Nuclear Instruments and Methods in Physics Research A ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The generalized centroid difference method for picosecond sensitive determination of lifetimes of nuclear excited states using large fast-timing arrays

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ARTICLE INFO

Article history:
Received 15 January 2013
Received in revised form
18 May 2013
Accepted 22 May 2013
Available online 3 June 2013

keywords:
Fast-timing arrays
Lifetime measurements
The centroid shift method
The MSCD method
$LaBr_3$(Ce) scintillators

ABSTRACT

A novel method for direct electronic "fast-timing" lifetime measurements of nuclear excited states via γ–γ coincidences using an array equipped with $N \in \mathbb{N}$ equally shaped very fast high-resolution $LaBr_3$(Ce) scintillator detectors is presented. Analogous to the mirror symmetric centroid difference method, the generalized centroid difference method provides two independent "start" and "stop" time spectra obtained by a superposition of the $N(N-1)$ γ–γ time difference spectra of the N detector fast-timing system. The two fast-timing array time spectra correspond to a forward and reverse gating of a specific γ–γ cascade. Provided that the energy response and the electronic time pick-off of the detectors are almost equal, a mean prompt response difference between start and stop events is calibrated and used as a single correction for lifetime determination. These combined fast-timing arrays mean γ–γ time-walk characteristics can be determined for 40 keV $< E_\gamma <$ 1.3 MeV with an accuracy less than 5 ps using a ^{152}Eu γ−ray source. Due to reduction and cancellation of many possible systematic errors, the lifetime determination limit of the method over the total dynamic range is mainly determined by the statistics. The setup of an $N=4$ detector fast-timing array delivered an absolute time resolving power of 3 ps for 10 000 γ–γ events per total fast timing array start and stop time spectrum. The new method is tested over the total dynamic range by the measurements of known picosecond lifetimes in standard γ−ray sources.

1. Introduction

The lifetime of a nuclear excited state is one of the most important observable in nuclear structure studies. The lifetime determines the reduced electromagnetic transition probability which is used to be compared with predictions derived using theoretical nuclear structure models and thus provides an essential nuclear observable to test the model dependent intrinsic structure of the nuclear excited states.

Using the electronic fast-timing technique in combination with very fast scintillator detectors, this technique is picosecond sensitive [1–3] and therefore is capable of overlapping with complementary techniques, such as the recoil distance method [4] and Coulomb excitation [5]. For the picosecond regime, the fast-timing technique is based on the determination of centroids of time distributions (first moment of a time spectrum [6]) generated as time difference spectra of consecutive γ–γ cascades measured using two start and stop γ−ray detectors. Assuming no background contribution, the experimentally obtained "delayed" time distribution $D(t)$ is a convolution of the normalized prompt response function (PRF) of the setup $P(t)$ with an exponential decay as

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

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0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.05.126

where n is the total number of detected γ–γ events in the time difference spectrum, λ is the transition (decay) probability and τ is the mean lifetime of the nuclear excited state interconnected by the γ–γ cascade and t_0 is the centroid of a Gaussian PRF $P(t)$. Eq. (1) is strictly valid for an ideal symmetric Gaussian PRF, however, an asymmetric "semi-Gaussian" PRF can also be obtained in real experiments [2,7,8]. The experimental PRF provides important information on timing characteristics and is obtained for lifetimes which are smaller than 1 ps (systematic errors are expected to be larger). The full width at half maximum (FWHM) of the PRF referred here as the "time-jitter" includes all possible experimental deviations from the ideal time pick-off of instantaneously occurring "prompt" γ–γ events represented by a $\delta-$function. The main contributions to the FWHM of the PRF can be given as follows: the crystal size contributes with a constant time-spread (time-jitter) related to time variations resulting from the different locations of the $\gamma-$ray interactions over the scintillator dimensions and includes the time-spread due to the additional photon time-of-flight of reflected scintillation photons [9] (the active scintillator surfaces are coated with reflexive materials in order to minimize losses of scintillation photons). The energy dependent time variations in the response of the detector to $\gamma-$ray interactions are statistically related to the energy transfer from the radiation to the optical levels of the scintillator, the decay time and the light yield of the scintillator, the scintillation light conversion efficiency of the photo-cathode and the photo-electron gain variance of the photo-multiplier tube (PMT) [9]. An additional non-linear electronic time-jitter is induced by the charge-sensitive time pick-off device due to statistical amplitude and rise-time fluctuations of the detector output pulses [8,10].

The FWHM of the PRF is related to the time-resolution of the setup and does not represent an absolute limitation but provides a rough estimate for the choice of method used to derive the lifetime. The slope method is used for lifetimes which are larger than the FWHM of the PRF. The lifetime is then obtained by a fit of the straight line observed on a semi-logarithmic plot of $D(t)$ outside the region of the PRF ($d\{\ln[D(t)]\}/dt = 1/\tau$ for $D(t) \gg P(t)$ [1]). Thus the experimental PRF in this case is not needed in contrary to the convolution method, where the complete time spectrum is fitted using Eq. (1). The limitation of the convolution method is given by the ability to distinguish between the slope of the delayed time spectrum and the "apparent slope" of the prompt time spectrum (the PRF) [1]. Lifetimes with values well below the FWHM can be determined if the PRF can be measured for the same conditions used to measure the delayed time spectrum [1] or if the PRF can be approximated by a Gaussian time distribution [2,7]. The limit of the lifetime determination can furthermore be reduced using the centroid shift method [6]. For the case of a Gaussian PRF with standard deviation $\sigma \cong$FWHM/2.355, the pure statistical time resolving power δt of a two detector timing system is given by

$$\delta t = \frac{\sigma}{\sqrt{n}} \cong \frac{\mathrm{FWHM}}{2.355\sqrt{n}} \tag{2}$$

where $n = \int_{-\infty}^{\infty} D(t)\,dt$ is the number of events in the time spectrum. Indeed, the centroid C^D ("center of gravity" [6]) of a time distribution $D(t)$ is defined in terms of stochastics as the expectation value $\langle t\rangle$ of the time over the time probability distribution as

$$C^D = \langle t\rangle = \frac{\int_{-\infty}^{\infty} tD(t)\,dt}{\int_{-\infty}^{\infty} D(t)\,dt}, \quad \delta C^D = \delta t = \sqrt{\langle t^2\rangle - \langle t\rangle^2} \tag{3}$$

with $D(t)$ of Eq. (1). According to the centroid shift method by assuming a symmetric Gaussian PRF, the centroid of a delayed time spectrum is displaced by the mean lifetime from the centroid of its convoluted PRF

$$\tau = C^D_{\mathrm{stop}} - C^P_{\mathrm{stop}} \tag{4}$$

or if the functions of the two detectors are interchanged to obtain the "anti-delayed time spectrum" [1]

$$\tau = C^P_{\mathrm{start}} - C^D_{\mathrm{start}} \tag{5}$$

where C^P is the "prompt centroid" of the PRF. The subscript "start" ("stop") indicates that the decay transition with its lifetime information provided the start (stop) timing signal of the two detector timing system.

The centroid shift method is in principle very simple since the mean lifetime is directly obtained from the centroids of the delayed and the prompt time spectrum which need to be measured under identical conditions. This implies the use of two different sources which generally introduce systematic shifts due to drifts in electronics as a function of time and possible differences in source position [1]. These possible systematic errors can be canceled by combining Eqs. (4) and (5). It is clear that for the case of a constant energy independent timing of both the start and stop detectors, the delayed and the inverse anti-delayed time spectrum can be compared without the need of determining the PRF, as the centroids of the two delayed "start" and "stop" time spectra are separated by 2τ, according to Eqs. (4) and (5) with $C^P_{\mathrm{start}} = C^P_{\mathrm{stop}}$. This "self-comparison method" is rarely achievable [1].

The major problem is that the prompt centroid is dependent on the timing response, i.e. the time versus energy relation $T(E_\gamma)$ (the time-walk characteristics) of both detectors of the γ–γ fast-timing setup, thus $C^P = C^P(E_\gamma) = T(E_{\mathrm{start}}) + T(E_{\mathrm{stop}})$. This spectral effect is mainly caused by the time pick-off device (described in Section 3), but also includes the time-shift due to energy dependent average path length (penetration depth) of the interacting $\gamma-$ray along the symmetry axis of the crystal, as the photon velocity inside the crystal is reduced by the refractive index of the scintillator [1]. Therefore, the essence is to determine this energy dependent time-walk of the prompt centroid between the two detectors as precise as possible. This is also important for lifetimes larger than the FWHM of the PRF where time spectra of different detector–detector combinations of an N detector timing system can be superimposed for the application of the slope method on the total fast-timing array time distribution. To simplify the analysis of electronically generated γ–γ time spectra, the concept of the "centroid difference" was introduced in 1997, whereby the prompt centroids C^P_{start} and C^P_{stop} are derived from a separate detector time-walk measurement using the prompt ^{60}Co source and includes other corrections [11]. The recently developed mirror symmetric centroid difference (MSCD) method uses a different ansatz, namely the centroid difference as a physical observable of a two detector timing system that was shown to be mirror symmetric with respect to the energy difference of the two $\gamma-$rays of the γ–γ cascade [3] (described in Section 2). This mirror symmetry provides additional data points for a precise calibration of the "prompt response difference" which is the combined γ–γ time-walk characteristics of the two detector timing system. Hence, the calibration of the single timing responses of both detectors is eliminated as well as many possible systematic errors [3,8].

Beside the excellent timing performance (FWHM ≈200 ps for two 1.5 in. × 1.5 in. cylindrical scintillators using the prompt ^{60}Co lines), the particular property of the $LaBr_3$(Ce) scintillator detector is a very good energy resolution of 3% at 662 keV which makes this detector exceedingly suitable for γ–γ fast-timing experiments. This has already been demonstrated also by using a small array of $LaBr_3$(Ce) detectors in fusion evaporation reactions [12,13]. However, the analysis of an N detector timing system becomes complex for $N < 2$ as the timing response of each single detector has to be calibrated [11,12]. Often, the Compton events of the Compton continuum of the 1173 keV $\gamma-$ray in ^{60}Co are used to simplify the calibration as an approximation of the detector time-walk for 300 keV $< E_\gamma <$ 1.17 MeV [11,12] (the reference timing signal is