

Christian Segebade  
Hans-Peter Weise  
George J. Lutz

# Photon Activation Analysis



Walter de Gruyter · Berlin · New York 1988

Christian Segebade  
Dr. Ing. Hans-Peter Weise  
Bundesanstalt für Materialprüfung  
Unter den Eichen 87  
D-1000 Berlin 45  
Federal Republic of Germany

George John Lutz, Ph. D.  
National Bureau of Standards  
Washington D. C.  
USA

*Library of Congress Cataloging in Publication Data*

Segebade, Christian, 1939 –  
Photon activation analysis.  
Bibliography: p.  
Includes index.  
1. Radioactivation analysis. I. Weise, Hans-Peter, 1942 –  
II. Lutz, G. J. (George John), 1933 – . III. Title.  
QD606.S44 1987 543'.0882 87-15602  
ISBN 0-89925-305-9 (U.S.)

*CIP-Kurztitelaufnahme der Deutschen Bibliothek*

**Segebade, Christian:**  
Photon activation analysis / Christian Segebade ; Hans-Peter Weise ;  
George Lutz. - Berlin ; New York : de Gruyter, 1987.  
ISBN 3-11-007250-5  
NE: Weise, Hans-Peter: ; Lutz, George:

Copyright © 1987 by Walter de Gruyter & Co., Berlin 30.

All rights reserved, including those of translation into foreign languages. No part of this book may be reproduced in any form – by photoprint, microfilm or any other means – nor transmitted nor translated into a machine language without written permission from the publishers. Printing: Gerike GmbH, Berlin. Binding: Lüderitz & Bauer GmbH, Berlin. Printed in Germany.

## Table of c

	Preface .
1	Activatio
1.1	Introduc
1.2	Types of
1.2.1	Neutron
1.2.2	Activatio
1.2.3	Photon a
1.3	Calculati
2	Photonu
2.1	General :
2.1.1	The abso
2.1.1.1	Excitatio
2.1.1.2	Giant dip
2.1.1.3	Interacti
2.1.2	The dees
2.2	( $\gamma$ , $\gamma$ )-re
2.3	Photonet
2.3.1	( $\gamma$ , $2n$ )-a
2.3.3	Reaction:
2.4	Yields of
2.5	Radionuc
2.5.1	Light targ
2.5.2	Medium
2.5.3	Fissile nu
2.5.4	Neutron-
3	Activating
3.1	Radionuc
3.2	Electron :
3.2.1	Van de G
3.2.2	Linear ac
3.2.2.1	General c
3.2.2.2	The accel
3.2.3	Betatron.
3.2.4	Microtror

# Table of contents

	Preface .....	1
1	Activation analysis – the general principle.....	3
1.1	Introduction and history of photon activation analysis .....	3
1.2	Types of nuclear reactions used for activation analysis.....	6
1.2.1	Neutron activation .....	6
1.2.2	Activation with charged particles.....	8
1.2.3	Photon activation .....	9
1.3	Calculation of the induced activity .....	13
2	Photonuclear reactions.....	19
2.1	General features of photonuclear reactions.....	20
2.1.1	The absorption of photons by nuclei .....	20
2.1.1.1	Excitation of individual nuclear levels .....	21
2.1.1.2	Giant dipole resonance .....	22
2.1.1.3	Interaction with high energy photons .....	26
2.1.2	The deexcitation of the nucleus after absorption of a photon.....	26
2.2	( $\gamma, \gamma$ )-reactions .....	27
2.3	Photoneutron reactions .....	31
2.3.1	( $\gamma, 2n$ )- and ( $\gamma, 3n$ )-reactions .....	43
2.3.3	Reactions with emission of charged particles.....	43
2.4	Yields of photonuclear reactions .....	46
2.5	Radionuclides produced through photonuclear reactions .....	51
2.5.1	Light target elements.....	51
2.5.2	Medium and heavy elements .....	51
2.5.3	Fissile nuclei .....	53
2.5.4	Neutron-induced reactions .....	54
3	Activating radiation sources.....	57
3.1	Radionuclide sources .....	57
3.2	Electron accelerators.....	59
3.2.1	Van de Graaff generator .....	60
3.2.2	Linear accelerator .....	61
3.2.2.1	General description .....	62
3.2.2.2	The accelerator used in the present work.....	65
3.2.3	Betatron.....	68
3.2.4	Microtron .....	70

part of this book may be  
- nor transmitted nor  
: publishers. Printing:  
rmany.

3.2.5	Other electron accelerators.....	72
3.3	Production and physical properties of bremsstrahlung .....	74
3.3.1	The spectrum of the bremsstrahlung photons (X-ray spectrum).....	74
3.3.2	Bremsstrahlung efficiency.....	78
3.4	The bremsstrahlung converter as a neutron source.....	84
3.5	Typical irradiation facility .....	89
3.6	Conclusion.....	92
4	Photon spectrometers.....	93
4.1	Detectors.....	95
4.1.1	Scintillation detectors .....	97
4.1.2	Semiconductor detectors.....	101
4.1.3	The pulse amplitude spectrum.....	109
4.1.4	Relevant characteristics of detectors.....	120
4.1.4.1	Maximum measurable count rate .....	120
4.1.4.2	Energy resolution .....	122
4.1.4.3	Full energy peak counting efficiency .....	126
4.1.4.4	Signal-to-Compton ratio.....	129
4.1.4.5	Relationship between photon energy and pulse height.....	130
4.1.4.6	Energy limits of the measurable photon spectrum .....	130
4.1.4.7	Detector geometries available.....	131
4.1.4.8	Miscellaneous aspects and summary.....	132
4.2	Photon counting electronics.....	138
4.2.1	Linear amplifiers.....	139
4.2.1.1	Preamplifiers.....	139
4.2.1.2	Spectroscopy amplifiers .....	140
4.2.2	Pulse height measurement.....	143
4.2.2.1	Single channel analysers .....	145
4.2.2.2	Multichannel analysers.....	146
4.2.2.3	Miscellaneous options .....	155
4.3	The spectrometers used for the present work .....	156
4.4	Preparation of semiconductor photon spectrometers for analysis.....	158
5	Properties and yields of radionuclides produced through photonuclear reactions.....	161
5.1	General remarks .....	161
5.2	Experimental conditions.....	162
5.2.1	Selection of the elements .....	162
5.2.2	Irradiation conditions .....	162
5.2.3	Measurement conditions and spectra processing.....	163
5.3	Data tables.....	165

3.2.5	Other electron accelerators.....	72
3.3	Production and physical properties of bremsstrahlung .....	74
3.3.1	The spectrum of the bremsstrahlung photons (X-ray spectrum).....	74
3.3.2	Bremsstrahlung efficiency.....	78
3.4	The bremsstrahlung converter as a neutron source.....	84
3.5	Typical irradiation facility .....	89
3.6	Conclusion.....	92
4	Photon spectrometers .....	93
4.1	Detectors.....	95
4.1.1	Scintillation detectors .....	97
4.1.2	Semiconductor detectors.....	101
4.1.3	The pulse amplitude spectrum.....	109
4.1.4	Relevant characteristics of detectors.....	120
4.1.4.1	Maximum measurable count rate.....	120
4.1.4.2	Energy resolution .....	122
4.1.4.3	Full energy peak counting efficiency .....	126
4.1.4.4	Signal-to-Compton ratio.....	129
4.1.4.5	Relationship between photon energy and pulse height.....	130
4.1.4.6	Energy limits of the measurable photon spectrum .....	130
4.1.4.7	Detector geometries available.....	131
4.1.4.8	Miscellaneous aspects and summary.....	132
4.2	Photon counting electronics.....	138
4.2.1	Linear amplifiers.....	139
4.2.1.1	Preamplifiers.....	139
4.2.1.2	Spectroscopy amplifiers .....	140
4.2.2	Pulse height measurement .....	143
4.2.2.1	Single channel analysers .....	145
4.2.2.2	Multichannel analysers.....	146
4.2.2.3	Miscellaneous options .....	155
4.3	The spectrometers used for the present work .....	156
4.4	Preparation of semiconductor photon spectrometers for analysis.....	158
5	Properties and yields of radionuclides produced through photonuclear reactions.....	161
5.1	General remarks .....	161
5.2	Experimental conditions.....	162
5.2.1	Selection of the elements .....	162
5.2.2	Irradiation conditions .....	162
5.2.3	Measurement conditions and spectra processing.....	163
5.3	Data tables.....	165

5.3.1	The photonuclear reactions of the elements.....	165
5.3.2	Low energy photon spectra.....	194
5.3.3	Low energy ( $E < 90$ keV) $\gamma$ -rays.....	213
5.3.4	High energy ( $E \leq 90$ keV) $\gamma$ -rays.....	218
5.3.5	Competing reactions in photon activation analysis.....	300
5.3.6	Sensitivities in photon activation analysis.....	305
6	Analytical application.....	311
6.1	Light element analysis.....	313
6.1.1	The analysis of light elements other than C, N, O and F.....	315
6.1.2	The analysis of carbon, nitrogen, oxygen and fluorine.....	317
6.1.2.1	Irradiation.....	317
6.1.2.2	Surface treatment.....	321
6.1.2.3	Activity counting.....	325
6.1.2.4	Reference materials.....	329
6.1.2.5	Interferences.....	329
6.1.2.6	Sensitivity.....	333
6.1.3	Carbon.....	336
6.1.3.1	Non-destructive analysis.....	336
6.1.3.2	Radiochemical analysis.....	337
6.1.3.3	Reference materials; error sources.....	351
6.1.3.4	Sensitivity.....	356
6.1.4	Nitrogen.....	358
6.1.4.1	Non-destructive analysis.....	358
6.1.4.2	Radiochemical analysis.....	359
6.1.4.3	Reference materials; error sources.....	361
6.1.4.4	Sensitivity.....	370
6.1.5	Oxygen.....	371
6.1.5.1	Non-destructive analysis.....	372
6.1.5.2	Radiochemical analysis.....	373
6.1.5.3	Reference materials; error sources.....	382
6.1.5.4	Sensitivity.....	386
6.1.6	Fluorine.....	388
6.1.6.1	Non-destructive analysis.....	388
6.1.6.2	Radiochemical analysis.....	390
6.1.6.3	Reference materials; error sources.....	396
6.1.6.4	Sensitivity.....	399
6.2	Single and multielement analysis ( $Z$ greater than 10).....	401
6.2.1	Introduction.....	401
6.2.2	Reference materials and radiation monitoring.....	403
6.2.3	General analytical procedure.....	410

6.2.3.1 Sample preparation, transfer and irradiation .....	410
6.2.3.2 Preparation for counting and photon spectroscopy .....	413
6.2.3.3 Data handling .....	415
6.2.3.4 Error sources .....	419
6.2.4 Applications .....	443
6.2.4.1 Systematic compilations .....	443
6.2.4.2 Environmental analysis .....	454
6.2.4.3 Analysis of biological material .....	480
6.2.4.4 Geochemical analysis .....	504
6.2.4.5 Analysis of raw materials and industrial products .....	516
6.2.4.6 Analysis of archaeological material and forensic analysis .....	529
6.2.4.7 Comparison studies; analysis of reference materials .....	540
6.2.4.8 Systematic single element study .....	568
 Bibliography .....	 615
 Subject index .....	 697

## Preface

This book is written to give, in a concentrated form, an overview of the application of photonuclear reactions to activation analysis. It is intended to accompany the analyst's work in the photon activation analysis laboratory as a practical usable reference. Emphasis is placed upon analytical qualitative and quantitative data which are based upon experimentally obtained results. Therefore, both a source of general information on photon activation analysis and a laboratory manual are combined in this book. The results of the authors' laboratory work and a large amount of literature data are evaluated and presented as completely as possible by the authors. Special knowledge of photonuclear physics is not required; only a very elementary theoretical introduction is given. More detailed information on the physical and mathematical theory should be sought in the special literature which is cited in the relevant chapters.

The first chapter opens with a short introduction into the subject and a short survey of the history of photon activation analysis. Then the different types of nuclear reactions used for activation analysis are discussed. Finally, the quantitative relation between activating radiation and the radioactivity induced in the irradiated material is evaluated.

The second chapter deals with the different types of photonuclear reactions. It commences with a historical summary of photonuclear research. The different photonuclear reaction mechanisms are then discussed, including the general nuclear properties of the reaction product nuclides.

In the third chapter, again after a short paragraph on the historical development, the principles of the photon sources which are used for activation analysis purpose are explained. Isotope sources, betatron, microtron and linear accelerator are included. Their properties are compared and discussed. Irradiation facilities and apparatus for sample handling are covered.

The fourth chapter is concerned with the radiation measurement systems used for photon activation analysis, especially high resolution photon spectrometers. After a few historical data, the different photon detectors and electronic devices for radiation counting are discussed.

The fifth chapter contains an extended compilation of the photonuclear yield data of analytical importance. All elements of the Periodic Table with few exceptions are



included. Reaction types and activity yields are based exclusively upon experiment. This chapter is intended to be used during practical analytical work, e.g. for identification of radionuclides by their photon emission energies, quantitative evaluation of interference reactions, estimation of analytical sensitivities etc..

Chapter six (section 6.1) deals with photon activation analysis of the light elements (C, N, O, F). This is a special application which entails problems which are different from those occurring during photon activation analysis of the heavier ( $Z$  greater than 10) elements. The different chemical separation procedures will be outlined.

In section 6.2 the analysis of the heavier elements is discussed. Cases of single- and multielement determinations are described. Summaries of fundamental photon activation analysis work presented in the literature are given as typical examples for the large variety of different problems. These include analyses of various material classes (organic matter, ores, rocks, water etc.) for different purposes (purity assessment, prospection, environmental analysis etc.).

The cited literature is as complete as possible to the authors and comprises (hopefully!) the most relevant publications on photon activation analysis.

The authors wish to express their appreciation to all who helped to realise this work in any way, be it by advice and critical and helpful discussion, or by practical cooperation during our laboratory work, data collection and evaluation, writing and reviewing. We are especially indebted to Professor R. Neider, who, as the head of our group, encouraged us to complete this work and had significant influence upon its contents by frequent advice and critical discussion.

This work would not have been realised without the help of: U. Coester, Th. Dudzus, Dr. H.-U. Fusban, Dr. P. Jost, M. Köhl, D. Lapuse, H. Pittelkow, Dr. P. Reimers, K. Saracoglu, B. F. Schmitt, I. Segebade, R. Wiese, B. Wilke and, in particular, Mrs. Mary Thomany and the ladies of the department 7.113, Mrs. Gabriel, Mrs. Glöckner and Mrs. Blamberg. Finally, the assistance of C. Retzlaff in the literature research is gratefully acknowledged.

Thanks to you all!

Berlin, Washington D.C., May 1987

C. Segebade  
H.-P. Weise  
G. J. Lutz