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Analysis using Ion Induced γ Rays

J. R. Bird, M. D. Scott, L. H. Russell and M. J. Kenny

AAEC Research Establishment, Private Mail Bag, Sutherland, N.S.W. 2232.

Abstract

Gamma ray energies and some thick sample reaction yields are summarized for proton, deuteron, triton, ^3He and α-particle induced γ rays which have been used in prompt nuclear analysis work.

The tabulation of ion induced γ-ray energies and intensities, for use in prompt nuclear analysis, would be straightforward if only one or a few ions and ion energies were in use, as is the case for neutron induced γ rays. This is not the case and the tabulation of useful information must involve a compromise between completeness and unwieldiness. For example, the table of γ-ray energies presented by de Meijer *et al.* (1973) includes all possible transitions in light elements as derived from the known energy levels of light nuclei. The table is so complex that it is of little use in analysis work, particularly that involving thick samples for which only the strongest γ rays are likely to be observed, and individual resonances are of little importance.

There have been many reports listing prompt γ rays which are useful in analytical applications and from these a compilation has been prepared in order of γ-ray energy. Table 1 includes γ rays from reactions with the following incident ions: ^1H, ^2D, ^3H, ^3He and ^4He. For proton induced γ rays, the table does not include all high energy γ rays from individual resonances since these are seldom used for analysis even though lists have been presented in the literature.

Measurements have been made, using the AAEC 3 MeV Van de Graaff accelerator, of the thick sample yield of γ rays from a number of elements. A Ge(Li) detector was used at a distance of 15·5 cm from the sample surface and at 135° relative to the direction of the incident ion beam. Elemental samples were mounted on a computer-controlled sample changer so that measurements could be sequenced to give a comparison of yields from various elements. Pulse height spectra in 8192 channels were stabilized using source γ rays at 0·511 and 1·274 MeV. A 0·6 mm thick aluminium window was used between the sample and detector in order to minimize γ-ray attenuation. The detector efficiency was 19% at 1·333 MeV, relative to a 7·5 by 7·5 cm NaI detector.

Spectral analysis to obtain peak areas was carried out using a peak search routine which has been checked in international comparisons of spectrum analysis techniques. Corrections for detector efficiency and solid angle have been made to obtain the yield values given in Table 2. The values for sodium were confirmed by comparison with yields observed from a crystal of NaCl and from a glass sample of known composition.

Table 1. Prompt γ-ray energies

E_γ (MeV)	Reaction	E_γ (MeV)	Reaction	E_γ (MeV)	Reaction
		Proton induced reactions			
0·099	^{195}Pt(p, p′)^{195}Pt	0·476	^{60}Ni(p, γ)^{61}Cu	1·273	^{29}Si(p, p′)^{29}Si
0·100	^{182}W(p, p′)^{182}W	0·477	^{7}Li(p, p′)^{7}Li	1·292	^{52}Cr(p, γ)^{53}Mn
0·110	^{19}F(p, p′)^{19}F	0·496	^{16}O(p, γ)^{17}F	1·318	^{65}Cu(p, γ)^{66}Zn
0·110	^{18}O(p, γ)^{19}F	0·555	^{104}Pd(p, p′)^{104}Pd	1·342	^{25}Mg(p, γ)^{26}Al
0·111	^{184}W(p, p′)^{184}W	0·560	^{76}Se(p, p′)^{76}Se	1·368	^{23}Na(p, γ)^{24}Mg
0·122	^{186}W(p, p′)^{186}W	0·568	^{37}Cl(p, α)^{34}S	1·368	^{24}Mg(p, p′)^{24}Mg
0·123	^{56}Fe(p, p′)^{56}Fe	0·574	^{68}Zn(p, γ)^{69}Ga	1·368	^{27}Al(p, α)^{24}Mg
0·126	^{54}Cr(p, γ)^{55}Mn	0·586	^{25}Mg(p, p′)^{25}Mg	1·379	^{56}Fe(p, p′)^{56}Fe
0·126	^{55}Mn(p, p′)^{55}Mn	0·595	^{55}Mn(p, p′)^{55}Mn	1·384	^{28}Si(p, γ)^{29}P
0·128	^{56}Fe(p, γ)^{57}Co	0·602	^{37}Cl(p, α)^{34}S	1·39	^{14}N(p, γ)^{15}O
0·136	^{57}Fe(p, p′)^{57}Fe	0·614	^{78}Se(p, p′)^{78}Se	1·437	^{9}Be(p, γ)^{10}B
0·136	^{181}Ta(p, p′)^{181}Ta	0·667	^{80}Se(p, p′)^{80}Se	1·46	^{29}Si(p, γ)^{30}P
0·168	^{66}Zn(p, γ)^{67}Ga	0·697	^{37}Cl(p, α)^{34}S	1·47	^{14}N(p, γ)^{15}O
0·170	^{26}Mg(p, γ)^{27}Al	0·709	^{29}Si(p, γ)^{30}P	1·54	^{24}Mg(p, γ)^{25}Al
0·170	^{27}Al(p, p′)^{27}Al	0·717	^{9}Be(p, γ)^{10}B	1·634	^{23}Na(p, α)^{20}Ne
0·176	^{66}Zn(p, γ)^{67}Ga	0·717	^{10}B(p, p′)^{10}B	1·643	^{28}Si(p, γ)^{29}P
0·185	^{67}Zn(p, γ)^{68}Ga	0·75	^{14}N(p, γ)^{15}O	1·72	^{28}Si(p, γ)^{29}P
0·192	^{197}Au(p, p′)^{197}Au	0·783	^{50}Cr(p, p′)^{50}Cr	1·760	^{56}Fe(p, p′)^{56}Fe
0·197	^{19}F(p, p′ γ)^{19}F	0·797	^{35}Cl(p, γ)^{36}Ar	1·763	^{34}S(p, γ)^{35}Cl
0·197	^{18}O(p, γ)^{19}F	0·806	^{32}S(p, γ)^{33}Cl	1·763	^{35}Cl(p, p′)^{35}Cl
0·200	^{77}Se(p, p′)^{77}Se	0·809	^{63}Cu(p, γ)^{64}Zn	1·778	^{27}Al(p, γ)^{28}Si
0·202	^{127}I(p, p′)^{127}I	0·830	^{25}Mg(p, γ)^{26}Al	1·778	^{28}Si(p, p′)^{28}Si
0·211	^{195}Pt(p, p′)^{195}Pt	0·834	^{65}Cu(p, γ)^{66}Zn	1·778	^{31}P(p, α)^{28}Si
0·239	^{77}Se(p, p′)^{77}Se	0·840	^{56}Fe(p, p′)^{56}Fe	1·80	^{24}Mg(p, γ)^{25}Al
0·239	^{195}Pt(p, p′)^{195}Pt	0·842	^{33}S(p, p′)^{33}S	1·809	^{26}Mg(p, p′)^{26}Mg
0·279	^{197}Au(p, p′)^{197}Au	0·843	^{26}Mg(p, γ)^{27}Al	1·84	^{25}Mg(p, γ)^{26}Al
0·280	^{105}Pd(p, p′)^{105}Pd	0·843	^{27}Al(p, p′)^{27}Al	1·922	^{56}Fe(p, p′)^{56}Fe
0·296	^{103}Rh(p, p′)^{103}Rh	0·845	^{24}Mg(p, γ)^{25}Al	1·95	^{28}Si(p, γ)^{29}P
0·309	^{109}Ag(p, p′)^{109}Ag	0·847	^{55}Mn(p, γ)^{56}Fe	1·972	^{35}Cl(p, γ)^{36}Ar
0·320	^{68}Zn(p, γ)^{69}Ga	0·871	^{17}O(p, p′)^{17}O	1·982	^{18}O(p, p′)^{18}O
0·320	^{51}V(p, p′)^{51}V	0·874	^{68}Zn(p, γ)^{69}Ga	2·02	^{33}S(p, γ)^{34}Cl
0·325	^{107}Ag(p, p′)^{107}Ag	0·913	^{52}Cr(p, γ)^{53}Mn	2·04	^{24}Mg(p, γ)^{25}Al
0·328	^{194}Pt(p, p′)^{194}Pt	0·933	^{56}Mn(p, n)^{56}Fe	2·05	^{32}S(p, γ)^{33}Cl
0·354	^{57}Fe(p, p′)^{57}Fe	0·945	^{24}Mg(p, γ)^{25}Al	2·127	^{37}Cl(p, α)^{34}S
0·356	^{196}Pt(p, p′)^{196}Pt	0·970	^{60}Ni(p, γ)^{61}Cu	2·144	^{11}B(p, γ)^{12}C
0·358	^{103}Rh(p, p′)^{103}Rh	0·976	^{25}Mg(p, p′)^{25}Mg	2·15	^{9}Be(p, γ)^{10}B
0·375	^{110}Pd(p, p′)^{110}Pd	0·992	^{63}Cu(p, γ)^{64}Zn	2·168	^{37}Cl(p, γ)^{38}Ar
0·379	^{52}Cr(p, γ)^{53}Mn	0·998	^{35}Cl(p, γ)^{36}Ar	2·209	^{35}Cl(p, γ)^{36}Ar
0·390	^{25}Mg(p, p′)^{25}Mg	1·013	^{26}Mg(p, γ)^{27}Al	2·237	^{35}Cl(p, α)^{32}S
0·406	^{198}Pt(p, p′)^{198}Pt	1·013	^{27}Al(p, p′)^{27}Al	2·237	^{31}P(p, γ)^{32}S
0·413	^{55}Mn(p, n)^{55}Fe	1·023	^{9}Be(p, γ)^{10}B	2·237	^{32}S(p, p′)^{32}S
0·414	^{9}Be(p, γ)^{10}B	1·035	^{55}Mn(p, γ)^{56}Fe	2·24	^{24}Mg(p, γ)^{25}Al
0·414	^{109}Ag(p, p′)^{109}Ag	1·039	^{65}Cu(p, γ)^{66}Zn	2·28	^{29}Si(p, γ)^{30}P
0·418	^{25}Mg(p, γ)^{26}Al	1·078	^{68}Zn(p, γ)^{69}Ga	2·357	^{12}C(p, γ)^{13}N
0·425	^{107}Ag(p, p′)^{107}Ag	1·14	^{12}C(p, γ)^{13}N	2·366	^{12}C(p, γ)^{13}N
0·429	^{10}B(p, α)^{7}Li	1·220	^{35}Cl(p, p′)^{35}Cl	2·38	^{14}N(p, γ)^{15}O
0·434	^{108}Pd(p, p′)^{108}Pd	1·266	^{31}P(p, p′)^{31}P	2·39	^{13}C(p, γ)^{14}N
0·439	^{23}Na(p, p′)^{23}Na	1·266	^{34}S(p, α)^{31}P	2·40	^{9}Be(p, γ)^{10}B
0·440	^{77}Se(p, p′)^{77}Se	1·266	^{56}Fe(p, p′)^{56}Fe	2·440	^{31}P(p, γ)^{32}S
0·452	^{24}Mg(p, γ)^{25}Al	1·266	^{30}Si(p, γ)^{31}P	2·59	^{18}O(p, γ)^{19}F

Table 1 (*Continued*)

E_γ (MeV)	Reaction	E_γ (MeV)	Reaction	E_γ (MeV)	Reaction
Proton induced reactions		*Deuteron induced reactions*		^{4}He *induced reactions*	
2·74	^{13}C(p, γ)^{14}N	0·717	^{9}Be(d, n)^{10}B	0·110	^{15}N(α, γ)^{19}F
2·835	^{27}Al(p, γ)^{28}Si	0·870	^{16}O(d, p)^{17}O	0·197	^{15}N(α, γ)^{19}F
2·86	^{23}Na(p, γ)^{24}Mg	1·274	^{28}Si(d, p)^{29}Si	0·351	^{18}O(α, n)^{21}Ne
2·92	^{26}Mg(p, γ)^{27}Al	1·634	^{19}F(d, n)^{20}Ne	0·39	^{7}Li(α, γ)^{11}B
2·99	^{29}Si(p, γ)^{30}P	1·778	^{27}Al(d, n)^{28}Si	0·414	^{6}Li(α, γ)^{10}B
3·01	^{9}Be(p, γ)^{10}B	1·95	Mg	0·417	^{23}Na(α, n)^{26}Al
3·04	^{14}N(p, γ)^{15}O	2·07	^{12}C(d, p)^{13}C	0·440	^{23}Na(α, α')^{23}Na
3·07	^{13}C(p, γ)^{14}N	2·77	Mg	0·478	^{7}Li(α, α')^{7}Li
3·18	^{26}Mg(p, γ)^{27}Al	3·09	^{12}C(d, p)^{13}C	0·583	^{19}F(α, n)^{22}Na
3·40	^{27}Al(p, γ)^{28}Si	3·30	Mg	0·717	^{10}B(α, α')^{10}B
3·41	^{33}S(p, γ)^{34}Cl	3·49	^{19}F(d, p)^{20}F	0·717	^{6}Li(α, γ)^{10}B
3·509	^{12}C(p, γ)^{13}N	3·67	^{12}C(d, p)^{13}C	0·72	^{14}N(α, γ)^{18}F
3·562	^{9}Be(p, α)^{6}Li	4·43	^{11}B(d, n)^{12}C	0·843	^{24}Mg(α, p)^{27}Al
3·585	^{9}Be(p, γ)^{10}B	4·43	^{14}N(d, α)^{12}C	0·871	^{14}N(α, p)^{17}O
3·780	^{31}P(p, γ)^{32}S	4·6	^{27}Al(d, n)^{28}Si	0·88	K
3·82	^{25}Mg(p, γ)^{26}Al	4·8	^{28}Si(d, p)^{29}Si	0·891	^{19}F(α, n)^{22}Na
3·83	^{23}Na(p, γ)^{24}Mg	4·9	^{28}Si(d, p)^{29}Si	0·937	^{14}N(α, γ)^{18}F
3·907	^{18}O(p, γ)^{19}F	4·90	^{27}Al(d, n)^{28}Si	1·002	^{23}Na(α, p)^{26}Mg
4·11	^{13}C(p, γ)^{14}N	5·29	^{14}N(d, n)^{15}O	1·014	^{24}Mg(α, p)^{27}Al
4·23	^{23}Na(p, γ)^{24}Mg	5·34	^{14}N(d, p)^{15}N	1·023	^{6}Li(α, γ)^{10}B
4·439	^{15}N(p, α)^{12}C	6·83	^{14}N(d, n)^{15}O	1·023	^{10}B(α, α')^{10}B
4·439	^{11}B(p, γ)^{12}C	7·34	^{14}N(d, n)^{15}O	1·039	^{26}Mg(α, n)^{29}Si
4·47	^{31}P(p, γ)^{32}S	8·28	^{14}N(d, n)^{15}O	1·08	^{14}N(α, γ)^{18}F
4·490	^{27}Al(p, γ)^{28}Si			1·130	^{23}Na(α, p)^{26}Mg
4·65	^{26}Mg(p, γ)^{27}Al			1·176	^{31}P(α, p)^{34}S
4·67	^{13}C(p, γ)^{14}N			1·262	^{27}Al(α, p)^{30}Si
4·70	^{25}Mg(p, γ)^{26}Al	*Triton induced reactions*		1·27	^{15}N(α, γ)^{19}F
4·71	^{9}Be(p, γ)^{10}B	0·657	^{16}O(t, n)^{18}F	1·275	^{19}F(α, p)^{22}Ne
4·80	^{31}P(p, γ)^{32}S	0·940	^{16}O(t, n)^{18}F	1·280	^{19}F(α, n)^{22}Na
4·909	^{18}O(p, γ)^{19}F	1·043	^{16}O(t, n)^{18}F	1·38	^{23}Na(α, p)^{26}Mg
6·131	^{19}F(p, α)^{16}O	1·085	^{16}O(t, n)^{18}F	1·395	^{18}O(α, n)^{21}Ne
6·85	^{9}Be(p, γ)^{10}B	1·568	^{18}O(t, p)^{20}O	1·43	^{6}Li(α, γ)^{10}B
6·919	^{19}F(p, α)^{16}O	1·632	^{12}C(t, n)^{14}N	1·524	^{39}K(α, p)^{42}Ca
7·119	^{19}F(p, α)^{16}O	1·982	^{18}O(t, p)^{20}O	1·528	^{19}F(α, n)^{22}Na
7·336	^{18}O(p, γ)^{19}F	2·313	^{12}C(t, n)^{14}N	1·54	^{27}Al(α, p)^{30}Si
7·479	^{9}Be(p, γ)^{10}B	5·271	^{16}O(t, α)^{15}N	1·720	^{24}Mg(α, p)^{27}Al
8·061	^{13}C(p, γ)^{14}N	5·299	^{16}O(t, α)^{15}N	1·746	^{18}O(α, n)^{21}Ne
8·283	^{14}N(p, γ)^{15}O	6·324	^{16}O(t, α)^{15}N	1·779	^{25}Mg(α, n)^{28}Si
8·686	^{18}O(p, γ)^{19}F			1·794	^{26}Mg(α, n)^{29}Si
9·172	^{13}C(p, γ)^{14}N			1·809	^{23}Na(α, p)^{26}Mg
9·737	^{27}Al(p, γ)^{28}Si			2·081	^{19}F(α, p)^{22}Ne
10·761	^{27}Al(p, γ)^{28}Si			2·10	^{14}N(α, γ)^{18}F
11·667	^{11}B(p, γ)^{12}C	^{3}He *induced reactions*		2·127	^{31}P(α, p)^{34}S
12·136	^{11}B(p, γ)^{12}C	0·413	^{11}B(^{3}He, α)^{10}B	2·132	^{23}Na(α, p)^{26}Mg
14·74	^{7}Li(p, γ)^{8}Be	0·477	^{7}Li(^{3}He, ^{3}He$'$)^{7}Li	2·15	^{6}Li(α, p)^{9}Be
15·25	^{7}Li(p, γ)^{8}Be	0·717	^{10}B(^{3}He, ^{3}He$'$)^{10}B	2·168	^{35}Cl(α, p)^{38}Ar
16·106	^{11}B(p, γ)^{12}C	1·632	^{12}C(^{3}He, p)^{14}N	2·210	^{24}Mg(α, p)^{27}Al
17·64	^{7}Li(p, γ)^{8}Be	1·634	^{18}O(^{3}He, n)^{20}Ne	2·236	^{27}Al(α, p)^{30}Si
18·15	^{7}Li(p, γ)^{8}Be	2·311	^{12}C(^{3}He, p)^{14}N	2·313	^{11}B(α, n)^{14}N

Table 1 (*Continued*)

E_γ (MeV)	Reaction	E_γ (MeV)	Reaction	E_γ (MeV)	Reaction
		^{4}He *induced reactions*			
2·366	$^{10}B(\alpha,n)^{13}N$	3·01	$^{6}Li(\alpha,\gamma)^{10}B$	4·0	$^{15}N(\alpha,\gamma)^{19}F$
2·54	$^{14}N(\alpha,\gamma)^{18}F$	3·183	$^{19}F(\alpha,p)^{22}Ne$	4·115	$^{31}P(\alpha,p)^{34}S$
2·541	$^{23}Na(\alpha,p)^{26}Mg$	3·303	$^{31}P(\alpha,p)^{34}S$	4·439	$^{9}Be(\alpha,n)^{12}C$
2·65	$^{15}N(\alpha,\gamma)^{19}F$	3·498	$^{27}Al(\alpha,p)^{30}Si$	4·439	$^{10}B(\alpha,d)^{12}C$
2·734	$^{24}Mg(\alpha,\gamma)^{28}Si$	3·684	$^{10}B(\alpha,p)^{13}C$	4·5	$^{14}N(\alpha,\gamma)^{18}F$
2·839	$^{24}Mg(\alpha,\gamma)^{28}Si$	3·770	$^{27}Al(\alpha,p)^{30}Si$	4·618	$^{25}Mg(\alpha,n)^{28}Si$
2·839	$^{25}Mg(\alpha,n)^{28}Si$	3·854	$^{10}B(\alpha,p)^{13}C$	4·84	Al
2·84	$^{18}O(\alpha,n)^{21}Ne$	3·869	$^{19}F(\alpha,p)^{22}Ne$	5·15	$^{15}N(\alpha,\gamma)^{19}F$
2·983	$^{23}Na(\alpha,p)^{26}Mg$	3·945	$^{11}B(\alpha,n)^{14}N$	5·18	$^{15}N(\alpha,\gamma)^{19}F$
3·0	$^{14}N(\alpha,\gamma)^{18}F$	3·97	$^{23}Na(\alpha,p)^{26}Mg$		

Table 2. Thick sample yields of proton induced γ rays

(1) Element	(2) Energy E_γ (MeV)	(3) Measured γ yield (counts sr^{-1} μC^{-1}) Present work (135°) E_p (MeV): 2·000	(4) 2·500	(5) Previous work (90°)[A] 2·000	(6) 2·500	(7) Yield curve Refs[B]
Li	14–18					1
Be	0·416	4×10^{2}	8×10^{2}			
	0·717	$3·9\times10^{3}$	$5·0\times10^{3}$			
	1·021	5×10^{2}	$1·5\times10^{3}$			
	7·5					1
B	0·430	$1·0\times10^{6}$	$2·5\times10^{6}$			
	0·717	$2·7\times10^{4}$	$1·5\times10^{5}$			
	4·439					1
	11–17					1
C	2·360, 9·18					1
F	6·13					1
Na	0·439	$1·2\times10^{6}$	$3·3\times10^{6}$	$1·4\times10^{7}$	$4·7\times10^{7}$	2
	1·368					
	1·630	$2·8\times10^{5}$	$1·6\times10^{6}$			
Mg	0·390	$3·7\times10^{3}$	$3·2\times10^{4}$	$3·3\times10^{3}$		
	0·586	$3·0\times10^{4}$	$9·6\times10^{4}$	$3·5\times10^{4}$	1×10^{5}	3
	0·843	—	7×10^{2}			
	0·976	$4·1\times10^{3}$	$3·9\times10^{4}$	$4·8\times10^{3}$		
	1·013	—	1×10^{3}			
	1·368	—	$2·1\times10^{5}$	$5·41\times10^{2}$		
Al	0·170	$1·0\times10^{3}$	$1·1\times10^{4}$			
	0·843	$2·5\times10^{4}$	$1·9\times10^{5}$	$2·6\times10^{4}$	$2·3\times10^{5}$	4
	1·013	$3·7\times10^{4}$	$3·8\times10^{5}$	$4·0\times10^{4}$	$4·5\times10^{5}$	4
	1·368	$1·0\times10^{4}$	$5·1\times10^{4}$	$9·8\times10^{3}$	$5·6\times10^{4}$	4
	1·778	$5·4\times10^{3}$	$8·2\times10^{3}$	$6·4\times10^{3}$	$1·1\times10^{4}$	4
	2·836	5×10^{2}	1×10^{3}			
Si	1·273					
	1·778	—	3×10^{2}			

[A,B] See footnotes at end of table.

Table 2 (*Continued*)

(1) Element	(2) Energy E_γ (MeV)	(3) Measured γ yield (counts sr^{-1} μC^{-1}) Present work (135°) E_p (MeV): 2·000	(4) 2·500	(5) Previous work (90°)[A] 2·000	(6) 2·500	(7) Yield curve Refs[B]
P	1·266			$1\cdot0\times10^3$	$7\cdot4\times10^4$	5
	1·778			$1\cdot73\times10^2$	$3\cdot3\times10^3$	5
	2·237			$1\cdot8\times10^3$	$3\cdot4\times10^3$	5
Cl	0·568				$2\cdot5\times10^3$	
	0·602				$7\cdot2\times10^3$	
	0·697				$5\cdot5\times10^3$	
	1·219				$1\cdot1\times10^4$	6
	1·643				$1\cdot9\times10^3$	6
	1·972				$1\cdot4\times10^3$	6
	2·128				$3\cdot4\times10^3$	6
	2·168				$3\cdot2\times10^3$	6
	2·209				$0\cdot6\times10^3$	

[A] References 2–6 in column 7.
[B] References: 1, Golicheff *et al.* (1972); 2, Deconninck (1972); 3, Demortier and Delsate (1975); 4, Deconninck and Demortier (1972); 5, Demortier and Bodart (1972); 6, Deconninck and Debras (1975).

Thick target yield curves have been reported previously for some reactions and the appropriate references are included in Table 2. Reported yields at 2·000 and 2·500 MeV are also included and, where a comparison is possible, the agreement is quite good, except in the case of sodium. It should be noted that the two sets of results are from measurements at different angles and little work has been done on angular distributions of thick target radiation. Further work of this kind is needed for use in planning prompt γ-ray analysis applications and for the interpretation of results observed in analytical work.

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