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New activation cross section data on longer lived radio-nuclei produced in proton induced nuclear reaction on zirconium

F. Tárkányi [a], F. Ditrói [a,*], S. Takács [a], A. Hermanne [b], M. Al-Abyad [c], H. Yamazaki [d], M. Baba [d], M.A. Mohammadi [d]

[a] Institute for Nuclear Research, Hungarian Academy of Sciences (ATOMKI), Debrecen, Hungary
[b] Cyclotron Laboratory, Vrije Universiteit Brussel (VUB), Brussels, Belgium
[c] Physics Department, Cyclotron Facility, Nuclear Research Centre, Atomic Energy Authority, Cairo 13759, Egypt
[d] Cyclotron and Radioisotope Center (CYRIC), Tohoku University, Sendai, Japan

HIGHLIGHTS

- Proton induced reactions on natural zirconium up to 65 MeV.
- Stacked foil irradiation technique coupled with gamma-spectrometry.
- Comparison of experimental data with the nuclear reaction model results in the TENDL-2013 library.
- Calculation and comparison of thick target integral yields.
- Comparison of the production routes of ^{90}Nb, ^{95m}Nb, ^{89}Zr and ^{88}Y medically relevant radioisotopes.

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ABSTRACT

The excitation functions of ^{96}Nb, ^{95m}Nb, ^{95g}Nb, ^{92m}Nb, ^{91m}Nb, ^{90}Nb, ^{95}Zr, ^{89}Zr, ^{88}Zr, ^{86}Zr, ^{88}Y, ^{87m}Y, ^{87g}Y, ^{86}Y were measured up to 70 MeV proton energy by using the stacked foil technique and the activation method. The new data were compared with the critically analyzed experimental data in the literature and with the TALYS based model results in TENDL-2013 library. The possible role of the investigated reactions in the production of medically relevant ^{90}Nb, ^{95m}Nb, ^{89}Zr, and ^{88}Y radionuclides is discussed.

1. Introduction

Production cross sections of proton induced nuclear reactions on metals are important for many applications and for development of improved nuclear reaction theory. In most applications high intensity, low and high energy direct or secondary proton beams activate technological elements and produce highly active radio-products. After recognizing the importance of knowledge of production cross sections we concluded that a systematic co-ordinated experimental and theoretical study is necessary, and we started a set of experiments with a large scope.

Our research in connection with the activation cross sections on zirconium is of importance and applies to different projects:

- Preparation of a nuclear database for production of ^{90}Nb, ^{95m}Nb, ^{89}Zr, ^{88}Y medical radioisotopes in the frame of IAEA Coordinated Research Project (Gul et al., 2001; IAEA, 2001, 2012–2016) using the ^{90}Zr(p,n)^{90}Nb, ^{96}Zr(p,2n)^{95m}Nb, ^{90}Zr(p,2n)^{89}Nb–^{89}Zr and ^{nat}Zr(p,x)^{88}Zr–^{88}Y production routes.
- We have also investigated alternative production routes of these radio-products on yttrium (Uddin et al., 2007; Uddin et al., 2005).
- Preparation of proton and deuteron activation cross section database for the Fusion Evaluated Nuclear Data Library (IAEA, 2004).
- Preparation of a database for the Thin Layer Activation (TLA) technique for wear measurement (IAEA-NDS, 2010)) and every day practice of wear measurement of zirconium alloy samples.

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

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Table 1
Summary of earlier experimental investigations on activation cross sections and yields of the proton induced nuclear reaction on zirconium. The investigated quantities of the nuclear reactions are indicated according to the conventions of the EXFOR system (IAEA, 2008).

Author	Target	Irradiation	Beam current measurement and monitor reaction	Separation method and measurement of activity	Nuclear reaction and measured quantity and number of measured data points	Covered energy range (MeV)
Blaser (Blaser et al., 1951)	^{nat}Zr nitrate	Cyclotron stacked foil	^{63}Cu(p,n)^{63}Zn ^{62}Ni(p,n)^{62}Cu	Geiger–Müller counter	40-ZR-96(P,N)41-NB-96,SIG, 15 40-ZR-92(P,N)41-NB-92,SIG, 10 40-ZR-91(P,N)41-NB-91-M,SIG, 12	2.73–6.67 3.5–6.67 3.5–6.66
Blosser (Blosser and Handley, 1955)	Single foil	Cyclotron	^{63}Cu(p,n)^{63}Zn	Geiger–Müller counter	40-ZR-90(P,N)41-NB-90-G,M+,SIG, EXP,1	12.7
Deleanu-Olkowski (Delaunau-Olkowsky et al., 1963)	^{90}Zr ^{91}Zr ^{94}Zr	Cyclotron	^{65}Cu(p,n)^{65}Zn	γ-NaI(Tl)	40-ZR-90(P,α)39-Y-87,SIG,EXP, 1 40-ZR-91(P,α)39-Y-88,SIG,EXP, 1 40-ZR-94(P,α)39-Y-91,SIG,EXP, 1	11.2 11.2 11.2
Kantelo (Kantelo and Hogan, 1976)	^{90}Zr-oxide	Cyclotron single target	^{63}Cu(p,x)^{63}Zn ^{65}Cu(p,x)^{64}Cu	γ-Ge (Li)	40-ZR-90(P,X)39-Y-86-G,M+,SIG, EXP,1 40-ZR-90(P,X)39-Y-87-G,M+,SIG, EXP,1 40-ZR-90(P,X)39-Y-88,SIG,EXP,1 40-ZR-90(P,X)39-Y-85-G,SIG,EXP+40-ZR-90(P,X)39-Y-85-M,SIG,EXP, 1	11.2 11.2 11.2 11.2
Birjukov (Birjukov et al., 1979)	^{91}Zr (63.63%)	Cyclotron single target	Beam current integrator	Neutron time of flight	40-ZR-90(P,N)41-NB-90,SIG, 1	11.2
Roughton (Roughton et al., 1979)	^{nat}Zr	Cyclotron single target irr.	Beam current integrator	γ-Ge(Li)	40-ZR-90(P,G)41-NB-91-M,PY, TT,15 40-ZR-94(P,N)41-NB-94-M,PY,TT, 13 40-ZR-96(P,N)41-NB-96,PY,TT, 12	1.75–6.426 3.056–5.953 3.057–5.954
Muminov (Muminov et al., 1980)	^{nat}Zr	Cyclotron		No chemical separationγ -Ge (Li)	40-ZR-0(P,N)41-NB-90-M,TTY, 3	9–11
Dmitriev (Dmitriev and Molin, 1981)	^{nat}Zr	Cyclotron single target	Faraday cup	γ-Ge(Li)	40-ZR-0(P,X)39-Y-88,TTY,DT, 1 40-ZR-0(P,X)40-ZR-95,CUM,TTY,DT, 1 40-ZR-0(P,X)41-NB-92-M,TTY,DT, 1 40-ZR-96(P,2N)41-NB-95-G,TTY,DT, 1	22 22 22 22
Regnier (Regnier et al., 1982)	^{nat}Zr	Cyclotron, linac stacked foil	^{27}Al(p,x)^{22}Na	γ-HPGe	40-ZR-0(P,X)40-ZR-88,CUM,SIG, 7	59–24,000
Dmitriev (Dmitriev, 1983)					40-ZR-92(P,N)41-NB-92-M,TTY,EXP, 1 40-ZR-92(P,2N)41-NB-91-M,TTY,EXP, 1 40-ZR-96(P,2N)41-NB-95,TTY,EXP, 1 40-ZR-90(P,X)40-ZR-89,TTY,EXP, 1 40-ZR-90(P,A)39-Y-87,TTY,EXP, 1 40-ZR-96(P,X)40-ZR-95,TTY,EXP, 1	22 22 22 22 22 22
Abe (Abe et al., 1984)	^{nat}Zr	Cyclotron multi-sample target method	^{65}Cu(p,n)^{65}Zn	γ-Ge(Li), HPGe	40-ZR-0(P,X)41-NB-90-G,M+,TTY,DT, 1 40-ZR-92(P,N)41-NB-92-M,TTY,DT, 1 40-ZR-96(P,N)41-NB-96,TTY,DT, 1	16 16 16
Isshiki (Isshiki et al., 1984)	^{nat}Zr	Cyclotron rotating target holder	^{nat}Ti(p,x)^{48}V	γ-Ge(Li)	40-ZR-0(P,N)41-NB-90-M,TTY, 1	10.4