Nuclear Instruments and Methods in Physics Research B 266 (2008) 5080–5086

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Isomeric yield ratios for the formation of ^{44m,g}Sc in the ^{45}Sc(γ,n), ^{nat}Ti(γ,xnp), ^{nat}Fe(γ,xn5p) and ^{nat}Cu(γ,xn8p) reactions with 2.5 GeV bremsstrahlung

Nguyen Van Do [a], Pham Duc Khue [a], Kim Tien Thanh [a], Le Truong Son [b,1], Md. Shakilur Rahman [c], Kyung-Sook Kim [c], Manwoo Lee [c], Guinyun Kim [c,*], Youngdo Oh [d], Hee-Seock Lee [d], Moo-Hyun Cho [d], In Soo Ko [d], Won Namkung [d]

[a] *Institute of Physics and Electronics, Vietnam Academy of Science and Technology, 10 Dao Tan, Hanoi, Viet Nam*
[b] *Institute of Engineering Physics, Hanoi University of Technology, 1. Dai Co Viet, Hanoi, Viet Nam*
[c] *Department of Physics, Kyungpook National University, 1370 Sankyuk-dong, Puk-gu, Daegu 702-701, Republic of Korea*
[d] *Pohang Accelerator Laboratory, Pohang University of Science and Technology, San 31 Hyoja-dong, Nam-gu, Pohang 790-784, Republic of Korea*

ARTICLE INFO

Article history:
Received 25 July 2008
Received in revised form 5 September 2008
Available online 23 September 2008

PACS:
25.40.Lw
25.20.Lj

Keywords:
Isomeric yield ratio
Photonuclear reaction
2.5 GeV bremsstrahlung
Activation method
High-purity germanium detector

ABSTRACT

We measured the isomeric yield ratios for the ^{44m,g}Sc isomeric pairs produced from four different photonuclear reactions ^{45}Sc(γ,n)^{44m,g}Sc, ^{nat}Ti(γ,xn1p)^{44m,g}Sc, ^{nat}Fe(γ,xn5p)^{44m,g}Sc, and ^{nat}Cu(γ,xn8p)^{44m,g}Sc by using the activation method. The high purity natural Sc, Ti, Fe, and Cu metallic foils in disc shape were irradiated with uncollimated 2.5 GeV bremsstrahlung beams of the Pohang Accelerator Laboratory. The induced activities in the irradiated foils were measured by the high-resolution γ-ray spectrometry with a calibrated high-purity Germanium (HPGe) detector. In order to improve the accuracy of the experimental results the necessary corrections were made in the gamma activity measurements and data analysis. The obtained isomeric yield ratios for the ^{45}Sc(γ,n)^{44m,g}Sc, ^{nat}Ti(γ,xn1p)^{44m,g}Sc, ^{nat}Fe(γ,xn5p)^{44m,g}Sc and ^{nat}Cu(γ,xn8p)^{44m,g}Sc reactions are 0.25 ± 0.03, 0.43 ± 0.05, 1.38 ± 0.14, and 1.89 ± 0.21, respectively. The present result for the ^{nat}Cu(γ,xn8p)^{44m,g}Sc reaction is in good agreement with the existing data. Our results for the ^{45}Sc(γ,n)^{44m,g}Sc, ^{nat}Ti(γ,xn1p)^{44m,g}Sc, and ^{nat}Fe(γ,xn5p)^{44m,g}Sc reactions are the first measurements at 2.5 GeV bremsstrahlung. The obtained results are compared with the corresponding values found in the literature. The relation between the isomeric yield ratios and the complexity of the photonuclear reactions is discussed.

1. Introduction

Since many years, the nuclear reactions leading to the residual nuclei with an isomeric state and unstable ground state have been subjected to extensive studies for better understanding of the mechanism of such reactions. The relative population of these two states is known as the isomeric ratio (IR), and expressed by IR = σ_m/σ_g where σ_m and σ_g denote the cross-section for the formation of a metastable (isomeric) state and an unstable ground state, respectively. Because of the isomeric state and the ground state strongly differ in spin values, the isomeric ratio can also 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) [1–3]. In case of the bremsstrahlung photon irradiation, due to the continuity of the energy spectrum, the isomeric ratio can also be represented through the yields of the two states instead of the two cross-sections, namely, IR = Y_{high}/Y_{low} [3–5].

The data for the isomeric ratios are of fundamental interest because they are useful for various studies related to nuclear reactions and nuclear structure such as transfer of angular momentum, spin dependence of nuclear level density, refinements in gamma transition theories and testing of theoretical nuclear models [6–10]. However, the knowledge regarding the formation of isomeric states is rather scanty and some discrepancies are still observed among the literature values which might be attributed to variations in experimental methods and/or the nuclear constants [9,10]. Therefore, till now a great interest has been paid to the measurements of isomeric ratios.

Most experimental results for isomeric ratios were determined for nuclear reactions induced by neutrons around 14 MeV [9–16]. Measurements for the nuclear reactions induced by bremsstrahlung photons are rare and were carried out mainly for simple reactions at low energies [17]. The reason is possibly the experimental difficulties, mainly the lack of intense photon sources and the inherent background problems at photon beams [18]. Although

* Corresponding author. Tel.: +82 53 950 5320; fax: +82 53 939 3972.
E-mail address: gnkim@knu.ac.kr (G. Kim).
1 Present address: Department of Physics, Brown University, USA.

0168-583X/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2008.09.017

the bremsstrahlung photons carry relatively small momentum, it is a good tool for investigating the dependences of isomeric yield ratios as functions of the incident photon energy and the mass difference (ΔA) between the product (A_p) and the target nucleus (A_t) [19].

The nuclear reactions considered in this investigation are ^{45}Sc(γ,n)^{44m,g}Sc, ^{nat}Ti(γ,xn1p)^{44m,g}Sc, ^{nat}Fe(γ,xn5p)^{44m,g}Sc, and ^{nat}Cu(γ,xn8p)^{44m,g}Sc. The nucleus ^{44m,g}Sc is a suitable product to study since it is almost screened from precursors and is convenient to measure with the activation method. Most of the ^{44m,g}Sc isomeric pairs found in literature were formed via simple reactions with incident projectiles of rather low energies. Mocoroa et al. [20] measured the isomeric cross-section ratio for the ^{44m,g}Sc radionuclide produced by ^{45}Sc(d,t)^{44m,g}Sc reaction in the deuteron energy range from threshold to 28.6 MeV. Kopecky et al. [21] determined the isomeric cross-section ratio for the ^{44m,g}Sc formed through the ^{nat}Ti(p,x)^{44m,g}Sc reaction in the energy range from 9.0 to 17.5 MeV. Eapen and Salaita [22] reported the isomeric cross-section ratio for the ^{44m,g}Sc radionuclide produced by ^{45}Sc(n,2n)^{44m,g}Sc reaction induced by 14.8 MeV neutrons. Kao and Alford [12] determined the isomeric cross-section ratio for the ^{44m,g}Sc radionuclide produced by the ^{45}Sc(n,2n)^{44m,g}Sc reaction with 15.1 MeV neutrons. Francois and Shakir [23] measured the isomeric cross-section ratio for the ^{45}Sc(n,2n)^{44m,g}Sc reaction induced by neutrons derived from the D–T reaction using deuterons accelerated to 300 keV in a Van de Graff accelerator.

There are number of isomeric yield ratios for the ^{44m,g}Sc isomeric pairs measured by photonuclear reactions. Most of them were measured with bremsstrahlung energies less than 2 GeV, except Danagulyan et al. [24], where it was measured in the energy region between 2 and 5 GeV. Zheltonozhski and Mazur [25] measured the isomeric yield ratio for the ^{45}Sc(γ,n)^{44m,g}Sc reaction with bremsstrahlung energies from 12.43 MeV to 20.83 MeV. Volpel [1] and Davidov et al. [26] measured the isomeric yield ratio for the ^{45}Sc(γ,n)^{44m,g}Sc reaction with photon energy of 45 MeV and 22 MeV, respectively. Walters and Hummel [8] measured with maximum bremsstrahlung energy up to 300 MeV. For the ^{nat}Fe(γ,xn5p)^{44m,g}Sc reaction, the isomeric yield ratios have been measured by Ericksson and Jonsson [18] and by di Napoli et al. [27] with photon energies of 250–800 MeV and 300–1000 MeV, respectively. The isomeric yield ratios of the ^{nat}Cu(γ,xn8p)^{44m,g}Sc reaction were measured by Bachschi et al. [28] with photon energy of 2 GeV, and by Danagulyan et al. [24] with photon energies between 2 and 5 GeV. Recently, we also measured the isomeric yield ratios for the following nuclear reactions ^{45}Sc(γ,n)^{44m,g}Sc, ^{nat}Ti(γ,xnp)^{44m,g}Sc at 65 MeV bremsstrahlung [29].

The aim of the present work is to extend our measurements to higher incident photon energy up to 2.5 GeV, and to determine the isomeric yield ratios for the ^{44m,g}Sc radionuclide produced by different photonuclear reaction channels ^{45}Sc(γ,n)^{44m,g}Sc, ^{nat}Ti(γ,xn1p)^{44m,g}Sc, ^{nat}Fe(γ,xn5p)^{44m,g}Sc, and ^{nat}Cu(γ,xn8p)^{44m,g}Sc. The experiment was done at the 2.5 GeV electron linac of the Pohang Accelerator Laboratory (PAL).

2. Experimental procedure

2.1. 2.5 GeV bremsstrahlung production

The experiment was carried out at the 10° beam line of the 2.5 GeV electron linac of the PAL. The details of the 2.5 GeV electron linac and its applications were described elsewhere [30,31]. The bremsstrahlung photons were produced when a pulsed electron beam hit a thin W target with a size of 50 mm × 50 mm and a thickness of 0.2 mm. The W target is located at 38.5 cm from the beam exit window.

2.2. Sample irradiation

High-purity natural Sc, Ti, Fe, and Cu foils in disc shape, made by Reactor Experiments Inc. (USA), were exposed to uncollimated bremsstrahlung beams from the PAL 2.5 GeV electron linac. The characteristics of the activation foils are given in Table 1.

The activation foils were placed in air at 24 cm from the W target and they were positioned at zero degree with the direction of the electron beam. A simplified experimental arrangement is shown in Fig. 1. In this work, three irradiations with durations of 64 min, 170 min and 240 min were performed. During the irradiation, the electron linac was operated with a repetition rate of 10 Hz, a pulse width of 1 ns, and the electron energy of 2.5 GeV.

2.3. Activity measurements

After an irradiation and an appropriate waiting time, the foils were taken off, and then the induced gamma activities of the irradiated foils were measured by using a gamma spectrometer, without any chemical purification. The gamma spectrometer used for the measurements was a coaxial CANBERRA high-purity germanium (HPGe) detector with a diameter of 59.2 mm and length of 30 mm. The HPGe detector was coupled to a computer-based multichannel analyzer card system, which could determine the photo-peak-area of the gamma ray spectra by using the GENIE2000 (Canberra) computer program. The energy resolution of the detector was 1.80 keV full width at half maximum (FWHM) at the 1332.5 keV peak of ^{60}Co. The detection efficiency was 20% at 1332.5 keV relative to a 7.62 cm diameter × 7.62 cm length NaI(Tl) detector. The photopeak efficiency curve of the gamma spectrometer was calibrated with a set of standard gamma sources: ^{241}Am (59.541 keV), ^{137}Cs (661.657 keV), ^{54}Mn (834.848 keV), ^{60}Co (1173.237 keV and 1332.501 keV), and ^{133}Ba (80.997 keV, 276.398 keV, 302.853 keV, 356.017 and 383.815 keV). The measured detection efficiencies were fitted by using the following function:

$$\ln\epsilon = \sum_{n=0}^{5} a_n \ln E^n, \quad (1)$$

where ε is the detection efficiency, a_n represents the fitting parameters, and E is the energy of the photopeak. The detection efficiencies as a function of the photon energy measured at different distances between the source and the surface of the detector were illustrated in [29].

Table 1
Characteristics of the Sc, Ti, Fe and Cu activation foils

Sample	Purity (%)	Diameter (mm)	Thickness (mm)
Sc	99.81	12.7	0.127
Ti	99.63	12.7	0.100
Fe	99.559	12.7	0.127
Cu	99.96	12.7	0.100

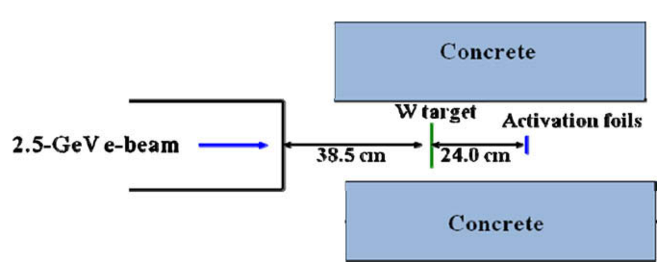

Fig. 1. Experimental arrangement for the irradiation of activation foils.