PRINCEPS: TOWARDS THE AUTOMATION OF SIMULTANEOUS γ-RAY AND INTERNAL CONVERSION ELECTRON ANALYSIS*

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A tool to analyse internal conversion electron energy spectra measured simultaneously with γ rays has been developed. It is based on the calculation of an electron energy spectrum by means of obtained γ-ray data, including resolution and efficiency parameters associated with the experimental setup and its comparison with the measured spectrum. Here, we present the working principle of the tool, demonstrate its performance with a standard ^{133}Ba calibration source, and report on conversion coefficients of three transitions feeding the 9^- isomeric state in ^{190}Tl, measured in an in-beam spectroscopy experiment.

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1. Introduction

Transitions from excited states in atomic nuclei predominantly proceed via γ-ray or conversion electron emission, depending on their electromagnetic character and multipolarity. Even though the accurate measurement of the anisotropy of γ-ray emission can provide a transition's multipolarity, this approach is challenging when electron emission dominates the de-excitation of the states of interest.

In order to extract the relevant internal conversion coefficients (ICCs) from an experimental electron spectrum, the coincidence analysis with γ rays is required. This process could involve the reconstruction of the electron spectrum according to the detected γ rays, with the aim of understanding

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non-reproduced peaks. A recent example of this method can be found in Ref. [1]. A step towards automation of this process has been achieved by the development of PRINCEPS (PRogram for INternal Conversion Electron and Photon Spectroscopy), a program based on ROOT [2]. Here, we present its working principle, as well as case studies for experimental spectra collected exploiting a ^{133}Ba calibration source and ^{190}Tl in-beam data with the SAGE spectrometer [3].

2. The PRINCEPS code

The aim of PRINCEPS [4] is to generate and overlay, over the measured experimental spectrum, the contribution of internal conversion electrons based on the simultaneously measured γ-ray energy spectrum. As an input, the user needs to declare the experimentally measured γ-ray information (energy, intensity, and multipolarity) which will be used to calculate the ICCs using the BrIcc conversion coefficient calculator [5]. In the special case of E0 transitions, the emitted electron intensity has to be provided as a fraction of the γ-ray intensity of a normalising transition. A visual comparison with the experimental electron spectrum is available following an electron background subtraction.

PRINCEPS requires an input file covering the following information:

- γ-ray transitions' information for all de-excitations which have been measured simultaneously with the electron spectrum of interest. Their intensity and the mandatory information to execute the BrIcc standalone version have to be provided.
- File paths of the experimental spectra and the electron background spectrum, if the subtraction has already been addressed, or ROOT TSpectrum parameters for the definition of the background.
- Settings for fine-tuning the output histogram, such as the histogram axis range or peak-labelling options for the electrons, *i.e.* labelling of only the K-conversion electron peaks or with a line connecting the centroids of the K-, L-, and M-components.
- User-defined full width at half maximum (FWHM) experimental values at different electron energies.
- γ-ray and electron detection efficiency parameters (a, b, c, d, and e) following the expression:

$$\varepsilon(E) \equiv \varepsilon\left(x(E)\right) = \exp\left(a + b\,x + c\,x^2 + d\,x^3 + e\,x^4\right) , \qquad (1)$$

where $x = \log_{10}\left(\frac{E}{E_0}\right)$, E stands for the measured energy and E_0 is a common scale factor to avoid numerical imprecisions.

The code is not limited neither by the number of transitions nor by the atomic number, as the number of existing atomic shells is determined automatically. PRINCEPS starts by interpreting the information from the input file. Next, it calls BrIcc and produces an output file for each transition. The energy of the electrons and the ICC for each of the subshells are read and stored in matrices.

The treatment is equal for all the de-excitations included. For each transition and shell, a Gaussian is generated, where the parameters are: the centroid (electron energy), the FWHM (fitted from input values), and the area expected to be present in the experimental electron spectrum. The latter is calculated using the ICC ($\equiv \alpha$) and the measured γ-ray intensity ($n_{\gamma,\,\mathrm{meas}}$). In this sense, every simulated Gaussian area ($n_{e,\,\mathrm{meas}}$) is calculated using the following relation ('meas' stands for the measured intensity and 'emit' for the emitted one):

$$n^S_{e,\,\mathrm{meas}} = \varepsilon^S_e\, n^S_{e,\,\mathrm{emit}} = \varepsilon^S_e\, \alpha^S\, n_{\gamma,\,\mathrm{emit}} = \frac{\varepsilon^S_e}{\varepsilon_\gamma}\, \alpha^S\, n_{\gamma,\,\mathrm{meas}}\ , \tag{2}$$

where S stands for a particular atomic subshell and ε is the corresponding experimental γ-ray or electron efficiency for a given energy.

In the case of E0 transitions, the number of electrons originating from the different atomic shells is extracted using the electronic factors' ratios obtained from BrIcc. The spectrum calculated (PRINCEPS spectrum) is the result of the sum of all the electron peaks.

The experimental electron energy spectrum is background-subtracted in order to reduce the events coming from various sources. This is achieved by adopting user-defined parameters for the TSpectrum class inside ROOT. The subtraction procedure is detached from the main processing and suitable for modifications or new ROOT-based routines. This subtraction may need to be fine-tuned for each specific case, due to the fact that the statistics available should be taken into account to represent the background properly. In the case of an externally fitted background, this can be used as the background subtraction spectrum. Finally, a plot is produced by overlaying the experimental background-subtracted spectrum and the PRINCEPS one, applying the settings requested in the input. An example of a benchmark test, employing a standard ^{133}Ba calibration source, is shown in Fig. 1. An overall excellent reproduction is achieved. The residuals are the difference between the experimental spectrum and the PRINCEPS one. The current version does not consider all sources of error such as the uncertainty in efficiencies. The uncertainties are determined using the standard counting statistical error on the spectrum and the calculated electron line shape. The experimental low-energy tail of the peaks is not matched due to practical purposes, as the simulated electrons are distributed within a Gaussian. This

is not an issue because this feature is only noticeable when high statistics are present. Nonetheless, skew-Gaussian distributions can be implemented on user's demand.

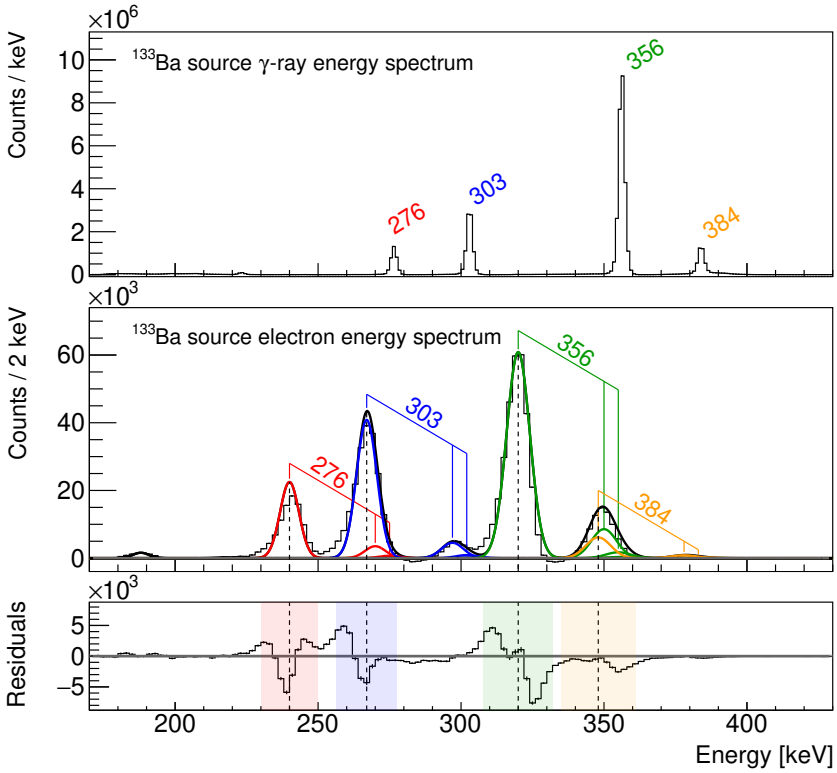

Fig. 1. (Colour on-line) γ-ray and electron energy spectrum measured with a ^{133}Ba source employing the SAGE spectrometer. The calculated spectrum obtained with PRINCEPS is overlaid with the measured one. The most prominent transitions are colour-coded, while the calculated total energy spectrum is in black. Transition energies in ^{133}Cs are labelled, whereas K-, L-, and M-components have been marked with lines. In the residuals, K-component 3σ energy widths are colour-shaded. A 3σ grey band is also shown according to the residuals uncertainty average.

3. Simultaneous in-beam γ-ray and electron spectroscopy of ^{190}Tl as a case study

An additional benchmark test was performed using the data collected during the S24 experiment [6], in the Accelerator Laboratory of the University of Jyväskylä, Finland. This experiment aimed to study ^{190}Pb via

the ^{159}Tb(^{35}Cl, $4n$) fusion–evaporation reaction employing the SAGE spectrometer coupled to the MARA separator [7, 8]. A few neighbouring nuclei were measured in the recoil-gated spectra, such as ^{190}Tl. An exemplary output from the PRINCEPS code is shown for recoil-gated spectra with a gate on the $11^- \rightarrow 10^-$ 272 keV transition of ^{190}Tl (Fig. 2). The band built above this state has been studied and conversion coefficients, as listed in Table 1, have been determined via independent fitting. The K-ICCs are compatible with pure M1 transitions, and so has been assumed for the calculation.

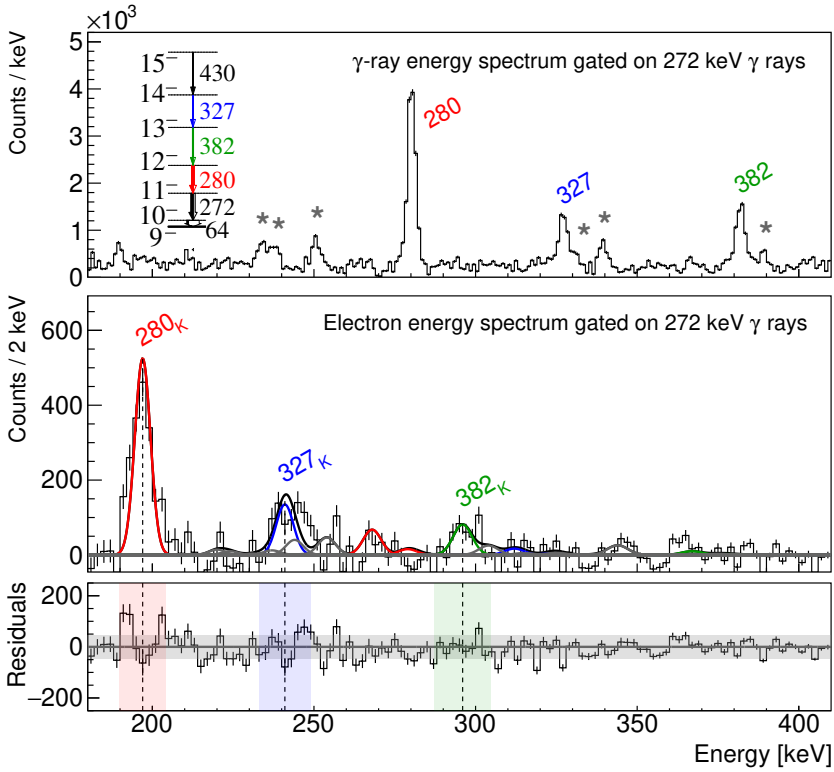

Fig. 2. (Colour on-line) Recoil-gated in-beam γ-ray (top) and electron (middle) energy spectra gated on 272 keV γ rays obtained for ^{190}Tl with SAGE. The PRINCEPS calculated spectrum is shown overlayed to the measured electron spectrum. The three most prominent transitions are colour-coded, not relevant peaks in grey, and the calculated total energy spectrum in black. The labelling refers to the K-conversion electrons. In the residuals, the main K-component 3σ energy widths are colour-shaded. A 3σ grey band is also shown according to the residuals uncertainty average. The partial level scheme of ^{190}Tl is displayed.

Table 1. Transition properties obtained for ^{190}Tl in the present work. Measured K-conversion coefficients have been compared with BrIcc [5] theoretical values for pure M1 and E2 transitions.

Energy [keV]	$J_i^\pi \to J_f^\pi$	$\alpha_{K,\mathrm{Exp}}$	$\alpha_K(\mathrm{M1})$	$\alpha_K(\mathrm{E2})$
280.5(3)	$12^- \to 11^-$	0.357(10)	0.386(6)	0.0752(11)
382.4(3)	$13^- \to 12^-$	0.196(12)	0.1668(24)	0.0364(5)
430.3(3)	$15^- \to 14^-$	0.123(20)	0.1217(17)	0.0279(4)

To conclude, an analysis using PRINCEPS starts with the determination of the setup-dependent γ-ray and electron efficiencies as well as calibration points for the energy dependence of the electron peaks' FWHM. It continues with the identification of γ-ray properties and corresponding nuclei of origin. The unknown ICCs can be obtained from the fit of the measured conversion electron peaks, either independently or from the PRINCEPS additional fitting feature. The performance has been studied under different setups and electron background profiles, not only with the SAGE spectrometer. PRINCEPS is a powerful tool as it can be used to facilitate and simplify the analysis of electron spectra when measured simultaneously with γ rays.

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