

# The Second Stage of BTN Neutron Space Experiment onboard the Russian Section of the *International Space Station*: the BTN-M2 Instrument

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**Abstract**—As recent studies onboard various spacecraft have shown, one unresolved technical problem of manned interplanetary flights at the moment is the high radiation background of interplanetary space, which, as in the case of a manned mission to Mars, can be critically dangerous for the crew. Work on this topic is being carried out by all space agencies. One such space experiment is represented by the BTN-Neutron experiment onboard the Russian section of the *International Space Station (ISS)*. The main result of the work was the construction of the BTN-M2 instrument for creating effective radiation protection onboard prospective manned spacecraft, creating an engineering model of the radiation background both inside and outside the *ISS*, and for registration of  $\gamma$  rays and neutrons during solar flares and cosmic  $\gamma$ -ray bursts.

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## 1. INTRODUCTION

In November 2006 onboard the Russian section of the *International Space Station (ISS)*, the BTN-M1 neutron spectrometer installed outside the pressurized compartment of the *Zvezda* module of the Russian section. This device was created to carry out the first stage of the BTN-Neutron experiment [1–3], which is still ongoing. Its scientific tasks primarily include continuous monitoring of the neutron component of the radiation background in a wide spectral range, including the search for its spatial (flying at different geomagnetic latitudes, including over the South Atlantic Magnetic Anomaly (SAMA)) and temporal variability (at different time scales, including episodes of strong solar proton events).

The neutron component of the radiation background in the vicinity of the *ISS* arises as a result of the interaction of charged particles (protons from radiation belts, charged particles of galactic and solar cosmic rays) with the material that makes up the *ISS*. The BTN-M1 neutron spectrometer makes it possible to measure neutron fluxes in different spectral ranges, from epithermal to fast neutrons, and to reconstruct the energy spectrum of neutrons from them, after which the power of the neutron component of the radiation dose can be estimated and compared with the data of other experiments on the *ISS* [2, 13]. In space outside the Earth's magnetosphere, the main contribution to the radiation dose onboard spacecraft

is made by charged particles, while neutrons make up only a small fraction of about 1–5% (see, for example, [8, 9]). For large space stations in low Earth orbit, such as the *ISS*, this ratio can change significantly. It has been shown that passive aluminum protection with a thickness of about 20 g/cm<sup>2</sup> does not reduce the level of radiation exposure of astronauts, since the equivalent values of the dose increase due to the processing of primary charged particles into secondary neutron radiation [10]. Measurements show that the average dose rate for charged particles on the *ISS* is about 650  $\mu$ Sv/day, while the neutron component can reach  $\sim$ 140  $\mu$ Sv/day [10–12]. So, for the *ISS*, the contribution of the neutron component reaches about 20% of the total dose.

In the process of conducting the BTN-M1 experiment for more than 15 years, variations in the neutron component of the cosmic background outside the *ISS* were monitored, which made it possible to estimate spatial variability (flights over high geomagnetic latitudes and SAMA) and long-term variations during an 11-year solar cycle [2, 13]. It was shown that the power of the neutron component of the radiation dose increases by a factor of  $\sim$ 100 when flying over the SAMA compared to flying over equatorial regions with a small geomagnetic cutoff index. During the 11-year solar cycle, the power of the neutron component of the radiation dose varied within 1.5–1.6 times (from minimum to maximum solar activity) [2, 13].

The obtained data correlate well with the data obtained by other dosimeters [2].

Thus, already when the first results were obtained from the BTN-M1 instrument, it became clear that the BTN-Neutron experiment would significantly benefit scientifically if similar instruments were to appear onboard the *ISS*, but installed inside the pressurized compartment and registering both secondary neutrons and  $\gamma$  rays. This would allow one to simultaneously obtain and compare measurements of the radiation background outside and inside the *ISS*. Therefore, it was decided to continue the BTN-Neutron experiment in terms of creating additional scientific instruments, which was named BTN-M2.

It was proposed to expand the functionality of the proposed instrument so as not to be limited only to the analysis of the radiation situation on the *ISS* in Earth orbit, as well as to obtain additional data on possible means of protection against secondary neutron radiation onboard a spacecraft, on the basis of which it would be possible to plan future manned expeditions into deep space to the Moon and Mars.

The creation of a permanent lunar base and the preparation of future expeditions to Mars are being actively discussed by various space agencies. Recent studies show that one of the most important tasks has been and remains the task of ensuring radiation safety of the crew in deep-space conditions [4, 5]. While during work in Earth orbit (at low orbital inclinations of below  $60^\circ$ ) this issue is partially resolved due to the shielding of cosmic rays by the Earth's magnetosphere, in the conditions of interplanetary flights and work in the Earth's radiation belts, the safety of the crew directly depends on the surrounding radiation situation.

The BTN-M1 instrument includes a scintillation detector based on CsI crystal. Its main purpose is for use in the anticoincidence circuit to protect the fast neutron detector from charged particles (mainly protons). However, this detector also effectively registers  $\gamma$  rays with energies from 60 keV to several megaelectronvolts with a rather high time resolution (1/4 s), which allows it to be used to observe the profiles of strong solar  $\gamma$ -ray flares and cosmic  $\gamma$ -ray bursts. This possibility is also preserved in the BTN-M2 instrument.

In addition, during the first stage of the BTN-Neutron space experiment, an adjacent field of research began to actively develop that was related to a fundamentally new cosmic phenomenon that is observed in the upper layers of the Earth's atmosphere. This phenomenon is associated with terrestrial  $\gamma$  flares (TGFs) [15, 16]. It has been supposed that TGF  $\gamma$  radiation arises due to bremsstrahlung of relativistic electrons, which are accelerated in a strong electric field from a discharge created by lightning. The photon energy can reach 20 MeV, and the characteristic duration of TGFs can be several milliseconds, and so the BTN-M1 instrument cannot register them. When developing

the electronics of the BTN-M2 instrument, the possibility of photon registration of  $\gamma$  rays with a very high temporal resolution was specially incorporated so that the BTN-Neutron experiment onboard the Russian section of the *ISS* played a role in the TGF international research program.

Thus, the main goals of the second stage of the BTN-Neutron experiment were defined as follows.

- Studying the radiation-protective properties of various materials for the development of effective radiation protection onboard advanced spacecraft and for the creation of radiation shelters for future manned expeditions to the Moon and Mars.
- Creation of an engineering model of the radiation background of neutrons both inside the pressurized compartments of the Russian section and outside under various flight conditions of the *ISS* in Earth orbit according to BTN-M1 and BTN-M2 data.
- Registration of  $\gamma$  rays and neutrons during solar flares and solar proton events (together with BTN-M1).
- Registration of TGF events and measurement of the  $\gamma$ -ray spectra of these events, testing the hypothesis that some of the TGFs has a neutron radiation component;
- Registration of cosmic  $\gamma$ -ray bursts.

## 2. DESCRIPTION OF THE DESIGN OF THE INSTRUMENT

### 2.1. General Structure

During the development of the second stage of the experiment, a concept was used that proved itself well in the first stage of the BTN-Neutron experiment: a device was already developed and flight tested, for which a "shell" was developed to adapt interfaces with the Russian segment of the *ISS*. In this case, the MGNS neutron and  $\gamma$ -ray spectrometer for the European mission BepiColombo [6, 14] was used as the detector part, with the only difference being that the electronics of a spectrometer with fast signal processing was used to detect cosmic and terrestrial  $\gamma$ -ray flares, which was also borrowed from the flight model of the ADRON-LR instrument of the Russian Luna-Globe mission (Luna-25) [7]. Thus, the entire detector part of the  $\gamma$  and neutron spectrometer (GNS) of the BTN-M2 device is based on already-proven technical solutions that have passed all stages of development, qualification tests, ground testing and flight tests. This minimizes all the risks associated with identifying problems at the later stages of testing and development.

One of the most important new parts of the instrument's design consists in removable shields, which contain assemblies of materials inside to study their protective properties against neutron radiation. In the process of conducting an experiment with the BTN-M2 instrument, it is planned to deliver to the Russian segment of

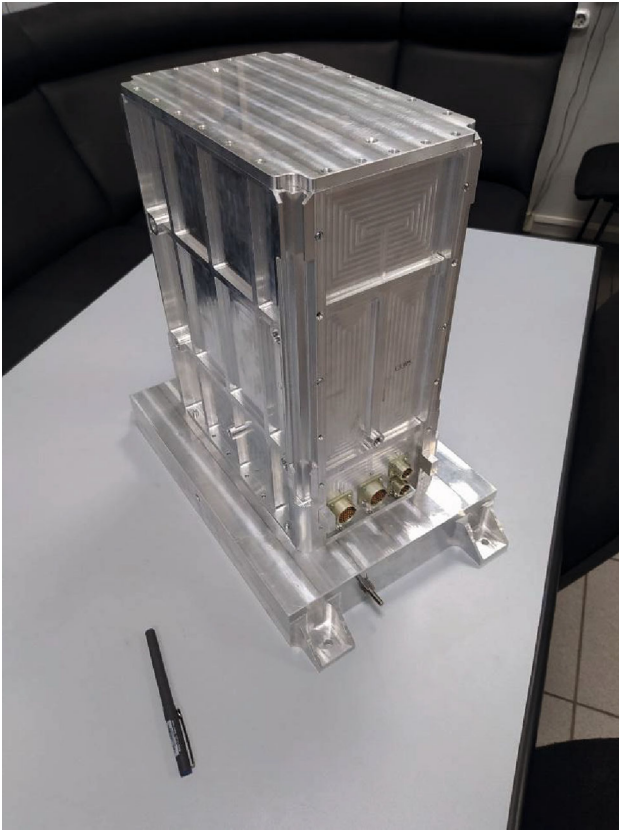


Fig. 1.

the *ISS* a second set of shields with other options for protective materials developed based on the results of the experiment from the first set of shields.

The detector part inside the shielded volume is fixed to a mechanical truss (Fig. 1), which ensures the integrity of the entire structure. This truss provides fastening of removable protective shields, as well as fastening of the device to a narrow module-shelf of a small laboratory module inside the pressurized compartment. The replaceable protective shields are completely passive elements of the mechanical design and are not shown in Fig. 1. A photograph of the entire BTN-M2 instrument assembled with protective shields is shown in Fig. 2.

A general block diagram of the electronics of the BTN-M2 device is shown in Fig. 3. The BTN-M2 instrument is a redundant device with two half-sets, one of which is in cold reserve. Primary power supply (+27 V) and switching of electronics half-sets are performed by relay commands from the onboard complex control system (OCCS). Confirmation of the operation of the first or second half-set, respectively, as well as monitoring of the thermal conditions of the device is carried out by the onboard measurement system (OMS) of the Russian segment of the *ISS*. Command and telemetric information is exchanged using a redundant 10/100-Mbit Ethernet interface. To switch to the redundant half-set of the device electronics, it is



Fig. 2.

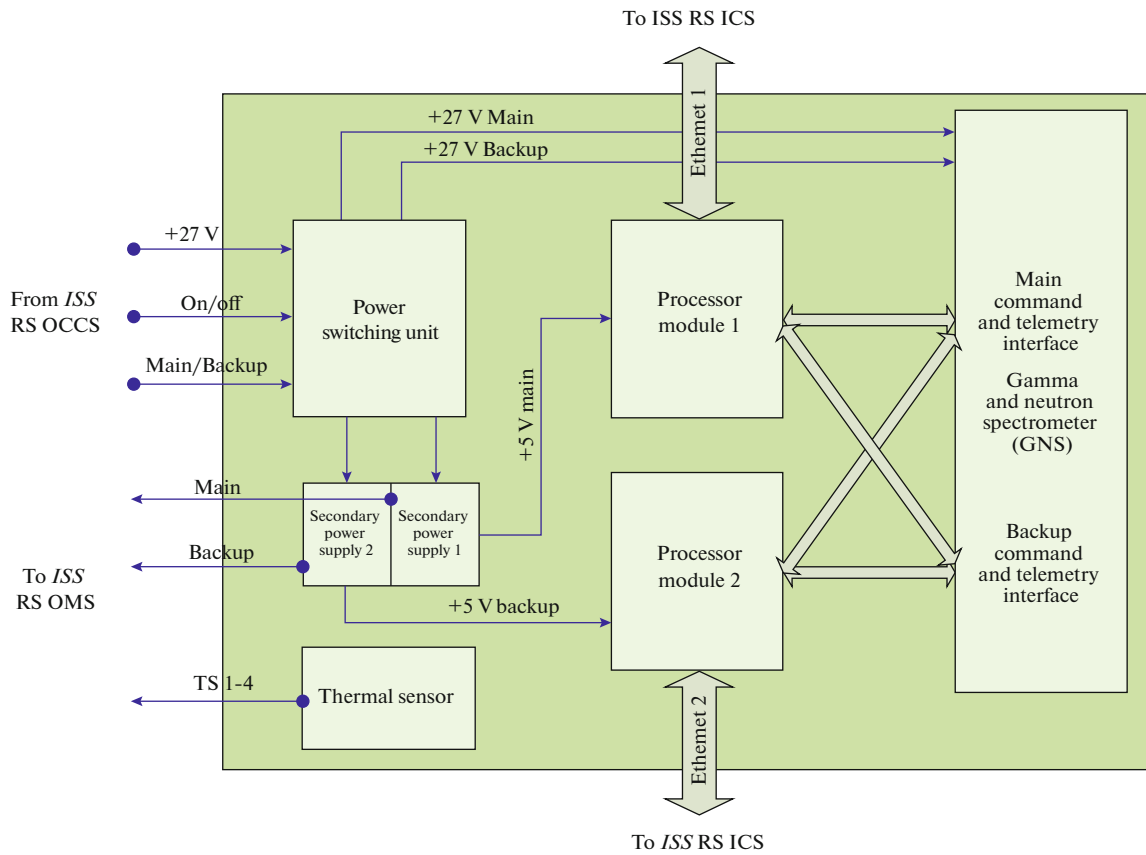


Fig. 3.

Table 1. Characteristics of BTN-M2 instrument

Parameter	Value
Dimensions	266 × 450 × 480 mm
Weight	Max. 42 kg (including protective shields)
Power consumption	No more than 15 W
Supply voltage	15–50 V
Starting current	No more than 700 mA
Working temperature range	–40 to +50°C
Command telemetry interface	Ethernet 10/100 bit
Volume of telemetry information	No more than 4 MB/day
Number of teams	No more than five teams/day
Internal memory, MB	2 GB
Installation location	PGO 1 MLM Russian Section of the ISS, URM-V, narrow shelf module
Radiation resistance	At least 5 krad
Assigned resource	Not less than 35000 h
Probability of uptime	Not less than 0.9

necessary to physically switch the interface cable to the redundant connector by means of the crew of the *ISS*. The summary characteristics of the BTN-M2 instrument are given in Table 1.

### 2.2. Design of the Detector Part

The block diagram of the detector part of the HNS is shown in Fig. 4, and the appearance is shown in Fig. 5. As noted above, the main detector unit (the GNS) is an almost complete copy of the MGNS device, which consists of five detector units, a digital control and signal processing core, redundant secondary power sources, and a redundant command–telemetry interface.

Detection of low-energy neutrons is carried out using three sensors that have the same LND 25169 helium counters with a gas pressure of 20 atm and different designs of external parts.

- The SD1 sensor has no shell and detects thermal and epithermal neutrons with energies from 0.025 eV to the upper sensitivity threshold of <500 eV.
- The SD2 sensor has a shell made of a cadmium sheet 1 mm thick and detects only epithermal neutrons with energies from 0.4 eV (the cadmium absorption threshold) to 500 eV. Comparison of the measurement

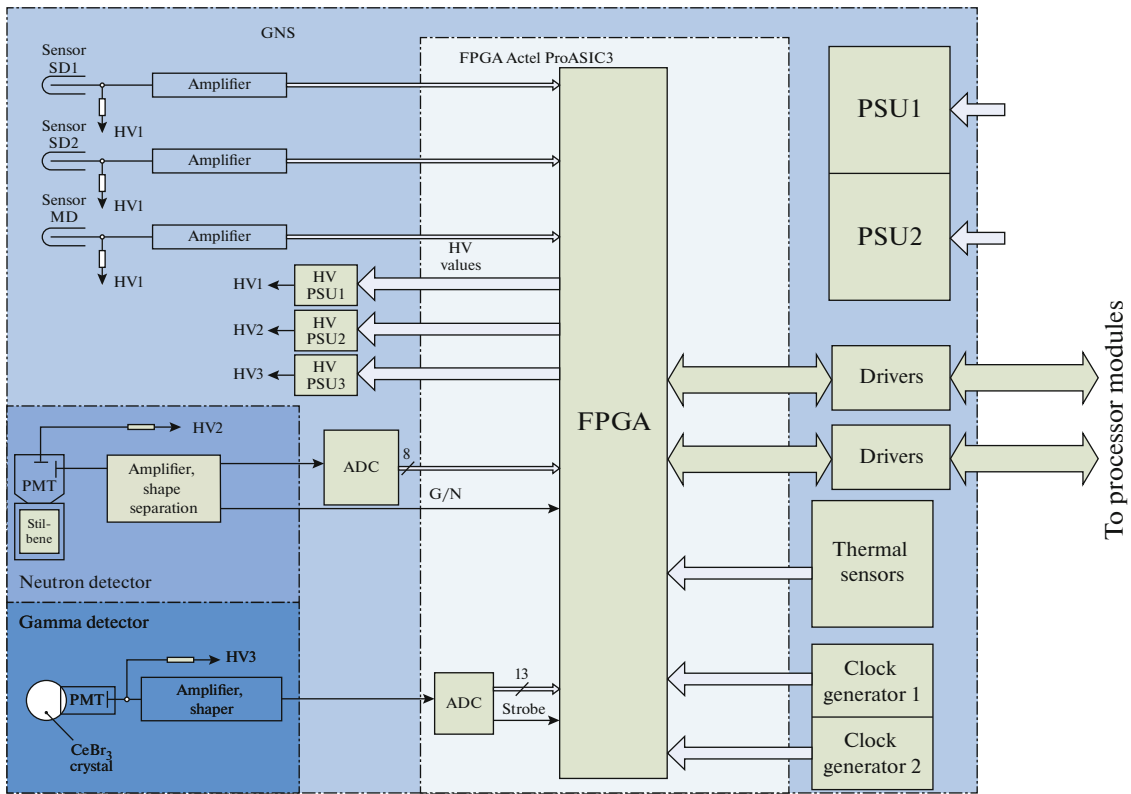


Fig. 4.

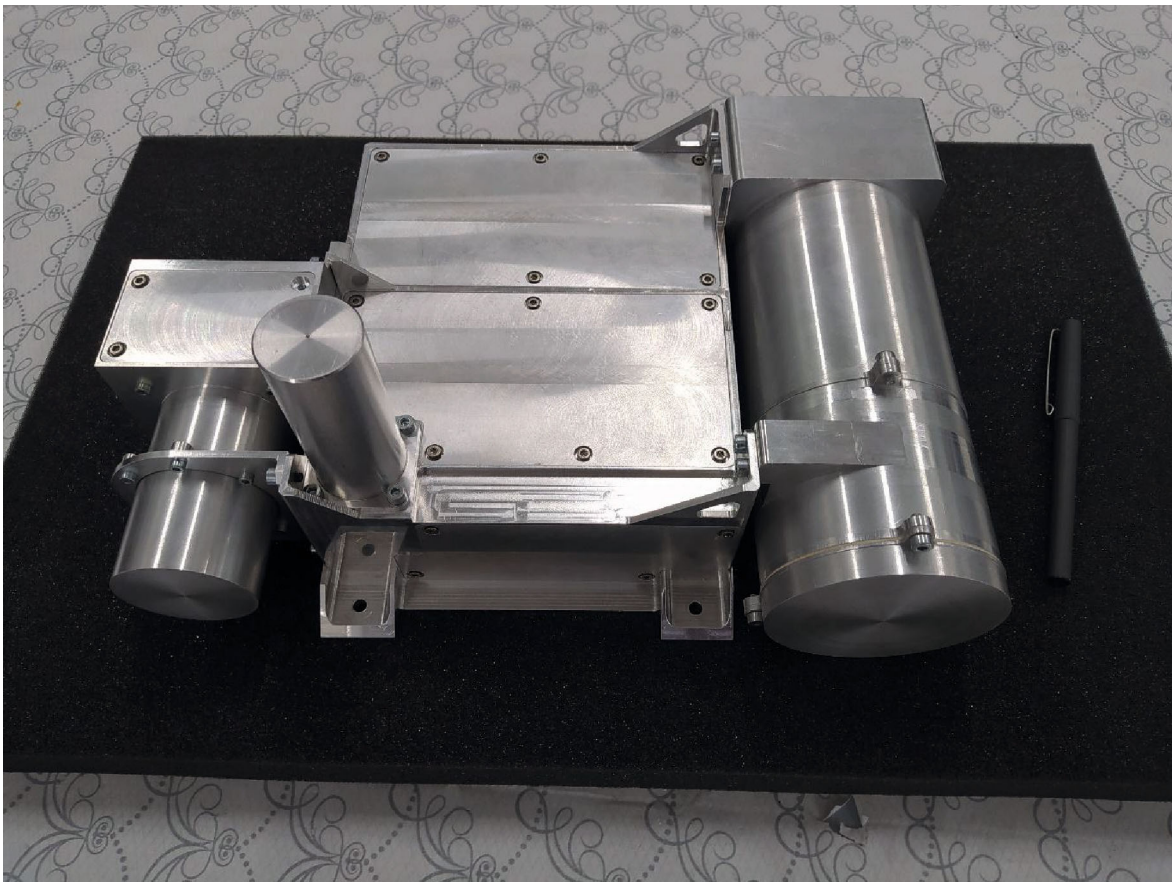


Fig. 5.



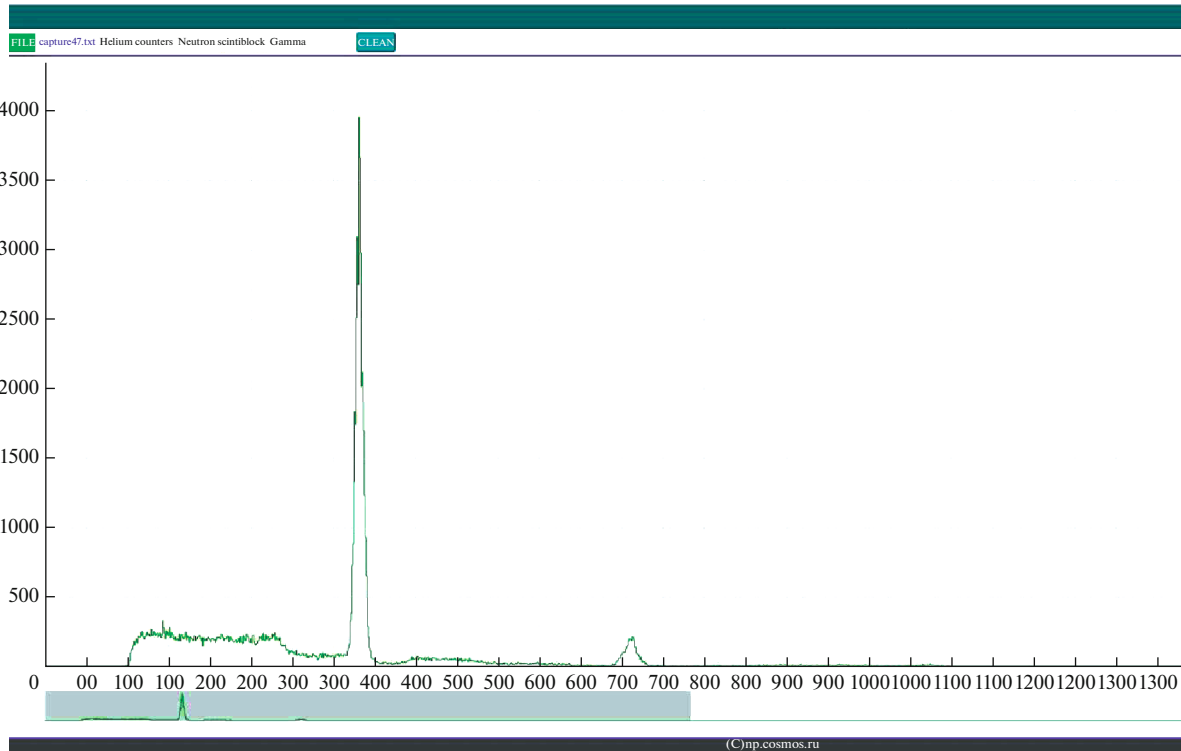


Fig. 6. Spectrum of a  $\gamma$  detector with a Cs-137 source. *X* axis, spectrometer channels; *Y* axis, readings.

data of the SD1 and SD2 detectors makes it possible to determine the thermal neutron flux.

- The MD sensor has a 1-mm-thick cadmium sheet sheath and a 10-mm-thick high pressure polyethylene neutron moderator sheath; this sensor detects neutrons with energies of 10 eV–1 MeV.

The detection of neutrons of different energies by the same neutron counters is ensured by the special physical properties of the shells of these sensors: for example, high-pressure polyethylene, which has a large amount of hydrogen in its composition, well moderates the initial neutrons to thermal and epithermal energies, thereby shifting the initial spectrum to a region of more low energies, where the counter has the maximum registration efficiency. A cadmium sheet shell with a thickness of at least 1 mm provides protection for SD2 and MD from a neutron flux with energies  $<0.4$  eV.

A scintillation detector of 0.1- to 8-MeV high-energy neutrons is based on a composite detector of stilbene and organic plastic with a Hamamatsu R5611 photomultiplier. This detector uses a shape discrimination circuit to discriminate neutron events in the scintillator from charged particle events. Thus, with its neutron detectors, the instrument covers the energy range from 0.025 eV to 8 MeV.

The scintillation  $\gamma$  detector uses a crystal of cerium bromide  $\text{CeBr}_3$  with a size of  $3 \times 3$ ". At present, this scintillator has one of the best spectral resolutions of all scintillation detectors. The signal read-

ing device is a Hamamatsu R1307 heavy-duty photomultiplier tube (PMT). This "detector–PM" pair has repeatedly demonstrated in several previous developments its reliability, low intrinsic noise, and spectral resolution of 4.3% at 662 keV (Fig. 6). As noted above, this instrument uses a spectrometer with reduced signal processing dead time ( $<4$   $\mu\text{s}$ ) to record profiles of  $\gamma$  events with high temporal resolution, and the energy range of the  $\gamma$  channel is 0.2–10 MeV.

All five detector units require high voltage with different values (600–1100 V), which is generated inside the device using low-current miniature high-voltage converters from PICO Electronics. Each of the converters has several fixed voltage values for selecting the optimal measurement mode for each of the detectors. High voltage values can be changed by commands from the ground.

The electronic core of the device is an Actel FPGA with a volume of 3 million gates, thanks to which almost all the main functions of the device are implemented:

- receiving and executing commands.
- processing and recording in the memory of events from five detectors.
- formation and transmission of photon words to processor modules.
- formation and transmission of service telemetric information (thermal sensor values, failures of high-voltage converters, device status, etc.).

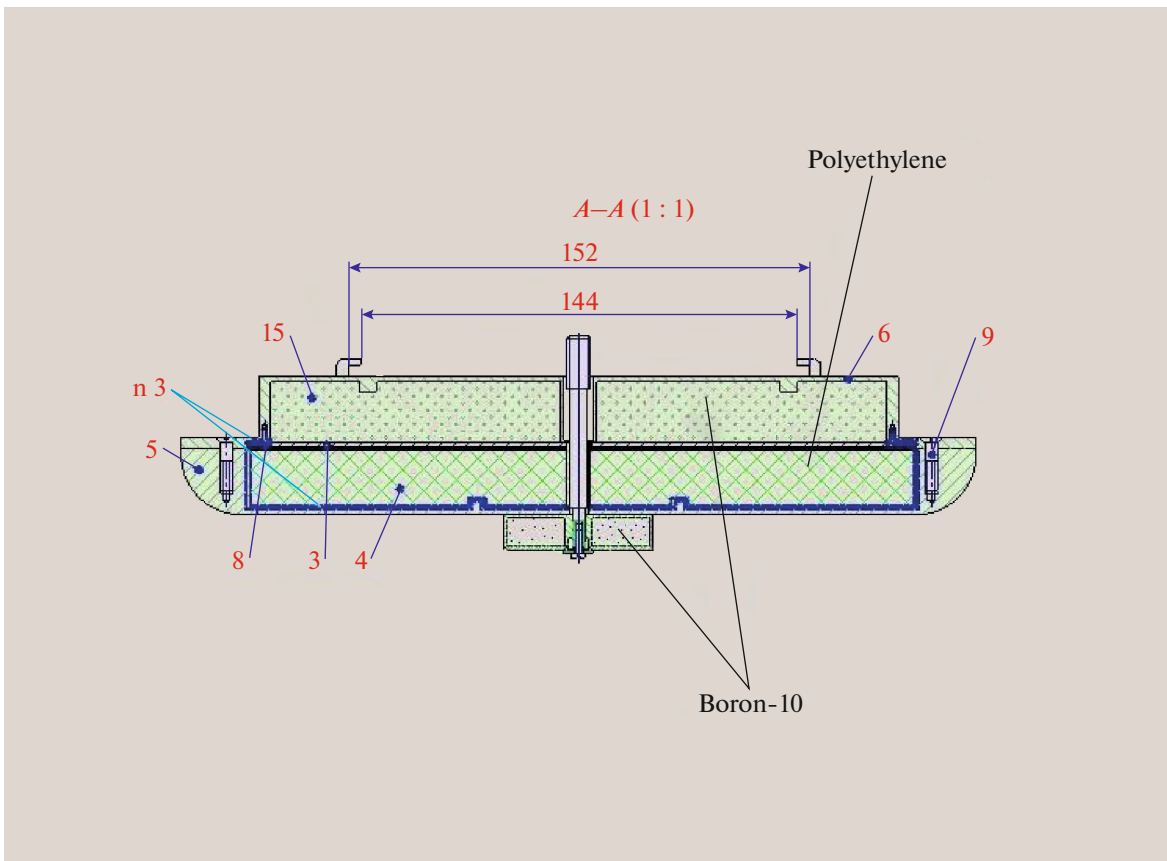


Fig. 7.

In the measurement mode, the GNS detector block generates “raw” information in the form of a bit stream of photon and neutron “words” with data on registration events in five detectors for subsequent processing of this information by the software of the processor modules. Each neutron (photon) word consists of 10 bytes of information in a strictly defined format, which contains: a synchro marker (1 byte), a detector channel number (1 byte), an amplitude value from the detector (2 bytes), and an internal time of the GNS with a reference resolution of 20 ns.

To prevent data loss during large loads of detectors (solar events,  $\gamma$ -ray flares, etc.), the GNS has a buffer for storing scientific data for 32 thousand registered events.

### 2.3. Protective Shields

One of the most important design elements of the BTN-M2 device is protective shields from the secondary neutron flux onboard the *ISS*, the effectiveness of which is planned to be measured during the experiment.

At the initial stage of the experiment with the BTN-M2 instrument, the first set of shields made of a layer of high-pressure polyethylene, which acts as a neutron moderator, and a layer of boron isotope  $^{10}\text{B}$

powder will be used operating as a low-energy neutron absorber. This two-layer pair has already confirmed its high efficiency in such space experiments as LEND (the NASA LRO mission) and FREND (the Russian–European mission ExoMars-2016). At the initial stage of the BTN-M2 experiment, it is planned to experimentally evaluate the shielding properties of the first set of shields from the point of view of biological protection. In the future, taking into account the measurement data, it is planned to create a second set of shields with a possible increase in the thickness of the layers and/or the addition of layers of other substances that absorb neutrons.

The cross section of one of the protective shields is shown in Fig. 7. The thicknesses and ratios of the protective layers were calculated based on the optimal ratio of shielding properties and mass characteristics: the polyethylene layer is 2 cm thick (above this thickness, the increase in the efficiency of moderating neutrons in the cosmic spectrum drops sharply), and the thickness of the absorbing boron layer occupies the entire remaining available mass of the instrument. At the preliminary stage, full-scale tests of the shielding properties of shields with a PuBe neutron source with the spectrum shown in Fig. 8 were carried out [17]. These tests showed a decrease in the thermal neutron flux by 60%

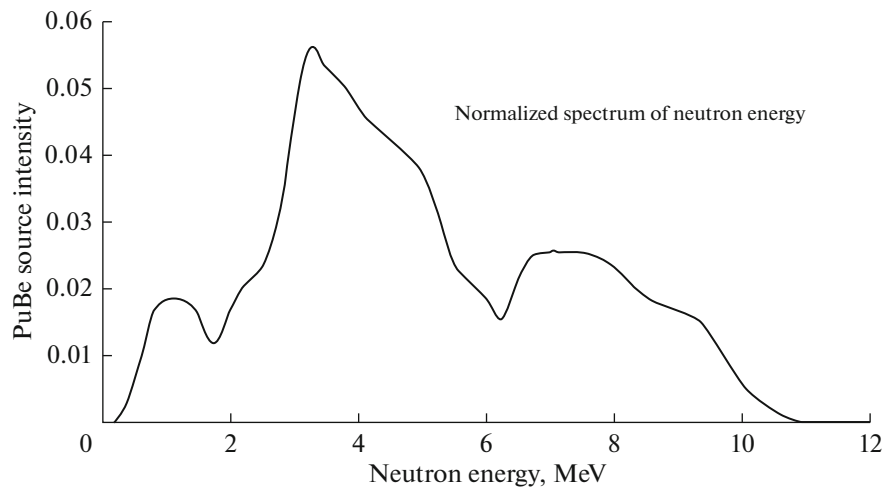


Fig. 8.

and that for epithermal neutrons by 35–40%. The efficiency of protection against high-energy neutrons was more than 50%.

A feature of the design of the shield and of the entire device as a whole is that there is not a single direct beam of passage of a radioactive particle that would bypass the protective layers of the shields. Since these shields are removable and replaceable, the experimental procedure involves comparing the radiation background in the vicinity of the device without protective shields and with installed shields for different neutron-flux directions inside the station.

Measurements of  $\gamma$  rays and neutrons in various instrument configurations will allow us to estimate the degree of anisotropy of the secondary radiation for different space flight conditions. Obviously, changing the configuration of the shields will require the active participation of research astronauts in the experiment.

At the next stage of the experiment, it is planned to deliver a second set of shields with other protective materials developed taking into account the results obtained at the initial stage onboard the *ISS*. As a result of the experiment, optimal combinations of the composition of materials that moderate and absorb neutrons will be found for their subsequent use onboard manned spacecraft in deep space.

#### 2.4. Interface Design with onboard *ISS* Systems

To meet the requirements of the *ISS*, as part of the command–telemetry interface, the device uses redundant Cool SpaceRunner-LX800 industrial processor modules from Lippert operating in the cold backup mode. These modules carry out command and telemetry exchange with the information and control system (ICS) of the *ISS* via the 10/100 Mbps Ethernet interface and reception of “raw” information from the detector unit of the GNS via the RS-422 interface (at

a speed of up to 1.5 Mbps), as well as preliminary processing of the received scientific information, depending on the specified mode of operation. The processor modules run under the Debian 10 operating system. All possible methods of improving the reliability of work are applied to the software modules, and the possibility of updating the software in flight is also provided.

### 3. COMMAND AND TELEMETRY INFORMATION

Control of the BTN-M2 device is carried out using the IMS by sending a fixed format with a sending frequency of no more than one command per second. All commands are subdivided into commands for the GNS detector unit and for interface processor modules that process information. The general list of commands is given in Table 2. Receipt and execution of each command sent to the device is confirmed by a response status packet with the result code of the command execution.

To control the BTN-M2 device, the following commands are provided.

1. *The command to set the level of discriminators* sets the noise level of the analog part in each of the analog paths of the detectors to discriminate between the useful signal and the noise.

2. *The command to adjust the high voltage on the detectors* provides the ability to selection of the optimal measurement mode. For scintillation detectors, an increase (decrease) in high voltage increases (decreases) the PMT gain and, thereby, narrows (expands) the energy measurement range of the corresponding measurement channel. For helium counters, high voltage adjustment allows compensating for thermal instabilities of the analog path;

3. *The mode selection command* allows the operating modes of the device to be set: the mode of transmis-



**Table 2.** List of BTN-M2 hardware commands

Number	Team	Command Receiver	Team assignment
1	Setting of discriminator levels	GNS	Sets the desired discriminator level for a specific detector channel
2	Setting high voltage levels	GNS	Sets the desired high voltage level for a specific detector
3	Working mode	PM	Sets the mode of processing “raw” data and the type of information produced
4	Spectrum accumulation time	PM	Sets the spectrum accumulation time in the spectrum generation mode
5	Burst options	PM	Sets parameters and criteria for burst logic triggers
6	System image	PM	Sets the system image number for the next boot of the active processor module
7	File size	PM	Sets the maximum size of the data file on the flash disk of the active processor module
8	Channel of exchange with GNS	PM	Establishes an active exchange channel with the GNS unit (main/backup)
9	Reboot	PM	Command to force reboot of the processor module

sion of initial data, the spectrum accumulation mode, and the burst mode.

The choice of operating mode will be dictated by the available volume of telemetry information transmitted to Earth. So, for the mode of transmission of initial data, the volume of telemetry is maximum, the instrument records each individual event in the detector in telemetry, and it is assigned an onboard time with high accuracy. In this mode, the processor module transmits data to the IMS without additional processing and the data received on the ground assumes the widest range of postprocessing, including accurate photon-by-photon recovering of time profiles. The estimated amount of daily telemetry in this mode during quiet solar activity can reach 2 GB/day.

In the spectrum accumulation mode, to reduce the telemetry load on the radio channel of the *ISS* processor, modules accumulate spectra from each of the detectors onboard for a set time, which is set by a command from the Earth, with subsequent transmission to the ICS. In this mode, the volume of daily telemetry is minimal (about 50 MB/day for a spectrum accumulation time of 20 s), but there is no possibility of recording time profiles of solar events and bursts in high temporal resolution. The volume of telemetry in this mode can be adjusted by changing spectrum accumulation time.

The burst mode is a palliative mode that has a low telemetry volume, but records time profiles of burst events with high temporal resolution when specified burst logic criteria are met.

4. *The command to change the spectrum accumulation time*; this command is relevant only in the burst and spectrum accumulation mode.

5. *The command to change burst logic parameters*; this command is relevant only in burst mode.

6. *The command to download new software* processor modules; a command may be needed in flight to expand the functionality of the instrument in the future.

7. *The file size-control command* for the transfer of scientific data from BTN-M2 to the ICS, the protocol is the NFS (network file system), where BTN-M2 acts as a server that stores data files. At certain intervals, the IMS retrieves new files from the device’s flash drive. The maximum size of these files is regulated by this command.

8. *The communication channel selection command* with GNS allows the main or backup RS-422 channel to be selected.

9. *The reload command* processor module reboots all instrument software.

Additionally, BTN-M2 synchronizes onboard time using the NTP protocol with one of the onboard servers of the *ISS* for writing the onboard time code (OTC) into each of the neutron or photon words, as well as for linking service telemetry information to trajectory data.

## CONCLUSIONS

At the moment, a prototype of the BTN-M2 instrument is undergoing a full cycle of qualification tests, including vibration, shock, and climatic tests, as well as electromagnetic compatibility tests, in accordance with the general requirements of RSC Energiya for space instruments installed on the Russian Section of the *ISS*. It is scheduled for operation of the flight unit onboard the *ISS* Science module is to start in 2023–2024.

The second stage of the BTN-Neutron space experiment with the BTN-M1 instrument outside the pressurized compartment of the Zvezda module and BTN-M2 in the pressurized compartment of the Nauka module will allow the following.

- To measure neutron fluxes and a wide range of energies along various directions inside and outside the pressurized compartment of the *ISS* in various geomagnetic conditions of orbital flight of *ISS* both during a quiet Sun and during solar flares or proton events.

- To study the absorbing characteristics of various protective shields from the secondary neutron flux onboard the *ISS*. Data obtained under flight conditions at high geomagnetic latitudes or in the SAMA region will make it possible to experimentally reproduce the conditions on an interplanetary spacecraft under the influence of galactic cosmic rays.

- To measure the energy spectra of secondary  $\gamma$ -ray fluxes along different directions inside the pressurized compartment of the *ISS* in various geomagnetic conditions of orbital flight of the *ISS* during a quiet Sun or during solar flares or proton events.

- To measure the fluxes and energy spectra of  $\gamma$  rays from solar flares, ground-based TGF  $\gamma$ -ray bursts, and space cosmic  $\gamma$ -ray bursts with extremely high time resolution and to test the hypothesis of possible sporadic neutron radiation of the Earth's atmosphere during TGFs.

#### CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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