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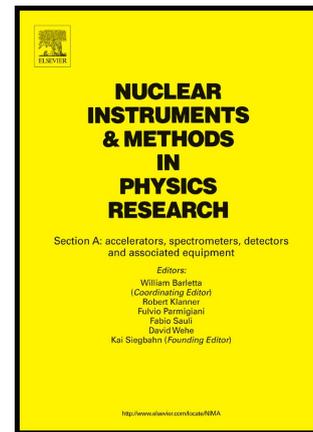
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Characterization of a cylindrical plastic β -detector with Monte Carlo simulations of optical photons

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1 Characterization of a cylindrical plastic β -detector with
 2 Monte Carlo simulations of optical photons

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24 **Abstract**

25 In this work we report on the Monte Carlo study performed to understand
 26 and reproduce experimental measurements of a new plastic β -detector with
 27 cylindrical geometry. Since energy deposition simulations differ from the ex-
 28 perimental measurements for such a geometry, we show how the simulation of
 29 production and transport of optical photons does allow one to obtain the shapes
 30 of the experimental spectra. Moreover, taking into account the computational
 31 effort associated with this kind of simulation, we develop a method to convert
 32 the simulations of energy deposited into light collected, depending only on the
 33 interaction point in the detector. This method represents a useful solution when
 34 extensive simulations have to be done, as in the case of the calculation of the
 35 response function of the spectrometer in a total absorption γ -ray spectroscopy

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36 analysis.

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38 Spectroscopy, optical photons

39 1. Motivation

40 In β -decay experiments, β -detectors are frequently used in coincidence with
41 neutron and/or γ detectors in order to clean the measurement by selecting only
42 the events coming from the decays. This method of rejecting the background
43 has been applied mainly with silicon detectors and plastic scintillator detectors.
44 It is important to maximize the β -detection efficiency in order to maximize the
45 statistics and lower the detection limit, as has been shown in different experi-
46 mental set-ups with germanium detectors [1, 2] or neutron counters [3]. In the
47 particular case of a Total Absorption γ -ray Spectroscopy (TAGS) experiment,
48 as well as in experiments with neutron detector arrays, large 4π detectors are
49 used in order to maximize the efficiency. If a β -coincidence condition is then
50 required, the statistics is reduced, since the total efficiencies of these kind of
51 detectors -close to 100% for a spectrometer such as the Decay Total Absorption
52 γ -Ray Spectrometer (DTAS) [4], and around 50% for a neutron detector array
53 such as the BEta deLayEd Neutron (BELEN) counter [5]-, have to be multiplied
54 by the corresponding efficiency of the β -detector. In the case of TAGS it is also
55 crucial to know accurately the β -detection efficiency, which depends strongly
56 on the endpoint energy of the β branches, affecting the β -gated spectrometer
57 response. Because of the continuum nature of β radiation, the low energy noise
58 discrimination threshold results in a large variation of efficiency over a wide
59 endpoint energy range.

60 A simple and convenient way to maximize the β -detection efficiency, mini-
61 mizing at the same time the γ sensitivity, is to build a hollow cylinder of thin
62 plastic scintillation material surrounding the source [1–3]. Closing one end of
63 the cylinder with scintillation material is a practical way to allow the attachment
64 of a photomultiplier tube (PMT) for light readout, while leaving the other end

65 free for transporting the radioactivity inside the detector, as will be shown in
66 Fig. 1. This geometry resembles the shape of a vase and can have a geometrical
67 efficiency close to 100% for sources at the bottom of the vase. A detector like
68 this was designed and built for experiments in conjunction with DTAS [4] and
69 BELEN [5], aimed at the study of the decay of exotic nuclei. In these experi-
70 ments the production of the isotopes of interest is low, thus the maximization
71 of the efficiency is a critical requirement.

72 However, a detector with such a geometry has a different response depending
73 on the interaction point of the β particle, as will be shown in this work. This is
74 related to the different light collection efficiency for interactions in the lateral
75 walls of the cylinder and in the bottom, where the PMT is coupled. This effect
76 entails a reduced amount of light collected in the photocathode of the PMT
77 from the lateral walls with respect to the bottom. As a result, the shape of
78 the recorded β spectrum is modified, and also makes it difficult to quantify the
79 threshold. This affects dramatically the efficiency curve of the β -detector, as
80 already mentioned. Therefore the quantification of the efficiency as a function
81 of the endpoint energy cannot be done on the basis of the energy deposited in
82 the detector alone, as we will see, and has to take into account the generation
83 and transport of the light in the detector.

84 A Monte Carlo (MC) simulation of the light transport can be used to model
85 the response of scintillation detectors. The light transport depends on a number
86 of parameters such as the index of refraction of all optical media, the quality of
87 optical reflectors, the state of surface finish, and light absorption and dispersion
88 in the medium, which are not always known. However it is possible to adjust the
89 parameters empirically to obtain a good reproduction of the measured response
90 [6]. A drawback of the MC simulation of light transport is the long computing
91 time required. This can be an inconvenience when the response has to be
92 computed for a large number of end point energies, as will be explained for the
93 TAGS technique. Therefore we have developed a parametric method that allows
94 the direct conversion of the energy deposited into light collected for this specific
95 geometry.



Figure 1: View of the cylindrical plastic β -detector with the aluminized-mylar reflector inside. The plastic is coupled to a light guide, and mounted in a support of aluminium designed to fit the end of the beam pipe at the IGISOL facility (Jyväskylä).

96 The cylindrical plastic detector is described in Section 2, and the measure-
 97 ments in Section 3. The MC simulations and the parametric method are dis-
 98 cussed in Sections 4 and 5, respectively.

99 2. Geometry and characteristics

100 The new cylindrical detector can be seen in Fig. 1. It is a vase-shaped cylin-
 101 der of 35 mm external diameter, 50 mm length and a wall thickness of 3 mm,
 102 made of EJ200 plastic scintillator, and manufactured by Scionix [7]. The bot-
 103 tom of the vase is optically glued to a 10 mm length Poly(methyl methacrylate)
 104 (PMMA) light guide with two diameters: the front one equal to the plastic de-
 105 tector diameter and the rear one of 39 mm, as can be seen in Fig. 2 bottom. The
 106 optical coupling between the light guide and the PMT was made with optical
 107 grease. We use a segmented 2×2 multi-anode Hamamatsu PMT R7600U-M4
 108 [8] with an effective area of 18 mm \times 18 mm, bi-alkali photocathode and 10-
 109 stage metal channel dynode structure, operated at an overall voltage of -800 V.
 110 The inner walls of the plastic detector were covered by a thin aluminized-mylar
 111 reflector in order to improve the light collection.

112 3. Experimental measurements

113 The four outputs of the PMT were wired in pairs for simplicity. These two
114 signals were integrated in CANBERRA 2005 preamplifiers [9], before being split
115 into two branches for energy and timing reconstruction. In the energy branch the
116 two preamplifier outputs were added and shaped with a CANBERRA 243 am-
117 plifier [9], whereas in the timing branch each preamplifier signal was processed
118 independently with an ORTEC 474 Timing Filter Amplifier and an ORTEC
119 584 Constant Fraction Discriminator [10]. Both timing signals were combined
120 in an ORTEC C04020 Quad 4-input Logic module [10] where a coincidence in
121 a narrow time interval (20 ns) was required to fire the trigger of the data acqui-
122 sition system. The coincidence requirement allowed the reduction of the noise
123 level and lowered the energy threshold for β signals.

124 This new plastic detector was used in the commissioning of the DTAS detec-
125 tor at the upgraded IGISOL IV facility of the University of Jyväskylä, Finland
126 [11], and it was characterized with a set of calibration sources (^{22}Na , ^{60}Co ,
127 ^{24}Na and ^{137}Cs). The sources were placed at the bottom of the detector, held
128 by a cylinder of 3M reflector material introduced inside the detector. The de-
129 tector was later used in the measurement of the β^- decay of ^{100}Tc [12]. In this
130 experiment, the ions were produced by (p,n) reactions on a Mo target situated
131 in the ion source of the IGISOL mass separator. The A=100 separated beam
132 was purified in the double Penning-Trap JYFLTRAP [13] to select ^{100}Tc , and
133 the nuclei were implanted on the aluminized-mylar reflector that covered the
134 bottom of the detector. Since ^{100}Tc decays to the stable ^{100}Ru this did not
135 represent an inconvenience.

136 4. MC simulations

137 Simulations were carried out with the Geant4 code [14]. The geometry of
138 the detector was defined in great detail, as can be seen in Fig. 2. This is
139 important mainly for the analysis of the TAGS data. The geometry of the

140 PMT was included following the data sheet description [15] and the informa-
 141 tion provided by Hamamatsu [16]. The photocathode structure and estimated
 142 thickness of the dead material were based on Chapter 7 of reference [17]. The
 143 internal aluminized-mylar cover is included, as well as the 3M reflector cylin-
 144 drical support that was used to hold the sources. The 3M reflector composition
 145 was estimated based on the details given in [18].

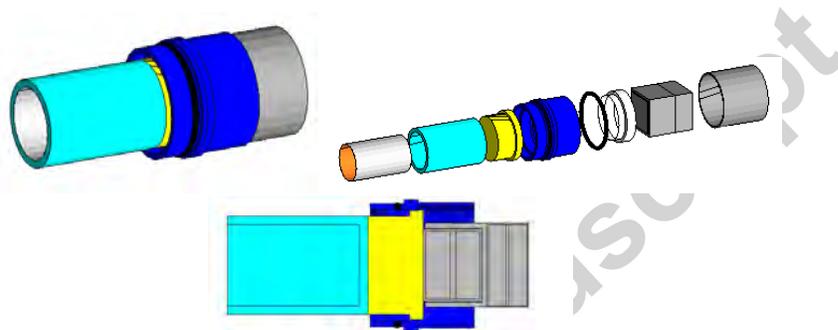


Figure 2: Geometry of the cylindrical β plastic detector included in the MC simulations. General view (up), separated components (middle) and lateral cut (bottom) are shown. The following elements are depicted: scintillator material (light blue), light guide (yellow), aluminium support (dark blue), o-ring (black), internal plastic holder (white), PMT plus PMT plastic holder (grey), and aluminized-mylar internal reflector (light grey and orange). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

146 The task of simulating the light response includes the production in the
 147 scintillator material and the transport of the resulting photons until they are
 148 absorbed in the photocathode of the PMT. The properties of the scintillator were
 149 taken from the EJ200 data sheet [19]: scintillator yield of 10 photons/keV, fast
 150 time constant of 0.9 ns and a refraction index of $n=1.58$. The refraction index of
 151 the PMMA and the PMT glass window were set to 1.49 and 1.47 respectively.
 152 It is of great importance to define properly the optical interfaces in Geant4
 153 [20, 21], since the result of the simulation is sensitive to the properties of the
 154 optical interfaces between the different materials [6]. We defined as dielectric-
 155 dielectric all the surfaces where we expected transmission and as dielectric-metal

156 all those where we expected reflection (in our case the interface between the
157 plastic and the aluminized-mylar). All the surfaces were assumed to be polished.
158 The reflectivity of the reflector was set to 1. In order to count the number of
159 photons collected in the photocathode, i.e. photons that suffer an absorption
160 process there, we assigned to the photocathode a constant absorption length of
161 10^{-9} m.

162 We compare in Fig. 3 the experimental spectrum with the simulation of the
163 energy deposited and of the light collected, both for a calibration source of ^{24}Na
164 and for the ^{100}Tc decay. We have used the DECAYGEN event generator [22]
165 to simulate the primary particles of the decays according to the information
166 available (γ and β intensities, branching ratios, etc). MC spectra have been
167 represented in experimental channels by applying a linear calibration in order
168 to be able to perform a comparison with energy and light simulations at the
169 same time. The calibration factor has been chosen to fit the low energy region
170 up to about 500 experimental channels, whereas a normalization factor is used
171 to match the number of counts. As can be observed, while the simulated energy
172 distribution fails to reproduce the measured spectrum, the simulated light dis-
173 tribution matches the experiment well, specially at low energies, where we are
174 interested in identifying the threshold as will be explained later. In particular,
175 a low energy bump can be distinguished coming from the interaction of the β
176 particles in the lateral walls of the detector. Only a small fraction of the light
177 produced there reaches the PMT, thus producing the bump. The higher part of
178 the light distribution above this bump is largely due to the interactions in the
179 bottom of the vase.

180 We did similar simulations for a second β -detector with planar geometry, a
181 scintillator disk of 3 mm thickness and 35 mm diameter made of EJ212. This
182 detector was used in another TAGS experiment at IGISOL [23, 24] to measure
183 the β -particles of the decay of several fission fragments in coincidence with
184 the DTAS detector. The β spectrum of the decay of ^{140}Cs measured with this
185 detector is shown in Fig. 4. In this case there are no essential differences between
186 simulations of the light collected and energy deposited, and both reproduce the

187 measurement.

188 5. Energy-Light parametrization

189 Apart from all the uncertainties in the optical parameters needed for the
 190 simulations with optical photons, an important issue is that they are computa-
 191 tionally very demanding. We needed 17 hours of CPU time to perform a 10^5
 192 events simulation with optical photons in an Intel Core i7-4770 CPU @ 3.40 Hz
 193 \times 8 Mb cache with 15.6 GB memory and 8 threads, in contrast to the 50 sec-
 194 onds for a 10^5 events simulation of the energy deposited. This introduces a
 195 disadvantage for the particular case of the TAGS technique, since systematic β
 196 distribution simulations have to be performed up to the Q_β of the decay in small
 197 steps (typically 40 keV) to construct the response function of the spectrometer
 198 [25]. For this reason a method of avoiding the simulation of optical photons
 199 has been developed. This method is based on a relationship found between the
 200 energy deposited at different locations in the scintillator material and the light
 201 collected in the photocathode. As can be seen in Fig. 5, when we plot light
 202 collected versus energy deposited for the ^{100}Tc simulation, most of the points lie
 203 in two well separated regions, depending on whether the energy is deposited in
 204 the bottom of the detector or in the lateral walls. These regions show a nearly
 205 linear dependence.

206 This relationship enables us to reproduce the experimental spectra just with
 207 the information of the energy deposited and the interaction point. For this we
 208 consider two functions, one for the energy deposited in the bottom and the other
 209 for the lateral walls. Each of these two functions, in turn, consists of a piecewise
 210 function with two quadratic regions:

$$L = \begin{cases} a_1 + b_1 E + c_1 E^2 & , \quad E \leq k \\ a_2 + b_2 E + c_2 E^2 & , \quad E > k \end{cases} \quad (1)$$

211 where L is the light, E the energy and k the energy value that separates
 212 both regions, where continuity is required.

213 The calibration coefficients obtained for Eq. 1 in the case of the lateral walls
 214 and of the bottom of the detector, are reported in Table 1, and they correspond
 215 to the red lines drawn in Fig. 5.

216 In order to apply the conversion procedure it is not enough to use the cal-
 217 ibration coefficients in Table 1. We explain, with the help of Fig. 6, the dif-
 218 ferent steps necessary to reproduce the light collection simulation with energy
 219 deposited. This figure shows a simulation of 10^4 events of mono-energetic elec-
 220 trons of 1 MeV interacting with the cylindrical detector. First, we use the
 221 calibration coefficients from Table 1 to convert energy into light. As already
 222 mentioned, it does not reproduce light simulations, as can be seen in Fig. 6
 223 (a). Second, a Gaussian spread, empirically found to be proportional to $E^{3/4}$, is
 224 introduced, as shown in Fig. 6 (b), in order to reproduce the width of the peaks
 225 produced by the interaction of the mono-energetic electrons. Finally, for 10% of
 226 the events interacting with the bottom of the detector we introduce a random
 227 loss of light collected. This corresponds to events in between both regions in
 228 Fig. 5. For this, we change the slope of the calibration with a random linear
 229 interpolation between the slope of the bottom and the slope of the lateral walls.
 230 It improves the comparison with light simulations, as can be seen in Fig. 6 (c).
 231 The result of following these steps, combining the calibration in Table 1 with
 232 the corrections explained here, is good agreement between light simulations,
 233 energy simulations converted to light, and experimental measurements, as can
 234 be observed in Fig. 3 for both the ^{24}Na calibration source and the ^{100}Tc decay.

235 In order to apply this procedure to calculate the β responses for a TAGS
 236 analysis, we have to convert the threshold in signal amplitude, or equivalently
 237 in light collected, into a threshold in energy, according to the calibration in
 238 Table 1. A threshold value in light of 11 a.u. set just above the noise has been
 239 identified by comparison with experimental measurements in Fig. 7, where the
 240 low energy region of the spectra in Fig. 3 is shown. Note that light units are
 241 used instead of experimental channels in order to do this identification process.

242 Due to the effect of the different light collection in the two regions of the
 243 detector, this threshold corresponds to 29 keV in the bottom, whereas for the

244 lateral walls of the detector it is 96 keV. To verify this equivalence, we simulated
245 four end-points of the ^{100}Tc decay, namely 3203 keV, 2072 keV, 1151 keV and
246 543 keV, and we calculated the efficiency above this threshold value for the light
247 simulation and for the energy converted into light. Both efficiencies are in very
248 good agreement, as shown in Fig. 8, with relative differences of $\sim 0.1\%$.

249 6. Conclusions

250 MC simulations with optical photons have been shown to reproduce the
251 shape of the experimental β spectra measured with a plastic scintillation de-
252 tector with a vase-shaped geometry, when energy deposited simulations turned
253 out to be insufficient. Furthermore, a method to directly convert the energy
254 deposited into the equivalent amount of light has been developed, and success-
255 fully applied to some experimental cases. This opens the possibility of avoiding
256 the very time-consuming simulations with optical photons for this type of de-
257 tector. In the particular case of a TAGS analysis, where we are interested in
258 doing extensive simulations of β particles in steps of 40 keV up to the Q_β , this
259 option provides an affordable way to calculate the response function of the spec-
260 trometer. In fact, this method has been applied to the TAGS analysis of the
261 measurement of the β^- decay of ^{100}Tc , that was mentioned in this work and
262 will be published in the near future [26].

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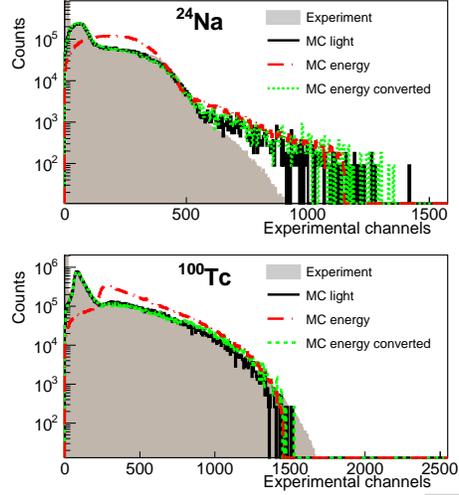


Figure 3: Comparison between the experimental and the MC spectra for ^{24}Na (up) and ^{100}Tc (bottom). Experiment (grey filled) is compared with simulations of energy deposited (dashed-dotted red), light collected (solid black), and energy deposited converted into light with the procedure explained in the text (dotted green). Note that energy simulations (dashed-dotted red) are performed with 10^6 events, while the rest correspond to 10^5 . (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

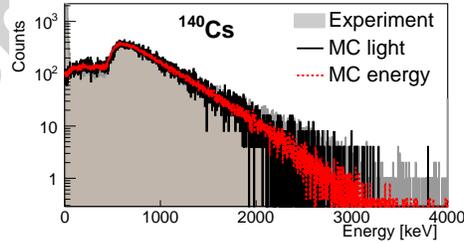


Figure 4: Comparison between the experimental and the MC spectra for a ^{140}Cs measurement performed with a plastic scintillator disk. Experiment (grey filled) is compared with simulations of energy deposited (dotted red) and light collected (solid black). Note that energy simulations (red) are performed with 10^6 events, while the simulations of light (blue) correspond to 10^5 . (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

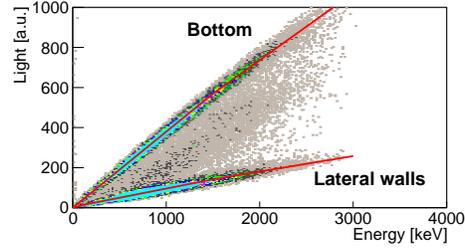


Figure 5: Simulation of the light collected vs. energy deposited for the cylindrical plastic detector in the ^{100}Tc measurement. Two different regions are distinguished and the calibration curves with the parameters from Table 1 are represented in red. The events in between both regions correspond to a 10% of those coming from the bottom, where less light than expected is collected.

<i>Part</i>	a_1 [a.u.]	b_1 [a.u. keV $^{-1}$]	c_1 [a.u. keV $^{-2}$]	k [keV]	a_2 [a.u.]	b_2 [a.u. keV $^{-1}$]	c_2 [a.u. keV $^{-2}$]
Lateral	0.0	0.1	0.0001	150	2.3625	0.1	-0.000005
Bottom	0.0	0.38	0.0	1500	22.5	0.38	-0.00001

Table 1: Energy-light calibration parameters for the lateral walls and the bottom of the cylinder following the Eq. 1. The parameter k separates two different energy regions.

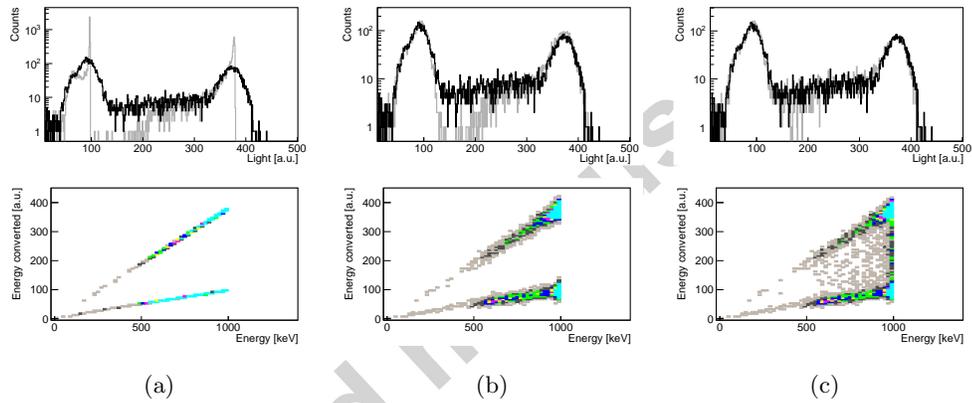


Figure 6: Figures (a), (b) and (c) represent different steps necessary to reproduce the simulated light collection with the results of the simulated energy deposition (for more details see the text). In the upper panel the simulation of optical photons (black) is compared with the energy converted into light (grey) for mono-energetic electrons of 1 MeV interacting with the detector. The lower panel shows the corresponding relationship between energy converted into light and energy deposited for this case.

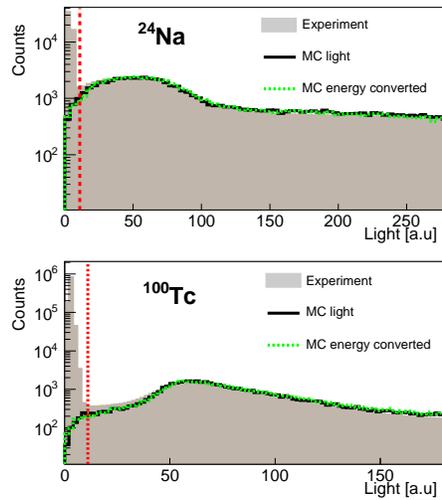


Figure 7: Zoom at low energies of the comparison between the experimental and the MC spectra in light units for ^{24}Na (up) and ^{100}Tc (bottom). Experiment (grey filled) is compared with simulations of light collected (solid black), and energy deposited converted into light with the procedure explained in the text (dotted green). The threshold value of 11 a.u. is depicted with a vertical dotted red line. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

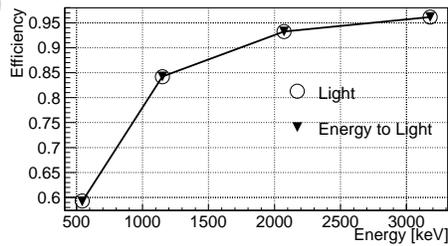


Figure 8: Efficiency of the cylindrical plastic detector for different β^- end-points. The results for light simulations (circles) are compared with the calculation using our procedure for converting energy deposited into light collected (triangles).