Shanghai laser electron gamma source and its applications*

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Abstract Shanghai Laser Electron Gamma Source, a high intensity beam line of γ-ray, is expected to generate γ-rays up to the maximum energy of 22 MeV by Compton backscattering between a CO_2 laser and electrons in the 3.5 GeV storage ring of the Shanghai Synchrotron Radiation Facility. The luminosity of SLEGS γ-ray beam is estimated to be $7\times10^7\ A^{-1}W^{-1}s^{-1}$ in a optimized setup. Indirect measurement of cross section of the key nuclear-astrophysics reaction $^{12}C(\alpha,\gamma)^{16}O$ and γ-ray-triggered transmutation of long-lived radioactive wastes are discussed based on the estimated SLEGS γ-ray beam properties.

Key words compton backscattering, γ-ray source, photonuclear reaction, radioactive wastes

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1 Introduction

In 1963, Milburn[1], Arutyunian and Tumanian[2] pointed out for the first time, that Compton BackScattering (CBS) of laser light off relativistic electrons should be a promising way to obtain polarized monochromatic γ-ray beam with small divergence angles.

Among γ-ray generating methods, the CBS technique has several advantages[3]. First, Compton scattering is well understood within the Quantum Electro-Dynamics (QED) framework. Second, the energy of a CBS γ-ray beam has a sharp cut-off near the maximum energy and the largest fraction of photons is in the high-energy region. Third, the divergence angles of a CBS γ-ray beam produced by relativistic electrons are very small. Moreover, the CBS technique offers a convenient way to steer the polarization of the γ-ray beam by changing the polarization of the injected laser beam.

LADON beam[4—7], the first CBS γ-ray source started its operation in 1978. Along with the rapid development of laser and accelerator techniques, more CBS γ-ray sources became practical during the last 30 years. Using those CBS γ-ray beams, scientists are able to carry out investigations of different regions: conservation and symmetry study, particle physics, nuclear physics, nuclear-astrophysics, etc., as well as various researches on applied physics.

The future Shanghai Synchrotron Radiation Facility (SSRF)[8] offers an opportunity to construct a high quality γ-ray beam line. Shanghai Laser Electron Gamma Source (SLEGS)[9, 10], a γ-ray beam line based on the CBS technique, has been proposed recently. In this paper, the proposed SLEGS facility is described in brief; two possible experiments based on SLEGS γ-ray beam are discussed.

2 SLEGS facility

Figure 1 illustrates a schematic view of the

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SLEGS. A polarized CO_2 laser beam ($\lambda = 10.64$ μm) is produced and focused in the laser system, then injected into the SSRF storage ring from the front-end downstream to the selected sector (the interaction region) by a thin reflecting mirror. The CO_2 laser beam is aligned to the straight track of the stored electron beam by a visible collimating laser. The CBS γ-rays are generated within a small forward cone along the moving direction of the incident electrons. The CBS γ-ray beam within the system acceptance penetrates the reflecting mirror, passes through the collimator, and then reaches the experimental area. At the end of the interaction region, a set of monitor detectors measures the remaining of the injected CO_2 laser beam for feedback and control.

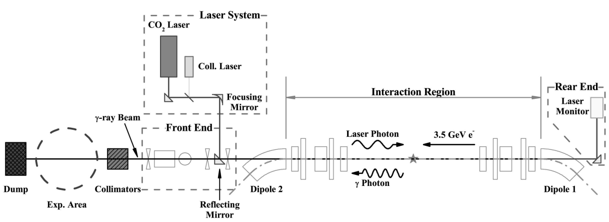

Fig. 1. The schematic view of SLEGS.

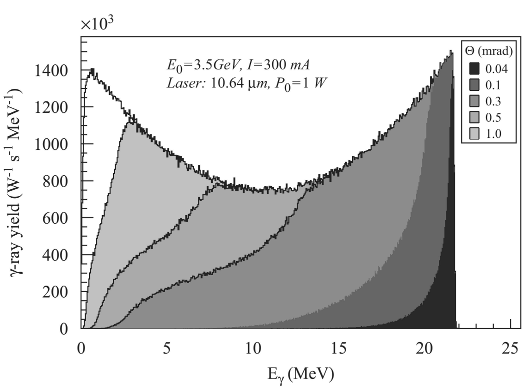

Fig. 2. The energy spectra of the CBS γ-ray beam at different collimation angles. See the text for more explanations.

A C++ program using Monte Carlo method was developed to simulate the generating process of the CBS γ-ray. The geometrical acceptance of the SLEGS facility was considered in the simulation. Parameters of the CO_2 laser beam were optimized to achieve the maximum luminosity of SLEGS γ-ray beam. Following the optimized setup, the CBS γ-ray luminosity can be as high as 7×10^7 $\mathrm{A^{-1}W^{-1}s^{-1}}$; considering the SSRF storage ring running in multi-bunch mode (beam current 300 mA), the flux of non-collimated SLEGS γ-ray is estimated to be $\sim 10^{10}\mathrm{s}^{-1}$ when a practical CO_2 laser with continuous output power $P_0 = 500$ W is employed[9].

The energy spectra of the CBS γ-ray beam at different collimation angles Θ are illustrated in Fig. 2, in which histograms filled with gray scale stand for Θ =0.04, 0.1, 0.3, 0.5 and 1.0 mrad, respectively, while the histogram filled with white represents the energy spectrum of non-collimated γ-ray beam.

3 Expected applications of SLEGS

SLEGS is expected to be a powerful platform for investigations of nuclear physics, nuclear-astrophysics, and applied physics. One of the possible experiment based on SLEGS γ-ray beam is the indirect measurement of cross section of the key nuclear-astrophysics reaction $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$[12]; another is the γ-ray-triggered transmutation of long-lived radioactive wastes[13].

3.1 Indirect measurement of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ cross section

Cross section of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction (σ_{CO}) in stellar circumstance is one of the key parameters nuclear-astrophysics[14, 15], because the abundance ratio of ^{12}C and ^{16}O is the beginning condition of the continuous stellar evolution, and determines the destiny of a star.

When the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction occurs, the temperature of star is about 0.2×10^9 K ($0.2T_9$), the corresponding $E_{\mathrm{c.m.}}$ of the reaction is about 0.3 MeV according to the Gamow theory. For $E_{\mathrm{c.m.}} = 0.3$ MeV, σ_{CO} is at the order of 10^{-17} barn. It is too hard to measure such a small value directly. Till now, there are no experimental data available below $E_{\mathrm{c.m.}} =$ 0.9 MeV. R-matrix formula and other theoretical approaches were used to fit the experimental data and extrapolated them down to $E_{\mathrm{c.m.}} = 0.3$ MeV and lower. Unfortunately, σ_{CO} at $0.2T_9$ deduced from various works differs from each other very much.

The photonuclear reaction $^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ ($Q =$ 7.162 MeV) is the reverse of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction. Once the cross section of $^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ reaction (σ_{OC}) is measured, the corresponding σ_{CO} can be determined by the detailed balancing principle. Calculation shows[12] that σ_{OC} is about 100 times larger than σ_{CO} at the same $E_{\mathrm{c.m.}}$ because of the absence of Coulomb barrier in photonuclear reaction.

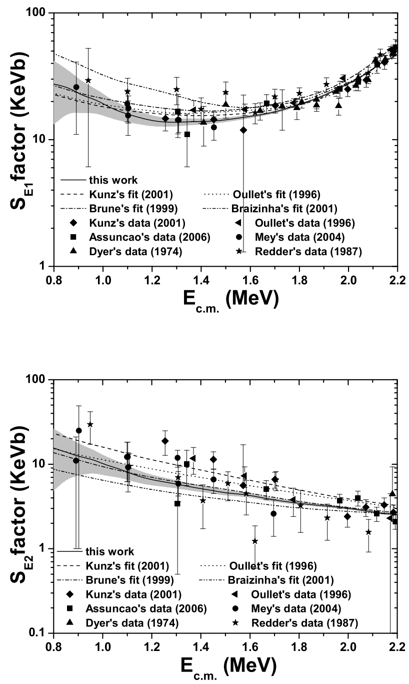

Fig. 3. The extracted S factors with statistical uncertainties of $^{12}C(\alpha,\gamma)^{16}O$ from existing data and theoretical calculations[12]. The gray band illustrates the statistical uncertainties of extracted S factors based on the simulation of the 100 hour beam time.

Using a CO_2 laser with output power at 10 kW order, the flux of non-collimated γ-ray beam produced by SLEGS is expected to exceed $10^{11}\ s^{-1}$. The S factors extracted from the simulation of the σ_{OC} measurement based on SLEGS γ-ray beam are shown in Fig. 3. One can find in Fig. 3 that, experiment of $^{16}O(\gamma,\alpha)^{12}C$ on SLEGS will bring a significant improvement of the status of $^{12}C(\alpha,\gamma)^{16}O$ studied.

3.2 γ-ray-triggered transmutation

Nuclear power generated from fission reactors is one practical way to overcome the energy crisis for human being. According to the "Moderate Development of Nuclear Power" utilized by Chinese government, more that 30 new reactor units will be constructed in China, and the total installed capacity of nuclear plants will be 3.6 times larger than that of present situation. Though only share a very small proportion, radioactive wastes from nuclear power plants are extremely hazardous and therefore have to be managed responsibly.

γ-ray-triggered transmutation of long-lived radioactive wastes were suggested recently, the demanded γ-ray can be generated by either bremsstrahlung method driven by ultra-high-power laser pulse[16—20], or CBS technique[21]. The future SLEGS γ-ray is suitable for γ-ray-triggered transmutation of several kinds of long-lived radioactive waste (LRW)[13].

The energy spectrum of SLEGS CBS γ-ray (adopting a CO_2 laser of 100 W) and the the (γ,n) reaction cross sections ($\sigma_{\gamma,n}$) of LRW ^{90}Sr ($T_{1/2}$ = 30 yr), ^{107}Pd ($T_{1/2} = 6.5\times10^6$ yr) and ^{135}Cs ($T_{1/2} = 2.3\times10^6$ yr) are shown in Fig. 4, the energy spectrum of bremsstrahlung γ-ray driven by $10^{20}\ W/cm^2$ laser pulse (repetition frequency $f = 1$ Hz) is also plotted for comparison. $\sigma_{\gamma,n}$ is assumed as a Lorentzian-like shape[13, 22], the corresponding parameters are taken from Ref[22]. One can find in Fig. 4, that the SLEGS γ-ray is more suitable to trigger (γ,n) reaction of these three LRWs than the bremsstrahlung γ-ray, since the bremsstrahlung spectrum drops exponentially near the $\sigma_{\gamma,n}$ peaks, while the SLEGS spectrum remains rather flat.

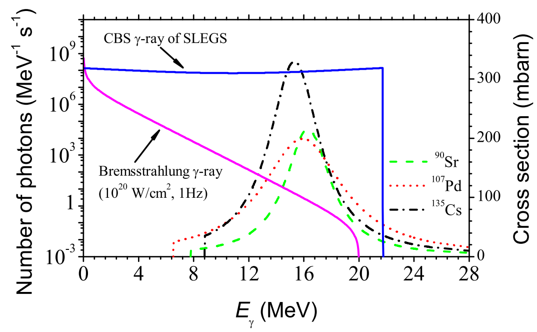

Fig. 4. The energy spectrum of SLEGS γ-ray and $\sigma_{\gamma,n}$ of ^{90}Sr (dash line), ^{107}Pd (dot line) and ^{135}Cs (dash-dot line). The energy spectrum of bremsstrahlung γ-ray driven by intensive laser pulse is also plotted.

Table 1 lists the estimated transmutation rates of SLEGS based CBS method (N_{CBS}) and bremsstrahlung method ($N_{brem.}$) for the above LRWs. The thickness of each pure LRW target is assumed to be 1 cm. One can find in Table 1 that N_{CBS} is about 10^4—10^5 times larger than $N_{brem.}$.

Table 1. Comparison between N_{CBS} and $N_{brem.}$, parameters of bremsstrahlung γ-ray are taken from Ref. [19]. n denotes the density of each LRW target.

	^{90}Sr	^{107}Pd	^{135}Cs
n [cm^{-3}]	1.76×10^{22}	6.8×10^{22}	8.36×10^{21}
N_{CBS} [s^{-1}]	1.6×10^6	9.4×10^6	1.3×10^6
$N_{brem.}$ [s^{-1}]	20	5.6×10^2	13[19]

4 Summary

In summary, properties of CBS γ-ray beam of the future SLEGS have been estimated. SLEGS is expected to be a powerful facility to provide intensive γ-ray beam up to the maximum energy of 22 MeV. The flux of non-collimated γ-rays is estimated to be 10^9—10^{10} s^{-1} when a CO_2 laser of several hundred Watt power is employed.

Indirect measurement of cross section of key nuclear-astrophysics reaction $^{12}C(\alpha,\gamma)^{16}O$ and γ-ray-triggered transmutation of long-lived radioactive wastes are discussed based on the estimated SLEGS γ-ray beam properties. The future SLEGS facility is expected to significantly improve the experimental study of $^{12}C(\alpha,\gamma)^{16}O$ reaction. The transmutation rate of CBS method based on SLEGS γ-ray beam is much higher than that of the bremsstrahlung method.

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