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A simple procedure for γ-γ lifetime measurements using multi-element fast-timing arrays

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ABSTRACT

The lifetimes of nuclear excited states are important observables in nuclear physics. Their precise measurement is of key importance for developing and testing nuclear models as they are directly linked with the quantum nature of the nuclear system. The γ-γ timing technique represents a direct lifetime determination by means of time-difference measurements between the γ rays which directly feed and decay from a nuclear excited state. Using arrays of very-fast scintillator detectors, picosecond-sensitive time-difference measurements can be performed. We propose to construct a symmetric energy–energy–time cube as is usually done to perform γ-γ coincidence analyses and lifetime determination with high-resolution germanium detectors. By construction, a symmetric mean time-walk characteristics is obtained, that can be precisely determined and used as a single time correction for all the data independently of the detectors. We present the results of timing characteristics measurements of an array with six $LaBr_3$(Ce) detectors, as obtained using a ^{152}Eu point γ-ray source. Compared with a single detector pair, the time resolution of the symmetrised time-difference spectra of the array is nearly unaffected.

1. Introduction

The standard γ-γ coincidence analysis to investigate the level scheme of a certain isotope is based on the construction of a symmetric (E_1, E_2, dt) cube. Symmetric means that the γ-ray energy projections of the E_1 and E_2 axes are equal as well as the two γ-γ time-difference spectra which are obtained when inverting the two energy selections set on the two symmetric energy axes. Indeed, the identical total time-difference spectra are inverted and mirror-symmetrically shifted from a certain reference zero time (more details are given in Section 2). This simple "time-symmetrisation procedure" is elegant and suitable for γ-γ coincidence and lifetime analyses with high-resolution germanium (Ge) detectors. The major advantage of this procedure is that the total statistics are incremented in one Ge-coincidence spectrum (with a time and an energy condition, also called "gate") or one Ge–Ge time-difference spectrum (with two energy gates). In general, detector-dependent time-walk effects (energy-dependent centroid position of prompt time distributions) are considered to be small compared to the time resolution of the Ge detectors and thus are neglected. Conventional large volume Ge detectors have a time resolution of about 6–10 ns [1].

Neglecting time-walk effects may be not appropriate when very fast scintillator detectors are used for picosecond-sensitive time-difference measurements. Although the individual detector time-walk characteristics can be adjusted, significant detector-dependent time-walk differences are observed from a real γ-γ fast-timing array. Dependent on the quality of the fast detector-output pulses and the adjustments (algorithm) of the time pick-off method (e.g. constant fraction discriminator), the time-walk differences between single detectors can be much larger than the time resolution of the individual detector [2]. Using cylindrical $1.5'' \times 1.5''$ inch $LaBr_3$(Ce) scintillators, the energy-dependent time resolution is in the range of 150–300 ps [3,4]. If the individual detector time walk is not taken into account, a degradation of the fast-timing-array time resolution is expected to result by the superposition and symmetrisation of the time-difference spectra of all detector pairs of the set-up. As a result of non-equal time-walk characteristics, asymmetric (non-Gaussian) prompt total time distributions are also expected to be obtained. Related to these problems, two different fast-timing array procedures can be found in the literature:

Procedure 1: The time differences are corrected event-by-event for the time-walk of the two corresponding detectors, and the resulting data is used to construct a time-walk corrected symmetric (E_1, E_2, dt) cube [5].

Procedure 2: An asymmetric $(E_{start}, E_{stop}, dt)$ cube is constructed by simple superposition of the data without detector-dependent time-walk corrections. A combined, so-called mean γ-γ time-walk characteristics

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is obtained, measured and used as a single correction for lifetime determination [6].

As will be reconsidered in this work, both procedures have their specific advantages but also some disadvantages. An overall simple and self-consistent procedure, which may combine the advantages of the two proposed procedures is desired by the scientific community.

2. Fast-timing considerations and the time-symmetrisation procedure

We first consider a simple γ-γ set-up with two detectors, each of them providing a time and an energy information when they are hit by a γ ray. If the two detectors are hit by two separated and time-correlated γ rays, e.g. due to the mean lifetime of an excited state, a more or less symmetric γ-γ time-difference distribution is observed. For lifetimes which are smaller than the statistical time resolving power of the set-up (about 1 ps for fast scintillators), an approximately Gaussian prompt time distribution is obtained. As will be discussed in the next sections, the prompt time distribution is not generally a symmetric Gaussian. Considering longer lifetimes ($\tau > 1ps$) and assuming that no time-correlated background contributes to the time distribution, the delayed time distribution in general corresponds to a convolution of the energy-dependent prompt time distribution $P(t)$ with an exponential decay as [7]:

$$D(t) = n\lambda \int_{t_-}^{t} P(t_0 - t')e^{-\lambda(t-t')}dt' \quad \text{with} \quad \lambda = \frac{1}{\tau}, \tag{1}$$

where n is the number of counts in the time distribution, t_0 is the centroid (centre of gravity) of $P(t)$ and t_- indicates the lower integration limit where $P(t_-) = 0$. λ and τ are the transition probability and the mean lifetime of the excited state.

2.1. The standard centroid-shift method

For lifetime determination in the sub-nanosecond region, the centroid-shift method is the most precise. The centroid of a time distribution $D(t)$ is defined as the mean value of the time over the time distribution [7,8]:

$$C[D(t)] = \langle t \rangle = \frac{\int_{t_{\min}}^{t_{\max}} t \cdot D(t)dt}{\int_{t_{\min}}^{t_{\max}} D(t)dt}. \tag{2}$$

In a realistic set-up, also uniformly distributed random coincidences (time differences) are recorded. To avoid possibly large systematic errors, the integration limits, $t_{\min}$ and $t_{\max}$, should be set just at the beginning and the end of the time distribution. The statistical error is given by the variance of $D(t)$:

$$\delta C = \sqrt{var[D(t)]} = \sqrt{\langle t^2 \rangle - \langle t \rangle^2}. \tag{3}$$

For the sake of simplicity, the time-difference is measured in one direction as:

$$dt_{21} = t_2 - t_1. \tag{4}$$

Here, detector 2 represents the stop signal and the start signal is given by detector 1. Selecting a γ ray which directly feeds a nuclear state with the start detector 1 and the decay γ ray with the stop detector 2, the well-known delayed time distribution is obtained (hereafter indicated with "d"). In the ideal case where no time-correlated Compton background contributes, the mean lifetime τ is directly determined by the centroid shift between the delayed and the corresponding prompt time distributions as [7,8]:

$$\tau = C[D_d(t)] - C[P_d(t)], \tag{5}$$

where P_d is measured under the same energy conditions as D_d. This condition cannot be delivered experimentally. The prompt time distribution, often called the "prompt response function" (PRF), is a function of the energy, which means that the centroid position, the full width at half maximum (FWHM) and the shape (the degree of asymmetry) of the PRF are dependent on the energy of the feeding and decaying γ rays. This is related to the intrinsic characteristics of the scintillator crystal (energy dependent light output [3]), the photomultiplier tube (gain variance and non-linearity [2,9]) and the time pick-off device (timing method, e.g. leading edge, and corresponding energy dependency [2,10]). In principle, precise knowledge on the experimental time-walk characteristics of the individual detectors $TW_i(E)$ is needed for centroid shift analyses. The time walk describes the energy dependent shift of the PRF centroid relative to a constant t_0. The centroid of any delayed time distribution can be written as:

$$C(D_d) = t_0 + [TW_2(E_2) - TW_1(E_1)] + \tau, \tag{6}$$

where t_0 is the reference zero time which can be measured, e.g. using the two 511-keV annihilation γ rays of ^{22}Na.

Now, the energy selection in Eq. (4) can be inverted to obtain the anti-delayed time-difference distribution ("a"). It follows:

$$C(D_a) = t_0 + [TW_2(E_1) - TW_1(E_2)] - \tau. \tag{7}$$

In general, the time-walk characteristics of the two detectors are not equal, hence:

$$TW_1(E_\gamma) \neq TW_2(E_\gamma) \tag{8}$$
$$\Longleftrightarrow |TW_2(E_2) - TW_1(E_1)| \neq |TW_2(E_1) - TW_1(E_2)|.$$

As a consequence of this "timing asymmetry", the reference zero time, which can be determined as $t_0 = [C(D_d) + C(D_a)]/2$, is not a constant but a nearly linear function of the energy difference $E_1 - E_2$ as shown in Ref. [11]. Inverting the anti-delayed time spectrum with respect to a constant t_0 and superimposing it with the delayed time spectrum would degrade the time resolution of the total time distribution. Also the shape of a total prompt time spectrum will be asymmetric. Therefore, the individual detector time-walk characteristics are proposed to be corrected before symmetrising the data with respect to a constant t_0 (*procedure 1* [5]). As the timing of a real γ-γ set-up is asymmetric, this requires a complicated iterative time-walk calibration procedure where the probability to introduce systematic errors should not be underestimated. Considering a large fast-timing array with N detectors, the tedious and possibly erroneous calibration needs to be done N times. In principle, the corrections can be verified for a residual difference between t_0 and the centroids of total prompt time distributions of the corrected and symmetrised data. This requires an additional analysis, and introduces an additional correction term to the sorting algorithm. The complex *procedure 1* is prone to possibly large systematic errors, as soon as the time-walk corrections are not properly measured and no appropriate γ-ray sources have been used to cross check the time-walk corrections over the energy region of the interest.

2.2. The generalised centroid-difference method

A remarkably simple approach is given by the Generalised Centroid Difference (GCD) method (*procedure 2* [6]). Without corrections, the delayed and anti-delayed time-difference distributions are generated by inverting the energy selection in Eq. (4) and the "centroid difference" as the relative time shift between the centroids of the two independent time distributions is measured and used for lifetime determination as:

$$\Delta C(E_1, E_2) = C(D_d) - C(D_a) = PRD(E_1, E_2) + 2\tau. \tag{9}$$

Here, the "prompt response difference" (PRD) represents the linearly combined, so-called γ-γ time walk, which can be expressed as $PRD(E_1, E_2) = C(P_d) - C(P_a)$. Combining Eqs. (6) and (7) and comparing it with Eq. (9), it follows:

$$PRD(E_1, E_2) = [TW_2(E_2) - TW_2(E_1)] + [TW_1(E_2) - TW_1(E_1)]. \tag{10}$$