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This is the author's accepted version of the contribution published as:

*Original*

The k 0-INRIM software: a tool to compile uncertainty budgets in neutron activation analysis based on k 0-standardisation / D'Agostino, G; Di Luzio, M; Oddone, M. - In: MEASUREMENT SCIENCE & TECHNOLOGY. - ISSN 0957-0233. - 31:1(2020), p. 017002. [10.1088/1361-6501/ab358f]

*Availability:*

This version is available at: 11696/61187 since: 2020-08-31T18:19:33Z

*Publisher:*

IOP

*Published*

DOI:10.1088/1361-6501/ab358f

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# The $k_0$ -INRIM software: a tool to compile uncertainty budgets in Neutron Activation Analysis based on $k_0$ -standardisation

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Submitted to: Measurement Science and Technology

**Abstract:** A software package was developed to evaluate the uncertainty of results provided by neutron activation laboratories adopting the  $k_0$ -standardisation method in trace elements analysis. The outputs are stand-alone and editable spreadsheet budgets based on a measurement equation including more than forty input quantities and written to consider the effect of correlations. The program, called  $k_0$ -INRIM, is presented to potential users and freely distributed alongside the user's manual. The measurement equation is reported and the main features are described together with the results obtained in a validation test. An uncertainty budget compiled using the software output is given as an example.

## 1. Introduction

Analytical methods based on Neutron Activation Analysis (NAA) are applied to determine trace amounts of elements in a wide range of materials. The multi-element capability of NAA is typically exploited with the  $k_0$ -standardisation to realize the traceability to SI via the so-called  $k_0$  factors [1] by using a standard of only one element selected as a monitor [2].

At present, the most comprehensive software packages available for processing  $k_0$ -NAA data are the Keyzero/SolcoiR and the  $k_0$ -IAEA [3]. The first is a commercial software [4] implemented with the support of the initial developers of the  $k_0$ -standardisation [5] whereas the latter is a free of charge software designed for and distributed by the International Atomic Energy Agency (IAEA) [6].

Despite the fact that these software packages have been developed and tested, they do not include the evaluation of the uncertainty following the Guide to the expression of Uncertainty in Measurement (GUM) [7]. Specifically, the uncertainty evaluated by the Keyzero/SolcoiR considers only the contribution due to counting statistics [8] while the uncertainty evaluated by the  $k_0$ -IAEA is based on the outdated classification and propagation of random and systematic sources [9].

An additional software, named ERON, was designed and freely distributed in 2008 to properly evaluate the  $k_0$ -NAA uncertainty [10]. However, since the output did not include the measurement result, its use requires a supplementary software to quantify the investigated element. Moreover, the effect of correlations was not entirely considered for.

To fill these gaps, we developed and tested a new data processing software, named  $k_0$ -INRIM, based on a measurement equation modeling most of the presently recognized influencing factors. The outputs are uncertainty budgets in agreement with the GUM recommendations and compiled in stand-

alone and user adjustable spreadsheets described in [11]; the information required to quantify the investigated elements and to assess their uncertainties is included.

The  $k_0$ -INRIM software overcomes the time-consuming compiling of the uncertainty budgets, one for each investigated elements, which makes cumbersome the application of the spreadsheet approach [11]. In addition, the program implements original methodologies both for gamma peak identification and for the calibration of the detector efficiency fully considering the effect of correlations. As a supplementary feature, detection limits according to the Currie's limit can be evaluated in the case of undetected elements.

The  $k_0$ -INRIM is free of charge and available for download together with the user's manual at the webpage of the Istituto Nazionale di Ricerca Metrologica [12].

Here we shortly present the software to potential users by i) pointing out the adopted measurement model, ii) describing the program features and iii) showing the results obtained in a validation test, including the establishment of the uncertainty budget of a quantified element. Additional and more detailed information is given in the user's manual available also in the supporting information of this paper.

## 2. Measurement model

The  $k_0$ -INRIM adopts the following equation to compute the mass fraction of the analyte in a measurement sample,  $w_a$ , traceable to the mass fraction of the monitor in a standard sample,  $w_m$ ,

$$w_a = \frac{\lambda \frac{(n_p/COI)(t_c/t_l) e^{-\mu(1-t_l/t_c)}}{(1-e^{-\lambda t_l})(1-e^{-\lambda t_c})} \Big|_a e^{(\lambda_a - \lambda_m)t_{dm} + \lambda_a \Delta t_d}}{\lambda \frac{(n_p/COI)(t_c/t_l) e^{-\mu(1-t_l/t_c)}}{(1-e^{-\lambda t_l})(1-e^{-\lambda t_c})} \Big|_m} \times \frac{k_{0Au}(m)}{k_{0Au}(a)} \frac{G_{thm} + \frac{G_{em}}{f} \left( \frac{Q_{0m} - 0.429}{\bar{E}_{rm}^\alpha} + \frac{0.429}{0.55^\alpha (1+2\alpha)} \right)}{G_{tha} + \frac{G_{ea}}{f} \left( \frac{Q_{0a} - 0.429}{\bar{E}_{ra}^\alpha} + \frac{0.429}{0.55^\alpha (1+2\alpha)} \right)} e^{\sum_{i=1}^h a_i (E_{pm} - E_{pa})^{2-i}} \frac{(1 - \delta \varepsilon_{rm} \Delta d_m) m_{std}}{(1 - \delta \varepsilon_{ra} \Delta d_a) m_{sm}} w_m, \quad (1)$$

where subscripts a and m refer to the analyte and monitor, respectively, and

- $\lambda = \ln(2)/t_{1/2}$  is the decay constant of a radionuclide having an half-life time  $t_{1/2}$ ,
- $n_p$  is the number of counts in the full-energy  $\gamma$ -peak,
- $COI$  is the true-coincidence correction factor,
- $t_c$  and  $t_l$  are the counting and live times of the detection system, respectively,
- $t_{dm}$  is the decay time of the monitor,
- $\Delta t_d = t_{da} - t_{dm}$  is the difference between the analyte and monitor decay times at their acquisition start times,
- $t_i$  is the neutron irradiation time,
- $\mu$  is the excess counting loss constant of the detection system,
- $k_{0Au}(m)$  and  $k_{0Au}(a)$  are the  $k_0$  factors of monitor and analyte versus Au, respectively,
- $G_{th}$  and  $G_e$  are the thermal and epithermal neutron self-shielding correction factors, respectively,

- $f$  is the (conventional) sub- to epi-cadmium neutron flux ratio,
- $\alpha$  is the epi-cadmium neutron shape factor,
- $Q_0$  is the ratio of the resonance integral (for a  $1/E$  neutron spectrum in the epi-cadmium region) to the thermal cross section,
- $\overline{E}_r$  is the effective resonance energy,
- $E_p$  is the energy of the  $\gamma$ -peak,
- $a_i$  are the  $h$  parameters of the model adopted to describe the full-energy  $\gamma$ -peak detection efficiency at the counting position,  $e^{\sum_{i=1}^h a_i (E_{pm} - E_{pa})^{2-i}}$ , with  $h = 4, 5$  or  $6$ ,
- $\delta\varepsilon_r$  is the relative variation of detection efficiency per unit of vertical position,
- $\Delta d$  is the vertical position difference between the sample and the reference source used for efficiency calibration at the counting position, and
- $m_{std}$  and  $m_{sm}$  are the standard and sample masses, respectively.

Definitions and details of the listed input quantities are given in [11].

### 3. Program features

The  $k_0$ -INRIM code was implemented using the open-source Python programming language [13].

The current version is limited to  $\gamma$ -counting setups assuring the best accuracy, i.e. where the measurement and standard samples have a point-like geometry and are counted at the same position with respect to the detector end-cap. The detection efficiency calibration is performed using a multi-gamma reference source.

It is worth to note that model (1) applies to the activation and decay paths types I, IIB, IVB and VI defined in [14]. The user is informed in the case of complex activation and decay paths that are not yet implemented or when non  $1/\nu$  nuclides requiring the application of Westcott formalism are selected.

Spectrum data can be imported by selecting an editable user template workbook or outputs from the commercial Ortec GammaVision [15] or HyperLab [16] gamma spectrum evaluation software. This significantly limits user errors during typing of the spectrum parameters, e.g.  $n_p$ ,  $t_c$  and  $t_l$ , in the spreadsheet budgets proposed in [11].

The combined uncertainty of the result and the individual contributions to the variance are obtained via matrix computations to consider the correlations. Data and calculation formulae are included in the uncertainty budget spreadsheet created by the software.

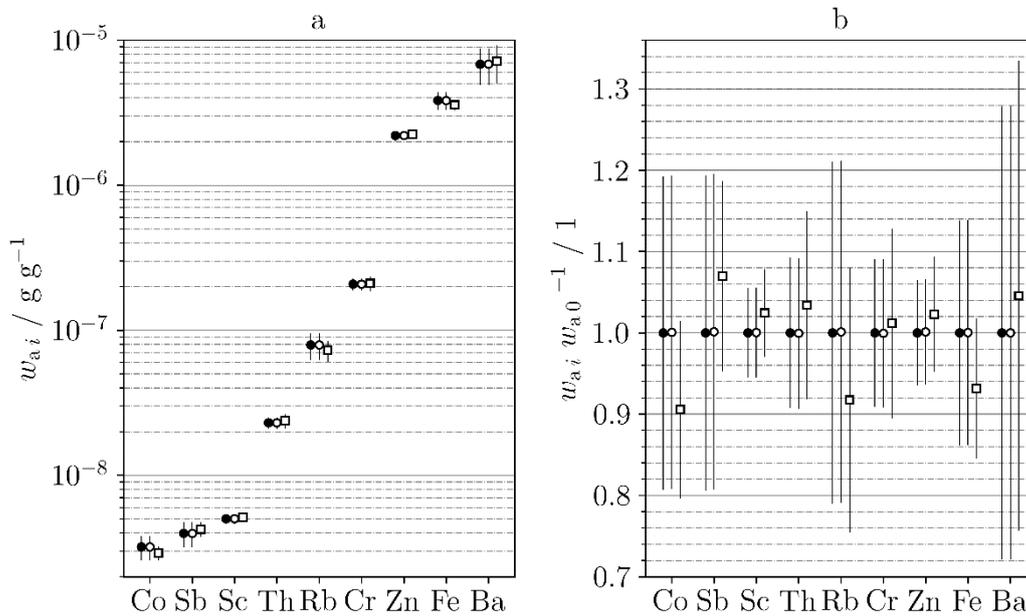
The program was designed to simplify as much as possible the data processing. Specifically, the workflow of the analysis proceeds downwards in the main window of the software interface, from where secondary windows are opened by pressing action buttons to i) set general settings, ii) import the user template workbook, iii) select the background spectrum, iv) perform the efficiency calibration of the detector, v) enter the neutron irradiation data, vi) select the sample and standard spectra and the emissions of the investigated and monitor elements, respectively, vii) select the elements for the detection limits and, finally, viii) process the data.

### 4. Code validation and uncertainty budget example

The absence of errors in the software code was checked by processing experimental data previously collected to determine traces of Co, Sb, Sc, Th, Rb, Cr, Zn, Fe and Ba in a sample of cerebrospinal fluid. The spectrum data were elaborated with Ortec GammaVision and the uncertainty budgets, published in [11], were manually established with the spreadsheet technique. Values and uncertainties, given in mass concentrations, were converted to mass fractions and used as a reference.

As a first test, the user template workbook was filled in with the published cerebrospinal fluid spectrum data and processed with the  $k_0$ -INRIM. As a second test, the collected cerebrospinal fluid spectra were elaborated with HyperLab and the outputs were straightforwardly imported and processed with the  $k_0$ -INRIM. In both cases, values and uncertainties of the remaining input quantities were kept fixed as in [11].

The comparison between the mass fraction values measured in the first and second test,  $w_{a1}$  and  $w_{a2}$ , respectively, and the reference values,  $w_{a0}$ , is shown in figure 1a. In addition, data were normalized with respect to the reference and plotted in figure 1b to highlight minor discrepancies.



**Figure 1.** Absolute (a) and normalized (b) mass fractions obtained in the first and second test,  $w_{a1}$  (hollow circles) and  $w_{a2}$  (hollow squares), respectively, compared to the reference values,  $w_{a0}$  (solid circles). The error bars indicate a 95% confidence interval.

The outcome points out that the use of the software allows establishing uncertainty budgets without introducing errors. In fact, there were no differences between values and uncertainties obtained in the first test with respect to the reference values. The departures observed in the second test were only due to differences of counts in the full-energy  $\gamma$ -peaks estimated with HyperLab and Ortec GammaVision; nevertheless, data are still compatible with the reference within their uncertainties.

As an example, table 1 reports the uncertainty budget of Cr compiled starting from the  $k_0$ -INRIM output obtained in the second test.

Quantity	Unit	Value	Standard uncertainty	Index
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$X_i$	$[X_i]$	$x_i$	$u(x_i)$	%
$n_{p\ a}$	1	51998	1059	23.7
$COI_m$	1	0.857	0.017	22.5
$k_{0\ Au(a)}$	1	0.002620	0.000013	1.4
$Q_{0\ a}$	1	0.53	0.11	4.7
$E_{p\ m}, E_{p\ a}, a_i$	1	0.3567	0.0062	17.0
$\Delta d_m$	mm	0.00	0.29	10.4
$\Delta d_a$	mm	0.00	0.29	9.8
$m_{std}$	g	0.008470	0.000050	2.0
$w_m$	$g\ g^{-1}$	0.004597	0.000046	5.7
$Y$	$[Y]$	$y$	$u_c(x_i)$	
$w_a$	$g\ g^{-1}$	$2.083 \times 10^{-7}$	$8.7 \times 10^{-9}$	100

**Table 1:** Uncertainty budget of Cr in cerebrospinal fluid. The index column gives the relative contributions of the standard uncertainty  $u(x_i)$  to the combined standard uncertainty,  $u_c(y)$ , of the output quantity  $Y$ ,  $w_a$ . Only the input quantities  $X_i$  with an index greater than 1.0% are listed.

## 5. Conclusions

The  $k_0$ -INRIM was developed and validated to establish uncertainty budgets of  $k_0$ -NAA measurements. In agreement with the GUM recommendations, the effect of correlated input quantities was fully considered for. This makes the program distinct among the existing software packages adopted for processing  $k_0$ -NAA data.

Stand-alone spreadsheet budgets described in [11] and implementing the formulae used for calculation are given as output of the elaboration to allow later adjustments or assessments of the uncertainty evaluation. The computerization, including efficiency calibration of the detector and user assistance in peak identification, the possibility of importing outputs from the most used gamma spectrometry software packages and the evaluation of the Currie's detection limits in the case of undetected elements are the main improvements with respect to the manual compiling required by the spreadsheet approach.

In addition to the mass fraction of the investigated element, the percentage contribution of each input quantity to the combined uncertainty is computed to highlight the main influence factors. Users aiming at decreasing the uncertainty might take advantage of this information to plan next measurements.

The program is freely available and open to further developments, e.g. the extension to complex activation and decay paths or the possibility to count sample and standard at different distances from the detector end-cap.

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