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The evaluation of transmutation of hazardous nuclear waste of ^{90}Sr, into valuable nuclear medicine of ^{89}Sr by ultraintense lasers

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Abstract

The analytical evaluation of the capability of Bremsstrahlung highly directional energetic γ-beam to induce photo transmutation of ^{90}Sr (γ,n) ^{89}Sr is presented. Photo transmutation of hazardous nuclear waste of ^{90}Sr, one of the two main sources of heat and radioactivity in spent fuel into valuable nuclear medicine radioisotope of ^{89}Sr is explained. Based on the calculations, a fairly decent fraction of gamma rays in this range are used in transmuting of ^{90}Sr into ^{89}Sr where according to the available experimental data it is shown that by irradiating a 1-cm thick ^{90}Sr sample with lasers of intensity of 10^{21} W/cm^2 and repletion rate of 100 Hz for an hour, the reaction activity would be 1.45 kBq. It is shown that there is not a linear relationship between the growth of the activity and increasing the laser intensity, but there is a dramatic increase in the growth rate especially between $10^{20}$and 10^{21} W/cm^2. In this work, the advantage of photonuclear transmutation over the neutron capture transmutation for ^{90}Sr isotope is also discussed.

Keywords: Intense laser; Isotope; Nuclear waste; Photonuclear reaction; Transmutation

INTRODUCTION AND MOTIVATION

In nuclear power generation, one of the serious problems is the production of radioactive nuclear wastes consisting of long and intermediate-lived fission products. Developing and applying advanced technologies in the area of long-lived radioactive waste utilization and transmutation is the focus of International Atomic Energy Agency (IAEA) programs, and investigation was carried out (Maschek *et al.*, 2008). Among the different options, recently, much attention is focused on the possibilities of laser transmutation by highly directional γ-beams, which is generated in ultra intense laser-solid interaction (Ledingham *et al.*, 2003; Magill *et al.*, 2003; Takashima *et al.*, 2005; Sadighi-Bonabi *et al.*, 2006, 2009*a*; Renner *et al.*, 2008). In the above mentioned works, a high brightness γ-beam with thresholds of about 5−11 MeV, which depends on the target parameters is required (Cowan *et al.*, 2000). When such a intense beam coincides with the resonance (γ, *n*) reaction, it can throw out a neutron from the nucleus, which will be explained in more detail later in this work. The bremsstrahlung γ-rays may also be generated by electrons from conventional reactors and accelerators where it has a wide spectrum and suffers from low conversion efficiency, which is due to poor coupling of energy by wide range spectrum of accelerated electrons. The production of suitable electron sources for producing the secondary photon beams have been an interesting subject where new ways are always searched (Mccall, 1982; Li *et al.*, 2009; Limin *et al.*, 2009). Since the direction of the scattered photons is given by the incident electron beam, thus, the wide spreading of the generated γ rays was not resolved properly. Other short wavelength sources such as free electron laser that can produce narrow-band pulses ($\Delta E/E = 1\%$) with a peak power at the GW level with wavelengths down to 32 nm, but in addition, the beam size with radius of $w_0 \approx 250$ μm is diffraction-limited, and suffers from overall efficiency from electron to photon of less than 0.01% (Ayvazyan *et al.*, 2006).

The first measurement of bremsstrahlung photons with energies more than 2 MeV was reported by Sherman *et al.* (1987) more than 20 years ago, by relativistic electrons from the interaction of pulses of 600 ps produced by CO_2 laser with solid target. Niu *et al.* (1991) reported the beam generations of three kinds of charged particles: electrons, light ions, and heavy ions. The ongoing development of ultra-intense laser techniques and by the advent of new

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laser systems in the production of extremely ultra-intense laser pulse through chirped pulse amplification and optical parametric chirp pulsed amplification techniques (Strickland & Morou, 1985; Perry, 1999), with the capability of delivering light pulses of high intensities (more than 10^{20} Wcm^{-2}) much attention has been devoted to the generation of high energy electrons from irradiating solid targets (Cowan *et al.*, 1999; Ledingham *et al.*, 2004). Recently, for generating a narrow spread of beam spectrum γ-rays from other techniques such as Compton scattering of laser photons with high current accelerators, is proposed for photonuclear reactions to increase the reaction efficiency (Imasaki *et al.*, 2008).

Ultra-intense femtosecond lasers have stimulated an increasing interest in the problem of laser and matter interaction. The laser-matter interaction meets the high energy physics in laser-plasma accelerators in generating highly collimated bright X/γ-ray sources (Giulietti *et al.*, 2005; Chyla, 2006; Bessonov *et al.*, 2008) and the production of thick ion blocks (Glowacz, 2006; Yazdani *et al.*, 2009; Hora, 2009; Azizi *et al.*, 2009; Hora *et al.*, 2009). These ultra intense lasers are also used to generate a quasi-Maxwellian and quasi-mono-energetic electron beams, and the recently introduced ellipsoidal bubble regime has demonstrated the generation of high-quality electron bunches with very high energies in relatively small energy spread (Malka & Fritzler, 2004; Glinec *et al.*, 2005; Zobdeh *et al.*, 2008; Sadighi-Bonabi *et al.*, 2009*b*, 2009*c*) and electron emittance of more than the conventional accelerator (Lifschitz *et al.*, 2006). The propagation of such intense laser field is investigated in various plasma conditions (Sadighi-Bonabi *et al.*, 2009*d*, 2009*e*). These lasers with narrow width spectrum of less than 1% may solve the problem of having low conversion efficiency from the electron beam to γ ray.

Up to now, photo transmutation of ^{129}I has been carried out successfully in experiment (Magill *et al.*, 2003; Ledingham *et al.*, 2003). Also, transmutation of ^{99}Tc has been conducted (Galy *et al.*, 2002) and no evidence for reaction was detected. This could be due to its very low (γ, *n*) reaction cross-section that could be below the detection limit. The purpose of the present work is to analytically investigate the possibility of ultra intense short pulse laser transmutations of ^{90}Sr (γ, *n*) ^{89}Sr.

STRONTIUM

Among the six major fission by-products of ^{235}U, ^{90}Sr, and ^{137}Cs, they all have half-lives of around 30 years, and contribute significantly to the short-term radioactivity and heat load, constituting a packaging problem. Thus, removal of these isotopes from the used fuel would relax the requirement for heat dissipation in a long-term burial depository. Neutron absorption cross-section for ^{137}Cs is 250 mbarn (Harada *et al.*, 1990), and even less for ^{90}Sr which is about 15.3 mbarn (Harada *et al.*, 1994), and later very minuscule amount of 10.1 mbarn is reported (Nakamura *et al.*, 2001). Thus, no neutron source is able to deliver a sufficiently large neutron flux to proceed with a faster transmutation than radioactive decay (Wydler *et al.*, 2001).

Strontium has 16 major radioactive isotopes in which ^{90}Sr has a half-life sufficiently long (28.8 years) to warrant any concern for nuclear waste management. ^{90}Sr naturally decays to ^{90}Y by emitting an energetic β, and ^{90}Y decays by emitting more energetic particles (0.94 MeV) with half-life of 64 h to ^{90}Zr. The main external health concern for ^{90}Sr is related to these energetic β particles from ^{90}Y (Giammarile *et al.*, 2001). The internal concern also comes from the ingesting or inhaling of ^{90}Sr by food, water, or air that has been contaminated by nuclear fallouts and accidents. Because of ^{90}Sr similarity to calcium, it is mistakenly deposited in bones, teeth, and soft tissues of the body that cause cancers and tumors. These tumors are associated with the β particles of ^{90}Sr decay chain (Giammarile *et al.*, 2001).

^{90}Sr with a half-life of 28.8 years transmutes in a (γ, *n*) reaction into ^{89}Sr, where β decays to ^{90}Y with a half-life of 50.52 days. ^{89}Sr, a valuable radioisotope that is analogy to calcium is concentrated in areas of high osteoblastic activity, which is used in nuclear medicine for bone cancer pain palliation (that improves the quality of life), cellular dosimetry, treatment of prostate cancer, treatment of multiple myeloma, osteoblastic therapy, and as a potential agent for the treatment of bone metastases from prostate and breast cancer (Giammarile *et al.*, 2001).

PHOTONEUTRON REACTIONS

One of the main goals of the nuclear waste management is the transformation of long-lived nuclides into short-lived nuclides. There are two important transmutation reactions, namely neutron capture (γ, *n*) reaction, and photoneutron (γ, *n*) reaction. The photoneutron (γ, *n*) cross-section is in general less compared to the typical (γ, *n*) reaction by a factor of $e^2/\hbar c \approx 10^{-2}$. Therefore, for many isotopes such as ^{129}I(γ, *n*)^{130}I reaction, this is a very useful reaction to transmute ^{129}I with half life of 1.6×10^7 years into ^{130}I with half life of only 12 h, or to transmute long-lived (2.3×10^6 years) ^{135}Cs into short-lived (only 19 s) ^{136}Cs isotope (Hatsukawa *et al.*, 1999). However, for many nuclides such as ^{133}Cs because of the presence of highly radioactive ^{137}Cs isotope the processing is very expensive, difficult, and dangerous (Sadighi-Bonabi *et al.*, 2006). This is because the stable ^{133}Cs transmutes into ^{134}Cs and then again by absorbing the second neutron it transforms into the above mentioned dangerous long-lived (2.3×10^6 years) waste of ^{135}Cs. This is the main problem in transformation ^{239}Pt on a well known ^{239}Pt nuclide with a half life of 24,000 years, which transforms into ^{240}Pt (6,500 years), ^{241}Pt (14 years), and ^{241}Pt (380,000 years) by absorbing one, two, and three neutrons, respectively. As a consequence for many isotopes, the transmutation through photoneutron is more feasible than the neutron capture reactions. For strontium, the measured cross-section for neutron capture through ^{90}Sr(γ, *n*)^{91}Sr reaction is only 10.1 ± 1.3 mbarn (Nakamura *et al.*, 2001) where, the cross-section for hotoneutron reaction of ^{88}Sr(γ, *n*)^{87}Sr is 207

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mbarn. This is 20 times more than the cross-section for the neutron capture. To the best of our knowledge, the cross-section to ^{90}Sr(γ, n)^{89}Sr was not reported. Furthermore, more neutron capture transforms the ^{90}Sr waste into even heavier strontium isotopes, which complicates the process (Pampin & Davis, 2008). The conversion efficiency for the photonuclear reaction on a nucleus with $A = 100$ and $Z = 42$ as an example of medium heavy nuclei such as stratum is 30% (Tajima & Ejiri, 2003).

Furthermore, when a nuclear is bombarded by an appropriate γ beam of certain energy, tuned to the giant resonance (GR), the cross-section is considerably increased. In this condition, protons and neutrons oscillate in opposite directions with isospin of $1/2$ and $-1/2$, respectively, and the electric dipole resonance (GR) is the isovector dipole resonance at the giant resonance energy, where the cross-section is on the same order of magnitude as the cross-sections of major reaction channels, and is larger than most (n,γ) reactions including ^{90}Sr (Habs *et al.*, 2009).

Generating neutrons in photoneutron reactions can be very useful in various applications. In addition to the well known applications of neutrons including nuclear energy, corrosion detection and space require detection of light materials such as explosives or pyrotechnic devices, in recent years, new applications of neutrons due to innovative techniques have emerged. Furthermore, in photonuclear reactions, the neutrons detection is a powerful diagnostic tool in measuring of the accurate amount of the products. Photonuclear (γ, n) reaction is used to produce cold polarized neutrons with a focusing ellipsoidal device where brilliant cold polarized micro-neutrons become available (Habs *et al.*, 2009). Photoneutron (γ, n) threshold energy is characteristic of the neutron binding energy in the target nuclide. For ^{63}Cu, Ta, and ^{197}Au, the threshold energy is almost 8, 9 and 10 MeV, respectively. This is higher than the normally required threshold energy for photofission reactions. For example, for ^{238}U (γ, f) reaction, it is only 5 MeV due to lower energy requirement of deforming into its fission nuclides (Cowan *et al*, 2000).

Norreys *et al.* (1999) reported one of the first successful experimental photoneutron (γ, n) reaction by a highly directional γ-ray beam from ultra short (700 f s), ultra intense ($I\lambda^2 = 10^{19}$ Wcm$^{-2}\mu$m^2) laser pulse on a copper target. The energy loss to bremsstrahlung scales as Z^2, so high Z material such as lead ($Z = 82$) was chosen as first target material to maximize the required γ-ray energy for the photonuclear reaction. Pieces of copper were placed around the lead target. The reported hotoneutron reactions ^{63}Cu (γ, n)^{62}Cu and ^{65}Cu (γ, n)^{64}Cu had threshold of about 10 MeV, and the largest reaction cross-sections being 60–70 mbarm at 15–18 MeV. In this work, a slab of tantalum is used as first target for maximum γ production and the detail is given in the next section.

THEORETICAL ANALYSIS

The procedure to estimate the number of reactions of ^{90}Sr (γ, n) ^{89}Sr per laser shot is nearly similar to Shkolnikov *et al.* (1997) approach and according to Magill *et al.* (2003) technique as follows: first, the Bremsstrahlung photon spectrum in terms of a constant for the specified target type and the effective temperature of photons, is determined using experimental data available for the activation of the first target. Then, using photon spectrum and the distribution function of reaction cross-section by integrating a multiplication of them over threshold energy and upper limit energy of the reaction, the number of reactions is also calculated. Shkolnikov *et al.* (1997) theoretically proposed the number of electrons dN_e/dE in 1 MeV at a given energy is fit fairly well to the following expression:

$$dN_e/dE \approx \nu_0 E \exp(-rE),\ \nu_0 = 3.303 \times 10^{10} MeV^{-2},\quad r \approx 1.2 MeV^{-1}. \tag{1}$$

Norreys *et al.* (1999) tried to find an exp ($-E_e/k_BT$) fit to their experimentally obtained data above 3 MeV photon energy spectrum, where E_e, k_B, and T are the electron energy, the temperature and the Boltzmann's constant, respectively. One of their proposed formulas for fully relativistic electron distribution function was a Boltzmann-like distribution E_e^2 exp ($-E_e/k_BT$). This form of electron distribution function experimentally proved for energy region up to 10 MeV (Ledingham *et al*, 2000; Behrens *et al.*, 2003) and used in some later works (Takashima *et al.*, 2005; Sadighi-Bonabi *et al.*, 2006; 2009*a*). A similar form also was also used initially by Magill *et al.* (2003) for both electron and photon distribution as following:

$$\frac{dN_\gamma}{dE_\gamma} = \frac{N_0}{k_B T_\gamma} \exp\left(-\frac{E_\gamma}{k_B T_\gamma}\right). \tag{2}$$

Where dN_γ/dE_γ, N_0, and k_BT_γ are the number of electrons per MeV, a constant and the characteristic temperature of γ photons, respectively. In the present work, we have used Eq. (2) and compared the calculated results with those obtained by the same parameters from $E_e^2\exp(-E_e/k_BT)$ similar to frequently used procedure (Ledingham *et al.*, 2000; Takashima *et al.*, 2005; Sadighi-Bonabi *et al.*, 2006; 2009*a*). The cross section of (γ, n) reactions assumed to be Lorentzian (Norreys *et al.*, 1999) as,

$$\sigma_{reac} = \sigma_{\max}\left[4\left(\frac{E_{\max} - E_\gamma}{\Gamma}\right)^2 + 1\right]^{-1}. \tag{3}$$

$\sigma_{\max}$ is the peak cross-section at $E_{\max}$ and Γ is the full width half maximum. Furthermore, using $\sigma_{\max}$ (γ, n) cross-section, the number of reaction can be evaluated similar to Magill *et al.* (2003) by the following:

$$N_{reac} = n_{tar} d_{tar} \int_{E_{thr}}^{E_{\text{int}}} \sigma_{\max}(\gamma, n) \frac{dN_\gamma}{dE_\gamma} dE_\gamma, \tag{4}$$

where n_{tar} is the density of target in (cm^{-3}), d_{tar} is its

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thickness of the target, E_{int} is the upper limit energy (MeV) that is specific for any reaction and E_{thr} is the threshold energy (MeV) to initiate the reaction. This can be calculated for any reaction and it is also available in the literature.

CALCULATIONS AND RESULTS

A primary target of tantalum with a thickness of 2-mm and the density of $n_{tar} = 5.54 \times 10^{22}$ (cm^{-3}) is irradiated by a *p*-polarized laser light of 10^{20} Wcm^{-2} intensity with a repetition rate of 10 Hz and the central wavelength of about 1 μm. Generated Bremsstrahlung energetic γ-rays penetrate into the secondary 1-cm thick ^{90}Sr target with the density of $n_{Sr} = 1.81 \times 10^{22}$($cm^{-3}$) to stimulate photo transmutation (γ, *n*). The schematic of supposed targets scenario is shown in Figure 1. As indicated in the figure, the direction of the incident ultra intense laser beam is assumed to be perpendicular to a plane parallel to the 2 mm thick tantalum target, and the emerged γ photon transmute the strontium target placed behind and parallel to the primary tantalum target. Tantalum has the advantage of high density (16.6 gcm^{-3}), high melting point (3017°C) and high resistant against cooling. The thickness of primary target is selected according to earlier experimental works and theoretically optimized thicknesses. In the initial experiments for highly directional γ photon for photonuclear reactions, the thickness of tantalum slab was 1.75 mm (Ledingham *et al.*, 2000). Later Magill *et al.* (2003) increased the tantalum thickness to 2 mm in ^{129}I (γ, *n*)^{128}I reaction and in the later works 2 mm thickness was used (Takashima, 2005; Sadighi-Bonabi, 2006). Based on the Berger *et al.* (1970) definition of Maximum bremsstrahlung efficiency, recently a simulation on the optimization of tantalum thickness for maximum bremsstrahlung photon yield is reported to be 1.88 mm for 10 MeV electron beam with an accuracy of ±4%–9% (Eshwarappa *et al.*, 2005). Inasmuch as the mentioned inaccuracy and the fact that the maximum photon number in their report peaked more like about 2 mm (see Fig. 2 of Eshwarappa *et al.*, 2005). Therefore, in the present work, we selected this amount as an optimum thickness for tantalum as a primary target. Furthermore, according to Berger's *et al.* (1970) definition, the efficient thickness of a target was selected to be half of the range of electron and also the increase in the bremsstrahlung yield with increasing the electron energy is linear (Eshwarappa *et al.*, 2005). Generated Bremsstrahlung energetic γ-rays penetrate into the secondary 1-cm thick ^{90}Sr target with the density of $n_{sr} = 1.81 \times 10^{22}$ (cm^{-3}) stimulate photonuclear ^{90}Sr (γ, *n*) ^{89}Sr reaction.

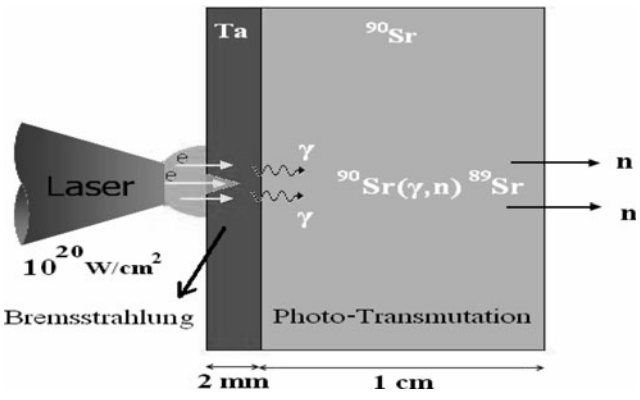

Fig. 1. Schematic scenario of laser pulse and targets is presented. Ultra intense laser pulse interacts with primary tantalum target to produce the relativistic electrons on its surface. These electrons generate Bremsstrahlung γ-ray in the first target's bulk where this ray transforms ^{90}Sr into ^{89}Sr through (γ, n) reaction in the second target.

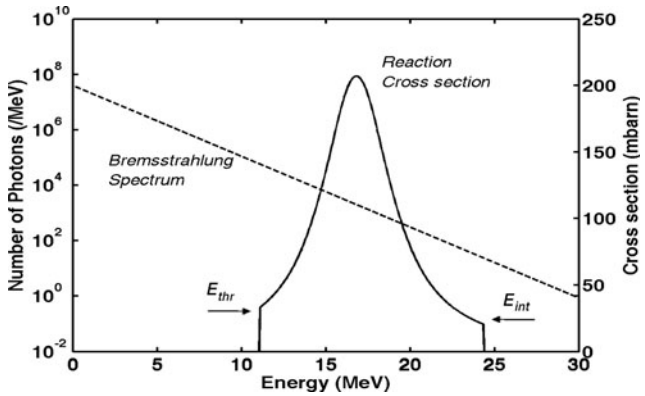

Fig. 2. The Lorentzian reaction cross-section of ^{90}Sr(γ,*n*)^{89}Sr with the experimental data available in Table 1. Also, the Bremsstrahlung spectrum of photons with an effective photon temperature of 1.7 MeV. $E_{\rm thr}$ is the threshold energy to initiate the reaction and $E_{\rm int}$ is the integral upper limit energy.

To obtain N_{reac} numerically for any reaction, the value of some of the parameters should be determined first. The photon temperature is the same as electron temperature in the relativistic case (McCall *et al.*, 1982) and slightly lower in the intermediate case of several MeV (Behrens *et al.*, 2003). The temperature of the electrons has been estimated by Wilks *et al.* (1992) for *p*-polarized laser light irradiated normally on the target as,

$$k_B T_\gamma(MeV) = 0.511\left[\left(\frac{1 + I\lambda^2}{1.37 \times 10^{18}}\right)^{\frac{1}{2}} - 1\right], \qquad (5)$$

I is in Wcm^{-2} and λ^2 is in μm^2. At about $10^{20}W/cm^2$, the hot electrons temperature is derived from the ponderomotive force calculated to be $k_B T_\gamma \approx 3$ MeV (Wilks *et al.*, 1992), but in practice, for a 2-mm tantalum target, it is a little lower and is about 1.7 MeV/k_B, and photon temperature of $T_\gamma = 1.2$ MeV/k_B (Magill *et al.*, 2003). The Bremsstrahlung γ-beam generated in the tantalum target can induce a (γ, *n*) reaction on ^{181}Ta itself to produce ^{180}Ta, which decays with a probability of 86% by electron capture in ^{180}Hf and with 14% by beta decay to ^{180}W. In contrast to strontium the photonuclear cross-section of ^{181}Ta is experimentally measured (Handbook on photonuclear data) and explained in Table 1. Using an equation similar to Eq. (4) for tantalum:

$$N_{Ta} = \frac{n_{Ta} d}{k_B T_\gamma} \int \sigma_{Ta}(\gamma, n) N_0 \exp(-E/k_B T_\gamma) dE. \qquad (6)$$

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Table 1. *(γ,n) reaction experimental data for ^{181}Ta and ^{88}Sr*

Target Type	σ_{max} (mbar *n*)	E_{max} (Mev)	Γ	E_{int} (MeV)	E_{thr} (MeV)
^{181}Ta	367	12.7	5	25.20	7.58
^{88}Sr	207	16.85	5	24.40	11.11

By using the photon temperature of T_γ and $E_{th} = 7.58$ MeV, $\sigma_{max} = 367$ mbarn, and $E_{max} = 12.7$ MeV from Table 1, and also the experimentally measured total number of (γ, n) reactions of ^{181}Ta per 10^{20} Wcm^{-2} Laser shot of $N_{reac} = 160$ (Magill *et al.*, 2003) the photon yield of $N_0 = 6.87 \times 10^7$ per MeV is obtained.

To the best of our knowledge, no experimental data exist for (γ, n) reaction cross-section of ^{90}Sr, but according to the compatibility of experimental data available for ^{88}Sr with the result of nuclear model codes for ^{90}Sr, the experimental data of ^{88}Sr were used (Table 1). Calculations similar to the above mentioned procedure is done for strontium with the obtained N_0 for the primary Ta target. Figure 2 shows the reaction cross-section of ^{90}Sr$(\gamma, n)^{89}$Sr and the bremsstrahlung spectrum of photons. From Figure 2 by having all the parameters obtained for the above mentioned reaction, evaluated value of the number of reactions is $N_{reac} = 117$ reactions per shot. This is calculated from the overlap of bremsstrahlung spectrum and the cross-section for the photonuclear reactions as indicated in Figure 2.

DISCUSSIONS

According to the 50.52 days half-life of ^{89}Sr and $N_{reac} = 117$, its activity per shot would be 1.86×10^{-5} Bq. If target is irradiated with a 10 Hz, 10^{20} W/cm^2 laser for an hour, its activity would be 0.67 Bq. Figure 3 shows the activity of ^{89}Sr as a function of irradiation time for several repetition rates with 10^{20} W/cm^2. When the repetition rate increases by a factor of 100 to 1 kHz, then its activity amount would be close to 67 Bq. So increasing the repetition rate of the laser has a direct effect on the yield of the reaction that requires technical improvement of high-power lasers to attain higher rates.

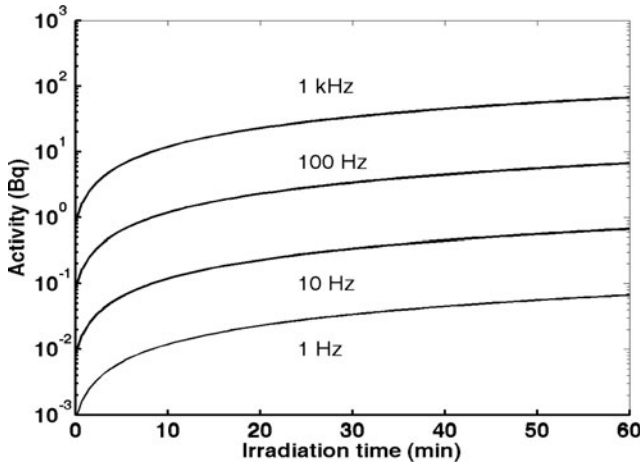

Fig. 3. Nuclear activity as a function of irradiation time for a secondary ^{90}Sr target with a first target of tantalum for a 10^{20} W/cm^2 laser in the repetition rates of 1, 10, 100 and 1 kHz.

In addition, increasing the effective temperature of hot electrons has a drastic influence on the total reaction activity. This can be done by increasing the intensity of the laser. The dependence of the electron temperature and the total number of electrons on the laser intensity experimentally showed to be $T_e \approx I^{1/2}$ and $N_e \approx I^{3/2}$, respectively (Gahn *et al.*, 2002). For a tantalum target assumed here, increasing the intensity from 10^{20} W/cm^2 by a factor of 10 would increase the electrons temperature to the limit that enhances the reaction yield by a factor greater than 200 to 145 Bq. By using the newly introduced laser system of 100 Hz, based on OPCPA technology (Ledingham *et al.*, 2004), the activity can be extended to 1.45 kBq at laser intensity of 10^{21} Wcm^{-2}. By increasing the electron temperature, the overlap of the cross-section with the bremsstrahlung spectrum dramatically increases where beyond an optimum intensity the overlap does not increase and it becomes constant. This optimum intensity belongs to a temperature of 16.85 MeV. The activity of reactions, also substantially depends on the produced isotope's half-life. For isotopes with several minutes half-life, activities over mega Becquerel would be attainable, just with 10^{20} W/cm^2 intensity and 10 Hz repetition rates. This will stimulate researchers to investigate possibilities of production of short-lived isotopes through photo transmutations.

Another procedure to calculate the number of ^{89}Sr reaction has been introduced, which is similar to ^{137}Cs$(\gamma, n)^{136}$Cs (Sadighi-Bonabi *et al.*, 2006). There, the bremssrahlung spectrum is obtained from relativistic electrons spectrum and the integrated-over-angle bremsstrahlung cross-section. The calculated value of the activity by that method for a laser system, similar to the one in this article, is 0.85 Bq for an hour, which is in good agreement with 0.67 Bq of the here mentioned method.

CONCLUSION

We have discussed the effect of laser intensity in laser transmutation of strontium and relativistic electrons effective temperature has been investigated. Figure 4 shows the activity of ^{89}Sr as a function of laser intensity. As shown in Figure 4, the growth of activity by increasing the laser intensity is not linear but has a dramatic increase especially between 10^{20} and 10^{21} W/cm^2. As the repetition rate is directly multiplied to the activity of the reaction by developing high repetition rate ultra intense lasers over kHz in future, more acceptable activities in mega and giga-becquerel could be achievable for lots of radioisotopes through photo transmutation productions. Radiation sources driven by ultra intense laser sources have benefits of being considerably

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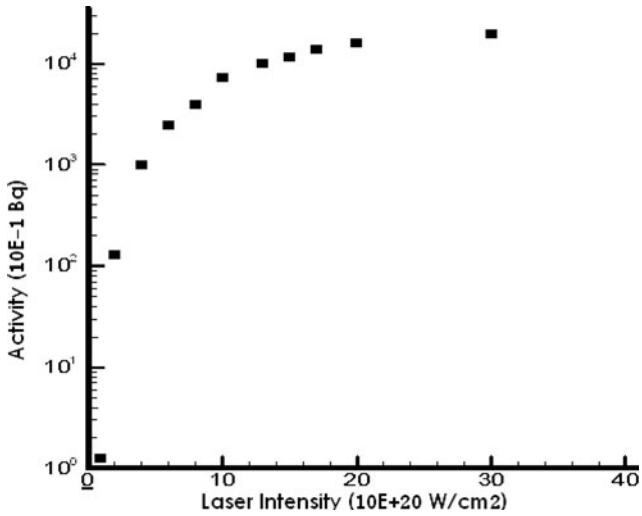

Fig. 4. The activity of $^{90}Sr(\gamma,n)^{89}Sr$ reaction in the laser intensities of 10^{20}, 5×10^{20}, $10^{21}$and 5×10^{21} for a 1-cm ^{90}Sr target bombarded by the γ–rays generated in the interaction of laser pulse with a 2-mm tantalum target.

compact and they are an interesting diagnostic tool of fast phenomena. Inasmuch as these systems generally suffer from poor wall-plug efficiency they are not suitable for transmuting bulk quantities with the present pulse repetition rate at high intensities, however, they are very suitable candidates for small quantities such as nuclear medicine radioisotopes.

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