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Position sensitivity in large spectroscopic LaBr3:Ce crystals for Doppler broadening correction

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ABSTRACT

The position sensitivity of a large $LaBr_3$:Ce crystal was investigated with the aim of correcting for the Doppler broadening in nuclear physics experiments. The crystal was cylindrical, 3 in × 3 in (7.62 cm x 7.62 cm) and with diffusive surfaces as typically used in nuclear physics basic research to measure medium or high energy gamma rays (0.5 MeV < E_γ < 20 MeV). The crystal was coupled to Position Sensitive Photomultipliers (PSPMT). The signals from the 256 segments of the four PSPMTs were acquired grouping them into 16 elements. An event by event analysis was performed and a positon resolution of the order of 2 cm was found. It was verified that this allows an important reduction of the Doppler broadening induced by relativistic beams in Nuclear Physics experiments.

1. Introduction

The properties of $LaBr_3$:Ce material are well known: it is an inorganic scintillator characterised by high yield, high density, excellent energy and time resolution [1]. Several groups have been investigating the position sensitivity properties of this material, mostly in medical field (see for example Ref. [2–7]). In this field, the goal is to locate the position of a well known gamma-emitter with a precision as good as possible. Usually, the detected gamma rays are the 140 keV from ^{99m}Tc or the 511 keV from the positron annihilation process. It was found that in gamma-cameras for small animal SPECT a sub-millimetre position resolution can be obtained due to the high light yield of $LaBr_3$:Ce (see for example Ref. [8–11]). Because of the high position resolution required, the crystals used in this field are rather thin, their thickness being of the order of 1 cm or less. Furthermore, they are provided with absorbing surfaces, so to avoid the reflected scintillation light to reach the photocathode and spoil the position sensitivity. However, this affects the energy resolution.

On the other hand, in nuclear physics basic research, $LaBr_3$:Ce crystals are employed to study the decay properties of nuclei populated via nuclear reactions. In this case, the position of the emitter is well known, while the energies of the gamma transitions are not known and may range up to several MeV. Therefore, detectors with good energy resolution and high efficiency are needed. These two requirements are fulfilled by diffusive surfaces in order to collect all the scintillation light, and large thicknesses (> 3 cm). Lately, the availability of exotic beams made possible to study nuclei far from stability via reactions where the nucleus under study is moving, it excites interacting with a target nucleus at rest and de-excites by radiation emission while it is still moving. These exotic beams can reach velocities up to v/c of the order of 0.7 or more [12,13]. In the lab system, the energy of a gamma ray emitted by a moving source depends on the emission angle due to the Doppler effect. Therefore, since the detector covers a non negligible solid angle, the detected energy resolution is deteriorated. To give an example, for a 3"x3" $LaBr_3$:Ce detector placed at 20 cm distance from the target, the resolution of 1 MeV gamma ray is 25 keV when the emitter is at rest, 70 keV when it moves with v/c=0.3 or 150 keV for v/c=0.7. The problem of Doppler broadening is quite serious in nuclear physics. In fact, it was one of the main reasons for the development of specific arrays made of segmented HPGe crystals [14,15]. With these arrays it is possible to track the gamma ray, to identify its first point of interaction, calculate the emission angle and convert its energy to the centre of mass value [16]. The energy resolution of these arrays is excellent, which is very advantageous in spectroscopy studies below particle threshold, but the system is complex, expensive, hardly transportable from one lab to the other, and the required data analysis is quite sophisticated.

On the other hand, an excellent energy resolution is only needed in spectroscopy studies of high density transitions spectra. In the two opposite cases of low density transition spectra or giant resonances at high excitation energies, 4 or 5% energy resolution

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at ~1 MeV would be sufficient [13]. Our purpose is to search for a position sensitive detector with good energy resolution, good efficiency for gamma-rays of energies up to several MeV's, relatively simple to handle and to transport. To this end, $LaBr_3$:Ce crystals are the best candidates, since they have good energy resolution and they are available in large volumes so that they can detect gamma-rays up to tens of MeV. Taking into account the intrinsic energy resolution of the $LaBr_3$:Ce, a spatial resolution of the order of the centimetre would be sufficient.

The position sensitivity properties of a 3 in × 3 in (7.62 cm × 7.62 cm) $LaBr_3$:Ce crystal having diffusive surfaces were already investigated using a statistical approach in [17–20], where it was found that the position sensitivity for such detector was of the order of the centimetre. In the present work we studied the position sensitivity on an event by event basis, as described in Section 2. We applied the results to a simulated case of Doppler broadening built in our laboratory, as discussed in Section 3. In Section 4 conclusions are drawn.

2. Measurements of the 662 keV gamma-ray from ^{137}Cs

The measurements were performed on an event-by-event basis. The scintillation light was collected by Position Sensitive Photomultipliers (PSPMT). We used Hamamatsu H8500 segmented PSPMT's, which have dimensions 2 in × 2 in and consist of 64 segments. Since the crystal surface is larger than each PSPMT, we used four of such tubes in the configuration shown in Fig. 1. The four PMT's we had available were different: two of them were characterised by 10 dynodes and a bialkal photocathode, while the other two had 8 dynodes and SBA photocathodes. The two types of PMT's had different performances, as listed in Table 1: when coupled singularly to the crystal, the 8 dynodes type provided an energy resolution of about 4% at 662 keV, while the 10 dynodes type resulted slightly worse. Note that in this case only about 55% of the crystal surface is covered by the PMT. In Fig. 2, the comparison of the 662 keV peaks of ^{137}Cs obtained with each of the four PSPMT's is shown. When the PSPMT's were used together covering the whole crystal surface, the energy resolution was 4%, corresponding to 26 keV. In this case, 120 segments were active (see the left part of Fig. 3). In order to simplify the setup, we short circuited segments in groups of 16, ending up with 12 macro active segments [19], as shown in the right part of Fig. 3. Note that, since the single segments have in principle different quantum efficiency

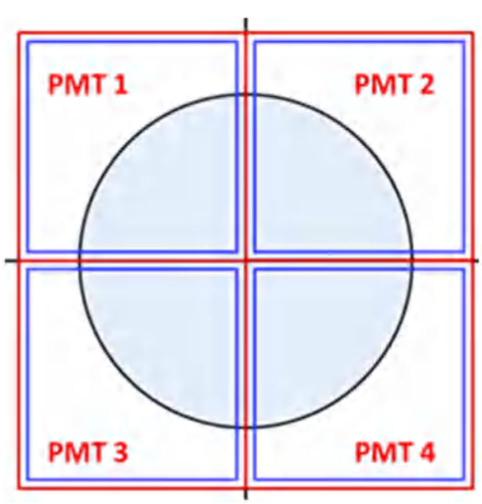

Fig. 1. Four segmented PMT's are coupled to the LaBr3: Ce crystal surface indicated by the blue circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
The properties of the four Hamamatsu H8500 PSPMT's used in this work are listed. In the last column, the energy resolution measured at the 662 keV transition of ^{137}Cs is reported for each PSPMT coupled singularly to the crystal (see inset in Fig. 2), covering about 55% of the crystal surface.

Serial n.	Dynodes	Photocathode	Resolution at 662 keV (%)
ZK0017	8	SBA	4.0
ZK0034	8	SBA	4.2
AA0471	10	Bialkal	5.1
AA0524	10	Bialkal	5.3

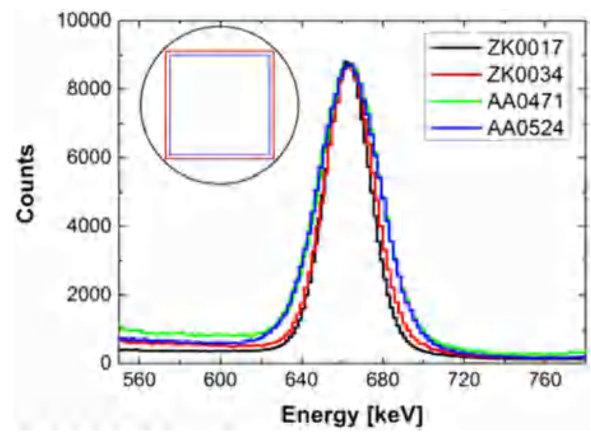

Fig. 2. The measurements of the 662 keV transition of a ^{137}Cs source using the four PSPMT's are compared. The PSPMT's are coupled singularly to the crystal as shown in the inset.

and gain, short circuiting a group of segments reduces the possibility of optimizing the performances of the PSPMT's by adjusting the gain of each single segment.

Measurements were performed with a 400 MBq ^{137}Cs source collimated in a 1 mm diameter beam spot. High voltage of −900 V was applied to the PSPMT's through a CAEN N1470 4 channel HV power supply. Data were taken using two 8 channels amplifier modules especially designed for PSPMT's [20], and a DAQ system based on KMax environment [21]. The source was placed in several (x,y) positions in the front face plane and the measured coordinates of each event were obtained calculating the centre of gravity of the light distribution:

$$x_{pos} = \sum (x_i * Q_i) / \sum Q_i \quad (1)$$

where x_{pos} is the calculated x-coordinate of the event, x_i are the x-coordinates of the centre of each segment and Q_i are the collected charges in each segment. A similar equation is used for the y-coordinate y_{pos}.

Gating on the 662 keV transition, we obtained Gaussian-like position profile distributions and the FWHM was about 2.3 cm. In Fig. 4, we show the source position profiles in the cathode plane corresponding to two source positions 4 cm apart along the x direction. We defined the origin in the centre of the cathode plane. On the top and on the right the projections on the x-axis and y-axis are shown, respectively. In x-projection the two profiles are well separated. Several measurements with the source placed in different positions between x = −2 cm and x = 2 cm and between y = −2 cm and y = 2 cm were performed. The upper panel of Fig. 5 shows the centroids of the measured distributions as a function of the source position in the x direction (full dots). The Field of View correction was performed by fitting the data with a 3rd degree polynomial (solid line in the figure). A similar procedure was undertaken for the y direction. With these corrections the source positions were very well reproduced, as can be seen in the bottom

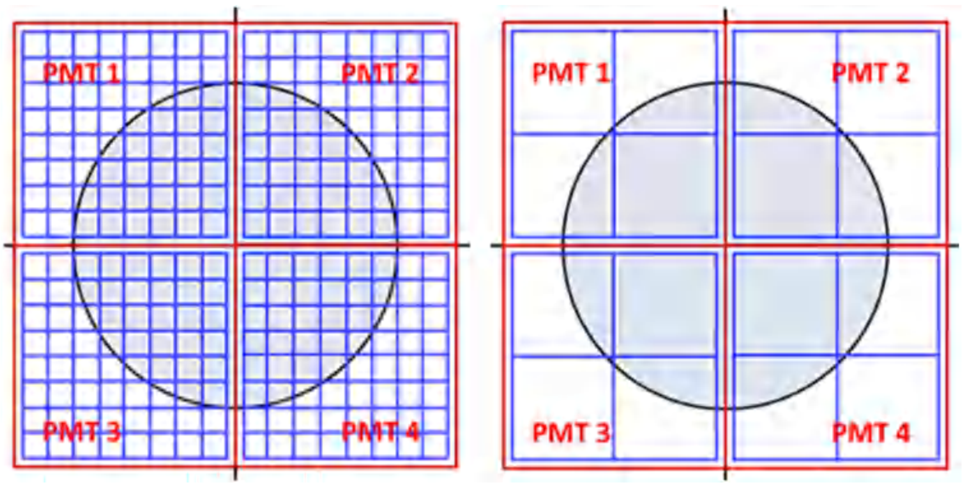

Fig. 3. Left: all the 256 segments (64 for each PMT) are shown; the segments covering the crystal face are 120. Right: segments were short circuited in groups of 16 in order to obtain 12 active macro segments, as shown. The four macro segments in the corner were not considered since they are outside the crystal surface.

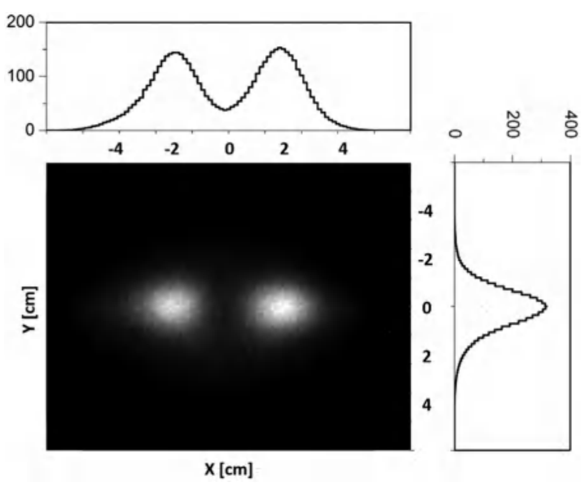

Fig. 4. The central plot shows the two-dimensional image corresponding to two source positions 4 cm apart in the x direction. On the top and on the right, the profiles on the x- and y- axes are shown, respectively. The origin corresponds to the centre of the crystal surface.

panel of Fig. 5, where the measured source positions (full triangles) are compared to the true source positions (open squares).

3. Doppler correction: 1836 keV from ^{88}Y

Our interest in large crystals is focused on the possibility to detect high energy gamma rays in nuclear physics experiments, therefore we investigated the position sensitivity of the 3"x3" crystal for gamma rays of 1836 keV from a ^{88}Y source. Since our final goal is the possibility to correct for Doppler broadening in inverse reactions, we are only interested in the position identification in the x-direction. Therefore, we collimated the source with 20 cm lead, leaving a window 5 cm high and 1 cm wide.

The effect of this large width was checked experimentally by performing a measurement with a 3 mm wide window. In the left panel of Fig. 6, the profile obtained with the 3 mm wide window (red squares) is compared to the one obtained with the 1 cm wide window (blu dots). In both cases the source was placed in the centre of the window. The two profiles are very similar, indicating that the resolution is determined by the intrinsic resolution of the crystal. In the central and right panels of Fig. 6, we show the profiles calculated assuming an intrinsic resolution of 0.01 mm

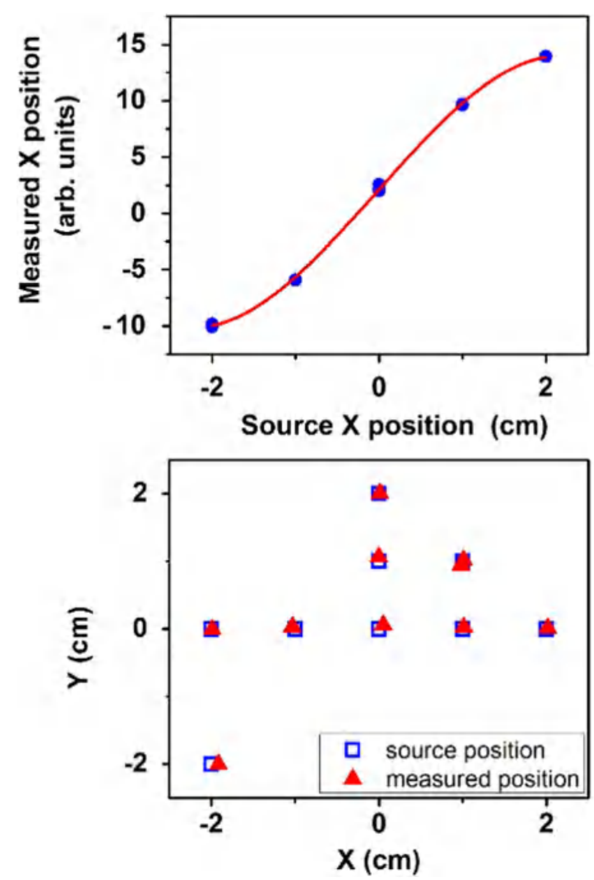

Fig. 5. The figure summarizes the results of a series of measurements with the collimated ^{137}Cs source in different positions, indicated by open squares in the bottom panel. The origin corresponds to the centre of the crystal surface. The upper panel shows the measured linearity along the x-axis. The vertical axis indicates the measured position source obtained using the centre of gravity Eq. (1). The scale is arbitrary. The full dots indicate the centroids of the x-profiles as a function of the source position. The solid line is a polynomial fit, used to calibrate the data. In the bottom panel, the measured source positions after calibration (red full triangles) are compared to the true source position (blu open squares). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(dashed lines) and an intrinsic resolution of 2 cm (solid line) for the 3 mm and 1 cm wide window, respectively. In both cases, the calculations took into account possible edge effects due to the lead

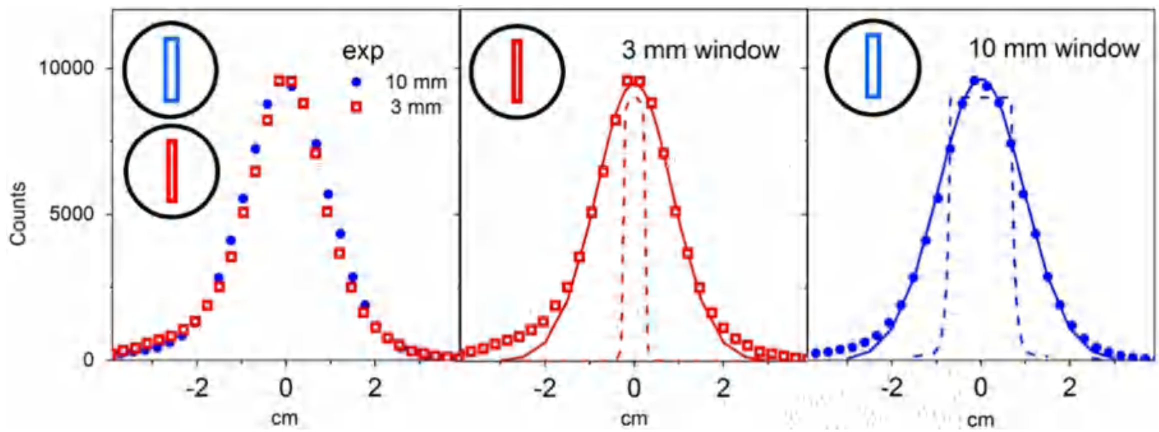

Fig. 6. Left panel: experimental profiles in the x-direction of the 1836 keV transition of a ^{88}Y shielded source with a rectangular slit 5 cm high and 3 mm wide (red squares) or 1 cm wide (blue dots). The shield consists of 20 cm Pb. The centre of the windows correspond to the centre of the crystal front face. The source is placed in the window centre. Central panel: the calculated profile of the 3 mm wide window assuming a 0.01 mm intrinsic resolution (not normalized, dashed line) or a 2 cm intrinsic resolution (solid line) is compared to the measured profile (points). Right panel: as the central panel but for the 1 cm wide window. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

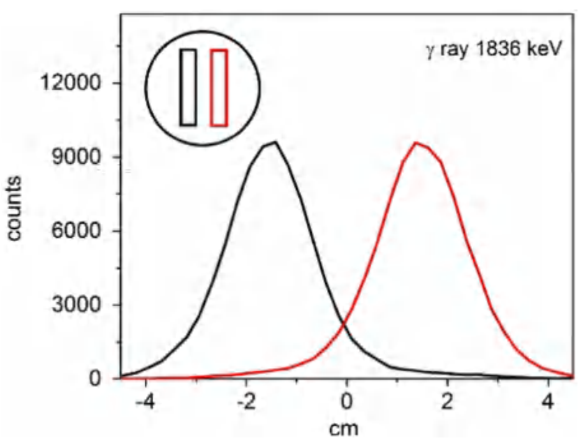

Fig. 7. The black Gaussian curve on the left represents the profile in the x-direction of the 1836 keV transition of a ^{88}Y shielded source with a rectangular slit 5 cm high and 1 cm wide whose centre is placed at $x=-1.5$, $y=0$ with respect to the crystal centre (see inset). The shield consists of 20 cm Pb. The red Gaussian on the right corresponds to the shield slit centre in position $x=1.5$, $y=0$ (see inset). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shielding. The comparison between the calculated profiles (solid lines in Fig. 6) and the experimental profiles (squares in the central and dots in the right panels of Fig. 6) indicates that intrinsic resolution of the crystal for γ rays of ~2 MeV is 2 cm. Fig. 7 shows the results of two measurements with the 1 cm wide window centre at (x,y)=(−1.5 cm, 0 cm) (black line) and (1.5 cm, 0 cm) (red line) with respect of the crystal centre, as shown in the inset of the figure. The two profiles are well separated.

In order to investigate whether this position resolution would be sufficient to correct for the Doppler broadening, we performed a set of measurements in which the ^{88}Y source was shielded by 20 cm Pb leaving a 1 cm wide opening, as shown in the left panel of Fig. 8. The set of measurements was performed with the detector shifted in 1 cm steps along the x-direction. The detector surface was covered by 6 measurements. The measuring time, corrected by the dead time, was the same for all of them. Fig. 9 shows the 6 x-profiles obtained. The different areas of the profiles reflects the fact that the active crystal area decreases when moving the window on the side of the detector. The measured energy resolution for the 1836 keV transition was 50 keV.

We then recalibrated each set of data assuming a moving source with v/c=0.5, with the detector placed at 20 cm distance

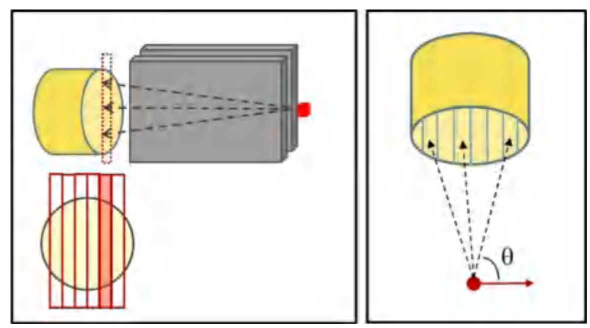

Fig. 8. The left panel shows the setup used for simulating a Doppler broadening effect: the ^{88}Y source (indicated by the red square) was shielded by 20 cm Pb, leaving a 1 cm wide opening, and the detector was moved in 1 cm steps along the x direction. A set of 6 measurements was performed. The right panel shows gamma-rays with the same energy emitted by a moving source and hitting the detector at different angles. In the lab system, the detected energy of the gamma rays is different depending on the angle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

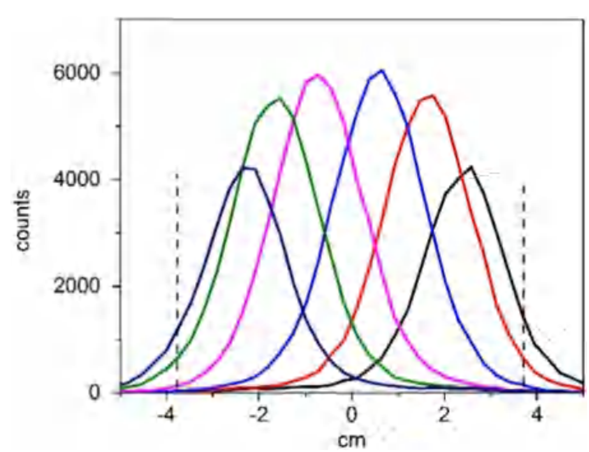

Fig. 9. The Gaussian curves represent the profiles in the x-direction of the 1836 keV transition of the ^{88}Y source collimated using 20 cm lead, with a 1 cm wide window as shown in Fig. 8. Each profile corresponds to a different x position of the window, as listed in the first column of Table 2. The crystal centre is in the origin, and the dotted lines represent the crystal limits.

and at 90° with respect to the source direction, as shown in the right panel of Fig. 8. In Table 2, the calculated incidence angle and the corresponding "lab energies" for the two transitions of ^{88}Y are

Table 2
Energy recalibration of the ^{88}Y data, assuming a moving source with v/c=0.5, and the detector placed at 20 cm and at 90° with respect to the source velocity direction. The first column indicates the centre position of the window source in the x direction relative to the crystal surface centre, the second column indicates the calculated lab angle, in the third and fourth columns the calculated "lab energies" of the ^{88}Y source transitions 898 keV and 1836 keV used for the calibration.

X (cm)	θ (°)	898 (keV)	1836 (keV)
2.5	97.1	732.3	1497.2
1.5	94.3	749.7	1532.7
0.5	91.4	768.1	1570.4
−0.5	88.6	787.5	1610.1
−1.5	85.7	807.9	1651.8
−2.5	82.9	829.1	1695.2

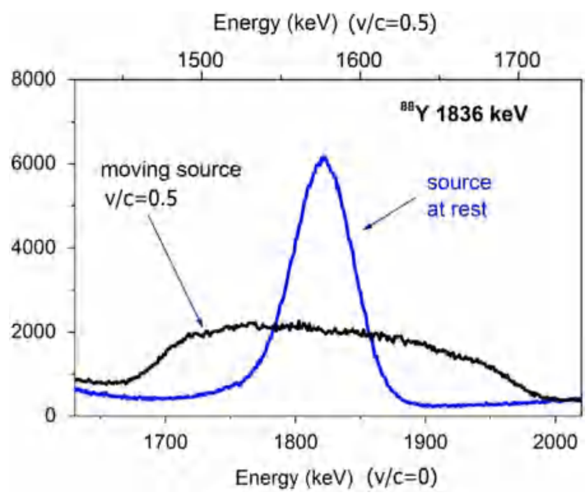

Fig. 10. The black line shows the spectrum of the 1836 keV simulating a source moving with v/c=0.5, as explained in the text. The energy scale is on the top of the figure. For comparison, the original spectrum is also shown (blue line, energy scale on the bottom of the figure). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

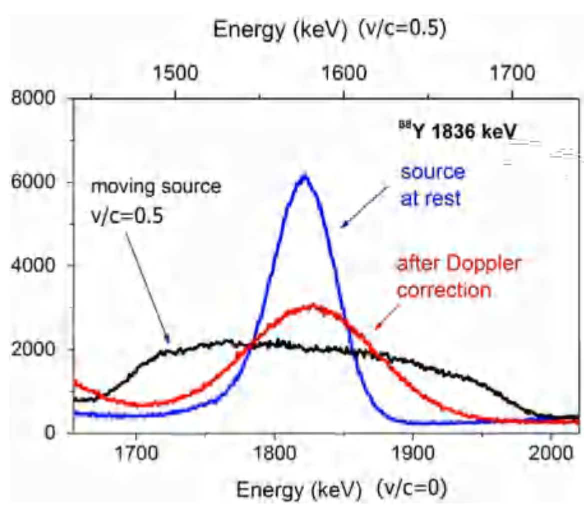

Fig. 11. The spectrum obtained after Doppler correction (red line) is compared to the spectrum simulating a source moving with v/c=0.5 (black line) and to the original spectrum (blu line). For details see the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reported. In the lab system, the energy corresponding to the 1836 keV transition would range from ~1500 keV for angles smaller than 90° to ~1700 keV for larger angles. Recalibrating each set of data and summing up the data, a spectrum was obtained which simulates the effect of Doppler broadening in an inverse reaction experiment. Fig. 10 shows the resulting 1836 keV peak (black line, energy scale on the top) compared with the original peak (blu line, energy scale on the bottom). The effect of the moving source simulation is to spread the 1836 keV peak over ~ 250 keV.

The successive step was to correct the "Doppler broadened" data via an event by event analysis, calculating the incidence angle from the measured position and transforming the "lab energy" into "c.m. energy". In the resulting spectrum, shown in Fig. 11 (red line), the 1836 keV peak has a FWHM of ~100 keV, with an improvement factor of ~2.5.

4. Conclusions

We investigated the position sensitivity of a spectroscopic 3 in × 3 in LaBr3: Ce detector using an intense ^{137}Cs collimated beam of 1 mm diameter (662 keV gamma ray) and a ^{88}Y source (1832 keV) collimated with 20 cm Pb leaving a 1 cm wide and 5 cm high window. The event-by-event analysis was performed using four Position Sensitive Hamamatsu H8500 PMT's, with segments short-circuited in groups of 16, so to have only four "macrosegments" for each PMT. The crystal surface was then covered by 12 such "macrosegments". By measuring the collimated sources in several positions, we found a position sensitivity with a resolution of the order of 2.3 cm for 662 keV and 2 cm for 1832 KeV gamma rays. In order to investigate whether this resolution would be sufficient to correct for Doppler broadening in nuclear physics experiments with exotic beams, we simulated experimentally the case of a 1836 keV gamma ray (^{88}Y source) emitted by a moving source with v/c=0.5 at 20 cm distance. The energy resolution, which is 50 keV for the source at rest, would then be ~250 keV for the moving source. By reconstructing the gamma interaction point we could correct for the broadening by a factor 2.5 and obtain a resolution of 100 keV. This demonstrates that the position sensitivity of large LaBr3: Ce might be used in nuclear physics experiments for studies where an energy resolution of 4–5% at 1 MeV is needed, and a correction of the Doppler broadening might be obtained with a relative simple setup and data analysis.

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