First results of \textit{ab initio} simulations of scintillation detector characteristics

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Abstract. We describe a new Monte-Carlo-simulation which models output signals of scintillator-photomultiplier tube (PMT) pairs. For the whole simulation from the initial photon-cascade within the scintillator to the final pulse as it is digitized at the output of the PMT only values from the scintillator’s and PMT’s technical manuals are used, no parameters need to be adapted. We find an excellent agreement between sampled and simulated signals. This allows to determine the influence of single parameters independent from the others. With a special focus on positron lifetime as well as perturbed angular correlation spectrometers, which have high demands on the \(\gamma\)-photon incidence time determination’s accuracy, the influence of the tts-parameter on the detector’s overall time resolution was studied in detail.

1. Introduction

While positron lifetime spectroscopy (PLS) and perturbed angular correlation spectroscopy (PAC) are rather different methods of material research, they both rely on the time resolution of the used detectors. The PAC method may additionally (depending on the used isotopes) have rather high demands on energy resolution in order to separate gamma peaks close in energy often appearing in more complex decays. The PAC method allows for the analysis of local magnetic fields and electric field gradients at radioactive probe atoms in condensed matter and is mainly used for the characterization of metals\cite{1} and semiconductors\cite{2}. It is based on measuring correlations between gamma photons emitted from useful decay cascades which may show a modulated anisotropy due to the hyperfine interaction of the state dependent atom moments with the surrounding magnetic fields and electric field gradients\cite{3}. PLS in contrast uses the statistically decaying lifetime of positrons in the sample to detect defects and voids in metals, crystals, semiconductors, polymers and meso-porous materials\cite{4, 5, 6, 7}.

Measuring energy and time of single \(\gamma\)-photons is usually accomplished with scintillator-photomultiplier-assemblies. These convert the incident photon into an electric pulse which carries time and energy information. Several years ago devices for digital processing of these signals became cheaper compared to their analog counter-parts.

Various groups have reported success of varying degree using digital equipment to extract the time- and energy-information \cite{8, 9, 10}. However their results showed to be difficult to reproduce and seems to heavily depend on “hand selected” PMTs. Several attempts of simulating the pulses...
coming from scintillator and photomultiplier where done but had deficiencies [11, 12]. They contained parameters that had to be “fitted to reality” and while they gave good results for one combination of scintillator, PMT and digital routine, the predictions for other combinations were out of scope. Additionally they did not reflect the physics of scintillators and photomultipliers.

2. The Simulation Method
When the $\gamma$-photon hits the scintillator it creates a photo electron which excites color centers. These color center excitations decay with a decay constant specific to the scintillation material and emit secondary photons in the visible or UV range. The total number of secondary photons corresponds to the incident $\gamma$-photon’s energy. The secondary photons enter the PMT, hit its photo cathode and produce photo electrons which are then accelerated and multiplied in a dynode system with typically eight to twelve stages. The electrons from the last dynode (typically several millions per single photo electron from the photo cathode) finally hit the anode. By connecting a transimpedance amplifier to the anode this transient charge is measured as a short voltage pulse over time.

The complete process is simulated by first creating the poisson distributed random number specifying the number of photo electrons emerging on the PMT’s cathode. The poisson
distribution’s $\lambda$ value is given by the scintillators and PMT’s overall efficiencies. Exponentially distributed random numbers are drawn from that distribution resembling the points in time each simulated secondary photon emerged from its color center’s decay. Then each of these cathode electrons is convolved with a function describing the temporal distribution of the associated anode electrons. This function is approximated by two gaussian functions to account for the multiplication by the dynodes as both base-material and coating have an influence here. It approximates curves published by PMT vendors and is scaled by the PMT’s rise time value according to the data-sheet. To account for the amplification (through each dynode’s gain and the total number of dynodes) and transit-time (TT) as well as transit time spread (TTS), the pulses are delayed by TT plus a gaussian distributed random number simulating the TTS and scaled by a cascade of poisson distributed random numbers. Then all these single pulses are added up to form the pulse as it is measured as a voltage across the input resistor of the digitizer. To compare the simulation with digitally recorded signals, two more steps are necessary: Additive white gaussian noise is added in order to simulate the analog noise of the input amplifier and the signal is quantized to a defined number of bits and filtered to re-construct the relation of frequency to effective-number-of-bits in the digitizer. The figure 1 shows each step. A more concise description of the simulation method will be published separately.

Even though we only used parameters from the data sheets of scintillators, photomultipliers and digitizers, the resulting pulses are in excellent agreement with the measured signals. We compared the general shapes for Lu$_{1.8}$Y$_{0.2}$SiO$_5$:Ce (LYSO), BaF$_2$, NaI:Ti and plastic scintillators in figure 2. Energy distribution and energy resolution, rise times and lengths of the simulated pulses excellently match their real-world counterparts.

3. Results from the Simulation: Transit Time Spread
The transit time is the mean time difference between the emission of a single photo electron from the cathode and the arrival of the corresponding electron bunch at the anode. The transit time spread (TTS) is the spread of the transit time due to different trajectories, spread in the initial energies of the secondary photons, irregularities in the dynode material and shape as well as the static electric field.

In order to compare the simulations with real events, numerous signals were recorded with
digitizers featuring a resolution of 8 bit at a sampling rate of 4 GS/s. As input for the simulations we used the technical details of R2059, R3377, R5320 tubes from Hamamatsu and the well-known XP2020URQ tube from Photonis from the data sheets. The simulation was done using different values for the TTS in order to investigate the time resolution’s dependency on this parameter. Figure 3 shows the results of these simulations. The comparison with the real TTS values of the R3377 and XP2020 PMTs show an excellent agreement. Also the time resolution of simulated signals is very close to the measured values. Remaining differences are in the range of fluctuations observable between tubes of the same type.

Obviously the TTS is not a limiting factor for the detector’s time resolution. The graphs show very clearly that the time resolution is significantly influenced by the TTS only in the case where it is higher than the signals’ rise time value.

4. Conclusion
Comparing the simulated signals to measured ones an excellent agreement is obtained. The major advantage of the presented simulation method is that it relies solely on parameters given in technical data sheets of scintillators (like [13]) and photomultipliers. The method successfully models the physics of scintillation detectors.
Very good agreement is found concerning time resolution, signal shape, rise time, pulse length, and energy resolution. Moreover it was shown that the signal rise time which depends on the scintillator’s properties as well as the PMT’s rise time value limits the achievable time resolution. Decreasing the transit time spread below the rise time value results in no significant improvement of the time resolution.

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Appendix A. References

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