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First neutron generation in the BINP accelerator based neutron source

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ABSTRACT

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 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. The results of the first experiments on neutron generation are reported and discussed.

1. Introduction

In 1998 at Budker Institute of Nuclear Physics an original source of epithermal neutrons had been offered on a base of the tandem accelerator with vacuum insulation VITA, suitable for wide use of BNCT in clinical practice (Bayanov et al., 1998). 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 the current stage the accelerator is constructed (Kudryavtsev et al., 2008). In this work the results of the first experiments on generating neutrons are presented.

2. Gamma-registration system

A γ-detector based on NaI $\varnothing 6\times 6$ 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 shells 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 wall thickness ~10 cm at 222 cm distance under the lithium target and covered with 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 to −4 mV and speed of signal analysis is up to 4×10^5 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 γ-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 5.66×10^7 Bq and energy of γ-quanta 1173 and 1332 keV, and ^{137}Cs with activity 2.15×10^8 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 indirectly by the coolant heating.

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. The γ-quanta with lower energy are also visible. These quanta are related to the work of the accelerator and–or hitting 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

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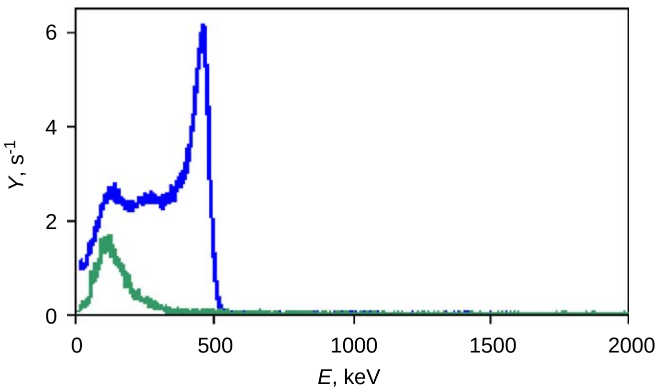

Fig. 1. Gamma spectra at the proton beam energy of 1.7 MeV (top curve); the spectrum at beam dumping on a wall of the vacuum chamber (bottom curve).

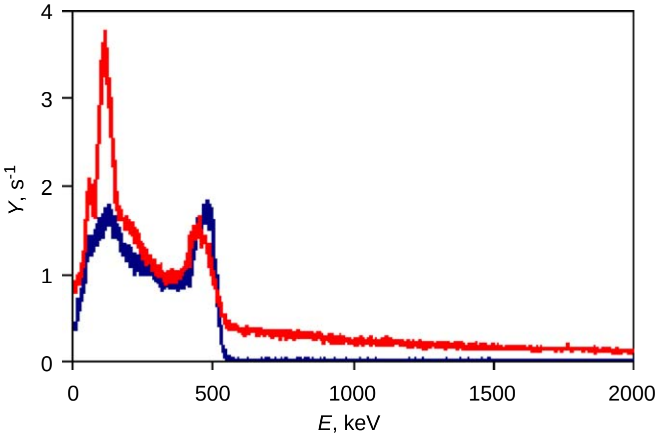

Fig. 2. Gamma spectra in case of the detector covered with borated polyethylene at dumping 1.92 MeV (top curve) and 1.7 MeV (bottom curve) proton beam on the lithium.

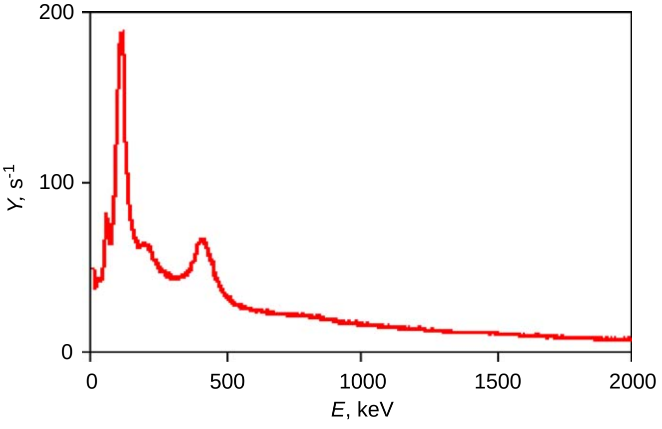

Fig. 3. Gamma spectrum in case of the detector without borated polyethylene protection at dumping 1.92 MeV proton beam on the lithium.

polyethylene to attenuate the neutron flux. The total count speed has increased ~2 times in comparison with the subthreshold mode. When the borated polyethylene is removed from the detector, the signal increases considerably (Fig. 3) that is associated with capture of neutrons by iodine. This sort of sensitivity of NaI detector to neutrons allows us to use it as activation detector as well.

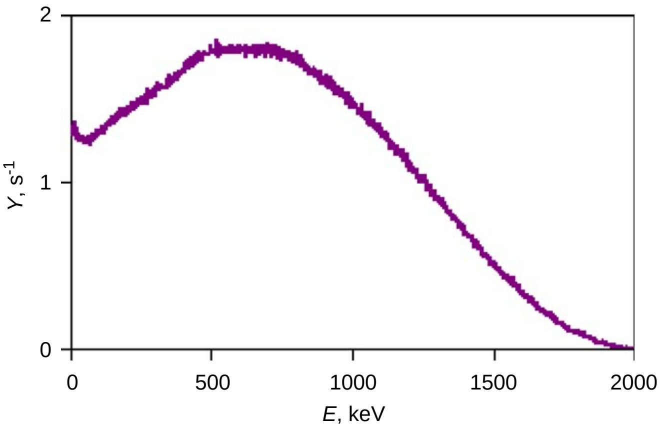

Fig. 4. Gamma spectrum of the activated detector (the measurement started 13 min after the termination of neutron generation and lasted 93 min).

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. Resonant integral of capture $\int \sigma \, dE/E = 140$ b. As the epithermal neutrons are of interest for neutron capture therapy the use of NaI as activation detector seems to be the ideal case.

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 which decays with a half-life time of 25 min. In 6.4% of cases decay takes place by electron capture without any radiation, in 93.6% through a β^- decay with emission of electron having energy up to 2.12 MeV. Apart from the radioisotope ^{128}I there is another radioisotope, ^{24}Na which appears in the scintillator with a speed level estimated to be of the order of 2% with respect to iodine. Fig. 4 shows the spectrum registered by the activated detector. Such spectrum is specific for β^- decay.

The measurement started 13 min after the termination of neutron generation and stopped at the 106th min, with an average count speed registered of 2000 s^{-1}. When estimating the neutron yield it is necessary to consider that the part of the activated nuclei decay during the time interval of measurement for the reason that time of neutron generation and time of spectral measurements are comparable to iodine half-decay period. About 2×10^7 nuclei of ^{128}I were estimated to be inside the scintillator by the measured activity. As generation of neutrons was carried out within 420 s, the speed of activation turns out to be equal to $5.4 \times 10^4\,s^{-1}$. It was calculated by MCNP code that at the proton current of 100 μA the neutron capture reaction rate for iodine should be $3.77 \times 10^4\,s^{-1}$, while for sodium $0.058 \times 10^4\,s^{-1}$. Hence it turns out that the proton beam current was equal to 140 μA in the experiment, that is in good agreement with current measurements.

5. The lithium target activation

As each neutron yielded in reaction ^{7}Li(p,n)^{7}Be is accompanied by the occurrence of ^{7}Be radioactive nuclei, the total yield of neutrons can be determined by measuring the remaining activity of lithium target. After the termination of neutron generation the

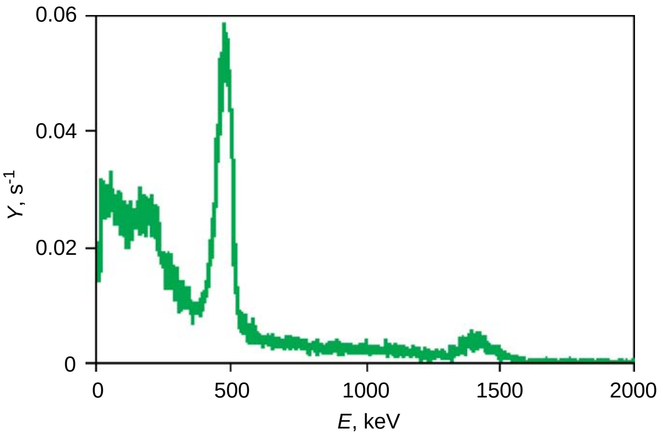

Fig. 5. Gamma spectrum of the activated target.

target with lithium layer has been taken out and placed 21 cm over NaI detector. In Fig. 5, 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 $2.6\times10^4\,\mathrm{s}^{-1}$ γ-quanta, and activity of beryllium turns out to be 2.6×10^5 Bq. In the given experiment the irradiation of the target with current 140 μA within 7 min was preceded by irradiation with approximately 2 times lower current within 6 min. Calculations show that the target activation reached 2.9×10^5 Bq, in good agreement with previous estimation. As the rate of decay of ^{7}Be radioactive nuclei is $1.51\times10^{-7}\,\mathrm{s}^{-1}$ the quantity of generated neutrons is 2×10^{12}, and the average neutron yield makes $2.9\times10^9\,\mathrm{s}^{-1}$.

6. Primary analysis of the generated neutron spectrum

For the primary analysis of the 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 $\sim10^{-3}$ bubble/neutron cm^2. BD100R detector, on the contrary, is sensitive to neutrons with energy more than 100 keV. In Fig. 6 two BDT detectors after neutron generation are shown. In the experiments performed the number of bubbles scored in BDT detector was 20 times greater than in BD100R one. Such a ratio corresponds to the expected spectrum with average energy 40 keV, realized in near-threshold mode.

Fig. 6. The BDT detectors after neutron generation.

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 by means of a γ-detector using a NaI scintillator through the measurement of the remaining activity of the target and as activation detector itself. The average neutron yield determined in the experiments is $2.6\times10^9\,\mathrm{s}^{-1}$ at the proton beam current $\sim$140 μA that is in good agreement with theoretical value. Preliminary conclusions about the spectrum of neutrons are made using bubble detectors and correspond quite well to theoretical predictions. A more detailed investigation of the neutron spectrum is planned in the future using time-of-flight technique.

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