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SENSITIVITIES FOR ACTIVATION ANALYSIS WITH THERMAL OR FAST NEUTRONS

by

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SYNOPSIS

This report introduces and contains a table of relevant data for activation analysis by means of slow (thermal) or fast (14 MeV) neutrons. Only the most sensitive reaction has been selected for each element and sensitivities are listed for fast neutron fluxes of 10^8 n/cm^2/sec or thermal neutron fluxes of 10^7 n/cm^2/sec. This information is of value in assessing the possible usefulness of neutron activation for analysis of materials of industrial interest.

RÉSUMÉ

Le présent rapport propose et contient un tableau de données pertinentes sur l'analyse d'activation à l'aide de neutrons lents (thermiques) ou rapides (14 MeV). Seule la réaction la plus sensible a été choisie pour chaque élément, et les sensibilités sont indiquées pour les flux de neutrons rapides de l'ordre de 10^8 n/cm^2/sec., ou pour les flux de neutrons thermiques de l'ordre de 10^7 n/cm^2/sec. Ces renseignements permettent d'évaluer l'utilité possible de l'activation des neutrons pour fins d'analyse de matériaux qui peuvent être intéressants du point de vue industriel.

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INTRODUCTION

Neutron activation analysis offers a relatively new, rapid, non-destructive means of analysing many metals and minerals of technical interest. It consists, essentially, of exposing the sample to a flux of fast or slow neutrons and determining the induced radioactivity by counting the emitted gamma radiation in a well-defined counter geometry. In many cases, identification of characteristic gamma-rays and utilization of differences in half-life of the induced radioactivity are required for identification and quantitative determination of the element of interest. To operate such an analytical system under the most favourable conditions, it is important to possess fairly complete information on the production conditions of the radionuclides concerned and on their sensitivity to either fast or thermal neutron bombardment.

Most of the results reported in the literature on neutron activation analysis have been obtained using a reactor as a neutron source. Although reactors are unrivalled as a high-flux source of thermal neutrons, their use introduces a number of complications, particularly when dealing with short-lived activities, unless an on-site experiment is possible. An alternative neutron source has become available commercially in recent years in the form of relatively low-cost accelerators that produce monoenergetic 14 MeV neutrons by the reaction

$$H^2 + H^3 = n + He^4.$$

These high-energy neutrons may be thermalised with a suitable moderator (e.g., water) to give an intense source of thermal neutrons. Although the thermal fluxes obtained in this manner are very modest by reactor standards, they are, nevertheless, in many cases adequate for analysis. In addition, the unmoderated 14 MeV neutrons may be used for activation and permit the use of a number of reactions (e.g., the analysis of oxygen by the $O^{16}(n,p)N^{16}$ reaction) which are impractical in a reactor because of its different neutron spectrum. Thus a neutron generator may be used in analysis as a practical source of thermal or fast (14 MeV) neutrons, and may become more attractive for industrial analytical applications.

In order to obtain an estimate of the analytical sensitivities that may be expected on activation, the following table has been prepared for all elements that give a product nuclide that decays by gamma-ray emission. Gamma-ray emitters have been selected because they may be identified and quantitatively estimated with a multi-channel gamma-ray spectrometer. Nuclides that only give rise to pure beta-ray emitters

following neutron activation have not been included in this compilation. The reactions given in the table are those that, based on available cross section and related data, appear to be the most sensitive for analytical purposes, using either fast or thermal neutrons.

DESCRIPTION OF THE TABLE

The calculated sensitivities are based upon the equation

$$R\,(d/sec/g) = \frac{A\sigma F}{W}\, f \left[1 - e^{-\frac{0.693\,t}{\tau_{\frac{1}{2}}}}\right],$$

where A = Avogadro's Number,

σ = cross section in cm^2 (1 barn = 10^{-24} cm^2),

F = neutron flux in $n/cm^2/sec$,

f = fraction of target isotope in the element (abundance),

W = atomic weight,

t = irradiation time,

$\tau_{\frac{1}{2}}$ = half-life of product nuclide.

For purposes of calculation, certain assumptions have been made, based on operating experience with a representative accelerator, for the variables in the above equation. These are:

(a) The maximum usable fast neutron flux available is 10^8 $n/cm^2/sec$ and the maximum usable thermal neutron flux 10^7 $n/cm^2/sec$. As the activation sensitivity is directly proportional to the flux, fluxes greater or less than these values will give a corresponding increase or decrease in sensitivity.

(b) Irradiation time (t) is taken as 40 minutes or four half-lives, whichever is shorter.

(c) Sensitivity is arbitrarily defined as the weight of an element (in μg) that yields 500 d/min at the end of the irradiation time. For a 1 g sample, this represents the parts per million concentration of the element, which may be detected. For a 10 g sample, the sensitivity (in terms of ppm) will be ten times greater. It is important to note that it is a limiting mass of the particular element that is being detected and this is assumed to be independent of the total sample weight. For very short-lived nuclides, where the half-life is comparable to, or less than, the measurement time, corrections have been applied to allow for decay during measurement.

(d) Where the decay scheme of the product nucleus is known, the sensitivity has been normalised to 100% emission of the most abundant gamma-ray, e.g., if the most abundant gamma-ray occurs in only 50% of the disintegrations, the effective sensitivity has been lowered by a factor of two.

The information listed in the table is largely self-explanatory. The cross section data are taken mainly from Hughes et al. (1) and the radiation data from Strominger et al. (2). In both cases their data have been modified, where necessary, in the light of more recent results appearing in the literature. The column headed F or T indicates whether a fast or a thermal neutron reaction is more sensitive. M in the gamma energy column indicates the emission of many gamma-rays.

The final column is headed "Notes", with the following significance:

(a) Assumes positron emission (and hence 0.5 MeV gamma) for 100% of the disintegrations;

(b) * indicates that only the relative intensity of the gamma radiations is known. The most abundant is assumed to be 100%;

(c) No information on the gamma decay scheme, other than gamma energies, is known.

In conclusion, it should be emphasized that the sensitivities shown are calculated and make no allowance for matrix effects that may be significant. Also, although half-lives and thermal neutron cross-sections are, for the most part, well established, fast neutron

cross sections are not as reliable and could be in error by as much as a factor of 2.

REFERENCES

1. Hughes, D.J. and Schwartz, R.B., Brookhaven Report BNL-325, (1958).

   Hughes, D.J., Magurno, B.A. and Brussel, B.K., Supplement No. 1 to BNL-325, (1960).

2. Strominger, D., Hollander, J.M. and Seaborg, G.T., Revs. Mod. Phys., 30, 585 (1958).

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TABLE 1

Neutron Activation Data

Z	Target Isotope	% Abundance	σ (barns)	F or T	Reaction	R (d/sec/g)	Half-life	Gamma Energy (MeV)	Sensitivity (μg)	Notes
7	N 14	99.63	0.005	F	N14(n, 2n) N13	2.06×10^4	10.0 min	β^+	4.05×10^2	(a)
8	O 16	99.59	0.033	F	O16(n, p) N16	1.35×10^5	7.3 sec	6.13(100)*, 7.12(7)*	3.85×10^2	(b)
9	F 19	100	0.016	F	F19(n, p) O19	5.05×10^4	29.4 sec	0.2(100)*, 1.366(67)*	3.1×10^2	(b)
10	Ne 22	8.82	0.036	T	Ne22(n, γ) Ne23	9.42×10^2	40.2 sec	0.44(32%), 1.65(1%)	4.23×10^4	
11	Na 23	100	0.05	F	Na23(n, p) Ne23	1.5×10^5	40.2 sec	0.44(33%), 1.65(1%)	3.1×10^2	
	Na 23	100	0.53	T	Na23(n, γ) Na24	4.15×10^3	15 hr	1.37(100%), 2.75(100%)	2.0×10^3	
12	Mg 24	78.6	0.19	F	Mg24(n, p) Na24	1.1×10^4	15 hr	1.37(100%), 2.75(100%)	7.6×10^2	
13	Al 27	100	0.07	F	Al 27(n, p) Mg27	1.55×10^5	9.45 min	0.843(70%), 1.015(30%)	77	
	Al 27	100	0.21	T	Al 27(n, γ) Al 28	4.7×10^4	2.27 min	1.78(100%)	2.0×10^2	
14	Si 28	92.27	0.22	F	Si28(n, p) Al28	4.34×10^5	2.27 min	1.78(100%)	22	
15	P 31	100	0.15	F	P31(n, α) Al28	2.91×10^5	2.27 min	1.78(100%)	33	
16	S 34	4.215	0.085	F	S34(n, p) P34	6.7×10^3	12.4 sec	2.13(25%)	1.67×10^4	
17	Cl 37	24.6	0.19	F	Cl 37(n, α) P34	7.84×10^5	12.4 sec	2.13(25%)	1.43×10^3	
	Cl 37	24.6	0.56	T	Cl 37(n, γ) Cl 38	1.15×10^4	37.29 min	1.60(31%), 2.15(47%)	1.56×10^3	
18	A 40	99.6	0.53	T	A 40(n, γ) A 41	1.75×10^4	110 min	1.29(100%)	4.76×10^2	
19	K 39	93.08	0.01	F	K39(n, 2n) K38	1.44×10^4	7.7 min	2.16(100%); β^+ (100%)	5.8×10^2	
20	Ca 48	0.185	1.1	T	Ca48(n, γ) Ca49	3.05×10^2	8.8 min	3.07(89%), 4.04(10%)	3.03×10^4	
21	Sc 45	100	10	T	Sc45(n, γ) $Sc46^m$	1.34×10^6	19.5 sec	0.142	15	(c)
22	Ti 48	73.45	0.06	F	Ti48(n, p) Sc48	5.35×10^2	44 hr	0.98(100%), 1.04(100%), 1.32(100%)	1.55×10^4	
	Ti 50	5.34	0.14	T	Ti50(n, γ) Ti51	9.37×10^2	5.79 min	0.32(95%), 0.92 (5%)	9.4×10^3	
23	V 51	99.76	4.5	T	V51(n, γ) V52	5.3×10^5	3.76 min	1.44(100%)	25	
24	Cr 52	83.76	0.07	F	Cr52(n, p) V52	6.78×10^4	3.76 min	1.44(100%)	2.0×10^2	
25	Mn 55	100	13.3	T	Mn55(n, γ) Mn56	2.39×10^5	2.576 hr	0.85(100)*, 1.81(30)*, 2.13(20)*	35	(b)
	Mn 55	100	0.03	F	Mn55(n, α) V52	3.28×10^4	3.76 min	1.44(100%)	4.0×10^2	
26	Fe 56	91.68	0.110	F	Fe56(n, p) Mn56	1.79×10^4	2.576 hr	0.85(100)*, 1.81(30)*, 2.13(20)*	4.65×10^2	(b)
27	Co 59	100	16	T	Co59(n, γ) $Co60^m$	1.53×10^6	10.47 min	0.059(99%)	5.5	
28	Ni 61	1.25	0.18	F	Ni61(n, p) Co61	5.52×10^2	99 min	0.072(100%)	1.51×10^4	
	Ni 64	1.16	1.52	T	Ni64(n, γ) Ni65	3.0×10^2	2.56 hr	0.37 (5%), 1.11 (13%), 1.49 (18%)	1.6×10^5	
29	Cu 63	69.1	0.5	F	Cu63(n, 2n) Cu62	3.26×10^5	9.8 min	0.66(2%), 0.85(1%), 1.18(1%), 1.35(1%), 1.46(1%), 1.98(1%), 2.24(1%); β^+	25.5	(a)

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TABLE 1 (Continued)

Z	Target Isotope	% Abundance	σ (barns)	F or T	Reaction	R (d/sec/g)	Half-life	Gamma Energy (MeV)	Sensitivity (μg)	Notes
30	Zn 64	48.89	0.22	F	Zn64(n, 2n) Zn63	4.93×10^4	38.3 min	0.96(8%), 1.89(4%), 2.60(0.5%); β^+	2.1×10^3	
	Zn 66	27.81	0.077	F	Zn66(n, p) Cu66	1.96×10^4	5.1 min	1.04(9%)	4.9×10^3	
31	Ga 71	39.8	5.0	T	Ga 71(n, γ) Ga72	5.7×10^3	14.1 hr	0.63(19%), 0.84(88%), 2.2(29%)	1.65×10^3	
32	Ge 74	36.74	0.015	F	Ge74(n, α) Zn71	4.6×10^3	2.2 min	0.12, 0.51	2.1×10^3	(c)
	Ge 74	36.74	0.04	T	Ge74(n, γ) $Ge75^m$	1.21×10^3	48 sec	0.139	1.06×10^4	(c)
33	As 75	100	5.4	T	As75(n, γ) As76	7.27×10^3	26.4 hr	0.56(45%) + others	5.0×10^2	
34	Se 76	9.02	7	T	Se76(n, γ) $Se77^m$	4.82×10^4	17.5 sec	0.16(internal conversion high)	4.6×10^2	(c)
35	Br 79	50.52	8.5	T	Br79(n, γ) Br80	2.52×10^5	17.6 min	0.62(6.7%); β^+ (3%)	5.7×10^2	
	Br 79	50.52	1.1	F	Br79(n, 2n) $Br78^m$	4.13×10^5	6.4 min	0.108, 0.046	20	(c)
36	Kr 84	56.9	0.1	T	Kr84(n, γ) $Kr85^m$	4.06×10^2	4.36 hr	0.15(74%), 0.31(16%)	2.1×10^4	
37	Rb 87	27.85	0.04	F	Rb87(n, α) Br84	4.68×10^3	30 min	M	1.78×10^3	(b)
38	Sr 86	9.86	1.65	T	Sr86(n, γ) $Sr87^m$	1.68×10^3	2.8 hr	0.39(79%)	6.3×10^3	
	Sr 88	82.56	0.018	F	Sr88(n, p) Rb88	8.04×10^3	17.7 min	M	1.04×10^3	(b)
40	Zr 90	51.46	0.08	F	Zr90(n, 2n) $Zr89^m$	2.71×10^4	4.4 min	0.588(100)*, 1.53(8)*; β^+	3.2×10^2	(b)
41	Nb 93	100	1.0	T	Nb93(n, γ) $Nb94^m$	6.46×10^4	6.6 min	0.042 (I.T., 99%+)	1.3×10^2	
42	Mo 97	9.45	0.11	F	Mo97(n, p) Nb97	2.08×10^3	72 min	0.66(100)*, 1.02(1)*	4×10^3	(b)
44	Ru 96	5.7	0.48	F	Ru96(n, 2n) Ru95	3.77×10^3	1.65 hr	M; β^+	2.2×10^3	(c)
45	Rh 103	100	12	T	Rh103(n, γ) $Rh104^m$	7×10^5	4.4 min	0.051, 0.077	12.5	(c)
46	Pd 104	9.3	0.13	F	Pd104(n, p) Rh104	6.38×10^3	44 sec	0.56(100)*, 1.2(5.8)*	2×10^3	(b)
47	Ag 109	48.65	113	T	Ag109(n, γ) Ag110	3.05×10^6	24.2 sec	0.66	6.0	(c)
	Ag 107	51.35	45	T	Ag107(n, γ) Ag108	1.29×10^6	2.3 min	0.63(1.9%)	4×10^2	
48	Cd 116	7.58	1.5	T	Cd116(n, γ) $Cd117^m$	8.8×10^2	2.9 hr	0.28, 1.27 + others	9.5×10^5	(c)
49	In 115	95.77	155	T	In115(n, γ) $In116^m$	2.4×10^6	54 min	0.14(3%), 0.41(25%), 1.09(54%), 1.27(75%), 1.49(21%), 2.09(25%)	5	
50	Sn 124	5.98	0.2	T	Sn124(n, γ) Sn125	6×10^2	9.5 min	0.33(99.7%), 1.39(1.9%)	1.39×10^4	
51	Sb 121	57.25	0.75	F	Sb121(n, 2n) Sb120	2.24×10^5	16.5 min	1.18(1%)	3.75×10^3	
52	Te 130	34.49	0.22	T	Te130(n, γ) Te131	2.18×10^3	24.8 min	M	3.64×10^3	(b)
53	I 127	100	5.6	T	I 127(n, γ) I 128	2.25×10^5	24.99 min	0.46(17%), 0.54(1.8%), 0.75(0.03%), 0.99(0.3%)	2.18×10^2	
54	Xe 134	10.44	0.2	T	Xe134(n, γ) Xe135	45.8	9.13 hr	0.25(~90%)	2×10^5	
55	Cs 133	100	3.0	T	Cs133(n, γ) $Cs134^m$	1.85×10^4	3.2 hr	0.127 (13%)	3.5×10^3	

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TABLE 1 (Continued)

Z	Target Isotope	% Abundance	σ (barns)	F or T	Reaction	R (d/sec/g)	Half-life	Gamma Energy (MeV)	Sensitivity (μg)	Notes
56	Ba 136	7.81	0.4	T	$Ba136(n,\gamma)Ba137^{m}$	1.36×10^{3}	2.6 min	0.662	6.1×10^{3}	(c)
	Ba 138	71.66	0.5	T	$Ba138(n,\gamma)Ba139$	4.4×10^{3}	84 min	0.16(21%), 1.43(2%)	9.4×10^{3}	
57	La 139	100	8.2	T	$La139(n,\gamma)La140$	3.90×10^{3}	40.2 hr	0.49(41%), 0.82(27%), 1.6(95%)	2.5×10^{3}	
	La 139	100	0.006	F	$La139(n,p)Ba139$	7.26×10^{2}	85 min	0.163(26%)	4.4×10^{4}	
58	Ce 140	88.48	0.012	F	$Ce140(n,\alpha)Ba137^{m}$	4.5×10^{3}	2.6 min	0.662	2.2×10^{3}	(c)
59	Pr 141	100	2.1	F	$Pr141(n,2n)Pr140$	8.6×10^{5}	3.4 min	β^{+} (54%)	20	
	Pr 141	100	10.8	T	$Pr141(n,\gamma)Pr142$	1.15×10^{4}	19.2 hr	1.57(4%)	1.62×10^{4}	
60	Nd 150	5.6	1.5	T	$Nd150(n,\gamma)Nd151$	2.95×10^{3}	15 min	0.117, 0.43 + others	2.8×10^{3}	(c)
62	Sm 154	22.53	5.5	T	$Sm154(n,\gamma)Sm155$	3.42×10^{4}	22.0 min	0.104(76%)	3.2×10^{2}	
63	Eu 151	47.77	670	T	$Eu151(n,\gamma)Eu152$	6.2×10^{5}	9.2 hr	0.122(7%), 0.84(11%), 0.96(9%)	1.2×10^{2}	
64	Gd 160	21.9	0.8	T	$Gd160(n,\gamma)Gd161$	6.68×10^{3}	3.73 min	M	1.36×10^{3}	(c)
65	Tb 159	100	> 22	T	$Tb159(n,\gamma)Tb160$	2.2×10^{2}	73 day	M	3.8×10^{4}	(b)
66	Dy 164	28.18	2000	T	$Dy164(n,\gamma)Dy165^{m}$	2.05×10^{7}	1.25 min	M	0.5	(c)
67	Ho 165	100	60	T	$Ho165(n,\gamma)Ho166$	3.72×10^{4}	27.3 hr	0.08(6%), 1.38(1%)	3.7×10^{3}	
68	Er 170	14.9	9	T	$Er170(n,\gamma)Er171$	2.78×10^{3}	7.8 hr	0.11(75%), 0.124(20.5%), 0.3(93%)	3.25×10^{3}	
69	Tm 169	100	130	T	$Tm169(n,\gamma)Tm170$	6.9×10^{2}	129 days	0.084(24%)	5×10^{4}	
70	Yb 176	12.73	5.5	T	$Yb176(n,\gamma)Yb177$	5.21×10^{3}	1.9 hr	0.15(6.4%), 1.09(1.9%), 1.24(1.7%)	2.5×10^{4}	
71	Lu 175	97.4	35	T	$Lu175(n,\gamma)Lu176^{m}$	1.36×10^{5}	3.7 hr	0.089	61	(c)
72	Hf 178	27.08	40	T	$Hf178(n,\gamma)Hf179^{m}$	6.8×10^{5}	19 sec	0.057, 0.215	40	(c)
73	Ta 181	100	0.9	F	$Ta181(n,2n)Ta180^{m}$	1.5×10^{4}	8.15 hr	0.093, 0.102	5.5×10^{2}	(c)
74	W 182	26.4	20	T	$W182(n,\gamma)W183^{m}$	1.73×10^{5}	5.5 sec	0.105(25)*, 0.155(10)*	3.65×10^{2}	(b)
75	Re 187	62.93	69	T	$Re187(n,\gamma)Re188$	3.83×10^{4}	16.7 hr	0.15(9%) - others	2.4×10^{3}	
76	Os 192	41.0	1.6	T	$Os192(n,\gamma)Os193$	3.1×10^{2}	31 hr	0.14(3%), 0.28(1.3%), 0.46(4%)	6.7×10^{5}	
77	Ir 191	38.5	260	T	$Ir191(n,\gamma)Ir192^{m}$	3.13×10^{6}	1.4 min	0.058 (internal conversion high)	3.35	(c)
78	Pt 198	7.2	3.9	T	$Pt198(n,\gamma)Pt199$	5.1×10^{3}	31 min	M	1.64×10^{3}	(c)
	Pt 198	7.2	2.8	F	$Pt198(n,2n)Pt197$	1.55×10^{3}	18 hr	0.077(30)*, 0.19(3.9)*	5.4×10^{3}	(b)

(Continued)

TABLE 1 (Concluded)

Z	Target Isotope	% Abundance	σ (barns)	F or T	Reaction	R d/sec/g	Half-life	Gamma Energy (MeV)	Sensitivity (μg)	Notes
79	Au 197	100	96	T	Au 197(n, γ)Au 198	2.04×10^4	2.7 day	0.41(95.6%)	4.3×10^2	
80	Hg 204	6.85	0.43	T	Hg204(n, γ)Hg205	8.8×10^2	5.5 min	0.2	9.5×10^3	(c)
81	Tl 205	70.5	0.003	F	Tl 205(n, p) Hg205	6.2×10^2	5.5 min	0.2	1.34×10^4	(c)
82	Pb 208	52.3	0.001	F	Pb208(n, p)Tl208	1.5×10^2	3.1 min	0.582(80%), 2.62(100%)	5.5×10^4	
	Pb 208	52.3	0.0016	F	Pb208(n, α)Hg205	2.4×10^2	5.5 min	0.203	8.8×10^4	(c)
90	Th 232	100	7.33	T	Th232(n, γ)Th233	1.35×10^5	22.4 min	M	62	(c)
92	U 238	99.3	2.74	T	U238(n, γ)U239	4.8×10^3	23.54 min	0.073	1.74×10^2	(c)

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