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Investigation of Compton Scattering for Gamma Beam Intensity Measurements and Perspectives at ELI-NP

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Abstract

Compton γ -ray sources have been in operation for over 30 years with new facilities being under construction or proposed. The gamma beam system under implementation at the Extreme Light Infrastructure – Nuclear Physics facility in Romania will deliver brilliant γ -ray beams with energies up to 19.5 MeV. Several instruments for measuring the parameters of the γ -ray beam are under development at ELI-NP. One of these instruments based on a High Purity Germanium detector is routinely used for beam energy measurements at other facilities. Here we investigate the use of a High Purity Germanium detector to continuously monitor the intensity of the ELI-NP gamma beam by measuring the inelastic scattering of photons. This method relies on both experimental and simulated data and it has been successfully tested during a recent experiment at the High Intensity γ -ray Source facility.

Keywords: ELI-NP; γ -ray beam; HPGe; GEANT4; Compton scattering;

1. Introduction

Compton γ -ray beams have been used for nuclear physics experiments since the early 1980's at the LADON facility at INFN National Laboratory of Frascati [1]. Several γ -ray source facilities were brought into operation over the last 30 years. The High Intensity γ -ray Source (HI γ S) in operation since the late 1990's at Duke University [2] is an intense, quasi-monochromatic, highly polarized γ -ray source dedicated to low and medium energy nuclear physics research.

A new Compton γ -ray source, under implementation at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility in Romania, will deliver quasi-monochromatic γ -ray beams with energies up to 19.5 MeV and exceptional parameters: small bandwidth ($\leq 0.5\%$), high spectral density ($\geq 10^4$ photons/s/eV), and high degree of linear polarization ($\geq 99\%$).

Measuring the spatial, spectral and temporal characteristics of γ -ray beams has been a longstanding problem since the early development of the γ -ray beam facilities. Precise and accurate measurements of the γ -ray beam properties at ELI-NP are required not only to ensure delivery of the γ -ray beam within the design parameters but also to fa-

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27 cilitate the scientific program [3, 4, 5, 6]. Sev- 69
 28 eral γ -ray beam monitoring instruments [7] are pro- 70
 29 posed at ELI-NP in combination with the exper- 71
 30 imental stations. The spatial parameters will be 72
 31 monitored using a scintillator coupled with a CCD 73
 32 system. The intensity and polarization parameters 74
 33 will be measured using the $d(\gamma, p)n$ reaction and 75
 34 two sets of neutron detectors depending on the en- 76
 35 ergy of the γ -ray beam [8]. Additional diagnostics 77
 36 instruments are under construction for measuring 78
 37 the time structure, intensity, and polarization of 79
 38 the beam using other methods [7]. 80

39 One instrument proposed for measuring the beam 81
 40 intensity and energy parameters is based on a large 82
 41 volume High Purity Germanium (HPGe) detector 83
 42 with an anti-Compton shield. In this paper, we 84
 43 investigate the use of Compton scattering for con- 85
 44 tinuously measuring the intensity and energy of the 86
 45 γ -ray beam at ELI-NP based on test experiments 87
 46 at HI γ S. The organization of this paper is as fol- 88
 47 low: In Sect. 2 we review general concepts in 89
 48 Compton scattering and define the method for in- 90
 49 tensity calculations. The experimental setup used 91
 50 for testing this method between 4.5 and 10 MeV at 92
 51 HI γ S is described in detail. In Sect. 3 we discuss 93
 52 the results of the beam energy and relative inten- 94
 53 sity measurements at HI γ S. Finally in Sect. 4, we 95
 54 present the development of an instrument based on 96
 55 an HPGe detector for continuously monitoring the 97
 56 γ -ray beam intensity at ELI-NP up to a photon 98
 57 energy of 20 MeV. The HPGe detector was charac- 99
 58 terized using accelerator-based high-energy photons
 59 and extensively simulated in GEANT4.

60 2. Method description

61 2.1. Compton scattering method

62 The differential cross section for Compton scat- 105
 63 tering can be calculated using the well-known 106
 64 Klein-Nishina expression [9]:

$$\begin{aligned}
 \frac{d\sigma}{d\Omega} = & r_e^2 \left[\frac{1}{1 + \alpha(1 - \cos\theta)} \right]^2 \\
 & \times \left(\cos^2\theta + \frac{\alpha^2(1 - \cos\theta)^2}{2[1 + \alpha(1 - \cos\theta)]} \right),
 \end{aligned}
 \tag{1}$$

65 where: r_e is the classical electron radius, $\alpha =$ 115
 66 $\hbar\omega/m_e c^2$, and θ is the scattering angle. If the ge- 116
 67 ometrical characteristics of the setup and the pa- 117
 68 rameters of the scatterer are known, Eq. 1 can be 118

used to calculate the incident intensity from the 69
 number of scattered photons. Hence, the inelas- 70
 tic scattering of photons can be used to conduct 71
 online γ -ray beam intensity measurements. This 72
 method requires the placement of an in-beam scat- 73
 tering target from which the incident photons will 74
 scatter into a detector placed at a predefined an- 75
 gle with respect to the beam axis. The complexity 76
 of a typical experimental setup makes the direct 77
 use of Klein-Nishina rather difficult. However, gen- 78
 eral particle transport codes such as GEANT4 [10] 79
 or MCNP [11] are suitable for this type of analysis. 80

Several factors will determine the accuracy of the 81
 Compton scattering based intensity measurement. 82
 The differential cross-section of Compton scatter- 83
 ing shows a strong ω and θ variation making the 84
 measurement sensitive to the photon energy and 85
 setup geometry. Hence, a precise measurement of 86
 the detector's position with respect to the beam 87
 axis is required in order to minimize the associated 88
 errors. Another important parameter that will in- 89
 fluence the accuracy of this method is the preci- 90
 sion with which the detection efficiency is known. 91
 Low-energy detection efficiency can be routinely ob- 92
 tained using standard calibration sources; however, 93
 for high energy, photons from (p, γ) or (n, γ) re- 94
 actions are needed in order to determine the detec- 95
 tor efficiency. If simulations are part of the analy- 96
 sis, additional uncertainties associated with Monte 97
 Carlo methods will contribute to the total uncer- 98
 tainty. 99

100 2.2. Experimental setup

101 The experimental instruments were positioned in 102
 the Upstream Target Room (UTR) at HI γ S as illus- 103
 104 trated in Fig. 1. The γ -ray beam was collimated 104
 to 12 mm diameter in a collimating assembly lo- 105
 cated in an upstream room and then entered the 106
 experimental room.

107 The γ -ray beam first interacted with a thin LiF 107
 108 target (300-600 $\mu\text{g}/\text{cm}^2$ LiF evaporated on 1.3 μm 108
 109 mylar backing) placed inside a vacuum chamber. 109
 The LiF target was surrounded by silicon detectors 110
 for detecting charged particles from the photodisin- 111
 112 tegration of ^7Li [12, 13]. Two gold foils, mounted 112
 on the exit flange of the vacuum chamber, were irra- 113
 114 diated at 9 and 10 MeV. The beam exited the vacuum 114
 chamber and passed through a 1-mm thick copper 115
 plate and a 4.5-cm long, 3.7-cm diameter heavy wa- 116
 117 ter cell. A scintillator and a CCD camera assembly 117
 [14] located in the back of the UTR were used for 118

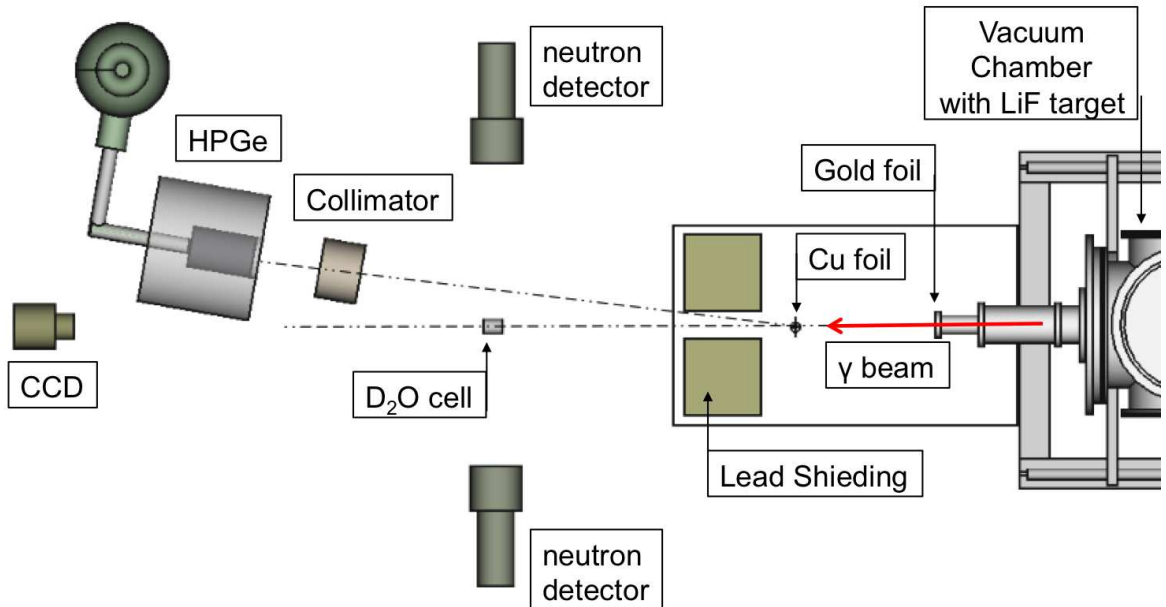


Figure 1: The layout of the experimental arrangement in the Upstream Target Room (drawing not to scale). The vacuum chamber housed a LiF target and a silicon detector array for detecting charged particles from the photodisintegration of ${}^7\text{Li}$. The other items in the setup were used for the characterization of the γ -ray beam.

119 finer target alignment and spatial characterization
 120 of the beam.

121 A 120% relative efficiency co-axial High Purity
 122 Germanium (HPGe) detector [15] was used to make
 123 measurements of the beam energy, energy spread,
 124 and intensity. The HPGe was mounted at the back
 125 of the UTR on a table which could be moved to
 126 several predefined positions. The motorized system
 127 could move the detector directly in the path of the
 128 γ -ray beam (the 0° position) or at an angle outside
 129 the path of the beam as shown in Fig. 1. Although
 130 the head of the HPGe detector was placed inside
 131 the anti-Compton shield, the anti-coincidence setup
 132 was not operational for this experiment. A copper
 133 collimator (11.43-cm long, 5.08-cm outside radius,
 134 and 0.953-cm hole radius) was positioned in front of
 135 the HPGe detector to better define the scattering
 136 angle and reduce the background rate. The HPGe
 137 energy signals were amplified and then sent to a
 138 Canberra Multiport II multichannel analyzer. The
 139 spectra were recorded using the GENIE 2000 soft-
 140 ware package.

141 2.3. GEANT4 simulations

142 A typical GEANT4 simulation requires at least
 143 three components: the physical processes, the geo-
 144 metrical description of the experimental setup and
 145 the particle source. For the current simulation, the
 146 physics was implemented using the Penelope low-
 147 energy electromagnetic model [16], which contains
 148 the physical processes required for photons, elec-
 149 trons, and positrons based interactions. The simu-
 150 lated geometrical setup was based on precise phys-
 151 ical measurements or estimates for the cases where
 152 measurements were not possible.

153 A schematic representation of the experimental
 154 setup is presented in Fig. 1. In order to obtain a
 155 valid model that accurately reproduces the response
 156 of the experimental detector, a detailed geometri-
 157 cal representation of the detector was constructed.
 158 The HPGe detector reproduction was based on the
 159 detector's technical drawings provided by the man-
 160 ufacturer. Slight adjustments were made in order to
 161 reproduce with good accuracy the response of the
 162 detector to standard calibration sources. Standard
 163 materials and compositions were used for the setup
 164 reconstruction. One of the important parameters of

165 the experimental setup that could not be precisely
 166 inferred from the experiment was the position of the
 167 beam spot on the face of the detector. The change
 168 in the beam position with respect to the center of
 169 the detector has a considerable effect in the peak to
 170 Compton ratio, especially for high energy photons.
 171 The best reproduction of the experimental data is
 172 obtained when the beam hits the face of the detec-
 173 tor 2.7 cm from the center of the detector, position
 174 that yields good agreement for all the energy cases
 175 available for this analysis. The third requirement
 176 for the simulation is the particle source. The spa-
 177 tial characteristics of the beam were inferred from
 178 images captured using a CCD camera. A probabili-
 179 ty density function was extracted from the beam
 180 spot image and was used to sample the individual
 181 positions of the photons at runtime.

182 These simulations were performed using the
 183 GEANT4 release 10.2.2.

184 3. Results and discussions

185 3.1. Gamma beam energy measurement

186 The energy parameters of the beam were deter-
 187 mined for several discrete energies in the 4.5 to 10
 188 MeV range using in-beam measurements, i.e. the
 189 HPGe detector was positioned at 0° with respect
 190 to the beam axis. In order to avoid radiation dam-
 191 age to the detector, the beam was attenuated before
 192 reaching the detector [17]. The count rate for the
 193 HPGe was kept in the 2-4 kHz range within a run
 194 time of about 5 min.

195 A two-step procedure was applied in order to ob-
 196 tain the γ -ray beam parameters. In the first step,
 197 a normal distribution fit of the full absorption peak
 198 was performed in order to determine an initial value
 199 for the energy parameters, i.e. full width half maxi-
 200 mum (FWHM) and centroid. The fitting procedure
 201 can be straightforward for low-energy photons but
 202 can get complicated for high-energy photons where
 203 the full energy deposition peak is not so easily dis-
 204 tinguished from the Compton background. In the
 205 second step of the procedure, we simulated the de-
 206 tector's response to a beam with the energy para-
 207 meters obtained from the fit. Slight adjustments
 208 were made to the beam parameters in order to ob-
 209 tain the best agreement between simulations and
 210 experiment. The level of agreement was quantified
 211 using the χ^2 metric. Figures 2 and 3 show the re-
 212 sults of the analysis for a photon energy of 4.5 MeV
 213 and 9.9 MeV, respectively.

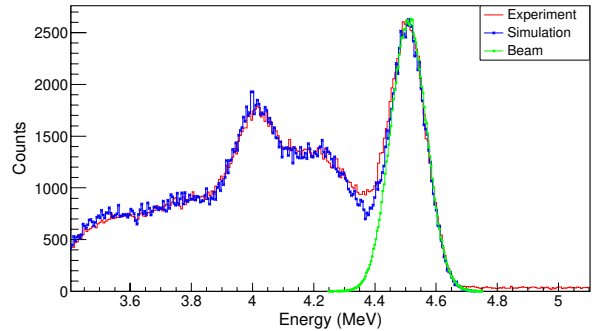


Figure 2: In-beam energy measurement spectra for 4.5 MeV photons. The simulated data (blue) is superposed on the experimental data (red). The energy distribution of the beam (green) is added for comparison.

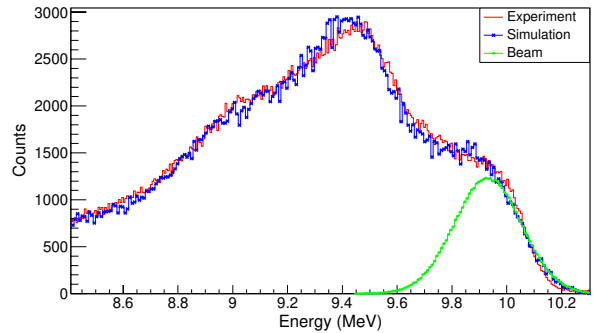


Figure 3: In-beam energy measurement spectra for 9.9 MeV photons. The simulated data (blue) is superposed on the experimental data (red). The energy distribution of the beam (green) is added for comparison.

214 The results of the analysis procedure for the 4.5
 215 – 10 MeV range are presented in Fig. 4. The plot
 216 shows a linear dependence between the calculated
 217 and the expected energies given by the accelerator
 218 parameters. Good agreement is observed for all but
 219 one point, for a photon energy of 8 MeV, which
 220 shows a disagreement of about 3 %. The values for
 221 the FWHM follow a linear dependence with respect
 222 to energy, between 3 % at lower energies and 4 %
 223 at the higher end of the energy range.

224 3.2. Intensity measurement using Compton scatter- 225 ing

226 In order to determine the intensity of the γ -ray
 227 beam the HPGe was moved out of the beam path
 228 and the attenuator was removed. A collimator was
 229 added in front of the detector in order to limit the

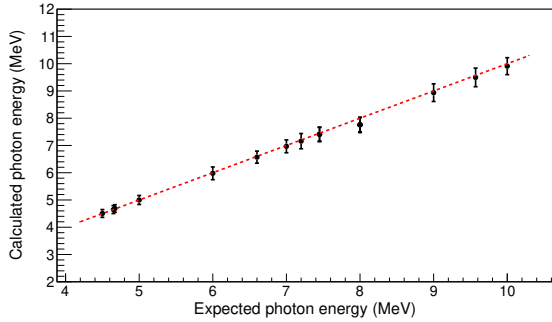


Figure 4: The calculated versus expected incident photon energy for the 4.5 to 10 MeV range. The FWHM is shown as uncertainty for the calculated data. The dotted line (red) represents a guideline for equal values of calculated and expected incident photon energies.

230 angular range of the scattered photons. The sim-
 231 ulated spectra for the Compton scattering config-
 232 uration were obtained using the energy param-
 233 eters calculated in section 3.1. Small adjustments
 234 have been made to geometrical parameters, scat-
 235 tering angle and the position of the collimator with
 236 respect to the detector's face, in order to obtain
 237 the best agreement between experimental and sim-
 238 ulated spectra. The best reproduction of the ex-
 239 perimental data is obtained when the detector is
 240 placed at an angle of about 9.1° , which differs by
 241 about 9 % from the measured value. The compar-
 242 ison between experimental and simulated spectra
 243 for photons of 4.5 MeV is presented in Fig. 5.

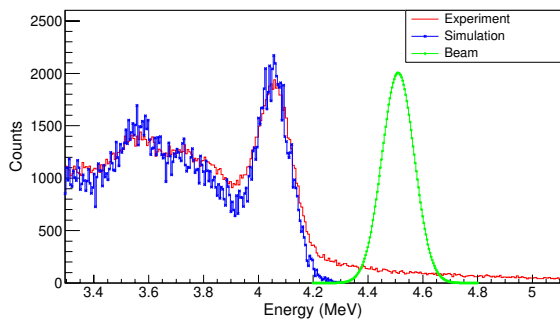


Figure 5: The energy spectrum of Compton scattered 4.5 MeV photons. The simulated data (blue) is superposed on the experimental data (red). The energy distribution of the beam (green) is added for comparison.

244 Once a good agreement is obtained between the
 245 simulated and experimental spectra, the intensity
 246 of the beam can be calculated using the number

247 of photons that were required to generate the sim-
 248 ulated spectrum and the acquisition time of the
 249 measurement. The results of such analysis are pre-
 250 sented in Fig. 6 together with beam intensity val-
 251 ues obtained from a paddle detector [18] situ-
 252 ated upstream from the experimental setup. The two
 253 intensity curves, obtained with the paddle detector
 254 and using the Compton scattering, were matched at
 255 10 MeV as this results in excellent agreement with
 256 the calculated intensity by the HI γ S operating pa-
 257 rameters [19].

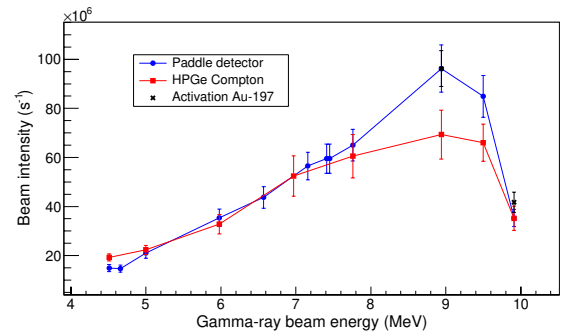


Figure 6: Beam intensity results for the 4.5 to 10 MeV range using Compton scattering and the paddle detector. Absolute values were obtained by using ^{197}Au activation.

258 The intensity curves in Fig. 6 were scaled to
 259 an absolute measurement using ^{197}Au activation
 260 values at 9 MeV [20]. There is good agreement
 261 between the beam intensity values obtained using
 262 Compton scattering and the paddle detector except
 263 at 9 and 9.57 MeV. The two runs at 9 and 9.57 MeV
 264 have indeed the highest dead times in the HPGe
 265 detector. Although the dead time was considered
 266 in the analysis, further investigation of the 120%
 267 HPGe under high rates should be performed in the
 268 future.

269 4. Proposed instrument at ELI-NP

270 The proposed setup for the intensity and en-
 271 ergy measurements at ELI-NP is presented in Fig.
 272 7. The setup is composed of a detection assembly
 273 which contains a 150 % relative efficiency HPGe
 274 coupled with a NaI(Tl) anti-Compton shield, a po-
 275 sitioning system that allows rotation and transla-
 276 tion with respect to the scattering target and a
 277 support structure for the ensemble. The rotating
 278 system will allow the positioning of the detection
 279 assembly on a 0 to 15° scale, with a precision better

280 than 0.01° . The anti-Compton shield has a single
 281 NaI(Tl) annular crystal configuration (110 mm
 282 inner diameter, 234 mm outer diameter, and 250 mm
 283 length) coupled to six, 51 mm diameter, photomul-
 284 tiplier tubes.

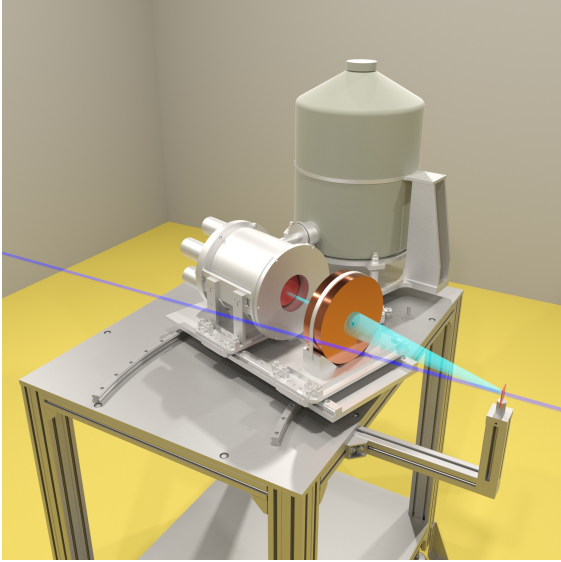


Figure 7: Proposed setup for energy and intensity measurements at ELI-NP.

285 In order to characterize and optimize the pro-
 286 posed instrument for energy and intensity measure-
 287 ments, an accurate reproduction of the setup was
 288 constructed using the GEANT4 simulation toolkit.
 289 Details about the HPGe detector modeling and the
 290 low energy efficiency measurements are presented in
 291 the previous work [21]. Given the wide energy range
 292 intended for this setup, measurements of the detec-
 293 tion efficiency at higher energies were required.
 294 In order to extend the efficiency measurements up
 295 to 11.6 MeV proton-capture reactions on ^{23}Na and
 296 ^{27}Al and standard calibration sources, ^{60}Co , ^{56}Co ,
 297 and ^{152}Eu were used. The analysis of the experi-
 298 mental data is made using the two-line method [22],
 299 which is based on the excitation of a gamma cascade
 300 which includes a high and low-energy γ -ray pair
 301 with a known branching ratio. By knowing the effi-
 302 ciency of the low energy gamma-ray, from standard
 303 calibration sources, one can determine the detection
 304 efficiency for the high energy photon. The measure-
 305 ments were performed using proton beams from the
 306 3MV Tandem accelerator of IFIN-HH [23]. Fig. 8
 307 presents the measured efficiency of the 150 % HPGe
 308 together with the simulated efficiency. A maximum
 309 relative difference of 14 % was observed between the

310 experimental and simulated data at the lowest en-
 311 ergies. This difference was attributed to poor char-
 312 acterization of the complex geometry in which the
 313 measurement of the detection efficiency with stan-
 314 dard source was carried out.

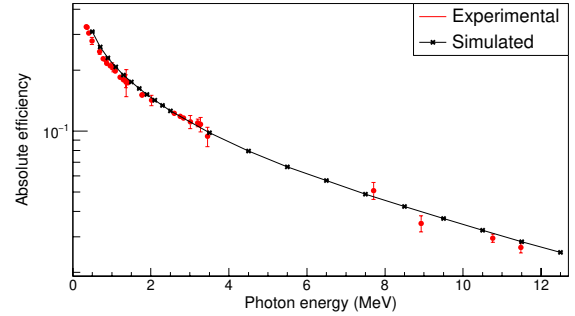


Figure 8: Absolute efficiency of a 150 % HPGe detector. The red and black markers represent the experimental and the simulated data for the 1-12 MeV range.

315 One of the main differences between the ELI-NP
 316 proposed setup and the one tested at HI γ S is the
 317 improved peak-to-total ratio (P/T). This improve-
 318 ment can be attributed to the larger detector size,
 319 a 150 % relative efficiency detector compared with
 320 the 120 % relative efficiency from HI γ S setup, and
 321 the addition of a Compton suppressor. The veto
 322 signal generated by the anti-Compton shield for the
 323 cases where only partial energy deposition is regis-
 324 tered by the HPGe detector will be used to reject
 325 unwanted events from the measured spectrum. The
 326 enhanced P/T will enable the use of the setup for
 327 the whole energy range of the γ -ray beam. An ex-
 328 ample of a simulated in-beam spectrum obtained
 329 for a photon energy of 20 MeV is shown in Fig. 9.
 330 Significant improvement can be observed with re-
 331 spect to the 10 MeV spectrum presented in Fig. 3
 332 where the full energy deposition peak is hardly no-
 333 ticeable from the Compton background, improve-
 334 ments that can be mostly assigned to the addition
 335 of the Compton suppressor.

336 To maximize P/T values one has to take into con-
 337 sideration the position of the beam with respect to
 338 the face of the detector. The well type shaped ger-
 339 manium crystal will exhibit lower intrinsic efficiency
 340 for a limited size beam incident in the center of the
 341 detector. P/T values for different positions on the
 342 face of the detector are presented in Fig. 10. Opti-
 343 mal values for the P/T ratio can be obtained when
 344 the γ -ray beam hits the detector 1 – 1.5 cm from
 345 the center of the detector.

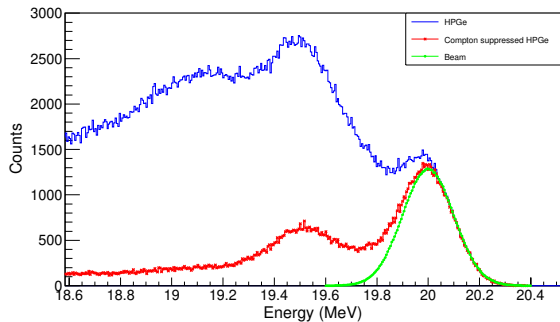


Figure 9: Simulated in-beam spectra for an incident beam of 20 MeV. The blue line shows the results obtained using a simple germanium detector; the red line shows the results obtained for a Compton suppressed germanium detector.

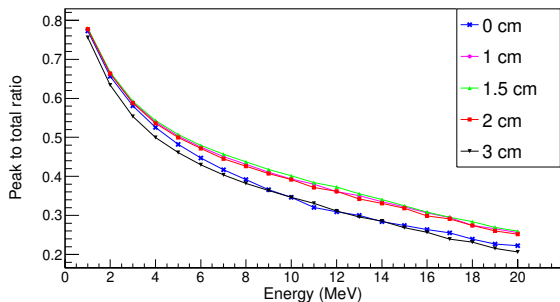


Figure 10: P/T values obtained from simulated data using the proposed ELI-NP setup. The figure shows the results obtained for multiple positions of the beam with respect to the center of the detector.

One of the parameters of interest for evaluating the setup is the amount of time required to obtain the characteristics of the beam. The primary constraint for the required acquisition time is imposed by the time structure of the ELI-NP gamma beam system [7]. The 100 Hz repetition rate of the macro-bunch structure will limit the germanium measuring rate to the macro-bunch frequency in order to avoid signal pile-up.

In the case of γ -ray beam energy measurements, the rate on the detector can be adjusted to reach the maximum allowed rate by the amount of attenuation that is applied to the incident beam, making this way the intrinsic detection efficiency solely responsible for the required acquisition time. Estimates of the measuring time needed, if a 3 % statistical uncertainty for the full energy deposition peak is targeted, are presented in Table 1.

For the intensity measurement case, the rate of

γ -rays at the detector is determined by multiple factors e.g., the energy and intensity of the beam, geometrical factors, and other setup parameters. In order to guarantee the agreement between simulation and measurement, the configuration of the setup shall be kept fixed. With this setting, the maximum γ -ray rate on the detector will be determined by the energy and intensity of the beam with a maximum rate constrained by the setup characteristics. Rate estimates relative to the maximum allowed rate of 100 Hz, for the entire energy range, are presented in Table 1.

5. Conclusions

This work investigates the possibility to measure γ -ray beam energy and intensity parameters using an HPGe detector. The presented methods make use of direct analysis of measured experimental spectra and simulations in order to obtain the beam parameters. The results for the γ -ray beam energy analysis procedure show that the experimental spectrum can be accurately reproduced by GEANT4 simulation and the beam parameters can be extracted under the assumption of a known energy distribution.

Despite the efforts made to describe the intensity measurement setup the simulated results lacked the accuracy obtained for the energy measurement, pointing to errors associated with the reproduction of the experimental setup. Regardless, the results obtained from the intensity analysis showed some degree of agreement with the results obtained from other methods. This method could yield a better description of the intensity of the γ -ray beam at ELI-NP by using a well characterized experimental setup.

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Energy (MeV)	1	2	4	6	8	10	12	14	16	18	20
Energy measurement time (s)	43	49	65	79	95	113	136	165	199	253	303
Intrinsic efficiency (%)	23.5	20.5	15.5	12.7	10.5	8.9	7.3	6.1	5.0	4.0	3.3
Scattering rate (Hz)	18.2	35.7	36.6	42.0	43.2	49.0	59.2	66.6	77.1	94.2	100.0

Table 1: Time and rate estimates for energy and intensity measurements with the proposed setup at ELI-NP. The estimates are calculated for a 3% statistical uncertainty in the final results.

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References

- [1] L. Federici, G. Giordano, G. Matone, G. Pasquariello, P. G. Picozza, R. Caloi, L. Casano, M. P. D. Pascale, M. Mattioli, E. Poldi, C. Schaerf, M. Vanni, P. Pelfer, D. Prospero, S. Frullani, B. Girolami, Backward Compton scattering of laser light against high-energy electrons: the LADON photon beam at Frascati, *Nuovo Cimento B* 59 (1980) 247.
- [2] V. N. Litvinenko, et al., Gamma-Ray Production in a Storage Ring Free-Electron Laser, *Phys. Rev. Lett.* 78 (1997) 4569.
- [3] G. Suliman, V. Iancu, C. A. Ur, M. Iovea, I. Daito, H. Ohgaki, Gamma-Beam Industrial Applications at ELI-NP, *Rom. Rep. Phys.* 68 (2016) S799–S845.
- [4] O. Tesileanu, M. Gai, A. Anzalone, C. Balan, J. S. Bihalowicz, M. Cwiok, W. Dominik, S. Gales, D. G. Ghita, Z. Janas, D. P. Kendellen, M. L. Cognata, C. Matei, K. Mikszuta, C. Petcu, M. Pfitzner, T. Matulewicz, C. Mazzocchi, C. Spitaleri, Charged particle detection at ELI-NP, *Rom. Rep. in Phys.* 68 (2016) S699.
- [5] F. Camera, H. Utsunomiya, V. Varlamov, D. Filipescu, V. Baran, A. Bracco, G. Colo, I. Gheorghe, T. Glodariu, C. Matei, O. Wieland, Gamma above the neutron threshold experiments at ELI-NP, *Rom. Rep. in Phys.* 68 (2016) S539.
- [6] C. A. Ur, A. Zilges, N. Pietralla, J. Beller, B. Boisdreffre, M. O. Cernaianu, V. Derya, B. Loher, C. Matei, G. Pascovici, C. Petcu, C. Romig, D. Savran, G. Suliman, E. Udup, V. Werner, Nuclear Resonance Fluorescence Experiments at ELI-NP, *Rom. Rep. Phys.* 68 (2016) S483–S538.
- [7] H. R. Weller, C. A. Ur, C. Matei, J. M. Mueller, M. H. Sikora, G. Suliman, V. Iancu, Z. Yasin, Gamma beam delivery and diagnostics, *Rom. Rep. in Phys.* 68 (2016) S447.
- [8] C. Matei, J. M. Mueller, M. H. Sikora, G. Suliman, C. A. Ur, H. R. Weller, Investigation of the $d(\gamma, n)p$ reaction for gamma beam monitoring at ELI-NP, *J. Instrum.* 11 (2016) P05025.
- [9] O. Klein, T. Nishina, uber die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac, *Z. Phys.* 52 (1929) 853–869.
- [10] S. Agostinelli, et al., GEANT4 - a simulation toolkit, *Nucl. Instr. and Meth. A* 506 (2003) 250–303.
- [11] X-5 Monte-Carlo Team, MCNP - A General N-Particle Transport Code - LA-UR-03-1987 (2003).
- [12] C. Matei, P-10-16 proposal at HIγS (2016).
- [13] C. Matei, D. L. Balabanski, O. Tesileanu, Y. Xu, M. L. Cognata, C. Spitaleri, Nuclear astrophysics measurements with ELISSA at ELI-NP, *Nuovo Cimento C* 39 (2017) 360.
- [14] C. Sun, Ph.D. thesis, Duke University (unpublished) (2009).
- [15] M. Blackston, Ph.D. thesis, Duke University (unpublished) (2007).
- [16] F. Salvat et al., Penelope - a code system for monte carlo simulation of electron and photon transport, Technical Report, Workshop Proceedings Issy-les-Moulineaux, France; AEN-NEA.
- [17] B. A. Perdue, Ph.D. thesis, Duke University (unpublished) (2010).
- [18] R. E. Pywell, O. Mavrichi, W. A. Wurtz, R. Wilson, Photon flux monitor for a mono-energetic gamma ray source, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 606 (3) (2009) 517 – 522. doi:<https://doi.org/10.1016/j.nima.2009.04.014>.
- [19] S. Mikhailov, Private communication (2018).
- [20] C. Matei, et al., in preparation (2018).
- [21] G. V. Turturica, G. Suliman, C. A. Ur, Monte Carlo simulations fo a large volume HPGE detector, *U.P.B. Sci. Bull. A* 78 (2016) 285–294.
- [22] Z. Elekes, T. Belgya, G. L. Molnar, A. Z. Kiss, M. Csatlos, J. Gulyas, A. Krasznahorkay, Z. Matea, Absolute full-energy peak efficiency calibration of a Clover-BGO detector system, *Nucl. Instr. and Meth. A* 503 (2003) 580.
- [23] D. G. Ghita, M. S. Dogaru, M. M. Gugiui, S. Dobrescu, C. Calinescu, G. Cata-Danil, M. Enachescu, P. Ionescu, N. Marginean, I. O. Mitu, D. V. Mosu, A. Pantelica, D. Pantelica, A. Petre, I. Popescu, B. Savu, T. B. Sava, C. A. Simion, C. Stan-Sion, M. Statescu, N. Zamfir, New developments at the Tandem accelerators laboratory at IFIN-HH, Proceedings of HIAT (2012) TUB02.