

**RADIO-
ACTIVATION
ANALYSIS**

**H. J. M. BOWEN and
D. GIBBONS**

RADIOACTIVATION ANALYSIS

BY

H. J. M. BOWEN and D. GIBBONS

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PREFACE

IN writing a book of this kind, it is always difficult to strike a balance between theoretical and practical aspects of the subject. We hope we have included enough information to enable the analyst to see what can be done using activation, and sufficient practical detail for him to do it.

Our colleagues have helped us in many ways, especially by reading portions of the manuscript and making suggestions for improvements. In particular, we should like to thank R. A. Allen, R. K. Barnes, G. B. Cook, G. E. Harrison, D. Mapper, C. E. Mellish, D. F. C. Morris, J. L. Putman, A. A. Smales, B. S. Smith, D. B. Smith, S. R. Stitch, and C. Whitehead for pointing out many errors, and P. A. Cawse and H. Simpson for assistance in the laboratory. Unpublished information has been supplied by a number of workers whose help is acknowledged in the text, including E. A. C. Crouch, P. H. Davenport, A. J. Fudge, H. Rauscher, A. J. Salmon, L. Salmon, I. R. Williams, E. J. Wilson, Johnson Matthey & Co. Ltd., and Thermal Syndicate Ltd. The majority of the figures are original, but we have made use of the following copyright illustrations: Fig. 3.5, K. G. Stephens and G. W. Williams, A.E.I., Aldermaston. Figs. 3.7 and 3.8, D. J. Hughes and R. B. Schwartz. Figs. 4.1 and 4.2, L. Nathans and G. D. Halpern. Fig. 4.4, N. Jarmie and J. D. Seagrave. Fig. 5.13, D. H. Peirson, by permission of Leonard Hill Ltd. Fig. 5.14, W. H. Ellett and G. L. Brownell, by permission of North Holland Publishing Co., Amsterdam. Figs. 5.16 and 5.17, J. L. Putman and W. H. Taylor, by permission of Pergamon Press. Fig. 6.2, R. A. Faires and B. H. Parks, by permission of George Newnes Ltd. Fig. 6.8, L. E. Glendenin, by permission of McGraw-Hill Ltd. Fig. 10.1, E. D. Goldberg, by permission of Pergamon Press. Fig. 10.4, E. Hamilton, by permission of Meddelelser om Grønland. Fig. 11.5, C. A. Tobias.

The final responsibility for the facts and opinions expressed in this volume is our own.

H. J. M. B.
D. G.

CONTENTS

1. Introduction	1
2. Theory of Activation Analysis	5
3. Activation by Neutrons	16
4. Activation by Particles other than Neutrons	29
5. Gamma Scintillation Spectrometry	44
6. The Determination of Radioactivity	72
7. Errors in Activation Analysis	92
8. Methods of Separation of Radionuclides	111
9. The Collection and Preparation of Material for Activation Analysis	129
10. Geochemical Applications of Activation Analysis	141
11. Biological Applications of Activation Analysis	166
12. Inorganic and Pure Chemical Applications of Activation Analysis	189
13. Radiochemical Separations	213
References	270
Index	289

INTRODUCTION

Most chemical research depends on methods of analysis, and the development of atomic science has resulted in some entirely novel methods whose full potentialities have not yet been realized. One of these methods, activation analysis, has accumulated such an extensive literature as to justify the production of the present volume (Gibbons *et al.*, 1957 and 1960; Koch, 1960). Recent review articles (Jenkins and Smales, 1956; Loveridge and Smales, 1957; Smales and Wager, 1960; Winchester, 1960; Meinke, 1960; Leddicotte *et al.*, 1959) and Symposia (Cook *et al.*, 1960) make it clear that nothing short of a book of this size is sufficient to cover the whole subject. Needless to add, the rapid developments in this field will ensure incompleteness at the time of going to press, although most relevant papers prior to 1960 have been examined.

Activation differs from most other methods of chemical analysis in that it is based on the properties of nuclei and not on the behaviour of the outer electrons. This implies, firstly, that it is purely a method of elementary analysis, and can only be used indirectly, in certain special cases, to analyse for constituent molecules. Secondly, it can be used to distinguish unequivocally between different isotopes of a single element. In view of the constancy of isotopic composition of most elements, the latter characteristic is of no importance in most applications, but has its uses in geochemical problems.

The activation process involves exposure to a source of particles or photons of sufficient energy to react with the constituent nuclei. Information can sometimes be gained by studying the prompt emission during the ensuing nuclear reactions. In the majority of cases, however, it is more convenient to study the radioactive nuclides produced, since these can be detected with great sensitivity (cf. Table 2.1). Calculation of this sensitivity, together with other mathematical aspects of the activation process, as well as the laws of radioactive decay, are dealt with in Chapter 2. Although in theory activation offers an absolute method of analysis, in practice a comparative method is almost always used, whatever the activating particle may be.

There is no question that neutrons, especially thermal neutrons, have been more widely used for activation than any other type of particle. This situation has arisen from a combination of circumstances. Firstly, the absence of an energy threshold for neutron reactions means that neutrons of negligible energy can react with all nuclei. Secondly, most nuclei have a high cross-section for thermal neutrons; and thirdly, nuclear reactors, with their enormous capacity for producing neutrons, are now widely available. Although neutrons can be produced in the laboratory by nuclear reactions, and from suitable accelerating machines, as described in Chapter 3, these provide lower fluxes than those obtainable in large research reactors. With thermal neutrons, the commonest reaction occurring is the (n, γ) process, whereby each activated isotope is increased in weight by one unit. When neutrons with energies in the MeV range are employed, other reactions such as (n, p) and (n, α) processes may be important, but seldom have large cross-sections. Finally, in the case of a few of the heaviest elements, neutron bombardment may lead to fission, with the production of a spectrum of radioactive nuclides spanning half the periodic table.

Charged particles, on the other hand, have been used much less widely in analytical work. Here there is always a threshold energy which must be exceeded before activation takes place at all. There are now available exceedingly powerful sources of protons and deuterons accelerated by high-voltage machines, and the cross-sections of light elements for these particles are comparable with those for neutrons. Unfortunately these particles have very little penetrating power in solid materials, and as a consequence they raise exposed targets to high temperatures. These factors have severely limited their practical application. At energies of 1-10 MeV the predominant nuclear reactions are (p, n) or (d, n) processes, but at higher energies many other nuclear reactions occur. Among these is the process of spallation, whereby a heavy element is degraded to a series of lighter ones, which is of importance in cosmology. However, such reactions are undesirable from the point of view of activation analysis. Photon activation has also been relatively neglected. Here the threshold energies are mostly higher (6-22 MeV) and the cross-sections of most nuclides much lower, so that full exploitation of its possibilities awaits the development of more powerful photon sources. It has been used to determine deuterium and beryllium, which emit prompt neutrons when activated with photons of low energy.

Since nearly all activated nuclides emit γ -rays, it should be possible to determine the elements present in an activated sample from its γ -ray

spectrum. The equipment required for this work is described in Chapter 5, and it appears that developments in this field are proceeding rapidly. The technique has been used for a great variety of qualitative and quantitative analyses, but there are several reasons why it is not universally applicable. In the first place the resolution of the method is relatively poor. Gamma spectra have broad peaks compared with those obtainable in, say, infra-red spectrometers, and have no fine structure to aid identification. As shown in Table 5.2, many nuclides may be responsible for a given peak, and so identification is not always unique. In addition, spurious peaks and undesirable background effects are caused by Compton scattering, and much effort has been devoted to eliminating this source of error. In view of these interferences, the ultimate sensitivity of gamma spectrometry is less satisfactory than that obtainable using radiochemical separation and a much simpler Geiger counter as detector. These less sophisticated detectors form the subject-matter of Chapter 6, which is largely concerned with beta counting. The preparation of samples for counting, the determination of half-life, beta energy, and self-absorption corrections are all discussed, and the advantage of the low background counts obtainable with Geiger counters is pointed out. Other types of counter, for example the proportional counter, have not been used very much for activation analysis. Autoradiography, a useful qualitative technique which has found restricted application to activated samples, is also briefly described.

Errors arising in activation analysis are different in kind from those found in classical techniques. They can come about by reason of inhomogeneities of the activating flux, by self shielding, or by interfering nuclear reactions, and so the preparation of suitable comparative standards is particularly important. On the other hand, the problem of reagent contamination, which is always present when determining trace elements by chemical methods, does not exist after activation. Since only radioactive elements are sought, it is customary to use chemical techniques which are not wholly quantitative and correct for losses as described in Chapter 8. Precipitation and solvent extraction have been very widely used, while volatilization and ion exchange are important for many radiochemical separations. Time is frequently a major limitation, since the half-life of many activated nuclides is so short. Hence attention is now focused on rapid methods of chemical separation. Neither chemical separation nor physical discrimination can give a reliable analysis if the sample is contaminated before activation.

Surface contamination can be removed after activation if the sample is a massive solid, but it is exceedingly difficult to prevent contamination of liquids. The recommendations for handling samples put forward in Chapter 9 will undoubtedly be improved as practical experience grows. However, it is clear that all samples are contaminated by handling, which should therefore be restricted to a minimum.

Practical applications of activation analysis constitute the bulk of the literature on the subject, apart from review articles. A condensed summary of these results, classified as geochemical, biological, and other applications, is set out in Chapters 10–12. It must be understood that it has not been possible to treat any detailed investigation as thoroughly as it merits, nor has it been easy to decide how much background knowledge should be inserted. In any rapidly expanding field it is difficult to pick out the part played by a single technique without either over-emphasizing or omitting all others, but it is hoped that a satisfactory compromise has been reached. Some attempt has also been made to emphasize the many gaps in our knowledge of elementary abundance which remain to be filled.

The last chapter in this book differs from all the others in its essentially practical character. Since techniques of radiochemical separation are mostly published in atomic-energy establishment reports, which have a restricted circulation, an attempt has been made to collect together techniques for all the stable elements which either have been adapted to, or appear suitable for, activation analysis. In some cases (e.g. magnesium, aluminium, lead, and the rare gases) the techniques have not been properly tested and are only inserted for completeness. In any case, it must be emphasized that the methods should always be tested prior to any particular application, partly to obtain the requisite dexterity, but mainly to ensure that no radionuclide other than that desired is coming through and interfering with the determination. Once such an interfering nuclide is identified, it is a relatively simple matter to adjust the chemical procedure to eliminate it.

THEORY OF ACTIVATION ANALYSIS

WHEN a material is bombarded or irradiated by the nuclear particles produced in a nuclear reactor, particle accelerator, or other suitable source, some of the atoms present in the sample will interact with the bombarding particles. These atoms may be converted into different isotopes of the same element, or isotopes of different elements, depending on the nature of the bombarding particles. In many cases, the isotopes produced are radioactive and are termed radioisotopes. If the radioactivity which is induced in one component of the material can be distinguished or separated from all other radioactivities arising at the same time, or originally present, then the amount of this induced radioactivity is a measure of the parent isotope, and therefore of the parent element, present in the original material.

Radioactive decay

Since induced radioactivity is measured in terms of the rate of decrease or decay of the radioactive atoms rather than in direct terms of the number of radioactive atoms present, it is worth while to mention briefly the laws of radioactive decay.

Radioactive decay is a purely random process and the probability of a given radioactive nucleus disintegrating is fixed and is independent of the presence or absence of other radioactive nuclei. Thus, the rate at which these radioactive nuclei disintegrate is dependent simply on the number present at any time and is expressed by the relationship

$$\frac{dN}{dt} = -\lambda N, \quad (1)$$

where N is the number of radioactive atoms at any time t ,
 λ is the radioactive disintegration constant.

The constant λ is a characteristic of the radioactive nuclei under consideration.

Integration of (1) gives

$$N = N_0 e^{-\lambda t}, \quad (2)$$

where N_0 is the number of radioactive atoms present at time $t = 0$.

If the time $t_{\frac{1}{2}}$ is measured during which the number of radioactive atoms decreases to half the number originally present,

$$\frac{1}{2}N_0 = N_0 e^{-\lambda t_{\frac{1}{2}}}, \quad (3)$$

hence

$$\ln 2 = \lambda t_{\frac{1}{2}}, \quad (4)$$

and

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}. \quad (5)$$

Thus, $t_{\frac{1}{2}}$ is a function of λ and is therefore also a nuclear constant. It is known as the half-life and is a characteristic of the nuclei under decay. Radioactive nuclei of different atomic weights and/or different atomic numbers mostly have different half-lives (Strominger, Hollander, and Seaborg, 1958), but occasionally two half-lives may be the same or too similar for any distinction to be made. Thus manganese 56 and nickel 65 have half-lives of 2.58 hours and 2.56 hours respectively.

Production of radioisotopes

When a radioisotope is produced at a constant rate, the rate of accumulation of the isotope is given by the difference between the rate of production and the rate of decay of the isotope. Thus

$$\frac{dN}{dt} = P - \lambda N, \quad (6)$$

where P is the rate of production of radioactive nuclei. Solution of (6) gives

$$N = \frac{P}{\lambda}(1 - e^{-\lambda t}) + N_0 e^{-\lambda t}. \quad (7)$$

In most cases, N_0 , the number of radioactive atoms present initially, is zero. Hence

$$N = \frac{P}{\lambda}(1 - e^{-\lambda t}), \quad (8)$$

and the rate of disintegration of these radioactive atoms at any time is given by

$$A = \lambda N = P(1 - e^{-\lambda t}). \quad (9)$$

Fig. 2.1 shows a typical growth curve in which it can be seen that the saturation activity S which occurs after an infinite irradiation time is reached within 1 per cent. after about seven half-lives.

From (9),

$$A_t = P(1 - [\frac{1}{2}]^{t/t_{\frac{1}{2}}}), \quad (10)$$

and when $t = t_{\frac{1}{2}}$,

$$A_{t_{\frac{1}{2}}} = P(1 - \frac{1}{2}) = \frac{1}{2}P. \quad (11)$$

Thus, unless it is absolutely essential to obtain the maximum activity possible, it is rather pointless to irradiate the material for much more than one half-life, as seven times as much irradiation will only produce

twice as much activity. It is also worth noting that for irradiation times shorter than one half-life, the relationship between induced activity and irradiation time is approximately linear.

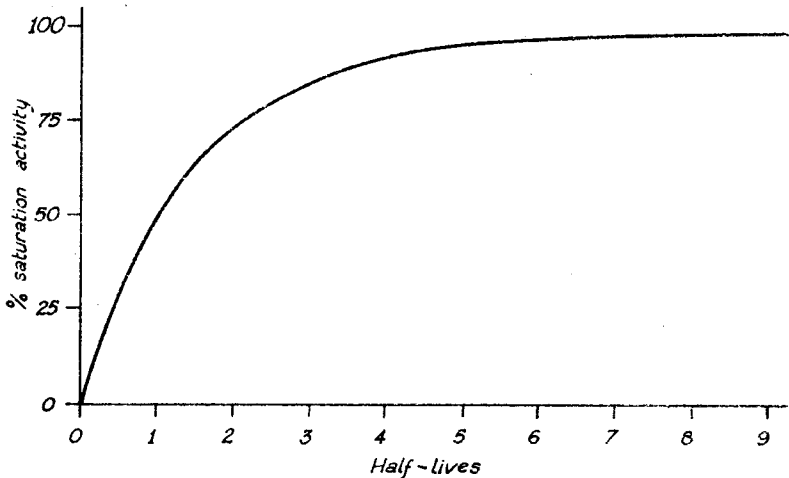


FIG. 2.1. Growth of radioactivity.

In some instances, as will be seen later, it may be more convenient to measure the radioactivity of a daughter product of the activated species, rather than measure the activated species itself. In these circumstances, the rate of production of the daughter (d) is given by the rate of decay of the parent (p):

$$P_d = \lambda_p N_p = P_p(1 - e^{-\lambda_p t}). \quad (12)$$

Thus, during activation of the parent, the rate of accumulation of the daughter is given by the difference between the rate of production from the parent and the rate of decay of the daughter:

$$\frac{dN_d}{dt} = P_p(1 - e^{-\lambda_p t}) - \lambda_d N_d. \quad (13)$$

The solution of this equation for the boundary conditions $N_d = 0$ when $t = 0$ is

$$N_d = \frac{P_p}{\lambda_d} (1 - e^{-\lambda_d t}) + \frac{P_p}{\lambda_d - \lambda_p} (e^{-\lambda_d t} - e^{-\lambda_p t}), \quad (14)$$

and the daughter activity at any time during activation of the parent

$$A_d = \lambda_d N_d = P_p(1 - e^{-\lambda_d t}) + \frac{\lambda_d P_p}{\lambda_d - \lambda_p} (e^{-\lambda_d t} - e^{-\lambda_p t}). \quad (15)$$

The two limiting conditions of equation (15) are obtained when the half-life of the daughter is much shorter than that of the parent

$$A_d = P_p(1 - e^{-\lambda_d t}), \quad (16)$$

and when the half-life of the daughter is much longer than that of the parent

$$A_d = P_p(1 - e^{-\lambda_d t}). \quad (17)$$

In equation (16) the daughter activity will reach half saturation in one parent half-life, while in equation (17) it will reach half saturation in one daughter half-life.

Activation analysis

When materials are irradiated for activation analysis the rate of production is effectively constant, regardless of the nature of the bombarding particles (subject, of course, to the flux of these particles remaining constant), since the number of inactive atoms which are activated is such a small fraction of the total present. Hence equation (9) derived above may be applied.

The rate of production

$$P = f\sigma N_i, \quad (18)$$

where N_i is the number of inactive atoms present, f is the flux of bombarding particles (in particles/cm²/sec), and σ is the activation cross-section for the reaction (in cm²) and is a measure of the tendency of the inactive atoms to interact with the bombarding particles. Hence the rate of disintegration or activity of the radioisotopes produced is given by

$$A = f\sigma N_i(1 - e^{-\lambda t}). \quad (19)$$

Since few elements are monoisotopic, only the fraction ϕ of the inactive atoms will take part in the reaction, where ϕ is the fractional abundance of the isotope concerned. Also, the number of atoms can be obtained from the weight W of the element present, its atomic weight M , and Avogadro's number. Hence

$$A = f\sigma \frac{W\phi}{M} (1 - e^{-\lambda t}) \times 6.02 \times 10^{23}. \quad (20)$$

In general, however, the activity will not be determined until a time T after the bombardment has ended, so that the radioactive atoms produced will have decayed by a factor $e^{-\lambda T}$. Hence

$$A = f\sigma \frac{W\phi}{M} (1 - e^{-\lambda t})(e^{-\lambda T}) \times 6.02 \times 10^{23}. \quad (21)$$

If this equation is rewritten

$$W = \frac{MA}{f\sigma\phi} \frac{e^{\lambda t}}{(1-e^{-\lambda t}) \times 6.02 \times 10^{23}}, \quad (22)$$

then, in principle, all the factors on the right are known or can be measured. Thus, it should be possible to calculate the weight of the element present. In practice, however, σ is not known with sufficient accuracy, f cannot be determined accurately, and it is not always easy to determine the absolute disintegration rate A . Consequently, a comparison procedure is invariably used, and the amount of activity from the sample is compared with that from a standard amount of the element being determined. It is then a simple matter to calculate the weight of the element in the sample from the relationship

$$\begin{aligned} \text{weight of element in sample} \\ = \text{weight of element in standard} \times \frac{C_x}{C_s}, \end{aligned} \quad (23)$$

where C_x is the observed counting rate of the sample, and C_s that of the standard, measured under comparable conditions.

Sensitivity of the method

If irradiation is carried out for a sufficient number of half-lives so that the factor $(1-e^{-\lambda t})$, known as the saturation factor, becomes effectively unity and, if the activity is determined within a small fraction of a half-life after irradiation ceases, the weight of the element in the samples is given by

$$W = \frac{MA}{f\sigma\phi \times 6.02 \times 10^{23}}, \quad (24)$$

and therefore the sensitivity of the method will be greater the higher the efficiency of the detection equipment, the lower the atomic weight of the element, the greater its activation cross-section, the greater its isotopic abundance, and the greater the flux of bombarding particles.

The efficiency of detection will be dealt with more fully later; it is sufficient to point out at this stage that efficiencies of 10-40 per cent. can be achieved without much difficulty, but 100 per cent. efficiency is only possible in favourable cases and then only with special apparatus and technique. The atomic weight is, of course, fixed for any particular element, but this dependence shows that, all other things being equal, the method of activation analysis is more sensitive for the lighter elements. The activation cross-section is also fixed for any given activation process, but is really the main factor affecting the sensitivity of the method since it can vary from less than a thousandth of a barn to

several thousand barns ($1 \text{ barn} = 10^{-24} \text{ cm}^2$) depending on the isotope and the method of activation. The isotopic abundance is also a fixed quantity, which varies widely through the periodic table, being unity for arsenic 75 and 0.0072 for uranium 235. Thus the sensitivity for monoisotopic elements is often better than for others. Multi-isotopic elements, on the other hand, offer a choice of radioactive isotopes and selection can then be made of the optimum conditions. However, if the half-lives of the several radioisotopes produced are fairly similar, difficulty may be experienced in determining these to prove the purity of the radioactivity being measured, and can lead to complicated extrapolations if the activities of samples and standards are not measured within a very short space of time. Finally, the flux of bombarding particles can only be as high as the maximum available in the irradiation equipment and can vary from about 10^4 neutrons/cm²/sec for a laboratory radium/beryllium neutron source to 10^{15} n/cm²/sec† for some atomic reactors. Cyclotrons and electrostatic generators, producing other particles, can give fluxes from 10^8 to 10^{15} particles/cm²/sec.

Thus it will be seen that, for given equipment, and a given element, the sensitivity of determination by activation analysis is fixed, since it is not practicable to determine less than a certain level of activity with a given apparatus. This activity level is usually taken as being equal to the background counting rate (i.e. the counting rate which is recorded even in the absence of a sample, due to natural activity in the material of the apparatus, to cosmic rays, and to inadequately shielded radioactive materials in the neighbourhood). If a simple Geiger-Muller counter assembly is used, and such an apparatus is in fact used more frequently than any other at present, then this lower limit is about 10 counts/min at an efficiency of about 10 per cent., corresponding to a disintegration rate of 100 disintegrations/min. If a flux of 10^{12} n/cm²/sec is assumed, corresponding to the maximum available in the Harwell reactor BEPO, then the sensitivity may be reduced to

$$\frac{M \times 100/60}{10^{12} \times \sigma_i \times 10^{-24} \times 6.02 \times 10^{23}} = \frac{M}{0.36 \sigma_i} \mu\mu\text{g} \simeq \frac{3M}{\sigma_i} \mu\mu\text{g}, \quad (25)$$

where σ_i is the activation cross-section in barns and incorporates ϕ . This then represents a handy formula for assessing the feasibility of any particular determination in the Harwell reactor and demonstrates the basically high sensitivity of the method since units of $\mu\mu\text{g}$ are used. Similar expressions are readily obtained for other irradiation units and

† n = neutron(s).

measuring equipment. Jenkins and Smales (1956) have listed calculated sensitivities for the determination of most elements by neutron activation analysis, while Anders (1960*a*) has listed experimentally determined neutron activation sensitivities (Table 2.1).

Other advantages

While the high sensitivity of the method of activation analysis is probably its most outstanding advantage, the fact that it is possible to eliminate errors due to contamination by impurities in reagents during processing is nearly as important. Once the sample has been removed from the irradiator, the analysis becomes one for the radioactive isotope of the element and not for the element itself. Thus it is possible to add several mg of the inactive element to act as a carrier for the trace quantity of radioactive atoms through any chemical purification stage, though care must be taken to ensure identity of chemical form. Incidentally, this introduces a further advantage in that the analysis is no longer on the micro-scale and conventional purification techniques of precipitation, etc., can be employed. Because several mg of the element are now present, the few μg of the element that are likely to arise from reagents are now negligible. Yet a further advantage arises in this carrier technique. If a known weight of carrier is added, and the weight of the final precipitate after purification is determined, it is possible to calculate the chemical yield of the process and so correct for any losses of radioactivity during this stage, since the radioactive yield will be the same as the chemical yield. Thus the purification need not be quantitative; centrifuging may be used instead of filtration without worrying about the small amount of precipitate which floats away with the supernatant solution, solutions need not be transferred quantitatively from one vessel to another, and purification procedures may be employed which, although highly specific, are not used in conventional analysis because of the low recoveries they introduce.

Finally, the remaining advantage of activation analysis is its specificity. Since the nuclear properties of a radioactive isotope, such as half-life, beta energy, and gamma energy are uniquely characteristic of that isotope, it is possible by measuring these quantities to ensure that the activity measured is appropriate to the element being determined. These factors, coupled with a specific radiochemical purification procedure where appropriate, all contribute to the high specificity of the activation method. While it is true that some radioisotopes have one nuclear property in common, it would be very strange if all were the

TABLE 2.1

Neutron activation sensitivities using a flux of 10^{12} n/cm²/sec

Element	Activated form	Half-life	Radio-chemical (a)	Gamma spectrometry (b)
Aluminium	Al 28	2.3 min	Low	3×10^9 (1.78 MeV)
Antimony	Sb 122	2.8 d	1×10^{11}	..
	Sb 122 (m)	3.5 min	..	4×10^9 (0.06 MeV)
Argon	A 41	1.8 hr	2×10^{10}	..
Arsenic	As 76	26.8 hr	2×10^{11}	1×10^7 (0.56 MeV)
Barium	Ba 139	85 min	1×10^{10}	2×10^9 (0.16 MeV)
Bismuth	Bi 210	5.0 d	2×10^9	..
Bromine	Br 80 (m)	4.6 hr	1×10^{11}	..
	Br 80	17.6 min	..	2×10^9 (0.64 MeV)
Cadmium	Cd 115	54 hr	1×10^{10}	..
	Cd 111 (m)	48.6 min	..	7×10^7 (0.24 MeV)
Caesium	Cs 134	2.3 y	2×10^{10}	..
	Cs 134 (m)	3.2 hr	..	2×10^9 (0.13 MeV)
Calcium	Ca 45	152 d	1×10^9	..
Cerium	Ce 141	32 d	1×10^{10}	..
	Ce 139 (m)	55 sec	..	1×10^7 (0.09 MeV)
Chlorine	Cl 38	37.3 min	2×10^9	7×10^7 (1.64 MeV)
Chromium	Cr 51	27 day	1×10^{10} *	..
	V 52	3.7 min	..	6×10^9 (1.47 MeV)
Cobalt	Co 60	5.2 y	2×10^{10}	..
	Co 60 (m)	10.5 min	..	8×10^9 (0.06 MeV)
Copper	Cu 64	12.8 hr	1×10^{11}	..
	Cu 66	5.1 min	..	3×10^9 (1.04 MeV)
Dysprosium	Dy 165	2.3 hr	1×10^{13}	..
	Dy 165 (m)	1.3 min	..	1×10^{11} (0.11 MeV)
Erbium	Er 171	7.5 hr	1×10^{11}	1×10^9 (0.11 MeV)
Europium	Eu 152 (m)	9.3 hr	1×10^{13}	2×10^7 (0.34 MeV)
Fluorine	O 19	29.4 sec	..	5×10^7 (0.19 MeV)
Gadolinium	Gd 159	13 hr	2×10^{10}	..
	Gd 161	3.6 min	..	6×10^7 (0.36 MeV)
Gallium	Ga 72	14.1 hr	1×10^{11}	2×10^9 (0.84 MeV)
Germanium	Ge 75	82 min	2×10^9	5×10^7 (0.26 MeV)
	Ge 75 (m)	48 sec	..	5×10^9 (0.13 MeV)
Gold	Au 198	2.7 d	2×10^{12}	1×10^9 (0.41 MeV)
Hafnium	Hf 181	45 d	2×10^{10}	..
	Hf 179 (m)	19 sec	..	2×10^{10} (0.22 MeV)
Helium	H 3	12.4 y†	2×10^9	..
Holmium	Ho 166	27.2 hr	2×10^{12}	5×10^8 (0.08 MeV)
Indium	In 116	54 min	1×10^{13}	7×10^{10} (1.27 MeV)
Iodine	I 128	25 min	1×10^{10}	3×10^9 (0.46 MeV)
Iridium	Ir 194	19 hr	1×10^{12}	8×10^8 (0.30 MeV)
	Ir 192 (m)	1.4 min	..	1×10^9 (0.06 MeV)
Iron	Fe 59	45 d	1×10^9	..
	Mn 56	2.6 hr	..	7×10^9 (0.85 MeV)
Krypton	Kr 85	4.4 hr	2×10^{11}	..
Lanthanum	La 140	40 hr	2×10^{11}	1×10^9 (0.50 MeV)
Lead	Pb 209	3.3 hr	2×10^9	..
Lithium	H 3	12.4 y†	2×10^{10}	..
Lutecium	Lu 177	6.8 d	2×10^{12}	2×10^9 (0.20 MeV)
	Lu 176 (m)	3.7 hr	..	2×10^9 (0.08 MeV)
Magnesium	Mg 27	9.6 min	2×10^9	5×10^7 (0.84 MeV)