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The activation of W and Zr by deuterons at energies up to 20 MeV

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Abstract. The proton and deuteron induced reactions are of a great interest for the assessment of induced radioactivity of accelerator components, target and beam stoppers. In order to investigate the important nuclides, we have carried up the irradiation experiments with the variable-energy cyclotron U-120 M of the NPI CAS Řež. The production cross sections of the nuclides ^{179,181,182m,182,183,184m,184,186}Re and ^{187}W from reaction on natural W were investigated by deuteron beams of 20 MeV energy. A part of preliminary results of deuteron activation of natural Zr is also shown. The stacked-foil technique was utilized. The comparison of present results to data of other authors and to predictions of evaluated data libraries is discussed.

1. Introduction

The description of deuteron-nucleus interaction represents important tests for both the quality of reaction mechanism models and evaluation of nuclear data request especially for fusion technology. Moreover, knowledge of excitation function has an importance for medicine, namely isotope ^{186g}Re is a ß-emitter which has been used in clinical trials and the isotope could be advantageously produced on a tungsten target by deuteron or proton irradiation.

The irradiation was carried out on CANAM infrastructure [1] of NPI CAS using an external deuteron beam of the variable-energy cyclotron U-120M operating in the negative-ion mode.

2. Experiment

2.1. Experimental set-up

Experimental facilities of CANAM (Center of Accelerators and Nuclear Analytical Methods) infrastructure are offered to the users in Open Access mode. CANAM infrastructure consists of three major research laboratories of the Nuclear Physics Institute of CAS.

- Laboratory of Tandetron – operating an accelerator Tandetron 4130MC
- Neutron Physics Laboratory (NPL) – providing facilities at the reactor LVR-15
- Laboratory of Cyclotron and Fast Neutron Generators (LC&FNG) – operating the isochronous cyclotron U-120M.

The activation cross sections for deuteron incident on natural W and natural Zr were measured by the stacked-foil technique. We carried out two experiments using cooled irradiation chamber that serves also as the Faraday cup. In the first run, the stack of high purity W (99.95%, 25 μm, Goodfellow) and Al (99.5%, 50 μm, Goodfellow) was irradiated by collimated deuteron beam of 20.1 MeV during 10.4 min with 0.329 μA mean current. The Zr foils (99.8% purity, 25 μm, Goodfellow) interleaved with Al foils (99.5%, 50 μm, Goodfellow) were irradiated during 10.35 min with 0.327 μA mean current and 20.0 MeV initial energy in the second run.

Several minutes after irradiation, the activities of the irradiated foils were measured by two calibrated HPGe detectors of 50% efficiency and of FWHM 1.8 keV at 1.3 MeV. The computers registering beam current and sample activities were time synchronized.

2.2. Data analysis

The energy of reaction in subsequent foils was calculated by using SRIM 2009 [2] code. The gamma-rays from irradiated samples were measured with HPGe. Activated isotopes were identified on the basis of $T_{1/2}$, γ-ray energies and intensities [3]. The measured activities were corrected for decay during and after the irradiation.

Measured errors consist of statistical error of peak determination and systematic errors of current certainty (5%), uncertainty of foil thickness (2%) and detector efficiency uncertainty (2%). The uncertainty of initial beam energy determination is 1% and beam energy spread is 1.8%.

3. Results

3.1. d + W

Natural wolfram consists of five stable isotopes – ^{180}W (0.12%),^{182}W (26.50%),^{183}W (14.31%), ^{84}W (30.64%) and ^{186}W (28.43%). The heavy target and reaction products lie in a well deformed region and have a large number of γ-transitions. Because the registered spectra are very complex, we carefully selected only the lines that belong to the isotope under interest. Inventory of applied γ-lines [3] used for cross section is in Table 1.

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Table 1. Isotopes observed from irradiated W foils.

Isotope	$T_{1/2}$	E_γ (keV)	I_γ(%)
^{179}Re	19.5 min	1680.24	13.0
		189.05	7.5
		401.82	7.2
^{181}Re	19.9 h	639.3	6.4
		558.1	2.1
		1440.5	1.9
^{182m}Re	12.7 h	470.32	2
		2057.39	0.92
		2016.0	0.79
		1957.28	0.45
^{182}Re	64.0 h	169.15	11.3
		1427.37	9.5
		256.45	9.5
		130.8	7.5
^{183}Re	70.0 d	162.32	23.3
		291.72	3.05
		99.08	2.69
		246.06	1.31
^{184}Ta	8.7 h	414.03	72
^{184m}Re	169 d	104.73	13.4
		920.93	8.14
		384.25	3.31
^{184}Re	38 d	1022.63	0.52
		539.22	0.327
^{186}Re	3.7183 d	137.16	9.42
^{187}W	23.72 h	685.77	27.3
		479.53	21.8
		618.36	6.28

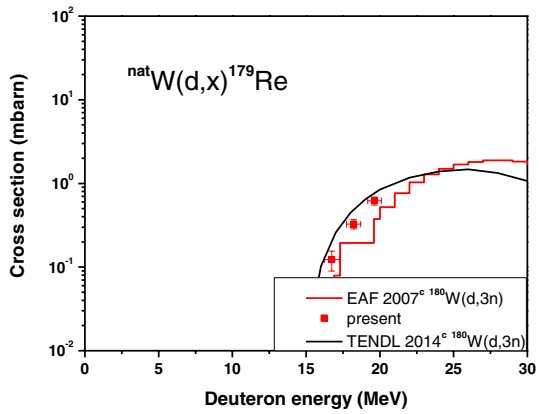

Figure 1. ^{nat}W(d,xn)^{179}Re production cross section.

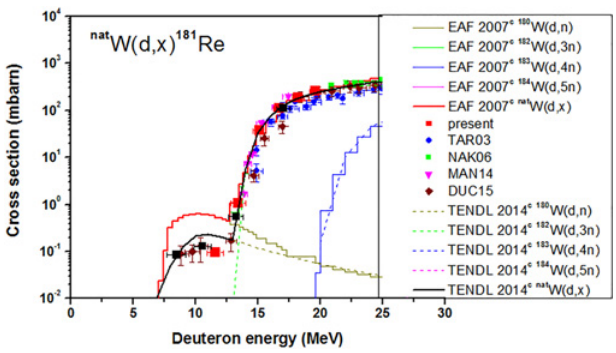

Figure 2. ^{nat}W(d,xn)^{181}Re production cross section.

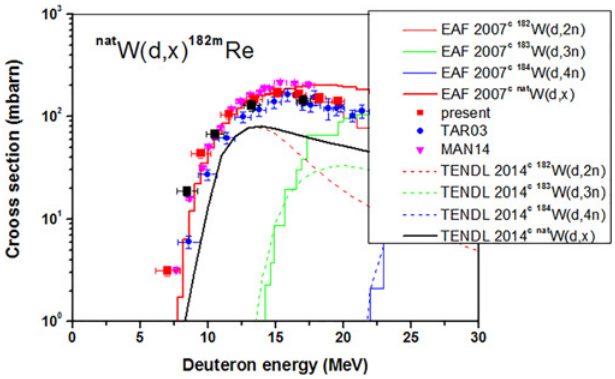

Figure 3. ^{nat}W(d,xn)^{182m}Re production cross section.

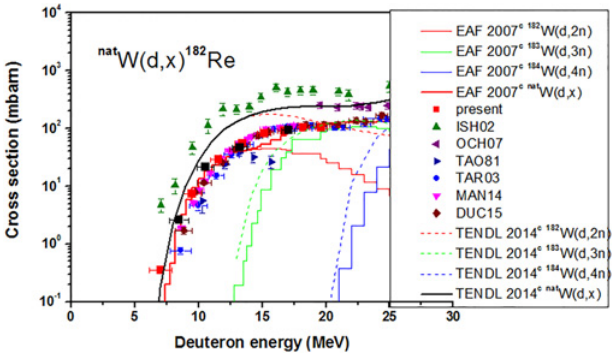

Figure 4. ^{nat}W(d,xn)^{182}Re production cross section.

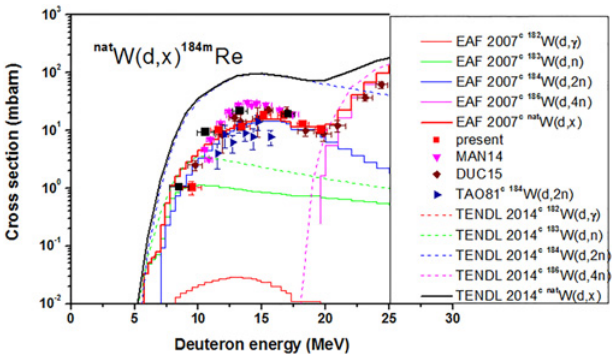

Figure 5. ^{nat}W(d,x)^{184m}Re production cross section.

We obtained excitation functions of 10 isotopes from the deuteron activation of natural W. Present results are shown in Figs. 1–10. They are compared to the results of previous authors [5–14] and to the evaluated data from EAF 2007 [15] and TENDL 2014 [16] libraries. All evaluated data are corrected/normalized to natural abundance of the sample

The ^{179}Re isotope is produced only in ^{180}W(d,3n) reaction. The cross section of the ^{nat}W(d,x)^{179}Re reaction was obtained for the first time (Fig. 1).

The ^{181}Re production reaction is shown in Fig. 2. While present data are in agreement previous data and TENDL 2014 prediction, EAF 2007 overestimates ^{180}W(d,n) reaction contribution.

The ^{nat}W(d,xn)^{182m}Re and ^{nat}W(d,xn)^{182}Re excitation functions are shown in Fig. 3 and Fig. 4, respectively. The isomer ^{182m}Re decays exclusively by EC-decay to ^{182}W. Data are in agreement with EAF 2007. TENDL 2014

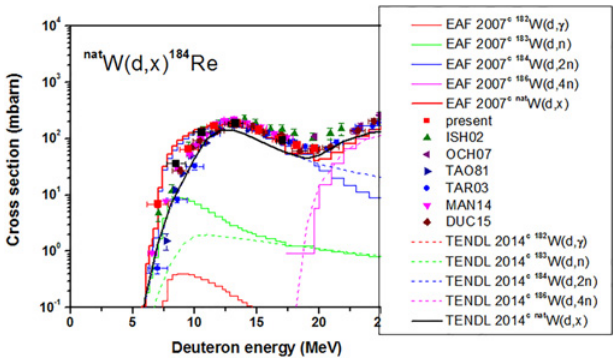

Figure 6. ^{nat}W(d,x)^{184}Re production cross section.

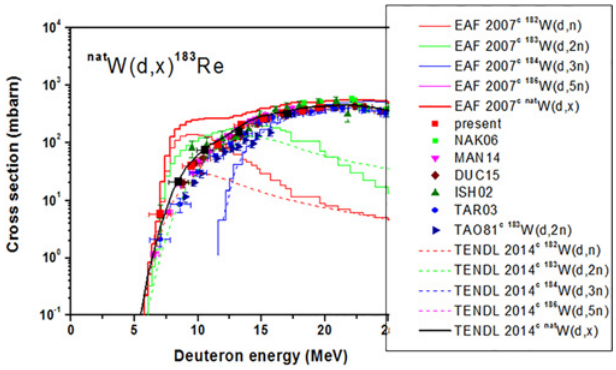

Figure 7. ^{nat}W(d,xn)^{183}Re production cross section.

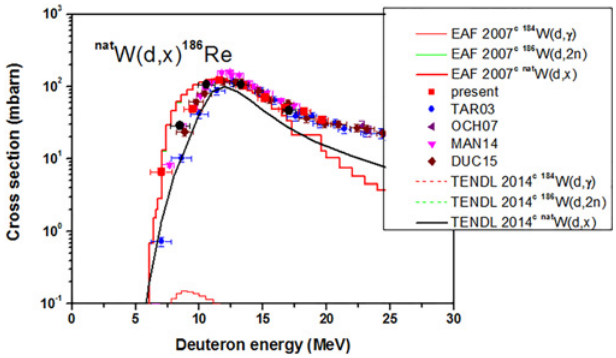

Figure 8. ^{nat}W(d,x)^{186}Re production cross section.

overestimates cross section values for the ground state at the expense of the isomeric state.

For the case of ^{nat}W(d,xn)^{184m}Re and ^{nat}W(d,xn)^{184}Re the excitation functions are shown in Fig. 5 and Fig. 6, respectively. TENDL 2014 overestimates the experimental values of cross sections for the isomeric state production.

The experimental values and TENDL 2014 are in agreement for the reaction ^{nat}W(d,xn)^{183}Re, EAF 2007 overestimates the contribution of (d,n) channel (Fig. 7).

The excitation function for ^{nat}W(d,x)^{186}Re reaction is shown in Fig. 8. The libraries do not agree on (d,2n) reaction here.

^{186}W(d,α^+)^{184}Ta is the main contributor for to the ^{184}Ta production. Present results are in agreement with EAF 2007 in contrast to the data of Demildt (from 1961) [14] that agree with TENDL 2014 (Fig. 9).

The single reaction ^{186}W(d,p)^{186}Re can produce ^{187}W. Both libraries have problems to describe this reaction,

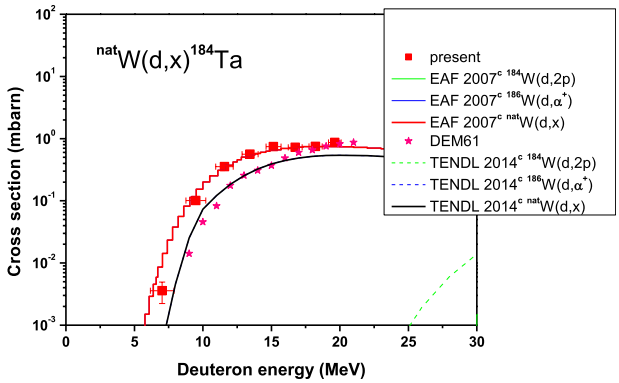

Figure 9. ^{nat}W(d,x)^{184}Ta production cross section.

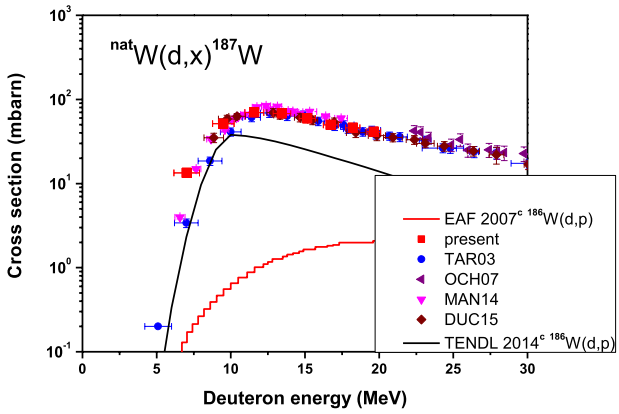

Figure 10. ^{nat}W(d,x)^{187}W production cross section.

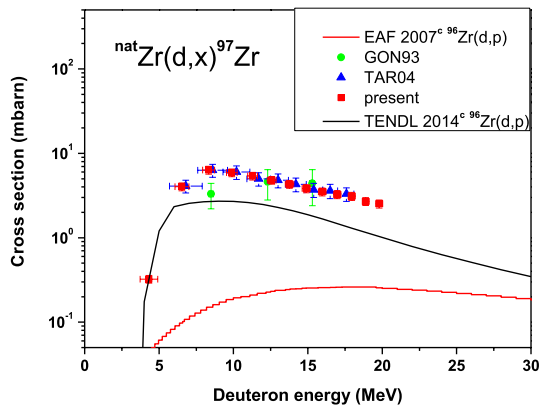

Figure 11. ^{nat}Zr(d,x)^{97}Zr production cross section.

although TENDL 2014 describes the rise of cross section at low energies (Fig. 10).

3.2. d+Zr

Natural zirconium consists also of five stable isotopes – ^{90}Zr (51.45%),^{91}Zr (11.22%),^{92}Zr (17.15%), ^{94}Zr (17.38%) and ^{96}Zr (2.80%). The deuteron activation cross sections were studied previously in [17–20]. We obtained preliminary data for 10 excitation functions that are in agreement with previous authors.

The activation cross sections with various outgoing channels are shown in Figs. 11–14 as an example. It is seen that ^{96}Zr(d,p) single reaction generating ^{97}Zr is

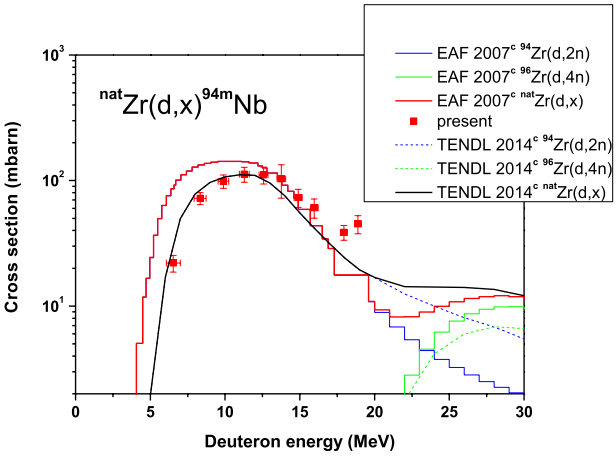

Figure 12. ^{nat}Zr(d,xn)^{94m}Nb production cross section.

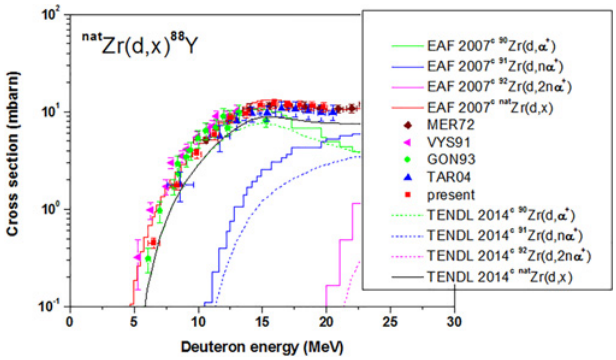

Figure 13. ^{nat}Zr(d,x)^{83}Y production cross section.

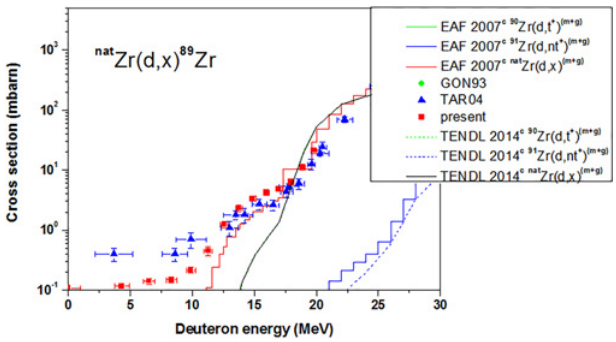

Figure 14. ^{nat}W(d,x)^{89}Zr production cross section.

much better described by TENDL 2014 than by EAF 2007 (Fig. 11). The same is valid for the ^{94}Zr(d,2n) reaction, the main contributor to ^{94m}Nb production (Fig. 12). Reactions with α particle in outgoing channel are rather well described by EAF 2007 (Fig. 13). This library has better predictions for (d,t$^+$) reaction (Fig. 14).

4. Conclusion

We may conclude that TENDL 2014 describes (d,p) and (d,xn) channels much better than EAF 2007. Both libraries satisfactory describe (d,xα^+) channel and (d,t$^+$) channel is better represent by EAF 2007 library.

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