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Activation cross-sections of proton induced reactions on natural Ni up to 65 MeV

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HIGHLIGHTS

- Production cross-sections of $^{nat}Ni(p,x)^{60,61}Cu$, $^{56,57}Ni$, $^{55,56,57,58}Co$ reactions up to 65 MeV.
- Comparison of results with theoretical codes ALICE-IPPE, TALYS 1.4 and TENDL-2012 library.
- Calculation and comparison of physical yields with literature experiments.
- Thin layer activation (TLA) curves for ^{57}Ni and ^{57}Co for industrial applications.
- The production rate for ^{55}Co was compared for proton and deuteron induced reactions on Ni.

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ABSTRACT

Production cross-sections of the $^{nat}Ni(p,x)^{60,61}Cu$, $^{56,57}Ni$, $^{55,56,57,58}Co$ nuclear reactions were measured in five experiments up to 65 MeV by using a stacked foil activation technique. The results were compared with the available literature values, predictions of the nuclear reaction model codes ALICE-IPPE, TALYS-1.4, and extracted data from the TENDL-2012 library. Spline fits were made on the basis of selected data, from which physical yields were calculated and compared with the literature values. The applicability of the $^{nat}Ni(p,x)^{57}Ni$, ^{57}Co reactions for thin layer activation (TLA) was investigated. The production rate for ^{55}Co was compared for proton and deuteron induced reactions on Ni.

1. Introduction

Nickel is one of the most frequently used structural materials (alloys, anti-corrosion), and its activation data are especially important when used in nuclear and space equipments working under intensive radiation. It was ranked among the high priority elements in the FENDL-3 work document “IFMIF deuteron and proton data needs” (Fischer, 2009). Nickel (especially in isotopically enriched form) plays an important role as target material for the production of medical radioisotopes ($^{60,61,62,64}Cu$ and $^{55,56,57,58}Co$ etc.) that are mostly produced via proton induced reactions. Therefore, activation cross-sections of proton induced reactions on natural nickel find importance in the aforementioned applications as well as for testing the predictive power of conventional nuclear reaction theory.

In a previous work we have investigated the activation cross-sections of the deuteron induced nuclear reactions on nickel (covering different applications of the produced radioisotopes) (Amjed et al., 2013). In this work the activation cross-sections of residual nuclei in Ni + p collisions have been measured.

Some of the following aims of the present investigation are closely connected to research projects coordinated by the IAEA.

- To update the nuclear data for the “Nuclear Data Libraries for Advanced Systems - Fusion Devices” IAEA FENDL-3 coordinated research program (Fischer, 2009) (all reaction products).
- To improve the IAEA database on thin layer activation (Thin Layer Activation-IAEA, ^{57}Co product) (Takács, 2010).

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- To perform further measurements and evaluation of data for the $^{nat}Ni(p,x)^{56,57,58}Co$ beam monitor reactions (Tárkányi et al., 2001) and for the production of the medically important radionuclides ^{55}Co and $^{60,61}Cu$ (Nichols and Capote, 2013).
- To check the predicting capability of the nuclear reaction model codes, particularly the widely used TALYS (Koning et al., 2012).
- The present-day EXFOR database contains numerous works, presenting mainly so called elemental and cumulative production cross sections of the proton-induced reaction products in natural nickel (see later). Due to the systematic work of Levkovskij (1991) and some other dedicated works, mainly related to medical isotope production (Qaim, 2011) and nuclear reaction theory studies, reaction cross sections (on separate target isotopes) for direct production of the relevant products are also available. In most cases the agreement between the different datasets is acceptable, but occasionally large disagreements still persist in some cases.

2. Experimental measurements and data evaluation

The general characteristics and procedures for irradiation, activity assessment and data evaluation (including estimation of uncertainties) were similar to those in our previous work (Amjed et. al., 2013). The main experimental parameters for the present study are summarized in Table 1 while the methods used in data evaluation and the decay data are collected in Table 1 and Table 2.

3. Nuclear model calculations

Many groups use the TALYS-based Nuclear Data Library (TENDL), which utilizes both default and adjusted TALYS calculations (a set of correcting parameters was obtained by fitting the original code results to selected experimental data and data from existing evaluations) (Koning et al., 2012). The TENDL library is well developed for neutron induced reactions but not so developed for charged particles. To validate the measured cross-sections, we compared them with the results taken from TENDL-2012 library and with theoretical calculations based on TALYS 1.4 code (Koning et al., 2011) and the ALICE-IPPE code (Dityuk et al., 1998)

The individual results of the reaction products of interest were weighted and summed according to the abundances of the isotopes of natural nickel (target). In case of cumulative formation, cumulative values were also included in the final results. For both theoretical models, TALYS 1.4 and ALICE-IPPE, we used only the default input parameter files.

4. Results and discussion

The experimental cross-sections for each radionuclide obtained in this work together with their uncertainties are given in Tables 4–8. They are elemental cross-sections measured on ^{nat}Ni targets. For each radionuclide our measured cross-sections are compared with the published results obtained from other laboratories. Renormalized cross-sections on enriched ^{58}Ni targets from literature are also presented in the figures, up to the threshold of reactions on ^{60}Ni (see references there). Theoretical predictions calculated by TALYS 1.4, ALICE-IPPE (with default parameters) and calculated results taken from TENDL-2012 (library) are also presented for comparison. The list of contributing reactions with their *Q*-values and thresholds is given in Table 3. Our experimental results are shown in Figs. 1–8.

When a reasonable amount of selected experimental data sets are available with corresponding estimated errors, a statistical fit over the data points can be performed to obtain the mean value of all the data. The spline fit method uses the technique of piece-wise approximation of experimental data by specifying important points (termed knots of the spline), applying individual interpolation in each interval between two knots, and matching these interpolations so that the first and second derivatives are continuous at the knots.

Table 1
Main experimental conditions and parameters

Series no:	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5
Accelerator	**MGC-20E** Cyclotron ATOMKI, DebrecenHungary	**CGR 560** Cyclotron of Vrije Universiteit Brussels, Belgium	**CGR 560** Cyclotron of Vrije Universiteit Brussels, Belgium	**CGR 560** Cyclotron of Vrije Universiteit Brussels, Belgium	**CYCLONE110** Cyclotron of Catholic University of Louvain, Louvain–la-–Neuve, Belgium
Irradiation year	2012	2013	2013	2012	2012
Primary energy	17 MeV	25 MeV	37 MeV	37 MeV	65 MeV
Range of the proton energy (MeV)	16.8–4.2 MeV	24.8–11.3 MeV	36.5–21 MeV	36.6–7.1 MeV	63.6–47.1 MeV
Method	Stacked foil	Stacked foil	Stacked foil	Stacked foil	Stacked foil
Target and thickness	^{nat}Ni foils, 9.9 μm	^{nat}Ni foils, 24.6 μm	^{nat}Ni foils, 46.2 μm	(Ga 70 Ni 30) Alloy 13.35 μm on 12.5 mm Cu	(Ga 70 Ni 30) Alloy , 17.75 μm on 25 mm Au
Number of target foils	19	19	19	20	18
Irradiation time	0.5 h	1 h	1 h	75min	1 h
Beam current	177.42 nA	132.26 nA	126 nA	88.4 nA	104.17nA
Monitor reaction, [recommended values]	$^{nat}Ti(p,x)^{48}V$ reaction Tárkányi et al. (2001)	$^{nat}Ti(p,x)^{48}V$ reaction Tárkányi et al. (2001)	$^{nat}Cu(p,x)^{62,65}Zn$ reaction Tárkányi et al. (2001)	$^{nat}Cu(p,x)^{62}Zn$ reaction Tárkányi et al. (2001)	$^{27}Al(p,x)^{24}Na$ reaction Tárkányi et al. (2001)
Monitor target and thickness	^{nat}Ti, 12 μm	^{nat}Ti, 10.9 μm	^{nat}Cu, 12.5 μm	^{nat}Cu, 12.5 μm	^{nat}Al, 26.96 μm
Detector	HpGe	HpGe	HpGe	HpGe	HpGe
γ-Spectra measurements	6 series	4 series	4 series	5 series	4 series
Cooling times	1.1–3 h, 3.5–7.3 h, 19.0–28.4 h, 30.0–125.0 h, 140.3–257.1 h, 277.4–621.5 h	5–11.3 h, 30.2–52.8 h, 683.5–724.6 h, 793.4–1015.8 h	5.4–13.2 h, 47.0–124.9 h, 148.5–289.3 h, 231.5–650 h	2.5–7.3 h, 22–37.8 h, 60.3–100.4 h, 286.7–434.8 h, 387.4–752.2 h	3.9–29.9 h, 21.4–25.4 h, 99.5–173.1 h, 943.6–1512.4 h