

ACTIVATION
ANALYSIS

HANDBOOK

R. C. KOCH

ACTIVATION ANALYSIS HANDBOOK

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FOREWORD

It may be said that a reactor or a cyclotron has a touch like that of the legendary King Midas—everything brought into it becomes radioactive. Indeed, the golden possibilities that streams of nuclear particles offer for chemical analysis were realized almost as soon as the types of radioactivity that they produce were understood. The concept of activation analysis is a simple one, and the possibilities of its application are great. However, the complexity of the problem is also very great.

In the modern day, the number of activities that can be produced in simple nuclear reactions is enormous. The 81 naturally occurring elements from hydrogen through bismuth have in the aggregate 270 stable nuclear forms or nuclides and 11 long-lived ones. Including isomeric pairs, there are about 220 different radionuclides formed by the (n, γ) or (d, p) reaction, about 280 are known for the (n, p) reaction, and over a hundred each for the (p, n) , (d, xn) , (d, α) , (α, xn) , (α, pxn) , (γ, n) , (γ, p) , and similar reactions that can be considered for activation analysis.

Thus, for the maximum use of this book, Dr. Koch had to acquaint persons who are not professional analysts with the potentialities of the method and with the main technical requirements for sample preparation, irradiation, monitoring, and radiometric assay. In addition, he had to present the nuclear chemistry considerations that can be exploited in activation analysis so that the analyst who is not a nuclear specialist can make a choice of the type of irradiation and can identify and handle the possible nuclear interferences. A glossary of 41 technical terms and analytic descriptions of nuclear reactions of interest are appended for both of these types of user.

The descriptive material in this book represents a scholarly and timely contribution to applied nuclear chemistry not duplicated in the existing reviews of activation analysis. The focus of attention is, for maximum generality, on the trace constituent, but the considerations that apply to the matrix material are given in discussion, and, of course, the nuclear data in the tables apply to it.

The bulk of this book is provided by the tabulations of nuclear reactions that have been used for activation analysis, together with other reactions that may be useful to the analyst or that may provide interference with reactions that are being considered. The pages of Table III present the elements, in order of atomic number. The left page presents data for neutron reactions (thermal neutrons, reactor neutrons, and fast neutrons). The right page gives analogous data for charged particle reactions. The organization of Table III and its conventions are illustrated in principle in Table II.

The data for slow neutron activation have been more widely exploited, and this is reflected in the greater number of literature analyses cited, and the greater detail with which Dr. Koch reports the nuclear properties of the (n, γ) reactions for each element. A special feature of the tables is the sections, for each element, which evaluate possible interfering primary, secondary, and second-order reactions, and possible self-shielding problems. At the bottom of each page is a list of sensitivities that would be achieved for selected reactions using the natural element under specified irradiation conditions.

The present tabulation goes beyond its predecessors in the amount of information tabulated in one place for neutron reactions on each element and the analytical implications of the data.

The parallel presentation of data for charged particle reactions is particularly useful, since much less has been done to exploit these analytically, and comparison with neutron reactions is generally illuminating.

References to data available through the middle of 1959 for excitation functions for charged particle reactions in the energy region up to about 30 Mev are included, with descriptions of those reactions that have thus far been exploited analytically. For the other reactions which could be developed for analysis, cross-sections at a typical useful energy are cited, together with an estimate of the sensitivity to be expected in analysis. The discussion of interferences includes the possibilities of formation of the radionuclide of interest by reactions of elements of neighboring atomic numbers and by reactions of secondary neutrons in the target.

This book should find an important place on the desk of every analyst who has access to neutrons, high energy photons, or charged particles. With the availability of service irradiations of targets that are then shipped to the analytical

laboratory, activation analysis can be used in every laboratory facing difficult problems of analysis of minor constituents, since most of the elements have activation products with long enough half-lives to permit assays hours to days after irradiation. The requirements of the electronics and nucleonics age for high purity and for control of minor constituents have also made possible the flexible and sensitive activation methods of determining concentrations. This book should contribute substantially to their development and application.

The basis for this book was a detailed survey of possibilities for activation analysis sponsored by the Air Force Cambridge Research Center of the Air Research and Development Command, Lexington, Massachusetts. I should like to express on behalf of the scientific community sincere appreciation for their cooperation and generosity in the prompt release of this work for publication.

CHARLES D. CORYELL

Cambridge, Massachusetts
July, 1960

PREFACE

During the last decade, activation analysis has been established as a sensitive tool for analysis of trace elements in many materials. The literature contains examples of the development of activation analysis techniques and of successful application of the techniques to solutions of problems in specific scientific disciplines. However, this information is found in a wide variety of sources. Analysts have long recognized a need for its collation and compilation into a single source so that the many phases of theoretical and applied activation analysis would be available in a convenient form for the practicing analyst and for other scientists who can effectively utilize activation analysis in their programs. The Activation Analysis Handbook is intended to serve as a reference source for experimental data and methods to be used by all scientists interested in the use or potential use of activation analysis as an analytical tool.

The original edition of the Activation Analysis Handbook, prepared under the sponsorship of the Air Force Cambridge Research Center of the Air Research and Development Command, contained literature available prior to October, 1958. Data for experimental methods and for nuclear reactions applicable to these methods were tabulated for each element. Since these two bodies of data are common to the trace elements to be analyzed rather than to the matrix materials, the tables were so oriented. However, typical examples of analyses in various matrices and of potential experimental problems which might be encountered in the analysis of a trace element in the presence of other elements are included in the tables. Analytical sensitivities achievable for each element using selected activation reactions under standard experimental conditions are also presented.

The introductory discussion is intended to serve both the scientist or engineer, who may recognize the need for an analytical or experimental method to assist in the solution of a research or engineering problem, and the analyst, who is responsible for providing such analyses. To acquaint the first group of readers with the potential applicability of activation analysis to their fields of interest, a description of its general theoretical and experimental considerations, including references to selected review articles, is presented. A more detailed discussion of specific aspects follows which, it is hoped, will help the analyst to select appropriate activation and analytical methods for a particular application. Sources of general radiochemistry methods for many elements have been noted in the text. However, since specific analytical or radioactivity measurement procedures must be devised for the particular analytical problem, and since detailed procedures for nearly every element are given in the sources listed in the tables, no attempt has been made to present such information in this book.

The present edition of the handbook incorporates a thorough revision of the tables and the bibliography of the original edition. The Addendum to the Bibliography represents the reported data reaching the author in the interval between completion of the original edition and September, 1959.

The author wishes to express his gratitude to the many members of the staff of Nuclear Science and Engineering Corporation who aided in the preparation of this handbook. Special acknowledgment is due to Dr. Paul Kruger and Professor Charles D. Coryell for their critical reviews of the text, to G. L. Grandy, I. J. Gruverman, and C. R. Wilson, for their assistance

in compiling the data, and to Mrs. R. White, Mrs. W. Kruger, and J. K. Schivley for their aid in preparing the manuscript. The author also wishes to acknowledge the cooperation and help-

ful comments of Mr. Clarence Turner and Mr. J. Paul Cali of the Air Force Cambridge Research Center, under whose auspices the original edition of this handbook was prepared.

R. C. KOCH

August, 1960

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INTRODUCTION

PURPOSE AND SCOPE

Activation analysis has assumed an important role in the determination of trace constituents in a wide variety of materials. As a result of rapid technological advances continued demand is expected for materials having high purity or rigid trace constituent specifications. These specifications may require analytical methods with sensitivities beyond those of most classical methods. For example, it is generally known that the transistor industry requires semiconductors with controlled concentrations of trace impurities, and that the reactor industry requires production of hafnium-free zirconium. The production of such materials demands stringent production quality control methods. It is expected that the principles of activation analysis will be applied to the development of new methods for such quality control and process automation. In addition, basic research and development programs in most branches of science and engineering will require both destructive and nondestructive analytical methods of high sensitivity. Activation analysis can be applied to many of these analytical problems. It also has potential for further development to meet the more stringent analytical requirements which are anticipated in the future.

Activation analysis may be defined as a method of measuring concentrations of constituents in a given sample by measuring the characteristic radiations emitted by the radioactive nuclides resulting from selected nuclear transformations. The unique combination of chemical and nuclear properties of each activation product provides a specific method for its identification and measurement. Of the several

possible transformations, one can be chosen based on certain factors. For example, for any given problem, a specific method can be selected based on the properties of the matrix, trace elements, the activation products of interest, the sensitivity required in the analysis, the presence of interfering reactions, the location of a suitable irradiation facility, and cost.

Although the experimental data required for comparing alternate methods are frequently available, they are scattered widely throughout the technical literature. This handbook has been prepared to collate and compile this information in a convenient reference form. Since there exist many published review articles for neutron activation analysis, it is not the purpose of this handbook to give a comprehensive review of all the available activation analysis data. Its purpose is to present a tabulation of the published data pertinent to activation analysis. In particular, this tabulation includes for each element: (1) data for activation analyses utilizing thermal and fast neutrons, charged particles, and photons; (2) nuclear data for these reactions; (3) nuclear data for other reactions potentially useful for activation analysis; (4) nuclear data for possible interfering reactions; (5) evaluations of these reactions; (6) sensitivities for the more important neutron and charged particle activation reactions for each element; and (7) complete bibliographical referencing for all of the data presented.

It is anticipated that the compilation of these data, together with a comprehensive bibliography, will enable the analyst to choose the optimum set of nuclear parameters and will guide him to detailed data for specific assay problems. In addition, it is hoped that this tabulation provides sufficient information to the

nonanalyst for proper evaluation of the applicability of activation analysis to his specific laboratory or production problem.

HISTORY AND GROWTH OF ACTIVATION ANALYSIS

After the discovery of induced, or artificial radioactivity by Curie and Joliot in 1933, its application to the solution of analytical problems was readily recognized. In 1936, Hevesy and Levi (H30) used thermal neutron activation to determine the concentration of dysprosium in impure yttrium. Subsequently, the same workers (H31) also detected traces of europium in gadolinium. In 1938, Seaborg and Livingood (S16) demonstrated that charged particle activation could be applied to analytical problems by determining trace quantities of gallium in high purity iron. These pioneers stimulated substantial interest in this new technique. By 1952, several review papers (B36, B45, E1, G17, G18, L4, L5, S58, T9, T18) had appeared which outlined the basic principles of the method and presented applications and experimental data, including both theoretical and experimental analytical sensitivities. Also, Taylor and Havens (T7, T8) discussed the early applications of neutron spectroscopy to chemical analysis. In 1952, Rodden (R10) presented a comprehensive review of the applications of nuclear chemistry, including activation analysis, to analytical problems, and summarized the techniques and sensitivities achieved at that time. Kohn (K25) summarized the applications of radioactivity techniques, including activation analysis, to metallurgical problems.

The increasing application of radionuclides and nuclear chemistry to analytical problems led to a rapid growth of activation analysis as an established laboratory technique by the time of the 1955 International Conference on the Peaceful Uses of Atomic Energy. This growth is evident from the decreasing intervals at which review articles were published during this period, both in the United States (B42, G19, L6, L7, L8, L9, M42), Canada (J11), Europe (H23, J1, L11, S29, S33, W14), and Japan (S3). Papers discussing applications of special analytical techniques, such as ion exchange (B41, C32), gamma spectrometry (C27, M48), and nuclear emulsion detectors (M17, M18), to activation analysis also appeared, along with a detailed discussion of its limitations and sources

of errors (P10). The use of low-level neutron sources for activation analysis (M33) and comparisons of this technique with spectrophotometry and other analytical methods were made (M30, M34, S30). Applications of activation analysis to the study of such diverse fields as archeology (A10, S10), biological systems (H4), dating of minerals (H28, M43), and determination of film exposure (B18, B19) were also reported.

In the period since the first Geneva Conference, Leddicotte (L1, L10, L21) has continued to review periodically recent developments in the field, as have workers in the United Kingdom and elsewhere. Cabell and Smales (C2) discuss the application of various radiochemistry methods to analytical chemistry, and Loveridge and Smales (L19), the application to biochemistry. Borg (B62), Lenihan and Smith (L23), and Druyan *et al.* (D16), review the applications of activation analysis in biological and medical research. Smales *et al.* (S71, S72), Reed (R19), and Winchester (W22) describe its geochemical applications, and Jervis and Mackintosh (J15) summarize its uses in reactor technology. Jenkins and Smales (J10) and Miller (M54) present reviews of its fundamental concepts, techniques, and applications. Other current articles by Taylor and Havens (T10), De (D5), Fouarge (F18), Schindewolf (S11), and Atkins and Smales (A23) summarize many pertinent data and applications of the technique. Merz and Herr (M53) demonstrate the use of activation analysis for determining isotopic abundances in selected elements. Fink (F6) discusses the effects of interfering nuclear reactions on the validity of activation analysis data, and Plumb (P9) discusses techniques for qualitative activation analysis. Examples of basic studies of selected analytical procedures are discussed by Brooksbank (B40, B66) and Miller (M54). Examples of analysis schemes for separating many elements from a single matrix by Kant *et al.* (K2), Thompson *et al.* (T16), Blanchard *et al.* (B60), and Albert (A4), and examples of the use of gamma spectrometry by Morrison and Cosgrove (C33, M47, M49), Salmon (S69), and Iredale (I1) have appeared. Gaittet and Albert (G28) present a complete routine system of control activation analysis for high purity iron and aluminum. The utilization of linear accelerators as irradiation facilities for thermal and fast neutron induced activation and photon

induced activation has been discussed by Burrill and Gale (B51), Turner (T20), and MacGregor (M1), respectively. Odeblad (O2) and Gill (G30) present the basic physical principles of the use of charged particle induced reactions for activation analysis. Mazari *et al.* (M51) describe a method of using proton scattering for analysis of selected elements.

The application of neutron activation analysis techniques to measurements of physical properties of materials, such as particle sizes (A2, A15, B11, B56, L21), the segregation of trace impurities or additives in a metal (E7, L2, P8), the homogeneity of charcoal (B23), and the analysis of surfaces (R15), has been reported. Also, activation analysis has been used to determine the efficiency of special purification steps for high purity metals (A4, C12, G28).

There are three additional review articles to be noted for their bibliographical summaries of the literature related to activation analysis. Two systematic literature reviews by Meinke (M31, M32) containing a total of 1872 references cover the application of nucleonics techniques to analytical chemistry and industrial problems. Pertinent literature concerning chemical and instrumental methods, new apparatus, and nuclear data sources are included.

Concurrent with the preparation of this handbook, Gibbons *et al.* (G5) have prepared a "Bibliography of Radioactivation Analysis," consisting of 261 references. This bibliography is indexed in such a manner that it exhibits separately (1) reviews and papers of general interest, (2) the matrices in which specific elements have been determined, and (3) the elements which have been determined in specific matrices. Although the bibliography in this handbook generally encompasses the scope of that of Gibbons *et al.* the special index and cross-reference system which they present is unique.

ACTIVATION ANALYSIS: THE GENERAL TECHNIQUE

The selection of activation analysis as the appropriate technique for solution of an analytical problem may be based on its sensitivity, speed, economy, convenience, or on the absence of other suitable methods. Sufficient qualitative and quantitative experimental data exist which make this selection possible for most cases.

At this point it is deemed desirable to review the mechanisms involved in activation analysis. A more complete discussion of them will be presented in subsequent sections. In general, these mechanisms consist of the following sequence of considerations and operations for a given analytical problem: (1) the selection of the optimum nuclear reaction; (2) the choice of a suitable irradiation facility; (3) the preparation of samples for irradiation; (4) the irradiation; (5) the post-irradiation assays; and (6) the evaluation of the experimental data.

The selection of an appropriate nuclear reaction for activation analysis is usually based on the physical, chemical, and nuclear properties of the matrix and trace elements, and of their activation products. These properties determine the sensitivity with which a given trace element can be measured, the importance of possible interfering reactions or competing activation products, the extent to which post-irradiation assay techniques must be provided, and the practicability of providing a sample suitable for irradiation. Other considerations such as the proximity to an irradiation facility or economic factors may also be important.

The selection of an irradiation facility is based primarily on the type of nuclear particle required. In the event that neutron activation is the selected method, a wide selection of nuclear reactors, linear accelerators, cyclotrons, and low intensity neutron sources is available for service irradiations (A16). The selection of a particular facility may also be based on the flux intensity required to achieve the desired sensitivity, the energy of the neutrons required, the physical properties of the specimens, the location of the facility, or the cost of the irradiation. For charged particle or photon activation, similar considerations prevail except that the availability of the desired irradiation conditions (*e.g.*, type of particle, beam energy, and intensity) will frequently limit the selection to one or two facilities.

The physical, chemical, and nuclear properties of the constituents of a sample and the properties of their activation products dictate the pre-irradiation treatment of the sample. Some facilities will not permit irradiation of powders, liquids, volatiles, or easily decomposed solids. Nuclear considerations may limit the mass of some samples both in neutron and charged particle irradiations. In addition, at

each facility, special irradiation capsules or special restrictions, such as forced cooling, may be required, thus limiting the size of the sample. Chemical decontamination of the surfaces of solids is frequently desirable, although extended purification steps are normally not required. However, any chemical or physical treatment of the sample prior to irradiation must be carried out in a manner which will avoid contamination.

Two general irradiation and analytical techniques apply to both neutron and charged particle activation analysis. These are commonly referred to as the absolute assay technique and the comparative assay technique.

The absolute assay technique requires that the activation be carried out in a neutron flux or particle beam of known intensity, that the pertinent nuclear data be known accurately, and that the radiometric assay be quantitative; *i.e.*, the measurement of the absolute disintegration rates of the activation products with suitably calibrated instruments is required. If this method is selected, the use of beam or flux monitors is recommended.

The comparative assay, or comparator technique utilizes standard samples of the trace elements which are irradiated simultaneously with the samples and assayed in the same manner. Since this technique requires relative measurements only and eliminates the need for certain accurate nuclear data, it usually yields more accurate analytical results with greater convenience than the absolute assay technique.

Hence, the comparative assay technique is more frequently used. If it is selected, suitable comparator samples must be prepared and encapsulated with the samples.

The optimum length and intensity of the irradiation are normally determined by the required sensitivity and the half-lives of the trace element activation products. However, the relative activation of the major constituents of the sample or the presence of interfering reactions may limit either the length or the intensity of the irradiation, and thus may modify the specification of the irradiation conditions for a given analytical problem.

The post-irradiation assays must be adapted to each combination of matrix and trace element. In general, chemical separations of the trace elements from the matrix and from each other are required. The extent of the separation procedures depends on the relative activation of the several constituents, the chemical properties of the activation products, and the half-lives of the species to be assayed. In cases where the major constituents are only slightly activated, gross beta or gamma counting or gamma spectrometry may suffice.

The evaluation of the experimental data allows the analyst to assign a reliability to the assay. Such an evaluation should take into consideration errors due to two general sources, analytical and nuclear. A detailed discussion of these sources of errors is given in the following chapters.

ACTIVATION ANALYSIS • THEORETICAL CONSIDERATIONS

BASIC CONCEPTS

The technique of activation analysis is based on the formation of radioactive nuclides as a net result of reactions between nuclear particles and the isotopes of the trace elements of interest. These isotopes are transformed into different isotopes of either the same or different elements. There are many nuclear reactions which, in principle, can be utilized for this purpose. However, only some of these reactions are of practical interest. In the great majority of cases, two-particle reactions are utilized; one particle being a reactant, and the other being a product. The particles which are available in sufficient intensity for general use as reactants are neutrons, protons, deuterons, tritons, alpha particles, and photons (or electrons). Examples of typical nuclear reactions of interest are summarized in Part II of the Glossary.

Prior to discussing in detail the considerations pertinent to the selection of specific activation analysis methods, the mathematical relationship between the activation processes and the analytical sensitivities will be reviewed. Rigorous treatment of the general rate equations governing the nuclear transformations and the decay of the activation products has been presented by Robinson (R16) and by Lewis (L13). In summary, the rate of formation of a particular activation product, R_F , in a given sample is proportional to the intensity of the flux or beam of incident particles, to the concentration of the target nuclide in the sample, and to the cross-section for the nuclear reaction. Thus, for the case of neutron irradiations

$$R_F = \phi n \sigma = \frac{\phi m N^{\circ} f \sigma}{A} \quad (1)$$

where

- n = the number of target atoms
- ϕ = the neutron flux (n/cm²-sec)
- m = the mass of the trace element in the specimen (gm)
- A = the atomic weight of the trace element (gm/gm-atom)
- f = the fractional isotopic abundance of the target nuclide
- N° = Avogadro's number (atoms/gm-atom)
- σ = the reaction cross-section (cm²/atom)

The decay rate, D , expressed in atomic disintegrations per second, of the product radionuclide in the specimen is given by

$$D = \lambda N \quad (2)$$

where

- N = the number of atoms of the nuclide in the specimen
- λ = the decay constant of the nuclide (sec⁻¹).

Therefore, the rate of change of the quantity of the activation product in the sample during the irradiation is given by

$$\frac{dN}{dt} = R_F - D = \frac{\phi m N^{\circ} f \sigma}{A} - N \lambda \quad (3)$$

It can be shown (e.g., F15) that the disintegration rate of the radionuclide in the specimen after an arbitrary irradiation time, t , is

$$D(t) = \frac{\phi m N^{\circ} f \sigma (1 - e^{-\lambda t})}{A} \quad (4)$$

For sufficiently long irradiation times, $e^{-\lambda t}$ approaches zero, and we have

$$D^{\infty} = \frac{\phi m N^{\circ} f \sigma}{A} \quad (5)$$

Therefore, Eq. (4) becomes the familiar expression

$$D(t) = D^{\infty}(1 - e^{-\lambda t}). \quad (6)$$

Equation (4) can be used to estimate the activation levels for the various elements in the sample under varying conditions of flux, irradiation time, and sample size. Equation (4) can also be transformed into the following convenient form for calculating the sensitivity for detection of an element under a specified set of irradiation and detection conditions,

$$m = \frac{AD(t)}{\phi N^{\circ} f \sigma (1 - e^{-\lambda t})} \quad (7)$$

where m is expressed in grams, and $D(t)$ is the minimum detectable disintegration rate for the activation product corrected for losses due to post-irradiation decay or assay.

A similar set of equations can be derived for charged particle induced reactions. In the simple case of a monoenergetic beam for which no significant energy degradation occurs within the target specimen, we have, by analogy to (4),

$$\begin{aligned} D(t) &= bn' \sigma (1 - e^{-\lambda t}) \\ &= \frac{bm' N^{\circ} f \sigma (1 - e^{-\lambda t})}{A} \end{aligned} \quad (8)$$

where

- b = the intensity of the particle beam striking the target sample (sec^{-1})
- m' = grams of the trace element per square centimeter of matrix
- n' = atoms of the target nuclide per square centimeter of matrix

and all other symbols have the same designation as in Eq. (4). Equation (8) reduces to (6) in a manner analogous to that for Eq. (4).

By transforming, we have

$$m' = \frac{AD(t)}{b N^{\circ} f \sigma (1 - e^{-\lambda t})} \quad (9)$$

Since charged particle beam intensities are frequently expressed in terms of the beam current, J , we have

$$b = kJ = 6.2 \times 10^{12} J \quad (10)$$

where J is expressed in microamperes. Hence, Eq. (8) becomes

$$\begin{aligned} D(t) &= \frac{Jm' N^{\circ} f \sigma (1 - e^{-\lambda t})}{A} \\ &\quad \times 6.2 \times 10^{12} \end{aligned} \quad (11)$$

and Eq. (9) becomes

$$m' = \frac{1.6 \times 10^{-13} AD(t)}{J N^{\circ} f \sigma (1 - e^{-\lambda t})} \quad (12)$$

While these expressions are useful for demonstrating the method of calculating activity levels and sensitivities, they are overly simplified for many applications in which neutrons, charged particles, or photons, having wide spectra of energy are utilized, or where the energies of charged particles are degraded in the sample. More exact equations can be derived for these cases in which the weighted mean of the product of the flux and cross-section over the entire energy spectrum is used. Hughes (H46) discusses an example of this technique for neutrons.

Equations (1) through (12) can be utilized for preliminary evaluation of activation analysis as a general method and also for the selection of activation reactions for specific applications. To complete this evaluation for a given activation analysis problem, nuclear data and experimental methods for the elements of interest are desired. Since these data are scattered throughout the literature, a major purpose of this handbook is their collation into a single source.

The types of nuclear data required include a compilation of the nuclear reactions useful for activation analysis, the cross-sections, excitation functions, and isotopic abundances of the stable nuclides, and the half-lives and decay schemes of the radioactive products. Other pertinent information includes a compilation of those reactions which may produce competing radionuclides, the cross-sections or excitation functions for reactions in elements other than the one of interest which may interfere with the analysis by producing the activation product of interest, and the radiation characteristics of the products of the competing reactions.

The information desired for the experimental methods includes examples of reactions which have been used successfully for activation analysis, the sensitivities achieved, the experimental techniques employed for sample preparation and for chemical and instrumental

assays, and the evaluation of errors from experimentation or from interfering nuclear phenomena.

SOURCES OF NUCLEAR DATA

Many compilations have been prepared for various types of nuclear data pertinent to activation analysis. Most of these compilations are listed in "A Directory to Nuclear Data Tabulations" (G7). The 1956 revision of the "Chart of the Nuclides" (S53) is a convenient source of data for the isotopic abundances and the thermal neutron cross-sections of stable nuclides, and the half-lives of radioactive nuclides. A trilinear chart (S63) presents similar data in a slightly different format. Strominger, Hollander, and Seaborg (S57) have tabulated the experimental data for nuclear properties of both stable and radioactive nuclides. The Nuclear Data Group at the National Research Council (W6) provides current additions and revisions to the data for half-lives, decay schemes, cross-sections, and other nuclear properties. Salmon (S69) has tabulated similar data for nuclides produced by thermal neutron activation. The Brookhaven National Laboratory group has prepared a 1958 revision (H49) of previous compilations (H47, H48) of neutron cross-sections and resonance parameters. These latter compilations include both graphical and tabular presentations of the data. In addition, Howerston (H54) presents detailed neutron cross-sections of each element at energies up to 14 Mev. Macklin *et al.* (M7, M50) and Booth *et al.* (B61) have measured the activation cross-sections of numerous nuclides for the 25-keV neutrons from an antimony-beryllium source, and Lyon and Macklin (L25) have made similar measurements for 195-keV neutrons. Resonance integrals for a number of the elements are included in papers by Macklin and Pomerance (M9), Klimenkov and Gryazev (K23), and Davis and Hauser (D4). The latter paper also presents data for elemental macroscopic cross-sections and for other neutron parameters.

To a review of the application of gamma spectroscopy in activation analysis, Salmon (S69) has appended tabulations of thermal neutron activation products according to half-life, gamma energy, and particle energy. Typical spectra of many of these nuclides are also shown.

Other available data for neutron reactions include presentations of thermal neutron activation cross-sections and the half-lives of the activation products (M35, M52) in a format useful for preparing estimates of sensitivities for different reactions; cross-sections for fast neutron induced reactions occurring in a thermal reactor and their application to activation analysis (M37); cross-sections of about sixty elements for neutron capture in a reactor having an average neutron energy of about 1.5 Mev (R11); and thermal neutron activation products tabulated according to half-life (G2, S69).

Tabulated data for charged particle reactions are less extensive. Jarmie and Seagraves (J8) present charged particle excitation functions for light elements, and Meinke *et al.* (A13, M36) have prepared bibliographies for charged particle excitation functions. Martin *et al.* (M15) have estimated yields for more than 100 nuclides resulting from proton induced reactions in cyclotron irradiations.

Other tabulations which present general data in convenient forms include lists of known radioactive nuclides in order of half-life (C17), of known beta emitters according to half-life and beta energy (H5), and of known gamma emitters according to the energy of their radiations (S45). Also, Freiling (F14) has prepared a nomogram for estimating activities produced in various materials during irradiation by various types of nuclear particles.

SOURCES OF EXPERIMENTAL METHODS

Many review articles containing activation analysis data have been cited in the introductory section of this handbook. These papers are useful as sources of general information and as bibliography sources for specific applications. The bibliographies illustrate the many applications in which activation analyses have been utilized and the diverse sources of detailed information on the subject. In order to complete the collation of the information necessary for evaluating proposed applications of activation analysis, the information given in these review articles has been augmented here with additional data obtained from a comprehensive literature survey.

This survey brings together the operational data which have been reported for activation analyses. It includes, for each element, the re-

actions which have been used, a brief description of the matrix, sensitivity, and flux or beam intensity, where available, and any new or unusual experimental techniques. The thresholds, cross-sections, and excitation functions for these reactions, where available, are presented in conjunction with the operational data. Where many papers are available for a given reaction, only representative examples have been described. However, all references pertinent to each element have been tabulated. It is hoped that the combination of this information with the tabulated nuclear data will greatly enhance the selection of the most appropriate nuclear reaction, irradiation facility, and experimental techniques for any activation analysis program.

SELECTION OF ACTIVATION REACTIONS

1. General Considerations

The selection of an appropriate activation reaction for a specific application is generally based on the nuclear properties of the matrix and of the trace elements of interest and on a review of available results of experimental activation analyses. However, the chemical and physical properties of the matrix and trace elements are also important. The tabulation of data in this handbook, together with the specific literature sources cited for the given application, will often serve as a sufficient source of information upon which to base this selection. If the properties of the matrix are especially troublesome, the cross-referenced index prepared by Gibbons *et al.* (G5) may provide a convenient directory to appropriate sources of information concerning that matrix.

The principal technical considerations in the selection of suitable nuclear reactions are that they (1) produce radionuclides which are retained in the sample and have appropriate half-life and decay characteristics for accurate measurements, (2) have optimum or sufficient sensitivities, (3) have no interfering reactions producing or consuming the desired activation product, (4) have no reactions producing competing radioactive isotopes of the same element as the activation product, and (5) that the requisite irradiation and post-irradiation assays are feasible.

2. Suitability of Activation Products

The suitability of an activation product is dependent on most of the other factors. It is important that the trace element activation products have chemical or physical properties which insure that they are retained in the sample. Adequate containment must be provided if it is necessary to utilize activation products which are volatile or which may form volatile compounds with other constituents in the sample. Also, the half-life of the activation product must be consistent with the time required for transportation from the irradiation facility and for performance of the post-irradiation assay. The suitability of other decay characteristics depends on the type of radioactivity measuring equipment available to the analyst and on the relative activation of other isotopes of the same element. In certain cases, the activation product may decay to a radioactive daughter which has more favorable decay properties. Finally, the need for a rapid, routine analytical procedure may dictate the use of a nuclear reaction which yields an activation product with a convenient half-life that is either easily separable from the matrix, or which requires no chemical separation or no complicated radioactivity measurements after irradiation. Thus, the choice of reaction may be partially dependent on the analytical requirements, partially on the availability or the proximity of a suitable irradiation facility, and partially on economic or administrative considerations.

3. Sensitivity Estimates

The sensitivity of an analytical procedure can be estimated from Eq. (7) for neutron activation or from Eq. (12) for activation by other particles. However, for short-lived activation products, delays due to transportation or extended chemical separations may result in reduced practical sensitivities. The sensitivity is also dependent upon the type of instrumentation used in the assay. Nuclear factors, such as interfering reactions or the macroscopic cross-section of the matrix, may limit the duration or intensity of the irradiation or the size of the sample, and thus further reduce the sensitivity. The dimensions of the irradiation location or of the largest irradiation capsule may also limit the size of the sample.