Beam Flux Measurement Using Photon Activation Analysis Method at SLEGS

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Abstract

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The Shanghai Laser Electron Gamma Source(SLEGS) has delivered a quasi-monochromatic, continuously energy-tunable gamma-ray beam. Based on the photon activation analysis(PAA) method, SLEGS has built and developed a photon activation analysis platform, including online activation and offline low-background HPGe detector measurement systems, as an alternative to direct measurement methods and a cross-tests at low throughput. Due to the short half-lives spanning from minutes to days and characteristics such as ease of fabrication, cost-effectiveness, and stability, gold (197Au) and zinc (64Zn) emerge as favorable activation targets in the gamma-ray beam flux monitor. Notably, their utility shows a multitude of advantages in monitoring the gamma-ray beam flux typically 105 photons/s with the energy of 13.16 to 19.08 MeV under the condition of the 3 mm coarse collimator. Especially in high-flux γ-ray beam experiments can be well applied.

Full Text

Preamble

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The Shanghai Laser Electron Gamma Source (SLEGS) delivers a quasi-monochromatic, continuously energy-tunable γ-ray beam. Based on the photon activation analysis (PAA) method, SLEGS has established a photon activation analysis platform comprising online activation and offline low-background HPGe detector measurement systems, serving as an alternative to direct measurement methods and providing cross-validation at low flux levels. Gold (^{197}Au) and zinc (^{64}Zn) emerge as favorable activation targets for γ-ray beam flux monitoring due to their short half-lives ranging from minutes to days, combined with characteristics such as ease of fabrication, cost-effectiveness, and stability. Their utility demonstrates numerous advantages for monitoring γ-ray beam flux at typical levels of 10^5 photons/s with energies from 13.16 to 19.08 MeV under conditions using a 3 mm coarse collimator. This approach proves particularly effective for high-flux γ-ray beam experiments.

Keywords: SLEGS, Laser Compton Scattering, Beam Flux, Photon Activation Analysis

Introduction

The Shanghai Laser Electron Gamma Source (SLEGS) represents one of the beamline stations constructed as part of the Shanghai Synchrotron Radiation Facility (SSRF) Project II. As the first pioneering Laser Compton Slant Scattering (LCSS) gamma source, SLEGS is characterized by its innovative approach employing a continuously variable collision angle from 20 to 160 degrees, enabling production of adjustable γ-ray energies within the range of 660 keV to 21.7 MeV [1, 2]. SLEGS serves as an important platform for fundamental and applied scientific research in photonuclear physics.

The γ-ray beam flux constitutes a crucial parameter for SLEGS, measurable through both direct and indirect methods. Large-volume scintillator detectors such as $LaBr_3$(Ce), BGO, and NaI enable direct measurement of γ-ray energy; however, limitations arise at high count rates (less than 10^6 cps) due to the long decay time of scintillators and the limited readout rate of PMTs. Plastic scintillator paddle detectors employed at HIγS permit beam flux measurement up to 3×10^7 photons/s with an accuracy of at least 2% [3].

At SLEGS, direct measurements are facilitated by a large NaI detector measuring Φ203.2 mm × 304.8 mm, read out directly by four PMTs. Additionally, a Φ76.2 mm × 101.6 mm $LaBr_3$(Ce) detector [4] and a Φ76.2 mm × 200 mm BGO detector monitor the attenuated beam. Indirect methods rely on nuclear reactions induced by γ-rays, such as d(γ, n)p in D_2O and deuterated benzene (C_6D_6) targets, used to monitor beam flux by counting neutrons at HIγS. The γ-ray flux calculated at 3 MeV reaches 1.2×10^7 photons/s with simulated detector efficiency, and the overall systematic uncertainty can be limited to below 5% [5, 6]. Another indirect method involves Compton scattering by a copper target, to be employed at ELI-NP for measuring relative beam flux [7]. Additionally, the photon activation method, which utilizes photonuclear reactions such as ^{197}Au(γ, n)^{196}Au, ^{27}Al(γ, x)^{24}Na, ^{93}Nb(γ, n)^{92} , Nb, and others, serves as a third approach for determining beam flux. Specifically for LCSS γ-ray beams at SLEGS, the ^{197}Au(γ, n)^{196}Au and ^{64}Zn(γ, n)^{63}Zn reactions have been selected to measure the γ-ray beam flux.

This article is organized as follows: Section 2 introduces the basic principles and methods of Photon Activation Analysis (PAA) [8, 9], including the γ-ray beam source and detection system. Section 3 reviews the data analysis procedures. Section 4 discusses future prospects for PAA, such as improvements in nuclear reaction data, development of new γ-ray sources, and integration of PAA with other techniques.

II. SLEGS Beamline and PAA Setup

A. γ-ray Beam Characterization

A Laser Compton scattering γ-ray beam was generated at the interaction chamber using a CO_2 laser with 10.64 μm wavelength operating at 1 kHz low frequency and 50 μs pulse width (equivalent to 5 W laser power). This laser beam collided with 3.5 GeV electrons in the SSRF storage ring, producing quasi-monochromatic γ-rays with energies varying from 0.25 to 21.7 MeV. The γ-ray beam flux ranged between 4.8$×10^{5}$ and 1.5$×10^{7}$ ph/s. The LCSS γ-ray beam was then directed through a vacuum pipeline, traversing a coarse collimator, fine collimator, and attenuator [10–12], before ultimately reaching the experimental hutch. This well-controlled transport setup ensures precise delivery of the γ-ray beam to the experimental station.

A diagram illustrating the online activation and offline measurement configuration is presented in [Figure 1: see original paper]. The activation platform, featuring a multi-slot target holder, is strategically positioned behind the beam pipe exit. A silicon pixel imaging detector (MiniPIX) facilitates beam spot imaging and reaction target localization. Additionally, a Φ76.2 mm × 101.6 mm $LaBr_3$(Ce) detector measures both the γ-ray beam flux and energy at the termination point of the LCS γ-ray beamline. [Figure 2: see original paper] shows the detector response to the γ-ray beam at collision angles of 124° and 132° using a 3 mm coarse collimator under 200 mm copper attenuation. The

profile of quasi-monoenergetic γ-rays overlaid on a continuous bremsstrahlung background is clearly visible. Utilizing the unfolding method, the corresponding gamma energy spectrum without detector response was successfully extracted, as shown in [Figure 2: see original paper] (pink and blue lines). A paper detailing the γ-ray beam unfolding is currently in preparation [13].

B. The Low Background HPGe Detector System

Characteristic γ-rays emitted from the irradiated sample are measured using an HPGe detector (ORTEC GEM70200-p). This detector achieves a relative efficiency of 55.2% at 1333 keV with an impressive energy resolution of 5.99 keV at 1333 keV (0.45%). To minimize background interference, 10 cm thick lead shields ensure low background counts of less than 5 cps within the 60 keV to 3000 keV region.

HPGe detector efficiency calibration is meticulously performed using standard gamma sources including ^{152}Eu (24.5 kBq), ^{137}Cs (8.177 kBq), ^{57}Co (80.73 kBq), and ^{241}Am (6.516 kBq). The absolute efficiency ( ) for the gamma source positioned at the same distance from the HPGe detector is determined by the expression given in Eq. (1):

N Ftsc $A_0 e^{-\lambda}$ I T

In this expression, N represents the photon peak counts obtained for the characteristic γ-rays of ^{152}Eu, ^{57}Co, ^{137}Cs, and ^{60}Co. A_0 denotes the source activity at calibration, T is the elapsed time since calibration, I denotes the characteristic γ-ray transition relative intensity, and T is the counting time. The correction factor for coincidence summing effects is denoted as F c. To estimate efficiencies corresponding to γ-rays emitted from the decay of ^{152}Eu, ^{57}Co, ^{137}Cs, and ^{60}Co, a linear parametric model represented by Eq. (2) is employed.

The fitted curve of interpolated detector efficiency and measured detector efficiency is visualized in [Figure 3: see original paper]. Furthermore, correction for summing coincidence effects is accomplished through Geant4 simulation [14], ensuring accurate corrections and enhancing the reliability of the calibration process.

The self-attenuation coefficient f due to γ-ray interactions within the sample thickness is given by Eq. (5):

$$= e^{+ \ n + \ n \ 2+ \ n \ 3+ \ n \ 4+ \ n \ 5} \ 1 - e^{-}\mu$$

III. Activation Data Analysis

Gold, a commonly utilized activation material, was chosen for comparison with zinc, a short-lived activation material. In this work, the γ-ray beam flux extracted from the ^{197}Au(γ, n)^{196}Au and ^{64}Zn(γ, n)^{63}Zn reactions was meticulously measured at SLEGS. Measurements spanned from 102° (13.16 MeV) to 139° (19.08 MeV), providing valuable insights into beam flux characteristics.

A. Calculation of the γ-ray Beam Flux

The γ-ray beam flux (E) (1/s) was determined by the activation Eq. (3):

E $= \sigma$(E)NAAbI ftfs

Here, N represents effective counts measured by the HPGe detector, Ab is the natural isotope abundance of the target. The time correction factor ft is shown below:

$(1 - e^{-}\lambda\ )e^{-}\lambda\ \ (1 - e^{-}\lambda\ )$

Where λ (1/s) is the decay constant, T is the irradiation time, and T (called cooling time) is the elapsed waiting time between the end of irradiation and the start of offline HPGe measurement.

B. Target Material for Activation

The ^{197}Au(γ, n)^{196}Au and ^{64}Zn(γ, n)^{63}Zn reactions have been specifically chosen to serve as monitors for the γ-ray beam flux at SLEGS. The single-neutron emission thresholds for ^{197}Au and ^{64}Zn are 8.073 MeV and 11.86 MeV, respectively. Consequently, the γ-ray beam flux can be effectively monitored within energy ranges of 8.07–21.00 MeV and 11.96–25.00 MeV for these reactions, ensuring comprehensive coverage across desired γ-ray beam energies. They exhibit a broader monitoring energy range. The giant resonance excitation functions for these reactions are depicted in Figure 4: see original paper and (b), encompassing both previously reported experimental data from the EXFOR database and evaluated cross-section data from ENDF/B-VIII and IAEA-2019 libraries. With their substantial cross-sections, these reactions facilitate short activation times, making them versatile for various experiments.

The half-lives of ^{196}gAu and ^{63}Zn are 6.1669 days and 38.47 minutes, respectively. [Figure 5: see original paper] illustrates the level scheme of ^{196}gAu decay and ^{63}Zn decay, along with characteristic γ-ray energies and intensities. Relative nuclear spectroscopic data were sourced from the NuDat 3.0 database [15]. Both reactions are well-suited for offline measurements, enhancing their utility in experimental settings.

The beam flux activation monitor utilized a natural gold target (^{197}Au 100%) with 99.99% purity and 0.5 mm thickness. Additionally, a natural zinc target (^{64}Zn 49.2%, ^{66}Zn 27.7%, ^{67}Zn 4.0%, ^{68}Zn 18.5%, ^{70}Zn 0.6%) with 99.99% purity and 2 mm thickness was employed. The target had a diameter of 10 mm, exceeding the γ-ray beam diameter restricted by a 3 mm coarse collimator. Strategically situated on a multi-slot target holder along the beam axis and precisely positioned in front of the experimental hutch, the target underwent meticulous irradiation by a focused γ-ray beam. This deliberate irradiation enabled controlled ^{197}Au(γ, n)^{196}Au and ^{64}Zn(γ, n)^{63}Zn reactions, playing a crucial role in the experimental procedure.

The ^{197}Au(γ, n)^{196}Au reaction produced unstable nuclei ^{196}mAu and ^{196}gAu.

Subsequently, ^{196}mAu underwent de-excitation by emitting γ-rays, leading to formation of ^{196}gAu. The decay of ^{196}gAu proceeded through either electron capture (93%), yielding ^{196}Pt, or β^- decay (7%), resulting in ^{196}Hg. The decay profile is visualized in Figure 5: see original paper, while additional reaction details are summarized in . The characteristic γ-rays from the ^{197}Au target irradiated with a 19.08 MeV γ-ray beam are clearly evident in Figure 5: see original paper. Notably, characteristic γ-rays of ^{196}gAu include peaks at 355.73 keV and 333.03 keV originating from β^- decay of ^{196}gAu, along with a peak at 426.10 keV corresponding to the isomeric transition (IT) decay of ^{196}gAu. These features contribute to comprehensive understanding of the experimental spectrum.

For ^{63}Zn, it undergoes β^+ decay, resulting in emission of a characteristic peak at 511 keV due to positron-electron annihilation. The gamma-ray spectrum recorded for zinc samples irradiated with 19.08 MeV photons is illustrated in Figure 5: see original paper. Experimental conditions included an irradiation time of t = 2 hours, a cooling period of T = 3.1 minutes, and a counting time of T = 2 hours. Notably, statistical errors associated with these measurements remain below 1%, highlighting the precision of the experimental data.

C. Characteristic γ-ray De-excitation Spectrum

The γ-ray beam flux was quantified through identification of characteristic transition peaks associated with the ground state of ^{196}gAu following the photoneutron reaction with ^{197}Au. This ground state possesses a half-life of 6.1669 days, making it a reliable marker for assessing γ-ray beam strength. Irradiation, cooling, and counting times were carefully chosen: t = 0.5637 days for irradiation, T = 2.24 days for cooling, and T = 224,309 seconds for counting. Notably, the cooling time exceeds two days, ensuring 99% decay of the excited ^{196}mAu state (E = 0.5957 MeV, $T_1/_2$ = 9.6 hours) to reach the ground state. This meticulous time allocation enhances the reliability and precision of experimental measurements. The distinct characteristic γ-ray transitions resulting from irradiation are clearly resolved.

IV. Results and Discussion

The γ-ray beam flux was determined through activation reactions ^{197}Au(γ, n)^{196}g+mAu and ^{64}Zn(γ, n)^{63}Zn, as well as direct measurements using a $LaBr_3$(Ce) detector. Results presented in [Figure 6: see original paper], obtained from activation reactions, exhibited excellent agreement with $LaBr_3$(Ce) detector results and Geant4 simulation outcomes.

Under conditions of a 3 mm coarse collimator aperture, the γ-ray beam flux ranged from 1.8×10^5 photons/s to 7×10^5 photons/s, varying with the collision angle between laser and electron beam (ranging from 102° to 139°, corresponding to γ-ray beam energies of 13.16–19.08 MeV). This substantiates the reliability and convenience of the photon activation analysis method, proving it as effective

as classical beam monitoring methods. When utilizing suitable short-lived target materials, this approach enables sensitive and rapid online monitoring across different energy regions.

At higher γ-ray beam flux levels, direct monitoring becomes challenging. In such cases, photon activation monitoring serves as an excellent means of flux indexing. Our group has also developed a rapid monitoring method for short-lived target materials, as detailed in subsequent references.

Total uncertainties in measured γ-ray beam flux for the ^{197}Au(γ, n)^{196}g+mAu, ^{64}Zn(γ, n)^{63}Zn reactions, and $LaBr_3$(Ce) detector are listed in .

Error analysis for γ-ray beam flux measurement encompasses several factors. These include statistical error of characteristic γ-ray counts (N), relative errors of decay constants (λ) taken from literature (0.01%) [33], and uncertainty in the ^{197}Au(γ, n)^{196}g+mAu and ^{64}Zn(γ, n)^{63}Zn cross-sections, which is negligible as indicated in [Figure 4: see original paper]. However, significant errors exist in experimentally measured cross-sections for the two reaction channels, some exceeding 10%. To mitigate this, we adopt IAEA data from the evaluation database as the standard cross-sectional value in data analysis.

Efficiency calibration relative errors of the HPGe detector are denoted as , and relative errors of the number of targets per unit area (N) are associated with target thickness. Given that experimental timing has picosecond-level confidence compared to irradiation time intervals of at least hours, T is considered negligible. Corresponding results are presented in .

V. Conclusion

A flux monitoring system utilizing the photon activation analysis (PAA) method has been developed at SLEGS. This system serves as a supplementary and cross-checking tool for direct measurements. The monitoring system comprises both online activation and offline low-background HPGe detector components.

In this setup, natural materials such as gold (Au) and zinc (Zn) have been selected as preferred target materials. This choice is based on the relatively short half-lives of ^{196}gAu and ^{63}Zn, which renders them stable for use at γ-ray flux levels exceeding 10^5 photons/s. The chosen materials are effective within the energy range of 13.16–19.08 MeV. This system proves particularly beneficial for high-flux γ-ray beam experiments.

The SLEGS activity platform, through this newly established flux monitoring system, enhances experimental capabilities, making it well-suited for conducting photoneutron cross-section measurements using quasi-monochromatic γ-ray beams.

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H-W Wang, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Note: Figure translations are in progress. See original paper for figures.