RESULTS OF FIRST EXPERIMENTS ON NEUTRON GENERATION IN THE VITA NEUTRON SOURCE

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Pilot innovative facility for neutron capture therapy was built at Budker Institute of Nuclear Physics, Novosibirsk. This facility is based on a compact vacuum insulation tandem accelerator (VITA) which is designed to produce proton current up to 10 mA. Epithermal neutrons are proposed to be generated by 1.915 MeV protons bombarding a lithium target using ^{7}Li(p, n)^{7}Be threshold reaction. Experiments on neutron generation have been started in the March of 2008. Gamma-ray spectrometer based on NaI scintillator was used for measuring gamma rays emitted by lithium under the action of protons, and by other nuclei under the action of neutrons. The gamma-ray spectrometer was calibrated by radioactive sources ^{60}Co, ^{137}Cs, ^{7}Be and ^{40}K. This spectrometer was used as activation detector due to capture of epithermal neutrons by iodine also. Bubble detectors were used for registration of fast and thermal neutrons. Total yield of neutrons was defined by ^{7}Be activity. Simulation of flux and spectrum of both gamma-ray and neutrons at 50 μm lithium thickness and 1.915 MeV proton beam were performed by means of PRIZMA code. Calculation of speed of detector activation had been carried out. In the report the results of the first experiments on neutron generation and results of simulations are presented and discussed. Prospect of accelerator based facility and near threshold regime of neutron generation for boron neutron capture therapy had been confirmed by current experiment. The immediate plans of target improvement and using of time-of-flight technique for neutron spectra measurement are declared.

1. Introduction

In 1998 at Budker Institute of Nuclear Physics an original accelerating source of epithermal neutrons had been offered on a base of the tandem accelerator with vacuum insulation VITA, suitable for wide using of BNCT in clinical practice [1]. It is offered to carry out generation of neutrons as a result of threshold reaction ^{7}Li(p, n)^{7}Be while dumping the 1.915 MeV 10 mA proton beam on lithium target. At present moment the accelerator is constructed [2]. In this work the results of the first experiments on generating of neutrons are presented.

2. Gamma-registration system

A γ-detector based on NaI Ø6 × 6 cm and Photonis XP3312B photomultiplier with the power supply optimized for spectrometer problems were used to register γ-radiation from lithium target. All elements of the detector are covered by metal shell and reliably protected from magnetic fields and electromagnetic noises. Stability of the power supply voltage is about 0.1 %. This detector was placed inside a lead shield with thickness of walls ~10 cm at 222 cm distance under the lithium target and covered by borated polyethylene when necessary. The collimator port size was 10 × 15 mm. The spectral analysis of scintillation impulses from γ-detector is carried out with the help of a high-speed spectrometer ADC, installed in the computer. The resolution of the ADC is 4096 channels at the amplitude of input impulses from -50 mV to -4 mV and speed of signal analysis is up to $4 \cdot 10^5$ imp/s. The software allows us to observe a spectrum accumulation in real time, to save and to display saved spectrums as well as to set the exposition time. Preliminary calibration of gamma-spectrometer was carried out with the help of the ^{40}K spectral line registered in the gamma background and using a calibrated radioactive source ^{60}Co with activity $5.66 \cdot 10^7$ Bq and energy of γ-quanta 1173 and 1332 keV, and ^{137}Cs with activity $2.15 \cdot 10^8$ Bq and energy 662 keV. The calibration confirmed the spectrometer system linearity and showed that NaI crystal has 9.5 % energy resolution and provides full absorption of energy for ~37 % of 662 keV gammas, that is close to the 447 keV spectral line.

3. Experimental results

For radiation safety the proton beam current on the target has been limited by size using a collimator to an order of ~100 μA. The proton current on the target was measured indirect by heating a coolant.

In Fig. 1 the spectrum registered at energy of protons lower than neutron generation threshold is shown. At energy of the proton beam 1.7 MeV the bright spectral line with energy 477 keV related to excitation of lithium nuclei by protons is visible. If conditions of the proton beam passage worsen, the yield of γ-quanta with this energy decreases as well. Also, the γ-quanta with lower energy are visible. These quanta are related to the work of the accelerator and-or hitting of the proton beam on constructional materials. Turning off the magnet directing the protons to the lithium target results in the situation that only a background radiation from working accelerator remains in a spectrum.

At proton energy increased up to 1.92 MeV, neutrons start to be generated and γ-quanta from activated elements of the accelerator construction appear in a spectrum (Fig. 2). We should notice that the detector has been covered with borated polyethylene to attenuate the neutron flux. The total count speed has increased ~2 times in comparison with subthreshold mode. When borated polyethylene is removed from the detector the signal increases considerably (Fig. 3) that is associated with absorption of neutrons by iodine. This sort of sensitivity of NaI detector to neutrons allows us to use it as activation detector as well.

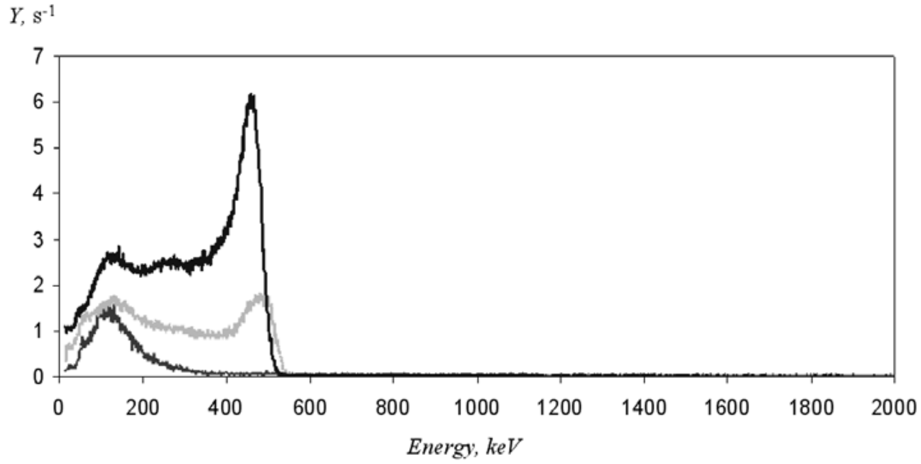

Fig. 1. Gamma spectra at the proton beam energy of 1.7 MeV: optimal beam passage (top curve); not optimal (middle curve); the spectrum at beam dumping on a wall of the vacuum chamber (bottom curve).

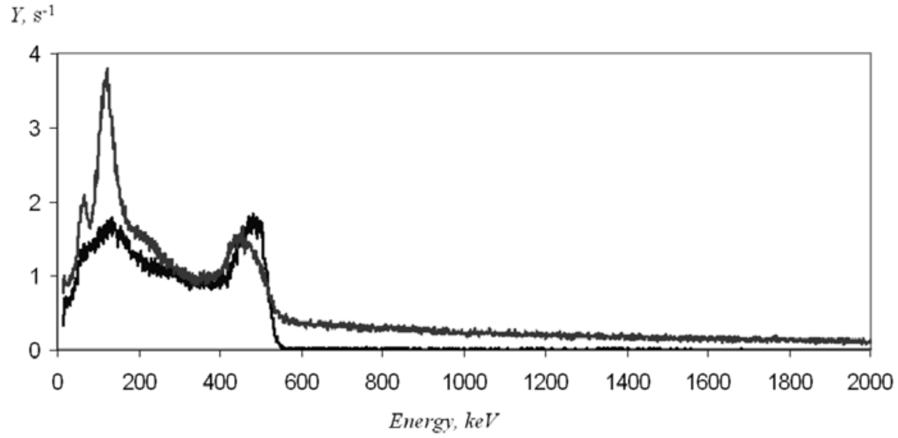

Fig. 2. Gamma spectra in case of the detector covered with borated polyethylene at dumping 1.92 MeV (top curve) and 1.7 MeV (bottom curve) proton beam on the lithium.

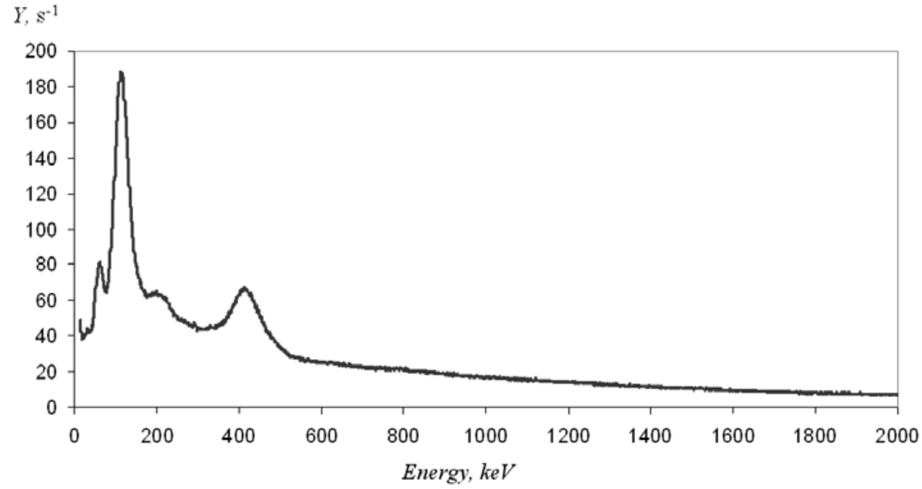

Fig. 3. Gamma spectrum in case of the detector without borated polyethylene protection at dumping 1.92 MeV proton beam on the lithium.

4. Usage of NaI as activation detector

^{127}I natural isotope has some resonances of neutron capture with energies from 20 eV to 1 keV with cross-sections about tens of barn (Fig. 4). Resonant integral of capture $\int \sigma \frac{dE}{E} = 140$ barn. As the epithermal neutrons are of interest for neutron capture therapy the use of NaI as activation detector seems to be the ideal case.

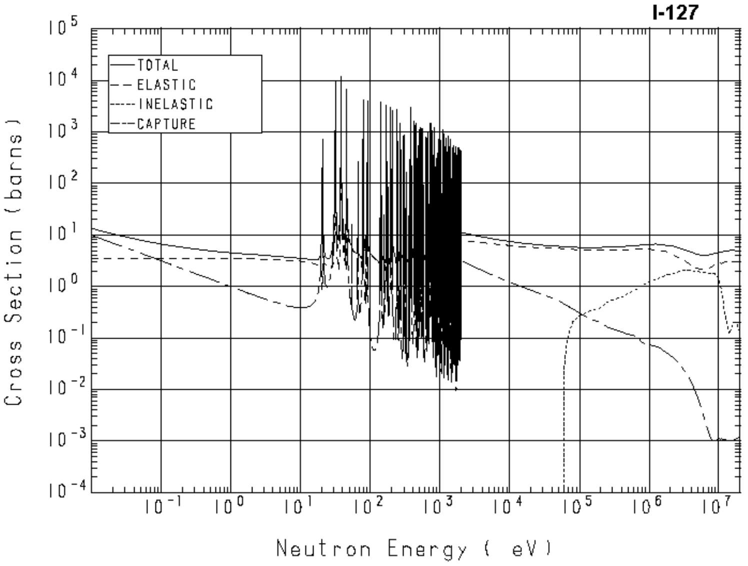

Fig. 4. Neutron capture and neutron scattering cross-sections of iodine-127.

Process of neutron capture by iodine-127 is accompanied by instant emission of 1.6 γ-quanta of which 0.3 have energy lower than 430 keV, and the others - from 4 to 6.7 MeV. It is proved in the measurements that spectral peaks are obviously visible at energies 63, 115, 202 and 416 keV which are in good agreement with transition energies between excitation levels in ^{128}I.

The ^{128}I isotope appeared as a result of neutron capture decays with a half-life time 25 min. In 6.4% of cases decay takes place by electron capture without any radiation, in 93.6 % – β^- decay with emission of electron with energy up to 2.12 MeV. Apart from radioisotope ^{128}I there is a radioisotope ^{24}Na which appears in the scintillator with a speed at level of 2 % from iodine. Fig. 5 shows the spectrum registered by the activated detector. Such spectrum is specific for β^- decay.

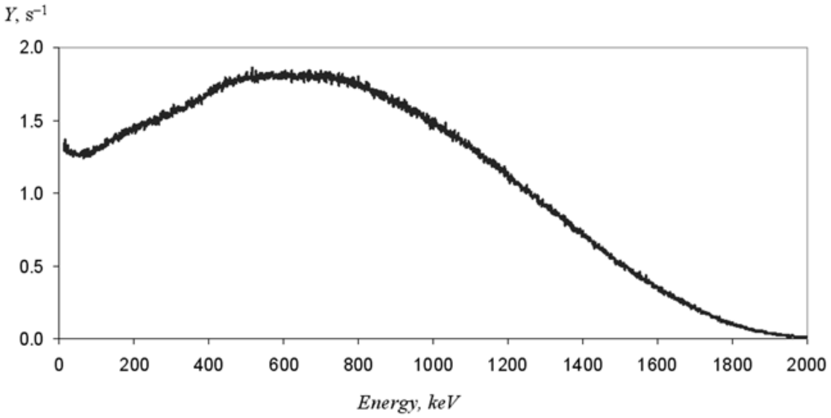

Fig. 5. Gamma spectrum of the activated detector (the measurement was begun in 13 minutes after the termination of neutron generation and proceeded within 93 minutes).

The measurement lasted from 13 to 106 minutes after the termination of neutron generation, and average count speed was 2000 s^{-1}. When estimating the neutron yield it is necessary to consider that the part of the activated nuclei decay to the moment of measurement for the reason that time of neutron generation and time of spectral measurements are comparable to iodine half-decay period. It is defined by the measured activity that there were ~2 · 10^7 nuclei of ^{128}I in the scintillator. As generation of neutrons was carried out within 420 seconds, the speed of activation turns out to be equal to 5.4 · 10^4 s^{-1}. It was calculated by MCNP method, that at the proton current 100 μA the speed of neutron capture for iodine should make 4.15 · 10^4 s^{-1}, for sodium 0.08 · 10^4 s^{-1}. Hence it turns out that the proton beam current was equal to 130 μA in the experiment, that is in good agreement with current measurements.

5. The lithium target activation

As getting of each neutron in reaction ^{7}Li(p, n)^{7}Be is accompanied by occurrence of ^{7}Be radioactive nuclei, the total yield of neutrons can be determined by measuring remaining activity of lithium target. After the termination of neutron generation the target with lithium layer has been taken out and placed 21 cm over NaI detector. In Fig. 6 the measured γ-spectrum of the activated target is presented on which the 477 keV peak of γ-quanta from beryllium decay is obviously visible. The measured count speed for this peak was 4.1 events in a second. Given that only 37 % of γ-quanta were found in the peak of full absorption, the target radiates $2.6 \cdot 10^4$ s^{-1} γ-quanta, and activity of beryllium turns out to be $2.6 \cdot 10^5$ Bq. In the given experiment the irradiation of the target with current 130 μA within 7 minutes was preceded by irradiation with approximately 2 times lower current within 6 minutes. Calculations show that the target activation reached 2.7 10^5 Bq. The good agreement is visible. As rate of decay makes $1.51 \cdot 10^{-7}$ s^{-1} from the total number of radioactive nuclei, the quantity of generated neutrons is $2 \cdot 10^{12}$, and the average neutron yield makes $2.9 \cdot 10^9$ s^{-1}.

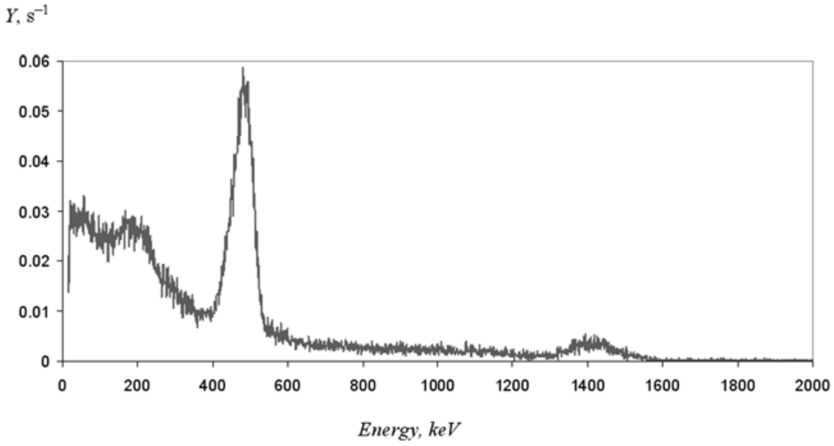

Fig. 6. Gamma spectrum of the activated target.

6. Primary analysis of the generated neutron spectrum

Fig. 7. The BDT detectors after neutron generation.

For the primary analysis of generated neutrons spectrum we used bubble detectors BDT and BD100R (Bubble Technology Industries, Canada). Detector BDT is a flask 19 mm in diameter 145 mm length and 58 g weight filled with polymer containing droplets of superheated liquid which structure is matched so that the detector has the maximum sensitivity at the thermal energies of neutrons ~10^{-3} bubble/neutron·cm^2. BD100R detector, on the contrary, is sensitive to neutrons with energy more than 100 keV. In Fig. 7 two BDT detectors after neutron generation are shown. In these experiments in BDT detector it was formed bubbles 20 times more than in BD100R detector. Such ratio corresponds to the expected spectrum with average energy 40 keV, realized in near-threshold mode.

7. Conclusion

At Budker Institute of Nuclear Physics the first experiments on generation of neutrons for BNCT are carried out by means of tandem-accelerator VITA. The neutron yield is defined with the help of γ-detector with NaI scintillator measure remaining activity of the target and as activation detector. The average neutron yield determined in the experiments is $2.6 \cdot 10^9$ s^{-1} at the proton beam current ~130 μA that is in good agreement with theoretical value. Preliminary conclusions about spectrum of neutrons are made using bubble detectors and correspond quite well to theoretical predictions. More careful studying of the neutron spectrum is planned on the future using time-of-flight technique.

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