Communications in Physics, Vol. 22, No. 1 (2012), pp. 75-81

MEASUREMENT OF THE YIELD RATIO OF THE ^{122m,g}Sb ISOMERIC PAIR ABOVE THE GIANT RESONANCE

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Abstract. *The yield ratio of the high-spin state of ^{122m}Sb (8^-) and the low-spin state of ^{122g}Sb (2^-) formed via the ^{123}Sb(γ,n)^{122m,g}Sb reaction has been measured as a function of the bremsstrahlung end-point energy in the range of 40-MeV to 60-MeV. Use was made of the activation technique in combination with high-resolution γ-ray spectrometry. The isomeric yield ratios for the ^{123}Sb(γ,n)^{122m,g}Sb reaction measured at 40-, 45-, 50-, 55-, and 60-MeV bremsstrahlung are 0.341 ± 0.022, 0.362 ± 0.020, 0.374 ± 0.021, 0.371 ± 0.021, and 0.367 ± 0.022. According to our knowledge, the present results are the first measurement.*

I. INTRODUCTION

The isomeric ratio is defined as the ratio of the cross-section for the production of an isomeric state over that of unstable ground state (σ_m/σ_g). Studies of isomeric ratios are of great importance in both fundamental nuclear physics research and applications [1-6]. So far, the isomeric ratios are mainly measured on nuclear reactions induced by neutrons [7-12], charged particles [13-16], and bremsstrahlung photons [3,5,17,18]. The measurement with gamma quanta as projectiles has some essential advantages in studying nuclear structure and nuclear reaction mechanism.

In the present work we have chosen the ^{123}Sb(γ,n)^{122m,g}Sb photonuclear reactionfor studies. From literature we have found some experimental data for the ^{123}Sb(γ,n)^{122m,g}Sb reaction, but all of them were measured at low-energies, from threshold up to 22-MeV [17,18]. For those reactions, the reaction mechanisms are well understood at low-energy, but very little is known in detail about the reaction mechanisms that proceed at higher energies. In this work we extend our measurements to higher incident bremsstrahlung energies, from 40-MeV to 60-MeV in order to obtain information about the mechanisms of photonuclear reactions at energies just above the giant resonance region. In order to improve the accuracy of the experimental results the necessary corrections were made. The experimental results can help in understanding the mechanisms of the ^{123}Sb(γ,n)^{122m,g}Sb reaction in the energy interval from the reaction threshold to just above the Giant Dipole Resonance (GDR) region.

II. EXPERIMENTAL

The experiments were performed at the 100-MeV electron linac of the Pohang Accelerator Laboratory (PAL), of which the details are described elsewhere [19-2]. The bremsstrahlung photons were produced when pulsed electrons hit a thin W target with a size of 100 mm × 100 mm and a thickness of 0.1 mm. The W target was located at 18 cm from the beam exit window.

In this experiment, high purity (99.999%) natural antimony samples (^{nat}Sb) in powder form (200 mesh), made by Johnson Matthey Company (USA) were used. The antimony powders were encapsulated into the same polyethylene capsules with a diameter of 12 mm.

For irradiation, the natural antimony sample was placed at 12 cm from the thin W-target. Each sample was irradiated for 20 min. During irradiation the electron linac was operated with a repetition rate of 15 Hz, a pulse width of 2.0 μs. Five irradiations were performed at energies of 40-, 45-, 50-, 55-, and 60-MeV respectively. The characteristics of the ^{123}Sb(γ,n)^{122m,g}Sb photonuclear reaction are listed in Table 1 [21].

Table 1. Nuclear reactions investigated and decay data of the isomeric pair ^{122m,g}Sb [21].

Nuclear reaction	Threshold energy, E_{th}(MeV)	Halflife, $T_{1/2}$	Spin and parity, J^{π}	γ-energy, E_γ [keV]	$\gamma-$ray intensity, I_γ (%)
^{123}Sb(γ,n)^{122m}Sb	9.103	4.191 min	8^-	61.41	55
				76.06	23
^{123}Sb(γ,n)^{122g}Sb	8.966	2.7238 d	2^-	564.12	71
				692.79	3.85
				1140.55	0.76

The γ-ray activities of irradiated samples were measured by using a high-purity HPGe detector (ORTEC) with energy resolution of 1.75 keV, and the relative efficiency is 10% at the 1332.5 keV γ-ray of ^{60}Co. The counting efficiency of the detector was determined experimentally using a set of γ-standard sources. The efficiency measurement was done by the same way as mentioned in ref.[22]. In order to optimize the dead time and the coincidence summing effect we have chosen the appropriate distance between the sample and the detector for each measurement. Each sample was measured several times in order to follow the decay of the different isotopes.

From the simplified level and decay scheme of the ^{122m,g}Sb given in Fig. 1 we can see that the isomericstate ^{122m}Sb (highspin state 8^-) with a half-life of 4.191 min decays to the unstable groundstate ^{122g}Sb (lowspin state 2^-) by an isomeric transition process and emits the 61.41 keV (55%) and the 76.06 keV (23%) γ-rays. The activity of the isomeric-state nuclide was measured by using the strongest γ-ray of 61.41 keV. Due to the half-life of the ^{123m}Sb is rather short, the measurement was started as soon as possible after the end of the irradiation. The unstable groundstate nuclei ^{122g}Sb with a half-life of 2.7238 d decays by both an EC and a β^-process to form the stable isotopes, ^{122}Sn and ^{122}Te. For the activity measurement, the interference free γ-ray of 564.12 keV (71%) was used. Due to the half-life of ^{122g}Sb is rather long, the measurement was started several hours after the end of the irradiation. A typical γ-ray spectra from the ^{nat}Sb sample irradiated with 50 MeV bremsstrahlung are given in Fig. 2.

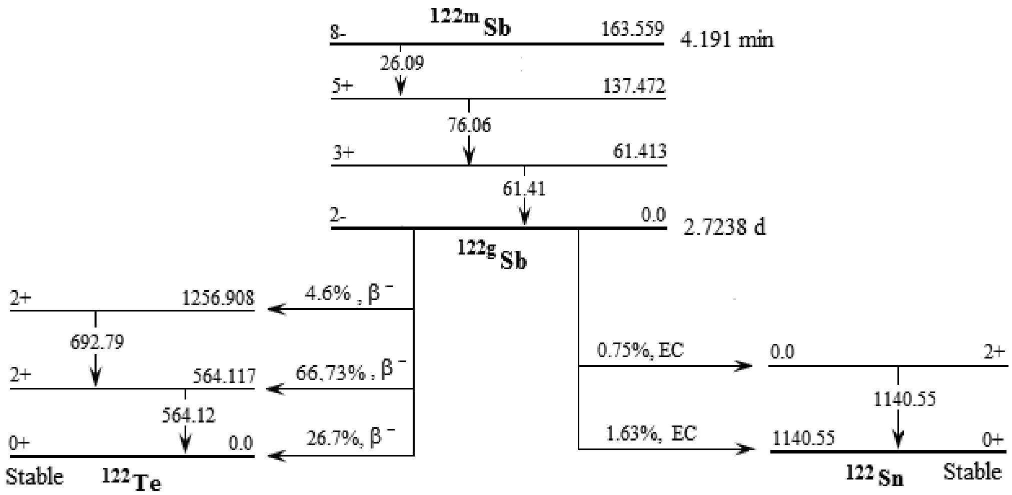

Fig. 1. Simplified decay scheme of the isomeric pair ^{122m,g}Sb. The nuclear level energies are in keV.

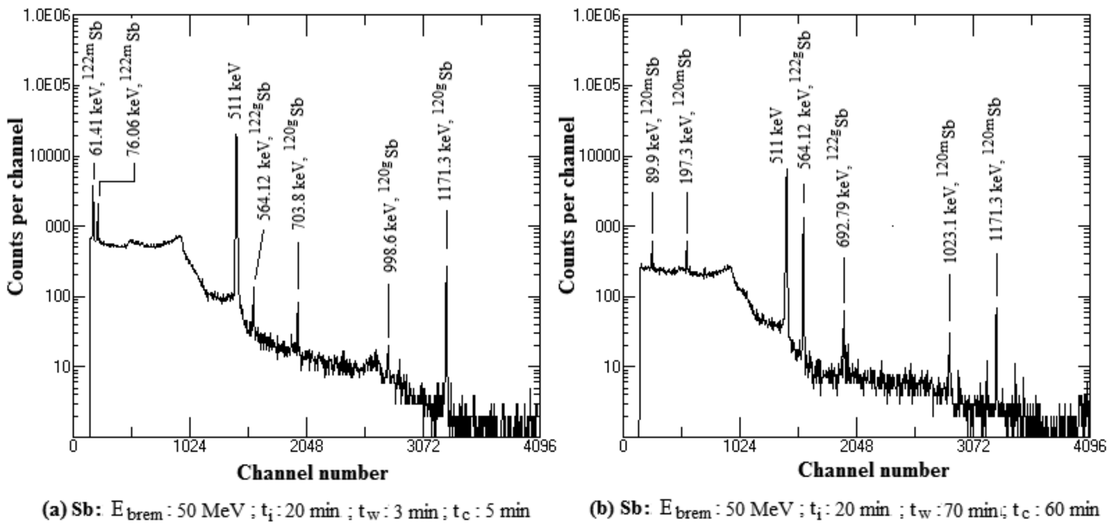

Fig. 2. Typical γ-ray spectra from the ^{nat}Sb sample the irradiated with 50 MeV bremsstrahlung.

III. DATA ANALYSIS

Due to the activation was performed by non-monoenergetic bremsstrahlung photons, the isomeric ratio is then expressed through the yields of the two states instead of the two cross-sections, namely: $IR{=}Y_m/Y_g$. The yield of the bremsstrahlung-induced reaction is given by:

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

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.

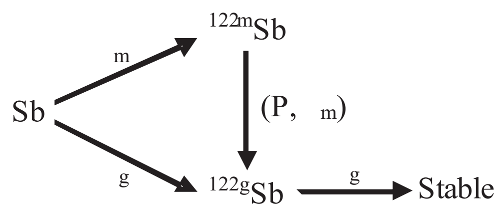

Fig. 3. Activation scheme for the population of isomeric state (^{122m}Sb) and unstable ground state (^{122g}Sb)

By taking into account the fact that the sample was irradiated by the pulsed bremsstrahlung beam, the relationship between the numbers of detected γ-rays, S_k and the reaction yield, Y_k *is* expressed as follows:

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

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.

From the schematic view for the production of the ^{122m,g}Sb isomeric pair shown in Fig. 3 we know that, when the bremsstrahlung radiations strike the ^{123}Sb nuclide, the metastable state nuclide ^{122m}Sb is formed directly from the ^{123}Sb nuclide with the probability of σ_m. However, the ground state nuclide ^{122g}Sb is formed in two ways, (1) directly from the ^{123}Sb nuclide with the probability of σ_g, and (2) indirectly through the decay of the metastable state nuclide ^{122m}Sb with the disintegration fraction of P. The production of the ^{122m,g}Sb isomeric pair and its decay during the activation time can be described by the following differential equations:

$$\frac{dN_m}{dt} = Y_m - \lambda_m N_m, \tag{3}$$

$$\frac{dN_g}{dt} = Y_g - \lambda_g N_g + P\lambda_m N_m, \tag{4}$$

By solving system of equations (3) and (4) we can derive the isomeric yield ratio as follows:

$$IR \equiv \frac{Y_m}{Y_g} = \left[\frac{\lambda_g F_m}{\lambda_m F_g} \times \left(\frac{S_g}{S_m} \times \frac{\varepsilon_m I_m}{\varepsilon_g I_g} - \frac{P\lambda_g}{\lambda_g - \lambda_m}\right) + \frac{P\lambda_m}{\lambda_g - \lambda_m}\right]^{-1}, \quad (5)$$

where S_m and S_g are the photo-peak areas for the detected γ-rays of the isomeric - and the ground-state, and the factor F_k is related as:

$$F_{k=m,g} = \frac{(1 - e^{-\lambda_k\,\tau}) \times (1 - e^{-\lambda_k\,t_i}) \times e^{-\lambda_k\,t_w} \times (1 - e^{-\lambda_k\,t_c})}{1 - e^{-\lambda_k\,T}} e^{-\lambda_k(T-\tau)} \quad (6)$$

After measurements, photopeak area analysis and making the necessary corrections such as counting losses due to the γ-ray self-absorption, the coincidence summing of cascade γ-rays and the variation of bremsstrahlung intensity during the irradiation [23-26], the isomeric yield ratio for the ^{122m,g}Sb isomeric pair was then calculated using the Eq. (5).

IV. RESULTS AND DISCUSSIONS

The isomeric yield ratios for the ^{123}Sb(γ,n)^{122m,g}Sb reactions together with reference data measured at lower bremsstrahlung energies, from 12- to 22-MeV [17,18] are given in Tab. 2 and illustrated graphically in Fig. 4. The main sources of the errors are statistical error, detection efficiency, photopeak area determination, coincidence summing effect and nuclear data used. The total uncertainties were estimated to be 5 - 7%.

Table 2. Isomeric yield ratios for ^{123}Sb(γ,n)^{122m,g}Sb reaction at different bremsstrahlung energies

Nuclear reaction	E_{Brem}(MeV)	IR=Y_{high}/Y_{low}	
		This work	Refs.
^{123}Sb(γ,n)^{122m,g}Sb	12	-	0.092±0.01 [17]
^{123}Sb(γ,n)^{122m,g}Sb	13	-	0.118±0.015 [17]
^{123}Sb(γ,n)^{122m,g}Sb	14	-	0.12±0.015 [17]
^{123}Sb(γ,n)^{122m,g}Sb	15	-	0.129±0.021 [17]
^{123}Sb(γ,n)^{122m,g}Sb	16	-	0.138±0.026 [17]
			0.15±0.01 [18]
^{123}Sb(γ,n)^{122m,g}Sb	17	-	0.162±0.03 [17]
^{123}Sb(γ,n)^{122m,g}Sb	18	-	0.154±0.02 [17]
^{123}Sb(γ,n)^{122m,g}Sb	19	-	0.182±0.02 [17]
^{123}Sb(γ,n)^{122m,g}Sb	20	-	0.16±0.014 [17]
^{123}Sb(γ,n)^{122m,g}Sb	21	-	0.191±0.012 [17]
^{123}Sb(γ,n)^{122m,g}Sb	22	-	0.213±0.036 [17]
^{123}Sb(γ,n)^{122m,g}Sb	40	0.341 ± 0.022	-
^{123}Sb(γ,n)^{122m,g}Sb	45	0.362 ± 0.020	-
^{123}Sb(γ,n)^{122m,g}Sb	50	0.374 ± 0.021	-
^{123}Sb(γ,n)^{122m,g}Sb	55	0.371 ± 0.021	-
^{123}Sb(γ,n)^{122m,g}Sb	60	0.367 ± 0.022	-

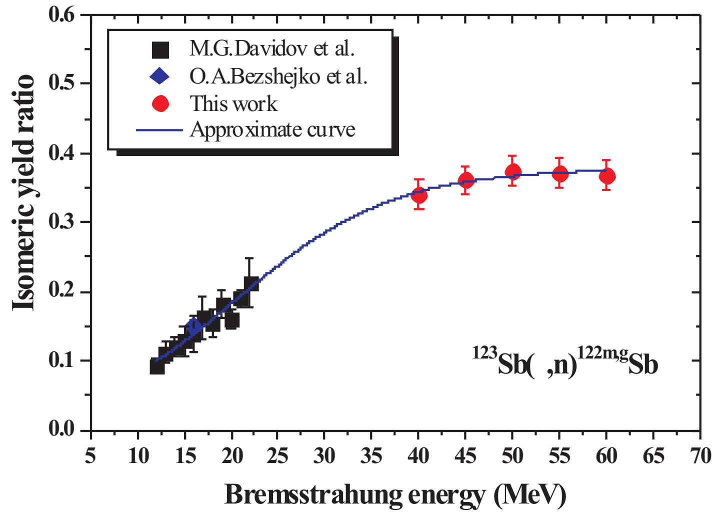

Fig. 4. The isomeric yield ratio for the ^{122m,g}Sb pair as a function of the incident beam energy.

From Fig. 4 we can see that, the isomeric yield ratios for the ^{123}Sb(γ,n)^{122m,g}Sb reaction increase rapidly with the increasing bremsstrahlung energies from the reaction threshold up to about 25-30 MeV, and then it seems saturated beyond 50 MeV. The transition from the previous data measured at low-energies, from 12 MeV to 22 MeV to the present data measured at higher energies, from 40- to 60-MeV is relatively smooth. The curve illustrated the energy dependence of the isomeric yield ratio for the ^{123}Sb(γ,n)^{122m,g}Sb reaction in the energy region from 12- to 60- MeV can be approximated by the expression:

$$IR = a/(1 + \exp(-q(E_{brem} - b)) \tag{7}$$

where: a = 0.378 $\pm$ 0.006; q= (0.120$\pm$0.009) [MeV^{-1}] and b = (20.575$\pm$0.515) [MeV] are the fitting parameters , and E_{brem} is the maximum end-point energy of the bremsstrahlung.

V. CONCLUSION

We have measured the isomeric yield ratios for the ^{123}Sb(γ,n)^{122m,g}Sb reaction at 40-, 45-, 50-, 55-, and 60-MeV bremsstrahlung energies. The present results are the first measurement. We observed that, the isomeric yield ratios for the ^{123}Sb(γ,n)^{122m,g}Sb reaction increase gradually with increasing the incident bremsstrahlung energies from the reaction threshold up to the GDR region, and then it seems saturated beyond 50 MeV. The increasing ratios indicate the increased momentum transfer to the compound nuclei and the saturated ratios at higher energies can be explained as increasing of the direct reaction mechanism, where emitted particles carry off a large fraction of energy and angular momentum.

ACKNOWLEDGEMENTS

The authors would like to express their sincere thanks to the support of the Pohang Accelerator Laboratory, POSTECH, Korea and of the Vietnam National Foundation for Science and Technology Development (NAFOSTED).

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Received 28 November 2011.