Experimental and theoretical cross section data of deuteron induced nuclear reactions on platinum

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Abstract

Additional experimental activation cross sections for deuteron induced reactions on platinum were measured in the 35–49 MeV energy range for the $^{nat}\text{Pt}(\text{d}, \text{xn})^{191,192,193,194,195,196\text{m}2,196\text{g},198\text{m},198\text{g},199}\text{Au}$, $^{nat}\text{Pt}(\text{d}, \text{x})^{189,191,193\text{m},195\text{m},197\text{g}}\text{Pt}$ and $^{nat}\text{Pt}(\text{d}, \text{x})^{188,189,190\text{m}2,190,192,194\text{m}2}\text{Ir}$ reactions by using the stacked foil irradiation technique and gamma ray spectrometry. The available experimental results are compared with the calculated values based on ALICE-D and EMPIRE-D model codes and with the theoretical predictions in the TALYS based TENDL-2017 library.

Keywords Platinum targets · Stacked foil technique · Deuteron induced reactions · Theoretical nuclear reaction model codes · Pt, Au and Ir radioisotopes · Thin layer activation

Introduction

Experimental activation cross section data of proton and deuteron induced reactions on platinum for production of medically relevant radioisotopes, for thin layer activation technology and for generally used activation data libraries [1–6] were reported by us earlier. The goal of this study was to clear the disagreement in our earlier measurement, and to compare all data with different theoretical models. Furthermore, we could determine new cross section for some reactions.

In our last investigation up to 50 MeV [6] we could deduce only scattered data for some activation products and for some reactions significant disagreements were found with earlier experimental data. During a recent investigation of activation data on other target elements we got the possibility to obtain additional results on platinum in the 35–49 MeV energy range. In the present report, we compare the new data with the literature values and in order

to investigate the prediction capability of theoretical results we made calculations with the ALICE and EMPIRE codes, modified to better represent deuteron induced reactions.

Experimental details and data analysis

Elemental experimental cross sections were determined by using the activation method, stacked foil irradiation technique and HPGe gamma ray spectrometry. Cross-section data were deduced relative to the excitation functions of the $^{27}\text{Al}(\text{d}, \text{x})^{22,24}\text{Na}$ monitor reactions [7] re-measured in the whole covered energy range.

The irradiation was made at an external beam line of the Cyclone 90 cyclotron of the Université Catholique in Louvain la Neuve (LLN) for 60 min with a 50 MeV energy extracted beam having 100 nA beam intensity. The targets were irradiated in a short Faraday cup.

The irradiated stack contained a sequence of 7 blocks of Hf (10.54 μm), Al (49.54 μm), Al (49.54 μm), Pt (19.29 μm), Al (49.54 μm), Al (49.54 μm), CuMnNi alloy (24.73 μm), Al (49.54 μm), Al (49.54 μm) followed by 13 blocks of Hf (10.54 μm) Al (10.85 μm), Al (49.54 μm), CuMnNi alloy (24.73 μm) and Al (10.85 μm). The 7 Pt targets covered the 49–35 MeV energy range.

Four series of gamma-ray spectra were measured to follow the decay, starting at 7.9–8.7 h, 21.3–25.1 h, 187.2–198.2 h and 2811.1–3022.9 h after the end of

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Table 1 Decay characteristic of the investigated reaction products and Q-values of the contributing processes

Nuclide spin/parity decay level energy	Half-life	$E_{\gamma}(\text{keV})$	I (%)	Contributing process	Q-value (MeV)
^{191}gAu 3/2 ⁺ ϵ : 100%	3.18 h	277.86 399.84 478.04 586.44 674.22	6.4 4.2 3.5 15.0 6.0	$^{190}\text{Pt}(\text{d},\text{n})$ $^{192}\text{Pt}(\text{d},3\text{n})$ $^{194}\text{Pt}(\text{d},5\text{n})$ $^{195}\text{Pt}(\text{d},6\text{n})$ $^{196}\text{Pt}(\text{d},7\text{n})$ $^{198}\text{Pt}(\text{d},9\text{n})$	1.55 –13.56 –28.17 –34.28 –42.20 –55.60
^{192}Au 1 [–] ϵ : 100%	4.94 h	295.96 308.46 316.51 612.46	23 3.5 59 4.4	$^{192}\text{Pt}(\text{d},2\text{n})$ $^{194}\text{Pt}(\text{d},4\text{n})$ $^{195}\text{Pt}(\text{d},5\text{n})$ $^{196}\text{Pt}(\text{d},6\text{n})$ $^{198}\text{Pt}(\text{d},8\text{n})$	–6.52 –21.14 –27.24 –35.16 –48.56
^{193}gAu 3/2 ⁺ ϵ : 100%	17.65 h	112.52 173.52 255.57 268.22 439.04	2.2 2.7 6.2 3.6 1.78	$^{192}\text{Pt}(\text{d},\text{n})$ $^{194}\text{Pt}(\text{d},3\text{n})$ $^{195}\text{Pt}(\text{d},4\text{n})$ $^{196}\text{Pt}(\text{d},5\text{n})$ $^{198}\text{Pt}(\text{d},7\text{n})$	–6.52 –12.43 –18.54 –26.46 –39.86
^{194}Au 1 [–] ϵ : 100% [–]	38.02 h	293.55 328.46 1468.88	10.58 60.4 6.61	$^{194}\text{Pt}(\text{d},2\text{n})$ $^{195}\text{Pt}(\text{d},3\text{n})$ $^{196}\text{Pt}(\text{d},4\text{n})$ $^{198}\text{Pt}(\text{d},6\text{n})$	–5.56 –11.66 –19.58 –32.98
^{195}gAu 3/2 ⁺ ϵ : 100%	186.01 d	98.86 129.74	11.21 0.84	$^{194}\text{Pt}(\text{d},\text{n})$ $^{195}\text{Pt}(\text{d},2\text{n})$ $^{196}\text{Pt}(\text{d},3\text{n})$ $^{198}\text{Pt}(\text{d},5\text{n})$	2.87 –3.23 –11.15 –24.56
$^{196\text{m}2}\text{Au}$ 12 [–] IT: 100% 595.66 keV	9.6 h	147.81 168.37 188.27	43.5 7.8 30.0	$^{195}\text{Pt}(\text{d},\text{n})$ $^{196}\text{Pt}(\text{d},2\text{n})$ $^{198}\text{Pt}(\text{d},4\text{n})$	3.41 –4.51 –17.92
^{196}gAu 2 [–] β^- : 7.0% ϵ : 93.0%	6.1669 d	333.03 355.73	22.9 87	$^{195}\text{Pt}(\text{d},\text{n})$ $^{196}\text{Pt}(\text{d},2\text{n})$ $^{198}\text{Pt}(\text{d},4\text{n})$	3.41 –4.51 –17.92
$^{198\text{m}}\text{Au}$ 12 [–] IT: 100% 811.7 keV	2.272 d	97.21 180.31 204.10 214.89 333.82	69 49 39 77.3 18	$^{198}\text{Pt}(\text{d},2\text{n})$	–3.33
^{198}gAu 2 [–] β^- : 100%	2.6947 d	411.80	95.62	$^{198}\text{Pt}(\text{d},2\text{n})$	–3.33
^{199}Au 3/2 ⁺ β^- : 100%	3.139 d	158.38 208.20	40.0 8.72	$^{198}\text{Pt}(\text{d},\text{n})$	4.254
^{188}Pt 0 ⁺ α : 2.6E–5% ϵ : 99.9999%	10.2 d	187.59 195.05 381.43 423.34	19.4 18.6 7.5 4.4	$^{190}\text{Pt}(\text{d},\text{p}3\text{n})$ $^{192}\text{Pt}(\text{d},\text{p}5\text{n})$ $^{194}\text{Pt}(\text{d},\text{p}7\text{n})$	–17.86 –32.97 –47.59
^{189}Pt 3/2 [–] ϵ : 100%	10.87 h	243.50 568.85 721.38	7.0 7.1 9.3	$^{190}\text{Pt}(\text{d},\text{p}2\text{n})$ $^{192}\text{Pt}(\text{d},\text{p}4\text{n})$ $^{194}\text{Pt}(\text{d},\text{p}6\text{n})$ $^{195}\text{Pt}(\text{d},\text{p}7\text{n})$	–11.14 –26.24 –40.86 –46.96
^{191}Pt 3/2 [–] ϵ : 100%	2.802 d	96.517 129.42 172.18 351.21 359.90 409.44 538.90	3.28 3.2 3.52 3.36 6.0 8.0 13.7	$^{190}\text{Pt}(\text{d},\text{p})$ $^{192}\text{Pt}(\text{d},\text{p}2\text{n})$ $^{194}\text{Pt}(\text{d},\text{p}4\text{n})$ $^{195}\text{Pt}(\text{d},\text{p}5\text{n})$ $^{196}\text{Pt}(\text{d},\text{p}6\text{n})$	4.22 –10.89 –25.50 –31.60 –39.53

Table 1 (continued)

Nuclide spin/parity decay level energy	Half-life	E_{γ} (keV)	I (%)	Contributing process	Q -value (MeV)
^{193m}Pt 13/2 ⁺ IT: 100% 149.78 keV	4.33 d	135.50	0.112	$^{192}\text{Pt}(\text{d,p})$ $^{194}\text{Pt}(\text{d,p2n})$ $^{195}\text{Pt}(\text{d,p3n})$ $^{196}\text{Pt}(\text{d,p4n})$ $^{198}\text{Pt}(\text{d,p6n})$	4.04 – 10.58 – 16.68 – 24.60 – 38.01
^{195m}Pt 13/2 ⁺ IT: 100% 259.29 keV	4.010 d	98.90 129.79	11.7 2.90	$^{194}\text{Pt}(\text{d,p})$ $^{195}\text{Pt}(\text{d,pn})$ $^{196}\text{Pt}(\text{d,p2n})$ $^{198}\text{Pt}(\text{d,p4n})$	3.88 – 22.25 – 10.15 – 23.55
^{197m}Pt 13/2 ⁺ β^- : 3.3% IT: 96.7% 399.59 keV	95.41 min	346.5	11.1	$^{196}\text{Pt}(\text{d,p})$ $^{198}\text{Pt}(\text{d,p2n})$	3.62 – 9.78
^{197g}Pt 1/2 ⁺ β^- : 100%	19.89 h	191.44	3.7	$^{196}\text{Pt}(\text{d,p})$ $^{198}\text{Pt}(\text{d,p2n})$	3.62 – 9.78
^{188}Ir 1 [–] ϵ : 100%	41.5 h	155.05 477.99 633.02	30 14.7 18	$^{190}\text{Pt}(\text{d,2p2n})$ $^{192}\text{Pt}(\text{d,2p4n})$ $^{194}\text{Pt}(\text{d,2p6n})$	– 16.56 – 31.67 – 46.28
^{189}Ir 3/2 ⁺ ϵ : 100%	13.2 d	245.08	6.0	$^{190}\text{Pt}(\text{d,2pn})$ $^{192}\text{Pt}(\text{d,2p3n})$ $^{194}\text{Pt}(\text{d,2p5n})$ $^{195}\text{Pt}(\text{d,2p6n})$	– 8.38 – 23.49 – 38.10 – 44.21
^{190m}Ir (11) [–] IT: 8.6% ϵ : 91.4% 376.4 keV	3.087 h	186.7 361.2 502.5 616.5	64.2 86.72 89.38 90.14	$^{190}\text{Pt}(\text{d,2p})$ $^{192}\text{Pt}(\text{d,2p2n})$ $^{194}\text{Pt}(\text{d,2p4n})$ $^{195}\text{Pt}(\text{d,2p5n})$ $^{196}\text{Pt}(\text{d,2p6n})$	– 2.01 – 17.12 – 31.73 – 37.84 – 45.76
^{190}Ir 4 [–] ϵ : 100%	11.78 d	186.68 361.09 371.24 407.22 518.55 557.95 569.30 605.14	52 13.0 22.8 28.5 34.0 30.1 28.5 39.9	$^{190}\text{Pt}(\text{d,2p})$ $^{192}\text{Pt}(\text{d,2p2n})$ $^{194}\text{Pt}(\text{d,2p4n})$ $^{195}\text{Pt}(\text{d,2p5n})$ $^{196}\text{Pt}(\text{d,2p6n})$	– 2.01 – 17.12 – 31.73 – 37.84 – 45.76
^{192g}Ir 4 ⁺ ϵ : 4.76% β^- : 95.24%	73.829 d	295.95 308.46 316.51 468.07 604.41	28.71 29.70 82.86 47.84 8.216	$^{192}\text{Pt}(\text{d,2p})$ $^{194}\text{Pt}(\text{d,2p2n})$ $^{195}\text{Pt}(\text{d,2p3n})$ $^{196}\text{Pt}(\text{d,2p4n})$ $^{198}\text{Pt}(\text{d,2p6n})$	– 2.90 – 17.51 – 23.61 – 31.54 – 44.94
$^{194m2}\text{Ir}$ (10,11) β^- : 100% 190.0 keV	171 d	328.5 338.8 390.8 482.6 562.4 600.5 687.8	93.0 55.0 35.0 97.0 35.0 62.0 59.0	$^{194}\text{Pt}(\text{d,2p})$ $^{195}\text{Pt}(\text{d,2pn})$ $^{196}\text{Pt}(\text{d,2p2n})$ $^{198}\text{Pt}(\text{d,2p4n})$	– 3.67 – 9.78 – 17.70 – 31.10

bombardment, respectively. Further experimental details are given in our previous work on deuteron induced reactions on manganese [8], which was irradiated in the same stack.

Gamma spectra were evaluated by automatic fitting algorithm included in the Genie 2000 package or in an iterative process using the Forgamma [9, 10] code. For data evaluation, NUDAT 2.6 [11] decay data were used (Table 1). As

natural platinum consists of several stable isotopes with following abundance (%): ^{190}Pt –0.01, ^{192}Pt –0.79, ^{194}Pt –32.9, ^{195}Pt –33.8, ^{196}Pt –25.3, ^{198}Pt –7.2, so called elemental cross sections were deduced.

The Q values of the contributing reactions (Q value calculator [12]) are also shown in Table 1 to indicate the reaction thresholds.

Fig. 1 Simultaneously measured experimental data of $^{27}\text{Al}(\text{d},\text{x})^{22,24}\text{Na}$ monitor reactions in comparison with the recommended values [7]

Uncertainty on cross-sections was determined according to the recommendation given in Ref. [13] by taking the sum in quadrature of all individual linear contributions: beam current (7%), target thickness or homogeneity (5%), detector efficiency (5%), photo peak area determination and counting statistics (1–20%).

The median beam energy in each target foil was obtained by a degradation calculation based on the calibrated primary energy, the stopping powers of Andersen [14] and the fitted monitor reactions (Fig. 1) [15]. Uncertainty of energy was estimated by taking into account cumulative effects during the energy degradation (primary energy, target thickness, energy straggling) and the applied correction to monitor reactions.

Abundance of isotopes of natural Pt (%): ^{190}Pt –0.01, ^{192}Pt –0.79, ^{194}Pt –32.9, ^{195}Pt –33.8, ^{196}Pt –25.3, ^{198}Pt –7.2.

The Q -values shown in Table 2 refer to formation of the ground state. Decrease Q -values for isomeric states with level energy of the isomer.

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: $\text{pn} \rightarrow \text{d} + 2.2$ MeV, $\text{p2n} \rightarrow \text{t} + 8.5$ MeV, $2\text{pn} \rightarrow {}^3\text{He} + 7.7$ MeV, $2\text{p2n} \rightarrow \alpha + 28.3$ MeV.

Theoretical calculations

The cross sections of the investigated reactions were calculated using the pre-compound model codes ALICE-IPPE [16] and EMPIRE-II [17] modified for deuterons by

Ignatyuk (D-versions) [18]. These modified codes named ALICE-D and EMPIRE-D were developed by including a simulation of direct (d, p) and (d, t) transitions with the general relations for a nucleon transfer probability in the continuum through an energy dependent enhancement factor for the corresponding transitions. The theoretical curves were determined using one recommended input data-set [19] without any optimization or adjustment of parameters to the individual reactions or stable target isotopes. Independent data for isomers with ALICE-D code were obtained by using the isomeric ratios calculated with EMPIRE-D.

The experimental data are also compared with the cross section data reported in the TENDL-2017 [20] on-line nuclear reaction data library. The TENDL-2017 library is based on both default and adjusted TALYS 1.9 model calculations [21].

We had many problems with these calculations. At the beginning the optical potential for deuterons was taken in accordance with the default RIPL recommendations [22]. As for this potential all Empire results were much higher than the ALICE results, we decided to make new calculations with the Perry potential [23], which we used earlier for the ^{197}Au target [24]. This resulted in certainly more consistency. However, the main problems relate to the levels schemes, which are poor for the most of Pt and Ir isotopes. There are too many low-value spin- and a strong deficit for high-spin levels. So, the calculated isomeric ratios are too low for most cases. In principle some corrections for the spin distributions can be made to get better agreement.

Table 2 The measured cross sections for the $^{nat}\text{Pt}(\text{d},\text{xn})^{191,192,193,194,195,196\text{m}2,196\text{g},198\text{m},198\text{g},199}\text{Au}$, $^{nat}\text{Pt}(\text{d},\text{x})^{189,191,193\text{m},195\text{m},197\text{g}}\text{Pt}$ and $^{nat}\text{Pt}(\text{d},\text{x})^{189,190\text{m},190,192,194\text{m}2}\text{Ir}$ reactions

E (MeV)	ΔE (MeV)	^{199}Au		$^{198\text{m}}\text{Au}$		$^{198\text{g}}\text{Au}$		$^{196\text{m}2}\text{Au}$		$^{196\text{g}}\text{Au}$		^{195}Au		^{194}Au	
		σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)
48.5	0.3	6.98	0.98	1.12	0.19	2.61	0.34	5.38	0.73	32	4.13	74.80	9.64	184.62	23.80
46.5	0.3	4.88	0.64	0.80	0.13	2.35	0.31	5.37	0.75	31.13	4.02	77.01	9.93	161.87	20.87
44.3	0.4	6.28	0.95	1.46	0.25	2.72	0.36	5.80	0.78	36.22	4.68	95.75	12.34	181.08	23.34
42.1	0.4	6.26	0.90	1.11	0.18	3.49	0.45	7.57	1.01	44.57	5.75	118.04	15.21	212.52	27.39
39.8	0.5	6.38	0.90	1.18	0.18	3.68	0.48	9.54	1.26	49.41	6.37	122.26	15.76	240.05	30.94
37.3	0.5	8.03	1.12	1.37	0.20	4.01	0.52	12.49	1.63	59.5	7.67	123.93	15.97	307.49	39.63
34.8	0.5	4.12	0.60	1.38	0.20	3.71	0.48	14.97	1.95	65.75	8.48	101.08	13.05	313.60	40.41
E (MeV)	ΔE (MeV)	^{193}Au		^{192}Au		^{191}Au		$^{197\text{g}}\text{Pt}$		$^{195\text{m}}\text{Pt}$		$^{193\text{m}}\text{Pt}$		$^{191}\text{Pt(cum)}$	
		σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)
48.5	0.3	207.38	26.73	399.97	51.63	363.64	47.20	28.67	3.76	63.75	7.16	202.34	29.54	341.19	38.42
46.5	0.3	218.67	28.25	358.37	46.28	286.30	37.27	27.81	4.29	60.54	6.80	140.49	22.85	261.64	29.52
44.3	0.4	266.44	34.40	403.86	52.14	254.97	33.29	27.92	3.70	67.39	7.58			235.37	26.56
42.1	0.4	283.00	36.57	450.46	58.14	215.68	28.21	25.19	3.73	77.89	8.75	99.75	20.86	205.35	23.20
39.8	0.5	321.22	41.47	440.24	56.82	142.41	18.78	33.06	4.26	78.67	8.84	132.34	23.39	136.42	15.48
37.3	0.5	330.04	42.68	434.29	56.06	66.76	9.20	35.15	4.49	77.81	8.74	63.59	14.57	76.57	8.83
34.8	0.5	284.24	36.70	310.24	40.07	7.80	2.22	27.01	3.63	67.34	7.57			85.78	9.77
E (MeV)	ΔE (MeV)	^{189}Pt		$^{194\text{m}2}\text{Ir}$		^{192}Ir		$^{190\text{m}2}\text{Ir}$		^{190}Ir		^{189}Ir			
		σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)	σ (mb)	$\Delta\sigma$ (mb)		
48.5	0.3	10.81	1.91	0.30	0.04	2.82	0.32	0.64	0.17	4.29	0.49	11.99	1.46		
46.5	0.3	9.21	1.61	0.21	0.03	2.51	0.28	0.90	0.19	3.70	0.43	9.10	1.14		
44.3	0.4	9.79	1.78	0.15	0.03	2.70	0.31	0.83	0.20	3.36	0.40	7.22	1.09		
42.1	0.4			0.24	0.03	2.97	0.33	0.67	0.18	3.58	0.42	6.08	0.86		
39.8	0.5			0.15	0.02	2.91	0.33			2.92	0.35	4.43	0.72		
37.3	0.5					3.15	0.36			3.04	0.35	1.93	0.47		
34.8	0.5					2.55	0.29			1.84	0.22				

Fig. 2 Excitation function of the $^{nat}\text{Pt}(\text{d},\text{x})^{199}\text{Au}(\text{cum})$ reaction in comparison with literature and theoretical values

Fig. 3 Excitation function of the $^{nat}\text{Pt}(\text{d},\text{x})^{198\text{m}}\text{Au}$ reaction in comparison with literature and theoretical values

Results and discussion

The measured experimental cross-section data are shown in Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22 and 23. The numerical values are presented in Table 2. The investigated radio-products can be produced directly, through the internal transition of a long-lived isomeric state and through the decay of an isobaric parent. We made theoretical model calculations also for production of a few radioisotopes measured by us earlier, but no new experimental data are presented in this study. Agreement of the available experimental data and the theoretical data can clearly be seen in the figures of the present

work. The comparisons result in different conclusions for each reaction, which is hard to explain. Some more detailed discussions are available in our previous work [6]. Therefore, in the summary we present only general conclusion on the predictive capability of the model calculations.

Radioisotopes of gold

$^{nat}\text{Pt}(\text{d},\text{x})^{199}\text{Au}(\text{cum})$ reaction The measured cross-sections of the ^{199}Au ($T_{1/2}=3.139$ d) are cumulative, produced directly through the $^{198}\text{Pt}(\text{d},\text{n})$ reaction and contribution of the β^- -decay of the shorter-lived parent ^{199}Pt ($T_{1/2}=30.8$ min) produced through the $^{198}\text{Pt}(\text{d},\text{p})$ process

Fig. 4 Excitation function of the $^{nat}\text{Pt}(d,xn)^{198g}\text{Au}$ reaction in comparison with literature and theoretical values

Fig. 5 Excitation function of the $^{nat}\text{Pt}(d,xn)^{196m2}\text{Au}$ reaction in comparison with literature and theoretical values

(Fig. 2). A good agreement with the earlier experimental studies [6, 7] in the overlapping energy interval is seen. Because none of the theoretical model code gave acceptable predictions for the experimental values an estimated prediction from the systematics has also been presented in Fig. 2, which is proved to be the best approximation both in trend and in values.

$^{nat}\text{Pt}(d,x)^{198m}\text{Au}$ reaction We could obtain cross section data for both longer-lived states of ^{198}Au . The cross sections for the ^{198m}Au ($T_{1/2}=2.272$ d, IT 100%) isomeric state are shown in Fig. 3. An acceptable continuation to higher energy

of the data of Ditroi et al. [4] is seen. All the three model codes predict a large peak around 16–17 MeV, which was not confirmed by any of the experiments.

$^{nat}\text{Pt}(d,xn)^{198g}\text{Au}$ reaction Independent, low, cross sections for direct production of the ground state of ^{198}Au ($T_{1/2}=2.6947$ d) are shown in Fig. 4 and are in acceptable agreement with the earlier values. The trends given by all model codes are good. The best value is estimated by the EMPIRE-D above 20 MeV, but it overestimates strongly around the maximum.

Fig. 6 Excitation function of the $^{nat}\text{Pt}(d,xn)^{196g}\text{Au}$ (cum) reaction in comparison with literature and theoretical values

Fig. 7 Excitation function of the $^{nat}\text{Pt}(d,xn)^{195}\text{Au}$ (cum) reaction in comparison with literature and theoretical values

$^{nat}\text{Pt}(d,xn)^{196m2}\text{Au}$ reaction Direct production cross-sections for the $T_{1/2}=9.6$ h isomeric state $^{196m2}\text{Au}$ are shown in Fig. 5 and agree well with the Ditroi et al. [6] data. All theoretical model codes recognize the two maxima, but all overestimate the experimental values.

$^{nat}\text{Pt}(d,xn)^{196g}\text{Au}$ (cum) reaction The cross sections for cumulative formation of the ground state ^{196g}Au ($T_{1/2}=6.1669$ d) measured after the complete decay of the two higher lying, short-lived, isomeric states ($m2-T_{1/2}=9.6$ h, $m1-T_{1/2}=8.1$ s) are shown in Fig. 6. Very good agreement with Ditroi et al. [6] was observed. All model codes describe the shape of the

excitation function almost correctly, the best value approximation is given by the EMPIRE-D code.

$^{nat}\text{Pt}(d,xn)^{195}\text{Au}$ (cum) reaction The cross-sections for formation of ^{195}Au ($T_{1/2}=186.01$ d) contain the decay of the $T_{1/2}=30.5$ s isomeric state (Fig. 7) and are lower than the rather scattered data of Ditroi et al. [6]. The theoretical codes follow the trend of the experimental curves, but give different value predictions.

$^{nat}\text{Pt}(d,xn)^{194}\text{Au}$ reaction The excitation functions for production of the directly produced ^{194}Au ($T_{1/2}=38.02$ h) are

Fig. 8 Excitation function of the $^{nat}\text{Pt}(d,xn)^{194}\text{Au}$ reaction in comparison with literature and theoretical values

Fig. 9 Excitation function of the $^{nat}\text{Pt}(d,xn)^{193}\text{Au(cum)}$ reaction in comparison with literature and theoretical values

shown in Fig. 8 and are in perfect agreement with Ditroi et al. [6]. The theoretical model codes give different values around the maxima, their approximation is acceptable only below 20 MeV.

$^{nat}\text{Pt}(d,xn)^{193g}\text{Au(cum)}$ reaction The measured cross-sections of ^{193g}Au ($T_{1/2}=17.65$ h) include the internal decay of the $T_{1/2}=3.9$ s isomeric state (Fig. 9) additional to the direct production. The new measurements are about 20% higher

than a part of the values in Ditroi et al. [6] but seem to agree better with the 2006 values [4]. All the theoretical model codes strongly overestimate the experimental values.

$^{nat}\text{Pt}(d,xn)^{192}\text{Au}$ reaction The activation cross sections for production of ^{192}Au ($T_{1/2}=4.94$ h) are shown in Fig. 10 and are between our earlier values given in Refs. [4] and [6]. The best prediction is given by the TENDL-2017, both other model codes strongly overestimate the experimental values.

Fig. 10 Excitation function of the $^{nat}\text{Pt}(d,xn)^{192}\text{Au}$ reaction

Fig. 11 Excitation function of the $^{nat}\text{Pt}(d,xn)^{191}\text{Au}$ reaction in comparison with literature and theoretical values

$^{nat}\text{Pt}(d,xn)^{191}\text{Au}$ reaction The cross section data of ^{191}Au ($T_{1/2} = 3.18$ h) include the contribution from the decay of the simultaneously produced short half-life isomeric state ($T_{1/2} = 0.92$ s, 100% IT) (Fig. 11). Good overall agreement with Ditroi et al. [6]. Only TENDL-2017 follows correctly the trend of the experimental values with considerable overestimation.

Radioisotopes of platinum

$^{nat}\text{Pt}(d,x)^{197m}\text{Pt}$ reaction We could not deduce cross section data for production of the ^{197m}Pt ($T_{1/2} = 95.41$ min), due to the long cooling time before measuring the first spectra. The

earlier experimental data and the theoretical predictions are shown in Fig. 12. In spite of the large experimental uncertainties the best approximation is given by the TENDL-2017.

$^{nat}\text{Pt}(d,x)^{197g}\text{Pt}(m+) (cum)$ reaction The measured production cross-section of ^{197g}Pt ($T_{1/2} = 19.8915$ h) is including the direct production, the contribution from internal transition ($T_{1/2} = 95.41$ min, IT: 96.7) of the isomeric state and from the β^- decay of the short-lived $^{197m,g}\text{Ir}$ isomers ($T_{1/2} = 5.8$ min and 8.9 min, respectively) (Fig. 13). Our new measurements are in better agreement with the Ditroi et al. [4] values than with the results in Ditroi et al. [6]. All the three theoretical model codes show the trend of the

Fig. 12 Excitation function of the $^{nat}\text{Pt}(d,xn)^{197m}\text{Pt}$ reaction in comparison with theoretical values

Fig. 13 Excitation function of the $^{nat}\text{Pt}(d,x)^{197g}\text{Pt}(m+)$ (cum) reaction in comparison with literature and theoretical values

experimental values, but strongly underestimate them. Only the prediction of EMPIRE-D is closed to the experimental results above 25 MeV. Even the systematics cannot reconstruct the experimental results.

$^{nat}\text{Pt}(d,x)^{195m}\text{Pt}$ reaction The excitation function of the high spin isomeric state ($T_{1/2}=4.02$ d) of ^{195}Pt is shown in Fig. 14 and confirm overall the previously measured values of [4] and [6]. All theoretical predictions follow the trend of the experimental values, but TENDL strongly overestimates,

while ALICE-D and EMPIRE-D giving approximately the same underestimated values.

$^{nat}\text{Pt}(d,x)^{193m}\text{Pt}$ reaction The cross sections for production of ^{193m}Pt ($T_{1/2}=4.33$ d, IT: 100%) are shown in Fig. 15. They include the contribution of 0.03% EC decay of ^{193m}Au ($T_{1/2}=3.9$ s). No earlier experimental data were found. Only the TENDL-2017 prediction gives an acceptable trend but with slight overestimation.

Fig. 14 Excitation function of the $^{nat}\text{Pt}(d,xn)^{195m}\text{Pt}$ reaction in comparison with literature and theoretical values

Fig. 15 Excitation function of the $^{nat}\text{Pt}(d,xn)^{193m}\text{Pt}$ reaction in comparison with theoretical values

$^{nat}\text{Pt}(d,x)^{191}\text{Pt}(\text{cum})$ reaction The cumulative cross-sections for production of ^{191}Pt ($T_{1/2} = 2.802$ d) includes direct production and formation through decay of ^{191}Au ($T_{1/2} = 3.18$ h) and is shown in Fig. 16. Above 40 MeV the new values are significantly lower than the Ditroi et al. [6] data. The three theoretical model calculations give different results, the best approximation is given by the EMPIRE-D up to 40 MeV, but above this energy the TENDL-2017 predictions are better.

$^{nat}\text{Pt}(d,x)^{189}\text{Pt}(\text{cum})$ reaction The cross-sections for production of ^{189}Pt ($T_{1/2} = 11$ h) are cumulative, measured after the complete decay of the two longer-lived states of the parent

^{189}Au ($T_{1/2} = 4.6$ min and 28.3 min) radioisotope (Fig. 17). Good agreement of the few data points with the earlier measurement [6] was found. In this energy range all the three theoretical codes give acceptable predictions.

$^{nat}\text{Pt}(d,x)^{188}\text{Pt}(\text{cum})$ reaction Only a single cross section point for formation of ^{188}Pt ($T_{1/2} = 10.2$ d) is available, reported in earlier work [6] (Fig. 18). The cross-section contains the contribution of the direct production and the simultaneous decay of the ^{188}Au ($T_{1/2} = 8.8$ min) parent. The theoretical model codes give very different predictions.

Fig. 16 Excitation function of the $^{nat}\text{Pt}(d,xn)^{191}\text{Pt}$ reaction in comparison with literature and theoretical values

Fig. 17 Excitation function of the $^{nat}\text{Pt}(d,xn)^{189}\text{Pt}$ reaction in comparison with literature and theoretical values

Radioisotopes of iridium

$^{nat}\text{Pt}(d,x)^{194m2}\text{Ir}$ reaction The measured spectra allow to get cross sections only for the second, long-lived ($T_{1/2} = 171$ d) metastable state (Fig. 19) out of the three longer-lived states of ^{194}Ir . Overall agreement between the new values and Ditroi et al. [6] was seen. TENDL-2017 and ALICE-D give similar trends, but with over- and underestimation. The EMPIRE-D prediction is much lower.

$^{nat}\text{Pt}(d,x)^{192}\text{Ir(cum)}$ reaction Our experimental data (Fig. 20) include the direct production of the ground state ($T_{1/2} = 3.8$ d) and the decay of the short-lived isomeric state $^{192m1}\text{Ir}$

($T_{1/2} = 1.45$ min). Overall agreement between the new values and Ditroi et al. [6] was seen. ALICE-D gives good approximation of the measured values in the whole energy region, while EMPIRE-D slightly overestimates. TENDL-2017 gives strong underestimated prediction.

$^{nat}\text{Pt}(d,x)^{190m2}\text{Ir}$ reaction The production cross sections of the second, high spin isomeric state $^{190m2}\text{Ir}$ ($T_{1/2} = 3.25$ h) are shown in Fig. 21 and agree well with the TENDL-2017 prediction while the values of the other codes are 4–10 times too high. No earlier experimental data are available in the literature.

Fig. 18 Excitation function of the $^{nat}\text{Pt}(d,xn)^{188}\text{Pt}$ reaction in comparison with theoretical values

Fig. 19 Excitation function of the $^{nat}\text{Pt}(d,xn)^{194m2}\text{Ir}$ reaction in comparison with literature and theoretical values

$^{nat}\text{Pt}(d,x)^{190}\text{Ir}(m+)$ reaction The measured cross sections of the ground state ($T_{1/2} = 11.8$ d) include, in addition to the direct production, the decay of the first metastable state $^{190m1}\text{Ir}$ ($T_{1/2} = 1.2$ h, IT 100%) and the second high-spin isomeric state $^{190m2}\text{Ir}$ ($T_{1/2} = 3.25$ h, IT 5.6%) (Fig. 22). Our new values are about 10% lower than Ditroi et al. [6]. TENDL-2017 underestimates, while EMPIRE-D and ALICE-D overestimate the experimental values.

$^{nat}\text{Pt}(d,x)^{189}\text{Ir}(cum)$ reaction The cross-section determined for ^{189}Ir ($T_{1/2} = 13.2$ d) is cumulative and contains the direct production and the contribution from the decay of ^{189}Pt

($T_{1/2} = 10.87$ h) (Fig. 23). Perfect agreement with Ditroi et al. [6] was found. In this energy region the TENDL-2017 prediction is acceptable, while the ALICE-D and EMPIRE-D results overestimate the experimental values.

$^{nat}\text{Pt}(d,x)^{188}\text{Ir}(cum)$ reaction The cross-section determined for ^{188}Ir ($T_{1/2} = 41.5$ h) is cumulative and contains the direct production and the contribution from the decay of ^{188}Pt ($T_{1/2} = 10.2$ d) (Fig. 24). In this energy region the TENDL-2017 prediction is acceptable with slight overestimation, while the ALICE-D and EMPIRE-D results overestimate the experimental values.

Fig. 20 Excitation function of the $^{nat}\text{Pt}(d,xn)^{192}\text{Ir}$ reaction in comparison with literature and theoretical values

Fig. 21 Excitation function of the $^{nat}\text{Pt}(d,xn)^{190m2}\text{Ir}$ reaction in comparison with theoretical values

Summary and conclusion

We report on new experimental cross sections leading to formation of $^{nat}\text{Pt}(d,xn)^{191,192,193,194,195,196m2,196g,198m,198g,199}\text{Au}$, $^{nat}\text{Pt}(d,x)^{189,191,193m,195m,197g}\text{Pt}$ and $^{nat}\text{Pt}(d,x)^{188,189,190m2,190,192,194m2}\text{Ir}$ in the 35–49 MeV energy range. For production of ^{193m}Pt and $^{188,190m}\text{Ir}$ no earlier experimental data were found. A partial or good agreement was found with the results of our previous studies in the overlapping

energy regions, but some cases there are large disagreements. The comparison with the theoretical predictions of TENDL-2017 shows moderate agreement or large disagreement especially for isomeric cross sections. The situation is nearly same in the case of ALICE-D and EMPIRE-D, which underline the importance of experimental data that can help to still improve the codes and models, especially for deuteron induced reactions.

Fig. 22 Excitation function of the $^{nat}\text{Pt}(d,xn)^{190}\text{Ir}$ reaction in comparison with literature and theoretical values

Fig. 23 Excitation function of the $^{nat}\text{Pt}(d,xn)^{189}\text{Ir}$ reaction in comparison with literature and theoretical values

The EMPIRE and TALYS are more recent and advanced codes comparing to ALICE. In practical applications the TALYS based TENDL library is most widely used due to availability of the calculated data in the web. In case of all codes there are significant problems for deuteron induced reactions. Therefore, detailed improvement in the model codes are under development in a few laboratories. The

ALICE-D and Empire-D are one way of improvement by using correction, based on systematics.

Knowing the results and adjusting the used parameters a better agreement can be reached. The aim of our calculation and comparison was to show the predictivity by standard parameters, illustrating reliability of the model codes in case of unmeasured excitation functions.

Fig. 24 Excitation function of the $^{nat}\text{Pt}(d,xn)^{188}\text{Ir}$ reaction in comparison with literature and theoretical values

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