Nuclear Instruments and Methods in Physics Research B 373 (2016) 17–27

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Activation cross sections of deuteron induced reactions on niobium in the 30–50 MeV energy range

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ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 16 February 2016
Accepted 16 February 2016
Available online 27 February 2016

Keywords:
Niobium target
Deuteron irradiations
Mo, Zr and Y radioisotopes
Medical radioisotopes
Thin layer activation

ABSTRACT

Activation cross-sections of deuterons induced reactions on Nb targets were determined with the aim of different applications and comparison with theoretical models. We present the experimental excitation functions of ^{93}Nb(d,x)^{93m,90}Mo, ^{92m,91m,90}Nb, ^{89,88}Zr and ^{88,87m,87g}Y in the energy range of 30–50 MeV. The results were compared with earlier measurements and with the cross-sections calculated by means of the theoretical model codes ALICE-D, EMPIRE-D and TALYS (on-line TENDL-2014 and TENDL-2015 libraries). Possible applications of the radioisotopes are discussed in detail.

1. Introduction

Activation cross sections of deuteron induced reaction on niobium are important for several practical applications as well as for basic nuclear physics needed for verification and improvement of nuclear reaction models. In the frame of a systematic study of the light ion induced reactions on structural materials, we reported earlier experimental cross section data on niobium for protons up to 67 MeV [1,2], deuterons up to 38 MeV [3,4] and alpha particles up to 43 MeV [5] and discussed the possible applications in more detail. As no datasets above 40 MeV for deuteron induced reactions are available (up to 40 MeV only our earlier results and a recent set of measurements by Avrigeanu [6], we extended the energy range of the experimental data up to 50 MeV in this work and included a comparison with theoretical calculations using different model codes.

2. Experiment

For the cross section determination an activation method based on stacked foil irradiation followed by γ-ray spectroscopy was used. The stack consisted of a sequence of Rh(26 μm), Al(50 μm), Al(6 μm), In(5 μm), Al(50 μm), Pd(8 μm), Al(50 μm), Nb(10 μm), Al(50 μm) foils, repeated 9 times and bombarded for 3600 s with a 50 MeV deuteron beam of nominal 32 nA at Louvain la Neuve (LLN) Cyclotron Laboratory. The beam current was more exactly estimated in the Farady cup and corrected by using the monitor reactions.

The activity produced in the targets and monitor foils was measured non-destructively (without chemical separation) using high resolution HPGe gamma-ray spectrometers (made by Canberra, coupled with a Multichannel analyzer running with the Genie 2000 software©). Three series of γ-spectra measurements were performed starting at 9.1–10.1 h, 28.6–44.7 h, and 458.4–533.4 h after EOB, respectively.

The evaluation of the gamma-ray spectra was made by both a commercial [7] and an interactive peak fitting code [8].

The cross-sections were calculated by using the well-known activation formula with measured activity, particle flux and number of target nuclei as input parameters. Some of the radionuclides formed are the result of cumulative processes (decay of metastable states or parent nuclides contribute to the formation process). Naturally occurring niobium is monoisotopic (^{93}Nb) and hence ^{93}Nb(d, x) reaction cross-sections (direct formation or cumulative production) are presented.

The decay data were taken from the online database NuDat2 [9] and the Q-values of the contributing reactions from the Q-value calculator [10], both are presented in Table 1.

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http://dx.doi.org/10.1016/j.nimb.2016.02.037
0168-583X/

Table 1
Decay and nuclear characteristic of the investigated reaction products, contributing reactions and their Q-values.

Nuclide Spin/parity Isomeric level	Half-life	Decay method	E_γ (keV)	I_γ (%)	Contributing process	Q-value (keV)
^{93m}Mo 21/2$^+$ 2424.97 keV	6.85 h	IT 100%	263.049 684.693 1477.138	57.4 99.9 99.1	^{93}Nb(d,2n)	−3413.59
^{90}Mo 0$^+$	5.67 h	EC 75.1% β$^+$ 24.9%	122.370 162.93 203.13 257.34 323.20 445.37 941.5 1271.3	64 6.0 6.4 78 6.3 6.0 5.5 4.1	^{93}Nb(d,5n)	−34260.98
^{92m}Nb 2$^+$ 135.54 keV	10.15 d	EC 99.935% β$^+$ 0.065%	912.6 934.44	1.78 99.15	^{93}Nb(d,p2n)	−11055.13
^{91m}Nb 1/2$^-$ 104.605 keV	60.86 d	EC 3.4% IT 96.6%	104.62 1204.67	0.574 2.0	^{93}Nb(d,p3n)	−18941.62
^{90}Nb 8+	14.60 h	EC 48.8% β$^+$ 51.2%	132.716 141.178	4.13 66.8	^{93}Nb(d,p4n) ^{90}Mo decay	−30989.3 −34260.98
^{89}Zr 9/2$^+$	78.41 h	EC 77.6% β$^+$ 22.4%	909.15	99.04	^{93}Nb(d,α2n) ^{89}Nb decay	−7768.43 −41097.4
^{88}Zr 0$^+$	83.4 d	EC 100%	392.87	97.29	^{93}Nb(d,α3n) ^{88}Nb decay	−17087.81 −53618.2
^{90m}Y 7$^+$ 682.04 keV	3.19 h	IT 99.9982% β$^-$ 0.0018%	202.53 479.51	97.3 90.74	^{93}Nb(d,pα)	+2703.71
^{87m}Y 9/2$^+$ 380.82 keV	13.37 h	IT 98.43% β$^+$ 0.75% EC 0.75%	380.79	78.06	^{93}Nb(d,αp3n) ^{87}Zr decay	−24986.77 −57736.59
^{87}Y 1/2$^-$	79.8 h	EC 99.82% β$^+$ 0.180 %	388.531 484.805	82.2 89.8	^{93}Nb(d,αp3n) ^{87}Zr decay	−24986.77 −57736.59

The Q-values refer to formation of the ground state. In case of formation of a higher laying isomeric state it should be corrected with the level energy of the isomeric state shown in Table 1. When complex particles are emitted, instead of individual protons and neutrons, the Q-values have to be decreased by the respective binding energies of the compound particles: np-d, +2.2 MeV; 2np-t, +8.48 MeV; 2p2n-α, +28.30 MeV.

Effective beam energy and the energy scale were determined initially by a stopping calculation [11] based on estimated incident energy and target thickness and finally corrected [12] on the basis of the excitation functions of the ^{24}Al(d,x)^{22,24}Na monitor reactions [13] simultaneously re-measured over the whole energy range. For estimation of the uncertainty of the median energy in the target samples and in the monitor foils, the cumulative errors influencing the calculated energy (incident proton energy, thickness of the foils, beam straggling) were taken into account. The uncertainty on the energy is in the ±0.5–1.5 MeV range, increasing towards the end of stack. The individual uncertainties occurred in the propagated error calculation are: absolute abundance of the used γ-rays (5%), determination of the peak areas (4–10%), the number of target nuclei (beam current) (5%), detector efficiency (10%). The total uncertainty of the cross-section values was estimated at 10–15%.

The beam intensity (the number of the incident particles per unit time) was obtained preliminary through measuring the charge collected in a short Faraday cup and corrected on the basis of the excitation functions of the monitor reactions compared to the latest version of IAEA-TECDOC-1211 recommended data base [13].

The uncertainty on each cross-section was estimated in the standard way by taking the square root of the sum in quadrature of all individual contributions, supposing equal sensitivities for the different parameters appearing in the formula. The following individual uncertainties are included in the propagated error calculation: absolute abundance of the used γ-rays (4–11%), determination of the peak areas including statistical errors (5%), the number of target nuclei including non-uniformity (5%), detector efficiency (10%) and incident particle intensity (7%).The total uncertainty of the cross-section values was evaluated to approximately 8–14%. [14].

3. Comparison with nuclear model calculations

The cross sections of the investigated reactions were compared with the data given in the last two on-line TENDL libraries to show the development of the predictions [15,16]. These libraries are based on both default and adjusted TALYS (1.6) calculations [17]. The cross sections of the investigated reactions were calculated by us using ALICE-IPPE [18] and EMPIRE-II [19] codes modified for deuterons by Igantyuk [20,21]. Independent data for isomers with ALICE-D code were obtained by using the isomeric ratios calculated with EMPIRE-II.

4. Results

The measured experimental cross-section data are shown in Figs. 1–10 together with the results of the earlier measurements and of the theoretical calculations. The numerical values are presented in Tables 2 and 3.

4.1. The ^{93}Nb(d,2n)^{93m}Mo reaction

The radionuclide ^{93}Mo has a metastable state with a half-life of 6.85 h and a long-lived ($T_{1/2}$ = 4.0 10^3 a) ground state. In the gamma spectra only the lines of the metastable state were detected. In the literature, apart from our earlier data [3,4], also a recent measurement by Avrigeanu et al. [6] was found and the four experimental data sets are agree well in the overlapping energy region (Fig. 1). All theoretical predictions significantly overestimate the experimental data (especially in case of TENDL-2015).