Nuclear Medicine and Biology 49 (2017) 30–37

Contents lists available at ScienceDirect

Nuclear Medicine and Biology

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

Excitation function and yield for the ^{103}Rh(d,2n)^{103}Pd nuclear reaction: Optimization of the production of palladium-103

Simone Manenti [a,*], María del Carmen Alí Santoro [b], Giulio Cotogno [c], Charlotte Duchemin [d], Ferid Haddad [d,e], Uwe Holzwarth [c], Flavia Groppi [a]

[a] LASA, Università degli Studi di Milano and INFN—Milano, via F.lli Cervi 201, I-20090 Segrate (MI), Italy
[b] Centro Atómico Ezeiza - Comisión Nacional de Energía Atómica, Presbítero Juan González y Aragón Nro.15, Ezeiza, Buenos Aires, Argentina
[c] Institute for Health and Consumer Protection, Joint Research Centre, European Commission, TP 500, I-21020 Ispra (VA), Italy
[d] SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS/IN2P3, Nantes, France
[e] GIP Arronax, 1 rue Aronnax, 44817 Saint-Herblain, France

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 25 February 2017
Accepted 28 February 2017

Keywords:
Palladium-103
^{103}Pd
Deuteron particle irradiation
Cross-section
Pd, Rh, Ru radioisotopes
Cyclotron

ABSTRACT

Deuteron-induced nuclear reactions for the generation of ^{103}Pd were investigated using the stacked-foil activation technique on rhodium targets at deuteron energies up to $E_d = 33$ MeV. The excitation functions of the reactions ^{103}Rh(d,xn)^{101,103}Pd, ^{103}Rh(d,x)^{100g,cum,101m,g,102m,g}Rh and ^{103}Rh(d,2p)^{103}Ru have been measured, and the Thick-Target Yield for ^{103}Pd has been calculated.

1. Introduction

^{103}Pd ($t_{1/2} = 16.991$ days [1]) decays almost exclusively (99.90%) by electron capture (EC) to ^{103m}Rh ($t_{1/2} = 56.12$ min) which de-excites through internal transition (IT). As a result of these processes (EC and IT) Auger-electrons and X-rays are emitted which are ideally suited for cancer therapy. Taking into account also the de-excitation of the "daughter" nuclide ^{103m}Rh, every 100 decays of ^{103}Pd are accompanied by the emission of about 263 Auger electrons, 188 low-energy conversion electrons and 97 X-rays [2]. These decay features and the practical absence of high-energy γ-rays make ^{103}Pd particulary suitable for interstitial brachytherapy: encapsulated in millimeter-size seed implants it is used in prostate [3], breast [4] or choroidal melanomas [5] cancer brachytherapy.

It has been shown that gold nanoparticles (Au NPs) distributed in the vicinity of ^{103}Pd radioactive implants can act as radiosensitivers that strongly enhance the therapeutic dose of radioactive implants [6,7]. A new strategy under development to replace millimeter-size seeds [8], consists in injecting radioactive nanoparticles in the affected tissues. The development of ^{103}Pd@Au NPs distributed in the diseased tissue, could increase the uniformity of the treatment compared to larger seeds, while enhancing the radiotherapeutic dose to the cancer cells through Au-mediated radiosensitization effect.

The synthesis of radiolabeled nanoparticles such as albumin micro- and nanospheres [9] or ^{103}Pd-labeled molecules for targeted therapy [10] requires the highest achievable Specific Activity (A_S), defined as the ratio between the activity of the radionuclide of interest and the mass of the sum of all radioactive and stable isotopes of the nuclide [11] (ideally approaching the theoretical carrier free value of $A_S(CF) = 2.76\ GBq \cdot \mu g^{-1}$). While for the seeds already in use the Specific Activity is practically unimportant, in the nanomedicine approach involving the synthesis of nanoparticles as nano-seeds or as drug carriers high Specific Activities have to be achieved and only the radioactive component should be present in the synthesis process. Therefore, a quantitative radiochemical separation of the Pd from the Rh target and its co-produced radionuclides is required which can be achieved by ion-exchange reactions or complexation [12].

Currently, ^{103}Pd is produced in reactors via the ^{102}Pd(n, γ) reaction with a very low A_S or in no-carrier-added form with accelerators using proton induced reactions [13].

Irradiation of pure palladium-102 (enriched from 3.2% natural abundance to 100%) to saturation ($t_{irr} \approx 85$ days) in a nuclear reactor with a flux of $10^{15} n \cdot s^{-1} \cdot cm^{-2}$ will lead to about 6.8% of ^{103}Pd.

* Corresponding author. Tel.: +39 02 503 19528.
E-mail addresses: simone.manenti@mi.infn.it, simone.manenti@gmail.com (S. Manenti).

http://dx.doi.org/10.1016/j.nucmedbio.2017.02.005
0969-8051/

The most widely used accelerator production method based on high-flux 18 MeV proton irradiation of a ^{103}Rh target in cyclotrons [14,15] allows to reach a yield [16] equal to 2.40 GBq·C^{-1} and of 3.25 GBq·C^{-1} if protons of 50 MeV could be used.

The use of a deuteron beam appears to be attractive for the production of several radionuclides since the (d,2n) reaction cross-section in the medium to high mass region is generally higher than that of (p,n) reactions [17]. However, studies on this alternative production methods using deuterons are scarce, and only two studies were reported at the beginning of this research work [18,19].

The present work presents experimental results for the cross-sections of the ^{103}Rh(d,2n)^{103}Pd reaction and of the co-produced radionuclides in the 5–33 MeV energy range.

2. Experimental

The excitation functions were determined using the stacked-foil technique. Stacks of thin foils consisted of alternating high purity aluminium (as energy degrader and monitor foils inserted between the Rh and the Ti targets), rhodium and titanium foils. In particular each stack was composed of four or five couple of Rh and Al foils, depending on the irradiation energy, and (i) by one Ti foil, inserted as final monitor foil in the stack for the JRC-Ispra irradiations or (ii) one Ti foil after each of the Rh/Al foils in the stack for the GIP-ARRONAX irradiations.

High purity ^{103}Rh targets (99.9%, Goodfellow Cambridge Ltd., Ermine Business Park, Huntingdon PE29 6WR, UK) had a nominal thickness of 12.5 or 25 μm (~ 15.1–31.7 mg·cm^{-2} with a general relative uncertainty of ±2%: these values of target thickness used in the calculation were measured accurately by weighing).

Low-energy irradiations were carried out on five stacks with the cyclotron (Scanditronix MC40, K = 38) of the JRC-Ispra at different incident energies covering the energy range from 16.6 MeV down to 5.2 MeV with a constant current of 100 nA for a duration of 1 h.

Each irradiation was carried out in an insulated target holder under vacuum, which was designed as an elongated Faraday cup to determine the integrated charge of the deuteron beam. Inside the Faraday cup a strong magnet was installed to avoid escaping of scattered or backscattered electrons as the loss of such electrons could lead to a virtually larger deuteron charge on the foil stacks. Two coaxial Al collimators (5 mm in diameter) were placed in front of the Faraday cup. Based on the distance between the collimators and the last couple of quadrupoles, a maximum broadening of the beam of a few μm was calculated. The charge was integrated by a current integrator (BIC Brookhaven Instruments Corporation, Austin, TX, USA; model 1000C), calibrated within 2% of uncertainty by an authorized calibration service (Nemko S.p.A., Biassono, MB, Italy). The incident deuteron energy had an uncertainty of ±0.20 MeV [20].

The reliability of the integrated current has been validated by the values of the cross-sections measured for ^{nat}Ti targets used as monitor foils, compared with the IAEA tabulated monitor reaction ^{nat}Ti(d,x)^{48} V [21].

Medium and high-energy irradiations were carried out with an IBA C70 cyclotron of the ARRONAX center, Saint-Herblain (FR). The ARRONAX cyclotron delivers deuteron beams at variable energies with an energy uncertainty of ±0.25 MeV [22]. The stacks were irradiated with an external deuteron beam. A 75 μm thick kapton foil was used as beam exit window, separating the beam line vacuum from atmospheric pressure in the vault. The stacks were located 68 mm downstream in air.

During the irradiation, an instrumented beam stop was used to control the beam current stability. However, it was not used as a Faraday cup with precise intensity measurements, since it is not under vacuum and is not equipped with a magnet to avoid escaping of scattered or backscattered electrons.

In this case, it was mandatory to use titanium and aluminium foils as degraders and as monitors to determine the experimental beam intensity value and energy from the ^{nat}Ti(d,x)^{48}V and ^{27}Al(d,x)^{24}Na IAEA tabulated monitor reactions [21] (Figs. 1 and 2).

Four different stacks were irradiated with a different incident energy in order to minimize energy straggling in a single experiment and to cover the energy range from 34 MeV down to 14 MeV, with an overlap of more than 2 MeV with the irradiations performed at the JRC-Ispra. The irradiations were carried out with a mean beam intensity of about 170 nA for 1 h.

The mean deuteron beam energy and energy degradation in each foil were computed by the Monte Carlo based computer code SRIM 2013 [23]. The uncertainty of the mean energy in each foil (± 0.2–0.4 MeV) includes the energy uncertainty of the extracted deuteron beam, as well as the uncertainties (± 0.1–0.3 MeV) in the mean mass thicknesses and the beam-energy straggling inside the target foils.

The activity of the radionuclides detected in each foil was measured at the LASA laboratory (INFN and Physics Dept. of University of Milan, Segrate MI), without any chemical processing, by calibrated high purity germanium (HPGe) detectors (EG&G Ortec, 15% relative efficiency, FWHM =2.2 keV at 1.33 MeV). The detectors were calibrated in energy and efficiency with certified ^{152}Eu and ^{133}Ba sources (CercaLEA, France and Amersham, UK). All foils were measured in the same geometrical position as that used for the calibration sources in order to avoid corrections for different geometries. The distance from the detector cap was sufficiently high to reduce dead time and pile up errors to negligible values (< 0.1%). The first measurements of the samples were generally started within a few hours (for the Ispra irradiations) or within 48 h (for ARRONAX irradiations) after the end of bombardment (EOB). The measurements continued for about six months in order to follow the decay of the main radionuclides and to let completely decay eventual "parent" radionuclides.

The overall uncertainty of the determined cross-sections is caused by several error sources in the measurement and evaluation process. Regarding the measurement process, a typical component is related to the statistical error in the peak counts: particular attention is given to reduce this value as low as possible (< 1%–18%, depending on the radionuclides and on the energies). Other significant error sources were: the target thickness and uniformity (< 2%, the integrated charge (≤ 2%), the uncertainty of the calibration sources (1.5% and 2.0%) and the fitting of the detector efficiency curves (< 1%), with an overall relative error of 4–20%.

The published data for the abundance of the gamma emissions and the half-lives were considered as being exact. Admittedly, especially the uncertainty of the low values of the abundance of the gamma emission of ^{103}Pd will add directly to the overall error in the determination of the reaction cross section [17]. Decay characteristics for the radionuclides in-

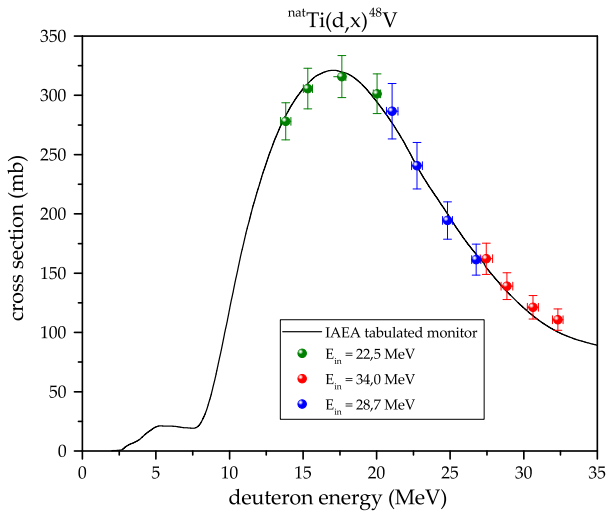

Fig. 1. Excitation function for ^{nat}Ti(d,x)^{48}V nuclear reactions.