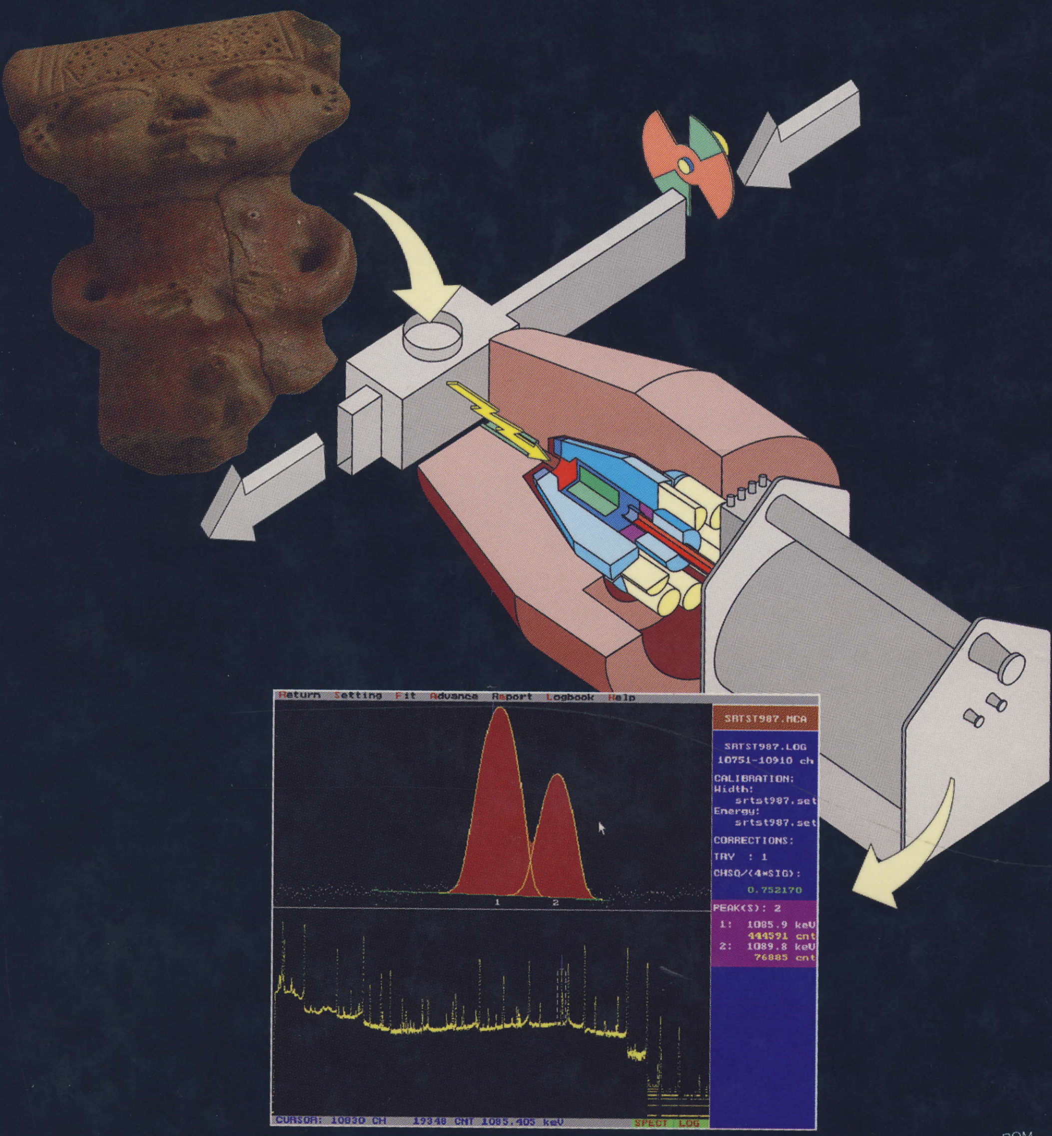
# HANDBOOK OF PROMPT GAMMA ACTIVATION ANALYSIS

## WITH NEUTRON BEAMS

Edited by Gábor L. Molnár

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# Handbook of Prompt Gamma Activation Analysis

## with Neutron Beams

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# Preface

Prompt Gamma Neutron Activation Analysis (or the more common usage, Prompt Gamma Activation Analysis, abbreviated as PGAA) is based on one of the most basic nuclear reactions, the radiative capture of neutrons. This nuclear reaction takes place for each isotope of every element, with the single exception of $^{4}He$. Therefore, in principle, a complete elemental and isotopic analysis can be performed using PGAA. Nevertheless this versatile nuclear technique has mainly been used as a supplementary analytical tool until recently. Many recent developments have been achieved at the leading laboratories of this field that make it timely to summarize the results in the form of this handbook.

The creation of this book was possible thanks to the cooperation of many specialists: radiochemists and physicists working in the fields of PGAA, traditional neutron activation analysis (NAA), gamma spectroscopy and nuclear data evaluation. The PGAA facility at the collimated thermal beam at NIST, USA began operation in the early eighties and has been mainly used for the analysis of biological samples by D. L. Anderson. A second PGAA system was installed at a guided cold neutron beam at the same reactor by R.M. Lindstrom towards the end of the 1980's. A PGAA facility operating with either the thermal or the cold beam was started at JAERI in Japan under the leadership of Chushiro Yonezawa in the early nineties.

The thermal neutron guides started operating at the Budapest Research Reactor in 1994. A PGAA facility of the Budapest Neutron Center was established in 1996. Since that time thousands of PGAA measurements were performed there for different fields of application and to the development the PGAA technique. A cold neutron source was installed at the reactor in 2000 at Budapest, improving the capabilities further.

The Department of Nuclear Research of the Institute of Isotopes, led by Gábor L. Molnár, proved to be an ideal laboratory for adopting and developing further the PGAA method. Professor Molnár organized the cooperation of colleagues from many different backgrounds to accomplish a very significant improvement in the methods and techniques of PGAA. Tamás Belgya developed $\gamma$-$\gamma$-coincidence techniques for PGAA applications and has been responsible for the sophisticated electronics. Zsolt Kasztovszky has been in charge of arranging different applications, and I myself have established the PGAA analytical data library and developed data reduction programs and techniques.

The large number of gamma-ray peaks appearing in prompt gamma spectra requires an accurate calibration of the detection system, and a reliable and reproducible identification of gamma lines. The principal reason that this useful technique did not become a standard nuclear analytical method has been the lack of an accurate and complete analytical library. The poor reliability of available spectroscopic data discouraged many scientists from using the PGAA (Molnár 2000). In parallel with the new, precise library measurements performed in Budapest, a thorough database was constructed as part of a Coordinated Research Program of the International Atomic Energy Agency. The library provided in this book results from the IAEA evaluation led by Richard B. Firestone from Lawrence Berkeley National Laboratory (IAEA 2004). It combines the precise Budapest elemental measurements with detailed isotopic measurements from the scientific literature.

Many review articles were published about PGAA and its applications (Anderson *et al.* 1982, Greenwood 1979, Lindstrom *et al.* 1997, Lindstrom *et al.* 1994, Paul and Lindstrom 2000, Shaw 1999) and a dedicated book has also appeared (Alfassi and Chung 1995). The idea of publishing a handbook that contains all up-to-date information needed to perform reliable analysis with the PGAA method, was born in the Budapest group. This new handbook summarizes the experiences collected at those PGAA facilities equipped with Compton-suppressed HPGe detectors and using cold and thermal neutron beams. This is the first time that an atlas of prompt gamma spectra with a data library for every naturally occurring element as measured with a high-resolution germanium detector has been published. It is mainly intended for analytical applications; however the tables have been constructed in a way that they could be used in other fields, as well.

In Chapter 1 the fundamentals of the PGAA method are given. Chapter 2 discusses beam and facility construction material considerations, and the most important facilities are also described. Chapter 3 addresses sample preparation and the use of standards. Chapter 4 is dedicated to the spectroscopy, the setting up of the data acquisition electronics and the calibration procedures required for the accurate analysis. Chapter 5 outlines the process of PGAA quantitative elemental analysis and discusses the most important factors affecting the analytical results, and Chapter 6 gives examples of the many applications of PGAA performed with neutron beams. Chapter 7 contains the experimental prompt gamma ray spectrum library measured in the Budapest thermal and cold neutron beams, and lists up to 100 of the most prominent prompt and delayed gamma rays. The appendix provides useful tables of frequently used nuclear and elemental data. The CD supplement contains high resolution drawings of the spectra (in PDF format) and the complete library of prompt and delayed gamma rays.

Gábor Molnár began the preparation of this handbook in the year 2000. He designed the content of the book, invited the co-authors to participate and coordinated the project. He planned to finish the book in 2003, but last fall his enthusiasm seemed to have deteriorated. He started reviewing the manuscripts, made some changes in chapter 3, generated the headings in Chapter 7 and thoroughly verified the data library and the atlas. Unfortunately he could not finish this work and was unable to start writing the chapters he was responsible for. Tragically, he passed away shortly after the Christmas holidays, which were spent in hospital. The rest of the work on the Handbook was passed on to his colleagues in the Department of Nuclear Research. Tamás Belgya and myself have prepared the missing chapters, Zsolt Kasztovszky has undertaken the updating of the chapter on applications of the method, while I finished the editing of the book.

Gábor Molnár's contributions to the development of the PGAA method were both broad-based and essential. In addition to this book, a special journal issue dedicated to his memory is also being edited, includes many papers on the projects he took part in or inspired in different laboratories. These papers, are cited throughout this book, and are to be published in the Gábor Molnár memorial issue of the Journal of Radioanalytical and Nuclear Chemistry, which is will appear at the end of 2004.

The authors hope that this handbook will contribute to the propagation of PGAA as a powerful nuclear analytical technique.

Let me give special thanks for the valuable and friendly support of Richard Lindstrom, Richard Firestone and also my colleague Tamás Belgya, who helped me considerably in solving numerous problems that arose while completing this book. The careful proofreading and the useful advice of Jesse L. Weil are also gratefully acknowledged.

*Zsolt Révay*

Budapest, June 28, 2004.

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