^{93}Nb(γ, n) reaction cross-section in the end-point bremsstrahlung energies of 12-16 and 45-70 MeV

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The medium-energy photon and neutron-induced reaction cross-sections of the structural materials (e.g. Fe, Ni, Cr) and cladding materials (Zr, Nb) are of interest for their applications in conventional reactors and ADSs [1. The presence of Nb in Zr-Nb alloys improves the thermal and multi-axial stress as well as the long term corrosion resistance and mechanical properties [2]. In ADSs, high energy photon in the form of bremsstrahlung radiations are produces along with high energy neutrons during spallation process. Thus it is important to study the photon, neutron and proton induced reaction cross-sections of Zr and Nb. In the present work we have determined the ^{93}Nb(γ, n) reaction cross-section at the end-point bremsstrahlung energies of 12, 14 and 16 MeV as well as 45, 50, 55, 60 and 70 MeV by the activation and the off-line γ-ray spectrometric techniques using the 20 MeV electron linac (ELBE) at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) Dresden, Germany and 100 MeV electron linac at Pohang Accelerator Laboratory (PAL), Korea.

Experimentally, 32.6-41.6 mg Nb metal (size=0.81-1cm^2 x0.05 mm) and 83.2-101.6 mg of Au metal (size=0.48 cm^{2}x 0.1 mm) wrapped with 0.025 mm thick Al were irradiated for 8.5-10.5 h with end-point bremsstrahlung energies of 12-16 MeV at HZDR, Dresden, Germanay using the rabbit facility. The bremsstrahlung radiation was generated by impinging the electron beam on a solid graphite beam dump. During the experiments, the electron LINAC was operated with a pulse repetition rate (PRR) of 13 MHz, a pulse width of 10 ps and an average beam current of 550 μA. Similar samples were also irradiated for 0.5-3 h with end-point bremsstrahlung energies of 45-70 MeV at PAL, Pohang, Korea. The bremsstrahlung was generated when a pulsed electron beam hit tungsten (W) metal foil with a size of 100 cm^2 x 0.1 mm. The current of the electron beam during irradiation was 10–35 mA at 3.75 Hz with a beam width of 1.5 μs. The γ- ray counting of the irradiated targets of Nb and Au along with an Al wrapper was done by using energy and efficiency-calibrated 90% HPGe detector coupled to a PC based 16K channel analyzer. The resolution of the detector system was 2.0 keV at 1332.0 keV of ^{60}Co.

The net peak area (A_{net}) corresponding to the photo-peak was calculated from the total peak-area after subtracting the linear Compton background. A_{net} of 333, 358, 426 keV γ-lines of ^{196}Au and 934.46 keV γ-line ^{92m}Nb are related to the photon flux (φ), target atom (N) and cross-section (σ) with the relation,

$$A_{net} = N\langle\sigma\rangle\ \varphi\ a\ \varepsilon\ (1- e^{-\lambda t})\ e^{-\lambda T}(1- e^{-\lambda CL})/\ \lambda$$

Where 'a' and ε are the γ-ray abundance of and its detection efficiency. *t, T, CL,* and *LT* are the irradiation time, cooling time, clock time and counting time, respectively.

The photo-peak activity of the ^{196}Au from the ^{197}Au(γ, n) reaction was used as the flux monitor [3]. The nuclear spectroscopic data were taken from ref. [4]. The flux-weighted average cross-section <σ> for ^{197}Au(γ, n)^{196}Au reaction used in the calculation of bremsstrahlung flux was obtained from the relation. $<\sigma> = \sum\varphi\,\sigma/\sum\varphi$. The bremsstrahlung spectrum was obtained using computer code GEANT4 [5]. Then the average <σ> for the ^{93}Nb(γ, n)^{92m}Nb reaction was calculated from the 934.5 keV photo-peak activity. The total ^{93}Nb(γ, n)^{92}Nb reaction cross-section then obtained using the isomeric ratio of 0.5 based on the ref. [6]. The ^{93}Nb(γ, n)^{92}Nb reaction cross-section at the end-point bremsstrahlung energies of 12, 14, 16, 45, 50, 55, 60 and 70 MeV from the present work and at 10 and 12.5 MeV from our earlier work [7] were plotted in Fig. 1. In the same figure, the flux-weighted values from the literature data [8] and theoretical value from TALYS [9] were also plotted for comparison.

It can be seen from Fig. 1 that the experimental ^{93}Nb(γ, n)^{92}Nb reaction cross-section are in good agreement with the theoretical values of TALYS [9]. From Fig. 1, it is also clear that the experimental and theoretical values increase from the threshold value of 8.83 MeV to 18.72 MeV. This is because the ^{93}Nb(γ, 2n) reaction has the threshold value of 18.72 MeV. When ^{93}Nb(γ, 2n) reaction cross-section start increasing, the ^{93}Nb(γ, n) reaction cross-section remain constant up to 25 MeV. Thereafter when ^{93}Nb(γ, 3n) reaction starts opening, the cross-section for ^{93}Nb(γ, n) reaction decreases slowly and for ^{93}Nb(γ,2n) reaction remains constant. This indicates that the shearing of excitation energy in different reactions channels. Further, it can be seen from Fig. 1 that the increase of ^{93}Nb(γ, n) reaction cross-section is very sharp from 8.83 to 15-20 MeV, which is the region of GDR. Thus in the beginning the sharp increase trend is due to the GDR effect besides the role of excitation energy.

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