Nuclear Instruments and Methods in Physics Research B 269 (2011) 1792–1800

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

Investigation of activation cross-sections of deuteron induced reactions on vanadium up to 40 MeV

F. Tárkányi [a], F. Ditrói [a,*], S. Takács [a], A. Hermanne [b], M. Baba [c], A.V. Ignatyuk [d]

[a] Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen, Hungary
[b] Cyclotron Laboratory, Vrije Universiteit Brussel (VUB), Brussels, Belgium
[c] Cyclotron Radioisotope Center (CYRIC), Tohoku University, Sendai, Japan
[d] Institute of Physics and Power Engineering (IPPE), Obninsk, Russia

ARTICLE INFO

Article history:
Received 28 March 2011
Received in revised form 5 May 2011
Available online 11 May 2011

Keywords:
Excitation functions
Deuteron reactions
^{nat}V targets
Theoretical calculations
^{51}Cr
^{48}V
^{48}Sc
^{47}Sc
^{46}Sc
^{47}Ca
Thick target yields

ABSTRACT

Experimental excitation functions for deuteron induced reactions up to 40 MeV on natural vanadium were measured with the activation method using a stacked foil irradiation technique. From high resolution gamma spectrometry cross-section data for the production of ^{51}Cr, ^{48}V, ^{48,47,46}Sc and ^{47}Ca were determined. Comparisons with the earlier published data are presented and results for values predicted by different theoretical codes are included. Thick target yields were calculated from a fit to our experimental excitation curves and compared with the earlier experimental data. Depth distribution curves used for thin layer activation (TLA) are also presented.

1. Introduction

It is essential to prepare a deuteron-induced activation cross-section database for different applications:

- for accelerator and target technology to produce high energy high intensity neutron fluxes for nuclear waste transmutation (ADS);
- intensive neutron sources (SNS, ESS, IFMIF);
- radioactive ion beam (RIB) production with neutrons (EURISOL, RIA, SPIRAL-2 ...);
- future controlled fusion experiments and reactors (ITER, DEMO, ...);
- space applications (resistance of electronics, shielding, ...);
- etc.

Intense deuteron beams play an important role also in the field of medical radioisotope production. Some radioisotopes can be produced with high yields only with deuterons (^{15}O, ^{57}Co, ^{111}Ag, ^{177}Lu,), while for some other important medium- and high-*Z* radioisotopes the (d,2n) reaction is more productive than the (p,n) on the same target material (^{64}Ni, ^{103}Pd,^{113}Sn(^{113m}In), ^{114m}In, ^{165}Er, ^{167}Tm, ^{169}Yb, ^{186}Re, ^{192}Ir, etc.).

In contrast to proton induced reactions the status of the experimental data for deuterons is rather poor (especially above 15–20 MeV), no systematical study has been performed earlier, the published data (except for a few well measured monitor and medically important reactions) show large discrepancies and the values collected in the EXFOR database are incomplete and contain mistakes. Confirmation of excitation functions by experimental assessment of integral yield or other benchmarks is also lacking. Moreover the reliability of presently used theoretical codes for deuteron induced reactions compared to proton and alpha induced reactions is low or moderate, due to the modeling problems of the deuteron stripping and pickup.

For several applications, however, a complete experimental or calculated data set is required to optimize thick target yields.

In connection with research projects on activation cross-sections for structural materials around IFMIF, on production cross-sections of diagnostic and therapeutic medical radioisotopes, on

* Corresponding author.
E-mail address: ditroi@atomki.hu (F. Ditrói).

0168-583X/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2011.05.003

nuclear reactions for wear control via industrial thin layer activation and for recommended monitor reactions for deuteron beam parameters, we hence performed a systematical experimental study of deuteron induced activation cross-sections for different targets during the last decades.

Today, this study involves around five hundred reactions taking place on the following 50 target elements: B, N, Ne, Al, Si, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Kr, Y, Zr, Nb, Mo, Rh, Pd, Ag, Cd, In, Sn, Te, Xe, Cs, La, Ce, Pr, Nd, Gd, Tb, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Os, Ir, Pt, Au, Tl, Pb. The – mostly new – measured excitation functions are compared with the literature experimental data and with the results of the nuclear reaction model codes ALICE-IPPE, EMPIRE-II, GNASH, PHITS and data in the EAF-2007 and TENDL 2009/2010 libraries based on subsequent versions of TALYS code.

Although a significant part of the measurements was already published, many still are waiting for the time consuming data evaluation.

Here we present the results on the vanadium target, for which preliminary results on $^{nat}V(d,x)^{51}Cr$ were presented at the ECAART 2010 conference, Athens, Greece [1] and NEMEA-6 (2010), Krakow, Poland [2].

Several authors published experimental cross-section data for deuteron induced reactions on ^{nat}V ([3–9]). A few works ([10–13]) reported experimental thick target yields.

The natural occurrence of the element vanadium consists of two isotopes: in more than 99.75% it is formed by stable ^{51}V while the very long lived ^{50}V ($T_{1/2} = 1.4 \times 10^{17}$ y) occurs only in 0.25%. Therefore experimental data on ^{nat}V can be in many cases interpreted as coming from monoisotopic targets.

2. Experimental

2.1. Materials and methods

The excitation functions for the $^{nat}V(d,x)$ reactions were measured at the cyclotrons of the Vrije Universiteit Brussel (VUB, Brussels, Belgium) and of Tohoku University (CYRIC, Sendai, Japan) using the stacked foil technique. The experimental set-up and data evaluation methods, including uncertainty estimation were similar to that described in our earlier publications [14–16]. Here only some specific characteristics of the experiment are described.

The stacks were irradiated using 21 MeV (VUB) and 40 MeV (CYRIC) incident deuteron energy. In experiments at the VUB-CGR560 cyclotron 15 natural high purity V foils (Goodfellow; >99.98%, thickness: 8.41 μm) were assembled together with interleaved Ti monitor foils of 12 μm thickness. At the CYRIC AVF110 cyclotron vanadium targets of 10 μm thickness and 112 μm Al monitor foils were used. The monitors were used as recoil catchers as well as for exact determination of beam intensity and energy by re-measuring the excitation function for the $^{nat}Ti(d,x)^{48}V$ reaction and $^{27}Al(d,x)^{22,24}Na$ reactions over the entire energy domain. The target stacks were irradiated in a Faraday-cup like target holder, equipped with a collimator (effective beam diameter on target is 5 mm) and a secondary electron suppresser. Irradiation took place at a constant beam current of 220 nA for 60 min (VUB) and 70 nA for 30 min (CYRIC), respectively.

The gamma activity of the produced radionuclides was measured with standard high purity Ge detectors coupled to acquisition/analysis software. Detector efficiencies for different measuring distances were carefully determined using calibrated reference sources. Measurements of the induced activity started in Brussels shortly after EOB (End of Bombardment) while in Sendai a cooling period of at least a day was applied due to the high produced activity. The samples were counted repeatedly at suitably large detector-sample distances (decreasing from 70 to 5 cm over time) to guarantee low dead times and to avoid pile-up effects. The evaluation of gamma-spectra was made by automatic peak evaluation programs and in a manually controlled interactive way.

2.2. Data processing

For most of the radionuclides assessed different independent γ-lines are available allowing an internal check on the consistency of the calculated activities.

The cross-sections were calculated from the well-known activation formula with input parameters: measured activity, particle flux and number of target nuclei. In this study only two radionuclides formed are the result of a cumulative process by decay of a parent nuclide. The exact physical situation will be discussed separately.

The decay and spectrometric characteristics, needed to transform count rates to activity of the different activation products at EOB were taken from the NUDAT2 data base [17] and are summarized in Table 1.

The number of incident particles was initially derived from total charge on target measured by the Faraday cup using a digital integrator. The mean energy in each target foil was estimated by calculation from the incident beam energy (determined from the TOF calibrated accelerator settings in Brussels [18] and from the magnetic bending calibrated accelerator settings in Sendai) and from the target thicknesses [19].

The beam energy and intensity parameters were further adapted by taking into account the comparison of the excitation function of $^{nat}Ti(d,x)^{48}V$ and $^{27}Al(d,x)^{22,24}Na$ reactions, re-measured over the whole energy domain studied with the recommended values in the updated version of IAEA-TECDOC 1211 [20] (Fig. 1). The uncertainties of the energies were estimated from the uncertainties of the cumulative contributing processes (taking into account possible incident energy variation depending on the calibration method, thickness variation of the different targets and straggling effects) resulting in around ±0.3 MeV for the first foil and about ±1.3 MeV for the last foils of a long stack.

The uncertainty on each cross-section was estimated in the standard way [21] 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 taken from NUDAT2 [17] (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 (5%). The total uncertainty of the cross-section values was evaluated to approximately 8–14%. The strongly non-linear effect of the possible uncertainty of the half-lives for samples measured shortly after EOB (small $T_{1/2}$) was not taken into account.

2.3. Model calculations

The modified codes [22,23] named ALICE-D and EMPIRE-D were used to analyse the present experimental results. In the modified version of ALICE-IPPE [24] and EMPIRE-II [25] simulation of direct (d,p) and (d,t) transitions with the general relations for a nucleon transfer probability in the continuum [26] is included through an energy dependent enhancement factor for the corresponding transitions. The data in the two versions of the TENDL [27] library (2009, 2010) based on latest calculations of the deuteron-induced reactions with subsequent versions of the TALYS code were used for a comparison too. The deuteron break-up contribution in TENDL-2009 was based on a purely empirical estimate on the basis of some scattered (d,n) and (d,p) measurements.