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Measurements and uncertainty propagation for the ^{nat}Ni$(p, x)^{61}$Cu reaction cross section up to the proton energies of 20 MeV

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Abstract

The ^{nat}Ni$(p, x)^{61}$Cu reaction cross sections relative to ^{nat}Cu$(p, x)^{62}$Zn monitor reaction with proton energies up to 20 MeV have been measured using the stack foil activation and off-line γ-ray spectrometric technique. The error analysis of the experimental data was done by using the concept of covariance analysis. The present experimental cross sections have been compared with TALYS-1.8 and the results obtained well predicted the present experimental cross sections at the proton energies of 7.25, 15.70 and 18.89 MeV. The results from TALYS calculation are also in agreement with the earlier measurements available in the literature between the proton energies of 3–15 MeV, which confirms the reliability of the database. The ^{nat}Ni$(p, x)^{61}$Cu reaction cross sections obtained in the present work have been further compared with the data from TENDL-2015 libraries. They are found to be in excellent agreement with TENDL-2015 at 7.25 and 15.70 MeV. The present results along with detailed covariance information, which takes into account various attributes influencing the uncertainties and also the correlation between them, emphasize their sig-

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nificance during evaluation process in the proton induced reactions of natural nickel for the production of medically relevant radioisotope, ^{61}Cu.

Keywords: $^{\mathrm{nat}}\mathrm{Ni}(p,x)^{61}\mathrm{Cu}$ reaction; Cross-section; Stack foil activation technique; Off-line γ-ray spectrometry; Covariance analysis; TALYS-1.8; TENDL-2015

1. Introduction

Nickel is one of the most frequently used structural materials (alloys, anti-corrosion), and thus its activation reaction cross-sections data are important when used in nuclear and space equipment working under intensive radiation [1]. Nickel is an important material used in accelerator and nuclear technology. It is incorporated in stainless steel, present as surface coating and is proposed as beam dump for high power accelerators [2]. Silvery-white metallic Ni is lustrous and resistive to corrosion. The vast industrial applications of nickel (Ni) metal, its compound and even its alloys have been perceived due to its physical and chemical properties. Hence, Ni has been given priority over other materials in a recent IAEA Coordinated Research Project on Nuclear Data Libraries for Advance Systems–Fusion Devices (FENDL-3) [3]. Moreover, the activation reaction cross-section data of nickel isotopes are of interest for the design studies of accelerator driven sub-critical system (ADSs) [4], thin layer activation (TLA) analysis and so on. Nickel can also be used as a target material for the production of several radionuclides of Co, Cu, Cr, Mn and Ni leading to industrial and medical application. Among them, produced radionuclides such as ^{60,61,62,64}Cu and ^{55,56,57,58}Co have potential applications in medicine [1,5]. The radionuclides ^{60,61,62,64}Cu are promising nuclides for labelling radiopharmaceuticals for Positron Emission Tomography (PET). Given their high positron branching ratio, ^{60}Cu ($T_{1/2} = 23.7$ min, $I_{\beta+} = 93\%$) and ^{62}Cu ($T_{1/2} = 9.7$ min, $I_{\beta+} = 98\%$) can render high quality PET images. However, their applications are limited by their short half-lives to uptake times shorter than 1 h. ^{64}Cu is an intermediate half-life nuclide ($T_{1/2} = 12.7$ h, $I_{\beta+} = 17.6\%$, $I_{\beta-} = 38.50\%$), currently used for imaging and therapy. Despite its less than desirable image quality, it is one of the few PET tracers available to study processes with uptake longer than 4 h [6]. ^{61}Cu ($T_{1/2} = 3.339$ h, $I_{\beta+} = 61\%$) is another radionuclide of copper with potential utilization in nuclear medicine due to its nuclear properties, desirable half-life and ease for production [7–9]. It decays mainly via positron emission accompanied with dominant γ-rays of 282.96 keV (12.2%) and 656.01 keV (10.8%). The detection sensitivity of ^{61}Cu is more than three times that of ^{64}Cu, when β^+ scintiscanning is used [10–12]. The relatively longer half-life of ^{61}Cu compared to ^{60}Cu and ^{62}Cu reduces the decay loss of radioactivity during the processing, and allows imaging of slower biological processes with low accuracy due to relatively high β^+ emission ratio [13]. ^{61}Cu could yield higher quality images than with ^{64}Cu, due to the higher positron decay branching and the shorter half-life. Thus, it covers the gap between the other radionuclides of copper and eases the commercial distribution from a centralized facility. For the investigation of copper distribution in patients suffering Wilson's disease ^{61}Cu[CuCl$_2$] has been used as a PET tracer [12]. It is considered to be a suitable candidate for studies of slow kinetics of larger proteins, such as peptides and antibodies, or cells [14]. ^{61}Cu is of special interest because of its large number of production possibilities. Several charged particles induced reactions on nickel, copper and zinc targets have been measured to produce ^{61}Cu [2,5,7,9,15–17]. In majority of the cases relatively high produc-