Draft

Photonuclear Reactions and Nuclear Transmutation

T. Tajima[1] and H. Ejiri[2]

1) Kansai JAERI
2) JASRI/SPring-8, Mikazuki-cho, Sayou-gun, Hyougo, 679-5198 JAPAN

Abstract

Photonuclear reactions are shown to be of potential interest for nuclear transmutation. Photonuclear cross sections are quite large at the giant resonance(GR) region of $E_\gamma = 15 \sim 30$ MeV. Major (γ, 2n) and (γ, n) reactions on long-lived nuclei may transmute them to short-lived or stable nuclei. The photonuclear cross-sections are rather uniform as a function of the mass number, and thus quite insensitive to nuclear species in contrast to (n,γ) reactions. Intense and well-collimated photon beams in the GR region can be obtained by inverse Compton scatterings of laser photons off high energy electrons. Here the laser photons are produced energetically inexpensive via the energy-recovery Free Electron Laser method, while the GeV electrons in a storage ring can be effectively used. Electron poitron pairs created by the photons in the GR region can be extracted and by-product neutrons from the photonuclear reaction may be used to transmute other nuclei.

1 Introduction

The study of natural abundance of heavy elements with proton excess indicates astrophysical nucleosynthesis that involves large flux of gamma rays, which transmute elements with less proton excess through photonuclear processes. In this note we consider an experimental simulation of such processes via Compton scattered gamma rays off energetic electrons and study the energy balance in these processes.

We find that when the energy of gamma rays is chosen at the giant resonance with sufficiently narrow spectrum, which is not a difficult ingredient of the Compton gamma production, a fairly decent fraction of the gamma energy can be utilized in transmuting these nuclei. In addition, when the sample is a cylinder with a narrow enough radius compared with the mean free-path of generated electron-positrons, a substantial fraction of the energy of these particles may be extracted before it becomes heat. Further, the neutrons from the (γ,n) photonuclear process can induce additional transmutation of the surrounding material that is appropriately chosen. This bred material can further decay, if so chosen, through the (n,γ) process, emitting additional gamma. If the energy of such a gamma is close to the original gamma, the above process may repeat more than once.

In order to make the original gamma rays with sufficiently high flux and energetically inexpensive, we suggest the Compton back-scattering process between high energy electrons in a storage ring and laser photons that are confined in a supercavity. The laser photons may be produced energetically inexpensive via the energy-recovery Free Electron Laser method.

In such a system, we may be able to realize an experimental apparatus with unparalleled gamma flux and high fluence of events that will open new scientific investigations into the above mentioned issues and perhaps a lot more scientific and technological issues of interest in nuclear physics. A potential application to the energy problem is one of them.

2 Photonuclear reaction and nuclear transmutation

Photonuclear reactions of (γ,2n) and (γ,n) have several unique features in view of their application for nuclear transmutation. They have been overlooked so far.

In fact (n,γ) reactions have been considered to be realistic reactions to be used for nuclear transmutation. The neutron-induced reaction is caused by the strong interaction, while the photonuclear reaction by the electromagnetic one. Accordingly the photonuclear cross-section is in general smaller than typical nuclear cross sections by a factor $e^2/\hbar c \sim 10^{-2}$.

The (n,γ)reaction Q value is typically $Q \sim +8$ MeV, while the photoreaction Q value is $Q \sim$ -8 MeV. Thus low energy thermal neutrons are used for the (n.γ) process, but medium energy neutrons with $E_n \geq 10$ MeV are needed for the photonuclear process. Low energy neutrons are easily obtained by using GeV protons. On the other hand energetic photons are hardly obtained by conventional methods.

Consequently feasibility of the photonuclear reaction has been considered to be far less than that of the neutron induced reaction. Recently application of photonuclear reactinos for nuclear transmutation has been discussed by one of the authors [1].

The present letter aims at showing that the photonuclear reaction has such unique features that make the reaction to be of potential interest for nuclear transmutation, at least for particular nuclei with small (n,γ) cross sections.

The main idea of the present method is two fold, the first is to tune the photonuclear reaction at the giant resonance region and the second is to use the medium-energy photon beam obtained by Compton back-scattering of FEL(free-electron laser) photons from GeV electrons in a storage ring.

Such intense photons in the 10 MeV region is interesting for studies of astronuclear and condensed matter science as well.

3 Unique features of the photonuclear reaction at the giant resonance region

Nuclei exhibit various types of giant resonances (GR's) when they are bombarded by appropriate beams with certain energies. The electric dipole resonance (GR) is the isovector dipole resonance at the energy $E(GR) = 15 \sim 20$ MeV. Protons with isospin t_z=-1/2 and neutrons with isospin t_z=+1/2 oscillate coherently with opposite directions. It is just the GR excited strongly by bombardment of photons tuned to the GR energy. Unique features of the photonuclear reaction at the GR region are as follow.

1. The cross section is quite large because of the coherent excitation. It amounts to almost one quarter of the geometrical nuclear cross section, and thus well compensate the weak strength of the electromagnetic interaction.

The energy integrated cross section is approximately given by

$$\sigma = \int \sigma(E)dE \sim 0.02A\ MeV barn, \tag{1}$$

where E is the photon energy and A is the nuclear mass number. Using a typical resonance width of $\Gamma \sim 5$ MeV, the cross section at the resonance peak is 0.4 barn for $A = 100$ nuclei. This is the same order of magnitude as the cross-sections of major reaction channels, and is larger than most of (n, γ) ones.

2. The GR is a macroscopic oscillation of a bulk of protons and that of neutrons. Accordingly the cross section, the resonance energy and the resonance width depend little on the mass number

and insensitive to individual nuclear structures. Actually the energy is expressed as

$$E(GR) \sim kA^{-1/5} = 20 \sim 15\ MeV, \tag{2}$$

for A = 30 - 200 nuclei, and the width is as broad as $\Gamma \sim 5$ MeV. Thus one can preferentially excite the GR in any nuclei with medium energy photons in the energy range of 10 $\sim$ 30 MeV.

This is in contrast to (n,γ) reactions by thermal neutrons. If the thermal neutron energy of $E \sim$ 0 MeV happens to coincide with a sharp (n,γ) resonance energy, the cross section gets large. In most nuclei however, the cross sections are small and depend much on individual nuclear species. Accordingly there are nuclei which are hardly transmuted by (n, γ) reaction.

3. The photonuclear reaction at the GR region is mainly (γ,2n) reaction, and partly the (γ, n) reaction. One or two neutron removal from long-lived nuclei may result in short-lived or stable nuclei. The photonuclear reaction with one or two neutron removal is complementary to the (n,γ) reaction with one neutron addition.

4.The medium energy photon beam with E = 10 $\sim$ 30 MeV can be obtained by the Compton back-scattering of low energy laser photons from GeV electrons in a storage ring. Merits of using such photons from the GeV electron ring are low emittance of the photon beam and no loss of the electrons in the ring.

Actually the photon scattered off the 8 GeV electron of the SPring-8 spread no more than sub m rad. Electrons scattered off the laser photon lose energy by 10-30 MeV, but still can remain in the ring. They are soon reaccelerated up to 8 GeV by at RF cavities.

5.The low energy laser photon can be efficiently produced via the energy-recovery Free Electron Laser method. They are confined in a supercavity at the interaction section of the electron ring.

6. The photon beam energy in the 15 $\sim$ 20 MeV range is used partly to transmute nuclei via (γ, 2n or n) reactions, and partly via electron pair creations. The neutron energy is typically a couple of MeV, and electron and positrons are in the 10 MeV region.

Since the photon beam is well collimated, target nuclei to be transmuted can be confined in a cylinder with mm in diameter and sub m in length. Then the electron positron pair escape from the target without much energy loss.

The (γ, 2n or n) reactions leave nuclei in excited states, which decay by emitting MeV γ rays. The numbers of the MeV neutrons, the MeV γ rays and the 10 MeV electron positron pairs are of the same orders of magnitude as the number of transmuted nuclei. These particles are used for basic and applied science and even for nuclear transmutation. Energies of the electron positron pairs should be recycled.

4 Evaluation of photonuclear processes at SPring-8

The 8 GeV electron in the SPring-8 can be used to test the photonuclear reaction in the GR region. The ultra-red laser photon interacts with the 8 GeV electron, and is scattered backward off the electron. The scattered photon gains a fraction of the electron energy depending on the scattering angle. The photon energy E_γ is expressed in terms of the laser photon energy E_l and scattering angle θ as

$$E_\gamma = \frac{4E_l E_e}{m^2 + 4E_l E_e} E_e f(\theta), \tag{3}$$

$$f(\theta) = \frac{1}{1 + (E_e^2 \theta^2)(m^2 + 4E_l E_e)^{-1}}, \tag{4}$$

where E_e and m are the electron energy and the electron rest mass, respectively. The photon energy gets maximum at the backward angle with respect to the incident laser photon, i,e. the forward angle of $\theta = 0$ along the electron beam direction.

The photon beam in the GR energy rigion from 20 MeV to 10 MeV is obtained by using the laser photon with $E_l = 0.02$ eV at the scattering angular range of $\theta = 0$ - 0.06 10^{-3}. The energy spectrum of the photon beam is shown in Fig. 1. The peak region of the photon beam overlaps well with the GR resonance region of medium heavy nuclei with $A \sim 60$ - 200.

It should be noted that the photon energy is proportional to the square of the electron energy and to the laser photon energy. Thus the laser photon with 0.08 eV scattered off the 4 GeV electron gives the same maximum energy as the one given above. Such lower energy electrons can be obtained by operating the SPring8- synchrotron as an electron storage ring.

The scattered electron, which is lower in energy by 20-10 MeV than 8 GeV, can be still in the acceptance region of the 8 GeV ring. Thus they can remain in the storage ring and be reaccelerated at RF cavities to the original 8 GeV.

The angle spread of the photon beam is within $\pm\, \theta = 0.06\ 10^{-3}$, and thus the beam spot is around 2.4 mm at 10 m from the interaction point. Then the nuclear target of a cylindrical form with 4 mm in diameter can be used to be bombarded by the photon beam The length of the cylinder target depends on the density and the radiation length. Here the radiation length for the 20-10 MeV photon is determined mainly by the cross-section of the electron pair production.

Let us discuss the photonuclear reaction on a nucleus with $A = 100$ and $Z = 42$ as an example of medium heavy nuclei. The GR energy, the width, and the cross section at the resonance peak are $E_\sim$ 18 MeV, $\Gamma \sim 5$ MeV, and $\sigma \sim 0.4$ barn.

Using a target with 0.5 kg / cm^2 and $A =$ X, 30 % of the photon beam loses the energy via the nuclear reaction, namely 25 % by the (γ, 2n) reaction, 5 % by the (γ, n) reaction, and 70 % via the electron positron pair creation. The cross-section of the electron positron pair creation is proportional to Z^2, while that of the photonuclear cross-section is to A. Thus the photon beam is more effectively used for nuclear ransmutation in lighte nuclei.

The (γ, 2n) and (γ,n) reactions leave residual nuclei in excited states, which decay by emitting a couple of MeV γ rays. The average neutron energy is given by the nuclear temperature of $kT \sim$ 2 MeV at the GR in $A = 100$ nuclei. The neutron and γ energies depend much on the number of emitted neutrons. In any case the energy balance is given as

$$E_\gamma \sim \Sigma(B_n + E_n) + \Sigma E_\gamma, \tag{5}$$

where B_n is the neutron biding energy and the photonuclear reaction Q value is assumed to be given as $Q \sim -\Sigma B_n$. If the neutrons are slow down and are captured, the binding energy is released by emitting γ rays with $\Sigma E_\gamma = \Sigma B_n$.

The pair electrons produced by the 20 MeV photon are emitted forward with the average momentum of $P_e \sim 10$ MeV $/c$. Since they have transverse momentum of around 5 $\sim$ 10 MeV / c, they are emitted outside the cylindrical target depositing little energy in the target.

In short the photon energy is almost (more than 90 %) converted to the electron kinetic energy, the neutron biding and kinetic energies and the Γ ray energy.

Let us discuss the numbers of the photons required for nuclear transmutation and the electron positron pairs, and those of the by-product γ rays and neutrons in the photonuclear reaction. We discuss, for example, transmuting 10 kg of $A = 100$ nuclei in a year. The total number of the target nuclei is 0.6 10^{26}. Using the target with 100 g/cm^2, and the average cross-section of 0.2 barn for the photons in the energy interval of 10-20 MeV, the photon intensity in the energy interval is 5 10^{26} /year, and 1.6 10^{19} /sec. The electron intensity in the SPring-8 can be 200 A, namely 1.2 1021. These numbers are listed in table 1.

The numbers of electron/positron pairs and neutrons are around 4 10^{26} and 10^{26}, respectively. The by-product neutrons may be very efficiently used for transmuting nuclei with large (n,γ) cross section.

Table 1: 'Photons, neutrons, electrons, and γ rays in photonuclear transmutation .

Number of nuclei/particles	Comment	
Target nuclei	0.6 10^{26} / y	A = 100 10 kg
σ	0.2 barn	GR peak $\sigma = 0.4$ barn
I_p	5 10^{26} / y 1.6 10^{19}	Photons in 10 - 20 MeV
I_n	1 10^{26}	$E_n \sim 2$ MeV
I_γ	4 10^{26}	$E_\gamma \sim 2$ MeV
I_e	4 10^{26}	e^+-e^- pair with $E_e \sim 7$ MeV

5 Laser photons

6 Electron storage ring

7 Target section

The photons in the GR region lose the energy mainly by the photonuclear reaction on the long-lived radioactive nuclei and on other nuclei in the target material and by the electron-positron pair creation. Chemical purification and isotope enrichment are necessary for efficient transmutation. Isotopic enrichment to the level of 85-90 % is quite realistic now by centrifugal separation and/or laser separation. Modest plants for these separation processes handle an order of 100 kg per year.

The electron positron pairs can be extracted along solenoidal magnetic field in pararrel to the photon beam.

8 Energy balance

9 Concluding remarks and discussions

In this letter the photonuclear reaction in the GR region is shown to be of potential interest for nuclear transmutation. The key elements are the large and uniform cross-sections of the (γ, 2n) and (γ, n) reactions at the GR region and the high quality intense photon beam produced via the Compton back-scattering of FEL laser photons off multi GeV electrons in a storage ring.

It is quite realistic to transmute long-lived nuclei of the order of 10 kg per year by utilizing XX watt FEL and 200 A electrons in a 8 GeV storage ring.

The present photonuclear reaction can be complementary to (n, γ) reactions. Actually (n, γ) reactions are quite effective for particular nuclei with large neutron capture cross-section. The photonuclear reaction, the cross-section of which does not depend much on individual nuclear speceis, can be used for transmuting other nuclei in general.

By-products of the photonuclear reaction are electron positron pairs in the 10 MeV range, a few MeV neutrons and a few MeV γ rays. In fact the initial photon beam energy is converted 80$\sim$90 %

to the electron-positron energy, and 10-20 % to the neutron and γ energies. The intensities of the neutrons and γ rays are roughly one quarter of the initial photon beam intensity.

The MeV neutrons are slow down and are utilized to transmute nuclei with large (n,γ) cross-section of $\sigma \geq 0.5$ barn. In other wards, a big photonuclear reaction plant is effective for most nuclei, i.e., for nuclei with the (n,γ) cross-section smaller than 0.5 barn via the photonuclear reaction, and for nuclei with the larger cross-section via the neutron capture reaction induced by the by-product neutrons.

It should be noted that the energy spectrum of the photon beam produced via the Compton back-scattering off the GeV electron has a peak around 20 MeV, but extends down to almost 0. The photons in the energy interval of 10-20 MeV are effectively used for photonuclear reaction, but the lower energy photons are converted to lower energy electron positron pairs. Thus one gets electron positron pairs with almost the same total energy as that of the photon beam. Recycling the electron positron energy is very interesting.

Low energy MeV γ rays are produced via the photonuclear reaction, the (n,γ) reaction and the Compton scattering of the incident low energy photon. The total energy of these MeV γ rays amounts to $1/3 \sim 1/4$ of that of the incident photons. Effective use of these γ rays should be considered.

The photonuclear transmutation is attractive from ecological view points. Electrons, once stored in a ring with a large radius, lose their energy only via interactions with the laser photons, and the energy loss is just the energy gain of the photons to be used for the photonuclear reaction and the electron pair production. There are no major energy loss to heat. Since the GeV electrons remain always in the ring, they do not produce radioactive nuclei. The photon beam with $E_\gamma \leq 20$ MeV is so well collimated that it does not produce radioactive nuclei except the short-lived nuclei transmuted from the long-lived ones. These are great advantages over the conventional method of neutrons produced by intense GeV proton beams.

Finally it is noted that all kinds of feasibility studies can be carried out by modifying existing synchrotrons, which are used presently just for providing GeV electrons once or twice a day into storage rings at synchrotron radiation laboratories. The 8 GeV synchrotron at SPring-8 is certainly of great interest [2].

References

[1] T. Tajima, XXXX YYYYY 2003.

[2] Y. Ohashi et al., Proceedings of the RCNP workshop on future projects of nuclear physics in Japan, RCNP Osaka University, July 2003.
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