Article:

Turturica, G. V., Matei, C., Pappalardo, A. et al. (19 more authors) (2019) Investigation of Compton scattering for gamma beam intensity measurements and perspectives at ELI-NP. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. pp. 27-32. ISSN: 0168-9002

https://doi.org/10.1016/j.nima.2018.12.048

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

G.V. Turturica[a,b], C. Matei[a,*], A. Pappalardo[a], D.L. Balabanski[a], S. Chesnevskaya[a], V. Iancu[a], C.A. Ur[a], H.J. Karwowski[c,d], K.A. Chipps[e], M.T. Febbraro[e], S.D. Pain[e], D. Walter[f], C.Aa. Diget[g], J. Frost-Schenk[g], M. Munch[h], G.L. Guardo[i,a], M. La Cognata[i], R.G. Pizzone[i], G.G. Rapisarda[i], K.Y. Chae[j], M.J. Kim[j], M.S. Kwag[j]

[a] *Extreme Light Infrastructure - Nuclear Physics, Horia Hulubei National R&D Institute for Physics and Nuclear Engineering, 077125 Magurele, Romania*
[b] *Politehnica University of Bucharest, Bucharest, Romania*
[c] *Department of Physics, University of North Carolina - Chapel Hill, Chapel Hill, North Carolina 27599, USA*
[d] *Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[e] *Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[f] *Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903, USA*
[g] *Department of Physics, University of York, York YO10 5DD, United Kingdom*
[h] *Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark*
[i] *INFN-Laboratori Nazionali del Sud, Catania, Italy*
[j] *Department of Physics, Sungkyunkwan University, Suwon 16419, Korea*

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 (HIγS) 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-

*Corresponding author
Email address: catalin.matei@eli-np.ro (C. Matei)

cilitate the scientific program [3, 4, 5, 6]. Several γ-ray beam monitoring instruments [7] are proposed at ELI-NP in combination with the experimental stations. The spatial parameters will be monitored using a scintillator coupled with a CCD system. The intensity and polarization parameters will be measured using the $d(\gamma, p)n$ reaction and two sets of neutron detectors depending on the energy of the γ-ray beam [8]. Additional diagnostics instruments are under construction for measuring the time structure, intensity, and polarization of the beam using other methods [7].

One instrument proposed for measuring the beam intensity and energy parameters is based on a large volume High Purity Germanium (HPGe) detector with an anti-Compton shield. In this paper, we investigate the use of Compton scattering for continuously measuring the intensity and energy of the γ-ray beam at ELI-NP based on test experiments at HIγS. The organization of this paper is as follow: In Sect. 2 we review general concepts in Compton scattering and define the method for intensity calculations. The experimental setup used for testing this method between 4.5 and 10 MeV at HIγS is described in detail. In Sect. 3 we discuss the results of the beam energy and relative intensity measurements at HIγS. Finally in Sect. 4, we present the development of an instrument based on an HPGe detector for continuously monitoring the γ-ray beam intensity at ELI-NP up to a photon energy of 20 MeV. The HPGe detector was characterized using accelerator-based high-energy photons and extensively simulated in GEANT4.

2. Method description

2.1. Compton scattering method

The differential cross section for Compton scattering can be calculated using the well-known Klein-Nishina expression [9]:

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

where: r_e is the classical electron radius, $\alpha = \hbar\omega/m_e c^2$, and θ is the scattering angle. If the geometrical characteristics of the setup and the parameters of the scatterer are known, Eq. 1 can be used to calculate the incident intensity from the number of scattered photons. Hence, the inelastic scattering of photons can be used to conduct online γ-ray beam intensity measurements. This method requires the placement of an in-beam scattering target from which the incident photons will scatter into a detector placed at a predefined angle with respect to the beam axis. The complexity of a typical experimental setup makes the direct use of Klein-Nishina rather difficult. However, general particle transport codes such as GEANT4 [10] or MCNP [11] are suitable for this type of analysis.

Several factors will determine the accuracy of the Compton scattering based intensity measurement. The differential cross-section of Compton scattering shows a strong ω and θ variation making the measurement sensitive to the photon energy and setup geometry. Hence, a precise measurement of the detector's position with respect to the beam axis is required in order to minimize the associated errors. Another important parameter that will influence the accuracy of this method is the precision with which the detection efficiency is known. Low-energy detection efficiency can be routinely obtained using standard calibration sources; however, for high energy, photons from (p,γ) or (n,γ) reactions are needed in order to determine the detector efficiency. If simulations are part of the analysis, additional uncertainties associated with Monte Carlo methods will contribute to the total uncertainty.

2.2. Experimental setup

The experimental instruments were positioned in the Upstream Target Room (UTR) at HIγS as illustrated in Fig. 1. The γ-ray beam was collimated to 12 mm diameter in a collimating assembly located in an upstream room and then entered the experimental room.

The γ-ray beam first interacted with a thin LiF target (300-600 μg/cm^2 LiF evaporated on 1.3 μm mylar backing) placed inside a vacuum chamber. The LiF target was surrounded by silicon detectors for detecting charged particles from the photodisintegration of ^{7}Li [12, 13]. Two gold foils, mounted on the exit flange of the vacuum chamber, were irradiated at 9 and 10 MeV. The beam exited the vacuum chamber and passed through a 1-mm thick copper plate and a 4.5-cm long, 3.7-cm diameter heavy water cell. A scintillator and a CCD camera assembly [14] located in the back of the UTR were used for

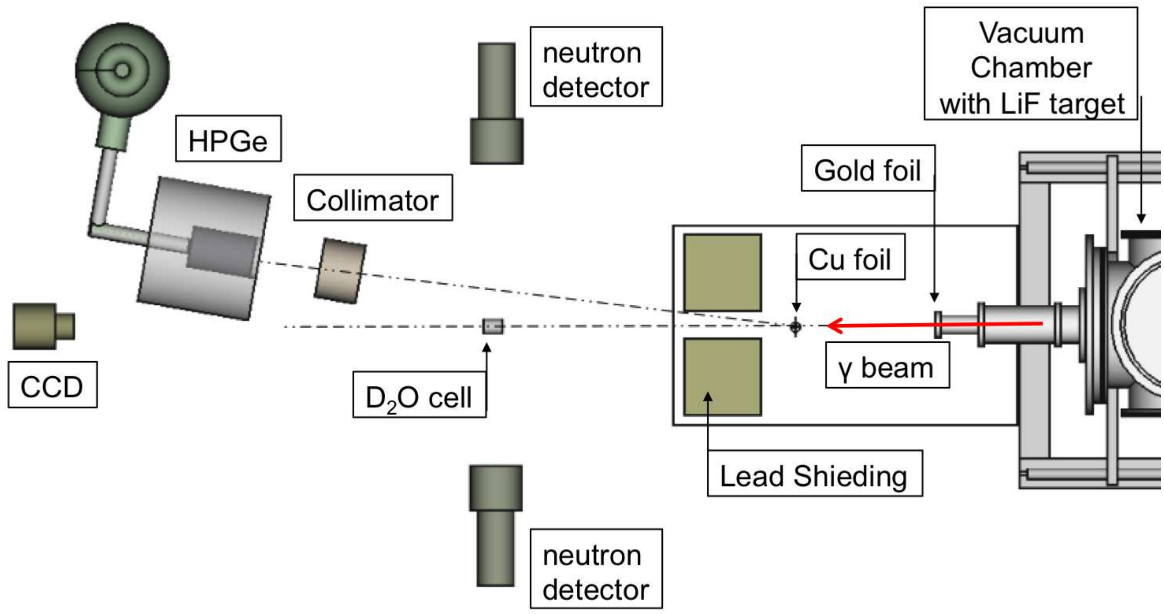

Figure 1: The layout of the experimental arrangement in the Upstream Target Room (drawing not to scale). The vacuum chamber housed a LiF target and a silicon detector array for detecting charged particles from the photodisintegration of ^{7}Li. The other items in the setup were used for the characterization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

finer target alignment and spatial characterization of the beam.

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

2.3. GEANT4 *simulations*

A typical GEANT4 simulation requires at least three components: the physical processes, the geometrical description of the experimental setup and the particle source. For the current simulation, the physics was implemented using the Penelope low-energy electromagnetic model [16], which contains the physical processes required for photons, electrons, and positrons based interactions. The simulated geometrical setup was based on precise physical measurements or estimates for the cases where measurements were not possible.

A schematic representation of the experimental setup is presented in Fig. 1. In order to obtain a valid model that accurately reproduces the response of the experimental detector, a detailed geometrical representation of the detector was constructed. The HPGe detector reproduction was based on the detector's technical drawings provided by the manufacturer. Slight adjustments were made in order to reproduce with good accuracy the response of the detector to standard calibration sources. Standard materials and compositions were used for the setup reconstruction. One of the important parameters of the experimental setup that could not be precisely inferred from the experiment was the position of the beam spot on the face of the detector. The change in the beam position with respect to the center of the detector has a considerable effect in the peak to Compton ratio, especially for high energy photons. The best reproduction of the experimental data is obtained when the beam hits the face of the detector 2.7 cm from the center of the detector, position that yields good agreement for all the energy cases available for this analysis. The third requirement for the simulation is the particle source. The spatial characteristics of the beam were inferred from images captured using a CCD camera. A probability density function was extracted from the beam spot image and was used to sample the individual positions of the photons at runtime.

These simulations were performed using the GEANT4 release 10.2.2.

3. Results and discussions

3.1. Gamma beam energy measurement

The energy parameters of the beam were determined for several discrete energies in the 4.5 to 10 MeV range using in-beam measurements, i.e. the HPGe detector was positioned at 0° with respect to the beam axis. In order to avoid radiation damage to the detector, the beam was attenuated before reaching the detector [17]. The count rate for the HPGe was kept in the 2-4 kHz range within a run time of about 5 min.

A two-step procedure was applied in order to obtain the γ-ray beam parameters. In the first step, a normal distribution fit of the full absorption peak was performed in order to determine an initial value for the energy parameters, i.e. full width half maximum (FWHM) and centroid. The fitting procedure can be straightforward for low-energy photons but can get complicated for high-energy photons where the full energy deposition peak is not so easily distinguished from the Compton background. In the second step of the procedure, we simulated the detector's response to a beam with the energy parameters obtained from the fit. Slight adjustments were made to the beam parameters in order to obtain the best agreement between simulations and experiment. The level of agreement was quantified using the χ^2 metric. Figures 2 and 3 show the results of the analysis for a photon energy of 4.5 MeV and 9.9 MeV, respectively.

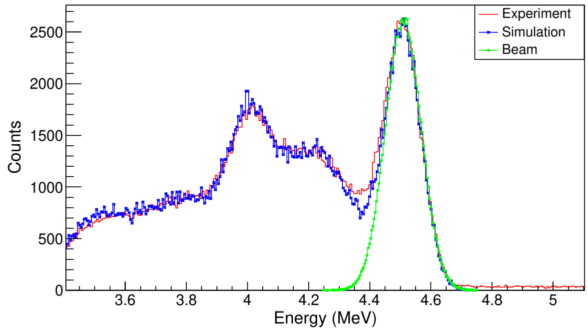

Figure 2: In-beam energy measurement spectra for 4.5 MeV photons. The simulated data (blue) is superposed on the experimental data (red). The energy distribution of the beam (green) is added for comparison.

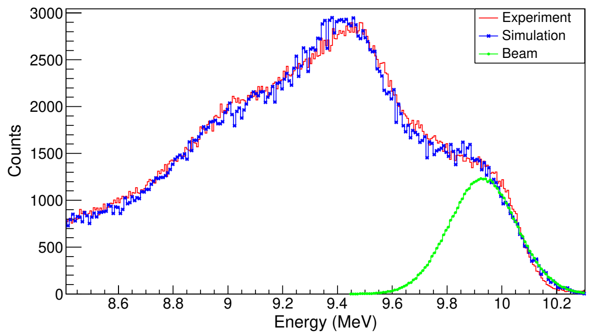

Figure 3: In-beam energy measurement spectra for 9.9 MeV photons. The simulated data (blue) is superposed on the experimental data (red). The energy distribution of the beam (green) is added for comparison.

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

3.2. Intensity measurement using Compton scattering

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

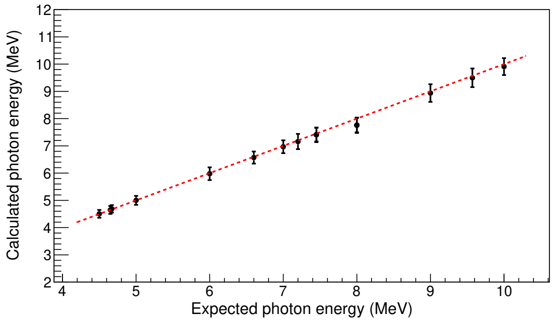

Figure 4: The calculated versus expected incident photon energy for the 4.5 to 10 MeV range. The FWHM is shown as uncertainty for the calculated data. The dotted line (red) represents a guideline for equal values of calculated and expected incident photon energies.

angular range of the scattered photons. The simulated spectra for the Compton scattering configuration were obtained using the energy parameters calculated in section 3.1. Small adjustments have been made to geometrical parameters, scattering angle and the position of the collimator with respect to the detector's face, in order to obtain the best agreement between experimental and simulated spectra. The best reproduction of the experimental data is obtained when the detector is placed at an angle of about 9.1°, which differs by about 9 % from the measured value. The comparison between experimental and simulated spectra for photons of 4.5 MeV is presented in Fig. 5.

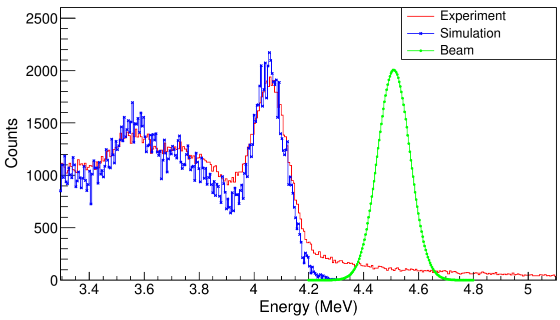

Figure 5: The energy spectrum of Compton scattered 4.5 MeV photons. The simulated data (blue) is superposed on the experimental data (red). The energy distribution of the beam (green) is added for comparison.

Once a good agreement is obtained between the simulated and experimental spectra, the intensity of the beam can be calculated using the number of photons that were required to generate the simulated spectrum and the acquisition time of the measurement. The results of such analysis are presented in Fig. 6 together with beam intensity values obtained from a paddle detector [18] situated upstream from the experimental setup. The two intensity curves, obtained with the paddle detector and using the Compton scattering, were matched at 10 MeV as this results in excellent agreement with the calculated intensity by the HIγS operating parameters [19].

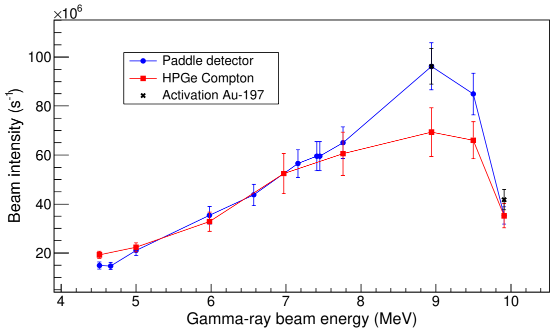

Figure 6: Beam intensity results for the 4.5 to 10 MeV range using Compton scattering and the paddle detector. Absolute values were obtained by using ^{197}Au activation.

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

4. Proposed instrument at ELI-NP

The proposed setup for the intensity and energy measurements at ELI-NP is presented in Fig. 7. The setup is composed of a detection assembly which contains a 150 % relative efficiency HPGe coupled with a NaI(Tl) anti-Compton shield, a positioning system that allows rotation and translation with respect to the scattering target and a support structure for the ensemble. The rotating system will allow the positioning of the detection assembly on a 0 to 15° scale, with a precision better than 0.01°. The anti-Compton shield has a single NaI(Tl) annular crystal configuration (110 mm inner diameter, 234 mm outer diameter, and 250 mm length) coupled to six, 51 mm diameter, photomultiplier tubes.

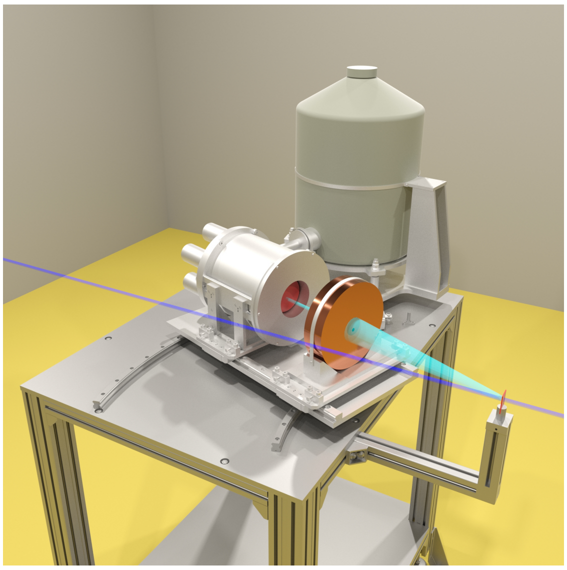

Figure 7: Proposed setup for energy and intensity measurements at ELI-NP.

In order to characterize and optimize the proposed instrument for energy and intensity measurements, an accurate reproduction of the setup was constructed using the GEANT4 simulation toolkit. Details about the HPGe detector modeling and the low energy efficiency measurements are presented in the previous work [21]. Given the wide energy range intended for this setup, measurements of the detection efficiency at higher energies were required. In order to extend the efficiency measurements up to 11.6 MeV proton-capture reactions on ^{23}Na and ^{27}Al and standard calibration sources, ^{60}Co, ^{56}Co, and ^{152}Eu were used. The analysis of the experimental data is made using the two-line method [22], which is based on the excitation of a gamma cascade which includes a high and low-energy γ-ray pair with a known branching ratio. By knowing the efficiency of the low energy gamma-ray, from standard calibration sources, one can determine the detection efficiency for the high energy photon. The measurements were performed using proton beams from the 3MV Tandem accelerator of IFIN-HH [23]. Fig. 8 presents the measured efficiency of the 150 % HPGe together with the simulated efficiency. A maximum relative difference of 14 % was observed between the experimental and simulated data at the lowest energies. This difference was attributed to poor characterization of the complex geometry in which the measurement of the detection efficiency with standard source was carried out.

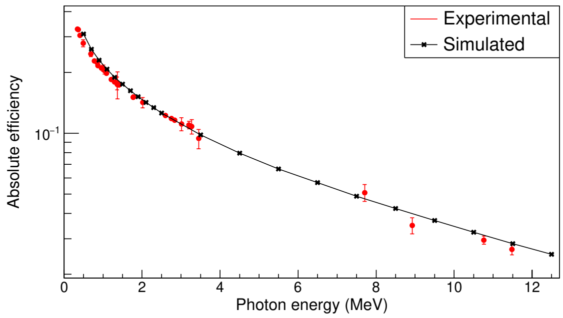

Figure 8: Absolute efficiency of a 150 % HPGe detector. The red and black markers represent the experimental and the simulated data for the 1-12 MeV range.

One of the main differences between the ELI-NP proposed setup and the one tested at HIγS is the improved peak-to-total ratio (P/T). This improvement can be attributed to the larger detector size, a 150 % relative efficiency detector compared with the 120 % relative efficiency from HIγS setup, and the addition of a Compton suppressor. The veto signal generated by the anti-Compton shield for the cases where only partial energy deposition is registered by the HPGe detector will be used to reject unwanted events from the measured spectrum. The enhanced P/T will enable the use of the setup for the whole energy range of the γ-ray beam. An example of a simulated in-beam spectrum obtained for a photon energy of 20 MeV is shown in Fig. 9. Significant improvement can be observed with respect to the 10 MeV spectrum presented in Fig. 3 where the full energy deposition peak is hardly noticeable from the Compton background, improvements that can be mostly assigned to the addition of the Compton suppressor.

To maximize P/T values one has to take into consideration the position of the beam with respect to the face of the detector. The well type shaped germanium crystal will exhibit lower intrinsic efficiency for a limited size beam incident in the center of the detector. P/T values for different positions on the face of the detector are presented in Fig. 10. Optimal values for the P/T ratio can be obtained when the γ-ray beam hits the detector $1 - 1.5$ cm from the center of the detector.

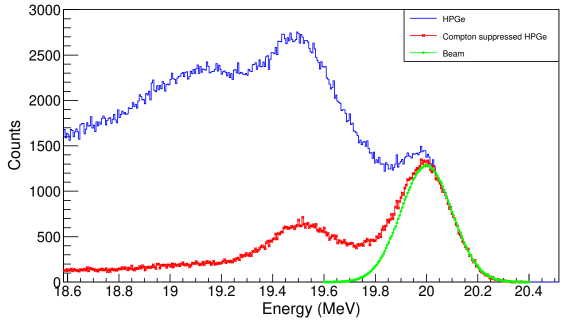

Figure 9: Simulated in-beam spectra for an incident beam of 20 MeV. The blue line shows the results obtained using a simple germanium detector; the red line shows the results obtained for a Compton suppressed germanium detector.

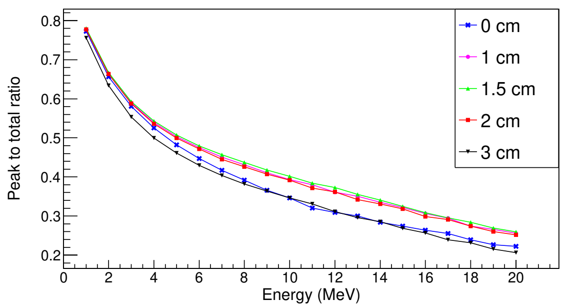

Figure 10: P/T values obtained from simulated data using the proposed ELI-NP setup. The figure shows the results obtained for multiple positions of the beam with respect to the center of the detector.

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.

6. Acknowledgements

The authors wish to thank B.A. Fallin from Duke University and U. Gayer from TU Darmstadt for sharing geometry files and calibration data for the 120% HPGe detector, E. Udup and A. Imreh from ELI-NP for the design of the support structure for the 150% HPGe detector, and HIγS personnel for the technical support during this experiment.

This work is supported by Extreme Light Infrastructure Nuclear Physics (ELI-NP) Phase II,

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.

a project co-financed by the Romanian Government and by the European Regional Development Fund–the Competitiveness Operational Programme (1/07.07.2016, COP, ID 1334).

This word is also partly supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (Nos. NRF-2016R1A5A1013277 and NRF-2018M7A1A1072274).

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. Prosperi, 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. Pfutzner, 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. Boisdeffre, 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(γ,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. Gugiu, 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.