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# Gamma-response characterization of a solution-grown stilbene based detector assembly in the 59 keV–4.44 MeV energy range; an alternative low-resolution gamma spectrometer

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**1 Title**

2 Gamma-response characterization of a solution-grown stilbene based detector assembly in the 59 keV  
3 - 4.44 MeV energy range; an alternative low-resolution gamma spectrometer

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**20 Abstract**

21 The photon response characterization of a Ø 25.4 mm × 25.4 mm solution-grown stilbene based  
22 detector assembly was performed in the 59 keV - 4.44 MeV energy range. Energy calibration was  
23 carried out using not only direct measurements but also via coincidence measurements in order to  
24 obtain more reliable results. Both methods gave consistent results. To establish an accurate model of  
25 the detector, its energy resolution was determined and included in MCNPX-PoliMi simulations. This  
26 model served to compute the gamma-response matrix in the 0.1-7.3 MeV energy range. This matrix  
27 was used as an input of the GRAVEL spectrum unfolding code when attempting to unfold the  
28 measured spectra of well-known sources. Despite a few discrepancies concerning peak intensities, the  
29 main gamma peaks were successfully identified in the 0.059-4.4 MeV energy range, thus confirming  
30 the utility of solution-grown stilbene as a low-resolution gamma spectrometer, especially for  
31 identifying the gamma component in neutron fields.

**32 Keywords**

33 Organic scintillator detector, solution-grown stilbene, energy calibration,  $\gamma$ -ray response matrix,  
34 spectra unfolding, GRAVEL, crystal scintillator, gamma spectrometer.

**37 1 INTRODUCTION**

38 Detectors based on organic scintillators are widely used in the field of fast neutron spectroscopy. Their  
39 popularity stems from their high detection efficiencies, sufficient energy resolution, and, for most  
40 types, their ability to discriminate neutrons and gamma rays via pulse shape discrimination (PSD)  
41 above a minimum threshold. While liquid scintillators, such as BC501A/NE213 [1][2][3], are the most  
42 commonly used due to their low production costs and the ease in which they are produced in large  
43 volumes, recent developments in solution-growth techniques have made it possible to produce high-  
44 quality single organic crystals of various hydrocarbonated compounds at a modest price. These  
45 developments revived an interest in crystal scintillators, such as stilbene, to use as neutron  
46 spectrometers covering an energy range from ~100 keV [4] to ~20 MeV in order to monitor spectra  
47 produced in beam facilities or zero-power experimental nuclear reactors.

48 The work presented in this paper is part of a larger study dedicated to assessing the neutron  
49 spectrometry performance of a  $\varnothing$  25.4 mm  $\times$  H 25.4 mm stilbene ( $C_{14}H_{12}$ ) detector assembly. A part of  
50 the gamma response, typically between  $\sim$ 340 keV and  $\sim$ 1.550 MeV, must be characterized so that it  
51 can be used to calibrate the neutron response. Nevertheless, carrying out a gamma characterization  
52 over a wider energy range can also be useful for determining the gamma component accompanying  
53 any neutron field.

54 To this end, two energy calibration techniques, one with direct measurements and one with  
55 coincidence measurements, were used to determine the calibration curve. A MCNPX-PoliMi model of  
56 the detector was built to help accurately determine the energy resolution of the detector. This model  
57 also served to construct the gamma response matrix of the detector, which was then used as an input  
58 parameter of the GRAVEL unfolding code for carrying out the deconvolution of experimental spectra  
59 of well-known gamma sources.  
60

## 61 **2 EXPERIMENTAL DETAILS**

### 62 **2.1 ORGANIC SCINTILLATOR DETECTORS**

63 Two cylindrical organic scintillators, listed in Table 1, are used in this work. The main detector is a  
64  $\varnothing$  25.4 mm  $\times$  25.4 mm solution-grown [5] stilbene, produced by InradOptics [6] and encapsulated in a  
65 0.5 mm thick aluminum cylinder. The other detector is only used to perform coincidence  
66 measurements and will not be described further. In earlier works [4] [7], the high voltage of the main  
67 detector was set to measure low energy neutrons (e.g. -1230 V to measure neutrons below 1 MeV). In  
68 the present work, as the goal was to accommodate a neutron energy range as wide as possible (up to  
69 17 MeV), the high voltage was set to -930 V, which corresponds to a gain reduction factor of about 40.  
70

71 INSERT TABLE 1 HERE  
72

### 73 **2.2 DATA ACQUISITION AND ANALYSIS**

74 Data acquisition was performed using a CAEN DT5730 digital acquisition (DAQ) system [10], with  
75 8.MCX data acquisition channels, 14-bit resolution, a 2-V maximum digitization window and a  
76 500.MHz sampling rate. Digital acquisition systems offer many advantages compared to analog  
77 systems, such as an ease of assembly, the capacity to timestamp at picosecond each triggering signal  
78 with a measured 1.ns resolution from DT5730's capability [4], an ability to support high count rates  
79 and enhanced neutron/gamma discrimination capabilities [11] [12]. After digitization, anode signals  
80 from the photomultipliers are processed by the Digital Pulse Processing - Pulse Shape Discrimination  
81 (DPP-PSD) firmware. This firmware timestamps the signals and computes two integrals over two  
82 different time-windows: one integral is called Long gate ( $Q_L$ ) and covers most of the signal, while the  
83 other is called Short gate ( $Q_S$ ) and covers only the fast part of the signal. The ratio of these two  
84 integrals provides our PSD information.

85 The data recorded are: time of radiation detection,  $Q_L$ ,  $Q_S$ , flags (firmware information about the signal  
86 recording status) and, if the "wave" mode is selected, the digitized signal itself. This last capacity was  
87 not used routinely as it requires considerable computational power, reduces the maximum count rate  
88 that the system can handle, and drastically increases data management and analysis requirements. All  
89 data produced in this work are processed and analyzed using the ROOT framework [13].  
90

### 91 **2.3 EXPERIMENTAL SETUPS**

92 In order to perform a complete gamma characterization of the stilbene detector, two sets of  
93 experiments were performed using several sources (see Table 2) available at the AMANDE facility  
94 [14]. The  $^{12}C^*$  first excited state decay of the  $^{241}AmBe$  neutron-gamma source [15] produces 4.438  
95 MeV gamma rays, which primarily interact with the matter through Compton scattering and pair  
96 production, thus producing a usable double escape peak at 3.416 MeV and a Compton edge.

97  
98  
99

INSERT TABLE 2 HERE

### 100 2.3.1 Direct measurements

101 For direct measurement, each gamma source was positioned at 100 mm from the detector front face to  
102 ensure a high number of counts in a reasonable amount of time with a relatively homogeneous detector  
103 irradiation, while avoiding too many pile-up events.  
104

### 105 2.3.2 Coincidence measurements

106 A known, but seldom-used energy calibration method is based on a gamma scattering coincidence  
107 technique [17] [18] [19] [20]. As shown in Figure 1, , for such measurements, the front face of the  
108  $\text{\O} 25.4 \times 25.4 \text{ mm}^3$  stilbene detector was placed at 240 mm from the front face of a  $\text{\O} 50.8 \times 50.8 \text{ mm}^3$   
109 stilbene detector, with their cylindrical axis being aligned. Gamma sources were placed inside a  
110 hollow lead cylinder (inner radius of 70 mm), at a distance of around 60 mm below the stilbene  
111 crystal, which was thus uniformly irradiated. Since the sources used can emit several gamma  
112 simultaneously, lead shielding was used to avoid direct and undesirable coincidences on the second  
113 detector. The coincidence window between the two detectors was set to 60 ns. According to the solid  
114 angle of the experimental set-up, only gamma rays that interacted with the main stilbene detector with  
115 a scattering angle around  $90^\circ$  (within  $\pm 9^\circ$ ) could induce the expected coincidences. The associated  
116 uncertainty on the deposited energy varies with the incident gamma ray's energy and reaches a  
117 maximum of  $\sim 9\%$  around 500 keV ( $\sim 7\%$  at 1500 keV).  
118

119 INSERT FIGURE 1 HERE  
120

## 121 3 ENERGY CALIBRATION

122 Energy calibration of a scintillator is performed by associating the known energy of a photoelectric  
123 peak, of a Compton Edge (CE) or of simple/double-escape peak to the corresponding discrete channel  
124 of the measured spectrum. However, due to the finite energy resolution of the detector, the exact  
125 position of the CE is not always easily identifiable. Figure 2 presents the  $^{207}\text{Bi}$  (a) and  $^{60}\text{Co}$  (b) spectra  
126 obtained with the  $\text{\O} 25.4 \times 25.4 \text{ mm}^3$  stilbene detector with (red solid line) and without (blue solid  
127 line) the coincidence method. Given the experimental setup described in section 2.3, in coincidence  
128 mode, each peak is induced by a gamma ray of given energy.  
129

130 INSERT FIGURE 2 HERE  
131

### 132 3.1 DIRECT MEASUREMENTS

133 In this work, an approach similar to that used to identify the distribution of recoil protons was used  
134 [21] to determine the CE position for direct measurements. Indeed, given the shape of the ideal  
135 spectrum (sharp drop at the CE position), and irrespective of energy resolution effects, the first-order  
136 derivative is assumed to take the form of an inverse Gaussian distribution, centered on the position of  
137 the CE (see Figure 3). Such a method was also used in previous works by [22] [23] [24].  
138

139 INSERT FIGURE 3 HERE  
140

141 In the energy range between 0.3 MeV and 2 MeV, the relationship between the integral charge (i.e.  
142 channel) and the energy deposited by gamma rays is almost linear (see black dashed line on Figure  
143 4(a.1)) [25]. Therefore, the calibration curve, denoted  $L_{Mean}$ , can be described using a first-order  
144 polynomial:

145  $L(\text{MeVee}) = b \cdot PH(\text{channel}) + a$  (1)

146 where  $a$  and  $b$  are parameters determined by fitting the calibration data points. Obtained values are  
 147 respectively  $b = (38.59 \pm 0.26) \times 10^{-4}$  and  $a = (2.1 \pm 0.4) \times 10^{-2}$  for a  $\chi^2/\text{ndf}^1$  of  $1.063 \times 10^{-4}/6$ .

148 However, for energies below 0.3 MeV and above 2 MeV, a simple linear fit is no longer sufficient to  
 149 reproduce the stilbene's gamma ray response and a second-order polynomial is considered:

150  $L(\text{MeVee}) = c \cdot PH^2(\text{channel}) + b \cdot PH(\text{channel}) + a$  (2)

151 where  $a$ ,  $b$  and  $c$  are parameters determined by fitting the calibration data points.

152 At low energy, calibration was performed using data from  $^{241}\text{Am}$  as the starting point. This data was  
 153 completed by a point at 0.344 MeV ( $E_{re}(180^\circ) = 0.197$  MeV), obtained using a  $^{152}\text{Eu}$  source. The  
 154 low-energy calibration curve is denoted  $L_{Low}$  (solid red line on Figure 4(a.2)) and its parameters, using  
 155 the notation from Eq. (2), are  $a = 0$  (imposed value),  $b = (41.5 \pm 0.5) \times 10^{-4}$  and  $c = (-7.77 \pm 2.16) \times 10^{-7}$ .  
 156 The associated  $\chi^2/\text{ndf}$  value ( $1.714 \times 10^{-5}/2$ ) indicates a better data/model agreement than for the  
 157 previous  $L_{Mean}$  result ( $\chi^2/\text{ndf} = 4.203 \times 10^{-5}/2$  in the same energy range). Similarly, to improve the  
 158 calibration process at high energy, the double escape peak at 3.416 MeV induced by the 4.438 MeV  
 159 gamma of  $^{12}\text{C}^*$  was included in the data set. The associated calibration curve is denoted  $L_{High}$  (see  
 160 blue solid line on Figure 4(a.1)) and its parameters are  $a = (3.4 \pm 0.6) \times 10^{-2}$ ,  $b = (38 \pm 0.3) \times 10^{-4}$  and  
 161  $c = (-9.1 \pm 2.8) \times 10^{-8}$ . The obtained  $\chi^2/\text{ndf}$  is  $2.105 \times 10^{-5}/2$ , which indicates, even for high energies, a  
 162 slightly better data/model agreement than for  $L_{Mean}$  result ( $\chi^2/\text{ndf} = 3.849 \times 10^{-5}/3$  in the same energy  
 163 range).

164 As can be seen on Figure 4(b), when comparing spectra calibrated using  $L_{Mean}$  and  $L_{High}$   
 165 (resp.  $L_{Low}$ ), discrepancies are obtained on the CE (resp. photoelectric peak) position. Using  $L_{Mean}$ ,  
 166 the 59.6 keV peak of  $^{241}\text{Am}$  is overestimated by 33.2% and the 4.196 MeV CE of  $^{12}\text{C}^*$  by 2%.  
 167 Therefore, using a purely linear calibration curve (i.e.  $L_{Mean}$ ) would result in a significant bias in the  
 168 low ( $< 0.3$  MeV) and a small but real bias in the high ( $> 2$  MeV) energy ranges. The observed non-  
 169 linearity may have several origins, among which the PMT, the non-linearity of the electron light and  
 170 the derivative-Gaussian fit method used to determine the CE position. Regarding the latter,  
 171 comparison to coincidence measurements (see Section 3.2) suggests that it is not the main source of  
 172 non-linearity.

173

174

INSERT FIGURE 4 HERE

175

### 176 3.2 COINCIDENCE MEASUREMENTS

177 As shown in Figure 2, in coincidence measurements, the recorded spectra take the shape of Gaussian  
 178 distribution, centered on the energy deposited by gamma rays scattering at  $90^\circ$ . Since the energy of  
 179 these photons is lower than that of photons scattered at  $180^\circ$  (see Table 2,  $E_{re}(90^\circ)$ ) the calibration  
 180 point is obtained for lower energies, and thus lower channels, than with a direct measurement.

181 The main advantage of the coincidence configuration is that, for each source, the peak positions  
 182 correspond to well-known energies, thus giving a direct calibration curve. As this calibration does not  
 183 depend on any assumption (for instance the position of the CE), it can be used to assess the accuracy  
 184 of other calibration methods, such as the derivative method used in the previous section. However, its  
 185 main drawback is that it requires about 200 times longer measurement times than direct measurements  
 186 in order to acquire sufficient data for a reliable measurement. Given the available sources (see Table  
 187 2), this calibration could only be established for energies below 2 MeV. For energies below 0.3 MeV,  
 188 the obtained calibration points exhibit the same non-linear behavior as that observed during direct

---

<sup>1</sup> Ndf (number of degrees of freedom) = number of data points – number of fitting function parameters (for the ROOT framework)

189 measurements. This proves the cause of the non-linear behavior is not to be found in the used  
190 derivative method. A parametrization with a second-order polynomial function below 0.3 MeV and a  
191 first-order polynomial up to 2 MeV was used to account for this non-linearity.  
192

### 193 3.3 PERFORMANCE COMPARISON OF CALIBRATION METHODS

194 Calibration curves obtained for direct (black solid square) and coincidence (black empty square)  
195 measurements are presented on Figure 5 (left). Corresponding equation parameters are presented in  
196 Table 3. Overall, the obtained curves present an excellent agreement with parameters compatible  
197 within uncertainties and a maximum deviation of 1.54% at 0.138 MeV. Figure 5 (right) compares the  
198 experimental spectrum of  $^{60}\text{Co}$  calibrated with (blue solid line) and without (red solid line) the  
199 coincidence method. Compared to the reference energies of  $^{60}\text{Co}$ , there are shifts of 0.38% and 0.57%  
200 at 1.173 MeV and of 0.08% and 0.35% at 1.332 MeV with and without the coincidence method,  
201 respectively.  
202

203 INSERT FIGURE 5 HERE

204  
205  
206 INSERT TABLE 3 HERE  
207

208 Results obtained by the direct and coincidence methods are in good agreement and both techniques  
209 provide an accurate calibration curve. Since direct measurements are much easier and faster, this  
210 approach will be kept for future work.  
211

## 212 4 MCNPX SIMULATIONS

213 To simulate stilbene's gamma ray response, the MCNPX Monte Carlo code has been chosen. It is used  
214 in photon-electron mode with the ENDF/B-VI photo-atomic data libraries to define material  
215 properties. The constructed geometric model is a simple one, which includes the stilbene crystal, its  
216 aluminum container, the Plexiglas light-guide and the PMT container, which was filled only with air.  
217 As mentioned in the previous section, organic scintillators have a finite energy resolution, which one  
218 must account for in order to perform accurate simulations. To this end, a Gaussian Energy Broadening  
219 (GEB) [27] function can be applied to simulation results.  
220

### 221 4.1 ENERGY RESOLUTION

222 The GEB function is expressed as a function of  $FWHM$ , which is written as:

$$223 \quad FWHM(E) = L(E) \cdot R(L(E)) = a' + b' \sqrt{E + c'E^2} \quad (3)$$

224 In Eq.(3),  $L(E)$  represents the light-output and  $R(L(E))$  the associated energy resolution,  $a'$ ,  $b'$  and  $c'$   
225 are parameters. From the empirical formula (1) [28]:

$$226 \quad R(L(E)) = \frac{\Delta L(E)}{L(E)} = 1.5 \cdot \frac{L_{1/2} - L_{MAX}}{L_{1/2}} \quad (4)$$

227 where  $L_{MAX}$  corresponds to the energy of the maximum counts (around the Compton edge) and  $L_{1/2}$   
228 to the energy where this count is halved, a first estimation of  $R(L(E))$  for the different sources listed  
229 in Table 2 was performed. Using the Pulse Height (F8) tally of MCNPX, ideal Compton spectra were  
230 computed and then convolved using the GEB function parametrized with the results from equation (3).  
231 Discrepancies were observed between simulations and experimental spectra, with an overestimation of  
232  $R(L(E))$ . Therefore, the  $R(L(E))$  value was fixed and manually adjusted until a good agreement was

233 reached between experimental and simulated data at the CE level. Afterwards, to expand  $R(L(E))$   
234 over the whole range of interest, data points thus obtained were fitted using the standard function [28]:

$$235 \quad R(L(E)) = \sqrt{\alpha^2 + \frac{\beta^2}{L(E)} + \left(\frac{\gamma}{L(E)}\right)^2} \quad (5)$$

236 in which the  $\alpha$ ,  $\beta$  and  $\gamma$  parameters respectively account for the light transmission from the scintillator  
237 to the photocathode, the statistical variation of the photoelectron production mechanism, and the noise  
238 contributions of the acquisition system. Eq. (3) and (5) parameters, which are listed in Table 4, were  
239 obtained by fitting the experimental data as shown in Figure 6. For the determination of the energy  
240 resolution at 4438 keV and referring to [29], we have accounted for an “apparent” resolution of 90  
241 keV ( $\pm 4$ .keV) arising from the Doppler broadening effect.

242  
243 INSERT FIGURE 6 HERE

244  
245 INSERT TABLE 4 HERE

#### 246 247 4.2 DIRECT MEASUREMENTS SIMULATIONS

248 Figure 7 presents the comparison between calibrated experimental spectra (blue solid line), after  
249 background subtraction, and simulated (black dashed line), accounting for the stilbene’s energy  
250 resolution, spectra of the  $^{22}\text{Na}$  (a) and  $^{207}\text{Bi}$  (b) sources. Experimental spectra are in good agreement  
251 with simulated results (less than 1% deviation on the position of the CE). Nevertheless, the simulation  
252 does not reproduce the experimentally observed Compton continuum. Non-modelled materials, such  
253 as the experiment table or the PMT’s components, which create backscatter contributions, could  
254 explain such a discrepancy.

255  
256 INSERT FIGURE 7 HERE

#### 257 258 4.3 COINCIDENCE MEASUREMENT SIMULATIONS

259 Since the F8 tally does not enable the selection of gamma rays scattered at a specific angle ( $90^\circ$  in this  
260 work), a modified version of the code, MCNPX-PoliMi (Polytechnic of Milano) [30], was used  
261 instead. Similarly, to the PTRAC option of MCNPX, MCNPX-PoliMi generates an output file that  
262 records, for each simulated history, information about collision events within a user-chosen cell.  
263 Among the recorded information, the particle type, deposited energy, number of collisions and  
264 incident energy of the interacting particle are of interest to our study. These data were processed using  
265 the MPPost (MCNPX-Polimi Post-Processor) software, developed by the same team [31], in order to  
266 account for the detector response.

267 Figure 8 shows the comparison between calibrated experimental and simulated broadened spectra of  
268  $^{60}\text{Co}$  (a) and  $^{152}\text{Eu}$  (b) sources. For both sources, the positions of the energy peaks in the experimental  
269 spectra are in good agreement with that of the simulated spectra. However, discrepancies can be  
270 observed on either side of the peak tails. A probable cause is that random coincidences and recoil  
271 electrons, which are not correctly simulated [32], are not accounted for.

272  
273 INSERT FIGURE 8 HERE

274  
275 Despite a few discrepancies, simulated spectra present a good agreement with experimental ones.  
276 Table 5 lists the obtained deviations on both the energy and the FWHM for each measured gamma ray.  
277 While the recoil electron energy is relatively well reproduced, with a maximum deviation of about 1%  
278 at 79.keV, the FHWM presents more significant deviations (up to 7% on the 0.63 MeV gamma ray  
279 from the  $^{152}\text{Eu}$  source). The most probable origin of these discrepancies is the simplified model of the

280 experiment, which does not reproduce the background caused by photon scattering, nor an eventual  
281 small shift in the source position.

282

283

284

INSERT TABLE 5 HERE

## 285 **5 GAMMA RESPONSE MATRIX AND SPECTRUM UNFOLDING**

### 286 **5.1 RESPONSE MATRIX CONSTRUCTION AND INTRINSIC EFFICIENCY**

287 For organic scintillators, as for many other detectors, the relationship between the incident particle  
288 flux  $\phi(E)$  and the measured response  $PH(L)$  can be formally expressed as:

$$289 \quad PH(L) = \int_0^{\infty} R(E, L)\phi(E)dE \quad (6)$$

290 where  $R(E, L)$  is the response matrix, *i.e.* the mathematical operator that contains the relevant  
291 normalized responses of the organic scintillator in its operational energy range, and thereby accounts  
292 for its energy resolution. The gamma-ray response matrix of the stilbene detector was constructed by  
293 performing 240 pointwise isotropic gamma simulations, each with  $10^9$  particles emitted by a source  
294 placed at 100 mm from the detector front face. The response matrix was constructed between 100 keV  
295 and 7.3 MeV (*i.e.* 30 keV/bin), each calculation yielding a simulated response between 0 and 8  
296 MeVee, tallied over 1024 bins. It is necessary to point out the calculated response matrix is an ideal  
297 one and in practice, the gamma scattering around the detector should be subtracted in order to  
298 correctly deduce an incident spectra  $\phi(E)$ .

299 The intrinsic gamma-ray efficiency  $\varepsilon(E)$  curve can be computed from the response matrix according to  
300 equation (7):

$$301 \quad \varepsilon(E_i) = \int_{L_{th}}^{L_M} R(E_i, L)dL \quad (7)$$

302 where  $R(E_i, L)$  is the gamma ray response at the incident energy ( $E_i$ ).  $L_M$  and  $L_{th}$  (in MeVee) are  
303 respectively the maximum and the threshold light output. Figure 9 shows, for four different threshold  
304 values, the calculated gamma efficiency curve of the stilbene up to 3 MeV. Results are in rather good  
305 agreement with experimental values obtained with a  $^{137}\text{Cs}$  (0.662 MeV) source. Above a 0.1 MeVee  
306 threshold, discrepancies observed remain below 1.6%. These discrepancies could be slightly reduced  
307 by improving the MCNPX model used to construct the gamma response matrix (*i.e.* by a better  
308 reproduction of the Compton continuum).

309

310

311

INSERT FIGURE 9 HERE

312

### 313 **5.2 SPECTRA UNFOLDING WITH GRAVEL ALGORITHM**

314 Unfolding (or deconvolution) is a procedure that addresses the inverse problem in Eq. (6), *i.e.* that  
315 gives the energy flux  $\phi(E)$  which generated the scintillator response  $PH(L)$ . Over the years, many  
316 methods and codes have been developed for this operation [33] [34]. In this work, the iterative code  
317 GRAVEL was chosen as it is widely used for unfolding spectra for both gamma rays [1] [35] and  
318 neutrons [36] [37]. GRAVEL uses an iterative algorithm based on the nonlinear least-squares method  
319 and only yields physically meaningful solutions (*i.e.* an everywhere positive flux). To start the  
320 iterative process, GRAVEL needs the experimental spectrum to be unfolded, the response matrix, an  
321 input flux (as a first solution to start the iterations), the maximum number of iterations to be performed  
322 and a  $\chi^2$  target. The code runs until either the maximum number of iterations or the defined  $\chi^2$  target  
323 value is reached. For all tested spectra, 50000 iterations were performed using a flat (all bins equal to  
324 1) input flux. Tests were performed to ensure that using such an input flux did not yield significant  
325 changes in the result compared to what is obtained when using a realistic input flux. The choice of



326 50000 iterations depends on the fact that for all tested sources they guarantee the minimum and stable  
327  $\chi^2$  value.

328 Gamma spectra unfolded by GRAVEL are compared with known theoretical peaks [16], in terms of  
329 peak average energy and emission intensity in order to assess the quality of the performed unfolding.  
330 Figure 10 presents the comparison results for  $^{12}\text{C}^*$  (a) and  $^{152}\text{Eu}$  (b). Experimental spectra were scaled  
331 to match the peak of highest emission intensity. Observed deviations on the peak energies and their  
332 emission intensities are reported in Table 6.

333

334

INSERT FIGURE 10 HERE

335

336

INSERT TABLE 6 HERE

337

338 For  $^{12}\text{C}^*$ , there is a deviation of 0.24% between the measured and theoretical energies. In addition,  
339 sporadic peaks are present at lower energies, probably caused by gamma scattering around the  
340 detector. For  $^{152}\text{Eu}$ , given the large number of energetically-close gamma lines (over 40 lines of  
341 similar intensities in the [0.45-0.7] MeV range for example) and the finite resolution of the stilbene  
342 detector, only 13 lines above 1% intensity could be considered. Indeed GRAVEL algorithm can't, in  
343 this case, unfold properly low intensity gamma rays which are too energetically-close. In this study,  
344 the limit is around 1%. Moreover, in the intervals 0.411-0.444 MeV, 1.085-1.112 MeV and 1.212-  
345 1.299 MeV, measurements are compared to the average of the theoretical peaks, weighted by their  
346 respective intensities, as the resolution of the detector was not good enough to separate the  
347 contributions. While deviations from the expected mean energies are less than 1%, deviations on peak  
348 intensities can reach up to 87.92% on the peak of lowest energy (0.244 MeV). These deviations are  
349 related to both the complexity of  $^{152}\text{Eu}$  source and the uncertainties associated to the stilbene response  
350 matrix. Nevertheless, unfolding a stilbene gamma spectrum permits, with sufficient accuracy, a peak  
351 identification, even for a complex source, thus demonstrating its capacity as a gamma spectrometer.

352

## 353 6 CONCLUSIONS

354 In this work, the complete gamma characterization of a  $\emptyset$  25.4 mm  $\times$  25.4 mm solution-grown stilbene  
355 based detector assembly has been performed. Gamma sources covering an energy range between  
356 0.059 MeV and 4.438 MeV were used to determine the energy resolution of the detector and perform  
357 its energy calibration. For the latter, consistent results were obtained between coincidence  
358 measurements and direct measurements, thus showing that applying a first-derivative method to  
359 determine the position of the Compton edge is accurate and reliable for calibration purposes.  
360 Nevertheless, as non-linearities were observed below 0.3 MeV and above 2 MeV, the calibration curve  
361 had to be adapted by introducing second-order polynomials in these ranges in order to use the stilbene  
362 as a broadband gamma spectrometer. Simulations were performed using a simple MCNPX-PoliMi  
363 model. They successfully reproduced the expected detector behavior around the Compton Edge,  
364 although the experimental Compton continuum could not be reproduced, probably because of the  
365 rather simple MCNP model used. The gamma-ray response matrix of the detector was built and the  
366 intrinsic efficiency curve computed for several thresholds. To validate the constructed matrix, spectra  
367 of known sources were unfolded using the GRAVEL iterative code. Results showed that the  
368 constructed matrix is sufficient to successfully identify the main gamma peaks present in the spectrum  
369 in the energy range between 0.059 and 4.4 MeV. These studies have demonstrated the capabilities of  
370 stilbene based detectors to serve as a low-resolution gamma spectrometer in the energy range between  
371 0.059 and 4.4 MeV. Future work will focus on the neutron response characterization of this detector  
372 assembly, using monoenergetic neutrons produced by the AMANDE facility and a white neutron  
373 spectrum produced by the PTB cyclotron [38]. The main objective of these measurements will be to  
374 obtain measured [39] [40] and, if possible, the simulated [41] neutron response matrices of the  
375 detector assembly to assess its performance as a broadband neutron spectrometer in mixed radiation

376 fields. In addition, as part of these measurements, anisotropy effects of the stilbene crystal [42] [43]  
377 will be investigated in more details as well as their impact on the neutron response.

378

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382

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505

## Captions with figures sizes

Figure 1 (Full color online): Picture of the coincidence experimental set-up.

(Size H 83.3 mm L 140)

Figure 2 (Full color online): Comparison between the experimental spectra with (w: red solid line) and without (w/o: blue solid line) the coincidence method for:  $^{207}\text{Bi}$  (a) and  $^{60}\text{Co}$  (b).

(Size H 74.4 mm L 190 mm)

Figure 3: Normalized and smoothed response given by  $^{137}\text{Cs}$  (black square) and its first order derivate (white square). The intersection between the experimental spectrum and the dotted line representing the centroid of the Gaussian distribution indicates the assumed CE position.

(Size H 70.1 mm L 85 mm)

Figure 4 (Full color online): Comparison of the energy calibration curves for high (a.1) and low (a.2) gamma energies; the larger error bars's size is comparable with the symbol one. (b.1) Comparison between  $^{12}\text{C}^*$  experimental calibrated spectra using  $L_{\text{Mean}}$  (black solid line) and  $L_{\text{High}}$  (blue solid line). (b.2) Comparison between  $^{241}\text{Am}$  experimental calibrated spectra using  $L_{\text{Mean}}$  (black solid line) and  $L_{\text{Low}}$  (red solid line) and the simulated spectrum (blue dashed line) using MCNPX (see Section 4).

(Size H 180.5 mm L 185 mm)

Figure 5 (Full color online): (Left) Comparison of the stilbene calibration data points obtained without (w/o: black solid square) and with (w: black empty square) the coincidence method; the larger error bars's size is comparable with the symbol one. Calibration points have been fitted using Eq. (1) (dashed line) in the energy range between 0.3 and 2 MeV and Eq. (2) (solid line) in the energy range between 0 and 0.3 MeV. For the calibration curves color is used: red for the curve obtained with the coincidence method and blue without it. (Right) Comparison between experimental calibrated spectra for  $^{60}\text{Co}$  using  $L_{\text{Mean}}$  parameters obtained with (blue solid line) and without (red solid line) the coincidence data.

(Size H 80.3 mm L 190 mm)

Figure 6: Energy resolution (a) curve of the stilbene obtained using Eq. (5). FWHM (b) curve of the stilbene obtained using Eq. (3) (black solid line) and  $a\sqrt{E}$  (black dashed line) with  $a = (8.12 \pm 0.51) \times 10^{-2}$ . For both data sets, the larger error bars's size is comparable with the symbol one.

(Size H 79.6 mm L 185 mm)

Figure 7 (Full color online): Comparison between simulated (dashed black line) and experimental calibrated (solid blue line) spectra for  $^{22}\text{Na}$  (a) and  $^{207}\text{Bi}$  (b).

(Size H 77 mm L 190 mm)

Figure 8 (Full color online): Comparison between the experimental spectrum found with the coincidence method and the corresponding simulated spectra obtained with MCNPX-Polimi for:  $^{60}\text{Co}$  (a) and  $^{152}\text{Eu}$  (b).

(Size H 77 mm L 190 mm)

Figure 9 (Full color online): Calculated efficiency curves, according to Eq. (7), for  $\text{Ø}25.4 \times 25.4 \text{ mm}^3$  stilbene with several thresholds (solid lines). Experimental efficiencies were obtained with a source of  $^{137}\text{Cs}$  (black solid squares).

(Size H 77 mm L 85 mm)

Figure 10: Full color online): Comparison between the stilbene unfolded spectra and the expect gamma peaks for:  $^{12}\text{C}^*$  (a) and  $^{152}\text{Eu}$  (b).

(Size H 77 mm L 190 mm)

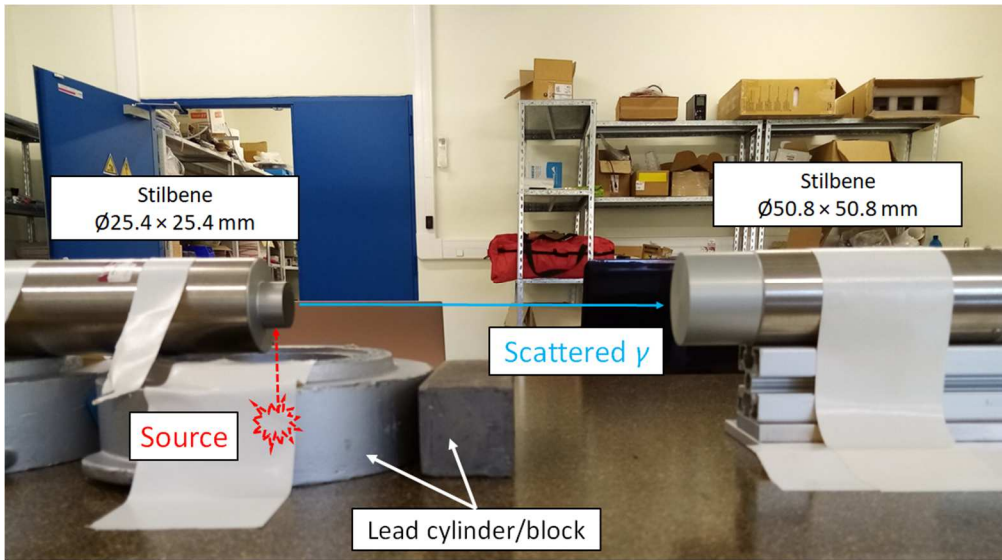


Figure 1

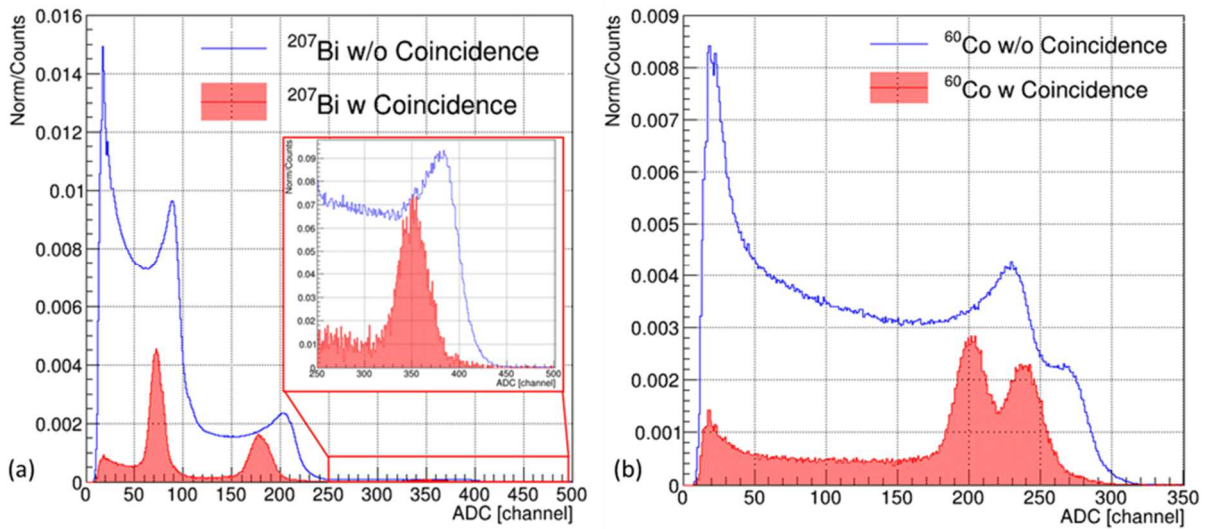


Figure 2

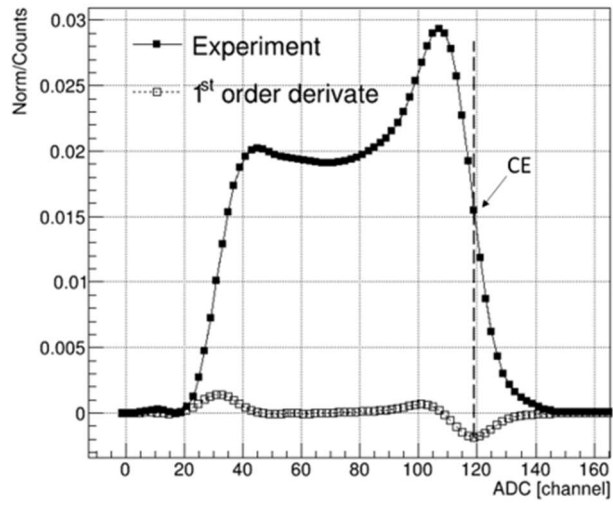


Figure 3

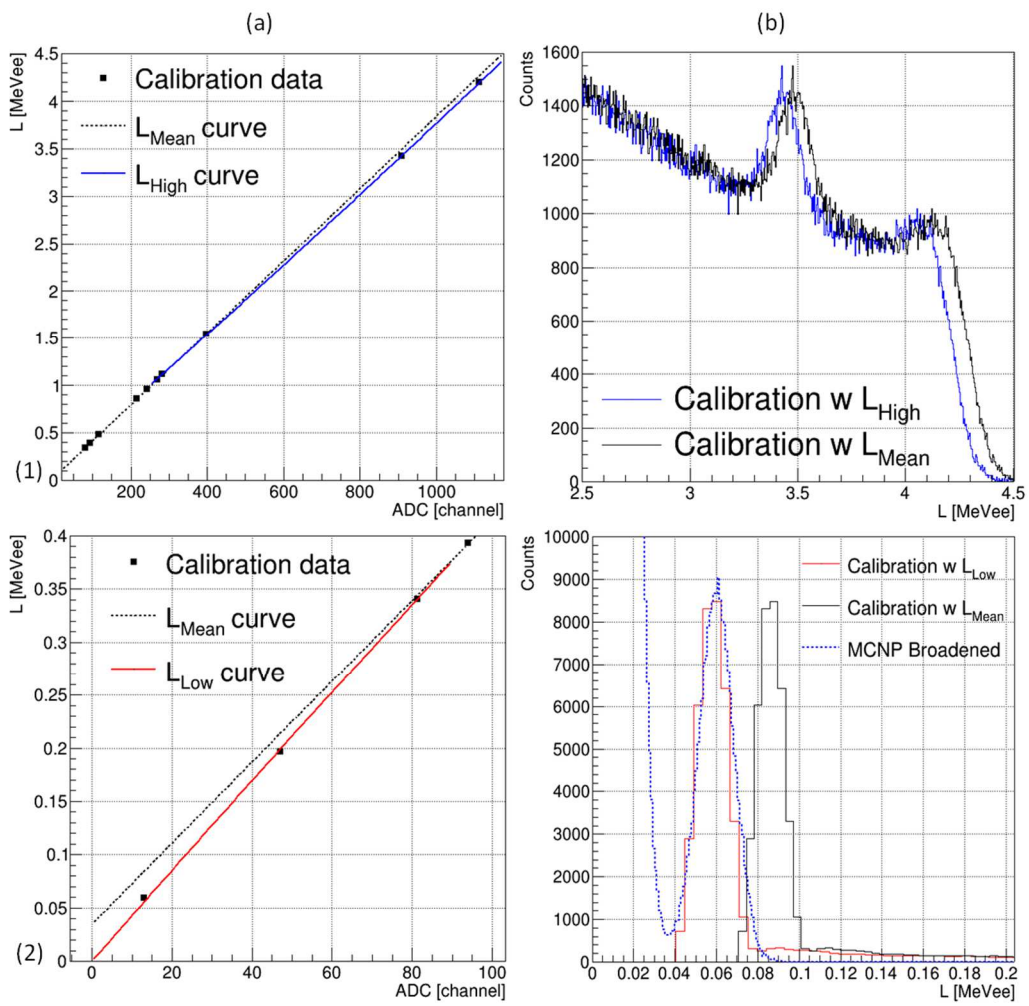


Figure 4



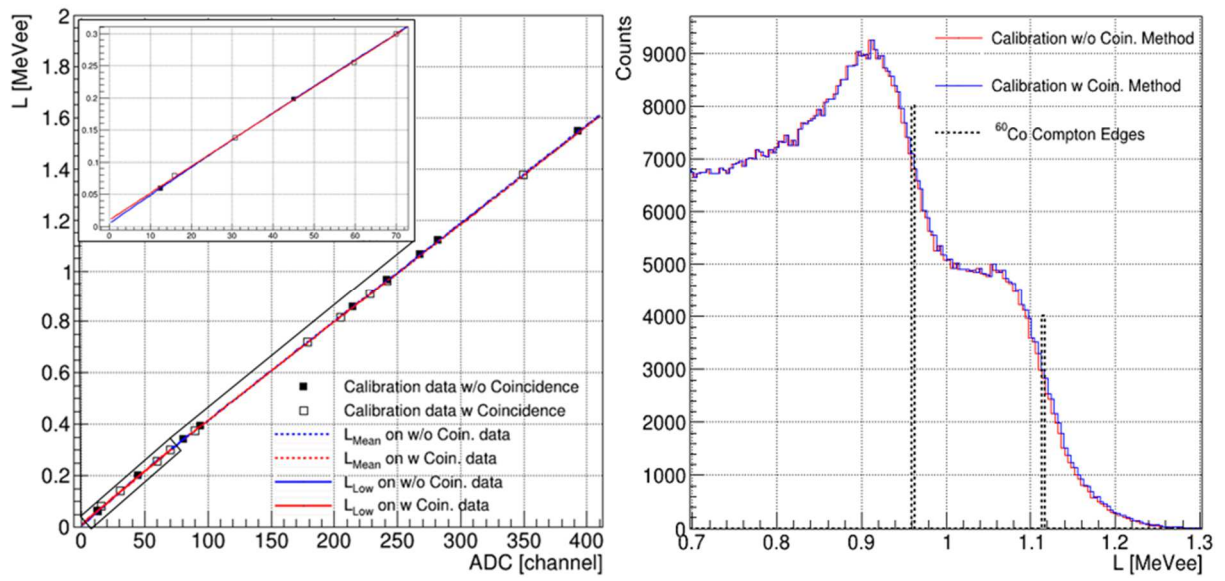


Figure 5

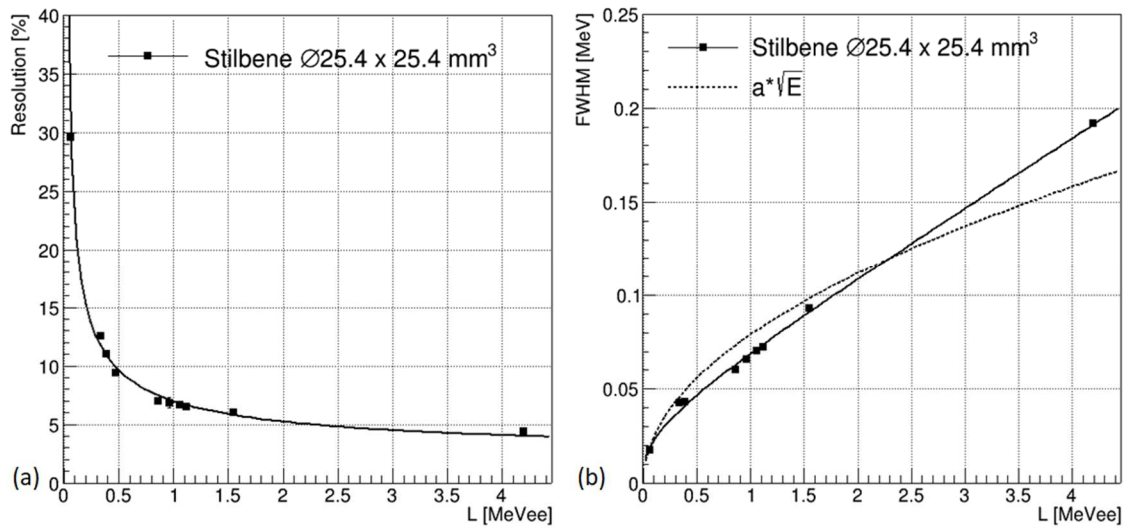


Figure 6

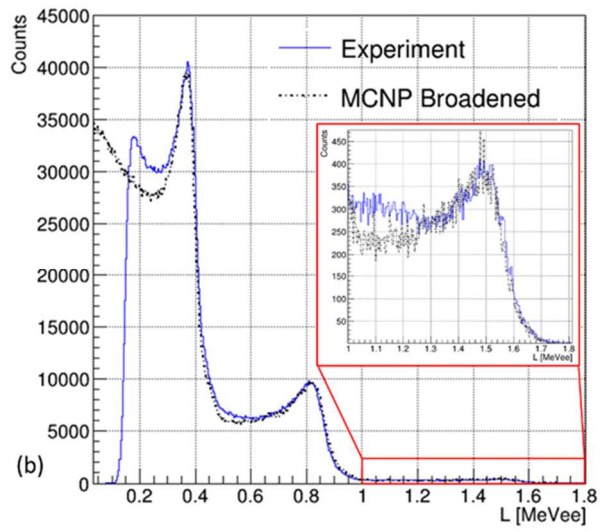
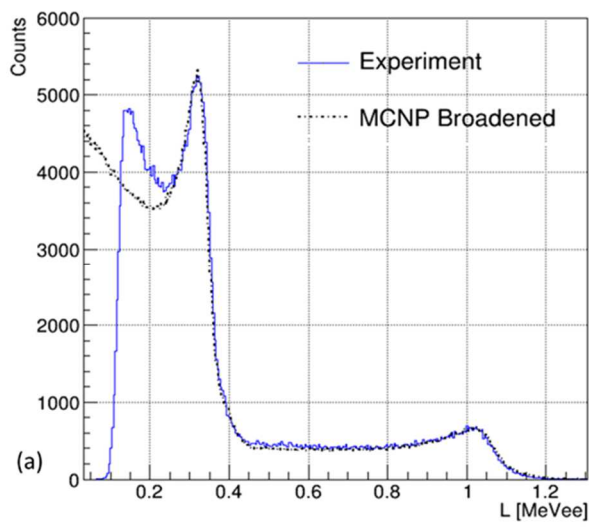


Figure 7

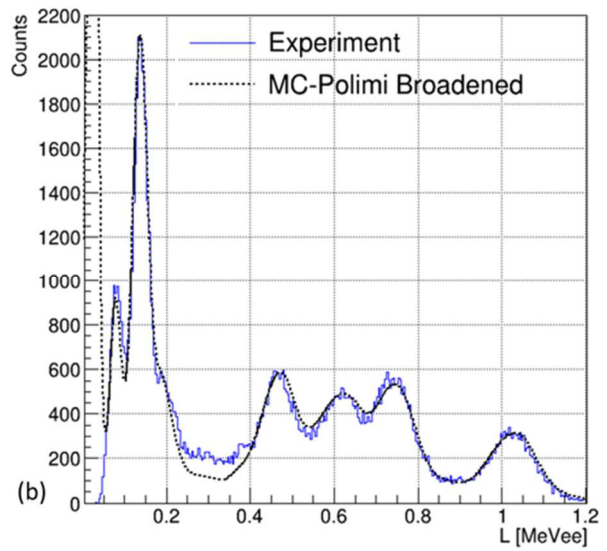
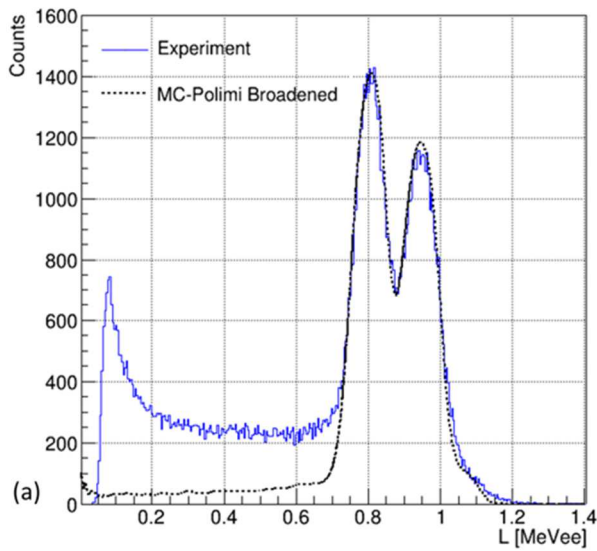


Figure 8

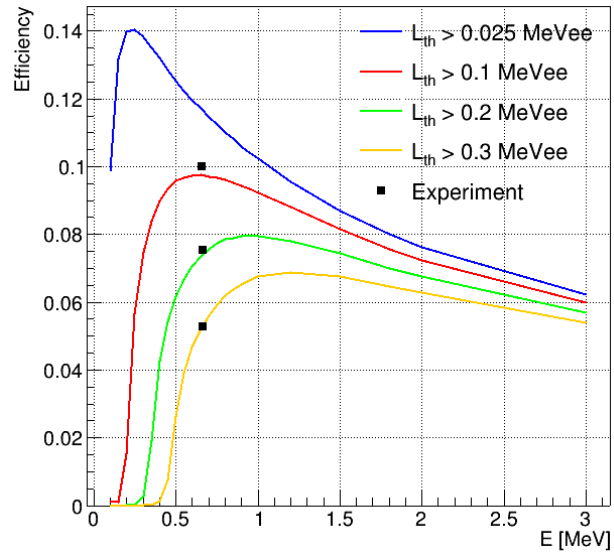


Figure 9

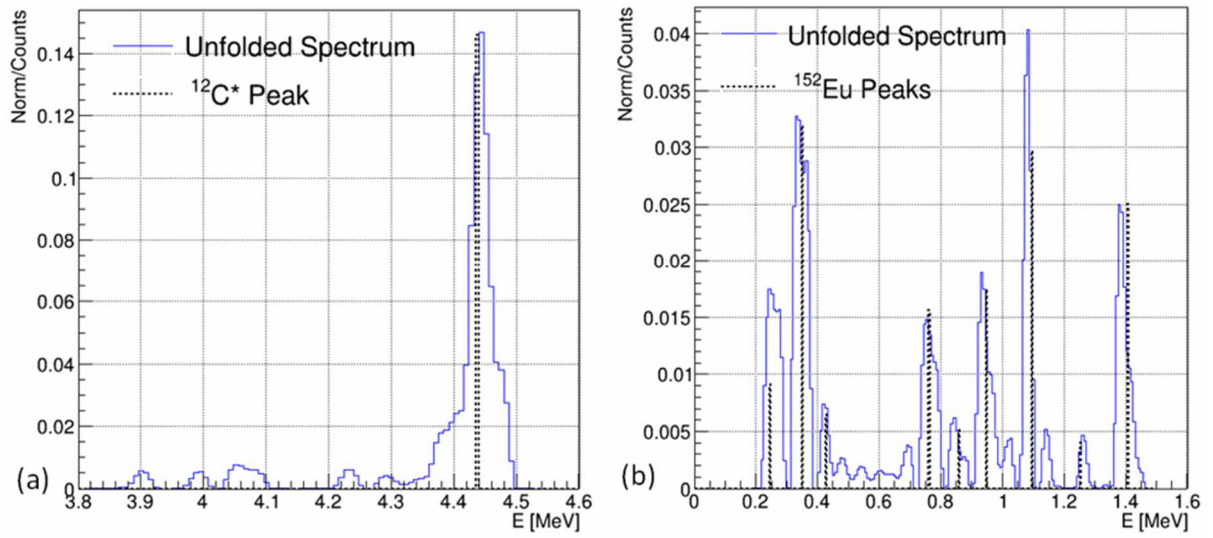


Figure 10

## Tables

Table 1: Characteristics of organic scintillators used in this work. The grey line indicates the stilbene detector under study.

Organic scintillator model	Type	Diameter [mm]	Length [mm]	Density [g/cm <sup>3</sup> ]	Photomultiplier model	Photomultiplier's voltage [V]
<b>Stilbene</b>	Crystal	25.4	25.4	1.15	ET-9214B [8]	-930
<b>Stilbene</b>	Crystal	50.8	50.8	1.15	ET-9266B [9]	-1100

Table 2: Gamma radionuclides used for the stilbene energy calibration,  $E_\gamma$  corresponds to the energy peaks produced by the sources, while  $E_{re}$  is the Compton edge energy (180° or 90° recoil electrons). Peak intensities were taken from the LARA library [16]. Sources with a grey background were used in coincidence measurements.

Source	$E_\gamma$ [keV]	$E_{re}(180^\circ)$ [keV]	$E_{re}(90^\circ)$ [keV]	Intensity [%]	Source activity [kBq]
<sup>241</sup> Am	59.6	Photoelectric interaction		35.92	-
<sup>137</sup> Cs	662	478	373	84.99	422.3
<sup>22</sup> Na	1275 511	1062 341	910 256	99.94 180.7	421
<sup>60</sup> Co	1332 1173	1117 963	962 817	99.9826 99.85	387.2
<sup>207</sup> Bi	1770 1063 570	1547 857 394	1374 718 301	6.871 74.58 97.76	384
<sup>152</sup> Eu	344 244	197 120	138 79	26.5 7.58	480
<sup>12</sup> C*	4438	4196	3980	85	16.5

Table 3: Stilbene detector calibration parameters with and without the coincidence method for two energy intervals. The  $L_{Low}$  parameters are obtained using Eq. (2) while  $L_{Mean}$  uses Eq. (1).

	Without the coincidence		With the coincidence	
	$L_{Low}$ [0, 0.3] MeV	$L_{Mean}$ [0.3, 2] MeV	$L_{Low}$ [0, 0.3] MeV	$L_{Mean}$ [0.3, 2] MeV
<b>a</b>	$(0.69 \pm 0.89) \times 10^{-2}$	$(2.93 \pm 0.11) \times 10^{-2}$	$(0.81 \pm 0.27) \times 10^{-2}$	$(2.9 \pm 0.3) \times 10^{-2}$
<b>b</b>	$(44.24 \pm 6.57) \times 10^{-4}$	$(38.56 \pm 0.04) \times 10^{-4}$	$(42.23 \pm 0.65) \times 10^{-4}$	$(38.63 \pm 0.17) \times 10^{-4}$
<b>c</b>	$(-4.95 \pm 8.71) \times 10^{-6}$	-	$(-1.27 \pm 0.24) \times 10^{-6}$	-

Table 4: Experimental parameters of equations (5) and (3).

$R(L(E))$			$FWHM(E)$		
$\alpha$ [%]	$\beta$ [%]	$\gamma$ [%]	$a'$ [MeV]	$b'$ [MeV <sup>1/2</sup> ]	$c'$ [MeV <sup>-1</sup> ]
$2.4 \pm 0.7$	$6.52 \pm 0.27$	$0.7 \pm 0.1$	$0.006 \pm 0.003$	$0.051 \pm 0.005$	$0.51 \pm 0.13$

Table 5: Deviations between experimental and simulated spectra for values on the midpoint ( $E_{re}$ ) and FWHM of Gaussian curves.

Source	$E_{re}(90^\circ)$ [MeV]	$E_{re}$ Deviation	FWHM Deviation
<sup>152</sup> Eu	0.079	(0.88 ± 0.03)%	(4.98 ± 0.07)%
<sup>152</sup> Eu	0.138	(0.43 ± 0.01)%	(2.92 ± 0.02)%
<sup>152</sup> Eu	0.470	(0.52 ± 0.05)%	(2.82 ± 0.11)%
<sup>152</sup> Eu	0.630	(-0.47 ± 0.11)%	(7.00 ± 0.36)%
<sup>152</sup> Eu*	0.750	(-0.57 ± 0.08)%	(2.24 ± 0.27)%
<sup>60</sup> Co	0.817	(-0.27 ± 0.04)%	(1.66 ± 0.14)%
<sup>60</sup> Co	0.962	(-0.09 ± 0.07)%	(1.59 ± 0.09)%
<sup>152</sup> Eu	1.033	(-0.40 ± 0.05)%	(3.88 ± 0.01)%

(\*The 0.75 MeV measurement corresponds to the average of the 1.085, 1.089 and 1.112 MeV gamma rays, which cannot be separated due to the limited resolution of the detector and of the experimental setup .)

Table 6: Deviation in mean energy value and intensity between the unfolded experimental spectra and theoretical values.

	Gamma Energy (MeV)	Intensity (%)	Mean energy deviation	Intensity deviation
<sup>152</sup> Eu	0.244	7.55	-0.20%	87.92%
<sup>152</sup> Eu	0.344	26.59	0.29%	0%
<sup>152</sup> Eu*	0.4275 (0.411/0.444)	5.358 (2.238/3.12)	0.23%	6.36%
<sup>152</sup> Eu	0.778	12.97	0.13%	-6.96%
<sup>152</sup> Eu	0.867	4.24	0.69%	17.03%
<sup>152</sup> Eu	0.964	14.5	0.73%	5.12%
<sup>152</sup> Eu*	1.0953 (1.085/1.089/1.112)	25.27 (10.13/1.73/13.41)	0.43%	31.76%
<sup>152</sup> Eu*	1.2555 (1.212/1.299)	3.04 (1.41/1.63)	-0.83%	7.15%
<sup>152</sup> Eu	1.408	20.85	0.75%	-2.17%
<sup>12</sup> C*	4.438	85	-0.24%	-