Vol. 14 (2021) *Acta Physica Polonica B Proceedings Supplement* No 4

# GAMMA-RAY SPECTROMETER ASSEMBLED FROM $9\times$CeBr$_3$-NaI(Tl) PHOSWICH DETECTORS*

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*(Received November 5, 2021; accepted November 5, 2021)*

The technique of using a cluster of $9\times$CeBr$_3$-NaI(Tl) phoswich detectors as a Compton suppression spectrometer for detecting low-energy $E\gamma < 4$ MeV $\gamma$-radiation is investigated. The characteristics of a phoswich detectors cluster and a High-Purity Germanium detector (HPGe) with a BGO shield are compared. The main characteristics of $\gamma$-ray spectrometer: the energy resolutions $\Delta E$, the total registration efficiency $\varepsilon_\gamma$ and the peak efficiency $\varepsilon_{\mathrm{PEAK}}$, depending on the energies $E\gamma$ of the registered $\gamma$-rays and on the distances to the source, are presented. It is shown that the Compton suppression coefficient values of both spectrometers are the same, while the peak efficiency of the phoswich cluster is three times higher than in the HPGe detector. The Compton suppression mode of the phoswich cluster is supposed to be used for studying $\beta$-delayed $\gamma$-decay processes, particularly direct $\gamma$-decay of Pygmy resonances.

DOI:10.5506/APhysPolBSupp.14.755

## 1. Introduction

A cluster of 9 phoswich detectors with the crystals size of $51\times51\times51$ mm$^3$ and $51\times51\times152$ mm$^3$ for CeBr$_3$ (LaBr$_3$) and NaI(Tl) respectively, is the basic element (Fig. 1) of a great variety in the PARIS [1] facility configurations. This spectrometer is being created within the PARIS international cooperation of participants from 10 countries including JINR, Dubna, Russia [2]. One of the general aims of the PARIS international cooperation is to study the processes of direct $\gamma$-decay of Giant Dipole Resonances (GDR)

* Presented at III International Scientific Forum "Nuclear Science and Technologies", Almaty, Kazakhstan, September 20–24, 2021.

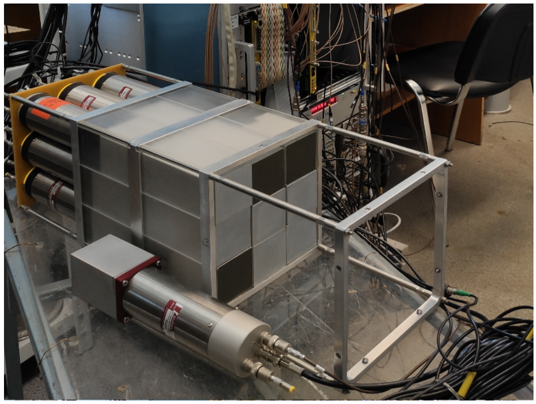

Fig. 1. The cluster of 9×$CeBr_3$-NaI(Tl) phoswich detectors manufactured by Scionix Holand B.V. [3].

and Pygmy Dipole Resonances (PDR) formed in heavy-ion reactions. These reactions have an essential feature, which consists in the fact that many reaction channels (deep-inelastic collision, fusion, incomplete fusion, *etc.*) proceed with a significant dissipation of projectile kinetic energy into excitation energy and input angular momentum. Cooling and dissipation of the introduced angular momentum of the reaction products are passing through the emission of statistical $\gamma$-quanta and $\gamma$-ray transitions of the yrast-line. Therefore, the direct $\gamma$-decay of GDR in heavy-ion reactions is accompanied by the $\gamma$-cascade with a large value of multiplicity $M\gamma$. Taking into account the time resolution of the DAQ system, the $\gamma$-ray emission processes run simultaneously. It leads to a «pile-up» effect (the overlapping of detection pulses). Thus, the value of the total energy of «pile-up» $\gamma$-rays can be close to the energy value of GDR $\gamma$-ray. The applying of single-crystal $\gamma$-detectors cannot separate the high-energy $\gamma$-ray and «pile-up» $\gamma$-rays. This problem can be solved by using telescopes or phoswich detectors. The telescope version for $4\pi$ spectrometers is difficult to design due to the close-packing detector structure.

For this reason, the phoswich detectors were chosen for the $4\pi$ $\gamma$-spectrometer PARIS. The $LaBr_3$ ($CeBr_3$) and NaI(Tl) components of phoswich detector have different decay time. The pulse-shape analysis allows us to measure the $\gamma$-ray energy losses in $CeBr_3$ and NaI(Tl) components of phoswich scintillator.

To study the decay processes accompanied by $\gamma$-radiation with small $M\gamma$ values, the efficiency of a phoswich detector cluster in the Compton suppression mode was investigated. In particular, there are processes such as $\beta$-delayed direct $\gamma$-decay of GDR and PDR in short-lived light neutron-rich nuclei.

The MULTI project of experimental setup at the Flerov Laboratory of Nuclear Reactions JINR, Dubna, Russia is devoted to studying the $\beta$-decay processes of exotic nuclei (decays through GDR and PDR, multi-neutron decay).

The MULTI experimental setup with two clusters of 9×CeBr$_3$-NaI(Tl) phoswich detectors is shown in Fig. 2. The MULTI consists of a target surrounding $4\pi$ $\beta$-counter located in the focal plane of the ACCULINNA-1 [4] or ACCULINNA-2 [5] fragment separator. The parameters of the ACCULINNA beam system and the thickness of d$E$ upstream detectors are adjusted hence the interest nuclei are stopped in the target. The $\beta$-counter is surrounded by $4\pi$-neutron counters consisting of $^3$He-proportional detectors in polyethylene moderators. On both sides of the target, there are two clusters of phoswich detectors for $\beta$-delayed $\gamma$-decay detection.

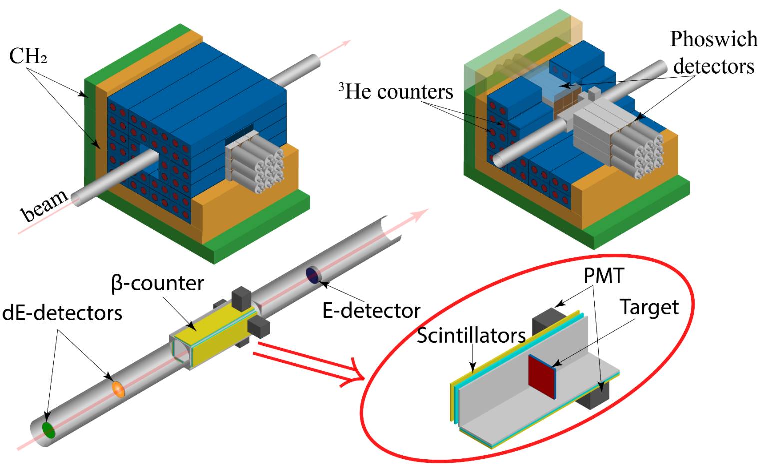


Fig. 2. The MULTI experimental setup.

## 2. Results and conclusions

To determine the Compton suppression efficiency (CSE) of detectors, the phoswich cluster has been compared with the Compton shielded HPGe detector with a sensitive area of 78 mm in diameter and 72.8 mm long [6]. These two spectrometers were simulated in the Geant4 Monte-Carlo code [7]. The Geant4 simulated spectra of isotropic $\gamma$-radiation with energy $E\gamma$ = 1173 keV are shown in Fig. 3. On the left-hand side of Fig. 3, there is the HPGe detector spectrum and on the right-hand side, there is the central detector of the cluster. The inclusive spectra of both detectors are presented as dashed lines. The Compton suppressed spectra of both detectors are shown as solid lines. For both simulations, the distance between the $\gamma$-source and the spectrometer frontages was 10 cm. The calculated Comp-

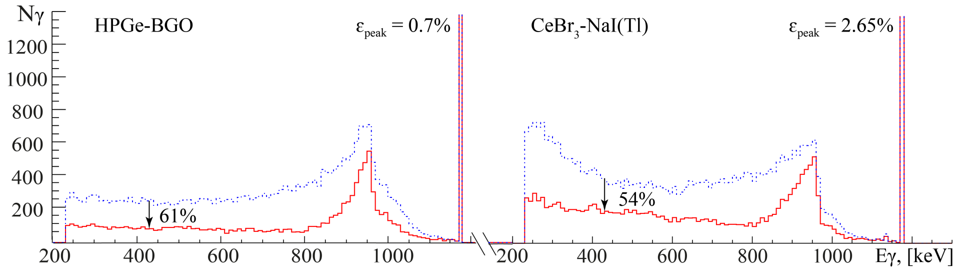


Fig. 3. The Geant4 calculated energy spectra of the HPGe-BGO detector (left) and central $CeBr_3$-NaI(Tl) detector of the cluster (right). The dashed lines are inclusive spectra, the solid lines are Compton suppressed spectra.

ton suppression efficiencies were $CSE_{Geant} = 54\%$ and 61% for the central detector of the cluster and the HPGe detector, respectively. At the same conditions, the peak efficiency of the central detector of the cluster and HPGe detector is $\varepsilon_{peak} = 2.65\%$ and $\varepsilon_{peak} = 0.7\%$, respectively. The «peak-to-total» ratio is $R_{CeBr_3} = 0.35$ and $R_{HPGe} = 0.36$, respectively. To check the results of Geant4 calculations, the same parameters as the above were measured for the phoswich cluster by the tagged $\gamma$-rays technique with $^{60}$Co $\gamma$-source. The method is based on selecting the events of total absorption of the $\gamma$-quant with $E\gamma = 1332$ keV in the trigger detector. Under this condition, the $\gamma$-quant with $E\gamma = 1173$ keV will be emitted into solid angle $4\pi - \Omega$ with known angular distribution (where $\Omega$ is the trigger detector solid angle). The energy spectrum of the $CeBr_3$-NaI(Tl) central detector of the cluster measured by the tagged $\gamma$-rays technique is shown in Fig. 4. The inclusive spectrum of the central phoswich detector is shown as the solid line. The Compton suppressed spectrum of this detector is presented as the bold line. The measurement was done at the same conditions as at Geant4 calculations. The measured Compton suppression efficiency was CSE = 52%, the peak efficiency $\varepsilon_{peak} = 2.6\%$, and the «peak-to-total» ratio

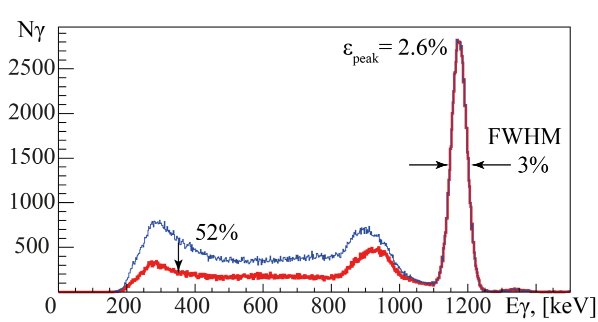


Fig. 4. The energy spectrum of $CeBr_3$-NaI(Tl) central detector of the cluster measured by the tagged $\gamma$-rays technique.

value $R_{\mathrm{CeBr}_3} = 0.33$ which are close to the calculated one. To get the Compton suppressed spectrum for each phoswich detector of the cluster, we have used the pulse shape analysis of scintillation pulses by Mesytec electronics VME modules [8]. During the measurements, we have checked the analogue and digital approaches of the pulse shape analysis based on MQDC-32 and MDPP-16 pulse processor units, respectively. As an example, the 2D-matrix of «digital» pulse shape analysis by MDPP-16 (QDC mode) is presented in Fig. 5. On the $X$-axis, there is the pulse charge value integrated under short integration time (25 ns) and on the $Y$-axis, there is a difference between long and short integrated time charges (380 ns). It is clearly visible from

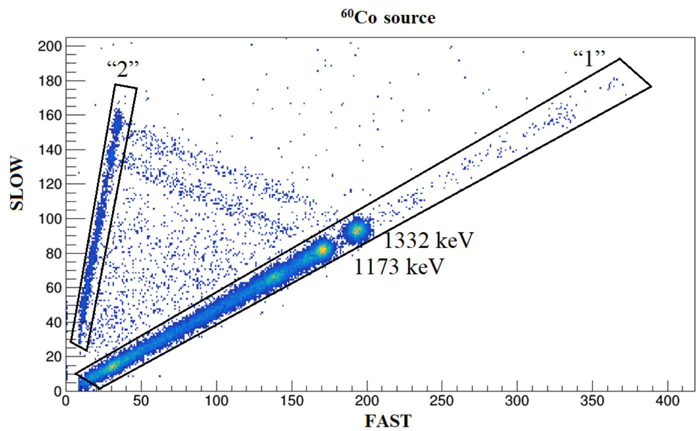


Fig. 5. 2D-matrix of MDPP-16 pulse processor unit (running in QDC mode). On the $X$-axis is the FAST with integration time 25 ns and $Y$-axis is the SLOW with an integration time 380 ns.

Fig. 5, that the events with $\gamma$-rays allocated mainly in $\mathrm{CeBr_3}$ and not passing into NaI(Tl) are filling the diagonal area "1" in 2D-matrix. The events with $\gamma$-rays allocated mainly in NaI(Tl) and passing through $\mathrm{CeBr_3}$ without energy losses in it are filling the diagonal area "2" in 2D-matrix. Therefore, the low-energy and high-energy $\gamma$-rays will fill the "1" and the "2" areas of 2D-matrix, respectively. There are two conditions for selecting events of full $\gamma$-ray absorption in the $\mathrm{CeBr_3}$ detector (*i.e.* for collecting the Compton suppressed spectrum in Fig. 4). The first condition is defined by "1" contour and the second one is defined by energy losses in the surrounding detectors. Additionally, the characteristics of the $\gamma$-ray spectrometer were obtained: the total registration efficiency $\varepsilon_\gamma$ and the peak efficiency $\varepsilon_{\mathrm{PEAK}}$, depending on the distances to the source, are presented in Fig. 6. In the conclusion, the main characteristics of the $\mathrm{CeBr_3}$-NaI(Tl) cluster measured by the tagged $\gamma$-ray method are compared with Geant4 calculations. The Geant4 analysis in the Compton suppression mode of $\mathrm{CeBr_3}$-NaI(Tl) cluster

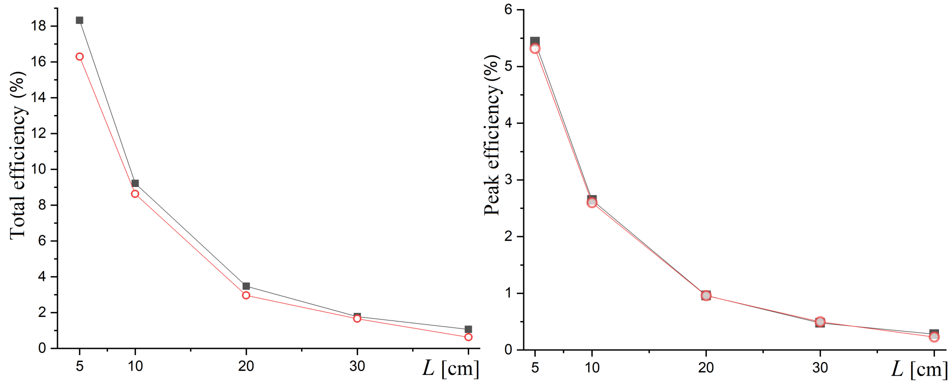


Fig. 6. Total efficiency and peak efficiency as a function of distance to $\gamma$-source $^{60}$Co. The measurements for target $\gamma$-quanta with $E\gamma = 1173$ keV. Squares — calculated results, circles — measured results.

and HPGe-BGO $\gamma$-ray detector was carried out. The Compton suppressed spectra of the $CeBr_3$-NaI(Tl) cluster were measured within the framework of two approaches: the analogue and the digital one. Both approaches have provided close results. However, the digital approach based on pulse processor MDPP allows to separate the scintillation pulses at lower values of the threshold. The cluster of $CeBr_3$-NaI(Tl) phoswich detectors will be used in the experiments at the FLNR, JINR (Dubna) for studying the $\beta$-decay processes, accompanied by the direct $\gamma$-decay of Giant Dipole Resonances and Pygmy Dipole Resonances. Also, $\gamma$-decay of the resonances formed in heavy-ion reactions will be studied in the experimental projects within the framework of the international cooperation PARIS.

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