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Measurements of high-energy γ-rays with $LaBr_3:Ce$ detectors

M. Ciemała [a,*], D. Balabanski [b], M. Csatlós [c], J.M. Daugas [d], G. Georgiev [e], J. Gulyás [c], M. Kmiecik [a], A. Krasznahorkay [c], S. Lalkovski [f], A. Lefebvre-Schuhl [e], R. Lozeva [g], A. Maj [a], A. Vitez [c]

[a] The Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland
[b] INRNE, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria
[c] Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary
[d] CEA, DAM, DIF, F-91297 Arpajon Cedex, France
[e] Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM), IN2P3-CNRS and Université Paris-Sud, Bât 104-108, F-91405 Orsay Cedex, France
[f] Faculty of Physics, University of Sofia, BG-1164, Bulgaria
[g] Instituut voor Kernen Stralingsfysica (IKS), Katholieke Universiteit Leuven, B-3001 Leuven, Belgium

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ABSTRACT

The full-energy peak efficiency calibration and the energy resolution measurements of the 2 in. × 2 in. $LaBr_3$ γ-ray detector are presented for γ-ray energies in the 700 keV–17.6 MeV range. Measurements were done using a combination of proton-capture nuclear reactions on ^{27}Al, ^{23}Na, ^{39}K, ^{7}Li and ^{11}B for high-energy γ-rays, and radioactive sources such as ^{60}Co and ^{152}Eu for the lowest energies. At high energies, two γ-rays in a cascade from proton resonance capture were employed using Al, Na_2WO_4, K_2SO_4 and $LiBO_2$ targets. The obtained results were compared to the simulations performed using a GEANT4 code.

1. Introduction

Lanthanum halide ($LaBr_3:Ce$) scintillators offer very good energy resolution (FWHM/E less than 3% at 662 keV), time resolution (about 250 ps) [1–3] and have recently become commercially available in sizes large enough for high-energy γ-ray measurements. Therefore, they are considered for use in novel γ-ray calorimeters, such as the PARIS array [4].

Test measurements, concerning detector efficiency and energy resolution, were performed in the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI). Low energy γ-rays were studied using ^{60}Co and ^{152}Eu isotope sources, while the high-energy region was covered by γ-rays emitted in (p,γ) reactions. Protons were accelerated to the resonance energies (from 441 keV up to 1416.1 keV) by a 5 MV Van de Graff accelerator, and impinged on different thin evaporated targets: Al, Na_2WO_4, K_2SO_4 and $LiBO_2$. The produced γ-rays possessed energies from 1.4 MeV up to 17.6 MeV.

2. Experiment

The measurements were performed using a cylindrical $LaBr_3:Ce$ scintillation detector (BrilLanCe 380 [5] with XP5500B phototube) of 2 in. length and 2 in. diameter. It was placed in the distance of 15.5 cm from the target, at the angle of 55° in respect to the proton beam direction. This distance was chosen to minimize pile-up effects. To avoid light saturation of the PMT and get a good linearity, phototube voltage was set to 570 V. Output signal was amplified by CAEN N568B amplifier, and integrated for 1 μs. Then, the signal was digitized using Silena 9418/6W ADC. Finally, the data were acquired by a computer-controlled multichannel (4096 channels) spectra analyzer.

At low energies the absolute efficiencies were measured using γ-ray sources: ^{60}Co, which had activity equal to 78.3 kBq during the measurements and ^{152}Eu with activity 54.3 kBq. They were placed in the distance of 15 cm from the front face of the $LaBr_3:Ce$ detector.

The measurement time was adjusted to the activities of the different sources in a way to get statistical errors smaller than 1% for most of the relevant peaks. The energies and intensities of the γ-rays emitted from the ^{152}Eu and ^{60}Co sources were taken from Ref. [6].

The efficiency measurements for the high-energy region were performed with proton beams from the 5 MV Van de Graff accelerator of ATOMKI. Proton beam energies (E_p) which were used are listed, for each reaction, in Table 1. Intensity of the proton beam varied from 1.5 to 2 μA, its energy spread was less than 1 keV.

The proton capture nuclear reactions were chosen as in the previous work [9] concerning germanium detector calibration. The targets were produced from materials suitable for proton capture. It means that the yield of γ-rays emitted from such reactions is high, the proton resonant energy is low and the target is easy to prepare. The produced targets were thin enough to avoid interferences with other resonances produced, in some cases, by

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[*] Corresponding author. Tel.: +48 693307953.
E-mail address: Michal.Ciemala@ifj.edu.pl (M. Ciemała).

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Table 1
Parameters of the (p, γ) reactions, energies (E_γ) and relative intensities (I_γ) of the γ-rays emitted by product nucleus [9,11,12].

Reaction	E_{res} (keV)	Q value (keV)	E_p (keV)	E_γ (keV)	I_γ	Target and its thickness ($\mu g/cm^2$)
$^{23}Na(p,\gamma)^{24}Mg$	1318.1	11 693	1323	1368.6(1)	1.000(2)	Na_2WO_4
				11 584.9(6)	0.960(2)	20
$^{23}Na(p,\gamma)^{24}Mg$	1416.9	11 693	1422	2754.0(1)	1.000(1)	Na_2WO_4
				8925.2(6)	0.985(1)	20
$^{27}Al(p,\gamma)^{28}Si$	767.2	11 585	770	2838.7(1)	1.0000(14)	Al
				7706.5(2)	0.9810(14)	15
$^{39}K(p,\gamma)^{40}Ca$	1346.6	8328	1351	3904.4(1)	1.000(1)	K_2SO_4
				5736.5(1)	0.965(1)	20
$^{11}B(p,\gamma)^{12}C$	675	15 957	676	4438.0(3)	1.0000(7)	$LiBO_2$
				12 137.1(3)	1.0000(7)	75
$^{7}Li(p,\gamma)^{8}Be$	441	17 255	450	17 619.0(6)	–	$LiBO_2$, 75

Nuclear data are taken from ENSDF [13]. Q values calculated by QCalc from NNDC [14].

lower energy protons. The target materials and their properties are listed in Table 1, including also the information of the (p, γ) reactions chosen for the measurements, such as proton capture resonance energy (E_{res}) and the amount of energy released by that reaction (Q value). The excitation energy of the resonance is equal to $E_{res} + Q$. The chosen proton energies were higher than E_{res} by average energy loss in the target. It is worth to notice, that Na_2WO_4 target was used in two reactions with different proton beam energies leading to different bound states which decay by the γ-ray emission.

The method called "point-pair" or "two-line" described in Refs. [7–10] was applied to obtain the efficiency calibration. It is based on measurement of two γ-ray transitions emitted in a cascade from the proton resonance capture reaction, possessing low and high energy. The energy of the lowest γ-ray transition was in the region of known efficiency, already calibrated by the sources, so its efficiency was obtained from the source measurements. The other belonged to the higher, uncalibrated energy range. Since both γ-rays are emitted in a cascade with the same intensity, therefore the efficiency for the high-energy γ-ray was easy to deduce. The procedure was repeated step by step using cascades with γ-ray pairs having higher energies, and in this way the absolute efficiency was obtained up to 12.1 MeV. Efficiency for 17.6 MeV cannot be obtained with this method, as in $^{7}Li(p,\gamma)^{8}Be$ reaction there are no two γ-rays in a cascade.

3. Results

The γ-ray spectra emitted from (p, γ) reactions were measured with the studied 2 in. × 2 in. $LaBr_3:Ce$ detector. Fig. 1 presents energy range above 2 MeV of the γ-ray spectrum obtained from the $^{23}Na(p,\gamma)^{24}Mg$ reaction. It should be noted that even for 17.6 MeV γ-ray energy, it is possible to see the full absorption, first and second escape peaks (Fig. 2). Because of the low phototube voltage the dependence between the channel number and energy was linear up to 10 MeV. For 12 MeV the non-linearity became 4% and at 17 MeV it increased up to 10% as can be seen in Fig. 3.

The γ-ray spectra were analyzed with the non-linear peak fitting software *Gaspan* [15].

The relative energy resolution (FWHM/E) was calculated from the data obtained in measurements. All data points with their uncertainties are presented in Fig. 4. Relative energy resolution improves with energy from 2.1% at 1.3 MeV to less than 1% at 10 MeV and reaches about 0.7% at 17.6 MeV, which is so far the best known value for scintillation detectors. Its dependence on the γ-ray energy (in keV) was fitted by the following function (dashed

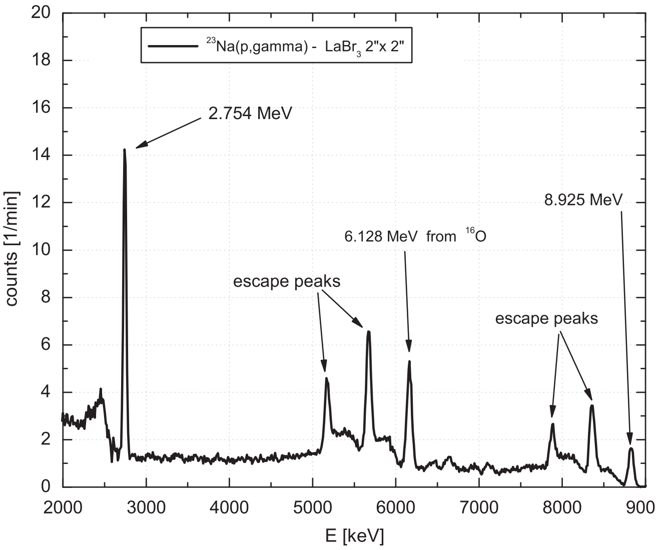

Fig. 1. Gamma-ray spectrum emitted by ^{24}Mg nuclei created in the $^{23}Na(p,\gamma)^{24}Mg$ reaction at the 1.318 MeV resonance energy, measured by a $LaBr_3:Ce$ 2 in. × 2 in. scintillation detector.

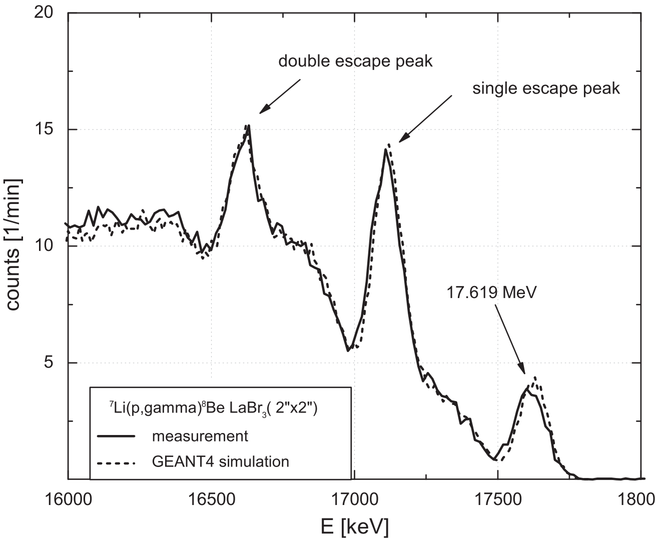

Fig. 2. Gamma-ray spectrum emitted by ^{8}Be nuclei created in the $^{7}Li(p,\gamma)^{8}Be$ reaction, measured by a $LaBr_3:Ce$ 2 in. × 2 in. scintillation detector. It is compared, after normalization to the full absorption peak, to spectrum simulated using a GEANT4 code.