LASER COMPTON SCATTERING GAMMA RAY INDUCED PHOTO-TRANSMUTATION

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Abstract

High brightness beams of gamma rays produced in the means of laser Compton scattering have the potential to induce photo-transmutation through (γ , n) reaction, which implies an efficient method to dispose long-lived fission products. Preliminary investigations have been carried out in understanding the feasibility of developing transmutation facility to repose nuclear waste. A laser Compton scattering setup has been built on NewSUBARU storage ring and worked steadily to generate gamma-ray beams for studying the relevant nuclear physics. This paper aims at exploring the dependency of nuclear transmutation efficiency on target dimensions and gamma ray features with employing ^{197}Au target. The experimental results are in agreement with the theoretical estimations.

INTRODUCTION

To repose long-lived fission products effectively is an attractive issue in management and disposal of nuclear waste. Recently a number of methods have been presented and discussed [1,2], involving transmutation by bombardment with neutrons from a reactor or a particle accelerator, and laser-driven gamma generation for photo-transmutation [3]. However, nuclear transmutation through photonuclear reaction induced by high brightness gamma ray generated from a storage ring based laser Compton scattering facility is considered by us as a promising alternative [4][5]. In accordance to the conceptual scheme, we carried out relevant researches both on laser Compton scattering to produce high brightness gamma ray and photonuclear reaction through nuclear giant resonance. We have reported the laser Compton scattering setup built on NewSUBARU storage ring elsewhere [6][7].

In this paper, we concentrate on exploring the nuclear transmutation efficiency and its dependency on target geometrical dimensions and properties of laser Compton scattering gamma rays, which is a key point for realization of nuclear transmutation facility.

LASER COMPTON SCATTERING GAMMA RAY

Our laser Compton scattering setup was built on one of the straight section of NewSUBARU storage ring, which provides 1GeV electron beam with average current up to 200 mA. A laser light of 1.064 μ m wavelength from Nd:YAG laser was guided into the vacuum chamber to collide with the electron beam in a head-to-head manner, and scattered gamma ray photons with maximum energy of 17.6 MeV. The gamma ray goes along the incident electron moving direction in a forward cone of angle $1/\gamma$, where γ is the relativistic factor of electron, namely, 0.5 mrad in our experiment for the 1 GeV electron beam. The interaction point was designed at the center of the straight section, where both the electron beam and laser transverse profiles were focused to the minimum.

The gamma ray generated from our laser Compton scattering setup is polarized, and its polarization is changeable with inserting a wave plate in the laser light path [4].

ESTIMATION OF TRANSMUTATION EFFICIENCY

When a beam of gamma rays strikes on a target, the photonuclear reaction rate (1/sec/m^3) is given by

$$R = N_0 \sigma_g(E) I(E,z) \tag{1}$$

where N_0 is the number of atom per volume, $\sigma_g(E)$ is the nuclear giant resonance cross section, and $I(E, z)$ is the gamma ray intensity, which is a function of photon's energy E and penetrating depth z in a target.

According to the fact that laser Compton scattering gamma ray features a circular transverse profile, we considered a cylindrical target with radius of a and length of b, and the integration of volume gives the total reaction rate

$$\widetilde{R} = \int R dV = N_0 \int \sigma_g(E) I(E,z) dV \tag{2}$$

The gamma ray intensity could be expressed as

$$I(E,z) = \xi \sigma_L(E) e^{-\mu z} \tag{3}$$

where ξ relates to the properties of electron beam and laser light for collision, $\sigma_L(E)$ is the laser Compton scattering cross section, and μ is the total linear attenuation coefficient given by

$$\mu = \mu_{PE}(E) + \mu_C(E) + \mu_{PP}(E) + \mu_{PN}(E) \tag{4}$$

where $\mu_{PE} = \sigma_{PE}(E) N_0$, $\mu_C = \sigma_C(E) Z N_0$, $\mu_{PP} = \sigma_{PP}(E) N_0$, $\mu_{PN} = \sigma_{PN}(E) N_0$, Z is the atomic number, $\sigma_{PE}(E)$, $\sigma_C(E)$, $\sigma_{PP}(E)$ and $\sigma_{PN}(E)$ represent cross sections of photoelectron, Compton, pair production and photonuclear reactions, respectively. Consequently, Eq. (2) could be rewritten as

$$\widetilde{R} = N_0 \xi \int_0^b \int_0^a \sigma_L(E) \sigma_g(E) e^{-\mu z} \cdot 2\pi\rho d\rho dz \tag{5}$$

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And we also have the following expressions to determine the energy of laser Compton scattering gamma photons [8]

$$E = \frac{E_m}{1+(\frac{\theta}{\theta_0})^2} \qquad \theta = \arctan(\frac{\rho}{L}) \tag{6}$$

$$E_m = \frac{x}{1+x}E_b \;\; \theta_0 = \frac{mc^2}{E_b}\sqrt{x+1} \;\; x = \frac{4E_b\upsilon_0}{m^2c^4}$$

where E_m is the maximum gamma ray energy, L is the distance from the interaction point to the front surface of target, E_b is the electron's energy, and υ_0 is the laser photon's energy.

The total injected gamma photons should be written as

$$F = \int I(E,0)ds = \xi\int_0^a \sigma_L(E)\cdot 2\pi r dr \tag{7}$$

Then, we achieved the expression for the transmutation efficiency defined as the quantity of transmuted nuclei by per photon,

$$\eta = \frac{\tilde{R}}{F} = \frac{N_0\int_0^b\int_0^a \sigma_L(E)\sigma_g(E)e^{-\mu z}\cdot 2\pi r dr\, dz}{\int \sigma_L(E)\cdot 2\pi r dr} \tag{8}$$

From Eq.(8) we understand that the efficiency depends on not only the parameters of the target itself, such as target species, radius and length, but also the characteristics of laser Compton scattering setup including the electron beam energy, the laser photon's energy and even the distance from interaction point to the target.

Calculations and pictorial illustrations of transmutation efficiency are made for a gold (^{197}Au) target, positioned on axis 15.35 m away from the interaction point. $\sigma_L(E)$ can be derived from klein-nishina formula [8], $\sigma_{PE}(E)$, $\sigma_C(E)$, $\sigma_{PP}(E)$ and $\sigma_{PN}(E)$ are same as in reference [5].The dependency of efficiency on target length is shown in Fig. 1, depicting

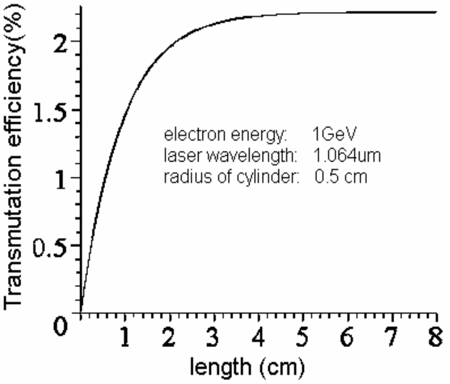

Fig. 1 Transmutation efficiency vs. the length of target

that the efficiency approaches constant when the length is longer than 5 cm. That is because all injecting gamma photons are absorbed after they travel such long a distance in target. The optimum radius of cylinder is about 0.5 cm as shown in Fig. 2, resulting in a maximum efficiency of 2.2%. And the efficiency falls

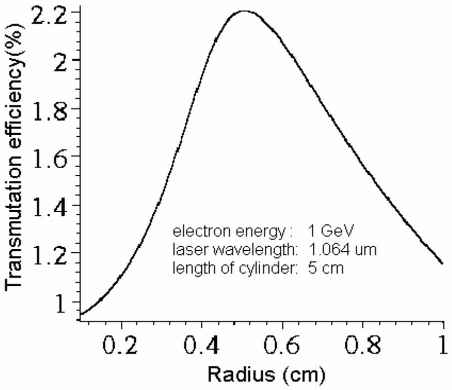

Fig. 2 Transmutation efficiency vs. radius of target

down when the radius continues growing, because a lot of low energy gamma photons are involved, which contributes little to the photonuclear reaction. Furthermore, the efficiency is sensitive to the electron beam energy as shown in Fig. 3, and the optimal energy is 950 MeV to make a peak of ~2.5%.

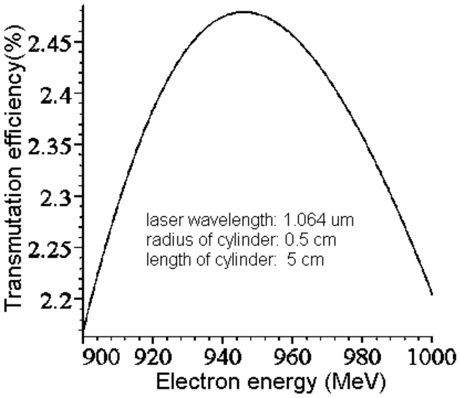

Fig. 3 Transmutation efficiency vs. electron beam energy

EXPERIMENT

Transmutation Efficiency

We use ^{197}Au samples for the nuclear transmutation experiment. The target was placed on axis receiving gamma ray irradiation, 15.35 m away from the interaction point, in front of a Germanium detector. In experiment, the Germanium detector was used to estimate the absorption ratio of gamma ray by the target. An example of measured energy spectra is shown in Fig. 4, where the

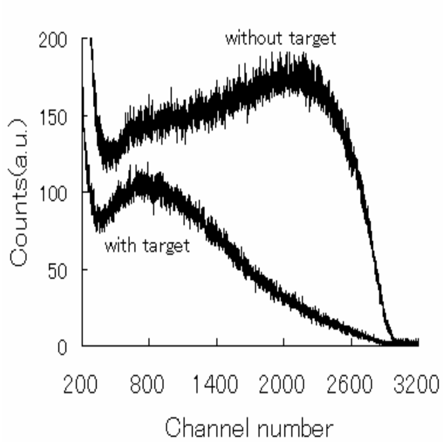

Fig. 4 Laser Compton scattering gamma ray energy spectrum with and without target, respectively.

difference between those two signals depicts the absorbed portion of gamma photons. Thus, one can deduce the total absorbed gamma photons in the duration of irradiation.

The ^{197}Au nucleus releases a neutron to undergo transmutation to ^{196}Au when absorption of gamma photons leads to (γ, n) reaction. ^{196}Au is unstable, and eventually transmuted to ^{196}Pb and ^{196}Hg in the way of radioactive decay. The transmutation from ^{196}Au to ^{196}Pb predominates and emits gamma ray of energy 355.73 KeV, which was able to be measured by a NaI(TI) detector. Through the measurement of radioactivity of irradiated target, the number of transmuted nucleus at the moment of end of irradiation can be deduced according to decay law

$$N_0 = \frac{\Delta N e^{\lambda t}}{1 - e^{-\lambda \Delta t}},$$

where N_0 is the number of undecayed nuclei, ΔN is the number of decays in the duration of Δt, λ is the decay constant, and t is the time interval from the end of irradiation to the beginning of activity measurement.

Two samples of cylinder gold target were employed in our experiment, with 5 cm long and radius of 0.25 cm and 0.5 cm, respectively. Both of them were irradiated with duration of 8 hours, and were processed with activity measurement separately. An example of emission spectrum was given in Fig. 5, showing the gamma ray rising from the decay process. The loss of the radioactivity inside the target was estimated by using EGS4 code [9]. And after data processing, we achieved the transmutation efficiency shown in Fig. 6, together with the calculation curve. The experimental results illustrate a little higher than the calculation, which might be the reason of secondary transmutation induced by electron-gamma showers occurring inside target. The errors come from the loss evaluation and statistical process, and with the promotion of our detecting system more precise measurement will be reached in the future.

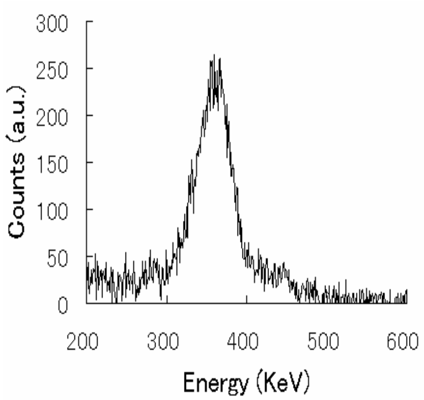

Fig. 5 Gamma ray energy spectrum of radioactivity of irradiated target

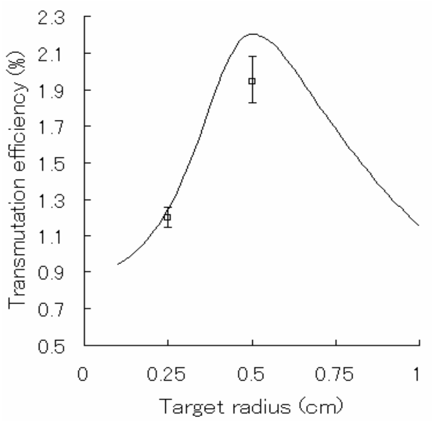

Fig. 6 Comparison of transmutation efficiency for experimental data and calculation curve

Secondary Gamma Ray

The interaction of high energy photons with matters raises secondary gamma rays, which is from the Compton scattering, bremsstrahlung and else effects. We performed experiments on measuring the secondary gamma rays.

A Germanium detector, with crystal measuring 64.3 mm in diameter and 60 mm in length, exhibiting 45% efficiency, was positioned 4 cm away the target, vertical to the beam line. The measurement was conducted for two targets, with radius of 0.5 cm and 0.25 cm, respectively. Their energy spectra (removed background) are shown in Fig. 7. It is known that the secondary gamma ray yield is small, especially the high energy photons. Generally speaking, the photonuclear reaction is induced by the photons with energy spanning from 8 MeV to 30 MeV, therefore, the secondary gamma ray will not contribute to the photo-transmutation.

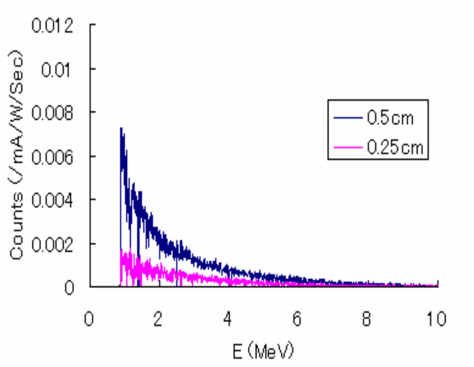

Fig. 7 Secondary gamma ray energy spectrum for target with radius of 0.5 cm and 0.25 cm, respectively.

CONCLUSION

Transmutation efficiency concerned with characteristics of target and gamma ray was studied experimentally with a storage ring based laser Compton scattering system, in order to investigate the feasibility of developing an efficient nuclear transmutation scheme to dispose the long-lived radioactive waste. We carefully analyzed the reaction rate of gamma ray with the nuclear giant resonance, and gave out the relation of transmutation efficiency with target dimensions and gamma ray properties. ^{197}Au rod target was used in irradiation experiments for demonstration, and the experimental results are close to the analytical estimations.

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