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P.P. Dmitriev, N.N. Krasnov and G.A. Molin

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YIELDS OF RADIOACTIVE NUCLIDES FORMED BY BOMBARDMENT OF A THICK TARGET WITH 22-MeV DEUTERONS

P.P. Dmitriev, N.N. Krasnov and G.A. Molin

Experimental results on the radionuclide yields from the bombardment of thick targets with 22-MeV deuterons are presented. Altogether, 208 yield values were measured for 151 radionuclides. The radionuclide formation reactions are given. This work was carried out in the cyclotron of the Institute of Physics and Power Engineering.

Reference [1] quotes the values of 188 yields measured for 140 radionuclides formed by the bombardment with 22-MeV protons of thick targets consisting of various chemical elements. The authors of this paper give 208 experimental values for 151 radionuclides created by bombarding a thick target with 22-MeV deuterons. The work was carried out on the cyclotron of the Institute of Physics and Power Engineering, Obninsk.

As noted in Ref. [1], the radionuclide yields from the bombardment of thick targets with charged particles are nuclear constants widely used for various applied problems and research efforts. The national nuclear data centres of several countries collect data on radionuclide yields for thick targets. Many of these data are recorded in the international exchange format EXFOR. A bibliography published in the United States of America [2] contains integral charged-particle nuclear data and many references to papers giving radionuclide yield values for thick targets. This bibliography identifies those papers where the results are recorded in the EXFOR format.

The radionuclide yields are given in Table 1. Column 3 indicates the particles emitted in the nuclear reactions which produce the radionuclides: n = neutron, p = proton, t = triton, $\tau = {}^{3}He$, $\alpha = {}^{4}He$ (alpha particle); as a weakly bound system the deuteron has a low emission probability, so it is not indicated. Column 3 also gives the reactions which have energy thresholds below 22 MeV. If the emitted particle is known, the radionuclide formation reaction can readily be identified. For instance, in obtaining ^{7}Be from

lithium, the emission of the particles n and 2n indicates the reactions (d,n) and (d,2n) for ^{6}Li and ^{7}Li : $^{6}Li(d,n)^{7}Be$, $^{7}Li(d,2n)^{7}Be$. In obtaining ^{7}Be from boron, the emission of αn and α2n indicates the reactions (d,αn) and (d,α2n) for the boron isotopes: $^{10}B(d,\alpha n)^{7}Be$, $^{11}B(d,\alpha 2n)^{7}Be$. The emission of 2p, τ, αn when obtaining ^{67}Cu from zinc indicates the reactions $^{67}Zn(d,2p)^{67}Cu$, $^{68}Zn(d,\tau)^{67}Cu$, $^{70}Zn(d,\alpha n)^{67}Cu$. A + sign in column 3 means that the cumulative yield of the radionuclide was measured: in some of the component reactions, a more short-lived isobaric nucleus is formed which subsequently decays into the radionuclide being obtained. For example, in obtaining ^{18}F from fluorine, the emission of t+3n indicates the reactions $^{19}F(d,t)^{18}F$ and $^{19}F(d,3n)^{18}Ne$ ($T_{\frac{1}{2}}$ = 1.67 s) → ^{18}F. Similarly, when obtaining ^{49}V from chromium, the emission of the particle τ+t+3n, αn, α2n indicates the following formation pathways for ^{49}V: $^{50}Cr(d,\tau)^{49}V$; $^{50}Cr(d,t)^{49}Cr$($T_{\frac{1}{2}}$ = 41.4 min) → ^{49}V; $^{50}Cr(d,3n)^{49}Mn$ ($T_{\frac{1}{2}}$ = 0.38 s) → ^{49}Cr → ^{49}V; $^{52}Cr(d,\alpha n)^{49}V$; $^{53}Cr(d,\alpha 2n)^{49}V$.

The notation used in column 3 is very much more concise than a full notation of the reactions would be. In the range of heavier nuclei the radionuclide yield from reactions involving emission of p2n and 2pn may exceed the yield from reactions emitting t and τ. In these cases it would have been necessary to indicate the simultaneous emission of t, p2n, τ and 2pn, but for the sake of brevity only the emission of t and τ has been recorded. Column 3 does not give the deuteron capture reaction $(d,\gamma)^{*/}$ in view of its relatively small cross-section. For the reactions given in this column, clearly, the various radionuclides' contribution to the yield may differ greatly because of the large differences between the effective reaction cross-sections averaged over the mean free paths and the considerable variation in the natural abundance of the stable isotopes of the element that is bombarded.

Column 4 gives the yield value for the radionuclide and, in brackets, the error. The third number, with a + or - sign, indicates the power of 10 by which the yield and error values must be multiplied. For instance, 34(4)+3 means 34 000 ± 4000; 14.6 (1.9)-4 means 0.00146 ± 0.00019; and so on. In this column the first two digits represent tens and units, respectively.

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*/ Emission of γ-quanta only.

The deuteron energy during bombardment was not always exactly equal to 22 MeV, but the deviations did not normally exceed $\pm$ 0.3 MeV. In these cases the radionuclide yield was determined by extrapolation of the yield to E_d = 22 MeV, using the known relative position of the yield-versus-deuteron energy curves for the particular type of reaction in the nuclear mass region in question. The extrapolation scarcely increases the error in the yield value at all because the deuteron energy deviations are only slight.

All yields were measured for the natural isotopic composition; when chemical compounds were bombarded the yield was recalculated for the pure element. Most of the yield values in Table 1 are given there for the first time, but some have been taken from published work where the radionuclide yield was measured as a function of the deuteron energy; the most recent such work is given in Ref. [3]. The method used to measure the activity of the radionuclides and the integrated radiation flux is described in Ref. [4]. The half-life, energy and γ-quantum yield used in measuring the nuclide activity are given in Ref. [1]. For 24 nuclides missing in Ref. [1] these data are given in Table 2 (for ^{103}Pd the more accurate γ-quantum yield of 357.6 keV was used). The data in this table are taken from Refs [5,6], the latest issues of Nuclear Data Sheets and other publications. Plans exist to publish radionuclide yields for a thick target and 44-MeV alpha particles.

Table 1

Yield of radioactive nuclides formed by bombardment of a thick target with 22-MeV deuterons

Radionuclide	Target	Emitted particles	Radionuclide yield, MBq/μA-h	Radionuclide	Target	Emitted particles	Radionuclide yield MBq/μA-h
^{7}Be	Li	n,2n	52(7)-1	^{51}Cr	V	n,2n	18,5(2,1)
	Be	tn	24(3)-3		Cr	p+n, t+3n	70(8)-2
	B	αn, α2n	13,5(1,8)-1		Mn	α2n	10,7(1,4)-3
^{11}C	B	n,2n	74(7,5)+2	^{52}Mn	Cr	2n,3n	13,3(1,5)
	C	t,tn	35(3,5)+1		Fe	α, α2n	10(1,5)-2
	N	αn, α2n	58(6)+2	^{54}Mn	Cr	n,2n	78(9)-3
^{13}N	C	n,2n	17,4(2)+3		Mn	t	10,4(1,2)-2
	N	t,tn	34(3,5)+2		Fe	2p, α, αn	10,7(1,5)-2
	O	αn, α2n	23(2,3)+1	^{56}Mn	Fe	2p, τ, α	48(7)
^{18}F	O	n,2n	92(10)-1		Co	αp	20(3)
	F	t+3n	74(7,5)+1	^{55}Fe	Mn	2n	80(5)-2
^{22}Na	Na	t+3n	83(4)-3		Fe	p+n, t+3n	58(8)-3
	Mg	α, αn	17(2,4)-2		Ni	αp	82(14)-4
^{24}Na	Na	p	11(1,6)+2	^{59}Fe	Co	2p	12(1,6)-2
	Mg	2p, τ, α	61(8)	^{55}Co	Fe	n,3n	77(11)-1
	Al	αp	44(6,5)		Ni	αn	14,6(2)
^{26}Al	Mg	n,2n	10(1,5)-3	^{56}Co	Fe	2n,3n	17(2,4)-1
^{42}K	Ca	2p, τ, α	74(11)-2		Ni	α, α2n	17(2,5)-2
	Sc	αp	18(2,6)	^{57}Co	Fe	n,2n,3n	37(5)-2
^{43}K	Ca	2p, τ	41(6)-3		Ni	τ+t+3n, αn	15,5(2)-2
^{47}Ca	Ca	t+τ	70(10)-4	^{58}Co	Fe	n,2n	23(3)-3
^{44m}Sc	Ca	n,2n	78(12)-2		Co	t	41(5)-2
	Sc	t	52(8)-1		Ni	2p, α, αn	16,6(2,2)-1
	Ti	α, αn, α2n	13(2)-1	^{60}Co	Co	p	85(13)-3
^{46}Sc	Sc	p	17(2,3)-1		Ni	2p, τ, α	26(4)-4
	Ti	2p, τ, α, αn	81(5)-2		Cu	αp	17(2,5)-4
^{47}Sc	Ca	3n	70(10)-3	^{57}Ni	Ni	t+3n	18(2,3)-1
	Ti	α, αn	96(5)-1	^{64}Cu	Cu	p,t	18(2,5)+1
^{48}Sc	Ca	2n	52(8)-2		Zn	2p, α, αn	41(6)
	V	αp	19(3-2)	^{67}Cu	Zn	2p, τ, αn	95(14)-3
^{44}Ti	Sc	3n	68(8)-5	^{62}Zn	Cu	3n	81(4)-2
^{45}Ti	Sc	2n	13,8(2)+2	^{65}Zn	Cu	2n	68(8)-2
^{48}V	Ti	n,2n,3n	15,7(1,7)		Zn	p+n, t+3n	85(11)-2
	Cr	α, α2n	74(9)-3	^{69m}Zn	Ga	2p, α	17(2,5)-1
^{49}V	Ti	n,2n,3n	81(5)-2	^{66}Ga	Zn	2n,3n	17(2)+1
	Cr	τ+t+3n, αn, α2n	59(11)-3	^{67}Ga	Zn	n,2n,3n	22(2,6)

Table 1 (continued)

Yield of radioactive nuclides formed by bombardment of a thick target with 22-MeV deuterons

Radio-nuclide	Target	Emitted particles	Radionuclide yield, MBq/μA-h	Radio-nuclide	Target	Emitted particles	Radionuclide yield MBq/μA-h
^{67}Ga	Ge	αn	31(4,4)-1	^{96}Tc	Mo	n,2n,3n	23(3)
^{68}Ge	Ga	3n	67(9)-3	^{97m}Tc	Mo	n,2n,3n	16(2)-2
^{69}Ge	Ga	2n	11,5(1,5)+1	^{103}Ru	Rh	2p	48(7)-4
^{71}As	Ge	n,3n	11,5(1,6)	^{102m}Rh	Ru	n,2n	41(6)-3
^{72}As	Ge	2n,3n	13(2)+1		Rh	t	52(8)-4
^{73}As	Ge	n,2n,3n	17(2,2)-1	^{102}Rh	Ru	n,2n	36(5,4)-2
^{74}As	Ge	n,2n	85(11)-1		Rh	t	74(11)-2
	As	t	96(13)-2	^{103}Pd	Rh	2n	26(3,2)
	Se	2p,α,αn,α2n	60(9)-2	^{106m}Ag	Ag	t	26(3,6)-2
^{76}As	Ge	2n	35(5)	^{108m}Ag	Ag	p,t	52(8)-6
^{75}Se	As	2n	27(4)-1	^{110m}Ag	Ag	p	22(3)-3
	Se	p+n,t+3n	16(2,4)-3		Cd	2p,τ,α, αn	20,4(3)-4
^{76}Br	Se	2n,3n	40(5)	^{111}Ag	Cd	2p,τ,α, αp+αn	27(4)-1
^{77}Br	Se	n,2n,3n	18(2,3)	^{107}Cd	Ag	2n	60(9)+1
^{82}Br	Se	2n	22,6(3)	^{109}Cd	Ag	2n	26(3,4)-2
	Br	p	43(6)		Cd	p+n,t+3n	11(1,6)-3
^{84}Rb	Rb	t	28(4)-2	^{115}Cd	Cd	p,t	11,5(1,7)
^{86}Rb	Rb	p,t	38(5,7)-1	^{111}In	Cd	n,2n,3n	32(4)
^{85}Sr	Rb	2n	47(6)-1	^{114m}In	Cd	n,2n	11(1,3)-1
^{86}Y	Sr	2n,3n	10,2(1,5)+1		In	p,t	10(1,3)-2
^{87m}Y	Sr	n,2n,3n	32(4)	^{113}Sn	In	2n	10(1,2)-2
^{87}Y	Sr	n,2n,3n	13,7(1,8)	^{117m}Sn	Sn	p,t	41(6)-2
	Zr	αn,α2n	11(1,5)-1	^{120m}Sb	Sn	n,2n	37(5)-1
^{88}Y	Sr	n,2n	35(4,5)-1	^{122}Sb	Sn	2n,4n	19(3)-1
	Y	t	57(7,5)-3	^{124}Sb	Sn	2n	32(5)-2
	Zr	α, αn,α2n	61(8,5)-3		Sb	p	11(1,6)-1
^{88}Zr	Y	3n	31(4,3)-2	^{121m}Te	Sb	2n,4n	78(11)-2
^{89}Zr	Y	2n	10,2(1,4)+1	^{121}Te	Sb	2n,4n	94(13)-1
	Zr	t+3n	35(5)	^{123m}Te	Sb	2n	72(10)-2
^{95}Zr	Zr	p,t+τ	26(4)-2	^{123}I	Te	n,2n,3n,4n	14,4(1,8)
^{92m}Nb	Zr	n,2n	30(4)-1	^{124}I	Te	n,2n,3n,4n	46(5,8)-1
	Nb	t	96(13)-2	^{125}I	Te	n,2n,3n	32(5,4)-2
^{95}Nb	Zr	n,3n	41(6)-2	^{126}I	Te	n,2r,4n	33(4,1)-1
^{95m}Mo	Nb	2n	17(2,5)+1	^{130}I	Te	2n	12,2(1,5)-1
^{93}Mo	Nb	2n	19(2,9)-5	^{131}I	Te	p+n	37(4,6)-1
^{95m}Tc	Mo	n,2n,3n	34(4)-4	^{127}Xe	I	2n	54(8)-1

Table 1 (concluded)

Yield of radioactive nuclides formed by bombardment of a thick target with 22-MeV deuterons

Radionuclide	Target	Emitted particles	Radionuclide yield, MBq/μA-h
^{135}La	Cs	2p	18(2,7)-1
^{134}Cs	Cs	p	15(2)-2
^{133m}Ba	Cs	2n	86(13)
	Ba	p,t,tn	33(5)-1
^{133}Ba	Cs	2n	78(12)-3
^{140}La	La	p	24(3,5)+1
	Ce	2p,α	44(6)-2
^{139}Ce	La	2n	15,6(2)-1
	Ce	p+n,t+3n	31(4,4)-1
^{141}Ce	Ce	p,t	14(2)-1
^{143}Ce	Ce	p	58(8)-1
^{142}Pr	Pr	p	17(2,4)-1
^{140}Nd	Pr	3n	29(4)
^{143}Pm	Nd	n,2n,3n,4n	18,5(2,6)-2
^{144}Pm	Nd	n,2n,3n,4n	21(3)-2
^{148}Pm	Nd	2n,4n	10,4(1,5)-1
^{148}Eu	Sm	n,2n,3n,4n	41(6)-2
^{150m}Eu	Sm	n,2n,4n	12,2(1,8)-4
^{152}Eu	Sm	2n,4n	59(9)-4
^{154}Eu	Sm	2n	70(11)-4
^{151}Gd	Eu	2n,4n	32(5)-2
^{153}Gd	Eu	2n	19(3)-2
^{155}Tb	Gd	n,2n,3n,4n	15(2,1)
^{156}Tb	Gd	n,2n,3n,4n	11,6(1,6)
^{166}Ho	Ho	p	34,5
^{165}Tu	Er	n,2n,4n	28(3,2)
^{166}Tu	Er	2n,3n,4n	27(3,1)+1
^{167}Tu	Er	n,2n,3n	10,7(1,2)
^{168}Tu	Er	n,2n,4n	48(5,6)-2
^{170}Tu	Er	2n	17(3,2)-2
^{173}Lu	Yb	n,2n,3n	13(1,8)-2
^{174}Lu	Yb	n,2n,4n	18(2,7)-3

Radionuclide	Target	Emitted particles	Radionuclide yield MBq/μA-h
^{175}Hf	Hf	p+n,t+3n,tn-4n	16,5(2,5)-2
^{181}Hf	Hf	p	56(8,-2
^{176}Ta	Hf	2n,3n,4n	13,7(2)+1
^{173m}Ta	Hf	n,2n,3n,4n	24(3,6)
^{182}Ta	Ta	p	38(5,3)-2
^{181}W	Ta	2n	49(7)-2
^{181}Re	W	n,3n,4n	29(4)
^{182m}Re	W	2n,3n,4n	10,5(1,4)
^{182}Re	W	2n,3n,4n	50(6,5)
^{183}Re	W	n,2n,3n	10,4(1,4)-1
^{184m}Re	W	n,2n,4n	22(3)-3
^{184}Re	W	n,2n,4n	93(12)-2
^{185}Os	Re	2n,4n	48(7)-2
^{193}Au	Pt	n,3n,4n	64(9)
^{194}Au	Pt	2n,3n,4n	46(7)
^{195}Au	Pt	n,2n,3n	21,5(3,2)-2
^{196}Au	Pt	n,2n,3n	63(9)-1
	Au	t	19(2,8)-2
^{198}Au	Pt	2n	22,3(3,3)-1
	Au	p	23(3,4)
^{199}Au	Pt	p+n	13,9(2)-1
^{197}Hg	Au	2n	24(3,6)
^{203}Hg	Hg	p, τ+t	21(3,1)-2
	Tl	2p,α	14,8(2,2)-3
^{200}Tl	Hg	n,2n,3n,4n	39(5,8)
^{201}Tl	Hg	n,2n,3n	20(3)
^{202}Tl	Hg	n,2n,4n	20(3)-1
^{202m}Pb	Tl	3n	52(7,8)
^{203}Pb	Tl	2n,4n	18(2,2)
^{205}Bi	Pb	n,3n,4n	21,5(3,2)-1
^{206}Bi	Pb	2n,3n,4n	13(2)
^{207}Bi	Pb	n,2n,3n	11,5(1,7)-3

Table 2

Characteristics of radionuclides used to measure activity

Nuclide	Half-life	Gamma quantum energy keV	γ-quantum yield per disintegr. %	Nuclide	Half-life	Gamma quantum energy keV	γ-quantum yield per disintegr. %
^{46}Sc	1,85 cyт	1312	100	^{134}Cs	2,06 лет	795,8	85
^{45}Ti	8,09 ч	511±	172	^{140}La	40,22 ч	1596	96
^{56}Mn	2,58 ч	1811	27	^{141}Ce	32,5 cyт	145,4	49
^{59}Fe	45,1 cyт	1292	44	^{143}Ce	33 ч	295,9	41,5
^{69m}Zr	14,0 ч	439,1	95,7	^{142}Pr	19,1 ч	1576	3,7
^{86}Rb	18,66 cyт	1078	8,8	^{166}Ho	27 ч	1379	0,93
^{87m}Y	13,2 ч	380,7	76,2	^{181}Hf	42,5 cyт	133	43
^{103}Ru	39,5 cyт	497,1	90	^{178m}Ta	2,45 ч	325,6	92
^{103}Pd	17 cyт	357,6	0,024	^{182}Ta	115 cyт	1221	27,3
^{111}Ag	7,45 cyт	342	8	^{193}Au	17,6 ч	268,2	3,88
^{131}I	8,04 cyт	364,5	82	^{198}Au	2,695 cyт	411,8	95,5
^{133}Xe	5,24 cyт	90	36,8	^{199}Au	3,13 cyт	158,4	37,3

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