Experiment on Iodine transmutation by laser Compton scattering gamma ray

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Abstract. A laser Compton scattering gamma-ray based nuclear transmutation is proposed to reduce the hazards of long-lived activity nuclear waste. In accordance with this proposal, a laser Compton scattering gamma-ray facility has been built on NewSUBARU storage ring. The facility provides 17.6 MeV gamma-ray photons, which is applicable to the nuclear transmutation research. In order to investigate the reaction rate of Iodine material, the \( ^{23}\text{Na}\)\textsuperscript{127}I target is adopted for the irradiation experiment. The results show that the experimental data is close to the simulation result.

1. Introduction
Some nuclear wastes have a long-lived activity, even longer than the life of the barrier to contain them for geological disposal; consequently, such nuclear wastes dissolve readily in ground water and move easily throughout the ecosystem posing radiological hazards. So, it is necessary to effectively eliminate the radioactivity of those nuclear wastes or convert them to less hazardous forms. Transmutation is considered as an approach by reducing the radioactive life of the nuclear waste through converting the nuclei of long-lived activity to its corresponding isotope of short-lived activity. High-energy photons, like gamma-ray, can induce nuclear reaction, which is regarded as an alternative to make transmutation. This method was originally proposed to use the bremsstrahlung gamma-ray inducing the photonuclear reaction (\( \gamma\),n), however, the poor coupling between the photon beam and the giant resonance is inevitable, since the bremsstrahlung photon spectrum is very wide.

In order to improve the coupling, a gamma-ray with an appropriate energy spectrum matching the characteristic of nuclear giant resonance is required. Fortunately, laser Compton scattering (LCS) gamma-ray looks a good choice \cite{1,2}. The LCS gamma-ray is generated from the collision of a laser light to a high-energy electron beam, and it holds a peak in the energy spectrum, which can overlap the peak of nuclear giant resonance and hence realize a good coupling. So, the LCS gamma-ray seems promising in nuclear transmutation.

The reaction rate of transmutation plays an important role in this proposal. In this paper, we experimentally investigate the reaction rate of Iodine.

2. Laser Compton scattering gamma-ray
We have developed laser Compton scattering setup on NewSUBARU storage ring. NewSUBARU is a racetrack shape electron storage ring synchrotron radiation facility \cite{3}. The circumference of the ring
is about 118 m, and that have two 12 m long straight sections. Electron beam is injected from 1 GeV linac. One of the straight sections of the ring was chosen to build interaction vacuum chamber, where the electron beam collides with the incoming laser light in a head-to-head manner. Thus, high energy photons are produced, going along the incident electron moving direction in a forward cone of angle $1/\gamma$, where $\gamma$ is the relativistic factor of electron, namely, 0.5 mrad for 1 GeV electron beam. The laser light with wavelength of 1064 nm comes from a Nd:YVO laser, consequently, the produced high-energy photons are gamma-ray photons, and the maximum gamma-ray energy is 17.6 MeV.

2.1. Newsubaru LCS facility

The interaction point was designed at the centre of the straight section, where both the electron beam and the laser light transverse profiles were focused to the minimum. A reflected mirror is located at the downstream end to guide the laser light travelling along the beam line through the interaction point, and the light is reflected out of the chamber by another upstream mirror [4,5]. The produced gamma-ray photons would go through the downstream mirror and reach the detector or irradiate the target. A schematic setup graph is as shown in Fig.1.

The laser is installed at the outside of the shielding wall and is injected into the vacuum duct using six mirrors deliberately arranged and a convex lens with focal length of 5 m in a well-designed position, 7.5 m away from the laser and 15 m away from the center point of the straight section. This results in a focused spot of light with radius of 0.82 mm. The electron beam size is determined by the $\beta$ function and emittance. For the NewSUBARU storage ring, at the center point of the straight section, these parameters are characterized as $\beta_x = 2.3 \text{ m}$, $\beta_y = 9.3 \text{ m}$, $\epsilon_x = 40 \text{ nm}$, and $\epsilon_y = 4 \text{ nm}$, resulting in the electron beam size of 0.30 mm for the horizontal direction and 0.19 mm for the vertical direction. Consequently, the size of electron beam is smaller than that of the laser beam at the interaction point.

2.2. Gamma-ray properties

The gamma-ray detector is located about 18 m from the electron-photon collision point. A high-purity Germanium coaxial detector is used with the detection efficiency of 45%. The measurements of gamma-ray photons are carried out at a lower current of several mA, to avoid saturations at the detector. An example of measured spectrum is shown in Fig. 2, with a lead collimator of 24 mm in diameter in front of the detector. The clear difference between the two signals of laser Compton scattering gamma-ray and the background shows a good signal-to-noise ratio. The background signal is due to the bremsstrahlung by the residual gases in the vacuum duct of the straight section. The maximum energy appears around 17 MeV, which is in agreement with the theoretical prediction. We simulated the process of generated gamma-ray transport from the source to the detector including photons passing through the reflected mirror, output window, collimator, and being detected by the detector, by employing the EGS4 code. After processing the
experimental data with 10 mm in diameter collimator, we achieved the actual gamma-ray generation rate of $5 \times 10^3$ photons/mA/W/s.

3. Nuclear transmutation

In accordance with the proposed scheme, experiments are developed to investigate the fundamental issues concerning nuclear transmutation on the NewSUBARU LCS gamma-ray facility.

The final goal of this research is to understand the feasibility of transmuting the long-lived fission products in nuclear wastes such as $^{129}\text{I}$ and $^{135}\text{Cs}$, through $(\gamma,n)$ reaction. As is known, $^{129}\text{I}$ is transmuted into $^{128}\text{I}$ by $^{129}\text{I} (\gamma,n) ^{128}\text{I}$ reaction, and the generated $^{128}\text{I}$ is unstable and is transmuted into stable nuclei $^{128}\text{Xe}$ with a short half-life of about 25 min by $\beta^-$ and $\epsilon$ decays. In such a way, $^{129}\text{I}$ can quickly lose its radioactive poison.

As the first step, we aim at exploring the reaction rate of gamma-ray to the nuclear giant resonance, which is defined as the number of transmutation nuclei by per gamma-ray photon.

3.1. Experimental target

Actually, it is hard to use the target of $^{129}\text{I}$ directly because of its hazard. Instead, we consider $^{127}\text{I}$ for the transmutation experiment since its photonuclear cross section is very near to that of $^{129}\text{I}$. Usually, the pure $^{127}\text{I}$ is unavailable, and its compound, sodium iodide $^{23}\text{Na}^{127}\text{I}$, is available to make a practical target. The transmutation processes for $^{23}\text{Na}$ and $^{127}\text{I}$ are given in Fig. 3. With absorbing a gamma photon, the $^{127}\text{I}$ nucleus possibly releases a neutron to undergo $(\gamma,n)$ reaction, and is transmuted to $^{126}\text{I}$. Furthermore, $^{126}\text{I}$ is unstable, and eventually is transmuted to $^{126}\text{Xe}$ and $^{126}\text{Te}$ in the way of radioactive decay $\beta^-$ and $\epsilon$, respectively. The $\beta^-$ in this process radiates 388.63 KeV photons with a half-life of 13.02 day, while $\epsilon$ decay radiates 666.33 KeV photons with a half-life of 13.11 day. The unstable $^{22}\text{Na}$ transmuted from $^{23}\text{Na}$ also radiates photons with energy of 1274.53 KeV through $\beta^-$ decay, and its half-life is 2.6 year. In measurement, the radiations from $^{126}\text{I}$ and $^{126}\text{Na}$ can be separated by the difference of photon energy and half-life.

3.2. Reaction rate simulation

The estimation of reaction rate is a complicated problem, since it is related to the gamma-ray energy, the geometry of target and the distance between the target and the origin point of gamma-ray generation. A Monte Carlo code, MCNP5, is used to simulate the whole process. MCNP5 is a general-purpose Monte Carlo N-particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. The code treats an arbitrary three-dimensional configuration of materials in geometric cells.

Based on the setup of NewSUBARU LCS gamma-ray, the simulation model is described as following. A cylindrical target is located at the center of the gamma-ray beam and 18.49 m away from the interaction point of the electron beam and laser light. The target is taken 5 cm in length, so that most of the gamma-ray photons are absorbed in the target. According to the definition mentioned above, the reaction rate depends on the target radius. The simulation result is given in Fig. 4. The
maximum reaction rate 1.32% appears at 0.5 cm radius. Also plotted in Fig. 4 is the result for pure $^{127}$I target, which shows higher reaction rate than $^{23}$Na$^{127}$I target.

3.3. Irradiation experiment

The gamma-ray is introduced to the hatch from the tunnel to irradiate the target. An image plate is placed before the target. The image plate can record the transited photons, therefore, the total photons enter the target can be deduced.

Through the measurement of radioactivity of irradiated target, the number of transmuted nucleus at the terminus of irradiation can be deduced according to the decay law.

The cylindrical $^{23}$Na$^{127}$I target, 5 cm long and 0.5 cm in radius, was irradiated for 8 hours. The loss of the radioactivity inside the target was estimated by the MCNP5 code, and after data processing, the reaction rate is achieved as shown in Fig. 5. The simulation curve is also plotted in Fig. 5 for comparison. The experimental results illustrate a good agreement with the simulation, and the errors come from the loss evaluation and statistical process. With the promotion of our detecting system, more precise measurement will be reached in the future.

4. Conclusion

A scheme of LCS gamma-ray induced transmutation is introduced. The reaction rate of transmutation of Iodine is studied through simulation and experiments. The LCS gamma-ray facility has been built on NewSUBARU storage ring to perform these experiments. The advantage of the LCS gamma-ray in coupling with the nuclear giant resonance is implied.

References

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