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THE STUDIES OF THE EXCITATION FUNCTIONS OF REACTIONS WITH EMISSION OF γ-QUANTA INDUCED BY PROTONS WITH ENERGY 200…1800 keV ON NUCLEI OF ^{10}B AND ^{11}B

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A systematic study of the relative thick-target yields of prompt γ-rays with the energies of the most suitable for elemental and isotopic analysis for stable boron isotopes following proton bombardment has been carried out at Ep = 200…1800 кeV. The relevant excitation function of γ-emission 429 keV from reaction $^{10}B(p,\alpha\gamma)^{7}Be$, 718 keV from reaction $^{10}B(p,p'\gamma)^{10}B$, 4.439 and 16.106 MeV from reaction $^{11}B(p,\gamma)^{12}C$ are depicted and a tables of yields of prompt γ-rays as function of proton bombardment energy are given. The experimental procedure is described. Particular aspects of the measuring techniques are discussed.

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INTRODUCTION

The studies of the excitation functions of reactions occurring on nuclei of stable boron isotopes irradiated by accelerated ions are of interest from a fundamental and applied point of view. In the first case, measurements of the cross sections for nuclear reactions at low protons energies are important for refining the S-factor in astrophysical research. In the second, the use of the products of nuclear reactions to determine the stoichiometry and impurities of boron in samples of various compositions and to determine the isotopic composition of boron contained in the samples under study. Since boron-containing substances are widely used in medicine, industry and nuclear power [1 - 4], information on the elemental and isotopic composition is extremely important at all stages of the extraction, production and use of boron and its compounds. Natural boron includes two stable isotopes, ^{10}B and ^{11}B, with a content of 19.7 and 80.3 at.%. accordingly, but there are some variations in isotopic abundance – about 1%.

Nuclear analysis, using the reactions induced by the charged particles from electrostatic accelerators (NRA) as well as mass-spectrometry, is the most suitable method as for the determination of the isotope composition and stoichiometry of the materials on the base of the boron, so and for the definition of small quantities of boron in matrices of different elemental composition. There have been some reports listing prompt γ-rays which are useful in analytical applications using NRA. These reports includes γ-rays from reactions with the incident ions: protons, deutrons, tritons, ^{3}He and α-particles [5] ore only protons [6, 7]. Some of these reports contain data on the energies of quanta emitted in reactions on nuclei of stable isotopes of boron [5, 7].

The information about the energy lines of gamma radiation suitable for the identification of boron and its isotopes contained in the aforementioned reports makes it possible to establish their presence in the objects of study, but it is not enough to select the optimal experimental conditions, if it is necessary to determine the elemental and isotopic composition of both pure boron and materials based on boron compounds. The most important tool that allows one to selectively change the ratio of the intensities of the registered γ-lines is the proton energy. Therefore, for the practical analysis of the elemental and isotopic composition, data on the change in the intensity of the γ-radiation yield, as a function of the proton energy are important.

The aim of work was to measure yields of γ-radiation as function of protons energy for a number of reactions of protons on nuclei ^{10}B, ^{11}B. To obtain these data series of measurements of spectra γ-radiation from thick boron target irradiated by beam of protons with energy range 200…1800 keV were made.

EXPERIMENTAL EQUIPMENT

The measurements presented in this work have been made, using the 2 MeV Van de Graaff accelerator "Sokol" NSC KIPT [8]. The irradiation chamber used in the experiment is located at the exit of the experimental channel of the accelerator, in which the accelerated particles are deflected at an angle of 45°. The Ge(Li) and scintillation NaI(Tl) detectors were used to register the γ-radiation excited in the nuclear reactions under study. The geometric layout of the experiment is shown in Fig. 1.

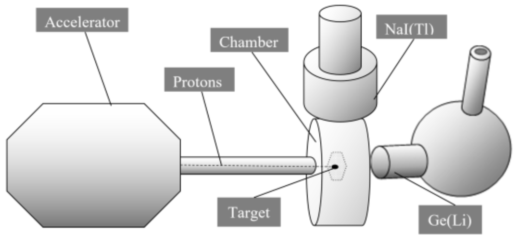

Fig. 1. Geometric scheme of the experiment

The protons from accelerator, passing along the ion pipeline, through the forming system, including tantalum diaphragms, reached the surface of the target, located in the measuring chamber, pumped to a pressure of 10^{-5} Torr. The direction of motion of the beam of protons coincided with the normal to the surface of the target. The charge of the protons on the target was measured with the help of a current integrator. The irradiation chamber was isolated from the ion guide and the alignment table and was used as a Faraday cup to measure the proton charge on the target.

The Ge (Li) detector, located in the horizontal plane at an angle of 0° to the beam axis was used to register γ-radiation with energies of 400…5000 keV. The resolution of the Ge (Li) detector was 2.5 keV for γ-quanta with an energy of 1332 keV, and its efficiency was equivalent to 19%, relative to a 7.5 by 7.5 cm NaI(Tl) detector.

That of the NaI(Tl) scintillation detector with a crystal volume of 160 cm^3. NaI(Tl), a large-volume detector, was also used to detect the high-energy γ-radiation with energies of 4000…17000 keV because of to significant decrease in the detection efficiency of the Ge(Li) detector in this region of photon energies. NaI(Tl) detector was installed vertically above the target at an angle of 90° relative to the direction of the proton beam.

MEASURING PROCEDURE

The energy calibration of the accelerator was performed using a resonance at an energy of 991.2 keV from the ^{27}Al(p,γ)^{28}Si reaction. We used calibrated radioactive sources based on ^{137}Cs, ^{60}Co, and ^{152}Eu isotopes to calibrate the spectrometric tract and determine the efficiency calibration of detectors.

The beam size on the target was varied using a set of diaphragms and was finally chosen with a diameter of 5 mm. The target for the measure of excitation function was prepared in the form of tablet from powder of boron of natural isotopic composition of 9 mm in diameter and 2 mm of thickness.

A Ge(Li) detector was used at a distance of 5 cm from the sample surface and at 0° relative to the direction of the incident ion beam. A 2 mm thick window between the sample and detector in the back wall of the chamber was used in order to minimize γ-ray attenuation.

NaI(Tl) detector was placed on 90° relative to the direction of the incident ion beam on distance of 4 cm from center of beam spot on target surface.

The γ-ray spectra were stored in the 8k emulator Nuclear Data analyzer "Green Star" production.

We are made a number of the measuring of spectra of γ-emission from of natural composition boron thick target using both Ge(Li) and NaI(Tl) detectors. The proton energy was varied in the range 200…1800 keV, the beam current was varied from 20 to 500 nA, depending on the load of the spectrometric channel. To reduce the load on the spectrometric path, absorbing filters made from lead foil were also placed in front of the detectors. The filter thickness in front of the NaI(Tl) detector was 13 mm and did not change during measurements. Foils with a thickness of 5 and 10 mm were installed in front of the Ge(Li) detector. The spectra at low proton energies – up to 400 keV were measured without an absorber.

RESULTS OF MEASUREMENT

Fragments of γ-radiation spectra from targets made of natural boron measured synchronously by both spectrometers are shown in Figs. 2-4. These spectra were measured at energy of protons 1800 keV, beam current 50 nA, charge 50 μC. Lead foil 5 and 13 mm thickness, respectively, was placed between the target and the Ge(Li) and NaI(Tl), detectors. The analyzer dead time in the channels of both spectrometers did not exceed 3%.

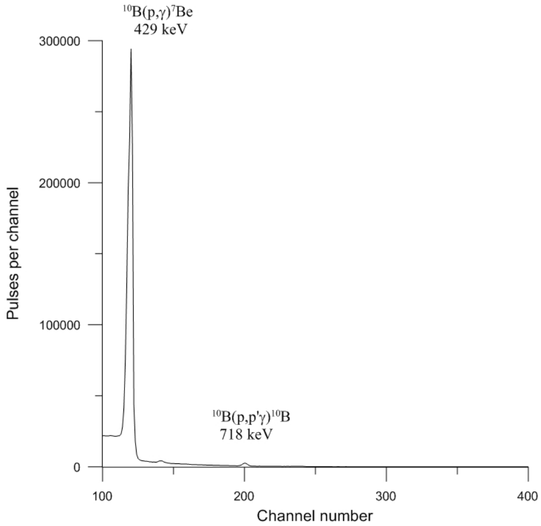

Fig. 2. A fragment of the low-energy part of the γ-ray spectrum measured by the Ge(Li) detector from a natural boron thick target protons irradiated

As follows from the Fig. 2, the line with an energy of 718 keV from the reaction ^{10}B(p,p'γ)^{10}B is significantly inferior to the intensity of the line with an energy of 429 keV from the reaction ^{10}B(p,αγ)^{7}Be

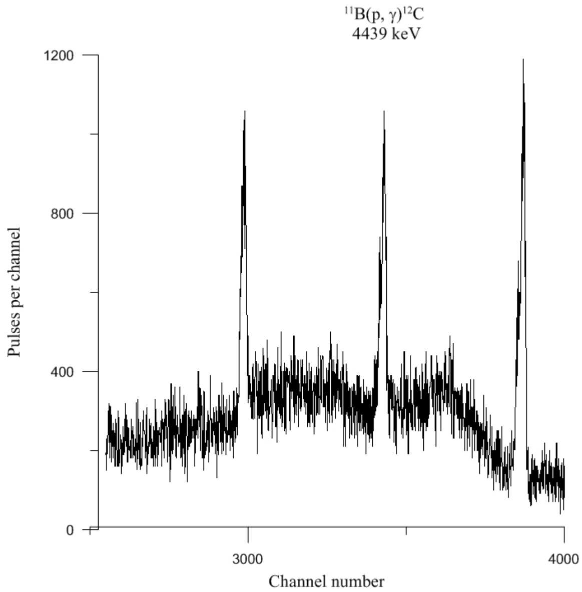

Fig. 3. A fragment of the middle-energy part of the γ-ray spectrum measured by the Ge(Li) detector from a natural boron thick target protons irradiated

On Fig. 4 a fragment is shown of the high-energy part of the γ-radiation spectrum measured by the NaI(Tl) detector when a natural boron thick target was irradiated by protons.

As can be seen from the Fig. 4, the spectrum contains three peaks at energies of 4.439; 11.667, and 16.106 MeV emitted in the reaction ^{11}B(p,γ) ^{12}C. The resolution of the NaI(Tl) detector is much worse than the Ge(Li) detector, but thanks to the higher efficiency of the first of them, yield of γ-emission with energy 16.106 MeV can be determined with less statistical error.

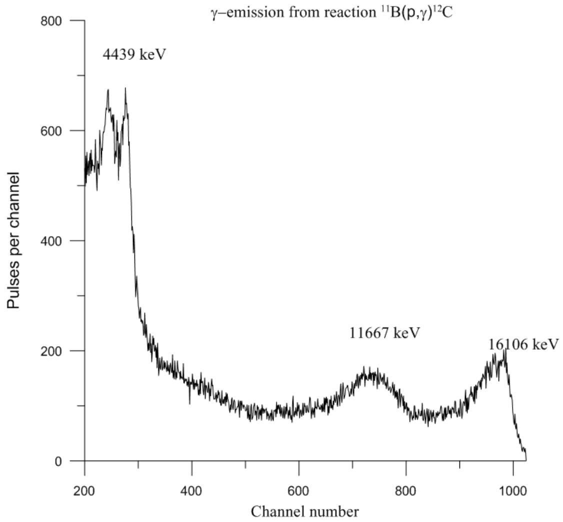

Fig. 4. A fragment of the high-energy part of the γ-ray spectrum measured by the NaI(Tl) detector from a natural boron thick target protons irradiated

Processing of spectral information was carried out using a semi-automatic routine which has been developed in NSC KIPT for determination of sum amounts under peak**.**

The main task of the study was to replenish the bank of experimental data, which are necessary to improve the accuracy of determining the elemental and isotopic composition of matter in solving materials science problems. Therefore, the functions of excitation of γ-radiation for reactions and energies of quanta, which are of the greatest interest for analytical applications, were studied. Selected reactions and energies of quanta for are given in Table 1.

Table 1

Reaction induced by protons on nuclei of stable boron isotopes for which yields of γ-ray from thick target were measured

Reaction	Energy of γ-quanta, keV
$^{10}B(p,\alpha\gamma)\,^{7}Be$	429
$^{10}B(p,p'\gamma)\,^{10}B$	718
$^{11}B(p,\gamma)\,^{12}C$	4439, 11667, 16106

The results of measurements are presents on Figs. 5-7 and in Tables 2-5.

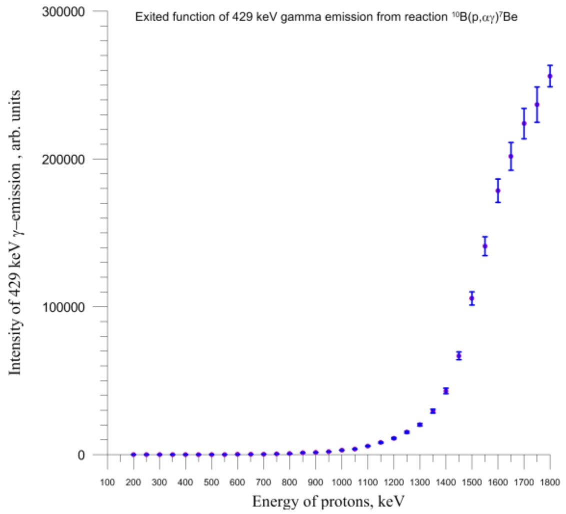

Fig. 5. Yield of γ-radiation with energy 429 keV as function of proton energy

Table 2

Yield of γ-rays emission with energy of 429 keV from reaction $^{10}B(p,\alpha\gamma)\,^{7}Be$

Proton energy, keV	Yield for 429 keV	Err
200	0.3	0.03
250	1.2	0.00
300	3.4	0.09
350	8.2	0.23
400	15.5	0.54
450	28.3	1.11
500	51.7	1.66
550	76.8	2.22
600	126.0	4.72
650	199.6	7.46
700	314.2	12.33
750	469.1	20.59
800	661.1	28.58
850	1310.0	58.08
900	1514.0	60.90
950	2008.1	91.59
1000	3008.5	137.39
1050	3799.5	174.75
1100	5834.9	270.35
1150	8166.7	378.57
1200	11072.1	487.52
1250	15163.9	668.86
1300	20231.3	792.22
1350	29431.0	1302.45
1400	43102.9	1881.38
1450	66864.5	2634.82
1500	105665.0	4465.24
1550	141004.1	6376.54
1600	178549.8	7912.23
1650	201771.3	9390.30
1700	223961.7	10277.81
1750	236773.3	11940.91
1800	256097.2	7255.18

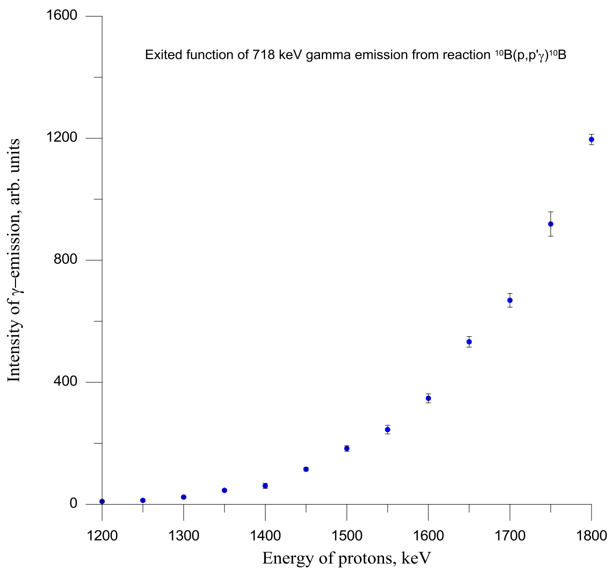

Fig. 6. Yield of γ-radiation with energy 718 keV as function of proton energy

Table 3

Yield of γ-rays emission with energy of 718 keV from reaction $^{10}B(p,p'\gamma)^{10}B$

Proton energy, keV	Yield for 718 keV	Err
1200	10	3
1250	13	3
1300	24	3
1350	46	4
1400	61	8
1450	115	6
1500	183	9
1550	245	14
1600	348	15
1650	533	17
1700	669	23
1750	919	40
1800	1196	17
1150	964.27	4.46
1200	1027.92	4.61
1250	1097.57	4.75
1300	1159.07	4.90
1350	1237.73	5.06
1400	1273.03	5.13
1450	1485.63	7.48
1500	1570.14	10.79
1550	1653.32	11.09
1600	1697.31	11.38
1650	1891.77	11.83
1700	2036.77	12.28
1750	2090.16	8.70
1800	2251.76	8.59

Table 4

Yield of γ-rays emission with energy of 4439 keV from reaction $^{11}B(p,\gamma)^{12}C$

Proton energy, keV	Yield for 4439 keV	Err
200	44.06	0.19
250	42.35	0.19
300	42.11	0.19
350	51.87	0.21
400	58.21	0.22
400	58.85	0.47
450	73.95	0.52
500	100.72	0.61
550	137.11	0.71
600	192.31	0.84
650	337.24	2.05
700	411.74	2.91
750	493.27	3.18
800	568.72	3.43
850	633.68	3.62
900	700.74	3.80
950	765.64	3.97
1000	810.88	4.09
1050	868.83	4.24
1100	920.00	4.36

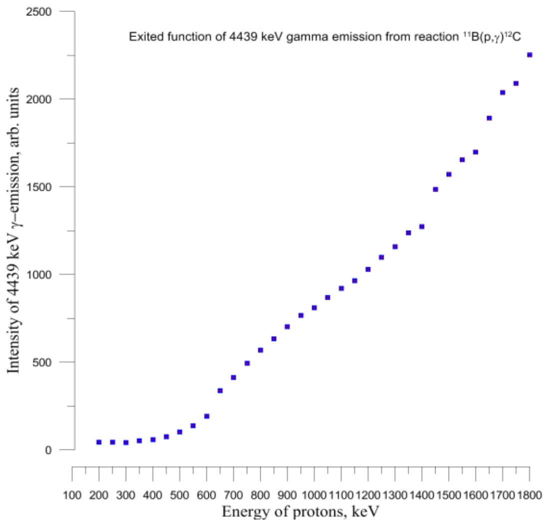

Fig. 7. Yield of γ-radiation with energy 4439 keV as function of proton energy

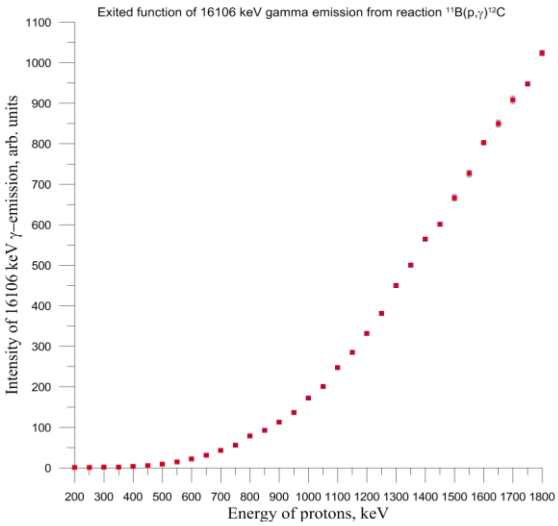

Fig. 8. Yield of γ-radiation with energy 16106 keV as function of proton energy

Table 5

Yield of γ-rays emission with energy of 16106 keV from reaction $^{11}B(p,\gamma)^{12}C$

Proton energy, keV	Yield for 16106 keV	Err
200	0.83	0.03
250	0.90	0.03
300	1.27	0.03
350	1.92	0.04
400	3.43	0.03
450	5.69	0.06
500	9.22	0.08
550	14.93	0.26
600	21.71	0.32
650	30.72	0.69
700	43.03	1.07
750	55.75	1.20
800	78.75	1.49
850	92.67	1.57
900	112.72	1.72
950	136.12	1.88
1000	172.02	2.12
1050	200.72	2.30

Continued Table 5

1350	500.03	3.60
1400	564.81	3.84
1450	601.46	2.86
1500	666.55	7.90
1550	726.53	8.27
1600	802.69	5.55
1650	850.04	8.93
1700	908.79	9.21
1750	947.81	3.87
1800	1024.19	6.63

CONCLUSIONS

The yields were measured of γ-ray emission as function of proton energy in range 200...1800 keV at energy γ-ray 429, 718, 4439, and 16607 keV from reaction $^{10}B(p,\alpha\gamma)$, $^{7}Be$$^{10}B(p,p'\gamma)$, and $^{10}B$$^{11}B(p,\gamma)$ ^{12}C.

The 2 MeV Van de Graaff accelerator "Sokol" NSC KIPT and two spectrometers on base Ge(Li) and NaI(Tl) detector were used et measurement. Data obtained are necessary to optimize experimental parameters at elemental and isotopic content determination of boron by NRA and were used by authors for these purposes at the studying of boron based materials developed in NSC KIPT [9, 10]. These data may in part be required for astrophysics researches, since there are missing data for the determination of cross-sections or S-factors of thermonuclear reactions, which are necessary for the understanding of nuclear reactions occurring in the stars.

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ДОСЛІДЖЕННЯ ФУНКЦІЙ ЗБУДЖУВАННЯ РЕАКЦІЙ З ВИПРОМІНЮВАННЯМ γ-КВАНТІВ ПРОТОНАМИ З ЕНЕРГІЯМИ 200…1800 кеВ НА ЯДРАХ ^{10}B ТА ^{11}B

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Проведено систематичне дослідження відносних виходів з товстої мішені миттєвого γ-випромінювання з енергіями найбільш придатними для елементного та ізотопного аналізів стабільних ізотопів бору при бомбардуванні протонами з енергіями Ep = 200…1800 кеВ. Відповідні функції збудження γ-випромінювання 429 кеВ з реакції $^{10}B(p,\alpha\gamma)^{7}Be$, 718 кеВ з реакції $^{10}B(p,p'\gamma)^{10}B$, 4,439 та 16,106 МеВ з реакції $^{11}B(p,\gamma)^{12}C$ зображено на рисунках, та наведено таблиці виходів миттєвого γ-випромінювання залежно від енергії протонів. Описано методику експерименту. Обговорюються окремі аспекти вимірювальної техніки.

ИССЛЕДОВАНИЕ ФУНКЦИЙ ВОЗБУЖДЕНИЯ РЕАКЦИЙ С ИЗЛУЧЕНИЕМ γ-КВАНТОВ ПРОТОНАМИ С ЭНЕРГИЯМИ 200…1800 кэВ НА ЯДРАХ ^{10}B И ^{11}B

В.В. Левенец, А.П. Омельник, А.А. Щур

Проведено систематическое исследование относительных выходов мгновенных γ-излучения из толстых мишеней с энергиями, наиболее подходящими для элементного и изотопного анализов стабильных изотопов бора при бомбардировке протонами при Ep = 200…1800 кэВ. Соответствующие функции возбуждения γ-излучения 429 кэВ из реакции $^{10}B(p,\alpha\gamma)^{7}Be$, 718 кэВ из реакции $^{10}B(p,p'\gamma)^{10}B$, 4,439 и 16,106 МэВ из реакции $^{11}B(p,\gamma)^{12}C$ изображены на рисунках, и даны таблицы выходов мгновенных γ-излучения в зависимости от энергии протонов. Описана методика эксперимента. Обсуждаются отдельные аспекты методов измерения.