

k0-INRIM User's Manual

version 1.5

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1 Introduction

A software package, called k0-INRIM, was developed to assist NAA analysts during data elaboration and uncertainty evaluation following the recommendations of the guide to the expression of uncertainty in measurement GUM [1]. The main aim was to make automatic the compiling of the uncertainty spreadsheet for the k_0 -NAA method described in [2].

Specifically, the software accepts as an input spectra information and experimental data to obtain the mass fractions of the investigated elements including their uncertainty budgets and detection limits.

The equation model (30) implemented in the present version applies to activation and decay path types I, IIA, IIB, IVB, VB, VC and VI defined in [3]. A warning message appears in the case of complex activation decay paths that are not yet implemented. Similarly, the user is informed when non- $1/v$ nuclides requiring the application of Westcott formalism are selected.

It is worth to note that the use of the current version is limited to the particular experimental setup for the gamma counting in which the measurement and standard samples, the first containing the investigated elements and the latter containing the monitor element, have point-like geometry. Moreover, both samples must be located at the same counting position with respect to the detector end-cap.

The calibration of the detection system requires the measurement of a multi-gamma reference source at the counting position of the samples.

Information concerning installation, use and output of the software is given in sections 2, 3 and ??, respectively. It is worth to note that the structure of the section 3 corresponds to the workflow of the analysis. Users can get started with the k0-INRIM software by following step-by-step instructions reported in section ??.

2 Software installation

The k0-INRIM is potentially multi-platform although this version has been tested only on 64 bit Windows systems (versions 7 and 10).

The software running requires the previous installation of the Python compiler, version 3.6 [4] or higher, freely available at <https://www.python.org/downloads/>. During the Python installation, click the “Add python3.x to PATH” check-box. Moreover, the k0-INRIM uses the additional modules "xlrd", "xlsxwriter", "numpy", "scipy", "pandas" and "matplotlib" [5, 6] available at the "pip" internet repository.

The k0-INRIM can be found as a zip folder download-able from the github repository (<https://github.com/marcodiluzio/k0-INRIM.git>), a simple unpack is required. In the unpack process, it is recommended to avoid system-reserved destinations, such as the C://Programs path, as this will prevent the writing of working files unless the user has administrator privileges; the «user» or «Documents» folders are suggested. Once unpacked, a «k0-INRIM» folder will appear in the destination. The main folder includes two additional «data» and «classes» folders, and the «k0-INRIM.py», «k0-INRIM.pyw», «LICENSE» and «requirements.txt» files, among others.

The «k0-INRIM.py» is the Python script using Python objects defined in the «naaobj.py», «GUI_things.py» and «recovery.py» supporting script files included in the «classes» folder. Those represent the source codes, accessible for expert users for further development. The «requirements.txt» file includes information of the required additional modules and «LICENSE» a copy of the software GNU general public license. The file «k0-INRIM.pyw» is equivalent to «k0-INRIM.py» and works only under Windows to start the program without the underlying console.

The software main settings are defined in the «k0-set.cfg» file included in «data» along with the i) «characterization», ii) «coincidences», iii) «facility», iv) «irradiation», v) «k0data», vi) «literaturedata», vii) «models», viii) «monitor_elements», ix) «results», x) «samples», xi) «saves», xii) «sources» folders storing information on i) detector characterizations, ii) literature data for true-coincidences correction, iii) irradiation facilities and detectors, iv) performed irradiations, v) nuclear data from the k_0 database [7], vi) data concerning γ -emissions, fast neutron reactions and self-absorption correction, vii) measurement models, viii) elements to be used as monitors for flux ad gradient evaluations, ix) results obtained from validation measurements, x) samples involved in analysis, xi) savefiles, xii) γ sources certificates, respectively.

3 Use

3.1 Main window

The software main window is opened by double clicking on the «k0-INRIM.py» file (or «k0-INRIM.pyw» on Windows). A supporting prompt window (console) is also opened to display user messages and software errors, if the software is started from the «k0-INRIM.py» file; closing this prompt window stops the program.

At first start-up the k0-INRIM automatically attempts to install the missing additional modules; for this procedure a working internet connection is required. (Figure 1)

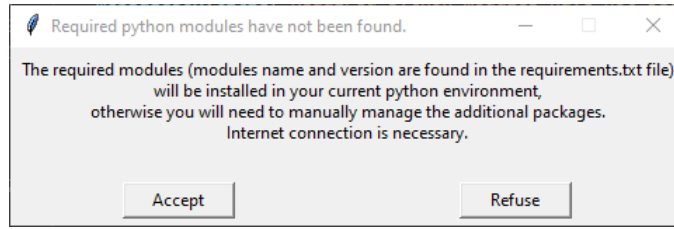


Figure 1: The start-up check for missing modules

In case some error occurs, modules have to be manually installed by opening a Windows prompt and entering the command *pip install module-name==version* by substituting for each *module-name==version* each name (with version number) as present in the «requirements.txt» file.

In the main windows (Figure 2) 8 separated regions can be identified, with titles in the upper left side, suggesting the preferable workflow to follow; they are: 1) *Utility*, 2) *Characterization*, 3) *Irradiation*, 4) *Background*, 5) *Standard*, 6) *Sample*, 7) *Limits* and 8) *Results*.

Each region contains buttons, comboboxes, sliders and spinboxes to perform actions. Finally, the bottom of the window includes a label where hints are printed and a progress bar to monitor advancement of tasks.

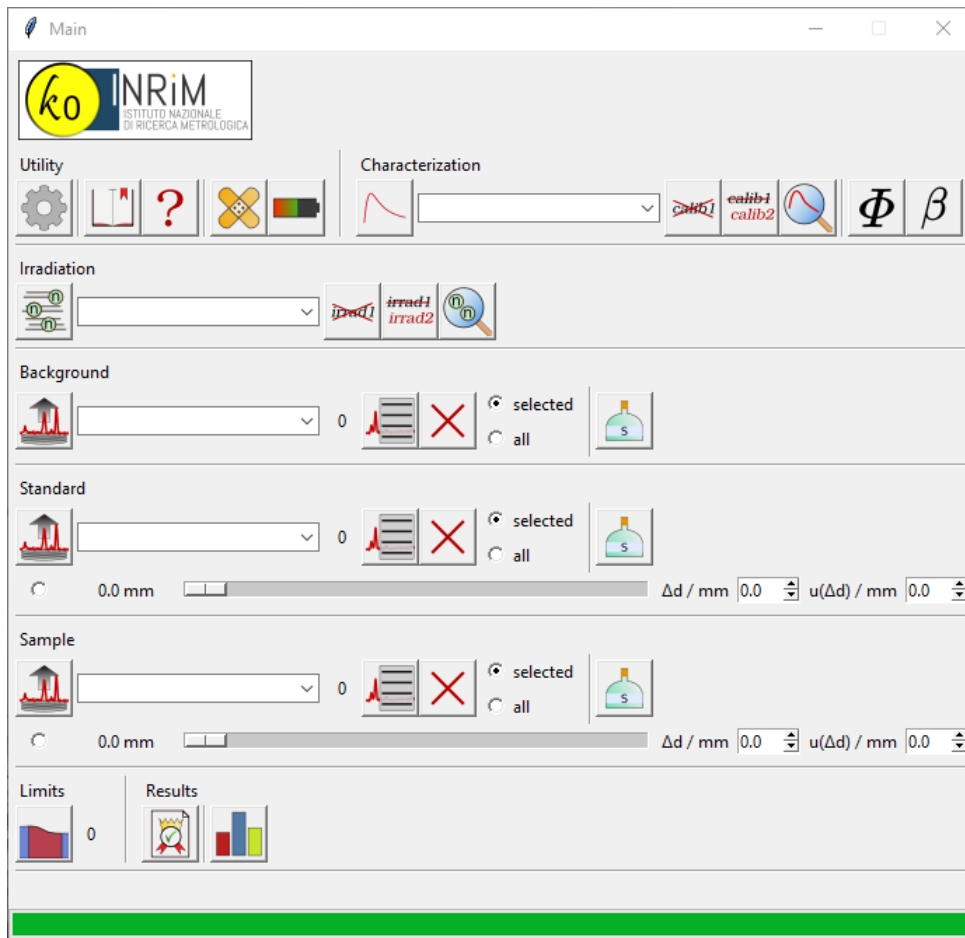



Figure 2: The main window of k0-INRIM software

3.2 Utility

This section provides buttons for  *Settings*,  *Browse databases*,  *Credits*,  *Save* and  *Load*.

3.2.1 Settings

The  button allows to set the general behavior of the software (Figure 3). Any change, if confirmed, will automatically make the current settings effective by restarting the program.

The first setting is the k_0 database version used to retrieve nuclear data. In the case of release of an updated version, save the new file in the «k0data» folder and replace the current selection with the new filename that appears in the drop-down menu.

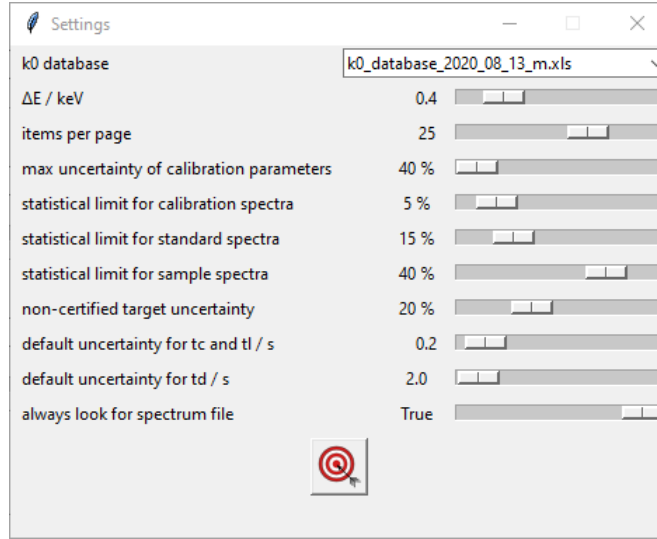


Figure 3: The settings window

The k_0 database installed by default is the most up to date version at the time of writing [7] with a couple of minor but necessary changes. Details of these changes are given in the «README_k0_database.txt» file in the «k0data» folder.

The second setting is the energy tolerance, ΔE , used to identify the gamma peaks of the spectra by comparison with the emission energies reported in the k_0 database, E_p . The software searches for entries satisfying the relationship: $E_p - \Delta E < E_{\text{meas}} < E_p + \Delta E$, where E_{meas} is the energy of the measured peak. The ΔE value shouldn't be neither too low or too high. In the former case the identification fails if the energy calibration is affected by minor biases while in the latter case multiple correspondences are returned. The default 0.3 keV value might be a reasonable compromise. If some mis-recognition is spotted it might depend from some energy bias present in the imported elaborated spectra, thus a check of those imported files is always suggested prior to starting the elaboration, alternatively, an enlargement of the ΔE setting might be a viable option.

The third setting affects the visual aspect of the peak list window (see paragraph 3.5) by adjusting the maximum number of listed peaks to appear in the screen.


The fourth setting defines the maximum allowed relative uncertainty for the parameters, a_i , modeling the detection efficiency (see paragraph 3.3).

The following three settings define the threshold maximum allowed peak statistical relative (percent) uncertainty while importing a spectrum peak-list; these settings are independent for calibration, standard and sample spectra, respectively.





The following one sets the uncertainty of those elements for which certified mass fraction values are not available.


The following two settings define the default values for the standard uncertainties of the input quantities t_c and t_l (this also affects Δt_d) and t_d (here and hereafter, see the equation model 30 for the adopted symbols of the input quantities).


The last one sets whether looking for the spectrum file (in .chn or .asc format) while importing peaklists; if the spectrum file is required by the software (as while importing peaklists of .csv format) it will be imported anyway.






The  *Confirm* button accepts the changes and restarts the program.




3.2.2 Browse database

The browse database subwindow offers the possibility to display and modify useful data to be used in the analysis. In particular, information about k_0 database, investigated samples, reference γ sources and irradiation facilities can be recalled here from the corresponding buttons:  k_0 database,  sample database,  source database and  flux evaluation history database.

The  button displays a read only window showing the entry of the k_0 database currently in use (Figure 4). For each line of the database target element, emitter, emission energy, k_0 value, activation/decay type, Q_0 value, \bar{E}_r value and affection by true-coincidence are showed.


The  button displays information about samples adopted in the analysis (as standard, monitor or even as blank) and stored in the «samples» folder. Information as name, description, sample type, physical state and composition can be recalled and modified (Figure 5).

At the bottom left of the window,  *add a new sample*,  *update changes to this sample*,  *delete sample* buttons allow to perform the corresponding actions. On the bottom right side the element combobox enable to select a specific element (ordered by Z number) while  *update element's values* and  *delete element's values* buttons perform the corresponding actions on the selected element. The g $g-1$ button switches between unit of measurements of mass fraction values (g g^{-1} , ppm and %).

A new sample is only created by pressing the  button and modifications performed on the selected sample are not saved on disc until the  or  button is pressed.




Databases manager							
k0 database (read only)							
	emitter	E / keV	k0 / l	type	Q0	Er	COI
F	F-20	1633.6	9.98e-04	I	2.20	44700.0	False
Na	Na-24	1368.6	4.68e-02	IVB	0.59	3380.0	True
Na	Na-24	2754.0	4.62e-02	IVB	0.59	3380.0	True
Mg	Mg-27	170.7	3.02e-06	I	0.64	257000.0	True
Mg	Mg-27	843.8	2.53e-04	I	0.64	257000.0	True
Mg	Mg-27	1014.4	9.80e-05	I	0.64	257000.0	True
Al	Al-28	1778.9	1.75e-02	I	0.71	11800.0	False
Si	Si-31	1266.2	1.45e-07	I	1.11	2280.0	False
S	S-37	3103.4	1.96e-06	I	1.12	13.7	False
Cl	Cl-38	1642.7	1.97e-03	IVB	0.69	13700.0	True
Cl	Cl-38	2167.4	2.66e-03	IVB	0.69	13700.0	True
Ar	Ar-41	1293.6	3.32e-02	I	0.63	31000.0	False
K	K-42	312.7	1.59e-05	I	0.87	2960.0	True
K	K-42	1524.7	9.46e-04	I	0.87	2960.0	True
Ca	Ca-47	489.2	9.14e-08	I	1.30	2925.0	True
Ca	Ca-47	807.9	9.20e-08	I	1.30	2925.0	True
Ca	Ca-47	1297.1	9.54e-07	I	1.30	2925.0	True
Ca	Sc-47	159.4	8.57e-07	IIA	1.30	2925.0	False
Ca	Ca-49	3084.4	1.01e-04	I	0.45	1330000.0	False
Sc	Sc-46	889.3	1.22e+00	IVB	0.43	5130.0	True
Sc	Sc-46	1120.5	1.22e+00	IVB	0.43	5130.0	True
Ti	Ti-51	320.1	3.74e-04	I	0.67	63200.0	True
Ti	Ti-51	928.6	2.65e-05	I	0.67	63200.0	True
V	V-52	1434.1	1.96e-01	I	0.55	7230.0	True
Cr	Cr-51	320.1	2.62e-03	I	0.53	7530.0	False
Mn	Mn-56	846.8	4.96e-01	I	1.05	468.0	True
Mn	Mn-56	1810.7	1.35e-01	I	1.05	468.0	True
Mn	Mn-56	2113.1	7.17e-02	I	1.05	468.0	True
Fe	Fe-59	142.7	1.33e-06	I	0.97	637.0	True


Figure 4: The k0 database window

The  button displays information about γ reference sources adopted in the characterization tasks and stored in the «sources» folder. Information as name, certificate date and activity of the emitters are reported (Figure 6).

Once a γ source is selected its name and date reported on the certificate appear in the destination.

To change the certificate date press the  button and confirm the new date from the dedicated sub-window (Figure 7).

At the lower part of the window,  *add a new source*,  *update changes to selected source*,  *delete the selected source* buttons allow to perform the corresponding actions. Below these, there are two sections divided by a vertical separator: on the left side controls affecting the whole source are found while on the right side controls affecting single emissions are present.

On the left side it is possible to select another γ source from memory and merge it with the selected source through  *merge with selected source* button. This process will add all the emissions of the merging source (the one recalled from the combobox next to the merge button) to the selected source (the one recalled from source name combobox) adjusting all activities to the certificate date

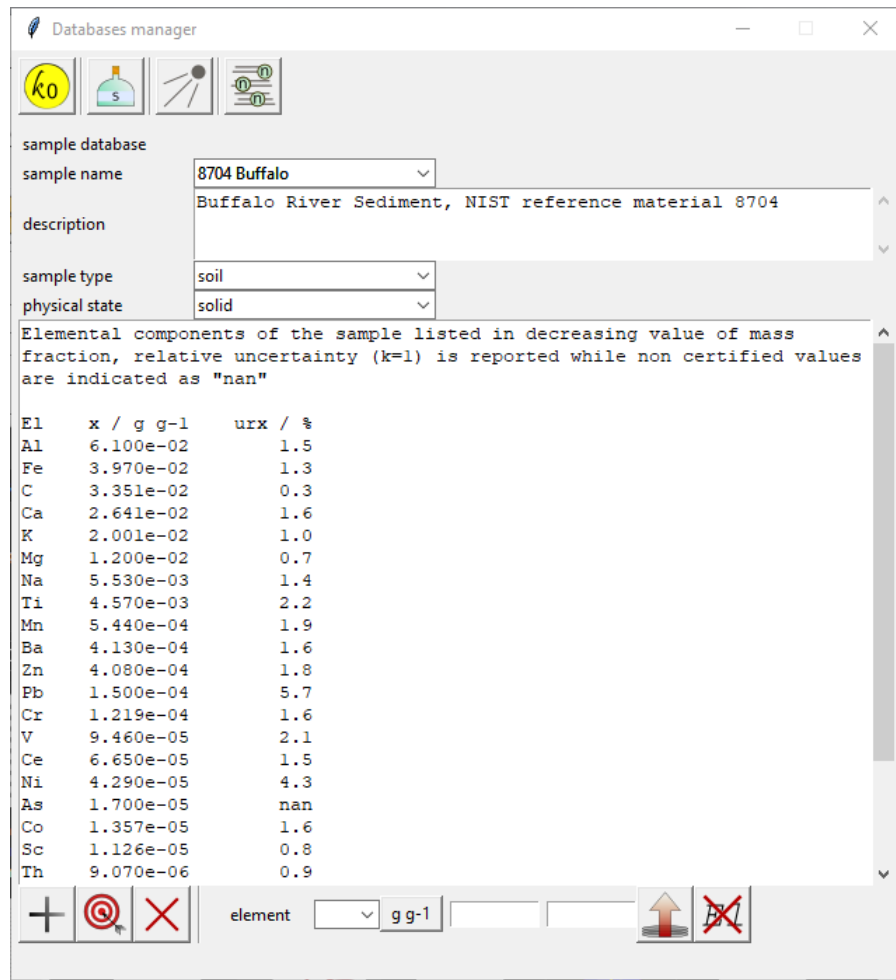








Figure 5: The sample database window

of the selected source.

From the emitter combobox an isotope can be chosen and added to the selected source by pressing the  *add or update an emitter* button after declaring its activity in Bq and half-life in s.

Any emission present in the selected source can be addressed with the combobox on the lower right side; from that it is possible to modify its gamma yield or COIfree status (if checked means that the emission is considered as coincidence-free during the detector characterization); to make those changes effective a click of the  *update data for the current emission* button is required. Alternatively, the emission can be deleted with the  *delete emission* button.

Also for this window, a new source is only created by pressing the  button and modifications performed on the selected source are not saved on disc until the  or  button is pressed.

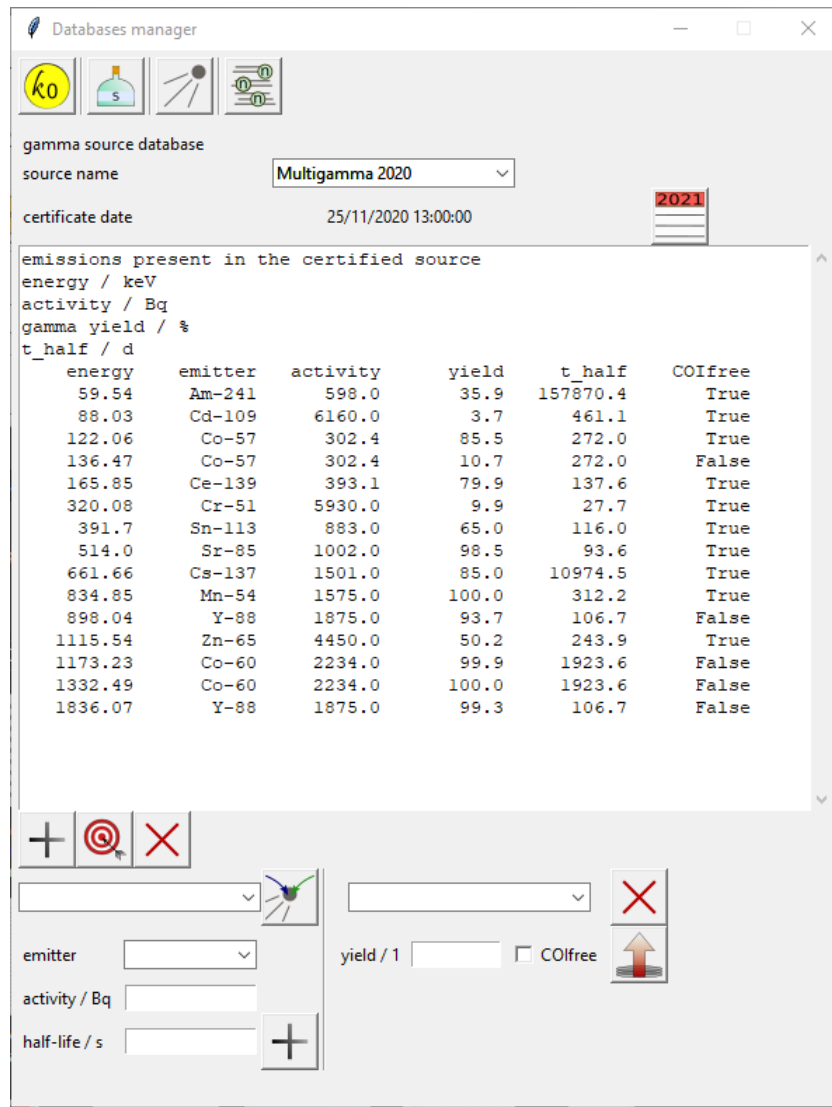



Figure 6: The γ reference source database window

The  button displays information about characterizations performed on the irradiation facilities; those data are stored in the «facility» folder. For each entry the channel name, measurement date, f value, α value, conventional thermal flux and β value are reported (Figure 8).



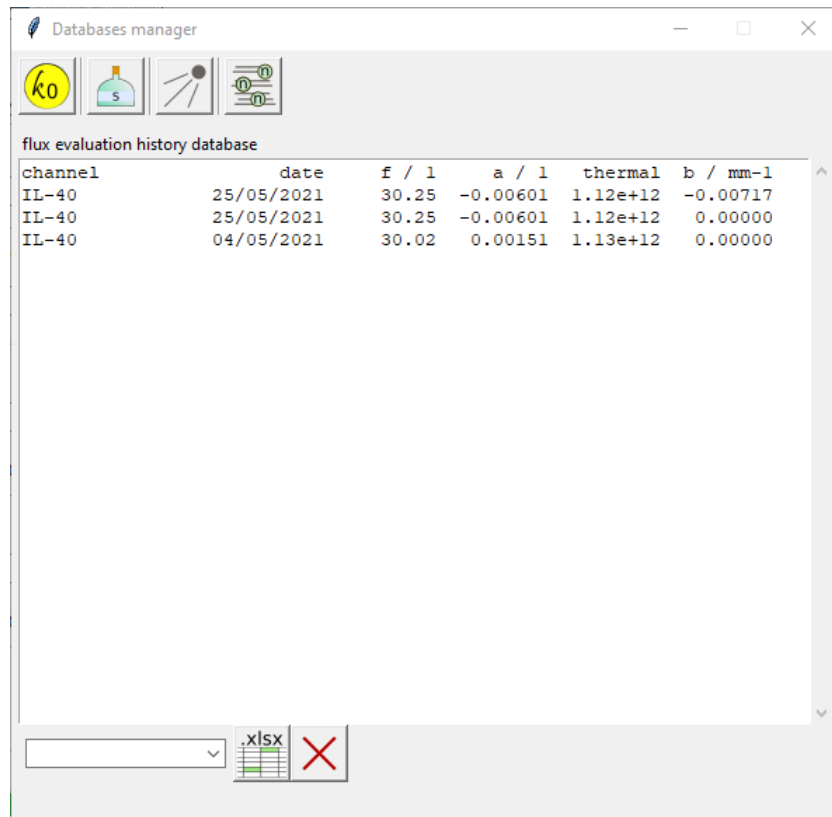
At the bottom of the window the selection can be filtered by channel name and then saved to an Excel file, or outdated entries can be deleted with the corresponding buttons,  *export selection as .xlsx file* and  *delete outdated measurements*, respectively; the latter command deletes all measurement but the most recent for any channel.



Figure 7: The change reference date sub-window



The screenshot shows a window titled 'Databases manager' with a toolbar containing icons for a yellow circle with 'k0', a blue bottle, a black dot, and a green circle with a cross. Below the toolbar is a table titled 'flux evaluation history database'.

channel	date	f / l	a / l	thermal	b / mm-1
IL-40	25/05/2021	30.25	-0.00601	1.12e+12	-0.00717
IL-40	25/05/2021	30.25	-0.00601	1.12e+12	0.00000
IL-40	04/05/2021	30.02	0.00151	1.13e+12	0.00000



At the bottom of the window, there is a dropdown menu and a button with a green grid icon and a red 'X'.

Figure 8: The flux evaluation history database window

3.2.3 Credits

This subwindow includes information about the version of the k0-INRIM used, contact emails and reference to scientific literature; moreover, it displays a copy of the GNU GENERAL PUBLIC license shipped with the software.

3.2.4 Save

The  button allows to save the current state of the program. It opens a subwindow (Figure 9) allowing to choose the filename, whether include the date and a further  button to perform the save.

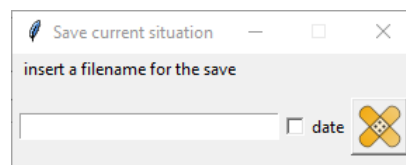





Figure 9: The save data sub-window

3.2.5 Load

The  button allows to restore the k0-INRIM to a previously saved state. It opens a subwindow (Figure 10) allowing to select one of the previously saved files from the combobox and, once selected recall it with the  *recall saved file* button or delete it with the  *delete saved file* button.

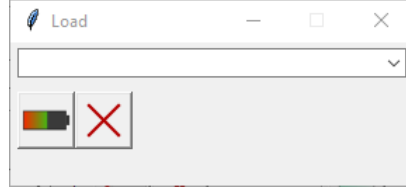








Figure 10: The load data sub-window


By pressing either button a confirmation subwindow will open requiring the user to confirm the choice. It is worth to note that recalling the saved file will restart a new instance of the program while losing all unsaved activity.

3.3 Characterization

This section provides tasks to manage characterization of detection efficiency and irradiation facilities. It provides a  *New detector characterization* button, a combobox to recall a previously saved detector characterization, three  *Delete detector characterization*,  *Rename detector characterization*,  *Display detector characterization* buttons to perform corresponding actions on the selected detector characterization, and two  *Flux evaluation* and  *Gradient evaluation* buttons to perform measurements on the irradiation facility.

3.3.1 New detector characterization

The *New detector characterization* task involves the creation of a new instance of detector characterization where data about detection efficiencies and other useful information are processed. The detector characterization consists of acquisitions of reference γ -sources in all counting positions. In order to benefit of the full potential of this procedure at least four different positions need to be used (acquiring all emissions in the farthest positions and only coincidence-free emissions in the others) otherwise some functionality, as corrections for vertical displacement and sample-geometry, will be missing.

The detector characterization window appears by pressing the  button in the main window (Figure 11).

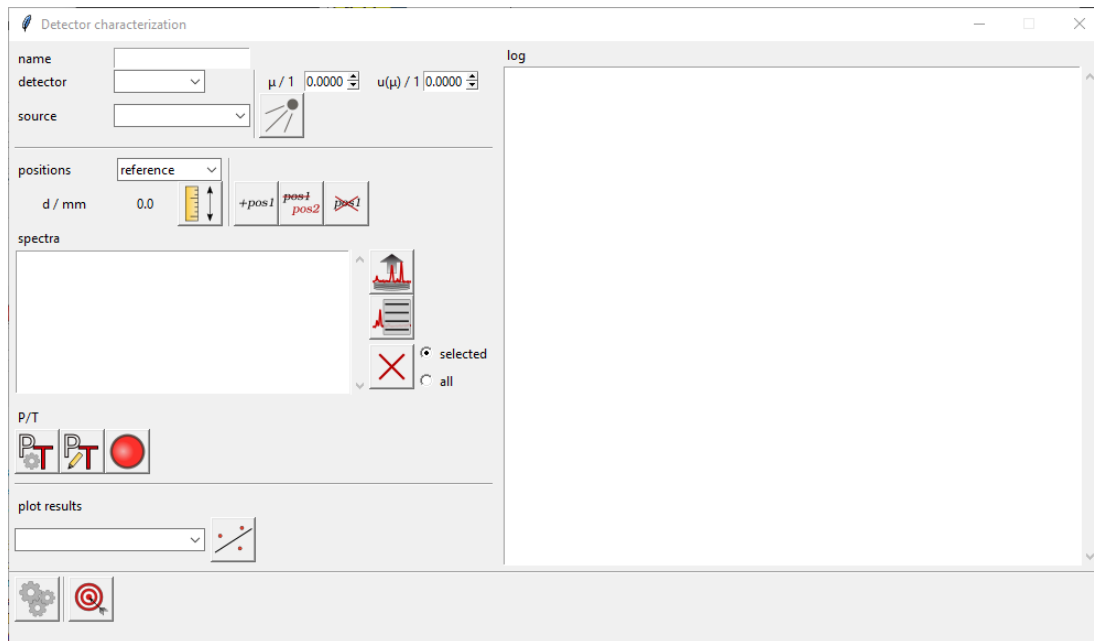



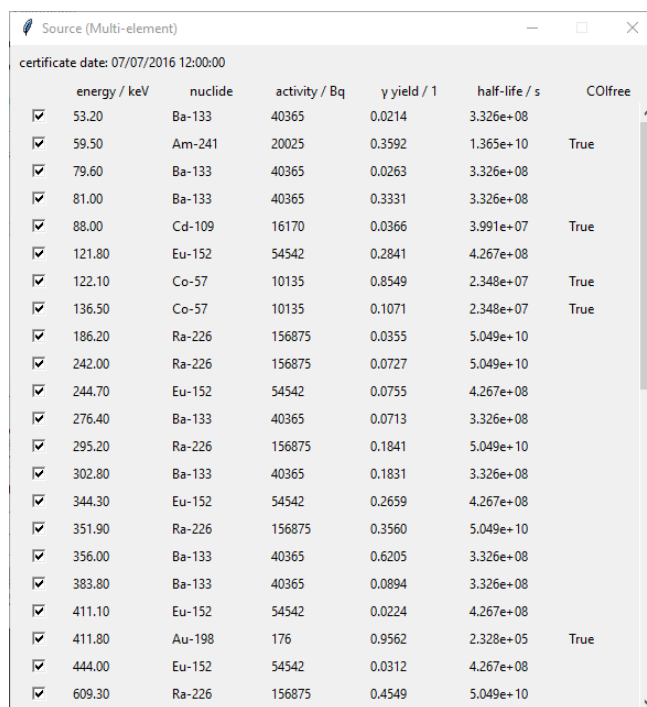
Figure 11: The new detector characterization window

The window is composed by some sections on the left hand side divided by horizontal separators. At the top of the window, information about the chosen name for the detector characterization, detector information and data about the γ source are required.

The detector name can be chosen by the combobox which keeps in memory all previously inserted detector information, moreover, values and uncertainty of excess counting loss constant of the detection system, denoted as μ , are required; these information are also stored in memory.

The source combobox allows to select the γ source to be used in the characterization, the source should represent all the emissions adopted for the task even if they come from different reference sources, and should be created accordingly in the *gamma source database* subwindow in the *Browse database* section (3.2.2). Gamma emissions from the source can be included or excluded for the

incoming characterization by selecting them through the  button. The selection emissions subwindow (Figure 12) displays the name and reference date of the source and lists all the emissions included in it; each emission line provides information about energy, nuclide identity, activity, gamma-yield, half-life, whether it is considered a coincidence free emission and has a checkbox that can be selected or deselected: if it's deselected that emission will be ignored in the following calculations.




energy / keV	nuclide	activity / Bq	γ yield / 1	half-life / s	COI-free
53.20	Ba-133	40365	0.0214	3.326e+08	
59.50	Am-241	20025	0.3592	1.365e+10	True
79.60	Ba-133	40365	0.0263	3.326e+08	
81.00	Ba-133	40365	0.3331	3.326e+08	
88.00	Cd-109	16170	0.0366	3.991e+07	True
121.80	Eu-152	54542	0.2841	4.267e+08	
122.10	Co-57	10135	0.8549	2.348e+07	True
136.50	Co-57	10135	0.1071	2.348e+07	True
186.20	Ra-226	156875	0.0355	5.049e+10	
242.00	Ra-226	156875	0.0727	5.049e+10	
244.70	Eu-152	54542	0.0755	4.267e+08	
276.40	Ba-133	40365	0.0713	3.326e+08	
295.20	Ra-226	156875	0.1841	5.049e+10	
302.80	Ba-133	40365	0.1831	3.326e+08	
344.30	Eu-152	54542	0.2659	4.267e+08	
351.90	Ra-226	156875	0.3560	5.049e+10	
356.00	Ba-133	40365	0.6205	3.326e+08	
383.80	Ba-133	40365	0.0894	3.326e+08	
411.10	Eu-152	54542	0.0224	4.267e+08	
411.80	Au-198	176	0.9562	2.328e+05	True
444.00	Eu-152	54542	0.0312	4.267e+08	
609.30	Ra-226	156875	0.4549	5.049e+10	




Figure 12: The emission source selection window

The emission selection is kept in memory until another source is selected.

Below the left top section, a region requiring information about distances in which the characterization is performed and the acquired spectra from the source, together with processes to perform a PT (peak-to-total) evaluation is present.

The combobox next to the label 'position' allows to select a specific counting position; all actions taken in this section refer to the currently selected counting position. The reference position, entered by default, represents the only mandatory counting position.

The value next to the label 'distance' indicates the distance from the detector end-cap of the current position, it is 0 by default but can be changed by pressing the  *Modify distance* button. This button will open a subwindow where to type the new value and validate it by pressing Enter from the keyboard.

The following  *Add a counting position*,  *Rename a counting position* and  *Delete a counting position* buttons perform the corresponding actions. There is no limit to how many positions can be set, however, if no spectra or no emissions are found in a particular position it will be excluded from processing.

The listbox below the label 'spectra' includes the filename of the spectra that are acquired at the current position (i.e. at the same distance from detector end-cap defined by the label 'd /

mm').



The *Add spectra to the current counting position* button allows to select spectra to include in the current position; valid input are peak lists (in .csv file format) from HyperLab elaborated spectra or reports (in .rpt file format) obtained from GammaVision. When one of these file types is selected the software proceeds to open it to gather the required information about gamma peaks, in the meanwhile the software also looks for a file in the same folder with same name but different type (.asc or .chn) in order to get information concerning the complete gamma spectrum. In case .asc or .chn spectrum is not found an error is raised (although, for compatibility reasons this behavior can be modified for .rpt files in the settings window through the option 'always look for spectrum file' (Figure 3)). The filenames of correctly spectra will be visible in the listbox.



The *Show the peaklist of selected spectrum* button allows to browse information about the currently selected spectrum (if no spectrum is selected the first one of the list is automatically open, if any). The peaklist window shows information about the directory where the file is located, and the name of files uploaded and whether they are identified as peak list (.csv or .rpt files) or spectrum (.asc or .chn files), the start acquisition time, real, live and dead time, together with the list of all γ -peaks reported in the peaklist (Figure 13).

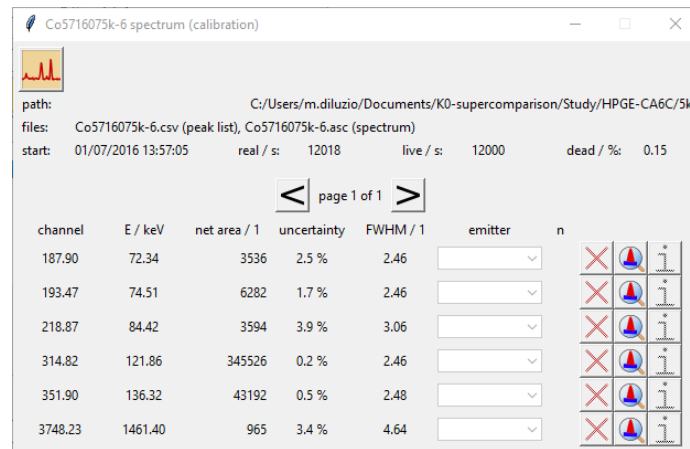


Figure 13: The peaklist window



The *Show spectrum profile* button, placed at the top-left of the window, allows to open a visualization of the spectrum profile (Figure 14), if any spectrum filetype was found when recalling the spectra.

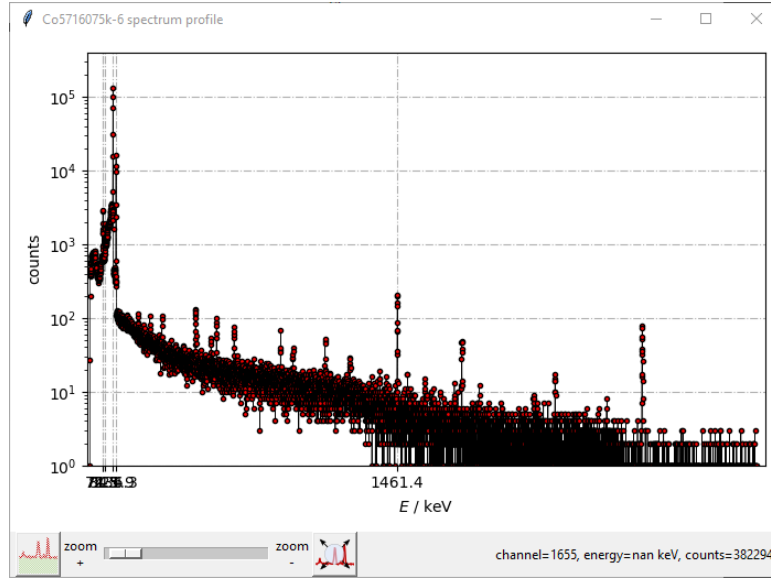











Figure 14: The spectrum window


The spectrum window displays a plot of spectrum profile with energies (in keV) on x -axis and logarithm of counts in the y -axis. If selected, a superimposed background is visualized (or hidden)




by pressing the  *Show background profile* button; the background profile, already scaled to the spectrum live time, is drawn as a green line. It is possible to navigate the spectrum profile plot by scrolling with the mouse-wheel; a zoomed-in visualization will be automatically prompted while the zoom level is adjusted by the corresponding slider between the 'zoom +' and 'zoom -' labels.



The  *Zoom y-axis* button adjusts the y -axis to the current content while navigating through the spectrum profile. At the bottom-right of the window information such as channel, energy and counts are displays depending on mouse position over the plot; a characterization should be selected in the main window for the energy to be showed.

Back to the peaklist window, the  *Previous page* and  *Following page* buttons browse the peaklist in order to reach all the peaks since the visualization is split in pages. Each page includes a number of lines selected in the settings menu (see paragraph 3.2.1). each line provides information or actions referred to the corresponding peak; in particular, the information are the centroid of the peak, the energy at given centroid, the net area with relative uncertainty, FWHM (in channels) and the number of correspondences found in k_0 database for that energy; those are reported below the labels 'channel', 'E / keV', 'net area / 1', 'uncertainty', 'FWHM / 1' and 'n' respectively. Actions allow to select a specific emission from those suggested by the software using the combobox below the label 'emitter', clear the selection, visualize the peak in the spectrum profile and get more information on the selected emission via    buttons. When dealing with calibration spectra all these actions but  *Go to peak* are disabled. The  button promptly adjust the x -axis of the spectrum profile plot to center the corresponding peak.

Back to the Detector characterization window, the spectra appearing in the spectra listbox can

also be deleted from the corresponding position by the  *Delete the selected spectra* button. The selector next to it allows to choose if only the selected spectrum should be deleted or all spectra of the current position; in both cases, a confirmation subwindow will be prompted. Note that this action does not delete from disc the original files of peak lists and spectra.

At the bottom of this section the Peak-to-Total (PT) region is found. Here, three buttons are present to perform an evaluation of PT for the current position, , insert PT data manually, , and displays PT data, .

PT is a key component to calculate coincidence corrections for closer counting positions and is, to some extent, independent from the rest of detector characterization meaning that a different reference source might be used with completely different emissions; due to this particularity, it is always suggested to perform the PT evaluation before the regular detector characterization. PT evaluation is achievable by pressing  or  button. In the first case an automatic evaluation based on acquisition of true-coincidence emissions is performed.

A subwindow will open requiring the introduction of all the needed information such as the background and true-coincidence free emissions spectra acquired at current position (Figure 15).

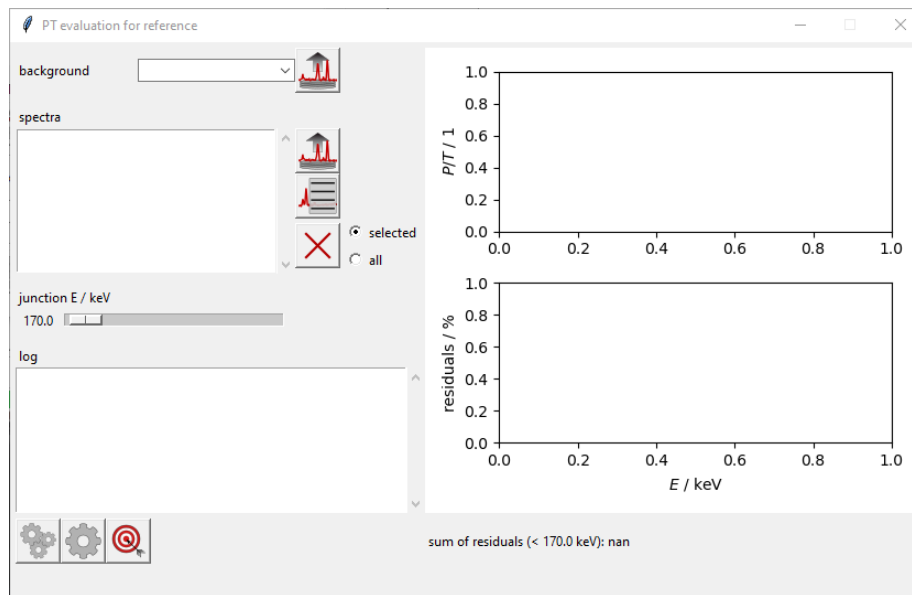





Figure 15: The PT evaluation window


Management of spectra is done with the usual buttons (, , and ). It is worth to note that if a background is already selected in the main window, as well as reference emission spectra in the current position, they are automatically recalled in the PT evaluation window. The slider below the label 'junction E / keV' indicates the energy where the software will set the discontinuity between the two equations used to draw the PT curve; in particular, below said point

a polynomial exponential equation is adopted while above that point a linear exponential equation is adopted, respectively [3] (eq. 1),

$$PT = \begin{cases} 10^{p_1(\log_{10} x)^2 + p_2 \log_{10} x + p_3} & \forall x : 0 < x \leq E_{\text{junction}} \\ 10^{s_1 \log_{10} x + s_2} & \forall x : x > E_{\text{junction}} \end{cases} \quad (1)$$

While x represents the energy of emission, parameters p_1 , p_2 and p_3 define the polynomial fit and parameters s_1 and s_2 define the straight line fit, respectively.

The log box in the lower part of the window and graphs at the right-hand side will display useful information while the evaluation process is started.

Once all the required information are introduced, the click of  button starts the PT evaluation; the process inquires the presence of the background spectrum and checks whether the number of channels corresponds to that of the reference emission spectra, then, reads the reference source file to retrieve information related to the true-coincidence free emissions and looks for the presence of corresponding γ -peaks in the acquired spectra. For each found emission the software gathers the information of net peak area from peaklist and calculates the total spectrum area, T , by subtracting the integral of the live time corrected background to the integral of spectrum profile, eq. 2:

$$T = \sum_{i=\text{channel}_0}^{\text{channel}_n} \text{counts}_{\text{src}}(i) - \frac{t_{\text{l src}}}{t_{\text{l bkg}}} \text{counts}_{\text{bkg}}(i), \quad (2)$$

with index i spanning over the number of spectra channels for the emitter source (subscript src) and background (subscript bkg), respectively, with the latter adjusted to comply the live time of the former. On top of that a further correction is also introduced at low channel numbers in order to take into account the lower energies being filtered by the discriminator; thus, a constant extrapolation until 0 energy is performed taking as reference the maximum count value among the first 20 channel with non-zero counts. Finally, in order to avoid non-physical behaviors all corrected channels showing a negative count are set to 0.


At this point, the dataset which is composed by energies and PTs (net area of peak divided by total spectrum profile) is split depending of the selected E_{junction} ; data coming from energies greater than E_{junction} are fitted with the corresponding linear equation (eq. 1). Once parameters s_1 and s_2 are obtained, the remaining part of dataset is fitted by minimizing the sum of residual function, σ_{res} , performed on the logarithm of first equation in 1:


$$\sigma_{\text{res}} = \sum (y_{\text{exp}} - p_1 (\log_{10} x)^2 + p_2 \log_{10} x + p_3)^2, \quad (3)$$

where, y_{exp} represents the experimental PT values.

On top of that, a couple of constraints are added to the minimization process in order to assure continuity around the E_{junction} point; to this aim the first derivative of the polynomial fitting equation is forced equal to the slope of the linear fitting equation and equality of y between the two fits is imposed at $x = E_{\text{junction}}$ point (eq. 4).

$$\begin{cases} 2p_1 \log_{10} E_{\text{junction}} + p_2 - s_1 = 0 \\ p_1 (\log_{10} E_{\text{junction}})^2 + p_2 \log_{10} E_{\text{junction}} + p_3 - (s_1 \log_{10} E_{\text{junction}} + s_2) = 0 \end{cases} \quad (4)$$

Whether a successful elaboration is completed a textual log will appear in the log box together with plots of experimental points, fitting curves and residuals in the graphics at the right-hand side. Moreover, a value identified as sum of residuals, including only data with energy below E_{junction} , is reported at the bottom of the graphics and is intended as an aid for the minimization of E_{junction} value itself since this task it is not performed automatically. Anytime the E_{junction} value is changed by the corresponding slider,  button has to be clicked again to confirm the new value.

The  button allows to manually tweak the values of the dataset, computed on the experimental data, if some mistake is suspected to be happened.

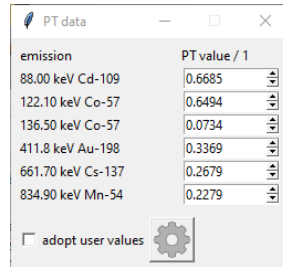





Figure 16: The window to manually tweak PT dataset

The subwindow (Figure 16) lists any energy and PT value, the latter is presented in a spinbox allowing manual modification. To make the dataset changes effective, the box with label 'adopt user values' should be checked before clicking the  button.

Finally the  *Confirm elaboration* button saves the current PT evaluation for the corresponding counting position.

The second PT evaluation method consists in the manual introduction (or modification) of the fitting parameters. By pressing the  button a subwindow appears with room to change the

value of any parameter and a plot to see the outcome due to the updated values (Figure 17).

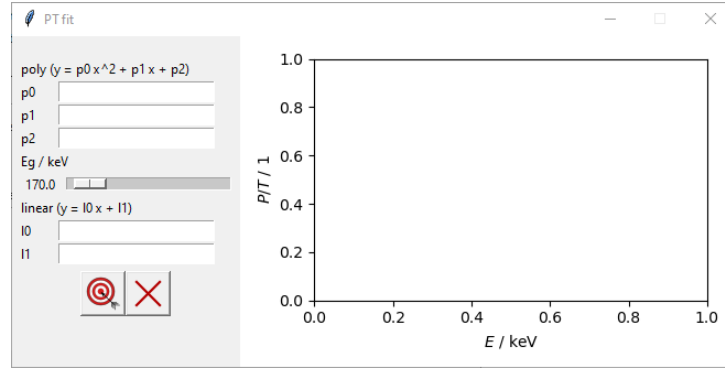











Figure 17: The window to manually tweak PT fitting parameters

The  *Save PT evaluation* button confirms the changes and updates the plot while the  *Delete PT evaluation* button deletes the current PT evaluation.

Independently from the evaluation method chosen, when a PT elaboration is saved for a certain counting position the button  becomes  making clear that the PT is now available for said position; clicking the  button shows the actual PT fitting parameters and plot similar to Figure 17 but with all options disabled. It is worth to note that the PT computation is issued without uncertainty evaluation, the uncertainty for the whole true-coincidence correction will be given.

The penultimate section in the Detector characterization window allows to recall plots at the various counting positions to have a glimpse of the fits, this is a useful resource in combination with the log box lying at the right-hand side of the window where textual information are reported. The selection of the plot is performed by the combobox below the label 'plot results' and the plot is visualized by clicking on the  *See details of fits* button; two types of plot can be recalled, a so-called position plot which shows information (ε or $k_{\varepsilon\Delta d}$ and d'_0 , see for reference) about a single counting position and the so-called emission plot which shows information (variation of count rate depending on counting position) about a single reference source emission. Each plot is accompanied by a further graphics bearing relative residuals information.

At the bottom of the window the two  *Elaborate detector characterization* and  *Save the current detector characterization* buttons allow to perform the corresponding actions.

By pressing the  button the elaboration starts. The first task consists of an integrity check to test whether all required information are correctly introduced. The software gathers data about the selected emissions of the reference source and looks for them in the spectra of reference position, with the discriminant being the ΔE setting in section 3.2.1. A unique peak must be assigned to the

reference emission; if the routine identifies multiple peaks assignable to the same emission, the one with the lowest statistical uncertainty is automatically selected (when this happens a notification is raised with detail of the selected peak). Otherwise, if for a certain emission no suitable peaks are found in the spectra, the emission is neglected for all the following calculations.

For any emission identified in the spectra at reference counting position information concerning channel centroid, literature energy taken by the source file, FWHM, efficiency and efficiency relative uncertainty are returned. The latter two data, denoted with ε and $u_r(\varepsilon)$, are calculated by means of experimental and literature input parameters:

$$\varepsilon = \frac{n_p \lambda t_c e^{\mu(1-\frac{t_1}{t_c})}}{t_1 e^{\lambda t_d} (1 - e^{\lambda t_c}) \Gamma A}, \quad (5)$$

where, n_p is the identified net peak area, λ is the emitter decay constant, t_c and t_1 are the real and live counting time, respectively, t_d is the decay time with respect to the certificate date, μ is the excess counting loss constant of the detection system, Γ is the emission gamma yield and A is the activity of the emitter. The relative uncertainty of ε is then assumed equal to the relative statistical uncertainty of the peak area.

Energy, FWHM and efficiency fits are calculated on data obtained in the previous process. For energy, a linear equation is adopted:

$$E = b_1 ch + b_2, \quad (6)$$

where, b_1 and b_2 are fitting parameters and ch is the channel number. For FWHM, a squared linear equation is preferred:

$$\text{FWHM} = \sqrt{c_1 ch + c_2}, \quad (7)$$

where, c_1 and c_2 are fitting parameters and ch is the channel number. Efficiency data are fitted with an exponential polynomial equation [8]:

$$\varepsilon = e^{a_1 E + a_2 + a_3 E^{-1} + a_4 E^{-2} + a_5 E^{-3} + a_6 E^{-4}}, \quad (8)$$

where, a_1 , a_2 , a_3 , a_4 , a_5 and a_6 are fitting parameters and E is the energy expressed in MeV. While energy and FWHM curves only affect detection limits calculations, efficiency fit (at reference) is key for the calculation of $k_\varepsilon \Delta E$ parameter. All these fits are returned with covariance matrices for uncertainty evaluation.

Calculations on all other counting positions are performed by selecting the true-coincidence free emissions from the reference source. The coincidence free emissions are looked for in the spectra of all positions and a 2d array including emissions count rate at every position is obtained:

$$\begin{array}{ccccccc}
C_{0,\text{ref},E_1} & C_{0,\text{ref},E_2} & C_{0,\text{ref},E_3} & C_{0,\text{ref},E_4} & C_{0,\text{ref},E_5} & \dots & C_{0,\text{ref},E_n} \\
C_{0,\text{pos } 1,E_1} & C_{0,\text{pos } 1,E_2} & C_{0,\text{pos } 1,E_3} & C_{0,\text{pos } 1,E_4} & C_{0,\text{pos } 1,E_5} & \dots & C_{0,\text{pos } 1,E_n} \\
C_{0,\text{pos } 2,E_1} & C_{0,\text{pos } 2,E_2} & C_{0,\text{pos } 2,E_3} & C_{0,\text{pos } 2,E_4} & C_{0,\text{pos } 2,E_5} & \dots & C_{0,\text{pos } 2,E_n} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
C_{0,\text{pos } n,E_1} & C_{0,\text{pos } n,E_2} & C_{0,\text{pos } n,E_3} & C_{0,\text{pos } n,E_4} & C_{0,\text{pos } n,E_5} & \dots & C_{0,\text{pos } n,E_n}
\end{array} \tag{9}$$

where, C represents a value of count rate evaluated at a certain time, for a well defined emission energy and at a counting position, in particular, C is calculated similarly to eq. 5:

$$C_0 = \frac{n_p \lambda t_c e^{\mu(1-\frac{t_1}{t_c})}}{t_1 e^{\lambda t_d} (1 - e^{\lambda t_c})}, \tag{10}$$

where C_0 is the count rate reported at a defined time, also in this case it is the reference certificate date.

The array in 9 is normalized with respect to the corresponding count rates at reference position and squared in order to get a pseudo linear trend of the normalized count rate over the counting distance along the columns [8].

$$\begin{array}{ccccccc}
1 & 1 & 1 & 1 & 1 & \dots & 1 \\
\sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 1,E_1}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 1,E_2}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 1,E_3}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 1,E_4}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 1,E_5}}} & \dots & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 1,E_n}}} \\
\sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 2,E_1}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 2,E_2}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 2,E_3}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 2,E_4}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 2,E_5}}} & \dots & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 2,E_n}}} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
\sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } n,E_1}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } n,E_2}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } n,E_3}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } n,E_4}}} & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } n,E_5}}} & \dots & \sqrt{\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } n,E_n}}}
\end{array} \tag{11}$$

In case values from matrix 11 are missing or not recognized by the software, the whole column will be dismissed for the following calculations. If the number of non-missing values along a column is more or equal to 4 (in matrix 11 at least 4 counting positions should be covered), a three-parameters polynomial fit is performed along each column to describe their $\sqrt{\frac{C_{0,\text{ref},E}}{C_{0,\text{pos } n,E}}}$ pseudo linear trend over

distance:

$$\sqrt{\frac{C_{0,\text{ref}}}{C_{0,d}}} = r_1 d^2 + r_2 d + r_3, \quad (12)$$

where, r_1 , r_2 and r_3 are fitting parameters and d is the distance from detector end-cap in mm, deduced from the counting positions. These fitting parameters are used to calculate the d'_0 value (the distance inside the detector providing the maximum γ -absorption [8]) at any counting position and energy. The d'_0 is evaluated by assuming a linearization of the trend along the distance:

$$y = r'_1 x + r'_2 \quad (13)$$

where, y is the linearized $\sqrt{\frac{C_{0,\text{ref}}}{C_{0,\text{pos}}}}$ trend, x is the independent variable (distance from detector end-cap), r'_1 and r'_2 are the linearized parameters that can be defined in terms of r_1 , r_2 and r_3 :

$$r'_1 = \frac{\partial y}{\partial d} = 2r_1 d + r_2, \quad (14)$$

$$r'_2 = y - r'_1 d = -r_1 d^2 + r_3. \quad (15)$$

The wanted d'_0 value is obtained by solving eq. 13 for x while $y = 0$, each time substituting d with the distance of a counting position:

$$d'_0 = -\frac{r'_2}{r'_1} = -\frac{-r_1 d^2 + r_3}{2r_1 d + r_2}, \quad (16)$$

where, d represents the distance at a certain counting position. Since d'_0 values are expected to be negative (due to the fact that they represent a distance inside the detector while the origin is on the end-cap), if they turn out as positive they are discarded since cannot be accepted for following processes. Uncertainties of d'_0 are taken into account by propagating uncertainties of parameters in the eq. 16.

A 2d array including d'_0 values for every position and energy is finally obtained, 17.

$$\begin{array}{ccccccccc}
d'_0(\text{ref}, E_1) & d'_0(\text{ref}, E_2) & d'_0(\text{ref}, E_3) & d'_0(\text{ref}, E_4) & d'_0(\text{ref}, E_5) & \dots & d'_0(\text{ref}, E_n) \\
d'_0(\text{pos } 1, E_1) & d'_0(\text{pos } 1, E_2) & d'_0(\text{pos } 1, E_3) & d'_0(\text{pos } 1, E_4) & d'_0(\text{pos } 1, E_5) & \dots & d'_0(\text{pos } 1, E_n) \\
d'_0(\text{pos } 2, E_1) & d'_0(\text{pos } 2, E_2) & d'_0(\text{pos } 2, E_3) & d'_0(\text{pos } 2, E_4) & d'_0(\text{pos } 2, E_5) & \dots & d'_0(\text{pos } 2, E_n) \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
d'_0(\text{pos } n, E_1) & d'_0(\text{pos } n, E_2) & d'_0(\text{pos } n, E_3) & d'_0(\text{pos } n, E_4) & d'_0(\text{pos } n, E_5) & \dots & d'_0(\text{pos } n, E_n)
\end{array} \quad (17)$$

From calculated d'_0 points for each counting position (along the rows of 17), an exponential polynomial weighted fit (eq. 18) is performed after first guess parameters are evaluated by performing a similar unweighted fit on $\ln |d'_0|$ values:

$$d'_0 = -e^{z_1 E + z_2 + z_3 E^{-1} + z_4 E^{-2} + z_5 E^{-3}}, \quad (18)$$

where, z_1, z_2, z_3, z_4 and z_5 , are fitting parameters and E is the emission energy in MeV. These fits will be adopted in case geometrical corrections are needed (small variability on nominal counting positions, extended samples).

In order to account the situation when sample and standard are acquired in different counting positions, a parameter called $k_{\varepsilon \Delta d}$ is introduced defining the efficiency ratio at reference position with respect to any other counting position [9]; its value is experimentally evaluated as in 11 but without applying the square root:

$$\begin{array}{ccccccccc}
1 & 1 & 1 & 1 & 1 & \dots & 1 \\
\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 1,E_1}} & \frac{C_{0,\text{ref},E_2}}{C_{0,\text{pos } 1,E_2}} & \frac{C_{0,\text{ref},E_3}}{C_{0,\text{pos } 1,E_3}} & \frac{C_{0,\text{ref},E_4}}{C_{0,\text{pos } 1,E_4}} & \frac{C_{0,\text{ref},E_5}}{C_{0,\text{pos } 1,E_5}} & \dots & \frac{C_{0,\text{ref},E_n}}{C_{0,\text{pos } 1,E_n}} \\
\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } 2,E_1}} & \frac{C_{0,\text{ref},E_2}}{C_{0,\text{pos } 2,E_2}} & \frac{C_{0,\text{ref},E_3}}{C_{0,\text{pos } 2,E_3}} & \frac{C_{0,\text{ref},E_4}}{C_{0,\text{pos } 2,E_4}} & \frac{C_{0,\text{ref},E_5}}{C_{0,\text{pos } 2,E_5}} & \dots & \frac{C_{0,\text{ref},E_n}}{C_{0,\text{pos } 2,E_n}} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{C_{0,\text{ref},E_1}}{C_{0,\text{pos } n,E_1}} & \frac{C_{0,\text{ref},E_2}}{C_{0,\text{pos } n,E_2}} & \frac{C_{0,\text{ref},E_3}}{C_{0,\text{pos } n,E_3}} & \frac{C_{0,\text{ref},E_4}}{C_{0,\text{pos } n,E_4}} & \frac{C_{0,\text{ref},E_5}}{C_{0,\text{pos } n,E_5}} & \dots & \frac{C_{0,\text{ref},E_n}}{C_{0,\text{pos } n,E_n}}
\end{array} \quad (19)$$

Fits for $k_{\varepsilon \Delta d}$ data are performed for each counting position (along the rows of 19) using an exponential polynomial unweighted fit (eq. 20):

$$k_{\varepsilon \Delta d_{\text{ref}}} = e^{j_1 E + j_2 + j_3 E^{-1} + j_4 E^{-2} + j_5 E^{-3} + j_6 E^{-4}}, \quad (20)$$

where, $k_{\varepsilon \Delta d_{\text{ref}}}$ denotes the efficiency ratio of the currently investigated positions referred to the reference counting position, j_1, j_2, j_3, j_4, j_5 and j_6 are fitting parameters and E is the energy in


MeV. The covariance matrix of the parameters is also returned in order to be able to evaluate the uncertainty of the curve. A check on the parameters' uncertainty is performed after a successful fit elaboration and the parameter which highest relative uncertainty, if is above the limit set in the settings window (see section 3.2.1), is discarded; the fit (and subsequent check) is reiterated until the condition is satisfied or in case only 4 fitting parameters are left.

During the elaboration process the software looks for PT fits already performed and includes them in the current characterization instance; if PT fits are missing in some position, a default value of 0 is adopted and coincidence corrections won't take place for those counting positions. It is thus necessary to manage PT elaborations before starting the detector characterization computation.


When a successful detector characterization is concluded, a confirmation message will appear while the logbox is compiled with useful information and the plot result section becomes active to display plots. If the elaboration stops due to some problem, the logbox should report the occurrence causing the halt. Anyway, the most causes of error might be:

- biases in the peaks of the peaklist or a non-suitable ΔE parameter resulting in mis-identification of peaks,
- errors in introduction of distances for counting positions,
- errors in introduction of distances for counting positions.



The  button allows to save the successful elaboration with filename chosen in the entry with label '**name**'. The process creates three files with the same name but different extensions that are saved in the «characterization» folder: the actual data recalled by the software (.pos), a copy of logfile (.txt) and a copy of the plots for fitted and experimental values (.pkl). It is worth to note that while saving, the software does not check if files with same name are already present in the folder, thus, it will overwrite those without asking for permission.

3.3.2 Delete detector characterization

If a previously saved detector characterization is selected from the combobox it can be deleted from disc by pressing the  button; a confirmation subwindow will appear before completing the procedure.

3.3.3 Rename detector characterization



If a previously saved detector characterization is selected from the combobox it can be renamed by pressing the  button; a subwindow will appear to type the new name (Figure 18).



Figure 18: The characterization rename subwindow

Pressing the enter key from keyboard allows to check the validity of the new name and confirm it, if successful.

3.3.4 Display detector characterization

If a previously saved detector characterization is selected from the combobox its information can be displayed by pressing the  button; this will open a subwindow recalling all information concerning the characterization that are stored on disc (Figure 19):

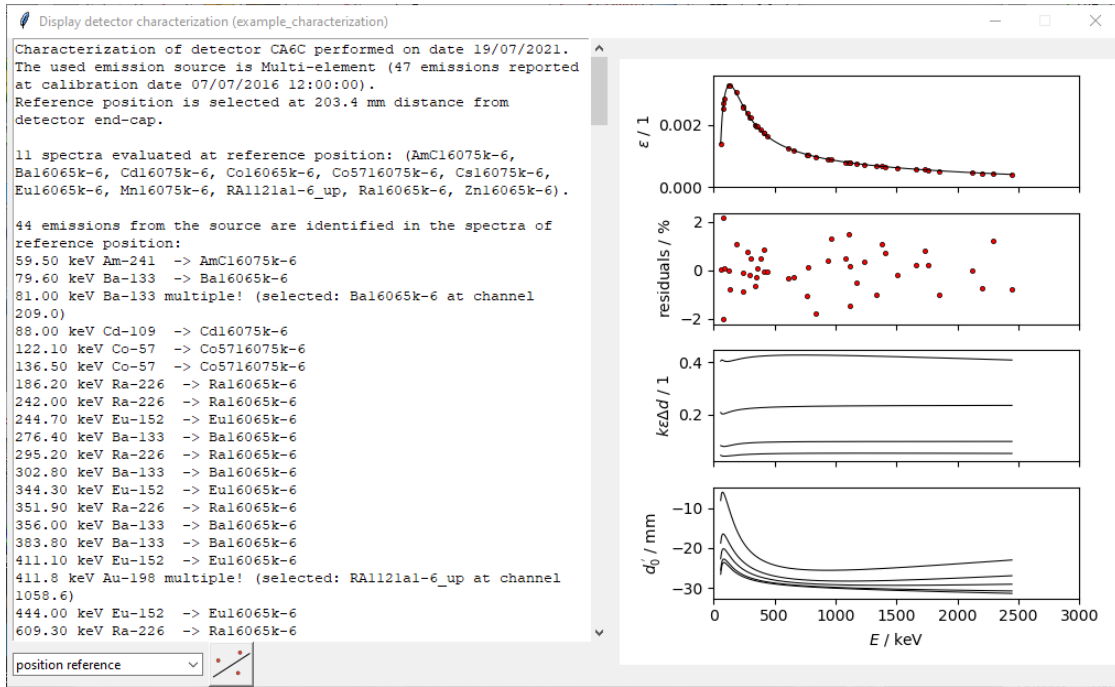



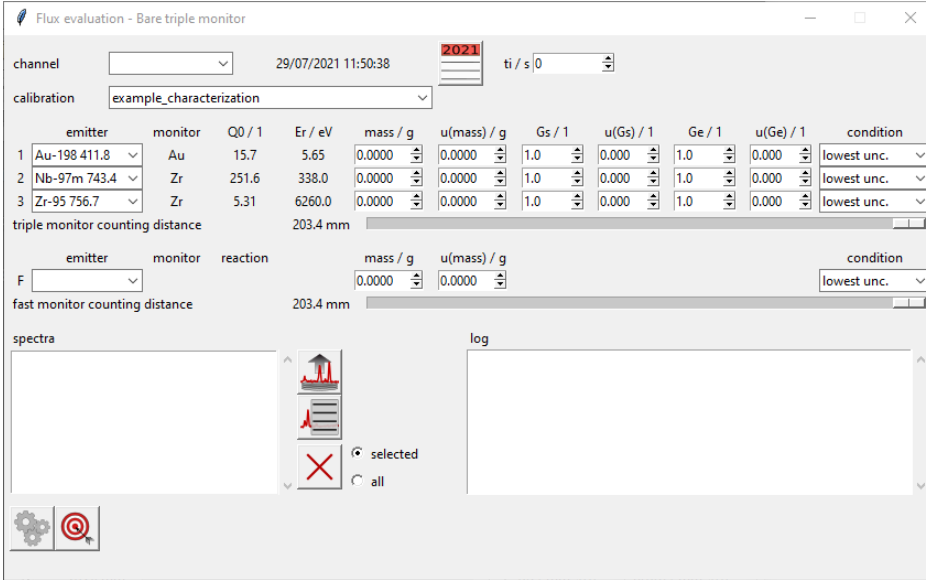
Figure 19: The detector characterization display subwindow

On the left-hand side the log is reported while on the right-hand side a summary of plots for detection efficiency at reference position, relative residuals of detection efficiency, $k_{\varepsilon\Delta d_{\text{ref}}}$ values at counting positions other than reference and d'_0 values at all counting positions. At the bottom-left of the window a region similar to the 'plot results' in new detector characterization window (see section 3.3.1) is present; similarly, this allows to display plots recorder during the characterization process.


3.3.5 Flux evaluation

The flux evaluation process, accessible with  button, introduces the capability to elaborate measurement of neutron flux parameters by means of the bare triple monitor method [citation].

The bare triple monitor consists in the co-irradiation of a flux monitor set (usually containing Au and Zr) and subsequent acquisition of activated nuclides to measure neutron flux parameters. The instance of the method implemented in this software is able to evaluate the thermal to epithermal conventional flux ratio (f), correction to the E^{-1} epithermal flux trend (α), conventional thermal flux (Φ_{th}), conventional epithermal flux (Φ_e), and fast flux (Φ_f), all defined within the Hogdahl convention.



Flux evaluation - Bare triple monitor

channel: 29/07/2021 11:50:38  ti / s:




calibration:

emitter	monitor	Q0 / 1	Er / eV	mass / g	u(mass) / g	Gs / 1	u(Gs) / 1	Ge / 1	u(Ge) / 1	condition
1 Au-198 411.8	Au	15.7	5.65	0.0000	0.0000	1.0	0.000	1.0	0.000	lowest unc.
2 Nb-97m 743.4	Zr	251.6	338.0	0.0000	0.0000	1.0	0.000	1.0	0.000	lowest unc.
3 Zr-95 756.7	Zr	5.31	6260.0	0.0000	0.0000	1.0	0.000	1.0	0.000	lowest unc.

triple monitor counting distance: 203.4 mm

emitter: monitor: reaction: mass / g: u(mass) / g: condition:


fast monitor counting distance: 203.4 mm

spectra   selected  all

log




Figure 20: The bare triple monitor subwindow

The flux evaluation subwindow requires multiple information concerning the measurement experiment. In particular, the name of the channel being investigated is entered in the entry labeled 'channel'; commas are not allowed in the channel name. The time of end irradiation for the mon-



itor set is modified with the  button, the default being the current date; the irradiation time in s is entered in the spinbox labeled 'ti / s'. The detector characterization in use is selected,


among the stored ones, by the combobox labeled 'calibration'; the choice of the characterization activates the independent sliders labeled 'triple monitor counting distance' and 'fast monitor counting distance' allowing to select the counting distances used for acquisition of the corresponding monitors. While the monitor for fast flux might be acquired at different distance with respect the triple monitor, the three emitters composing the triple monitor have to be acquired at the same position with respect to each other (and likely as far as possible to detector end-cap) to assure minimum measurement uncertainty.

For each monitor (the triplet labeled as '1', '2' and '3' and the fast labeled as 'F') a line of information has to be filled. For each one the emitter has to be identified by means of the combobox below the label 'emitter'. Said combobox includes all emitters from Au and Zr by default, however, additional emitters might be added by writing the atomic symbols of their targets, separated by a space, in the first line of «flux.txt» file found in the «monitor_elements» folder. The software will search the k_0 database for any emission obtained from the targets in the «flux.txt» file which undergo activation-decay types I or IIA. Mass of the element in the monitor and its uncertainty are required in the corresponding spinboxes labeled 'mass / g' and 'u(mass) / g'. Room to insert self-shielding corrections for the triple monitor set (thermal and epithermal) is placed in the corresponding spinboxes labeled 'Gs / 1', 'u(Gs) / 1', 'Ge / 1' and 'u(Ge) / 1', respectively. The combobox labeled 'condition' allows to choose various condition to discriminate the peak to adopt for calculation when multiple spectra of the monitor set are recalled; the options are: 'lowest unc.' selecting the peak with lowest statistical uncertainty, 'shortest' selecting the peak found in the spectrum with smaller live time, 'longest' selecting the peak found in the spectrum with greater live time, 'earliest' selecting the peak found in the spectrum acquired after shorter decay time, 'latest' selecting the peak found in the spectrum acquired after longer decay time.

The listbox in the bottom left-hand side, labeled 'spectra', lists all the recalled spectra adopted for the evaluation; the three , , and  buttons allow to perform actions such as import, display and delete spectra, respectively.

The textbox in the bottom right-hand side, labeled 'log' provides useful information when a successful elaboration is completed.

At the bottom of the window the two  *Compute flux parameters* and  *Confirm obtained values* buttons allow to perform the corresponding actions.

The  button starts the elaboration process by searching the recalled spectra to find the peaks related to the selected monitors, successively, specific count rate (C_{sp}) is calculated for each emitter (eq. 21 for type I activation-decay, eq. 22 for type IIA activation-decay).

$$C_{sp} = \frac{n_p \lambda t_c}{t_l (1 - e^{-\lambda t_l}) e^{-\lambda t_d} (1 - e^{-\lambda t_c}) COI m}, \quad (21)$$

$$C_{\text{sp}} = \frac{n_p (\lambda_3 - \lambda_2) t_c}{t_l \text{COI} m \left(\frac{\lambda_3}{\lambda_2} (1 - e^{-\lambda_2 t_i}) e^{-\lambda_2 t_d} (1 - e^{-\lambda_2 t_c}) - \frac{\lambda_2}{\lambda_3} (1 - e^{-\lambda_3 t_i}) e^{-\lambda_3 t_d} (1 - e^{-\lambda_3 t_c}) \right)}, \quad (22)$$

where, n_p is the net peak area, λ is the decay constant (λ_2 and λ_3), t_c is the real counting time, t_l is the live counting time, t_i is the irradiation time, t_d is the decay time from irradiation end, COI is the true-coincidence correction factor and m is the monitor element mass. The uncertainty is estimated by propagation of the relative uncertainties of n_p , COI and m .

The α value is calculated by solving the corresponding implicit function [10]:

$$\begin{aligned} & \left(\frac{1}{\frac{C_{\text{sp},1} k_{0,2} \varepsilon_2}{C_{\text{sp},2} k_{0,1} \varepsilon_1} - 1} - \frac{1}{\frac{C_{\text{sp},1} k_{0,3} \varepsilon_3}{C_{\text{sp},3} k_{0,1} \varepsilon_1} - 1} \right) G_{e,1} \left(\frac{Q_{0,1} - 0.429}{\bar{E}_{r,1}^\alpha} + \frac{0.429}{(2\alpha + 1) 0.55^\alpha} \right) + \\ & - \left(\frac{1}{1 - \frac{C_{\text{sp},2} k_{0,1} \varepsilon_1}{C_{\text{sp},1} k_{0,2} \varepsilon_2}} \right) G_{e,2} \left(\frac{Q_{0,2} - 0.429}{\bar{E}_{r,2}^\alpha} + \frac{0.429}{(2\alpha + 1) 0.55^\alpha} \right) + \\ & + \left(\frac{1}{1 - \frac{C_{\text{sp},3} k_{0,1} \varepsilon_1}{C_{\text{sp},1} k_{0,3} \varepsilon_3}} \right) G_{e,3} \left(\frac{Q_{0,3} - 0.429}{\bar{E}_{r,3}^\alpha} + \frac{0.429}{(2\alpha + 1) 0.55^\alpha} \right) = 0, \end{aligned} \quad (23)$$

where, subscripts 1,2 and 3 indicate monitors labeled '1', '2' and '3', respectively, C_{sp} is the specific count rate at saturation (eq. 21,22), k_0 is the composite nuclear constant defined by De Corte [3], ε is the detection efficiency, G_e is the epithermal self-shielding factor, Q_0 is the resonance integral to thermal cross section ratio and E_r is the effective resonance energy.

The uncertainty of α is evaluated by reiterating eq. 23 several times while changing one input parameter at a time of a value equal \pm its standard uncertainty. Those sensitivity coefficients are propagated with the covariance matrix of input parameters to get the variance of α and, subsequently, the uncertainty.

The knowledge of α is introduced in the following calculations to evaluate f :

$$f = \frac{\frac{k_{0,2} \varepsilon_2}{k_{0,3} \varepsilon_3} G_{e,2} \left(\frac{Q_{0,2} - 0.429}{\bar{E}_{r,2}^\alpha} + \frac{0.429}{(2\alpha + 1) 0.55^\alpha} \right) - \frac{C_{\text{sp},2}}{C_{\text{sp},3}} G_{e,3} \left(\frac{Q_{0,3} - 0.429}{\bar{E}_{r,3}^\alpha} + \frac{0.429}{(2\alpha + 1) 0.55^\alpha} \right)}{G_s \left(\frac{C_{\text{sp},2}}{C_{\text{sp},3}} - \frac{k_{0,2} \varepsilon_2}{k_{0,3} \varepsilon_3} \right)}, \quad (24)$$

with its uncertainty evaluated by propagation of sensitivity coefficient and covariance matrix. It is worth to take into account that eq. 24 assumes the thermal self-shielding parameter (G_s) being the

same for the two monitors; moreover, monitor 2 and 3 are chosen since in the default configuration they represents the two monitors of Zr element, giving the best uncertainty on f evaluation as some of the parameters cancel out.

Thermal and epithermal conventional fluxes are calculated only if Au-198 441.8 keV is selected among the monitor since the software needs some literature value that, for the Au emission, is hard-coded in the file itself.

$$\Phi_{\text{th}} = \frac{C_{\text{sp,Au}} M_{\text{Au}}}{\theta_{\text{Au}} \Gamma_{\text{Au}} \varepsilon_{\text{Au}} N_A \sigma_{0,\text{Au}} \left(G_s + \frac{G_{\text{e,Au}}}{f} \left(\frac{Q_{0,\text{Au}} - 0.429}{E_{\text{r,Au}}^\alpha} + \frac{0.429}{(2\alpha+1)0.55^\alpha} \right) \right)}, \quad (25)$$

$$\Phi_{\text{e}} = \frac{C_{\text{sp,Au}} M_{\text{Au}}}{\theta_{\text{Au}} \Gamma_{\text{Au}} \varepsilon_{\text{Au}} N_A \sigma_{0,\text{Au}} \left(G_s f + G_{\text{e,Au}} \left(\frac{Q_{0,\text{Au}} - 0.429}{E_{\text{r,Au}}^\alpha} + \frac{0.429}{(2\alpha+1)0.55^\alpha} \right) \right)}, \quad (26)$$

where, the subscript Au refers to the Au-198 411.8 keV monitor, M is the molar mass, θ is the isotopic abundance, Γ is the γ -yield, N_A is Avogadro constant, σ_0 is the (n, γ) reaction cross section to 2200 m s⁻¹.


The last elaboration performed concerns the fast flux, whether a fast monitor is selected in the corresponding combobox in the flux evaluation window:

$$\Phi_{\text{f}} = \frac{C_{\text{sp,F}} M_{\text{F}}}{\theta_{\text{F}} \Gamma_{\text{F}} \varepsilon_{\text{F}} N_A \sigma_{\text{f,F}}}, \quad (27)$$

where, the subscript F refers to the selected fast monitor and σ_f is the U-235 averaged fast reaction cross section.

Uncertainty of all fluxes is evaluated by propagation of sensitivity coefficients and covariance matrix.

A successful elaboration of flux parameters fills the logbox at the right-hand side of the window with useful information about the process and results; it also gives, for α and f index of the five most important contributors to their estimated uncertainties. In addition, after a couple of

checks on the calculated results, it allows to save the obtained data with the  button. Saved information are appended to the «channel.csv» file in the «facility» folder and can be recalled by the browse databases command (see section 3.2.2).

3.3.6 Gradient evaluation

The gradient evaluation process, accessible with  button, introduces the capability to elaborate measurement of neutron flux gradients within vertical positions of an irradiation channel.

The so-defined vertical count rate gradient due to unit distance of irradiation position (β) is evaluated as the ratio of specific count rate for two known samples over the distance between their irradiation positions.

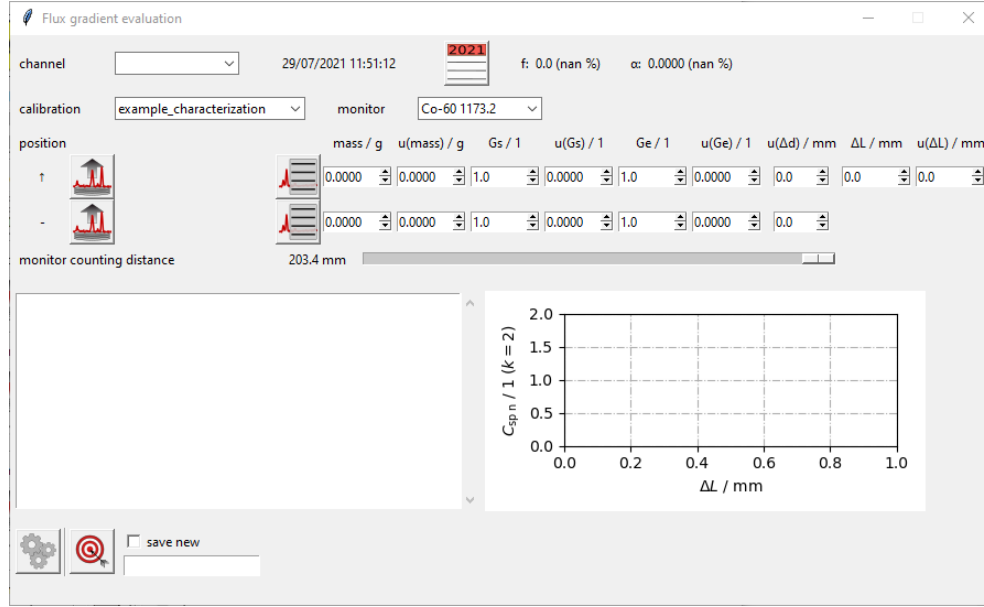





Figure 21: The flux evaluation subwindow

The flux gradient evaluation subwindow requires multiple information concerning the measurement experiment. In particular, the name of the channel being investigated is recalled by the combobox labeled 'channel'; when a channel is selected the corresponding f and α values appear in the labels 'f:', 'alpha:' at the right-hand side. The time of end irradiation for the monitor set is


modified with the  button, the default being the current date. The detector characterization in use is selected, among the stored ones, by the combobox labeled 'calibration'; the choice of the characterization activates the slider labeled 'monitor counting distance' allowing to select the counting distances used for acquisition of the corresponding monitors. The emission to be used as monitor is selected in the combobox labeled 'monitor'; all the simple activation-decay emissions present in the k_0 -database are eligible as monitor, thus, additional emitters might be added by writing the atomic symbols of their targets, separated by a space, in the first line of «gradient.txt» file found in the «monitor_elements» folder. The two monitors are identified with the labels '↑' and '↓', referring to the one placed higher and the one placed lower in the irradiation

facility, respectively. A spectrum for both monitor needs to be recalled with the  button and can be displayed with  button. Values and uncertainties for masses (labeled 'mass / g' and

'u(mass) / g'), thermal self-shieldings (labeled 'Gs / 1' and 'u(Gs) / 1'), epithermal self-shieldings (labeled 'Ge / 1' and 'u(Ge) / 1') are required in the corresponding spinboxes. In addition, uncertainty on counting positioning might be included for both monitor in the spinboxes labeled 'u(Δd) / mm'. Finally, the distance with uncertainty of the higher monitor with respect to the lower one is required in the corresponding spinbox labeled ' ΔL / mm' and 'u(ΔL) / mm'; this distance should always be positive since the reference system used for this software considers distances going upwards as positive.

In the lower part of the window a log box is found in the left-hand side and a plot in the right-hand side; those will provide useful information while starting the process.

At the bottom of the window,  *Evaluate* and  *Save elaboration* buttons allows to perform the corresponding actions.





Clicking the  starts the evaluation of gradient by retrieving literature data of the selected monitor from the k_0 -database and inspecting the spectra to find the monitor peaks. For both monitor is calculated:

$$\varsigma = \frac{n_p t_c}{t_l e^{-\lambda t_d} (1 - e^{-\lambda t_c}) m \left(\frac{d_{\text{ref}} - d'_0}{d_{\text{ref}} + \Delta d - d'_0} \right)^2 \left(G_s + \frac{G_e}{f} \left(\frac{Q_0 - 0.429}{E_r^\alpha} + \frac{0.429}{(2\alpha + 1)0.55^\alpha} \right) \right)}, \quad (28)$$

$$\beta = \frac{\frac{s_+}{s_-} - 1}{\Delta L}, \quad (29)$$

where, .

3.4 Irradiation

This section provides tasks to manage information concerning the irradiations performed on the samples to analyze. It provides a  *New irradiation* button, a combobox to recall a previously saved neutron irradiations, three  *Delete irradiation*,  *Rename irradiation*,  *Display irradiation* buttons to perform corresponding actions on the selected irradiation data.

3.4.1 New irradiation

New irradiation

The 'Irradiation' subwindow contains the following fields and controls:

- irradiation code**: A text input field.
- channel name**: A dropdown menu.
- Parameters table**: A table with two columns, 'x' and 'u(x)', each with a spin button.
- end of irradiation date**: A date field showing '30/07/2021 12:20:29' and a calendar icon.
- irradiation time / s**: A spin button set to '0.0'.
- Target icon**: A red bullseye icon with a mouse cursor.

	x	u(x)
f / 1	0.0	0.0
α / 1	0.0000	0.0000
ϕ_{thermal} / cm-2 s-1	0.00e+00	0.0e+00
$\phi_{\text{epithermal}}$ / cm-2 s-1	0.00e+00	0.0e+00
ϕ_{fast} / cm-2 s-1	0.00e+00	0.0e+00
β / mm-1	0.0000	0.0000

Figure 22: The new irradiation subwindow

3.4.2 Delete irradiation

Delete

3.4.3 Rename irradiation

Rename

The 'Irradiation' subwindow shows the rename functionality with the following elements:

- Current name**: A dropdown menu showing 'example_irradiation'.
- New name**: A text input field containing 'example_irradiation_new_name'.
- Buttons**: A red 'X' button and a green 'OK' button.

Figure 23: The rename irradiation subwindow

3.4.4 Display irradiation

Display

Display irradiation (example_...			
end of irradiation	30/08/2018 16:53:00		
	x	u(x)	ur(x)
flux exposure / s	43200.0	30.0	0.1 %
channel	IL-40		
	x	u(x)	ur(x)
f / 1	30.25	2.61	8.6 %
α / 1	-0.0060	0.0140	233.8 %
thermal flux / cm-2 s-1	1.12e+12	3.6e+10	3.2 %
epithermal flux / cm-2 s-1	3.71e+10	2.1e+09	5.7 %
fast flux / cm-2 s-1	1.39e+11	2.4e+09	1.7 %
β / mm-1	-0.0072	0.0010	13.6 %

Figure 24: The display irradiation subwindow

3.5 Background

Background

3.5.1 Open background

Open background

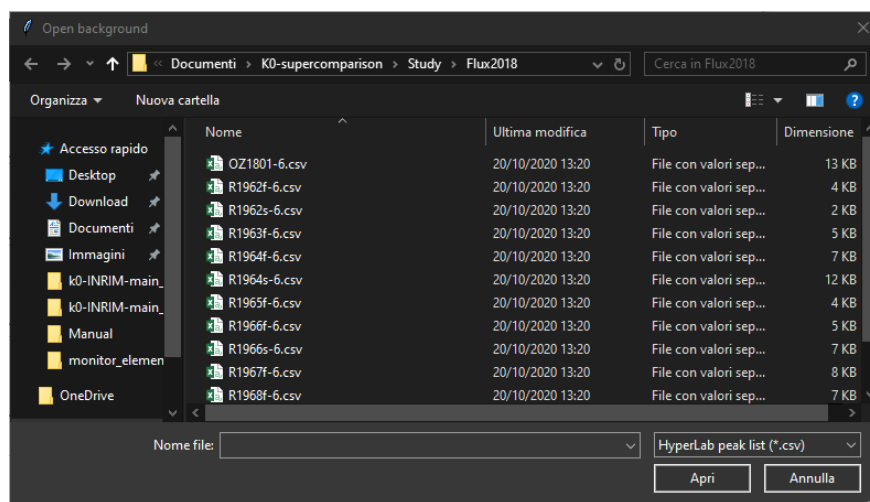


Figure 25: The window to recall spectra

3.5.2 Background peaklist

Background peaklist

3.5.3 Delete background

Delete background

3.5.4 Define sample

Define sample

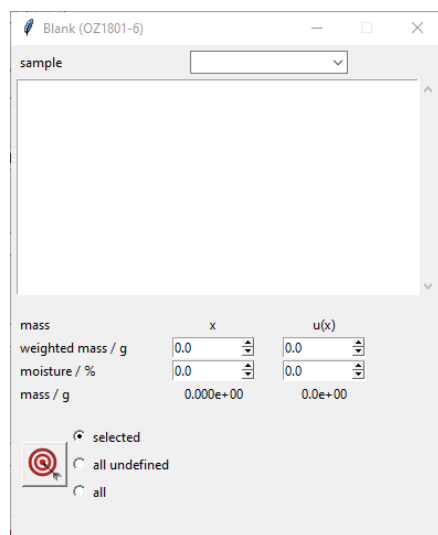


Figure 26: The window to recall spectra

3.6 Standard

Standard

3.6.1 Open standard

Open standard

3.6.2 Standard peaklist

Standard peaklist

3.6.3 Delete standard

Delete standard

3.6.4 Define sample

Define sample

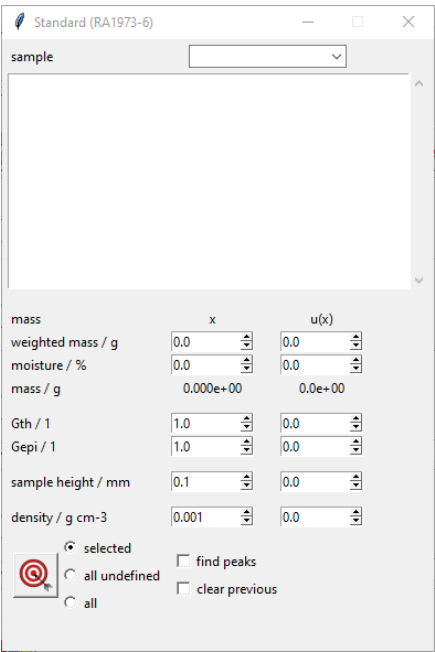


Figure 27: The window to recall spectra

3.7 Sample

Sample

3.7.1 Open sample

Open sample

3.7.2 Sample peaklist

Sample peaklist

3.7.3 Delete sample

Delete sample

3.7.4 Define sample

Define sample

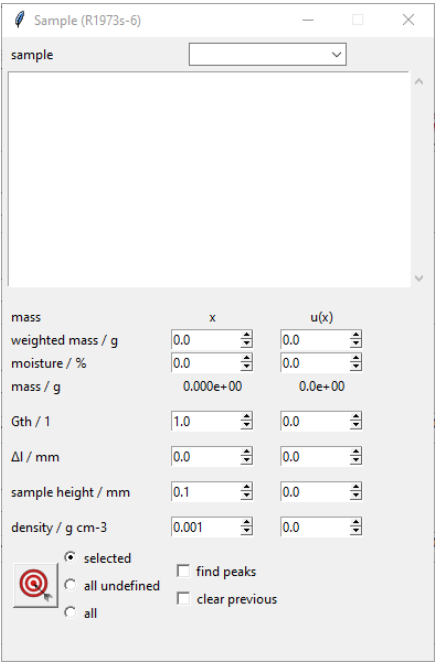


Figure 28: The window to recall spectra

3.8 Limits

Detection limits.

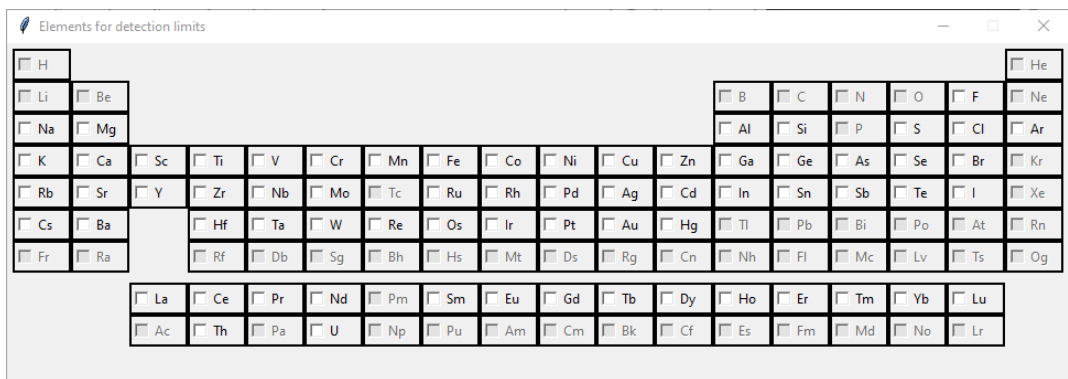


Figure 29: The element selection window

3.9 Results

Results

3.9.1 Elaborate

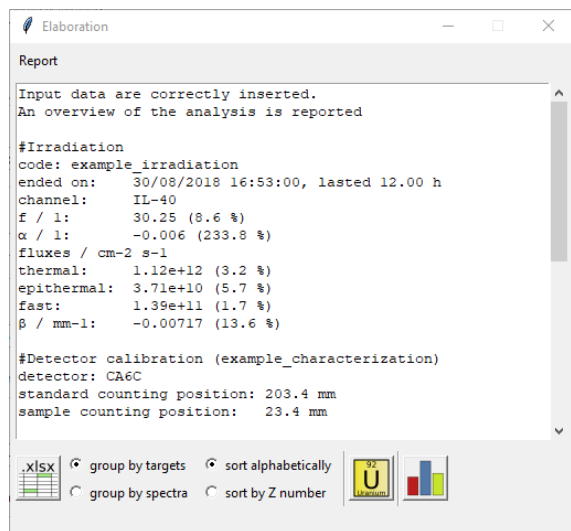


Figure 30: The element selection window

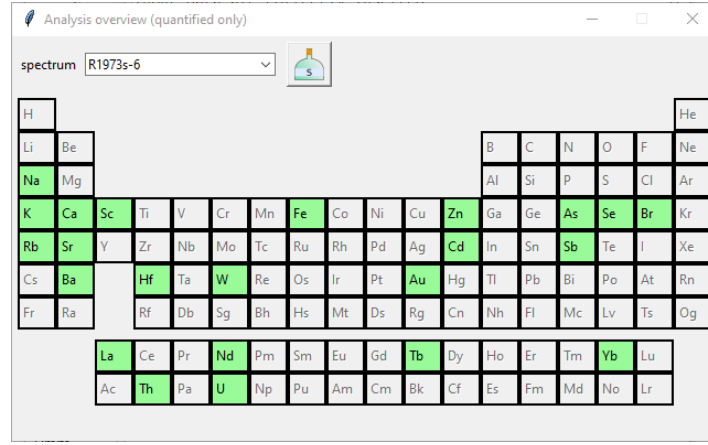


Figure 31: The element selection window

According to the GUM recommendations the following measurement model [12], adopted for computations, is displayed in the worksheet:

$$w_a = \left(\frac{\lambda \frac{(n_p/COI)(t_c/t_l)e^{\mu(1-t_l/t_c)}}{(1-e^{-\lambda t_i})(1-e^{-\lambda t_c})} \Big|_a}{\lambda \frac{(n_p/COI)(t_c/t_l)e^{\mu(1-t_l/t_c)}}{(1-e^{-\lambda t_i})(1-e^{-\lambda t_c})} \Big|_m} e^{(\lambda_a - \lambda_m)t_{d\ m} + \lambda_a \Delta t_d} \frac{1}{1 + \beta \Delta l_a} \frac{k_{0\ Au(m)}}{k_{0\ Au(a)}} \frac{G_{th\ m} + \frac{G_{e\ m}}{f} \left(\frac{Q_{0\ m} - 0.429}{E_{r\ m}^\alpha} + \frac{0.429}{0.55^\alpha(1+2\alpha)} \right)}{G_{th\ a} + \frac{G_{e\ a}}{f} \left(\frac{Q_{0\ a} - 0.429}{E_{r\ a}^\alpha} + \frac{0.429}{0.55^\alpha(1+2\alpha)} \right)} k_{\varepsilon \Delta E} \right) \quad (30)$$

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

- $\lambda = \ln(2)/t_{1/2}$ 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 γ -peak,
- COI is the true-coincidence correction factor,
- t_c and t_l are the counting and live times of the detection system,
- $t_{d\ m}$ is the decay time of the monitor,
- $\Delta t_d = t_{d\ a} - t_{d\ m}$ is the difference between the analyte and monitor decay times at their acquisition start times,
- t_i is the neutron irradiation time,

- μ is the excess counting loss constant of the detection system,
- $k_{0\text{ Au}}$ is the k_0 factor,
- G_{th} and G_{e} are the thermal and epithermal neutron self-shielding correction factors,
- f is the (conventional) sub- to epi-cadmium neutron flux ratio,
- α 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,
- \bar{E}_{r} is the effective resonance energy,
- E_{p} is the energy of the γ -peak,
- a_i are the h parameters of the model adopted to describe the full-energy γ -peak detection efficiency at the counting position, $\varepsilon_{\text{p}} = e^{\sum_{i=1}^h a_i E^{2-i}}$, with $h = 4, 5$ or 6 ,
- $\delta\varepsilon_{\text{r}}$ is the relative variation of detection efficiency per unit of vertical position,
- Δd 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.

See [2] for details

For each input quantity, X_i , the unit, $[X_i]$, the value, x_i , the standard uncertainty, $u(x_i)$, the relative uncertainty, $u_r(x_i)$, the sensitivity coefficient, c_i , and the contribution to the variance, $I / \%$ are given at the top-left of the worksheet (Figure ??). The sensitivity coefficient is obtained by calculating the equation model increasing and decreasing x_i to $x_i + u(x_i)$ and $x_i - u(x_i)$, respectively, to account for possible model non-linearity.

3.9.2 Validation of results

Validation

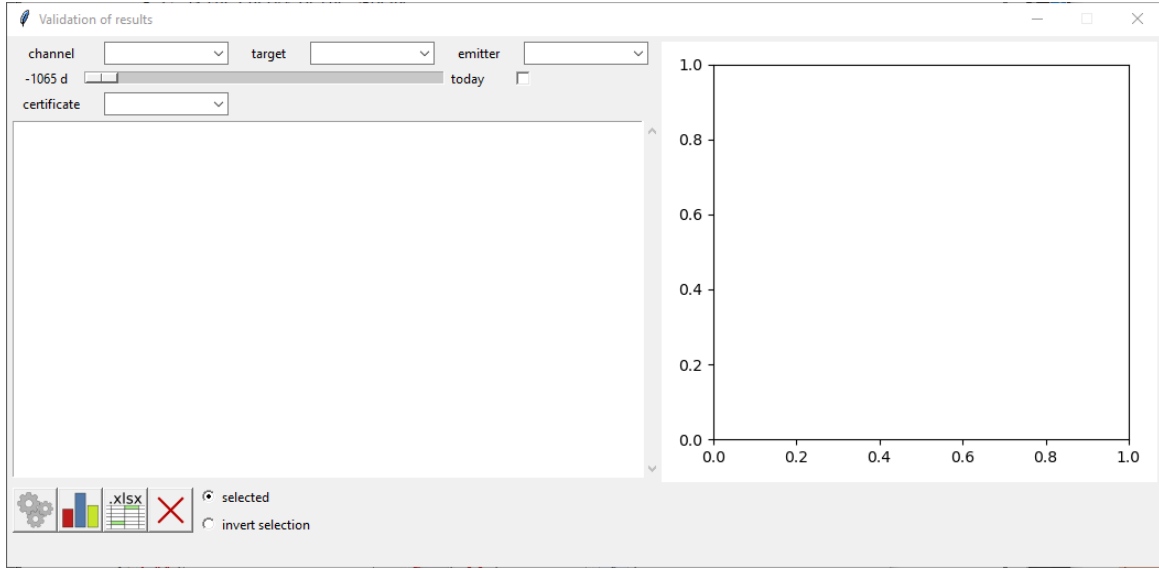


Figure 32: The element selection window

4 Sources of input quantities

Source		X_i
User template / GV ¹⁾ / HL ²⁾	x_i	$n_{p\ m}, n_{p\ a}, t_{c\ m}, t_{c\ a}, t_{l\ m}, t_{l\ a}$
	$u(x_i)$	$n_{p\ m}, n_{p\ a}$
Interface input fields	x_i	$t_i, COI_m, \mu, G_{th\ m}, G_{th\ a}, G_{e\ m}, \alpha, f, m_m, m_a, w_m$
	$u(x_i)$	$t_{c\ m}, t_{c\ a}, t_{l\ m}, t_{l\ a}, t_i, COI_m, \mu, G_{th\ m}, G_{th\ a}, G_{e\ m}, \alpha, f, \Delta d_m, \Delta d_a, m_m, m_a, w_m, \Delta t_d, t_{d\ m}, E_{p\ m}, E_{p\ a}$
Code predefined dataset	x_i	$\Delta d_m, \Delta d_a, COI_a, G_{e\ a}$
	$u(x_i)$	$\delta\varepsilon_{r\ m}, \delta\varepsilon_{r\ a}, COI_a, G_{e\ a}$
k_0 -database	x_i	$k_{0\ Au}(m), k_{0\ Au}(a), E_{r\ m}, E_{r\ a}, Q_{0\ m}, Q_{0\ a}, \lambda_m, \lambda_a, E_{p\ m}, E_{p\ a}$
	$u(x_i)$	$k_{0\ Au}(m), k_{0\ Au}(a), E_{r\ m}, E_{r\ a}, Q_{0\ m}, Q_{0\ a}, \lambda_m, \lambda_a$
Computation results	x_i	$a_i, \delta\varepsilon_{r\ m}^{3)}, \delta\varepsilon_{r\ a}^{3)}, \Delta t_d, t_{d\ m}$
	$u(x_i)$	$a_i^{4)}$

Table 1: Input quantities, X_i , grouped depending on the input source of their values, x_i , and uncertainties, $u(x_i)$. ¹⁾ ORTEC GammaVision, ²⁾ HyperLab, ³⁾ the source is the software interface if a single spectrum of the reference source is collected, ⁴⁾ the correlation matrix is included.

5 Bibliography

References

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6 Versions

o Changes of version 1.5

- implementation of the possibility to assign different counting positions to standard and sample spectra, the overall uncertainty
- COI correction automatically implemented based on the literature data from De Corte thesis
- latest k0 database (k0_database_2020_8_24) adopted by default

o Changes of version 1.2

- introduction of an additional module in the Irradiation window to automatically evaluate f and α parameters with triple bare method (Au+Zr)
- introduction of thermal flux correction factor (β) and vertical position variability in the irradiation channel in the measurement model in order to evaluate the effect of positioning in phase of irradiation
- implementation of some complex activation-decay paths (IIA and more)

o Changes of version 1.1

- installation procedure is simplified, download and installation of Anaconda package is no longer necessary nor recommended; presence of additional packages is checked during the first start-up of k0-INRIM software, however, a working internet connection is still required
- calibration window is completely redesigned and calibration savefiles now contain more information; moreover, when a new calibration is saved the calibration combobox is instantly updated, thus, the Refresh button is removed
- symbols and units not appearing correctly in the output file have been corrected
- options to reduce the number of peaks displayed in the peaklist by including a check on the maximum statistical uncertainty are added depending on the type of spectrum
- latest k0 database (k0_database_2019_04_04) adopted by default

- o Changes of version 1.01

- equation 4 is corrected (an exponent was misplaced in the previous version due to a typing error); please always refer to equation 4 reported in the current user's manual version
- figure 25 is modified according to the corrected model