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Preliminary analysis of cross section measurement of proton-induced reactions on natural niobium

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1. Introduction

Niobium is one the important materials that can be used as a superconductive material in high temperature engineering systems and also as an alloying element for strengthening steel, niobium alloys are used to make the coil windings for superconducting magnets. Proton-induced reactions are important for either practical applications or basic nuclear physics [1]. Several researches have studied the proton-induced reactions on Nb. However, at high proton energies it seems that there are not enough measured cross sections.

In this work, the preliminary analysis of the proton-induced reactions on natural niobium are presented over the proton energy of 58 to 99 MeV. The measured data in the present work are compared with other experimental data in the literature. Furthermore, the residual nucleus production cross sections of the interested radionuclei were extracted from TENDL-2019 (TALYS-based Evaluated Nuclear Data Library) [2] and compared to the experimental data.

2. Methods and Results

2.1 Experiment

Cross sections for production of residual nuclides were determined by the stacked foil activation method and gamma spectrometry. Five high purity 50 µm Nb (8.57 gcm^{-3}, 99.9%) foils were used as targets. Al (100 µm, 2.69 gcm^{-3}, 99.99%) and Au (30 µm, 19.3 gcm^{-3}, 99.99%) monitoring foils were sandwiched between two Al foils to avoid cross contamination and recoil effects. 2 mm-thick lead foils were used as proton energy degraders. The irradiation was performed at Korea Multipurpose Accelerator Complex (KOMAC) with incident proton energy of 100 MeV. The cross-sectional size of all foils was 5 × 5 cm. Total thickness to stop 100-MeV protons was calculated by SRIM [3] code and it was large enough to stop the proton beam.

γ-ray spectrum analysis of activation foils started after the irradiation using HPGe detectors. The energy resolution of detector was 1.71-keV full-width at half-maximum (FWHM) at the 1.33-MeV peak of ^{60}Co. The absolute efficiency of HPGe detectors were obtained using standard multiple γ-ray sources. Depending on the half-life of a radionuclide, the γ-ray spectrum analysis was performed several times. Canberra's Genie-2000 (version 3.2) [4] γ-ray analysis software was used for analyzing γ-ray spectra.

2.2 Proton energy and intensity determination

The proton beam intensity was measured by the activation analysis method. Au and Al foils were placed at the front of the target stack to measure proton beam intensity via the monitor reactions ^{27}Al(p, 3p1n)^{24}Na, ^{197}Au(p, p1n)^{196}Au, and ^{197}Au(p, p3n)^{194}Au. The energy of incident proton beam was calibrated to be 100.1 ± 0.1 MeV on the target. Uncertainty of the proton beam intensity measurement by the activation analysis was estimated by possible uncertainties of measured yields (~2.0 %), used cross section (~8.3 %) and mass of the monitor activation foils (~0.01 %). The overall uncertainty in the beam intensity measurement was estimated to be approximately 9 %. The measured beam intensity using different monitor reactions were averaged and it was obtained as $(1.01 \pm 0.091)\times10^{12}$ protons/s. Additionally, the proton energy striking on each Nb foil was calculated using SRIM code to be 99.3 ± 0.1, 90.0 ± 0.48, 80.6 ± 0.73, 70.0 ± 0.82, and 58.1 ± 1.19 MeV.

2.3 TENDL library

The tabulated results of TENDL-2019 calculated by the default parameterization of the TALYS code [5] are used to be compared with the experimental data. TALYS is a computer code system for the prediction and analysis of nuclear reactions which simulates reactions that involve neutrons, γ-rays, protons, deuterons, tritons, hellions and alpha-particles, in the 1 keV to 200 MeV energy range and for target nuclides of mass 12 and heavier.

2.4 Measured cross sections

The measured cross sections for ^{93}Nb (p, x) ^{92m,90}Nb are shown in Figs. 1, 2 and are compared with the experimental data in the literature [6] together with the data from TENDL-2019. Uncertainties of the presented cross sections were estimated as the sum in quadrature of possible individual relative uncertainties and it was approximately 11.3 %.

2.4.1 ^{93}Nb (p, pn) ^{92m}Nb reaction

^{92}Nb has the ground state with the half-life of 3.47×10^{7} y and the metastable with half-life of 10.15 d. By considering the long-lived ground state of ^{92}Nb, the

measured cross sections with short measurements indicate the cross sections of the metastable of ^{92m}Nb. ^{92m}Nb decays via electron capture (EC; 100%) to ^{92}Zr, emitting γ-ray of 934.44 keV (I_γ: 99.15%) which was used to measure the yields of ^{92m}Nb.
The measured cross sections were compared to other experimental data in the literature as well as TENDL-2019 as indicated in Fig. 1. It can be seen that our measured data are well consistent with Titarenko *et al.* Ditroi *et al.* and Michel *et al.* between 58 to 100 MeV. On the other hand, TENDL library could predict the reaction threshold energy and can reproduce the experimental data well up to 20 MeV. From 20 to 70 MeV, TENDL is deviated from the experimental data and again is in agreement with the measured data after 70 MeV.

2.4.2 ^{93}Nb (p, x) ^{90}Nb reaction

^{90}Nb (EC; 100 %) has a half-life of 14.6 h and can be produced via different nuclear reaction channels ^{93}Nb(p,nt)^{90}Nb, ^{93}Nb(p,d2n)^{90}Nb as well as the decay of ^{90}Mo (5.67 h). Therefore, the measured cross sections are cumulative cross sections. ^{90}Nb was identified by 141.178 keV (I_γ: 66.8%) and 1129.224 keV (I_γ: 92.7%).
Fig. 2 shows the present results and literature data together with TENDL-2019 data. Our measured data are in good agreements with other experimental data. It is obvious that TENDL can estimate the reaction threshold and reproduce the experimental data quite well up to 40 MeV and it underestimates the measured data above 40 MeV. The reason could be that as the proton energy increases, more nuclear reaction channels are open that can emit more particle with higher mass such as deuteron and triton. Consequently, nuclear models are unable to reproduce the measured cross sections.

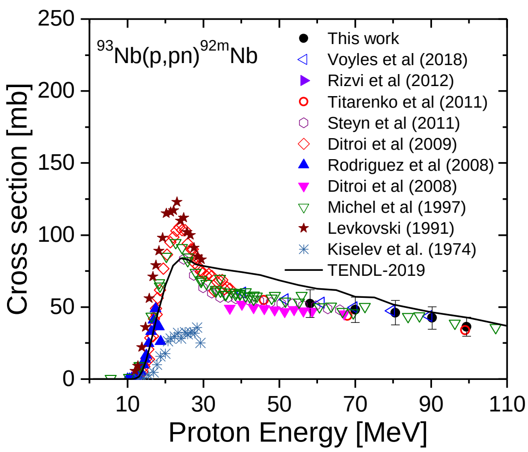

Fig. 1. Measured cross sections of ^{93}Nb(p, pn) ^{92m}Nb compared with other experimental data and TENDL. Experimental data are taken from EXFOR [6].

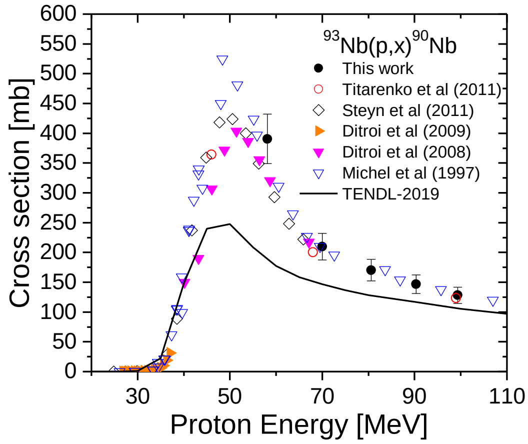

Fig. 2. Measured cross sections of ^{93}Nb (p, x) ^{90}Nb compared with other experimental data and TENDL library. Experimental data are taken from EXFOR [6].

3. Conclusions

The cross sections of ^{93}Nb (p, pn) ^{92m}Nb and ^{93}Nb (p, x) ^{90}Nb were measured between 58 to 100 MeV proton energies. The results were in agreements with other experimental data. TENDL-2019 was also used to be compared with the experimental data. TENDL could show the reaction threshold similar to the measured data. However, at higher photon energies, channels such as (p,d2n) is open and can make the reaction more complex so that TENDL cannot predict the measured data well particularly for ^{93}Nb (p, x) ^{90}Nb reaction.

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