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Abstract

The Shanghai Laser Electron Gamma Source (SLEGS) generates quasi-monoenergetic, continuously energy-tunable MeV gamma beams through laser-electron inverse Compton scattering, and represents the only Laser Compton Scattering (LCS) gamma source facility internationally that can continuously vary the collision angle. Gamma activation serves as an effective approach for investigating material properties. This paper describes the gamma activation platform at SLEGS, encompassing the online activation process, offline low-background measurement, energy efficiency calibration of High Purity Germanium (HPGe) detectors, among other aspects. The current simple low-background shielding reduces the background count rate of the measurement system to approximately 5.2 cps/(60 keV-3 MeV energy region). The activation platform of the SLEGS gamma source provides favorable conditions for conducting gamma activation measurement research and will play a significant role in future investigations across nuclear physics, nuclear astrophysics, medical applications, materials science, environmental science, and related fields.

Full Text

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Abstract

The Shanghai Laser Electron Gamma Source (SLEGS) generates quasi-monoenergetic, continuously energy-tunable MeV gamma rays through inverse Laser Compton Scattering (LCS) between laser photons and electrons. SLEGS represents the world's only LCS gamma source capable of continuously varying collision angles. Gamma activation analysis serves as an effective method for investigating material properties. This paper introduces the gamma activation platform at SLEGS, encompassing online activation procedures, offline low-background measurements, and energy-efficiency calibration of High Purity Germanium (HPGe) detectors. The current simple low-background shielding reduces the system background count rate to approximately 5.2 counts per second in the 60 keV–3 MeV energy region. The SLEGS activation platform provides favorable conditions for gamma activation measurement research and will play a significant role in future investigations across nuclear physics, nuclear astrophysics, medical applications, materials science, and environmental science.

Keywords: gamma source; gamma activation; low-background measurement; SLEGS

Gamma rays serve as ideal probes for nuclear technology and application research, capable of penetrating thick materials while producing ionization and excitation effects. They find widespread applications in nuclear reactions, nuclear structure, nuclear energy, and nuclear medicine. Activation methods include proton activation, neutron activation, and gamma activation. Activation measurements are extensively employed in nuclear reaction cross-section measurements, nuclear energy development, nuclear waste processing, nuclide composition analysis, beam calibration, medicine, and archaeology [?, ?]. China has constructed various neutron and proton sources, including reactor thermal neutron sources, DD/DT fast neutron sources [?], accelerator-based thorium molten salt reactor white neutron sources [?], the China Spallation Neutron Source (CSNS) [?], and widely used electrostatic and tandem accelerator proton sources. These facilities have significantly advanced neutron and proton activation techniques for nuclear analysis, materials testing, and medical appli-

cations. Gamma activation represents another important activation technique beyond proton and neutron methods. In gamma activation, atomic nuclei absorb high-energy gamma rays, exciting target nuclei to short-lived excited states. Subsequently, the target nuclei emit secondary radiation or particles (such as gamma rays, neutrons, protons, alpha particles, or fission fragments) to produce radioactive residual nuclei. By measuring the characteristic gamma rays emitted during de-excitation of these residual nuclei, their properties can be determined. This method provides a powerful tool for studying nuclear reactions and structures, offering crucial insights into nuclear properties and decay processes.

Early exploratory research on gamma activation techniques utilized bremsstrahlung gamma rays and nuclear reaction gamma rays from accelerators, investigating nuclide content determination for carbon, nitrogen, oxygen, scandium, and copper [?, ?] and analyzing the feasibility of gamma activation methods using bremsstrahlung sources [?]. The China Institute of Atomic Energy performed activation measurements of the $^{197}\text{Au}(\gamma, n)$ reaction cross-section using 9.17 MeV monoenergetic gamma rays from proton capture reactions [?]. The scarcity of gamma source facilities has limited the development of gamma activation methods in China. The successful commissioning of the Shanghai Laser Electron Gamma Source (SLEGS) in December 2021 [?, ?] provides a new platform for gamma activation research in China. SLEGS generates MeV gamma rays through collisions between 3.5 GeV electrons from the Shanghai Synchrotron Radiation Facility storage ring and 10.64 μm CO_2 lasers. SLEGS operates in two modes: oblique incidence and backscattering, corresponding to collision angles of 20–160 degrees and 180 degrees, respectively. By adjusting the collision angle between the laser and electron beams, continuously energy-tunable quasi-monoenergetic gamma beams can be produced [?, ?, ?, ?], with gamma energies ranging from 0.25 to 21.7 MeV and integrated fluxes of 2.1×10^4 – 1.2×10^7 photons/s. SLEGS enables fundamental research in nuclear physics and nuclear astrophysics, as well as applied research in gamma irradiation and gamma imaging. The gamma energy range of SLEGS covers the pygmy dipole resonance and giant dipole resonance regions of photonuclear reactions, facilitating gamma activation studies. The gamma activation method based on SLEGS can be applied to gamma beam flux calibration, photonuclear reaction cross-section measurements for medical isotopes [?, ?], and cross-section measurements of key nuclides in nuclear astrophysics [?], making important contributions to China's photonuclear reaction database and medical applications.

2 Principles and Methods of Gamma Activation

In a photonuclear reaction $A(\gamma, b)C$, a gamma beam with flux ϕ_b (1/s) bombards target nuclei A with areal density n_A (atoms/cm²), producing N_{reac} (1/s) reaction particles. The reaction cross-section σ_{reac} is given by:

$$\sigma_{\text{reac}} = \frac{N_{\text{reac}}}{\phi_b n_A}$$

If the residual nucleus C is radioactive, it can be measured through its de-excitation gamma rays. The decay constant λ (1/s) relates to the half-life $T_{1/2}$ as $T_{1/2} = \ln 2/\lambda$. The number of produced residual nuclei N_{prod} is:

$$N_{\text{prod}} = \sigma_{\text{reac}} n_A C_{i\gamma} A_b \frac{1}{\lambda} (1 - e^{-\lambda t_{\text{irrad}}})$$

where t_{irrad} is the irradiation time, A_b is the target isotopic abundance, and $C_{i\gamma} = e^{-(\mu/\rho)_{\text{ox}} x}$ is the incident gamma attenuation factor with x (g/cm^2) as the areal density, obtained from the National Institute of Standards and Technology (NIST) database. The number of decaying residual nuclei N_{decay} is:

$$N_{\text{decay}} = N_{\text{prod}} e^{-\lambda t_w} (1 - e^{-\lambda t_m})$$

where t_w is the cooling time between irradiation cessation and the start of offline HPGe measurement, and t_m is the offline measurement duration. After irradiation stops, the produced radionuclides decay exponentially. The activation, cooling, and measurement processes are illustrated in Figure ??.

Photonuclear reaction cross-sections are typically on the order of millibarns (mbar), generally below 500 mbar for heavy nuclei and 100 mbar for light nuclei. Consequently, gamma activation does not require long cooling times, and offline measurements can commence immediately after activation, which is particularly advantageous for short-lived nuclides. As an important activation technique, gamma activation finds applications in:

- 1) **Gamma activation flux monitoring:** Used for beam intensity calibration and monitoring in bremsstrahlung and laser-electron gamma source facilities;
- 2) **Gamma Activation Analysis (GAA):** Measuring nuclide composition in ancient gold coins, bronze artifacts, and other materials to analyze their origin and age;
- 3) **Photonuclear cross-section studies:** Measuring resonance cross-section data of key nuclides for nuclear astrophysics p-process studies and medical isotope production.

Beam flux represents a critical parameter for gamma beams, and precise measurement of gamma beam flux is essential for nuclear reaction cross-section measurements. Online activation combined with offline decay measurement provides an effective method for gamma beam flux calibration. Figure ?? shows photonuclear reaction cross-sections for short-lived nuclides suitable for gamma beam monitoring. Using available cross-section data for these nuclides enables gamma beam flux monitoring. The SLEGS activation analysis technique can

also be applied to photonuclear reaction cross-section measurements for medical isotopes and radioactive nuclei, such as low-abundance nuclides in nuclear astrophysics p-process studies. Photonuclear reaction cross-section measurements are crucial for understanding nucleosynthesis in nuclear astrophysics [?].

The effective counts N_γ measured by the detector are given by:

$$N_\gamma = \frac{N_{\text{decay}} I_\gamma}{\eta C_{o\gamma}}$$

where I_γ is the gamma relative intensity obtained from the National Nuclear Data Center (NNDC), η is the detection efficiency, and $C_{o\gamma} = e^{-(\mu/\rho)_{o\gamma}x}$ is the attenuation factor for characteristic decay gamma rays [?]. Irradiation duration is typically determined by the reaction product of interest. The yield of radioactive nuclides gradually approaches saturation over time, and irradiation beyond three half-lives provides no additional yield.

3 Gamma Activation Platform Layout

The SLEGS gamma activation experimental platform is located at the beam exit front-end of the BL03SSID beamline experimental hutch in the Shanghai Synchrotron Radiation Facility hall, as shown in Figure ???. The platform features multiple easily interchangeable target holders for simultaneous activation of various materials, enabling efficient utilization of the gamma beam. The gamma beam spot can be selected using coarse collimators with \$2 mm or \$3 mm dimensions, while \$10mmdiameteractivationtargetdiscsareemployed.Attheexperimentalhutchend,avariable-thicknesscopperattenuator(temporarilyinstalled)andalargeLaBr₃ detector placed in a beam dump enable online monitoring of attenuated beam flux. LaBr₃ detector signals are acquired by a CAEN DT5730B waveform digitizer and analyzed online using CAEN CoMPASS data acquisition software.

Due to collimation, the gamma beam spot aligns with the synchrotron radiation and bremsstrahlung X-ray beams from the SLEGS beamline. Beam spot positioning employs a Czech-made MiniPIX photon-counting X-ray silicon position-sensitive detector utilizing the Timepix chip (256\$×\$256 pixels, 55 μm pixel size) developed by CERN, enabling measurement of X-ray position and energy for imaging, diffraction, spectroscopy, particle tracking, and space radiation detection. A mechanical control platform adjusts the target holder position to the beam center, and precise alignment is achieved using specially shaped positioning targets combined with MiniPIX imaging probes. Beam spot measurements are shown in Figure ??.

4 Low-Background Measurements for Gamma Activation

SLEGS plans to construct two offline low-background activation measurement systems comprising ORTEC P-type HPGe detectors and low-background lead

brick shielding to accommodate alternating offline measurement requirements. HPGe detector parameters are listed in Table ???. An offline measurement target holder has been designed (see inset in Figure ??) to accurately constrain the relative position between activated targets and the HPGe detector for offline measurement of de-excitation gamma rays and HPGe detection efficiency calibration.

4.1 Background Measurement

The natural background primarily originates from environmental radionuclides, cosmic rays, and radionuclides in shielding materials. Lead bricks provide excellent shielding against gamma rays, and low-background lead bricks effectively shield environmental gamma background. Background measurements were performed under four conditions: no shielding, 50 mm ordinary lead bricks, 50 mm low-background lead bricks, and 100 mm low-background lead bricks. The results demonstrate that low-background lead bricks effectively shield gamma rays below 500 keV. The 50 mm low-background lead bricks achieve a background count rate of approximately 12 counts per second in the 60 keV–3 MeV region, while 100 mm low-background lead bricks reduce this to approximately 5.2 counts per second, showing that simple low-background lead brick shielding provides effective suppression of natural gamma background.

4.2 HPGe Detector Calibration

Prior to offline measurement of characteristic decay gamma rays from activated reaction targets, energy and efficiency calibration of the HPGe detector is required. Standard calibration sources $^{57,60}\text{Co}$, ^{137}Cs , ^{241}Am , and ^{152}Eu were used, with source parameters listed in Table ???. Additionally, ^{176}Lu in LYSO scintillation crystals and ^{40}K in potassium chloride were utilized for energy and efficiency calibration. The full-energy peak efficiency ϵ of the HPGe detector is given by:

$$\epsilon = \frac{N}{A_0 e^{-\lambda T} B_r t F_{tsc}}$$

where N is the gamma-ray count in the full-energy peak, A_0 is the source activity at certification, T is the time elapsed since source certification, t is the measurement duration, B_r is the specific activity of characteristic gamma rays, and F_{tsc} is the summing correction coefficient. Monte Carlo GEANT4 simulations were performed for summing effect corrections [?].

The HPGe detection efficiency ϵ can be expressed by the multi-parameter exponential formula:

$$\epsilon = e^{a+b \ln E+c \ln E^2+d \ln E^3+e \ln E^4+f \ln E^5}$$

where E is the gamma-ray energy in keV. The measured detection efficiency is shown in Figure ??(b), with fitting parameters $a = 51.7708$, $b = -35.05867$, $c = 0.1243$, $d = -1.9167$, $e = -0.3257$, and $f = -29.8688$.

5 Research and Outlook

The first HPGe detector (ORTEC GEM-70200-P) low-background shielding and offline test measurements for the SLEGS gamma activation platform have been completed. Gold target activation measurements have yielded excellent gamma beam intensity data, consistent within experimental uncertainties with online gamma flux measurements from the LaBr₃ detector installed at the beamline end, validating the reliability of SLEGS activation measurement techniques. A batch of short-lived radionuclide activation measurements has been completed, with experimental data to be published shortly. The second HPGe detector (ORTEC GEM-50195-P) low-background shielding is currently under construction. The construction of the SLEGS gamma activation platform and the development of gamma activation methodology have been progressively established. Based on this platform, various gamma activation studies can be conducted using photonuclear reactions [?].

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