STUDY OF THE ^{nat}Sm$(\gamma, xn)^{143m,g}$Sm REACTIONS INDUCED BY BREMSSTRAHLUNG WITH END-POINT ENERGIES JUST ABOVE GDR REGION

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Abstract. *We investigate the energy dependence of the isomeric yield ratios for the $^{nat}Sm(\gamma,xn)^{143m,g}Sm$ reactions with bremsstrahlung energies of 40-, 45-, and 50-MeV, just above the giant dipole resonance (GDR) region by the off-line γ-ray spectrometric method. The bremsstrahlung photons were produced from the 100 MeV electron linear accelerator (linac) at the Pohang accelerator laboratory (PAL), Pohang, Korea. In order to improve the accuracy of the experimental results the necessary corrections were made. The present results are compared with similar literature data of the $^{nat}Sm(\gamma,xn)^{143m,g}Sm$ reactions measured at various photon energies and of the $^{nat}Sm(n,2n)^{143m,g}Sm$ reaction induced by 14 MeV neutrons in order to examine the effects of an excitation energy and an input angular momentum.*

Keywords: Isomeric yield ratio; Photonuclear reaction; $^{nat}Sm(\gamma,xn)^{143m,g}Sm$; GDR region; 40-, 45-, and 50-MeV bremsstrahlung; HPGe detector..

I. INTRODUCTION

The isomeric cross section ratio is defined as the ratio of production cross-section for the so-called metalstable or isomeric-state (σ_m) to ground-state σ_g) i.e., σ_m/σ_g. The relative population of both ground and isomeric states is governed by many factors such as type and energy of incoming projectile, spin distribution of the compound nucleus, the number and type of nuclear particles ejected that carry away energy and angular momentum,... Studies of isomeric cross-section ratios may provide important information about the nuclear structure and nuclear reaction mechanism.

Most of the existing isomeric ratio data related to the nuclear reactions induced by neutrons [1–3] and charge particles [4, 5]. The measurements with nuclear reactions induced by photons are relatively scare and mostly with low energies [6–8]. Photons carry relatively small momentum and don't introduce a large angular momentum into the compound nucleus, but it is a good tool for investigating the dependence of isomeric yield ratios on both the incident photon energies and on the mass difference between the target and product nuclei [9, 10]. At low photon energies the compound nuclear reaction is dominant, and the reaction mechanism is well studied. However at higher energies, above the GDR region the multi-particle photonuclear reactions can

take place, and little is known about such complexity reaction mechanisms. The photonuclear data measured at energies above the GDR region are very scanty.

We have chosen the ^{nat}Sm(γ,xn)^{143m,g}Sm reaction induced by bremsstrahlung with energies of 40-, 45-, and 50-MeV for the investigation. So far, this photonuclear reaction was studied in the low energy region, from 12- to 35-MeV [11–14]. In this energy region the compound nuclear reaction mechanism is dominant. Now we extend our measurements to higher energies in order to provide the new isomeric yield ratio data at energies just above the GDR region. We also compare the isomeric ratios for the ^{143m,g}Sm isomeric pair produced from different reaction channels with two different incoming projectiles, bremsstrahlung photons and 14 MeV neutrons, namely from the ^{nat}Sm(γ,xn)^{143m,g}Sm and ^{nat}Sm(n,2n)^{143m,g}Sm reactions. The isomeric ratio data obtained at different photon energies and from different reaction channels may help to examine the effects of the excitation energy and input angular momentum.

II. EXPERIMENTAL

The experimental procedures for the determination of the isomeric yield ratio are described in detail elsewhere [10], and only a brief outline is given here.

The experimental samples were prepared from high-purity samarium foil of natural isotopic composition. The characteristics of the samples are given in Table 1. The bremsstrahlungs were produced by bombarding the accelerated electrons into the tungsten target, which was located at 18 cm from the exit window and perpendicular to the electron direction. The size of the tungsten target is 100 mm × 100 mm and a thickness of 0.1 mm. The details of the 100-MeV electron linac and the bremsstrahlung production are described elsewhere [10,15]. For irradiation, the sample was located at 12 cm from the W target. The irradiations were performed at 40-, 45-, and 50-MeV bremsstrahlungs. The nuclear reaction of interest is the ^{nat}Sm(γ,xn)^{143m,g}Sm and its main characteristics are given in Table 2 [16].

Table 1. Characteristics of the Sm foil samples

Foils	Size (mm)	Thickness (mm)	Weight (g)	Purity (%)	E_{brem}. (MeV)
Sm1	15×15	0.1	0.1400	99.9	40
Sm2	15×15	0.1	0.1594	99.9	45
Sm3	15×15	0.1	0.1423	99.9	50

Table 2. Main characteristics of the ^{nat}Sm(γ,xn)^{143m,g}Sm nuclear reaction [16]

Nuclear reaction	Half life, $T_{1/2}$	Jπ	Gamma ray energy (keV) and intensity (%)
^{nat}Sm(γ,xn)^{143m}Sm	66 sec	11/2-	687.7(0.19); 754.4(90.1)
^{nat}Sm(γ,xn)^{143g}Sm	8.75 min	3/2+	272.18(0.38); 1056.58(2.39); 1514.98(0.83)

After irradiation and appropriate waiting time, the induced gamma activities of the samarium samples were measured by using a well calibrated gamma spectrometer based on a high purity germanium (HPGe) detector coupled to a PC-based multichannel analyzer. The detection

efficiency was 20% at the 1332.5 keV peak of ^{60}Co relative to a 7.62 cm diameter $\times$ 7.62 cm length NaI(Tl) detector. The detector efficiency was measured by using a set of standard gamma sources. The experimental procedures for the HPGe detector efficiency calibration were described in details elsewhere [17].

The irradiation, waiting and counting times were decided based on the half-life and the activity of the radioactive isotopes of interest. The half-life of the ^{143m}Sm is short ($T_{1/2} = 66$ sec) therefore the activity measurement was started soon (around 50 sec) after the end of the irradiation. The half-life of the ^{143g}Sm isotope is 8.83 min, therefore several γspectra were measured In order to minimize the uncertainties caused by summing coincidence and pile-up effects, we have chosen the appropriate distance between the sample and the detector for each measurement. The measured sample was attached on a plastic holder and can be set at a distance from 0.5- to 10-cm from the surface of the HPGe detector. The typical γ-peaks of the ^{143m,g}Sm isomeric pair are shown in Fig. 1. The measured γ-spectra were analyzed by using the software GammaVision, version 5.10, (EG&G ORTEC, USA). The radioactive isotopes under consideration were identified based on their characteristic γ-ray energies and half-lives. The activity of the activated sample can be determined based on the measured gamma's peak area, γ-ray intensity, and the detection efficiency at the photopeak energy.
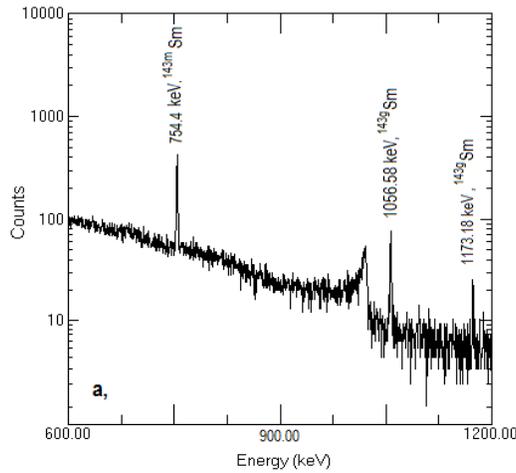
Fig. 1. Part of γ-ray spectrum taken from the ^{nat}Sm sample irradiated with 50 MeV bremsstrahlung with $t_i = 5$ min, $t_w = 1$ min, and $t_c = 3$ min.

III. DATA ANALYSIS

Usually, the isomeric state and the ground state strongly differ in spin values, therefore the isomeric ratio can be represented as a ratio of the cross-sections for the production of high-and low-spin states, namely *IR=σ(high-spin)/σ(low-spin)* [18]. When the activation is performed by bremsstrahlung photons with a continue energy spectrum, the isomeric ratio is expressed through the yields of two states instead of two cross-sections, namely *IR=Y$_{high-spin}$/Y$_{low-spin}$*[18,19], and

the yield of the reaction is expressed as follows

$$Y_k = \int\limits_{E_{th}}^{E_{\gamma max}} \sigma_k(E)\phi_k(E)dE \qquad (1)$$

where $k(=m,g)$ represents the isomeric state (m) or the ground state (g) of an isomeric pair, $\sigma_k(E)$ is the energy dependent reaction cross-section, $\phi_k(E)$ is the number of γ quanta in the bremsstrahlung spectrum with energy E, $E_{\gamma max}$ and E_{th} are the maximum bremsstrahlung end-point energy and the reaction threshold, respectively.

In this work, the pulsed bremsstrahlung beam was used for the sample irradiation, and the relationship between the reaction yield, Y_k and the number of counts in a photopeak of γ-ray, S_k is expressed as follows [19]:

$$Y_k = \frac{S_k \lambda_k (1 - e^{-\lambda_k T})}{N_0 I_k \varepsilon_k (1 - e^{-\lambda_k \tau})(1 - e^{-\lambda_k t_i}) e^{-\lambda_k t_w}(1 - e^{-\lambda_k t_c})} \qquad (2)$$

where N_0 is the number of target nuclei, I_k is the intensity of the measured γ-ray, ε_k is the detection efficiency for the γ-ray of interest, λ_k is the decay constant of the $k(=m,g)$ state, τ is the pulse width, T is the cycle period, t_i is the irradiation time, t_w is the waiting time, and t_c is the counting time.

By taking into account the fact that the ground state nuclides could be formed in two ways, directly from the target nuclides and indirectly through the decay of the metastable state nuclides, the isomeric yield ratio can be computed from the following equation [19]:

$$IR \equiv \frac{Y_m}{Y_g} = \left[\frac{\lambda_g F_m}{\lambda_m F_g} \times \left(\frac{S_g}{S_m} \times \frac{\varepsilon_m I_m}{\varepsilon_g I_g} - \frac{P\lambda_g}{\lambda_g - \lambda_m} \right) + \frac{P\lambda_m}{\lambda_g - \lambda_m} \right]^{-1}, \qquad (3)$$

where S_m and S_g are the photo-peak areas for the detected γ-rays of the isomeric- and the ground-state, P is the branching ratio for the decay of the isomeric state to the ground state, and the factor F_k is related as [19]:

$$F_{k=m,g} = \frac{(1 - e^{-\lambda_k \tau}) \times (1 - e^{-\lambda_k t_i}) \times e^{-\lambda_k t_w} \times (1 - e^{-\lambda_k t_c})}{1 - e^{-\lambda_k T}} e^{-\lambda_k(T-\tau)} \qquad (4)$$

The isomeric yield ratio for the $^{nat}Sm(\gamma,xn)^{143m,g}Sm$ reactions was determined based on the γ-activities of the isomeric-state $^{143m,g}Sm$ (high-spin state 11/2-) and the ground-state ^{143g}Sm (low-spin state, 3/2$^+$). The activity of the ^{143m}Sm was measured based on the 754.4 keV γ-peak, and that for the ^{143g}Sm was measured based on the 1056.58 keV γ-peak, respectively. The 754.4 keV γ-peak is interference free, but the 1056.58 keV γ-peak is overlap with the 1057.1 keV γ-peak of the ^{141m}Sm formed via the $^{nat}Sm(\gamma,xn)^{141m,g}Sm$ reaction. The contribution of the ^{141m}Sm to the common peak 1056.58-1057.1 keV was separated based on the following equation:

$$S_{(1057.1keV)} = S_{(431.6keV)} \times \frac{\varepsilon_{(1057.1keV)}}{\varepsilon_{(431.6keV)}} \times \frac{I_{(1057.1keV)}}{I_{(431.6keV)}} \qquad (5)$$

where the 431.6 keV is the γ-ray emitted from the ^{141m}Sm and interference free, and the $S_{(1057.1keV)}$ and $S_{(431.6keV)}$ are the net peak areas of the 1057.1 keV and 431.6 keV γ-rays, the $\varepsilon_{(1057.1keV)}$ and $\varepsilon_{(431.6\,keV)}$ are the detection efficiencies of the 1057.1 keV and 431.6 keV γ-rays, that can be derived from the experimental efficiency curve, and the $I_{(1057.1\,keV)}$ and $I_{(431.6\,keV)}$ are the γ-ray

branching fractions of the 1057.1 keV and 431.6 keV, that can be obtained from the literature [16], respectively.

      After spectra measurement and data analysis the isomeric yield ratios for the isomeric pairs of interest were computed using the Eq. (3).

IV. RESULTS AND DISSCUSIONS

      The present isomeric yield ratios for the ^{nat}Sm$(\gamma,xn)^{143m,g}$Sm reactions together with the reference data are given in Table 3 and illustrated graphically in Fig. 2. This figure shows the trend of energy dependence of the isomeric yield ratios for the ^{nat}Sm$(\gamma,xn)^{143m,g}$Sm reactions over a wide range of energies, from the reaction threshold to 50 MeV bremsstrahlung. As can be seen, the isomeric yield ratios increase rapidly as the bremsstrahlung energies increase from the reaction threshold up to the GDR region, at approximately 20 MeV, and then they seem saturated. However, from about 35-40 MeV they appear to increase slightly again. The rapidly increasing part can be explained on basis of a compound nuclear reaction mechanism in which the increased momentum was transferred to the compound nuclei. At higher energies, the direct reaction can also be occurred and the directly ejected particles carry away a relatively large angular momentum, and only a fraction of the energy and angular momentum of the incident bremsstrahlung photons are transferred to the target nucleus. From about 35-40 MeV together with the ^{144}Sm$(\gamma,n)^{143m,g}$Sm reaction (with threshold energies of 11.06 MeV and 10.52 MeV for the production of the ^{143m}Sm and ^{143g}Sm, respectively), the following multi-neutron reactions such as ^{147}Sm$(\gamma,4n)^{143m,g}$Sm, ^{148}Sm$(\gamma,5n)^{143m,g}$Sm, ^{149}Sm$(\gamma,6n)^{143m,g}$Sm, and ^{150}Sm$(\gamma,7n)^{143m,g}$Sm with threshold energies of about 32.79-, 40.93-, 46.8-, and 54.79-MeV can also be occurred. Obviously, the energy dependence of the isomeric yield ratios for the ^{143m,g}Sm reaction in the energy region from the threshold energy to about 35 MeV can be explained based on the compound and the direct reaction mechanisms [19]. The slightly increasing tendency from about 35 MeV bremsstrahlung energy can be attributed to the contribution from the multi-neutron reactions ^{nat}Sm$(\gamma,xn)^{143m,g}$Sm with the number of neutrons ejected $x \geq 4$ and the threshold energy is greater than about 35 MeV.

Table 3. Isomeric yield ratios of the ^{nat}Sm$(\gamma,xn)^{143m,g}$Sm photonuclear reactions at different bremsstrahlung energies.

$E_{\gamma max}$ (MeV)	Y_{high}/Y_{low}				
	Palvanov *et al.* [11]	Mazur *et al.* [12]	Belov *et al.* [13]	H.D.Luc *et al.* [14]	This work
12	–	0.0013±0.0013	–	–	–
15	0.0252±0.0039	0.020±0.0024	–	0.031±0.003	–
20	0.0433±0.0029		–	–	–
25	0.041±0.002		0.046±0.005		–
30	0.0443±0.0031				–
35	0.0422±0.0029				–
40					0.0429±0.0033
45					0.0572±0.0037
50					0.0556±0.0036

In literature we have found some reference data for similar isomeric pair induced from the ^{144}Sm(n,2n)^{143m,g}Sm reaction with 14 MeV neutrons. The reported isomeric data are as follows: 0.75±0.07 [11], 0.70±0.06 [14], 0.871±0.096 [20], 0.635±0.088 [21], and 0.782±0.078 [22]. Obviously, the isomeric ratios for the ^{144}Sm(n,2n)^{143m,g}Sm reaction induced by 14 MeV neutrons are lager compare with the isomeric yield ratios of the ^{nat}Sm(γ,xn)^{143m,g}Sm reactions. It is understandable due to the larger input angular momentum of the 14 MeV neutrons.
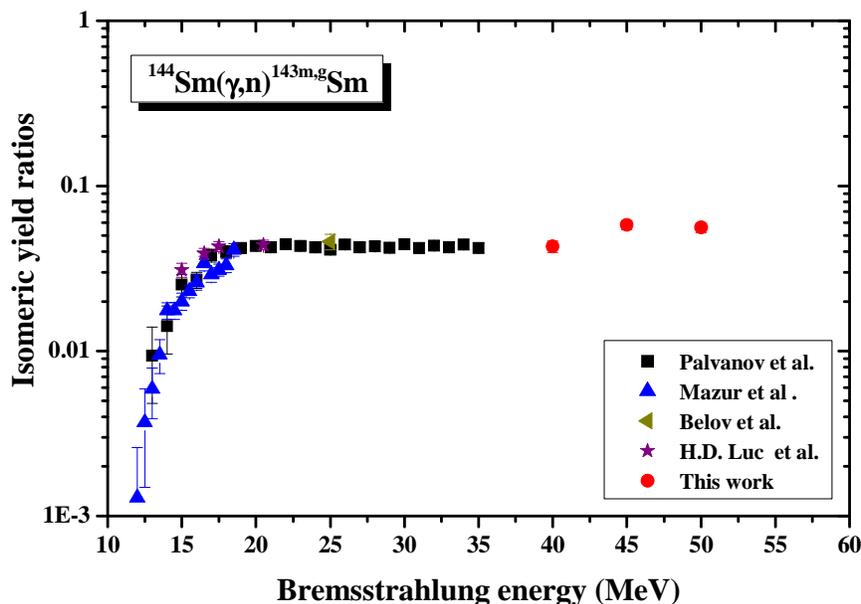
Fig. 2. Energy dependence of the isomeric yield ratio for the ^{nat}Sm(γ,xn)^{143m,g}Sm reaction.

V. CONCLUSION

We have measured the isomeric yield ratios for the ^{nat}Sm(γ,xn)^{143m,g}Sm reactions with bremsstrahlung end poind energies just above the GDR region. The present results for the ^{nat}Sm(γ,xn)^{143m,g}Sm reactions are the first measurement at 40-, 45-, and 50-MeV bremsstrahlung energies. The experimental results confirm the effects of the excitation energies and the input angular momentum of the incoming projectiles.

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