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First Experiments on Neutron Detection on the Accelerator-Based Source for Boron Neutron Capture Therapy

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Abstract—A pilot accelerator-based source of epithermal neutrons, which is intended for wide application in clinics for boron neutron capture therapy, has been constructed at the Budker Institute of Nuclear Physics (Novosibirsk). A stationary proton beam has been obtained and near-threshold neutron generation regime has been realized. Results of the first experiments on neutron generation using the proposed source are described.

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Presently, boron neutron capture therapy (BNCT) [1] is considered to be a promising method for the selective treatment of malignant tumors. The results of clinical tests, which were carried out using nuclear reactors as neutron sources, showed the possibility of treating brain glioblastoma and metastasizing melanoma not subject to treatment by other methods [2, 3]. The broad implementation of the BNCT in clinics requires compact inexpensive sources of epithermal neutrons. In 1998, specialists of the Budker Institute of Nuclear Physics (Novosibirsk) in collaboration with Physical Power Engineering Institute and Medical Radiology Center (Obninsk) proposed a source of epithermal neutrons based on an electrostatic tandem accelerator with vacuum insulation, operating in a near-threshold regime [4]. In this source, a 10-mA beam of 1.915-MeV protons bombarding a lithium target produces neutrons via ^{7}Li(p, n)^{7}Be reaction (with a threshold at 1.882 MeV). The resulting flux of neutrons with an average energy of 40 keV can be used, after certain retardation, for BNCT purposes.

Recently, a pilot variant of the proposed accelerator-based source has been constructed [5], which produces a stationary beam of protons with an energy of 1.92 MeV and a current of up to 3 mA. This Letter presents results of the first experiments on neutron generation using this source.

In the proposed facility, neutrons are generated via the proton bombardment of a lithium target. The proton beam at the accelerator output has a diameter of 2 cm and is characterized by fairly high energy stability with a spread below 2 keV. Since the neutron production via ^{7}Li(p, n)^{7}Be reaction is accompanied by the formation of a radioactive ^{7}Be isotope, the possibility of studying the activated target was provided by reducing the beam current on the target to ~100 μA. The lithium target was a water-cooled copper disk with a diameter of 10 cm, covered with a 50-μm-thick lithium layer on the side exposed to the proton beam [6]. The current to the target can be evaluated by monitoring the temperature of the cooling agent.

Gamma radiation arising in the proton-bombarded target was registered by a detector based on a NaI crystal (Ø6 × 6 cm) and a Photonis XP3312B photoelectron multiplier, which was equipper with a collimator, a high-speed spectrometric analog-to-digital converter, and a processor with special software for analysis of the spectrum of γ quanta. The detector was usually arranged at a distance of 222 cm behind the neutron-generating target and protected by a lead shield with a wall thickness of ~10 cm and, in some cases, with a boron-doped polyethylene screen. The input hole dimensions of the collimator were 10 × 15 mm. The gamma spectrometer was calibrated with respect to a ^{40}K spectral line registered in the background radiation with respect to radioisotope sources of ^{60}Co (with an activity of 5.66×10^7 Bq and the gamma quantum ener-

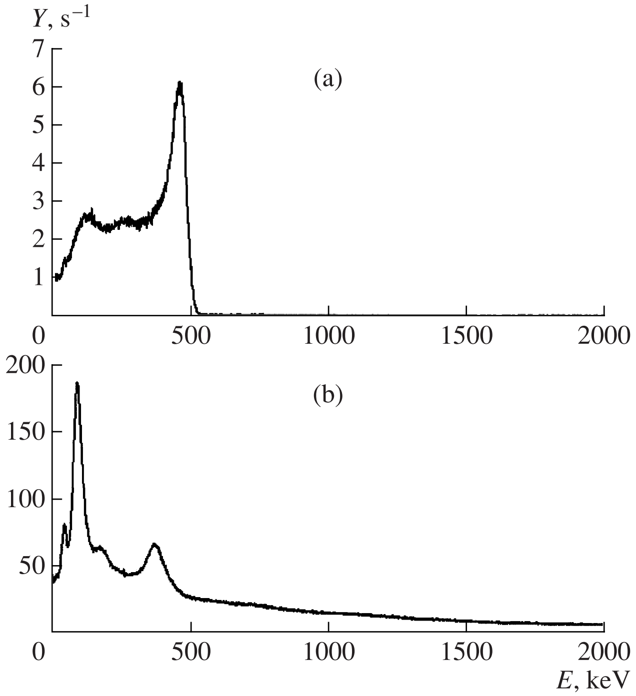

Fig. 1. Typical γ spectra measured at a proton energy of (a) 1.7 MeV and (b) 1.92 MeV.

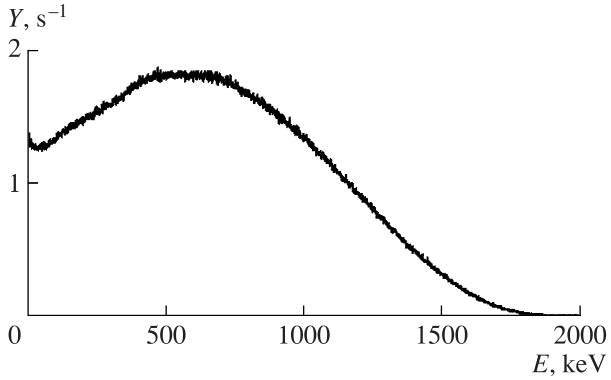

Fig. 2. Typical γ spectrum of the activated NaI detector.

gies of 1173 and 1333 keV) and ^{137}Cs (2.15×10^8 Bq, 662 keV). The results of calibration confirmed the energy linearity of the spectrometric system and showed that the available NaI crystal ensured the energy resolution on a level of ~7% and the complete absorption of ~37% γ quanta with an energy of 662 keV.

Figure 1 shows the spectra of γ quanta measured at a proton energy of 1.7 MeV (i.e., below the threshold of reaction with a neutron yield) and 1.92 MeV. The spectrum obtained in the subthreshold regime exhibits a pronounced line at 477 keV, which is related to the excitation of lithium nuclei by protons. In the regime of neutron production, additional γ quanta appear due to the capture of neutrons by structural materials of the facility and (predominantly) by iodine atoms in the scintillator crystal, which was checked by additional screening of the detector with boron-doped polyethylene that significantly attenuated the neutron flux.

Possessing high sensitivity with respect to neutrons, the NaI detector could be used in the activation mode. The ^{128}I isotope formed upon capturing a neutron has a half-decay time of 25 min. The decay proceeds in 6.4% cases with electron trapping via a nonradiative channel and in 93.6% cases with electron emission (β^- decay) with energies up to 2.12 MeV. In addition to ^{128}I, there also appears the ^{24}Na isotope at a rate of about 2% of that for ^{128}I. Figure 2 shows a spectrum measured using the activated detector upon neutron generation, which is typical of the β^- decay. Using the neutron count rate and generation time, it was possible to determine the rate of detector activation. Monte Carlo simulations allowed us to establish that this rate of detector activation took place at a proton beam current of 140 μA.

Since the production of every neutron via ^{7}Li(p,n)^{7}Be reaction is accompanied by the formation of a radioactive ^{7}Be isotope with a half-decay time of 53 days, the residual activity of a lithium target could be used to determine the total neutron yield. After termination of the neutron generation, the target unit was disassembled and the target was extracted and placed at a distance of 21 cm over the NaI detector. The spectrum of γ quanta measured using the activated target exhibited an intense peak at 477 keV due to decay of the beryllium isotope with a count rate of 4.1 cps. Taking into account that only 37% of γ quanta account for the total absorption, we evaluated the total flux of γ quanta from the target as 2.6×10^4 s^{-1} and the activity of beryllium as 2.6×10^5 Bq. In the given experiment, the irradiation of the target at a current of 140 μA for 7 min was preceded by exposure at a half smaller current for 6 min. Calculations showed that the target activation reached 2.7×10^5 Bq, which is in good agreement with the experimental data. The total neutron yield in this experiment was about 2×10^{12}.

The primary analysis of the spectrum of generated neutrons was performed using bubble detectors of the BDT and BD100R types (Bubble Technology Industries, Canada). The BDT device comprises a transparent vessel with a diameter of 19 mm, a length of 145 mm, and a weight of 58 g, filled with a polymer containing dispersed overheated liquid. The liquid composition is selected so as to achieve maximum sensitivity (about 10^3 bubbles/neutron cm^2) for thermal neutrons. In contrast, BD100R is most sensitive to neutrons with energies above 100 keV. In the experiments under consideration, a 15–20-times-greater number of bubbles was formed in BDT than in BD100R, which corresponded to a calculated spectrum with an average energy of 40 keV in the near-threshold generation regime.

The experiments also confirmed the ability of a target to ensure effective heat removal of 318 W/cm^2 at a lithium surface temperature below 180°C. The current was strongly restricted, but the beam was not scanned over the target surface, so the current density was about half as small as the nominal value. No visible changes were found in the lithium layer, which was evidence for the absence of significant evaporation. Therefore, the temperature of lithium was below its melting point due to effective heat removal.

Thus, a pilot accelerator-based source of epithermal neutrons, which is specially designed for wide use in oncology clinics for BNCT, is successfully operating in the neutron generation regime. A γ detector based on an NaI scintillator crystal was used to determine the neutron yield and to measure the spectrum of accompanying γ radiation. The neutron yield was evaluated at 2.6×10^9 s^{-1} at a proton beam current of 140 μA, which agrees well with the results of calculations. Preliminary data on the spectrum of neutrons, which is also in agreement with theoretical predictions, were obtained using bubble type detectors. Now we are planning to perform accurate measurements of the neutron spectrum using the time-of-flight technique and to obtain a therapeutic beam of epithermal neutrons.

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REFERENCES

1. G. Locher, Am. J. Roentgenol. Radium Ther. **36**, 1 (1936).
2. H. Hatanaka, Basic Life Sci. **54**, 15 (1990).
3. H. Hatanaka and Y. Nakagawa, Int. J. Radiat. Oncol. Biol. Phys. **28**, 1061 (1994).
4. B. F. Bayanov, V. P. Belov, E. D. Bender, et al., Nucl. Instr. Meth. Phys. Res. A **413**, 397 (1998).
5. A. Kudryavtsev, Yu. Belchenko, A. Burdakov, et al., Rev. Sci. Instr. **79**, 02C709 (2008).
6. B. Bayanov, V. Belov, V. Kindyuk, E. Oparin, and S. Taskaev, Appl. Radiat. Isotopes **61**, 817 (2004).

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