ISSN 0020-4412, Instruments and Experimental Techniques, 2017, Vol. 60, No. 4, pp. 522–525. © Pleiades Publishing, Ltd., 2017.
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NUCLEAR EXPERIMENTAL TECHNIQUE

Studying the Energy Stability of a Vacuum-Insulated Tandem Accelerator Using γ-Resonance Reactions

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Received September 15, 2016

Abstract—Experiments on the detection of γ rays generated in the $^{13}C(p, \gamma)^{14}N$ reaction at the Novosibirsk vacuum-insulated tandem accelerator were carried out. Owing to the updated detection system, it was possible to measure the energy spread of beam protons and develop a method for long-term stabilization of the slow drift of the beam energy. The measured energy spread was 1.20 ± 0.15 keV, which was only 0.07% of the total beam energy. This makes the tandem accelerator developed by the vacuum-insulated Budker Institute of Nuclear Physics an attractive tool for solving various research and applied problems.

DOI: 10.1134/S0020441217040029

1. INTRODUCTION

A unique tandem accelerator with vacuum insulation of its electrodes was built at the Budker Institute of Nuclear Physics for generating a proton beam with a current of approximately 10 mA and an energy of 2.5 MeV. The accelerator was developed as a basis for a compact source of epithermal neutrons from $^7Li(p, n)^7Be$ reaction for carrying out neutron-capture therapy of tumors under clinical conditions [1]. The high energy stability of the generated beam ($dE/E < 0.1\%$) is one of the necessary important properties of the accelerator. This stability is needed both for therapy and for alternative applications: in studies on the detection of blasting explosives using γ-resonance absorption method [2], in investigations of the parameters of the neutronless thermonuclear fusion reaction $^{11}B(p, \alpha)\alpha\alpha$, or in metrology applications of the accelerator neutron source, e.g., in calibration of the dark-matter detector [3].

A set of experiments on the detection of resonance γ rays generated on graphite targets by a high-power proton beam made it possible to study the energy stability of the vacuum-insulated tandem accelerator. An advanced detection system for radiation generated in the $^{13}C(p, \gamma)^{14}N$ reaction was developed for this study. Experimental data on the energy stability of the proton beam were obtained and the small energy spread of beam particles was confirmed. A slow drift of the beam energy was discovered during long-term operation of the accelerator. For this drift to be eliminated, a system of long-term stabilization of the proton-beam energy was developed and tested.

2. MATERIALS AND METHODS

Monochromatic resonance γ rays are generated in the $^{13}C(p, \gamma)^{14}N$ reaction. This reaction is one of the reactions of the solar fusion cycle and is used, in particular, for energy calibration of accelerators. The 9.17-MeV γ rays are generated at a resonance proton energy of 1746.6 ± 0.9 keV; at that, the are no any other cases for this process, so the word "case" makes wrong understanding width of the resonance energy level of a ^{14}N nucleus is only 128 eV [4, 5].

Owing to the small width of the proton-capture resonance, the slope of the measured excitation curve of this spectral line is determined by the energy spread of beam protons, which allows one to study the energy characteristics of the beam with a high precision.

The 9.17-MeV γ rays may be absorbed in the resonance manner by nitrogen nuclei, which forms the basis for the γ-resonance method for detecting nitrogen-containing substances (explosives and narcotics) [6]. One feature of their generation by nitrogen nuclei is that γ rays are emitted by nuclei moving as a result of proton recoil, which, due to the Doppler effect, leads to the dependence of the γ-ray energy on the exit angle. Therefore, resonant γ rays appear to be directed within a narrow cone with a vertex angle of 80.66° with respect to the proton-beam direction. The width of this cone and the monochromaticity of the generated γ-ray beam are affected by the energy spread of the proton beam, which results in the stringent requirements for the stability of the proton energy in practical application of resonance γ rays.

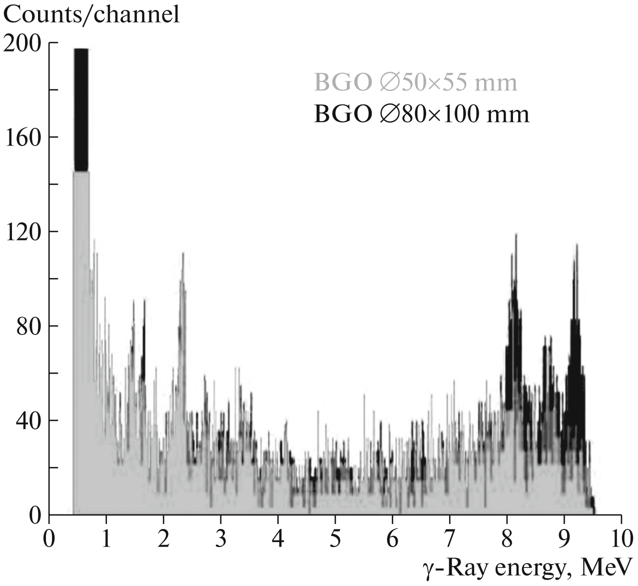

Fig. 1. The comparison of the resolution of the detectors based on BGO scintillators with different sizes.

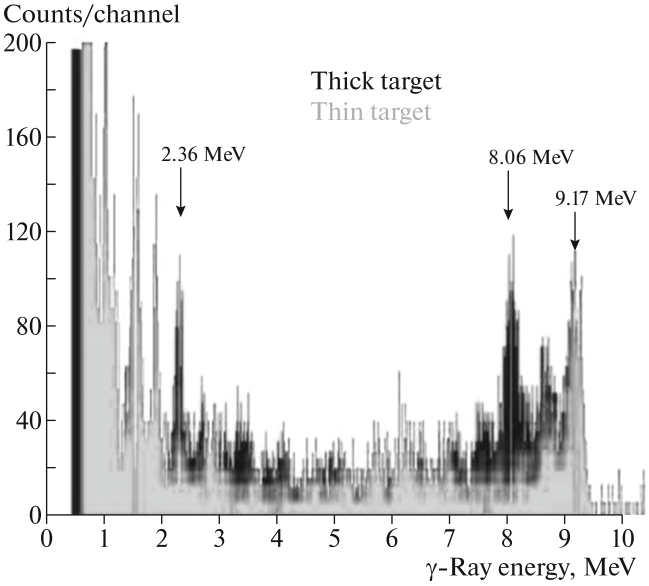

Fig. 2. The comparison of the radiation spectra generated using the thick and thin graphite targets.

Specially developed thick and thin (quasi-thin) graphite targets enriched in ^{13}C isotope were used in the experiments [7]. In this case, the intensity of the spectral line with an energy of 9.17 MeV was analyzed. The test facility described in [8] was used to detect γ rays. We did not succeed in attaining good resolution in the detection of γ rays with energies over 8 MeV in the first experiments conducted at this facility. For the described set of experiments, a detection system was assembled on the basis of a scintillation detector with a bismuth orthogermanate (BGO) with a larger size: ∅80 × 100 mm instead of ∅50 × 55 mm. This allowed us to efficiently discern the main spectral lines in the high-energy spectrum region [9].

3. EXPERIMENTAL RESULTS

3.1. The Resolution of the Detectors and Spectra Generated Using the Thick and Thin Targets

Owing to the use of the larger scintillation crystal, the detector resolution for high-energy γ rays was substantially increased. The spectra of γ rays that are generated on the thick graphite targets and measured by detectors with “small” and “large” BGO crystals are presented in Fig. 1 for comparison. The comparison of the spectra generated using thick and thin graphite targets is shown in Fig. 2. It is assumed that the thin target allows generation of only one required spectral line. Nevertheless, the experiment shows that we do not succeed in eliminating parasitic spectral lines, since the presence of ^{12}C in the target substance, as well as the high-melting substrate material (tantalum) make their own contributions to the generation of γ rays.

The clear-cut recognition of spectral lines with energies of 8.06 and 9.17 MeV makes it possible to normalize the intensity of the resonance spectral line by the non-resonance one when carrying out experiments on the γ resonance absorption [2], since the intensities of both lines at an invariable proton-beam energy depend on the beam current in a similar manner, but the character of their absorption differs in the presence of nitrogen nuclei in the composition of the absorbing material. The use of such normalization substantially simplifies the making of measurements and is promising for practical application in the detection of nitrogen-containing substances.

3.2. The Excitation Curves

The excitation curve of the resonance spectral line for the thick and thin targets can be measured by smoothly varying the accelerating voltage. If the proton energy exceeds the resonance value in the case of the thick target, the yield of 9.17-MeV γ rays must increase up to the maximum value and then remain unchanged with a further increase in the energy. In the case of the thin target, the γ-ray yield increases to the maximum value in a similar manner, but drops again when the proton energy exceeds the resonance energy by the value of the ionization loss in the thin target. The measured excitation curves are shown in Fig. 3. The energy spread of beam protons determined by the slope of the excitation curves is 1.20 ± 0.15 keV, which makes 0.07% of the total beam energy. Energy monochromaticity as high as this satisfies the requirements for the beam both in the task of neutron generation in the near-threshold regime of reaction ^{7}Li(p, n)^{7}Be [10] and in the task of resonance γ-ray generation for the detection system of nitrogen-containing substances [11].

The measured width of the excitation curve for the thin target is 19 ± 1 keV and is determined by the ionization loss of protons in the graphite layer of the target. The reverse slope of the excitation curve can be attributed both to the simultaneous existence of the initial energy spread of beam protons and the spread of the ionization loss, whose value can thus be determined (it is 2.6 keV). The evaluated ionization loss of protons in the 0.53-μm-thick graphite target and the spread of the ionization loss, which are analytically determined using the GEANT-4 program, are 19.1 and 2.8 keV, respectively, thus demonstrating good agreement with the data obtained in the experiment.

The angular spread of protons at the exit from the thin target obtained in the same calculations is 3.51 mrad. Taking the fact into account that the natural width of the resonance radiation cone is 3.1 mrad, one can draw a conclusion that proton scattering in the target can considerably increase the width of the resonance radiation cone and thereby substantially lower the contrast of measurements in detection of resonance γ rays. Therefore, an excess of the beam energy over the resonance value even by 5 keV makes a substantial contribution to the width of the resonance radiation cone. For practical application of the method for γ-resonance detection of nitrogen-containing substances, it is desirable that a proton beam with the energy maximally approaching the reaction threshold be used, thereby providing the maximum monochromaticity of the resonance γ-ray beam.

The repeated measurements of the excitation curves at different instants of time demonstrate a slow drift of the accelerating voltage. In particular, the proton energy may change by 20 keV over 2 h. This fact should be taken into account if the accelerator is used in applications requiring a high long-term stability of the beam energy.

3.3. Long-term Stabilization of the Beam Energy

The high instantaneous stability of the proton-beam energy makes it possible to carry out radiation generation when the beam energy only slightly exceeds the threshold energy. An additional detector measuring the intensity of the 9.17-MeV spectral line can be used for long-term stabilization of the proton-beam energy. The detector must be placed at a minimum distance from the graphite target to provide the maximum counting rate. In this case, a short-term (1 s long) measurement allows one to count events, whose quantity is sufficient for determining the spectral-line intensity with a precision as high as 1–2% and to introduce correction to the accelerating voltage if the measured intensity deviates from the specified value.

A small (∅50 × 55 mm) BGO crystal was used for testing this energy stabilization technique. This crystal was placed at a distance of 30 cm from the graphite target. The voltage corresponding to the resonance line intensity at a level of 80% of the maximum value was selected to be the point for the stabilization. The resonance spectral line was automatically recognized using the Levenberg–Marquardt algorithm of nonlinear approximation, and its intensity was normalized to the proton-beam current. If the normalized counting rate deviated from the mean value by more than 0.5 Hz/μA, a decision was automatically made to change the accelerating voltage by 1 kV in the required direction. The counting rate of resonance γ rays during a 2.5-h-long experiment is shown in Fig. 4. In the course of this experiment, the drift of the excitation curve exceeded 3 kV. The curve discontinuities correspond to the repeated measurements of the excitation curve for verifying the existing drift of the beam energy.

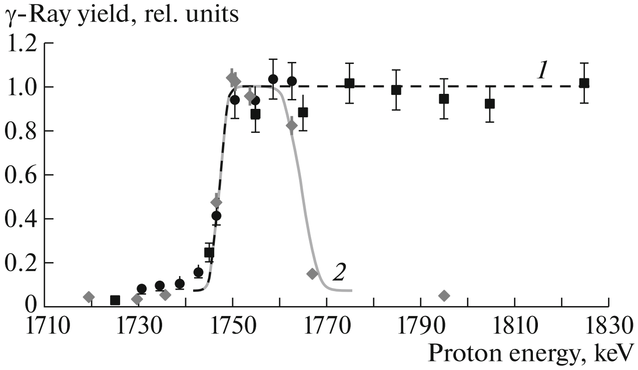

Fig. 3. The measured excitation curves for (*1*) the thick and (*2*) thin targets.

This energy stabilization method is also applicable to neutron generation near the threshold of ^{7}Li(p, n)^{7}Be reaction. Due to the fact that the neutron yield rapidly increases near the reaction threshold and the intensity of concomitant γ rays with an energy of 478 keV also increases, the energy can be stabilized using a neutron or γ-ray detector.

4. CONCLUSIONS

The radiation detection system was produced on the basis of a scintillation detector. It possesses a sufficient energy resolution for detection of high-energy γ rays generated in the ^{13}C(p, γ)^{14}N reaction. Experiments on the detection of γ rays generated on graphite targets under exposure to a high-power proton beam were conducted. The excitation curves of the 9.17-MeV spectral line were measured for γ-ray generation on the thick and thin graphite targets. The energy stability of the beam generated in the vacuum-insulated tandem accelerator was studied in the course of the experiments. The measured energy spread of beam protons was 0.07%. This low value makes the vacuum-insulated tandem accelerator built at the

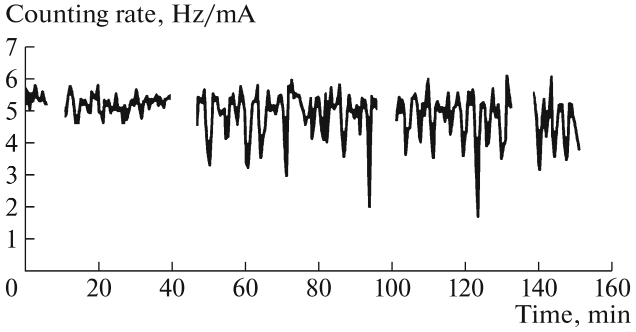

Fig. 4. The counting rate of γ rays as a result of automatic correction of the accelerating voltage during 2.5-h operation.

Budker Institute of Nuclear Physics an attractive tool for solving various research and applied problems. In particular, this small energy spread allows the generation of the neutron flux near the energy threshold of reaction ^{7}Li(p, n)^{7}Be, which possess the maximally favorable spectrum for carrying out boron-neutron-capture therapy of tumors. It also allows generation of a resonance radiation flux in reaction ^{13}C(p, γ)^{14}N with a high monochromaticity for use in detection systems for nitrogen-containing explosives. The system of long-term energy stabilization of the proton beam was proposed to eliminate the slow energy drift. This system is based on the monitoring of the radiation intensity, which varies with tuning-out from the resonance energy of the used reaction. The experimental testing of the system was performed using γ rays generated in the ^{13}C(p, γ)^{14}N reaction. In the future, this system can be adapted for use with other threshold reactions, in particular, with the ^{7}Li(p, n)^{7}Be reaction.

The results of this study can be used for further investigations of the properties of nuclear reactions resulting in the generation of high-energy γ rays and the processes of their resonance absorption: in particular, for more detailed measurements of the cross sections and the branching ratios in reaction ^{13}C(p, γ)^{14}N, as well as for investigations of the resonance γ-ray absorption by nitrogen nuclei.

ACKNOWLEDGMENTS

This work was supported by the Russian Science Foundation (project no. 14-32-00006) with the support of the Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences).

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Translated by N. Goryacheva