator EG-5. The preliminary characterization of the neutron beams is described in [2]. The results of the experimental checking of the SD, MD and LD sensitivities at the neutron beams are given in [3].

Calculation of the spectrometer efficiency

The calculation of the neutron detection efficiency by the stilbene detector was carried out with the SCINFUL-R code [4]. This is the most precise code now for calculation of the carbon-contained detector efficiency up to neutron energy 80 MeV and takes into account 38 many-particle reactions n + ^{12}C. The code calculates the transport of neutrons and gammas in the detector and its response functions (apparatus spectra). The apparatus spectrum of the stilbene detector is determined by the non-linear energy dependences of light outputs of all secondary charged particles. There is a lack of the reliable experimental data about the light outputs of charged particles in stilbene contrary to the NE-213 detector. The light outputs were measured for protons only [5, 6] in the energy range to 15 MeV. The description of the experimental data by the well-known Birks relationship between the light output and the energy loss of ionizing particle in a small element of the

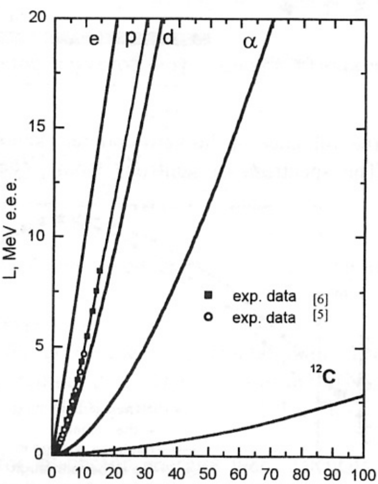

Fig. 2. The calculated and measured response-energy functions of stilbene scintillator

track was applied in [6] and the necessary coefficients in the Birks formula for the protons were fitted. It allows to find the dL/dx = f(dE/dx) dependences for other charged particles in stilbene. The comparison between calculated and measured responses of stilbene for electrons, protons, deuterons, alphas and carbon ions is presented in Fig. 2.

The detector signal from the particles is proportional to the integral of dL/dx on the track length (total light output). It was find out that the goodness of the experimental data fit is strongly depends on the accuracy of the dE/dx at low energies. At integration the data from TRIM code [7] were used. The matrix of obtained data on the secondary particles total light outputs vs. their energies was applied then in the SCINFUL-R code for calculation of the apparatus spectra from neutrons.

The presence of the thick CsI(Tl) scintillator disturbs the field of neutrons irradiated the stilbene. The results of neutron interactions with the CsI(Tl) are quantitative and qualitative changes of the neutron fluence within the cavity of the veto counter. The other effect of veto counter presence is the decreasing of the spectrometer efficiency because of the detection by the CsI(Tl) some secondary protons, neutrons and gammas escaping from the stilbene. These events are not registered owing to the anticoincidence circuit. The calculation of these effects influence to the spectrometer efficiency was done by the MCNP4C code [8] for the detailed construction of the detectors. With aid of the PTRACK option were calculated the spatial, energy and angular distributions of the neutrons coming in the stilbene detector at three geometries of the spectrometer irradiation (Fig. 3). The geometry 1 corresponds the real position of the instruments on the Martian orbit. The calculation shown that the influence of the veto counter cannot be ignored even for small energies of initial neutrons. The spectrum of neutrons from ^{252}Cf source coming in the butt-end of "bare" stilbene detector (geometry 1, distance between the source and the detector – 1.5 m) and the calculated total spectrum of the neutrons coming in the stilbene detector with the CsI(Tl) at the same position are demonstrated in Fig. 4 for example. It is obviously, that the main distinction between the spectra is observed at low neutron

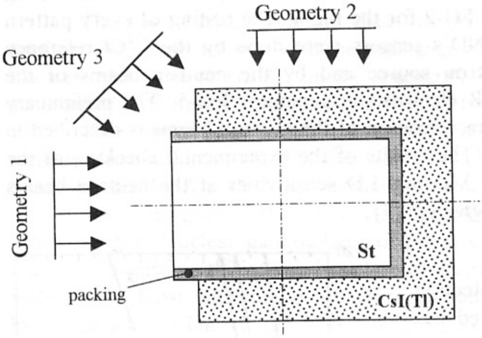

Fig. 3. The geometries of th spectrometer irradiation which were use for the calculation of the spectromete efficiency

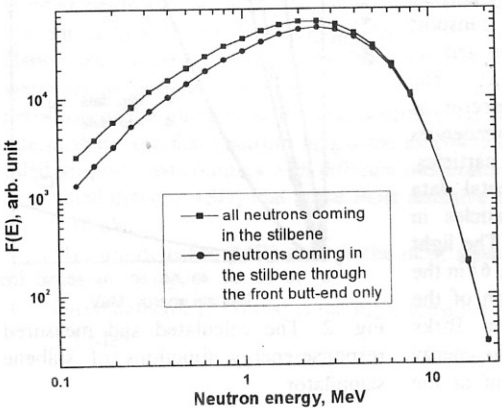

Fig. 4. The comparison of the ^{252}Cf neutrons spectrum for geometry 1, and the calculated spectrum of all neutrons coming in the stilbene detector with the CsI(Tl)

energy. In this case the CsI(Tl) is the source of the additional neutrons and the contribution of these neutrons is 22.3%. This contribution varies from 28 % at neutron energy 0.5 MeV to 20 % at energy 15.5 MeV.

In the case of geometry 3 the veto scintillator recovers practically the stilbene detector and the flux of the initial neutrons coming in the stilbene is lower than at the "bare" stilbene case. On the other hand the CsI(Tl) gives birth the neutrons with smaller energy as compared with initial neutrons. The number of absorbed in CsI(Tl) initial neutrons and the number of the additional neutrons with smaller energies are approximately equal in the geometry 3, but the portion of the neutrons with the smaller energies to averages about 20 %. The geometry 2 is the intermediate case.

The surroundings of the stilbene spectrometer also disturb the neutron field. It was shown in [3] that the influence of SD and MD moderators on the sensitivity of LD counter is little at neutron energies above some MeV. As for the stilbene spectrometer the role of the neighboring hydrogen-contained mass is negligible owing to the high threshold of neutron detection.

For the estimation of the influence "self-restraint" events on the spectrometer efficiency were calculated the numbers secondary protons, gamma rays and deuterons detected in the CsI(Tl) simultaneously with the detection of the primary neutron in the stilbene. The total amount of such events is increased with growth of neutron energy. The threshold of the veto counter signal registration is low and assumed zero at the calculation. The energy losses in the stilbene crystal packing for the charged secondary particles were taking into account only. At neutron energy 20 MeV the anticoincidence circuit prohibited 8,3 % events from neutrons detected in the stilbene. Therefore, consideration of this effect was given in the calculation of the spectrometer efficiency at the neutron energies above 5 MeV.

The neutron detection efficiency of the spectrometer depends on the fixed threshold of the signal registration. The calibrations of all stilbene detectors with gamma-rays of ^{137}Cs, ^{60}Co and ^{88}Y were done for the definition of the thresholds and apparatus scales in electron equivalent energy (e.e.e.) units. The edges of Compton electron spectra for these sources are given in Table 1.

Table 1. The gamma lines of the sources (E^{γ}) and the edges of corresponding Compton electron spectra (E^{e}_{max}).

^{60}Co		^{137}Cs		^{88}Y	
E^{γ}, MeV	E^{e}_{max}, MeV	E^{γ}, МэВ	E^{e}_{max}, MeV	E^{γ}, MeV	E^{e}_{max}, MeV
1,1732	0,963	0,661	0,477	0,898	0,699
1,3325	1,118			1,836	1,612

The dependences of E^{e}_{max} on the positions of the Compton edges (N_{ch}) were fitting by following relationship:

$$E\ (\text{MeV e.e.e.}) = a + b\cdot\exp(N_{ch}/c). \qquad (1)$$

Here a,b,c are the coefficients determined by the fitting of the experimental data. The approximations $E(N_{ch})$ for FU-1 and KDI are demonstrated in Fig. 5. The values of the $E(N_{ch})$ at $N_{ch} = 0$ are the thresholds of spectrometers in MeV e.e.e. (KDI – 0.09; FU-1 – 0.15; FU-2 – 0.25).

Apparatus spectra from the stilbene detector for all photon energies were calculated with the MCNP4C code at different resolution values and transformed to scales with using the dependences (1). The account of the proper apparatus resolution of the spectrometer the obtained apparatus spectra convoluted with the normalized normal distribution with different standard deviations. The values of the standard deviations for each HEND patterns were choused by the criterion of better agreements calculated and measured apparatus spectra for gamma rays. The comparison of measured and calculated ^{88}Y spectrum for KDI at proper spectrometer resolution 15 % is presented in Fig. 6 as an example. For FU-1 and FU-2 the proper spectrometer resolutions are 10 and 12 %.

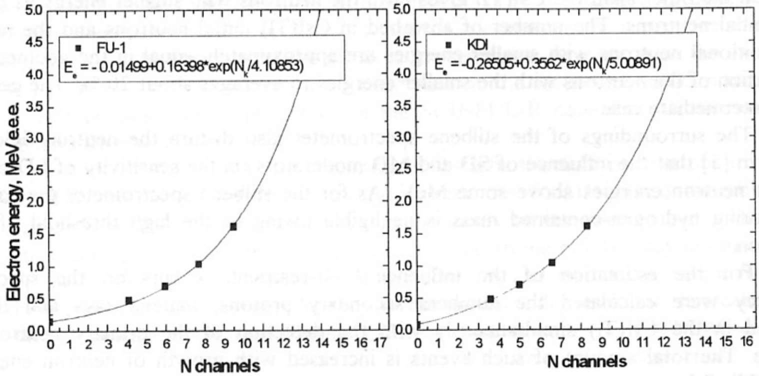

Fig. 5. The approximations of the scale distributions of FU-1 and KDI patterns stilbene spectrometers. The solid points – experimental data, lines – fit

The thresholds of the spectrometers were checked also by the measurements of the spectrometer sensitivities to neutrons from reference ^{252}Cf source in geometry 1. In order to

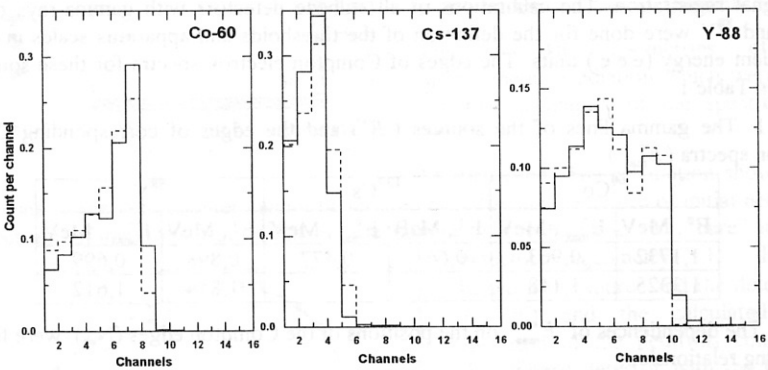

Fig. 6. The measured and calculated apparatus spectra of KDI stilbene spectrometer for gammas. Solid lines – the experimental spectra, dashed lines – the calculated spectra

account the neutron background the measurements were done at some different distances between the source and the stilbene. The multiscattered neutrons background level in the big dwelling was assumed as constant not far from the source (R ≤ 3 m). At this assumption the readings of the spectrometer $N_t(R)$ at distance R can be described by following:

$$N_t(R) = N_b + N_s/R^2, \qquad (2)$$

where N_s – the spectrometer readings because of the direct source neutrons, N_b – the contribution of the background neutrons to $N_t(R)$. The fitting of the experimental data by (2) allowed finding N_s. The spectrometer sensitivities (with account of the CsI(Tl) influence) at above-mentioned thresholds were calculated then for ^{252}Cf neutrons in real geometry of irradiation. The measured and calculated sensitivities are presented in Table 2.

Table 2. The comparison of the calculated and measured average sensitivities (cm^2) of the spectrometers for neutrons of the reference ^{252}Cf source.

Pattern	FU-1	FU-2	KDI
Calculation	1,537	0.888	2,014
Measurement	1.540	0.881	2.007

Experimental testing of the calculated sensitivities

The physical calibrations of the HEND stilbene spectrometers were performed in Joint Institute for Nuclear Research at the electrostatic accelerator of ions (EG-5) with thin lithium target. The energy range of quasi-monoenergetic neutrons from the $^7Li(p, n)^7Be$ reaction was 0.1 – 1.0 MeV. The details of the calibration of the SD, MD and LD at the EG-5 neutron beams are described in [3].

The experimental values of the stilbene spectrometer efficiencies η_{SC} were found by the comparison of the spectrometer readings with the readings of the LD counter at neutron beams from lithium target:

$$\eta_{SC}(E) = N_{SC}(E) \cdot \eta_{LD}(E) / N_{LD}(E) \quad (3)$$

Here η_{LD} is calculated efficiency of the LD (Fig. 7), N_{SC} and N_{LD} are the synchronous readings of the stilbene spectrometer and LD readings. The calculation of the $\eta_{LD}(E)$ was checked experimentally at the neutron beams of the EG-5 generator [3] and the results of the testing are shown in Fig. 7 as well. Because of the HEND compactness the neutron fluxes through the stilbene detector and LD were practically equal at the distance between the HEND and the target more than 3 m. The choice of the LD as reference instrument in this measurement was stipulated for low sensitivity to the background neutrons and weak influence of the surroundings to its sensitivity.

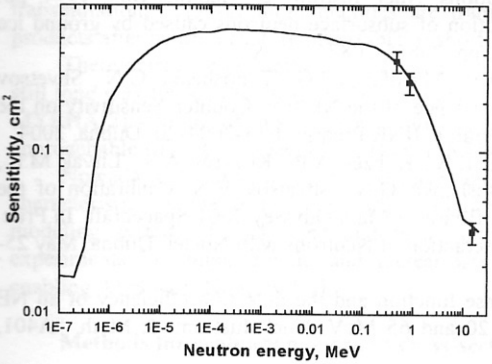

Fig. 7. The energy dependent sensitivity of the LD. The points are the experimental data

The results of the calculated η_{SC} testing at neutron energies to 1 MeV for all HEND patterns are given in Fig. 8. As a whole the agreement between calculations and experiments is quite satisfactory. The calculated spectrometer sensitivities for HEND patters for the geometry 1 in the complete energy range are presented in Fig. 9. The sensitivities without account of the veto counter influence are given as well for example.

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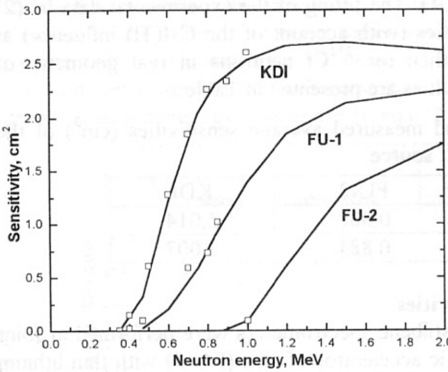

Fig. 8. The testing of the calculated efficiencies of the stilbene spectrometers with the monoenergetic neutrons

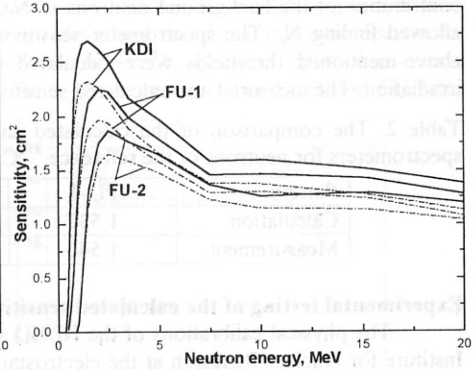

Fig. 9. The HEND patters spectrometer sensitivities with account of the veto counter influence (solid lines) and without it (dashed lines)

References

1. Drake D.M., Drosg M., Byrd R.C., Reedy R.C., Clark D.A. Experimental and numerical simulation of Martian neutron distributions. Nucl. Instrum. & Methods B84, 1994, pp. 337-356; Feldman W. et al. Redistribution of subsurface neutrons caused by ground ice on Mars, J. Geophys. Res., v. 98, 1993, pp. 20855-20870.
2. Krylov A.R., Pikelner L.B., Kobzev A.P., Mitrofanoy I.G., Timoshenko G.N., Shvetsov V.N. Measurement of the Energy Dependence of the Neutron Counter Sensitivity on the Neutron Beam of the Electrostatic Generator. JINR Preprint E13-2004-20, Dubna, 2004.
3. Bystritski V.M., Krylov A.R., Pikelner L.B., Kobzev A.P., Kozyrev A.S., Litvak M.L., Mitrofanov I.G., Tretyakov V.I., Timoshenko G.N., Shvetsov V.N. Calibration of the HEND Neutron Counters Mounted on Board of Mars Odyssey 2001 Spacecraft. In Proc. of the XIII International Seminar on Interaction of Neutrons with Nuclei, Dubna, May 25-27, 2005.
4. Meigo S. Measurements of the response function and the detection efficiency of an NE 213 scintillator for neutrons between 20 and 65 MeV, Nucl. Iustrum. & Meth. A401, 1997, pp. 365-378.
5. Fowler J., Roos C. Phys. Rev, v. 98, 1955, pp. 996.
6. Craun R.L., Smith D.L. Analysis of response data for several organic scintillators. Nucl. Iustrum. & Meth. 80, 1970, pp. 239-244.
7. Biersack J.P., Haggmark L. Nucl. Instr. and Meth., v. 174, 1980, p. 257; Ziegler J.F., Biersack J.P., Littmark U. The stopping and range of ions on solids. Pergamon Press, New York, 1996.
8. MCNP – A General Monte Carlo N-Particle Transport Code, LANL Report LA-13709-M, Version 4C, 2000.