New Approach to the Analysis of Total Absorption Spectra

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Abstract. Total Absorption Spectroscopy is a powerful technique to study the Gamow-Teller β -strength in nuclei far from stability. It has not been widely used however, because of the complexity of the data analysis. We present several new improvements related to the analysis problem: a) precise numerical correction method for electronic pulse pileup, b) a Monte Carlo simulation of the response of a NaI(Tl) total absorption spectrometer that considers the light yield non-proportionality, and c) three different methods to solve the inverse problem.

The determination of the β -decay strength distribution is of fundamental importance to our understanding of the nuclear structure. Experimentally the β -strength can be determined from the β intensity or feeding probability (per unit energy interval) I_β :

$$S_\beta(E_x) = \frac{I_\beta(E_x)}{f(Q_\beta - E_x)T_{1/2}} \quad (1)$$

where f stands for the statistical rate Fermi function of the available energy in the decay $Q_\beta - E_x$ and $T_{1/2}$ is the β -decay half-life. We are particularly concerned with the investigation of the problem of the missing Gamow-Teller (GT) strength: the consistent overestimation of the strength for the transitions governed by the GT spin-isospin operator $\vec{\sigma}\vec{\tau}$. We have shown [1] that even an array of 42 large Ge detectors closely packed missed a substantial fraction of the GT strength in the ^{150}Ho (2^-) decay ($Q_{\text{EC}} = 7.4$ MeV). A solution is given by the Total Absorption Gamma-ray Spectroscopy with high efficiency scintillation detectors [2]. An ideal Total Absorption Spectrometer (TAS) with 100 % peak efficiency sums up the energy of every γ -ray cascade de-exciting a fed level in the daughter nucleus and

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FIGURE 1. Left: experimental TAS spectrum of the ^{46}Sc decay (dotted) compared with the simulated response (solid) added to the calculated pileup distortion (dashed). Right: experimental TAS spectrum of the ^{24}Na decay (dotted) compared with the simulated response (solid) added to the calculated pileup distortion (dashed). The arrow marks the region where the pileup becomes a significant contribution in the spectra.

registers a count at the corresponding level energy. The spectrum obtained is proportional to the sought $I_\beta(E_x)$. A real TAS has always limited efficiency, and the beta intensity has to be extracted from the measured spectrum using the spectrometer response. The TAS used at the GSI (Darmstadt) on-line mass separator [3] for our experiments in the ^{146}Gd and ^{100}Sn regions consists of a $\varnothing 35\text{ cm} \times 35\text{ cm}$ NaI(Tl) detector. The relation between a measured TAS spectrum $\mathbf{d}$ and the level feeding distribution $\mathbf{f}$ ($\equiv NI_\beta$, N = number of decays) is best represented by the equation:

$$d_i = \sum_{j=0}^{j_{\max}} R_{ij} f_j, \quad i = 1, i_{\max} \quad \text{or} \quad \mathbf{d} = \mathbf{R} \cdot \mathbf{f} \quad (2)$$

Each column j of the response matrix $\mathbf{R}$ represents the average response of the spectrometer to the decay into the levels in the energy bin labeled by the channel j . $\mathbf{R}$ depends on the emitted radiation as well as on the apparatus and is constructed [5] in terms of the individual quanta responses intervening in the decay. The way to accomplish this task is based on Monte Carlo simulation. The Monte Carlo code GEANT3 [6] was chosen because of its powerful geometry package, which allowed an extremely detailed modelization of the geometry of the spectrometer. It was necessary to include the non proportional light yield of NaI(Tl) [7] to γ radiation in the simulation [5]. This non-proportional light production has the striking consequence that γ -ray sum peaks are displaced in the measured spectrum with respect to single γ -ray peaks. It is no longer possible to talk strictly about an energy calibration of a TAS spectrum since the counts in a certain channel correspond to different deposited energies. In Fig.1 we compare the experimental TAS spectra (dotted) for the ^{46}Sc ($Q_{\beta^-} = 1176\text{ keV}$) –left– and ^{24}Na ($Q_{\beta^-} = 5516\text{ keV}$) –right– decays with the corresponding simulated responses (solid) added to the calculated pileup distortion (dashed). The excellent overall agreement between the simulated and

FIGURE 2. Experimental spectra for the $^{150}\text{Ho}(2^-)$ decay (dotted), corresponding reconstructed responses (solid) and difference Δ_{counts} over σ_{exp} (solid) below. Left: EC. Right: β^+ .

experimental responses reflects the quality with which $\mathbf{R}$ is obtained. The pileup distortions present in both experimental spectra is also excellently reproduced by the calculated ones (dashed). Even for low counting rates, TAS spectra have to be corrected from electronic pulse pileup distortions. Pileup happens when two or more events occur so close in time that the corresponding electronic signals overlap and are processed as a single pulse carrying a wrong amplitude information. This effect has an influence on the accurate determination of the spectrum end-point and also introduces a large deviation on the deduced β -strength. We have developed a numerical method based on the true pulse shape of the energy signals [4] that allows a very precise calculation of the distortion.

The TAS employed in our experiments allows to distinguish between the competing EC and β^+ processes. Two Si(Li) detectors surrounding the source permit to establish a coincidence between the β particles and an energy signal in the NaI(Tl), while a small Ge detector placed close and above the source allows to make the same for the characteristic X-rays emitted after the EC process. Two spectra are obtained in this way, and its independent analysis guarantees the consistency of the results. The corresponding feedings $\mathbf{f}$ fulfilling Eq.(2) are then obtained by three different methods: Linear Regularization [8], Maximum Entropy [9] and Iterative Bayesian [10]. These methods require some a priori information on the de-excitation pattern in order to construct the response matrix $\mathbf{R}$. This apparently dramatic problem is however solved by the high efficiency of our TAS and some knowledge on the low energy part of the decay scheme. Only assumptions on the branching ratios for the high energy part of the level scheme are needed. In Fig.2 we show the experimental (dotted) and reconstructed spectra (solid) corresponding to the EC –left– and β^+ –right– processes for the $^{150}\text{Ho}(2^-)$ decay. The difference Δ_{counts} between both experimental and simulated spectra relative to the experimental uncertainty are plotted below (solid) for each case indicating the accuracy obtained with the Iterative Bayesian method. The large deviations for β^+ case below channel 100 are due to a ^{150}Er contamination and have no influence in the analysis. Such a good agreement is also achieved with the two other methods. The

FIGURE 3. Feeding distributions normalized to 100 for the $^{150}\text{Ho}(2^-)$ decay obtained with the Iterative Bayesian (solid), Maximum Entropy (dotted) and Linear Regularization (dashed) methods. Left: EC. Right: β^+ .

consistency of the results obtained by the three methods shown in Fig.3 guarantees the reliability of the extracted β -feeding.

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