YIELDS OF CYCLOTRON PRODUCED MEDICAL ISOTOPES: A COMPARISON OF THEORETICAL POTENTIAL AND EXPERIMENTAL RESULTS *

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Abstract

Experimentally obtained yields of most of the medical radioisotopes, produced with cyclotrons through different nuclear reactions at various bombarding energies in laboratories around the world, are presented. These yields are compared with those calculated using experimentally measured cross sections (where available) at similar bombarding conditions. Where experimental cross sections are unavailable, empirically constructed excitation functions have been used.

The information provided in this paper would be a valuable aid in selecting the most suitable nuclear reaction and bombarding conditions for producing a particular radioisotope and in assessing various losses of the isotope during chemical processing of the irradiated target.

Introduction

Production of radioisotopes for diagnostic studies is by far the most well known medical application of cyclotrons, and most medical cyclotrons are occupied in the production of various isotopes for research and routine work in nuclear medicine and nuclear biology. Generally neutron-deficient, carrier free, and shorter-lived isotopes, which cannot be produced in a reactor, are produced with cyclotrons. However, at the same time, neutron enriched isotopes can also be produced with cyclotrons, if required, through reactions of the type (d,p), (^{3}He,p), (α,p) etc.

Method and Results

Cyclotron production of most of the isotopes in current use has been summarized in Table I.

Thick-target yields at saturation of most isotopes through different nuclear reactions have been calculated[1] using experimentally measured (for ^{11}C, ^{13}N, ^{15}O, ^{18}F and ^{52}Fe) or empirically constructed excitation functions[2] and range-energy data[3]. In the calculations, the isotopic abundance of the particular isotope contributing to the nuclear reaction has been taken into consideration. However, the matrix which slows down the incoming particle beam in the target is assumed to consist of only the element taking part in the nuclear reaction, which is true when elemental rather than compound targets are being used. The calculated yields are designed as guide-lines only to optimize actual production and may be in error by as much as a factor of two in the case of empirically constructed excitation functions[2]. For comparison between the actually measured and calculated yields, the saturation yields would have to be converted into yields at time 't' where 't' is the time for actual bombardment, by using the factor $(1 - e^{-\lambda t})$.

In compiling the Table, an attempt has been made to include most of the published data regarding the production of various isotopes, in biomedical use, using different nuclear reactions. However, it is possible that some particular isotope publications might have been inaccessible or inadvertently ommitted. Only the first or the first significant published paper for radioisotope production under any particular bombarding conditions, such as energy, target material etc., has been included.

The operating costs of a small cyclotron in a developed country are estimated to be around US$60-90 per hour of useful machine time. Keeping this figure in mind, one can calculate the expected cost per millicurie of any particular isotope. However, the man-hours required for the chemical processing of the irradiated target must also be included in the overall cost estimate.

TABLE 1

Isotope	Reaction	Energy (MeV)	Target	Production yield μCi/μAh, unless otherwise indicated	Ref.	Calculated yield at saturation[1]	
						mCi/μA	Energy(MeV)
^{11}C	^{11}B(p,n)			-------	---	405	11.5
	^{10}B(d,n) $^{11}B(\overset{+}{d},2n)$	14	B_2O_3	5 mCi/min CO - 100 mCi per litre of H_2 carrier gas - 70 mCi per 35 ml of He CO_2 - 50 mCi in 35 ml of He	4	80	14
	^{12}C(^{3}He,α)	15-18	CaC_2	2500	5	87 115	15 18
	^{14}N(p,α)	15	$LiNH_2$	18 mCi/18 min of $H^{11}CN$	6	---	---
	"	18	5% H_2 in N_2	90 mCi/μAh	7	---	---
^{13}N	^{12}C(d,n)	14	Graphite	30 mCi/ml in gas form 100-300 μCi per ml in solution	8	300	14
	^{14}N(^{3}He,α)	30	N_2	15 mCi/μAh	9	38	30

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* This work has been supported by a grant from the Colgate-Palmolive Pty. Ltd.

Isotope	Reaction	Energy (MeV)	Target	Production yield μCi/μAh, unless otherwise indicated	Ref.	Calculated yield at saturation[1]	
						mCi/μA	Energy (MeV)
^{13}N	^{16}O(p,α)	18	H_2O	24 mCi/μAh as NH_3	10	---	---
^{15}O	^{14}N(d,n)	5	4% O_2 in N_2	120 mCi of O_2 per litre of carrier gas, 40 mCi/ml of H_2O	4	12.5	5
	^{14}N(^{3}He,d)	---	----	-------	---	26	17
	^{16}O(p,pn)	27	O_2	1.5mCi of ^{15}O per 15 ml of CO_2 - 6mCi/min of O-15 labelled CO_2 at 15μA	11	---	---
^{18}F	^{16}O(α,d)	30	H_2O	1100	12	5.4	30
	(α,pn)	40	"	11000	13	27	40
	(α,2n)	40	O_2	14300	13	---	---
		65	H_2O	19000	14	---	---
	^{16}O(^{3}He,p)	22	H_2O	6000	15	12	9.5
	(^{3}He,n)	30	H_2O	8500	13	32	30
		---	----	-------	---	43	35
	^{19}F(^{3}He,α)	---	----	-------	---	8	30
	^{20}Ne(d,α)	8	Neon Gas	10000	16	52	8
		---	----	-------	---	100	16
^{28}Mg	^{27}Al(α,3p)	45	Al	6.2	17	---	---
		140	Al	35	18	---	---
^{43}K	^{40}Ar(α,p)	17	Argon	57	19	9	17
^{52}Fe	^{50}Cr(α,2n)	30	natural Cr	3.3	20	.007	30
	^{52}Cr(^{3}He,3n)	45.5	"	50	21	9	45
	^{55}Mn(p,4n)	23		0.7	22	0.18	23
		65	MnO_2	160	23	90	65
^{62}Zn	^{63}Cu(p,2n)	38 → 18	Cu-foils 1.6g/cm^2	6000	24	---	---
	^{60}Ni(α,2n)	30	natural Ni	100	25	6	30
^{67}Ga	^{65}Cu(α,2n)	30	natural Cu	160	26	8	30
	Zn(p,xn)	22	natural Zn	430	27	95	22
	Zn(d,xn)	8	"	100	28	2	8
	"	"	"	30	22		
	"	16	"	340	29	--	--
	"	16	enriched ^{66}Zn (90%)	946	29	--	--
^{77}Br	^{75}As(α,2n)	28	As_2O_5	160	30	25	28
	"	28	As_2O_3	290	31	--	--
	"	28	As metal	170	31	--	--
	^{79,81}Br(α,6n)	100	NaBr	322	32	---	---
	(α,pxn)						
	(d,pxn)	55 → 20	"	550	33	---	---
	(d,xn)	"	"	640	33	---	---
^{81m}Kr		Decay product of ^{81}Rb					
^{85m}Kr	^{84}Kr(d,p)	15	Kr	790	34	60	15
^{81}Rb	^{79}Br(α,2n)	30	NaBr	2000	35	18	30
		50	"	2900	36		
	^{81}Br(^{3}He,n)	22	NaBr	30	37	0.13	22
^{82m}Rb	^{81}Br(^{3}He,2n)	22	NaBr	80	37	1.2	22
^{83}Rb	^{83}Kr(p,n)	22	Natural Kr-gas	7	38	60	22
^{85}Sr	^{85}Rb(d,2n)	13	RbCl	15	39	70	13
^{87}Y	^{85}Rb(α,2n)	32	RbCl	174	40	30	32

Isotope	Reaction	Energy	Target	Production yield μCi/μAh, unless otherwise indicated	Ref.	Calculated yield at saturation[1]	
						mCi/μA	Energy (MeV)
^{111}In	^{109}Ag(α,2n)	30	natural Ag	200	41	9	30
	Cd(p,xn)	15	natural Cd	140	22	35	15
	^{111}Cd(p,n)	16	enriched ^{111}Cd	515	42	150	16
	^{112}Cd(p,2n)	22	natural Cd	1035	43	300	22
	^{110}Cd(d,n)	12	natural Cd	117	43	20	12
^{123}I	^{121}Sb(α,2n)	25	natural Sb	150	44	3	25
		25-36	enriched ^{121}Sb	900	45	6-30	25-36
	^{121}Sb(^{3}He,n)	23	natural Sb	24	25	0.22	23
	^{122}Te(d,n)	6-9	enriched ^{122}Te	100	45	0.3	9
	^{123}Te(p,n)	15.5	enriched ^{123}Te	450	46	140	16
	^{124}Te(p,2n)	30	enriched ^{124}Te	40000	47	1300	30
^{123}Xe	^{122}Te(α,3n)	46	enriched ^{122}Te	5000	48	70	46
	^{123}Te(^{3}He,3n)	30	enriched ^{123}Te	750	49	20	30
	"	32	enriched (^{123}Te (88%)	4954	50	25	32
		35	"	6441	50	30	35
	^{124}Te(^{3}He,4n)	38	enriched ^{124}Te (96%)	1000	50	8.5	38
		52	"	7155	50	33	52
	^{127}I(p,5n)	60 → 50	NaI powder 1.5g/cm^{2}	5600	24	---	---
		52	CH$_{2}$I$_{2}$ (Circulating liquid)	1000	51	---	---
		53	" "	2200	52	---	---
		72	KI & NaI	11500	53	---	---
	^{127}I(d,6n)	78	NaI	8000	54	---	---
^{127}Cs	^{127}I(^{3}He,3n)	22	NaI	500	55	6	22
^{129}Cs	^{127}I(α,2n)	30	NaI	170	56	18	30
		35	"	300	57	30	35
		36	"	700	58	30	36
^{157}Dy	^{159}Tb(p,3n)	30	Terbium foil	23000	59	500	30
			TbCl$_{3}$.6H$_{2}$O	2500	60	---	---
	^{155}Gd(α,2n)	30	Gd	80	61	3	30
^{197}Hg	^{197}Au(p,n)	12.5	Gold	14	62	2	12.5
^{197m}Hg	^{197}Au (p.n)	12.5	Gold	15	62	10	12.5
^{203}Pb	^{203}Tl(p.n)	15	Tl metal	50	63	1	15
	^{203}Tl(d,2n)	16	Tl$_{2}$O	100	4	6	16
^{204}Bi	^{206}Pb(p.3n)	32	Pb	2000	64	180	32
^{206}Bi	^{207}Pb(p.2n)	22	Pb	700	65	110	22
	^{206}Pb(d.2n)	16	Pb	30	4	6	16

Isotope	Reaction	Energy (MeV)	Target	Production yield µCi/µAh, unless otherwise indicated	Ref.	Calculated yield at saturation[1] mCi/µA	Energy (MeV)
^{201}Tl	^{203}Tl(p,3n)	30	natural Tl	700	66	---	---
	Hg(p,n)	14	natural Hg	180	67	---	---
		16	"	350	67	---	---
		20	"	350	67	---	---

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