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Thermal neutron capture and resonance integral cross sections of ^{45}Sc

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ABSTRACT

The thermal neutron cross section (σ_0) and resonance integral (I_0) of the ^{45}Sc(n,γ)^{46}Sc reaction have been measured relative to that of the ^{197}Au(n,γ)^{198}Au reaction by means of the activation method. High-purity natural scandium and gold foils without and with a cadmium cover of 0.5 mm thickness were irradiated with moderated pulsed neutrons produced from the Pohang Neutron Facility (PNF). The induced activities in the activated foils were measured with a high purity germanium (HPGe) detector. In order to improve the accuracy of the experimental results the counting losses caused by the thermal (G_{th}) and resonance (G_{epi}) neutron self-shielding, the γ-ray attenuation (F_g) and the true γ-ray coincidence summing effects were made. In addition, the effect of non-ideal epithermal spectrum was also taken into account by determining the neutron spectrum shape factor (α). The thermal neutron cross-section and resonance integral of the ^{45}Sc(n,γ)^{46}Sc reaction have been determined relative to the reference values of the ^{197}Au(n,γ)^{198}Au reaction, with $\sigma_{o,Au}$ = 98.65 ± 0.09 barn and $I_{o,Au}$ = 1550 ± 28 barn. The present thermal neutron cross section has been determined to be $\sigma_{o,Sc}$ = 27.5 ± 0.8 barn. According to the definition of cadmium cut-off energy at 0.55 eV, the present resonance integral cross section has been determined to be $I_{o,Sc}$ = 12.4 ± 0.7 barn. The present results are compared with literature values and discussed.

1. Introduction

The knowledge of thermal neutron capture cross sections and resonance integrals are of great important in fundamental nuclear research and in various fields of applications [1,2]. In this work we have chosen the ^{45}Sc(n,γ)^{46}Sc reaction for study. Scandium is used increasingly in aluminum alloys and the ^{46}Sc radioactive isotope is used as a tracing agent in refinery crackers for crude oil [3] as well as in biological and medical studies [4]. The accurate knowledge of the ^{45}Sc(n,γ)^{46}Sc reaction cross section is helpful in the production of the important radioactive isotope ^{46}Sc.

In literature we have found 12 experimental thermal neutron capture cross sections [5–16] and 10 evaluated data [17–21], and 5 experimental resonance integral cross sections [5,7,15,22,23] and 10 evaluated data [17,19–21,24] of the ^{45}Sc(n,γ)^{46}Sc reaction. All these experimental data have been measured before 1985 and they are still scattered. The experimental thermal neutron cross sections existing in the literature vary from 22 ± 4.4 barn [16] to 31.8 ± 1.6 barn [15], differ by about 45%. The experimental resonance integrals vary from 10.7 ± 0.9 barn [23] to 14.2 barn [22], differ by about 33%, respectively. The large discrepancies among the existing reference data make it difficult to produce the best value for applications. Therefore, it is necessary to measure additional data for better comparison and evaluation.

In this work we used the pulsed neutrons generated from the PNF based on the 100-MeV electron linac to produce the ^{45}Sc(n,γ)^{46}Sc reaction. The experiment was carried out by using the activation method in combination with the Cd-ratio method. The aim of this work is to provide additional thermal neutron cross section and resonance integral of the ^{45}Sc(n,γ)^{46}Sc reaction for evaluation and applications. In order to improve the accuracy of the experimental results, the corrections for the counting losses caused by the γ-ray attenuation (F_g), self-shielding of thermal (G_{th}) and resonance neutrons (G_{epi}) as well as true γ-ray coincidence summing effects were made. In addition, the neutron spectra in actual irradiation positions are more or less deviated from this ideal $1/E$ distribution shape, and the real neutron spectra are approximated by the $1/E^{1+\alpha}$ distribution. Therefore, in order to improve the accuracy of the resonance integral, the effect of

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non-ideal epithermal spectrum was taken into account by determining the neutron spectrum shape factor (α).

2. Experimental procedure

2.1. Sample preparation and irradiation

Two high-purity (99.81%) scandium foils (Sc1 and Sc2) in disc-shaped with a thickness of 0.127 mm and the weight of 0.0512 g and 0.0475 g, made by Reactor Experiments Inc. (USA) were prepared as the activation samples. In addition, two gold foils (Au1 and Au2) with a purity of 99.95%, a thickness of 0.03 mm, and the weight of 0.0706 g and 0.0693 g, respectively. Six indium foils with a purity of 99.95%, a thickness of 0.05 mm, and the weights are varied from 0.0495 to 0.0514 g. The prepared foils were irradiated by moderated neutrons produced from the PNF based on the 100-MeV electron linac of the Pohang accelerator laboratory (PAL), Pohang, Korea. The details of the PNF were described elsewhere [25–27]. The neutrons were produced by impinging the accelerated electron beam upon the water-cooled Ta-target, which was set at the center of a cylindrical water moderator contained in an aluminum cylinder with a thickness of 0.5 cm, a diameter of 30 cm, and a height of 30 cm. The bremsstrahlung radiations produced from the tantalum target, which in turn generate photoneutrons though the (γ,xn) reactions. The resulting neutron spectrum is a continuous distribution in the energy range from thermal to few tens of MeV. The high energy neutrons were slowed down by the cooling water inside the water moderator. The distribution of neutrons with and without water moderator were described elsewhere [28,29]. In this experiment the water level of 5 cm above the Ta target surface was chosen. At this condition, the cadmium ratio defined as $CR = (R/R_{Cd})$, where R and R_{Cd} are reaction rates per atom for bare and Cd-covered isotope irradiation, was measured to be 2.88 ± 0.04 for ^{197}Au and 20.49 ± 0.32 for ^{45}Sc, respectively.

For the irradiation, two sets of samples containing scandium and gold foils, one set is bare and the second set is wrapped in 0.5 mm cadmium were prepared and then irradiated simultaneously on top of the water moderator of PNF. The neutron fluence exposed to each scandium and gold foil was extrapolated from the activities of the indium monitors placed alternatively between the scandium and gold foils as shown in Fig. 1, where Sc1(Cd) and Au1(Cd) denote the foils covered with Cd shield. The irradiation time was four hours. During irradiation, the electron linac was operated at a repetition rate of 15 Hz, electron beam current of 50 mA and electron energy of 70 MeV. The nuclear reactions to be considered here are ^{45}Sc(n,γ)^{46}Sc, ^{197}Au(n,γ)^{198}Au, and ^{115}In(n,γ)^{116m}In, respectively. The nuclear data used in the analysis are given in Table 1 [30].

2.2. Activity measurement

Following the irradiation, the induced activities of the activated foils were measured by a well calibrated HPGe detector (Canberra GC2018) with a diameter of 59.2 mm and a thickness of 30 mm coupled to a PC-based multichannel analyzer card system, which can determine the photo-peak area of the γ-ray spectra by using the Canberra software GENIE2000. The energy resolution of the detector system was 1.8 keV full width at half maximum (FWHM) at the 1332.5 keV peak of ^{60}Co. The detection efficiency is 20% at 1332.5 keV relative to a NaI(Tl) detector with a size of 7.62 cm diameter $\times$ 7.62 cm length. The absolute photopeak efficiencies and total efficiencies of the HPGe detector were measured with the calibrated γ-sources such as ^{241}Am (59.541 keV), ^{137}Cs (661.675 keV), ^{54}Mn (834.848 keV), ^{60}Co 1173.228 keV and 1332.492 keV), and ^{133}Ba (80.998-, 276.399-, 302.851-, 356.013-, and 383.848-keV). The details of the detector efficiency calibrations were illustrated elsewhere [31,32].

For the activity measurements, the waiting and measuring times were chosen based on the half-life of each radioactive isotope and statistics of the γ-peaks of interest. Generally, for all measurements, the dead times were kept below 3% by varying appropriate distance between the sample and detector. In this experiment, firstly we measured the activities of the indium monitors because the half-life of the ^{116m}In is shorter compare with that of the ^{46}Sc and ^{198}Au. The activity of the ^{116m}In radioactive isotope was determined based on the 1293.56 keV (84.8%) γ-ray, and that of the ^{198}Au was determined based on the 411.80 keV (95.62%) γ-ray. In case of the ^{46}Sc radioactive isotope, the activity was determined based on both the 889.277 keV (99.984%) and 1120.54 keV (99.987%) keV γ-rays, respectively.

3. Data analysis

3.1. Determination of thermal neutron cross section

The thermal neutron cross section for the ^{45}Sc(n,γ)^{46}Sc reaction has been determined relative to that of the ^{197}Au(n,γ)^{198}Au reaction as follows [33,34]:

$$\sigma_{0,Sc} = \sigma_{0,Au} \times \frac{R_{Sc} - F_{Sc,Cd}R_{Sc,Cd}}{R_{Au} - F_{Au,Cd}R_{Au,Cd}} \times \frac{G_{th,Au}}{G_{th,Sc}} \times \frac{g_{Au}}{g_{Sc}} \quad (1)$$

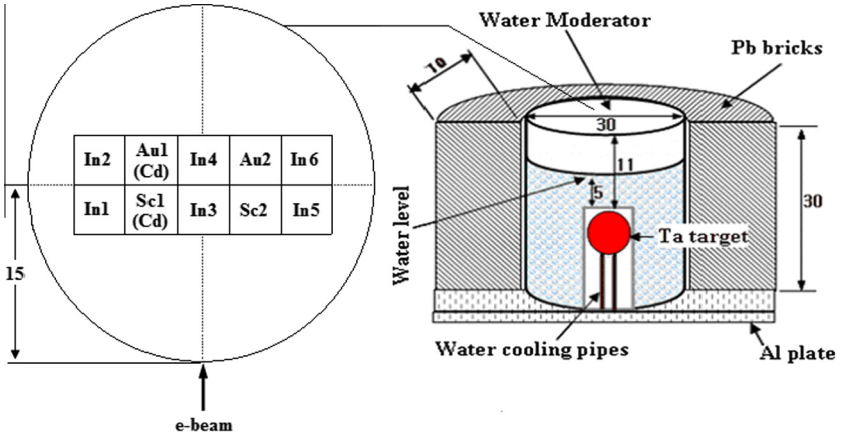

Fig. 1. Configuration of the neutron source based on the Ta target and water moderator system and the experimental arrangement of the activation foils. The numbers in this figure refer to dimension in cm.