GAMMA RAY BEAM TRANSMUTATION

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Abstract

We have proposed an approach to use a gamma ray for nuclear transmutation by Compton scattering of laser photons with high current accelerator. We had demonstrated laser Compton scatter to obtained 20MeV gamma ray to address transmutation rates with the giant resonance of Au and ^{129}Iodine.. Experiments for measurements of neutron spectrum and pair production positron and electron were performed for energy balance of this scheme and for target conditions. The results showed reaction rate was about 2~4% for appropriate photon energies and neutron energy was up to 4MeV in the calculation.

1. Introduction

To convert our energy resources to carbon dioxide free materials in near future is strongly required to avoid the global warming. Among them, the fission energy is favorable, but the issue of a nuclear waste will be taken place. One will repose nuclear waste geologically. For most of the waste are expected to repose in enough time of their active life except ^{129}Iodine. Iodine has a very long life of more than 16millon years and has a high chemical activity. Beside these, iodine is hard to include in the normal reposing container due to their low temperature boiling point. So iodine is recognized as discrete waist for transmutation.

There have been several proposals to the transmutation. The transmutation by a giant nuclear resonance had been directed using the bremsstrahlung gamma ray generated by electron beam. The conversion efficiency from the electron beam to gamma ray is low and the spectrum is wide, which made a poor coupling of energy to the giant resonance for the transmutation. Gamma ray from Compton scattering, which we have proposed for nuclear transmutation have several advantages as better coupling tuning, narrow spread of beam spectrum with sharp shooting. [1,2]

In section 2, principals of this scheme are presented. Generation of gamma ray has been carried out on New Subaru, electron storage ring of the energy up to 1.5GeV. Nuclear transmutation experiments have been performed with generating 17MeV laser Compton gamma-ray. These are noted in section 3. Future prospects are noted in section 4 and summary is addressed in section 5.

2. Principals of the scheme

2.1. Laser Compton scattering

The principals of the scheme are shown in Fig. 1. High energy and high brightness electron beam with sufficient high average current is supplied by electron accelerators of storage ring or energy recover linac. The Compton scattering is induced by intense laser and generates high brightness gamma ray. The gamma ray energy is tuned by the energy of the electron beam and the laser wavelength and is coincided with the peak of E1 giant resonance. Neutrons are generated in this process, which are used for energy generation in the surrounding blanket to get an energy balance.

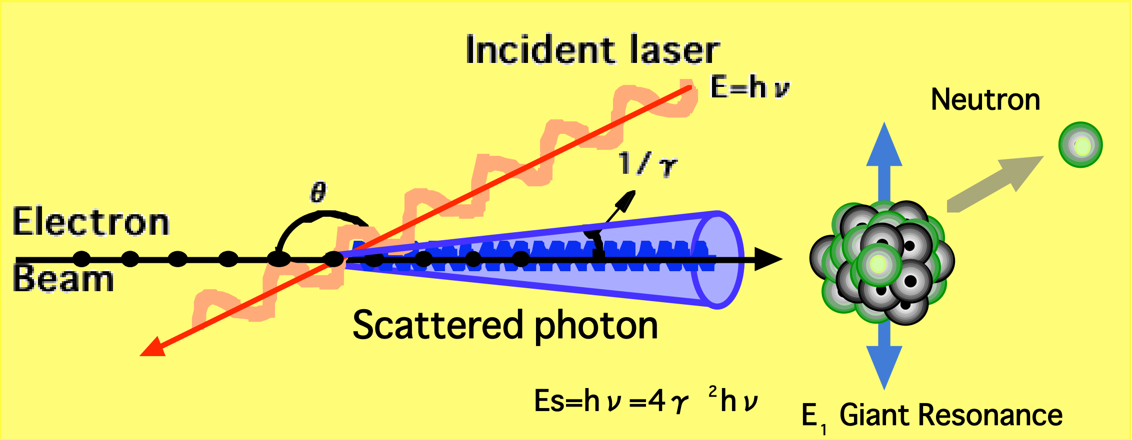

Fig. 1. Schematic picture of Compton scattering. The gamma photon induces a resonance of target ant change the nucleus with neutron emission.

The gamma ray energy of the Compton scattered photon becomes $4\gamma^2$ times of incident photon energy $h\nu$ with the solid angle of $1/\gamma$, where γ is the Lorenz factor. The interaction angle θ is to be taken near 2π to get a maximum interaction. The direction of the scattered photon is given by the electron beam direction as well known.

The target of the transmutation for ^{129}I will be with a small diameter of 1cm. The beam divergence angle is small enough in this case. So typical target size is several cm in a distance of more than 10m from beam-laser interaction point and target thickness of several cm. For the ^{129}I target, they come to change into Xe gas after the gamma ray transmutation so the separation is not required essentially.

2.2. Gamma ray generation efficiency of total system

The efficiency of gamma ray generation is roughly estimated as shown in Fig.2 as

$$\eta_g = P_g[P_o + P_b\tau_L/\tau_L + (P_{sr} + P_g)/\eta_a + P_L/(\eta_L M)]^{-1} ,$$

P_g is a gamma-ray power, P_o is a power to operate the accelerator including utility of cooling and so on, P_b is a power for beam injection time τ_i of beam life time τ_L when storage ring is used for electron source, P_{sr} is a power of total radiation energy loss of the accelerator, and η_a and η_L are efficiencies of the accelerator and laser, respectively. M is a number of multiplication factor of laser photon storage rate of 5000. This equation is reduced to $\eta_g = P_g / \{(P_g/\eta_a) + (P_L/M\eta_L)\}$. Finally, we get $\eta_g = \eta_a$ roughly. The efficiency of electron accelerator can be taken as 80% with the energy recovery system of linac or storage ring.

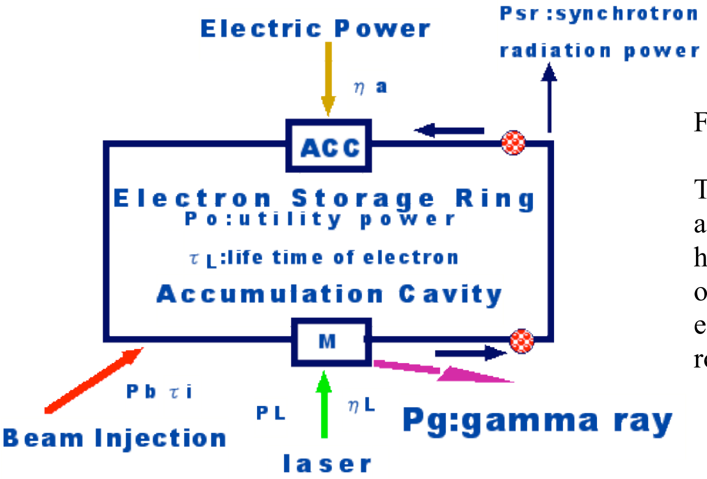

Fig. 2 A typical energy flow of this scheme. The efficiency of gamma-ray generation is roughly reduced to accelerator efficiency. This picture shows a case of electron storage ring.

2.3. Transmutation target

The reaction rate R_{rea} of gamma ray for the transmutation is written as

$$R_{rea} = \left\langle \sigma_{gr}(E_p) \right\rangle \Big/ \left\langle \sigma_{pa}(E_p) + \sigma_{gr}(E_p) + \sigma_{co}(E_p) + \sigma_{pe}(E_p) \right\rangle ,$$

$\sigma_{pa}(E_p)$ indicates cross section of pair creation for gamma photon energy of E_p, $\sigma_{gr}(E_p)$ indicates that of giant resonance, $\sigma_{co}(E_p)$ indicates that of Compton scattering of electrons in the target and $\sigma_{pe}(E_p)$ indicates that of photoelectron.[3.4]

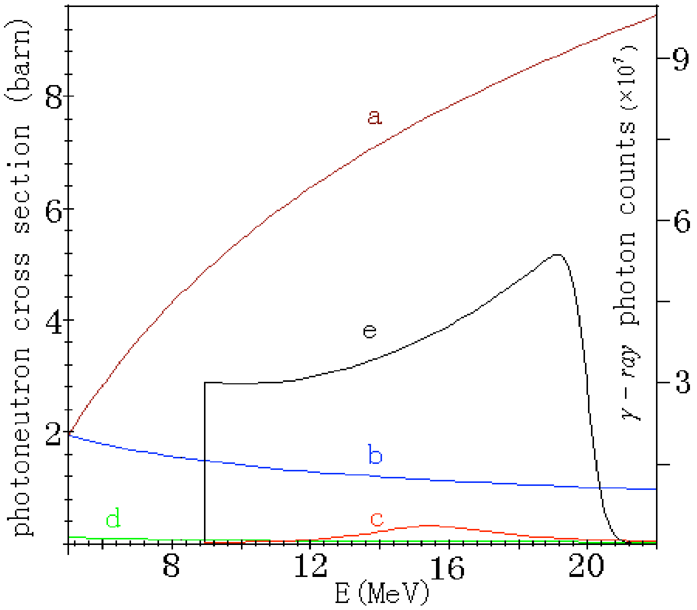

Fig.3. Coupling of γ ray to nuclear giant resonance of ^{129}I. Crosssections of gamma ray photon for the typical target interactions is indicated. Curve a shows pair creation, and b corresponds to Compton scatter by target atom electron and c corresponds to giant resonance and d corresponds to photo-electron effect. Curve e denotes γ ray photon by Compton scattering.

The cross sections of each process have been already investigated, precisely. A typical cross-section of each process is shown in Fig. 3 for ^{129}I target comparing with gamma r ay energy spectrum.

3. Transmutation Experiments on New Subaru

3.1 Reaction rate study by Au target

Experiments for transmutation were performed on New Subaru storage ring. Au targets were used. In this target, component is one isotope of Au 187 so we can get précis rate of reaction. The results are shown in Fig. 4. [4

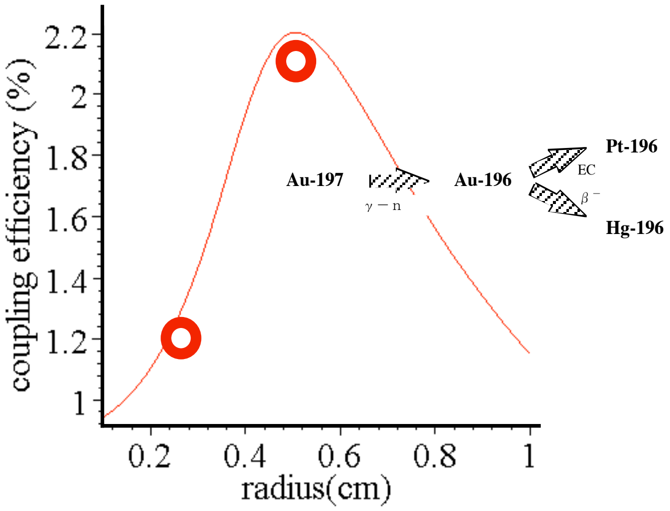

Fig. 4 Experiment results of Au targets for reaction rate (round mark), ^{197}Au was transmuted into ^{196}Au and changed into Pt or Hg as shown in figure. We measured the decay curves from which we got a number of ^{196}Au. We also measured a gamma-photon number at the same time. The reaction rates were estimated by theoretically and compare with the experiments, which were corresponded well each other.

Gold rods of 5cm in length with a radius of 0.25 cm and 0.5cm were used and target was irradiated in 8 hours on-axis of gamma ray. The target was set at 15 m away from the interaction point. The transmutation process of this target is shown in Fig. 4, and the decay occurs from Au-196 to Pt-196, giving rise to radioactivity in the form of gamma-ray photons with a peak energy of 355.73 keV in the energy spectrum. This radioactivity was measured by a NaI (TI)) detector, and the activity decay was indicated a good agreement with the half-life of 6.183 D. Through data processing, we concluded that the number of transmuted nuclei was 3.165×10^6.

The experiment results were close to the theoretical analysis as shown a slid line in Fig. 4 .

3.2. Iodine target experiment

Experiments on Iodine[5)] are performed on New Subaru Beam Line 1 using natural ^{23}Na^{127}I target. Their reactions are shown in Fig5. Na has a very small cross section

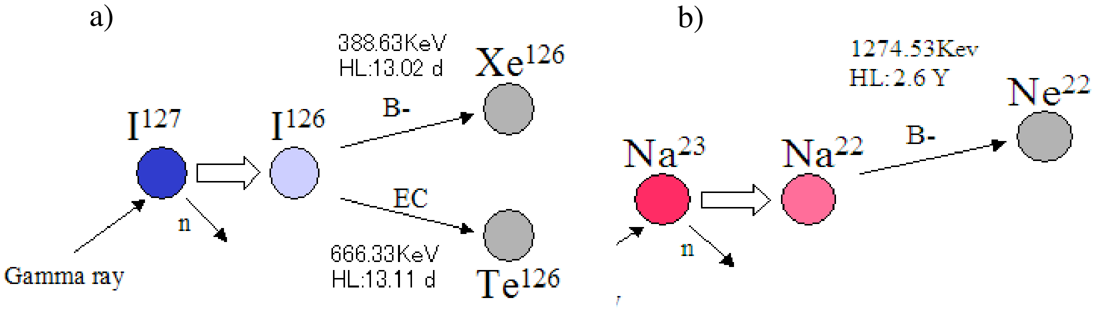

Fig.5. ^{23}Na^{127}I target reactions for iodine a) and sodium b).

of giant resonance and long decay time. So we can neglect the Na in this target. The reaction rate of ^{23}Na giant resonance is 1/50 at 17MeV gamma ray and decay time is 73 of ^{127}I target. In the same way, we can estimate the reaction rate as Au.

Figure 6 shows reaction rate for each component of ^{23}Na^{127}I target. The energy of gamma ray was 17MeV in the experiments. Using this reaction rate, we estimated the transmutation iodine number, which is calculated by the reaction rate.

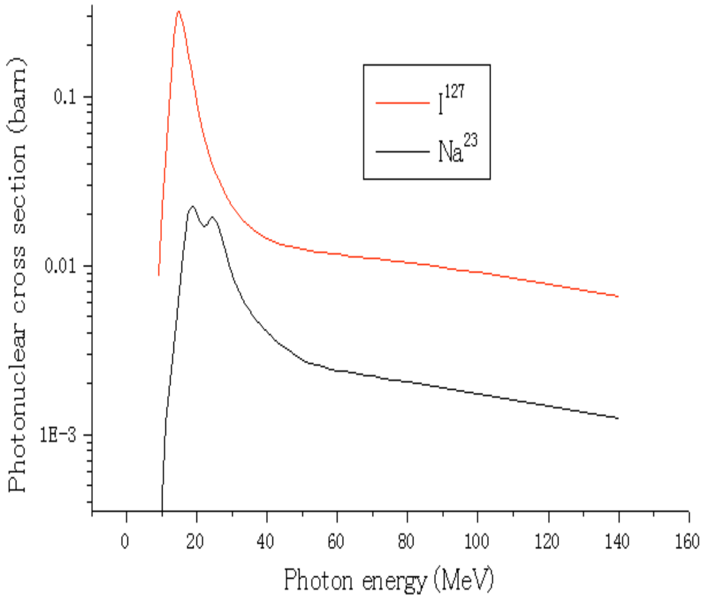

Fig.6.. ^{23}Na^{127}I target reactions rate for each species

To performe the iodine transmutation, their emitting radiation and their decay rate were measured as shown in Fig.7. From results, we can identify the iodine transmutation and their rate, which is correspondent to the predicted one.

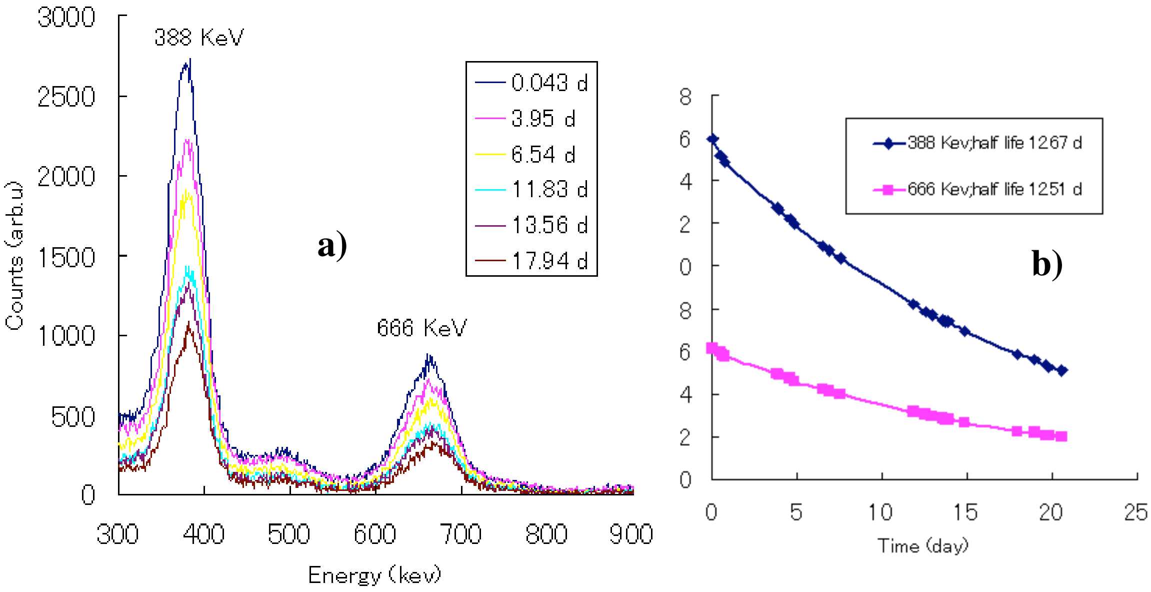

Fig.7. Radiation energy spectrums a) and their decay b) from transmuted ^{127}iodine.

4.Future prospects

4.1 Energy recover from bi-product neutron and heat

The neutrons are produced as bi-product of transmutation reaction of E1 giant resonance, which can cause the energy production. Neutron energy was calculated and measured for this purpose. The second or third target is a kind of fission target. The reaction in the target multiplies the neutron number and/or to makes energy to balance the total system. The second and target are kind of fissionable blanket. Reactions are induced 3 or 4 times by MeV neutrons and make heat which cause the total energy balance of the system. Figure 8 shows an simple schematic drawing for this system.

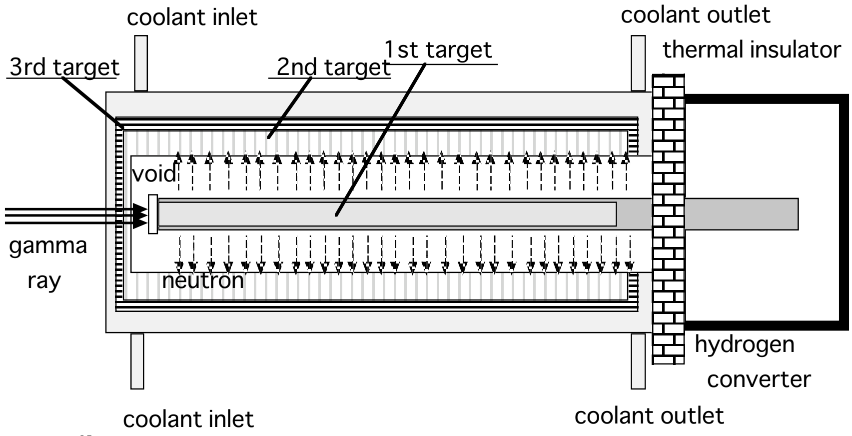

Fig.8. System for energy balance of the transmutation gamma ray in this scheme.

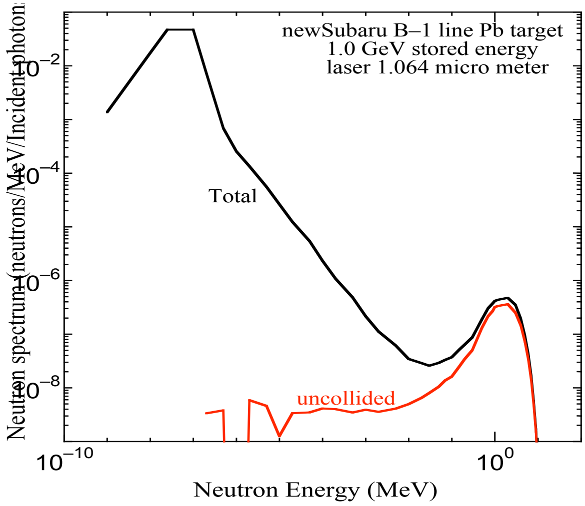

Fig.9.. Calculated neutron energy spectrum. The main energy of neutrons is 1 to 3MeV.

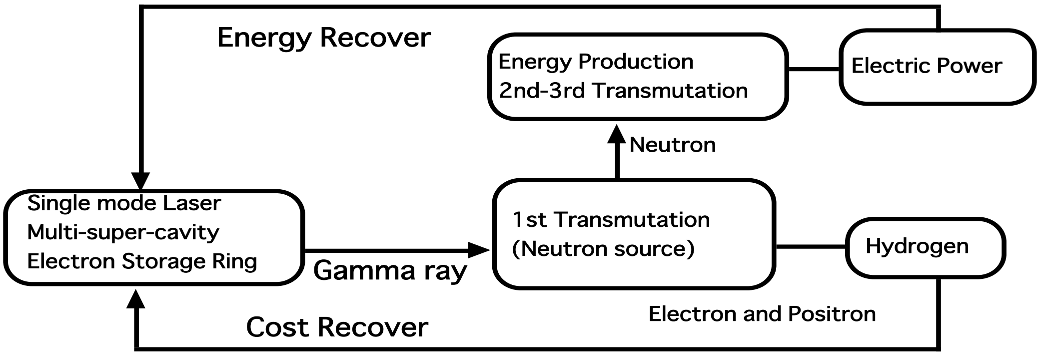

Fig.10. Scheme diagram of the system for transmutation.

The target is heated by the electron and the positron, which are generated by the pair creation. This heat energy density is high enough to make hydrogen efficiently. This becomes to be out put of the system and may become a recover for initial cost beside the energy balance.

4.2. Laser storage cavity.

Laser photon storage cavity is a Fabry-Perot interferometer with a high quality mirror pair. The mirrors are required to have not only a high reflectivity (R=99.9～99.999%) but also a low loss (1～10 ppm). To evaluating the characteristics of the optical cavity、reflectivity R, transference T and loss A are important parameters and they related each other as $R+T+A=1$. The cavity transmittance and reflectivity can be easily written as follows, respectively.

$$\eta_T = \left(\frac{T}{A+T}\right)^2 \text{ and , } \quad \eta_R = \left(\frac{A}{A+T}\right)^2 .$$

Then, we can estimate the storage rate in the cavity as η_T/T shown in Fig.11. We can expect the photon storage rate up to 10^5 using high quality mirror.

Experiments for photon storage and interaction with electron beam were performed. Field generated inside the cavity can be given by the ratio of transmitted power divided by the transmittance. We obtained a storage rate around 10000 on a cavity shown in Fig.11 with stability longer than 10 hours. We measured the decay time of the accumulation photon in the cavity after we rapidly cut off the laser for storing. We also measured the scattered photon number of Compton scattering to evaluate the laser intensity in the cavity. In both experiment, storage rates agreed very well each other, which are plotted as marks in Fig.11. This high photon storage reduce a requirement for laser in this transmutation.

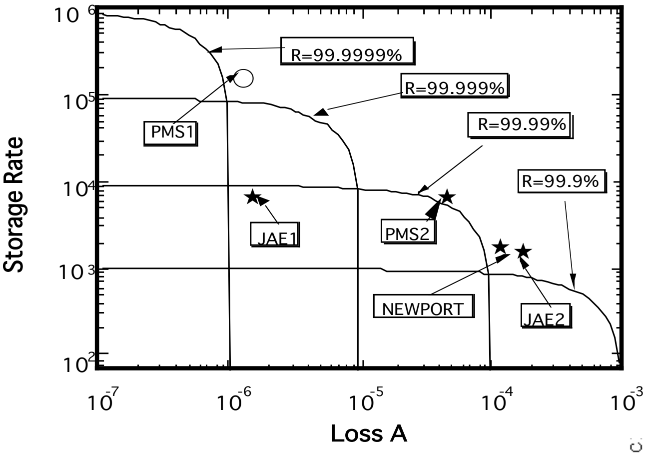

Fig.11. Theoretical curves and experimental results of photon storage rate of mirror pair with energy loss A. PMS, JAE and so on are the names of mirror manufacturer.

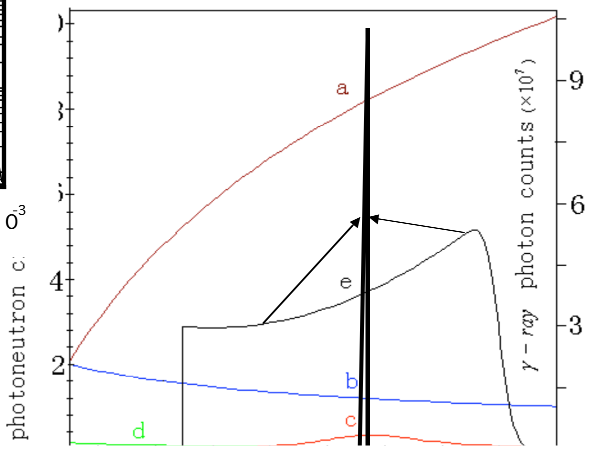

Fig.12. Calculated photon spectrum reflected from well bunched electron beam.

4.3 Bunched electron beam Compton scattering (BECS)

When electron beam is bunched strongly by intense laser or mechanical method and bunched electron beam density grow up more than the cur-off density of laser, laser photon is reflected totally by the bunched electron beam as a total mirror.[6)]

For CO_2 laser, the electron density more than $10^{19/}$cm^3 reflects laser totally. For electrons with kinetic energy of 3GeV, reflected photon energy was 20MeV at this case. Estimated spectrum is indicated in Fig.13. The spectrum is narrower than the usual Compton scattering so the energy of photon can be concentrate at the peak of cross section. This implies the increment of reaction rate of transmutation as shown in Fig.13. Investigation shows promising results to make high reflectivity.

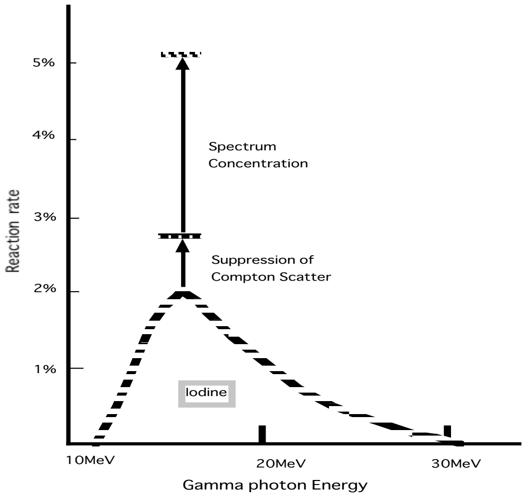

Fig.13.Reaction rate for BECS photon,

5.Summary

We have studied an alternative way of transmutation of nuclear waste. Here we have note this approach of the gamma ray nuclear transmutation by Compton scattered photons of stored laser in a cavity and high current accelerator. A laser photon storage and interact with beam to produce Compton scattering were performed.

The reaction rate estimation and experiments were performed. The results corresponded well to the theoretical one. A main target of the transmutation is Iodine 129. We are performed ^{127}Iodine experiment with NaI targets. Besides this, neutron production rates were also calculated and performed experimentally. The detail of the energy spectrum of neutron is important for the energy balance and second transmutation. This is under investigation by experiments and simulations.

There are still many issues for this approach as follows.

1.Energy balance by neutron.
2.Accelerator with high beam current.
3.BECS feasibility

We need more innovations for this transmutation of the issues in near future.

References

[1] K. Imasaki *JPN PAT* **2528622** (1994), and J. Chen and K. Imasaki, Development of a Compact High Bright Radiation X-ray Source, *Nucl. Instr. Meth.* **A341** pp.346 (1994)

[2] S.Miyamoto et al.,Laser Compton Back-scattering gamma-ray beamline on New Subaru, Radiation measurements 41 pp179 (2007)

[3] D. Li, K. Imasaki, S. Miyamoto, S. Amano and T. Mochizuki, Spatial Distribution of Polarized Gamma Ray Generated Through Laser Compton Scattering On New SUBARU Storage Ring, *The Rev. Laser Engin.* **32** pp.211 (2004)

[4] D. Li, K. Imasaki, M. Aoki, S. Miyamoto, S. Amano and T. Mochizuki, Analysis on Coupling Gamma-ray to Nuclear Giant Resonance, *J. Nucl. Sci. and Tech.* **39**, pp1247 (2002).

[5] J. Magill et al., Appl. Phys. B 1 (2005) and Laser and Nuclei, Springer LNP 694 (2006)

[6] Private communication at New Subaru meeting, M. Fujiwara. (2007)