THE YIELDS OF CYCLOTRON PRODUCED MEDICAL ISOTOPES

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Abstract.- The yields of most medical radioisotopes produced with cyclotrons of different sizes through various nuclear reactions, in laboratories around the world, and reported in the literature since 1977, are presented. This compilation, combined with our previous publication on this subject, would be of great assistance in selecting the most suitable nuclear reaction and bombarding conditions for producing a particular radioisotope.

1. Introduction.- Production of radioisotopes for medical use is by far the most widely used and profitable application of cyclotrons. Presently, many isotopes are being produced by cyclotrons around the world for research and routine work in fields like nuclear medicine, nuclear biology, etc. Generally, neutron-deficient, carrier-free and short-lived isotopes, which cannot be conveniently or at all produced with a reactor, are produced with cyclotrons. However, at the same time, neutron-enriched isotopes can also be produced with a cyclotron, if required, through nuclear reactions of the type (d,p), (^{3}He,p), (α,p), etc.

In a recent publication we presented the yields of most cyclotron-produced isotopes of medical interest, which were reported in the literature until 1977.[1)] In that paper we also compared the experimentally obtained yields, under various bombarding conditions, with those calculated under similar conditions using experimentally measured or empirically constructed excitation functions.

In the present paper we have considered only those publications which have appeared since 1977, or which were inadvertently omitted from the previous publication and have since come to our notice. This, combined with our previous publication, should provide the most comprehensive compilation of the yields of cyclotron-produced medical radioisotopes, and help in choosing the most suitable method for producing a particular isotope.

2. Method and results.- The production mode and respective yields of radioisotopes at different energies, and from various targets, are summarized in table 2. The yield figures given in the table are either actually obtained production yields or those calculated by authors from experimentally measured excitation functions. In certain cases the yields at saturation (corresponding to irradiation time much longer than the half-life) as calculated by various authors, are also given.

In compiling the table, every effort has been made to include most of the significant published data, since 1977, regarding the production of various isotopes for biomedical applications. However, it is possible that some publications might have inadvertently been omitted.

The actual production cost of any particular isotope, dollars per millicurie, can be easily estimated from the yield figures, the running cost of the accelerator, the cost of the materials and the man-hours involved (which can be seen from respective references). When one does these calculations one finds that, in most cases, the actual cost of producing an isotope is much less than that charged by the commercial organizations.

TABLE 1

THE PRODUCTION MODES AND YIELDS OF VARIOUS CYCLOTRON-PRODUCED ISOTOPES.
$T_{\frac{1}{2}}$ - half-life, m - minutes, h - hours, d - days, Energy A→B means that the target is not thick, but reduces the energy from A(MeV) to B(MeV), Sat.-yield at saturation. Yields calculated (and not measured) by authors from their experimental cross-sections are indicated by * , and those from theoretically predicted excitation functions by # (Code STAPRE) or ## (Code ALICE).

Isotope	$T_{1/2}$	Reaction	Target	Energy (MeV)	Production Yield μCi/μAh, unless otherwise indicated	Ref.
^{18}F	1.83h	$^{16}O(\alpha,d)$	SiO_2	55	7000	2
		$^{16}O(^3He,p)$ + $(^3He,n)$	H_2O	40	20000	3
^{28}Mg	21h	Cl(p,6pxn)	NaCl	160	15	4
^{30}P	2.5m	$^{27}Al(\alpha,n)$	Al	28→10	4740 μCi/μA min. *	5
		^{31}P (p,pn)	PCl_5	35→19	18710 μCi/μA min. *	
^{38}K	7.71m	$^{35}Cl(\alpha,n)$	NaCl	14.7	1500 μCi/μA (Sat.)	6
		$^{40}Ar(p,3n)$	Ar-gas	29.8	4400	7
					5200 μCi/μA (Sat.) *	7
^{48}Cr	23h	$Ti(^3He,xn)$	Natural Ti	135→22	91 *	8
			Natural Ti	36→22	30 *	8
^{52}Fe	8.2h	^{55}Mn (p,4n)	Mn 2.62g/cm^2	70→50	200	9
		$^{58}Ni(p,3p4n)$	Ni 0.45g/cm^2	200→198.6	120	9
		$^{52}Cr(^3He,3n)$	Natural Cr	33	20	10
			Natural Cr	40	50	11
		$^{50}Cr(\alpha,2n)$	Natural Cr	65	8 μCi/μAh/gm	12
		Ni(p.spallation)	Ni (Thin)	200	67	10
			Ni (Thin)	588	700 *	13
^{55}Co	18.2h	$^{55}Mn(^3He,3n)$	Natural Mn 154 mg/cm^2	40→23	103	14
			75 mg/cm^2	37→29	52	14
		$^{58}Ni(p,\alpha)$	99.95% ^{58}Ni 138 mg/cm^2	12.8→9.2	460	14
		Ni + p	Natural Ni 113 mg/cm^2	12.5→9.2	215	14
		$^{54}Fe(d,n)$	98.19% ^{54}Fe 74 mg/cm^2	10.0→3.9	690	14
		Fe + d	Natural Fe	10.0→3.9	90	14
		$^{56}Fe(p,2n)$	99.93% ^{56}Fe 321 mg/cm^2	32.0→28.0	1000	14
		Fe + p	Natural Fe 1600 mg/cm^2	40.0→20.0	3780	14
		$^{56}Fe(p,2n)$	Natural Fe thick	20	400 *	15
			"	25	1800 *	15
			"	30	3000 *	15
			"	35	4000 *	15
			"	40	4500 *	15
		Fe + ^3He	Natural Fe thick	25	21	16
^{57}Ni	36.0h	Fe + ^3He ($^{56}Fe(^3He,2n)$)	Natural Fe thick	25	32	16
^{61}Cu	3.41h	$^{58}Ni(\alpha,p)$ +	Natural Ni 73 mg/cm^2	21	3500	17
		$^{58}Ni(\alpha,n)^{61}Zn\rightarrow^{61}Cu$	"	14	71	18

Isotope	$T_{1/2}$	Reaction	Target	Energy (MeV)	Production Yield µCi/µAh, unless otherwise indicated	Ref.
^{61}Cu		$^{61}Ni(p,n)$	Natural Ni 386 mg/cm^2	14	71	18
		$^{59}Co(\alpha,2n)$	Natural Co 250 mg/cm^2	40	6000	19
			"	30	4000	19
			"	20	1000	19
		$^{59}Co(^3He,n)$	Natural Co thick	40	112	19
			"	30	45	19
			"	25	24	19
			"	20	8	19
		$^{63}Cu(^3He,\alpha n)$	Natural Cu 97 mg/cm^2	24	540 *	20
		$^{64}Zn(d,\alpha n)$	Natural Zn 134 mg/cm^2	15	930 *	21
^{64}Cu	12.9h	$^{64}Zn(d,2p)$	Natural Zn thick	16	143	22
^{67}Cu	61.9h	$^{67}Zn(d,2p)$ + $^{67}Zn(d,2pn)$	Natural Zn thick	16	0.123	22
^{62}Zn	9.15h	$^{63}Cu(p,2n)$	Natural Cu 360 mg/cm^2	22	2300	23
		Ni + ^3He	Natural Ni thick	23	5600	24
^{67}Ga	78.1h	Zn + α	Natural Zn thick	25	165	25
^{72}As	26h	From ^{72}Se - Generator				
^{72}Se	8.4d	$^{70}Ge(\alpha,2n)$	Natural Ge thick	38.4	16	26
			"	34	36.5 *	26
			"	25	540 µCi/µA (Sat.) *	27
			"	30	1620 " *	27
			"	35	3510 " *	27
			"	40	5130 " *	27
		$^{75}As(p,4n)$	Natural As thick	35	270 " *	28
				40	15130 " *	28
			"	45	78900 " *	28
			"	50	173000 " *	28
^{73}Se	7.1h	$^{72}Ge(^3He,2n)$ +	Natural GeO_2 70 mg/cm^2	29→18	174	27
		$^{73}Ge(^3He,3n)$	151 mg/cm^2	37→18	403	27

Isotope	$T_{\frac{1}{2}}$	Reaction	Target	Energy (MeV)	Production Yield μCi/μAh, unless otherwise indicated		Ref.
^{73}Se		$^{72}Ge(^3He,2n)$	Enriched $^{72}GeO_2$ 96.4%	29→18	723		27
			"	37→18	933		27
			Natural GeO_2 thick	15	540 μCi/μA (Sat.)	*	27
			"	20	2970 "	*	27
			"	25	5400 "	*	27
			"	30	8110 "	*	27
			"	35	9460 "	*	27
			"	40	13510 "	*	27
		$^{70}Ge(\alpha,n)$ +	Natural GeO_2 71 mg/cm^2	26→10	218		27
		$^{72}Ge(\alpha,3n)$	" 180 mg/cm^2	40→10	537		27
		$^{72}Ge(\alpha,3n)$	Enriched $^{72}GeO_2$ 96.4% 71 mg/cm^2	26→10	0		27
			" 62 mg/cm^2	40→10	428		27
			Natural GeO_2 thick	15	810 μCi/μA (Sat.)	*	27
			"	20	4050 "	*	27
			"	25	5950 "	*	27
			"	30	7030 "	*	27
			"	35	7570 "	*	27
			"	40	10000 "	*	27
		$^{75}As(p,3n)$	Natural As thick	25	2700 "	*	28
			"	30	94600 "	*	28
			"	35	297300 "	*	28
			"	40	513500 "	*	28
			"	45	675700 "	*	28
			"	50	783800 "	*	28
^{75}Br	1.7h	$^{76}Se(p,2n)$	Se-enriched powder 92.4%	28→22	11800 *		29
		$^{76}Se(d,2n)$	"	35→29	82000 *		29
		$^{75}As(^3He,3n)$	Natural As	34→24	6000 *		29
		$^{75}As(\alpha,4n)$	"	64→54	7500 *		29
^{77}Br	57h	$^{77}Se(p,n)$	Na-Selenate 92.4% ^{77}Se	12→9	430		30
		$^{78}Se(p,2n)$	Na-Selenate 97.9% ^{78}Se	25→20	4300		30
		Se(p,xn)	Thick natural Se	10	12000 μCi/μA(Sat.)	*	31
			"	15	30000 "	*	31

Isotope	T½	Reaction	Target	Energy (MeV)	Production Yield µCi/µAh, unless otherwise indicated	Ref.
^{77}Br		Se(p,xn)	Thick natural Se	20	105000 µCi/µA (Sat.) *	31
			"	30	286000 " *	31
			"	40	413000 " *	31
			"	50	678000 " *	31
		$^{79}Br(p,3n)^{77}Kr \rightarrow ^{77}Br$	KBr Natural	65	82000 *	32
			"	45	48000 *	32
			"	32	10400 *	32
			Li Br	45	85000 *	33
			"	40	60000 *	33
			Na Br	45	68000 *	33
			"	40	48000 *	33
			K Br	32	2300	34
		$^{79}Br(p,3n)$	Natural Br	25	5000 µCi/µA (Sat.) *	31
			"	30	54000 " *	31
			"	35	146000 " *	31
			"	40	235000 " *	31
			"	50	346000 " *	31
		Br(p,xn)	Natural NaBr	30	200 *	35
			"	40	3000 *	35
			"	50	5000 *	35
			"	60	7000 *	35
			"	70	10000 *	35
			"	80	16000 *	35
$^{81, 82m}Rb$	4.7h 6.4h	Kr(p,xn)	Natural Kr-gas	32→16	17300 (at E.O.B. + 3h)	36
^{81}Rb	4.7h	$^{82}Kr(p,2n)$ + $^{83}Kr(p,3n)$	Natural Kr-gas	32→16	11600	37
		$^{80}Kr(^{3}He,pn)$	^{80}Kr gas 37% enriched	20	226	38
		$^{80}Kr(d,n)$	"	8	700	38
		$^{85}Rb(p,p\ 4n)$	^{85}Rb Cl thick 100% enriched	70	31200 *	39
		$^{85}Rb(p,5n)^{81}Sr$ $^{81}Sr \rightarrow ^{81}Rb$ (After chemical separation from ^{81}Sr)	"	70	2300 (at 96.4 min.)	39
		Rb + p	Rb Cl thick natural	70	22500	39
		$^{79}Br(\alpha,2n)$	Natural KBr thick	15	90 *	40
			"	20	500 *	40
			"	25	1000 *	40
			"	30	2000 *	40
			"	35	2700 *	40

Isotope	$T_{\frac{1}{2}}$	Reaction	Target	Energy (MeV)	Production Yield µCi/µAh, unless otherwise indicated	Ref.
^{81}Rb		^{79}Br(^{3}He,n) +	Natural K Br thick	15	24 *	40
		^{81}Br(^{3}He,3n)	"	20	300 *	40
			"	25	1100 *	40
			"	30	2000 *	40
			"	40	2800 *	40
^{87m}Sr	2.83h	From ^{87m} Y - Generator				
^{87m}Y	12.7h	^{87}Rb(^{3}He,3n) +	Natural Rb Cl	20	13 *	41
			"	25	44 *	41
		^{85}Rb(^{3}He,n)	"	30	83 *	41
			"	35	97 *	41
		^{85}Rb(α,2n) +	Natural Rb Cl thick	25	1110 *	41
		^{87}Rb(α,4n)	"	30	1480 *	41
			"	40	1850 *	41
			"	50	2130 *	41
			"	60	2600 *	41
^{97}Ru	2.9d	Mo + α	Natural Mo, 0.15 mm	22	26	42
			"	27	66	42
			"	29	75	42
			" 0.10 mm	25	54	42
			"	27	60	42
			"	30	69	42
		Mo + ^{3}He	"	30	53	42
^{123}I	13.3h	^{121}Sb(^{3}He,n) +	Natural Sb, 40 mg/cm^{2}	23	240	43
		^{123}Sb(^{3}He,3n)	" 106 "	40	165	11
		^{123}Sb(^{3}He,3n)	^{123}Sb, 99%, 27mg/cm^{2}	42	500	44
		^{125}Te(p,3n)	^{125}Te, 95.5% 23mg/cm^{2}	36	850	44
			" 13.9 "		225	44
		^{123}Te(p,n)	^{123}TeO$_{2}$ enriched to 83.5%, 86.4 mg/cm^{2}	15→13	4100	45
		^{124}Te(p,2n)	^{124}TeO$_{2}$ enriched to 91.86%, 323 mg/cm^{2}	26→20	20000	45
			^{124}Te, 96.5%	26→21	8000-12000	46
^{123}I		^{124}Te(p,2n)	99.9% ^{124}Te, 256 mg/cm^{2}	25.8	10600 *	47
			" 519 "	27	20400 *	47
			91.9% " 346 "	26	14900 *	47
			" 415 "	25	17500 *	47
			" 912 "	28	33600 *	47
			" 415 "	25	18100 #	48
			" " "	25	15900 ##	48

Isotope	$T_{\frac{1}{2}}$	Reaction	Target	Energy (MeV)	Production Yield µCi/µAh, unless otherwise indicated	Ref.
^{123}I		^{124}Te(p,2n)	91.9% ^{124}Te, 930 mg/cm	28	35400 #	48
			" "	28	30905 ##	48
^{123}X	2.1h	^{122}Te(^{3}He,2n)	73% ^{122}Te 8 mg/cm^{2}	17.9	7	49
			90.9% " 132 "	27	530	50
		^{122}Te(^{3}He,2n) + ^{123}Te(^{3}He,3n)	Natural Te	30→25	20	51
		^{127}I(p,5n)	$CH_2I_2 + I_2$ cirulating aqueous solution	58→48	9000	52
			CH_2I_2 circulating liquid	54	2000	53
			Pure I_2 melted at 110^{0}C	80 + 100	16000 of ^{123}I using the gas generation system	54
		^{127}I(p,5n)	$CH_2I_2 + I_2$	60	400000 *	55
			"	80	950000 *	55
			"	100	1140000 *	55
			"	120	1350000 *	55
			"	140	1560000 *	55
			"	160	1730000 *	55
			KI	60	300000 *	55
			"	80	650000 *	55
			"	100	850000 *	55
			"	120	1020000 *	55
			"	140	1180000 *	55
			"	160	1310000 *	55
			KI in H_2O	60	90000 *	55
			"	80	200000 *	55
			"	100	270000 *	55
			"	120	325000 *	55
			"	140	375000 *	55
			"	160	420000 *	55
			NaI, 2g/cm_2	60→44	15300 *	48
			NaI, 2.53g/cm_2	65→46	18400 *	48
^{125}Xe	17h	Te(^{3}He,xn)	Natural Te, thick	20	20 *	56
			"	25	40 *	56
			"	30	115 *	56
			"	35	180 *	56
			"	40	280 *	56
^{127}Xe	36.4d	^{127}I(d,2n)	CH_2I_2 flowing target	26	60	53

Isotope	$T_{\frac{1}{2}}$	Reaction	Target	Energy (MeV)	Production Yield µCi/µAh unless otherwise indicated		Ref.
^{167}Tm	9.6d	$^{167}Er(p,n)$	Er_2O_3, natural	15	20		57
			$^{167}Er_2O_3$, 93% enriched	15	75		57
		$Er(^3He,pxn)$	Er_2O_3, natural	40	81	*	58
		(α,pxn)	"	40	32	*	58
		$^{165}HO(\alpha,2n)$	Ho_2O_3 "	40	49	*	58
			$HoCP_3$ "	32	20		59
^{178}Ta	2.1h	Generator produced from ^{178}W					
^{178}W	21.5d	$^{181}Ta(p,4n)$	Ta-metal, 1 MeV thick	34	1100		60
			Ta natural, 0.127 mm	40	55		61
			"	47	19.6		61
			"	80	5.4		61
			"	97	4.0		61
^{197}Hg	65h	$^{197}Au(d,2n)$	Gold, natural	22→8	600	*	62
^{197m}Hg	24h	"	" "	22→8	1500	*	62
^{199}Tl	7.4h	$^{197}Au(\alpha,2n)$	Gold, natural, thick	25	470	*	63
			" " "	30	1500	*	63
			" " "	.40	2000	*	63
^{201}Tl	73h	Decay product of ^{201}Pb					
^{201}Pb	9.4h	Tl(p,xn)	Thick, natural Tl	45	28200	*	64
			" "	28	5800	*	64
			" "	24	1800	*	64
		Tl(d,xn)	" "	33	6300	*	65
			" "	28	1750	*	65
			" "	25	340	*	65
		$^{205}Tl(p,5n)$	^{205}Tl, 99.46%	46→38	2100 (E.O.B. + 32h)		66
			" "	50→37.5	3550	*	66
			" "	45→37.5	2050	*	66
			" "	40→37.5	450 (E.O.B. + 32h)	*	66
^{203}Pb	52.1h	Tl(p,xn)	Thick, natural Tl	45	7100	*	64
			" "	28	3500	*	64
			" "	24	1600	*	64

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