2011 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC): Valencia, Spain. 23-29 October 2011
(2011). IEEE, 72-74.
DOI: http://dx.doi.org/10.1109/NSSMIC.2011.6154403

Assessment of New Photosensors for Fast Timing Applications with Large Scintillator Detectors

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Abstract **– The measurement of absolute nuclear transition probabilities is a very sensitive tool to study the structure of the atomic nucleus. Direct access to transition rates can be achieved via the lifetime of the nuclear levels de-populated in radioactive decay. The Advanced Time-Delayed (ATD) method, or Fast Timing, is a well-established technique to measure lifetimes down to a few ps. The development of the technique was based on the use of BaF_2 detectors, but a recent major breakthrough occurred with the introduction of $LaBr_3$(Ce) crystals, uniting excellent time response with much superior energy resolution than BaF_2 crystals. Relatively large $LaBr_3$(Ce) cylindrical detectors of typically 1.5"x1.5" are employed for fast timing, in combination with fast 2-inch photomultiplier tubes from Photonis such as the linear focused 8-stage XP20D0. Another option for a 2-inch fast phototube is the 8-stage *Hamamatsu* R9779, whose timing properties have already been tested with small LSO crystals. New possibilities are also offered by novel photosensors such as silicon photomultipliers, which are intrinsically fast. In this work we have investigated the performance of the *Hamamatsu* R9779 photomultiplier tube, and the viability of $CeBr_3$ crystals for fast-timing applications.**

I. Introduction

The measurement of absolute nuclear transition probabilities is a very sensitive tool to study the structure of the atomic nucleus. Direct access to transition rates can be achieved via the lifetime of the nuclear levels de-populated in radioactive decay. The Advanced Time-Delayed (ATD) method, or Fast timing [1], is a well-established technique to measure lifetimes ranging from 5 ps to 50 ns with count rates as low as 5 decays per second. The development of the technique was originally based on the use of Barium difluoride (BaF_2) inorganic crystal with excellent time response, on the introduction of photomultiplier anode timing and on the combination of the fast BaF_2 scintillators with high-resolution HPGe detectors to provide a good energy selection.

A recent major breakthrough occurred with the introduction of $LaBr_3$(Ce) detectors, uniting excellent time response with much superior energy resolution in comparison to BaF_2 crystals. The energy resolution is also an advantage for fast timing due to the much improved peak to background ratio. We have used these detectors for fast timing applications for more than 5 years. Relatively large $LaBr_3$(Ce) cylindrical (or tapered) detectors of typically 1.5" × 1.5" have been employed, in combination with *Photonis* fast 2-inch photomultiplier tubes of the XP20 series, which include a screening grid at the anode. The linear focused 8-stage XP20D0 PMT [2] has been usually used but, due to the very high light yield of $LaBr_3$(Ce) crystals, it needs to be operated at low HV to avoid the deterioration of energy linearity. Another option for a 2-inch fast phototube, more compelling since the shutting down of the photomultiplier production at *Photonis*, is the 8-stage *Hamamatsu* R9779 PMT. This PMT includes an acceleration ring at the front-end and its timing properties have already been tested with small LSO crystals [3] and plastic scintillators [4].

Another feasible solution is the use of novel photosensors such as single photon avalanche diodes [5], normally referred as silicon photomultipliers (SiPMs, MPPCs...), which are intrinsically fast [6]. The timing performance of small 3 × 3 × 5 mm^3 $LaBr_3$(Ce) crystals coupled to 3 × 3 mm^2 SiPMs have been successfully explored in [7] in view of possible applications to TOF-PET.

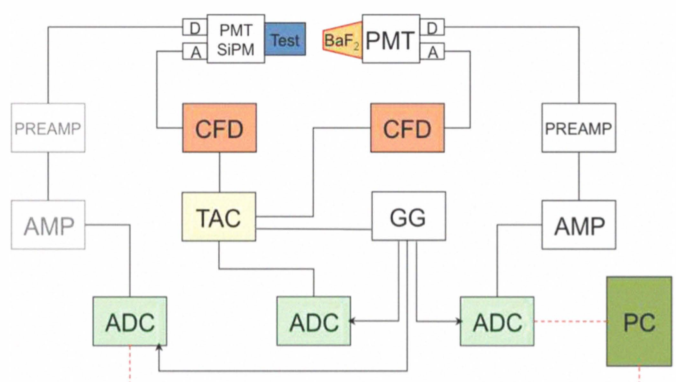

Fig. 1. Schematics of the electronics for the timing test bench.

In this work we investigate the time resolution of a Hamamatsu R9779 fast photomultiplier tube coupled to a fast plastic scintillator and to a $LaBr_3$(Ce) 1" × 1" cylinder crystal. Furthermore we have investigated the viability of $CeBr_3$ crystals for fast-timing applications. We also explore the new possibilities offered by silicon photomultipliers, which are intrinsically fast, by investigating the timing performance of

This work was supported in part by Comunidad de Madrid (ARTEMIS S2009/DPI-1802) and the Spanish Ministry of Science and Innovation (grants FPA2010-17142 and CSPD-2007-00042, Ingenio2010).

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LaBr$_3$(Ce) crystals coupled to *Hamamatsu* S11830-3344MF 4 × 4 monolithic MMPC arrays and SenSL 4 × 4 SPMMicro-3035x13 SiPM arrays.

II. Set Up for Timing tests

Our timing test bench consists on a reference detector and a test detector coupled to standard NIM front-end electronics, as depicted in Figure 1. The fast signals are processed by ORTEC 935 Constant Fraction Discriminators, which are individually optimized for delay and walk, and taken to an ORTEC 567 TAC. The TAC amplitude output signals are sent to an ADC, which is gated on the ^{60}Co full energy peaks. The reference detector consist on a small truncated cone BaF$_2$ crystal coupled to a *Photonis* XP2020 URQ PM tube by means of standard silicon grease. The photomultiplier is operated at low HV. All the tests described below are performed with a ^{60}Co gamma source in a close geometry, with selection of the full energy peaks at 1173 and 1332 keV.

To check the reference time response, a system with two equal BaF$_2$ crystals and photomultipliers has been set up. The intrinsic resolution of the TAC and ADC electronics was checked to be of the order of 16 ps. The stability of the setup against temperature was monitored and if necessary corrected for. The reproducibility of the measurement was also carefully monitored, with several short measurements taken over large periods of time. For the full energy peaks of ^{60}Co the total time FWHM resolution obtained is 115±3 ps, as shown in Figure 2, yielding 82±2 ps for each of the two BaF$_2$ plus XP2020 URQ detector assemblies.

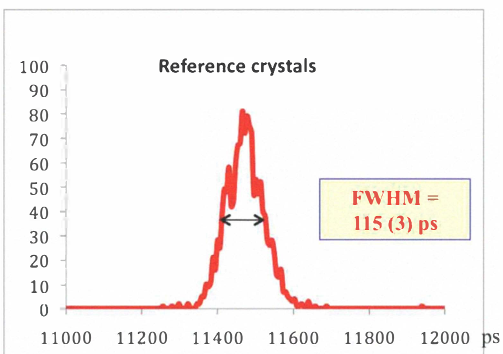

Figure 2: Time resolution of the system for coincidences between two reference BaF$_2$ crystals coupled to XP2020 URQ Photonis photomultipliers.

III. Test of the Hamamatsu R9779 Photomultiplier

A viable alternative to the *Photonis* fast 2-inch photomultiplier, particularly after the discontinuing of the production of Photonis photomultipliers, is the 8-stage Hamamatsu R9779. This photomultiplier has an accelerator ring at front-end, with anode rise time of 1.8 ns and Transit Time Spread (TTS) of 250 ps. Its timing properties have already been tested with small LSO crystals [3] and plastic scintillators [4]. In [3] timing tests are reported versus an EJ-200 10 mm disk coupled to XP2020Q, and unfolded FWHM time resolutions given are 192 and 210 ps at 511 keV, whereas FWHM time resolutions of 181 and 154 ps are given for the *Photonis* XP20D0 photomultiplier. Furthermore, worse timing uniformity than Photonis XP20D0 is reported.

In order to study the performance of the Hamamatsu R9779 we have compared its time response to a fast XP20D0 Photonis photomultiplier, also with 8 dynodes, 1.6 ns anode rise time, and 520 ps TTS. For the comparison we have used a very fast response NE111A plastic disk of 25 mm diameter and 5 mm height, which is know to provide very good time response of about 60 ps with a XP2020Q PMT [8]. A FWHM time resolution of 75±4 ps for NE111A plastic is obtained for the XP20D0 PMT whereas better time resolution of 50±3 ps is achieved for R9779, as shown in Figure 3.

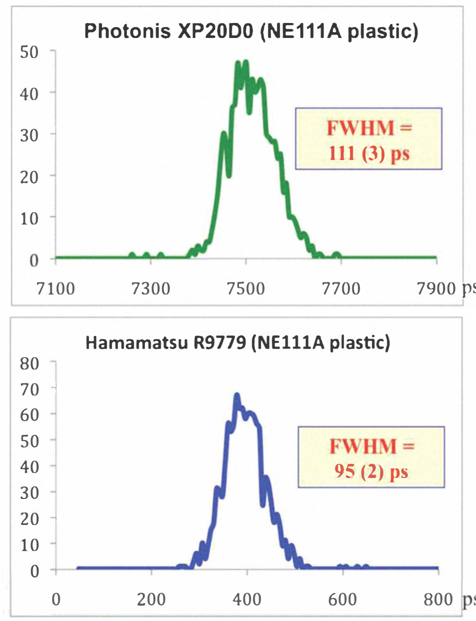

Figure 3: Time resolution of the system for coincidences between a reference BaF$_2$ crystal coupled to XP2020URQ and a NE111A plastic coupled to a Photonis XP20D0 (above) and Hamamatsu R9779 (below).

IV. Test of LaBr$_3$(Ce) coupled to the Hamamatsu R9779 Photomultiplier

Given the excellent performance of the Hamamatsu R9779 photomultiplier with our fast reference plastic, we have tested the response with one of our standard LaBr$_3$(Ce) crystal. For the test we have used a cylindrical 1" × 1" detector by *St Gobain*, whose time resolution was previously measured to be 123±5 ps FWHM for ^{60}Co using an XP2020 URQ PM tube. For R9779 the rise time of the anode signal taken from the 20% to the peak is 6 ns, as shown in Figure 4.

For the R9779 we have measured a FWHM time resolution of 122±3 ps, similar to what was obtained for the same crystal with a XP2020 URQ PMT. For a comparison, a time resolution of 107±4 ps FWHM was obtained in [2] for an equivalent 1" × 1" LaBr$_3$(Ce) crystal and using Photonis XP20D0 PM tube.

We have also tested our standard LaBr$_3$(Ce) crystal coupled to Hamamatsu S11830-3344MF 4x4 monolithic MMPC arrays and SenSL 4x4 SPMMicro-3035x13 SiPM arrays. The timing performance of small 3 × 3 × 5 mm^3 $LaBr_3$(Ce) crystals coupled to 3 × 3 mm^2 SiPMs have already been successfully investigated in [7]. We have developed a readout circuit for which rise time (20% to maximum) is about 20 ns. The impedance values are still to be fine-tuned and CFD timing is under test.

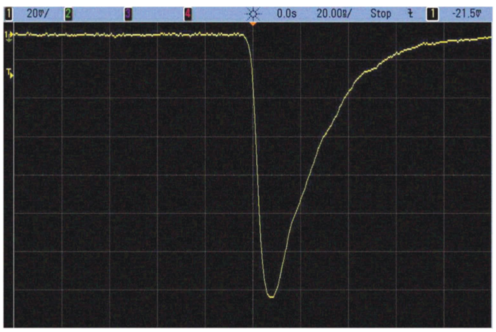

Figure 4: Anode signal of a 1" × 1" $LaBr_3$(Ce) coupled to the R9779 Photomultiplier taken with a 2 Gs/s oscilloscope. The rise time of the signal from the 20% to maximum is 6 ns.

V. Test of new $CeBr_3$ crystals

$CeBr_3$ scintillators are an alternative to $LaBr_3$(Ce) crystals with good intrinsic timing properties, no internal activity, good energy resolution of about 4% at ^{137}Cs, and very competitive price. Similar time response of $CeBr_3$ to $LaBr_3$(Ce) has been reported [9]. For our tests we have used two cylindrical detectors with dimensions 1" diameter x 1" height, and 30 mm diameter x 30 mm height, respectively, which are commercially available from Scionix.

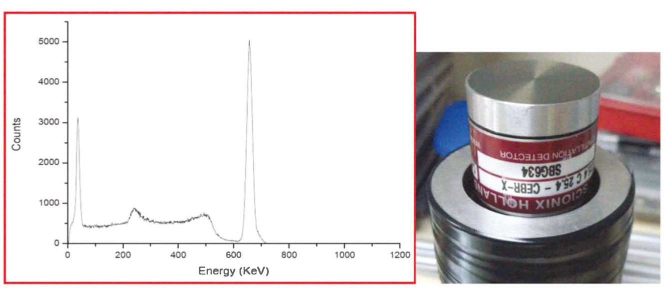

Figure 5: Energy spectrum for a Scionix 25.4 mm x 25.4 mm $CeBr_3$, shown to the right, coupled to R9779 photomultiplier.

Our smaller crystal shows about 20% better energy resolution that the larger one. It is worth noting that a peak sensing multichannel analyzer yields better results than high quality NIM modules, which are basically designed for HPGe. The energy resolution is consistently better without the use of preamplifier (ORTEC 113) or NIM amplifiers.

The time response has been investigated for both $CeBr_3$ crystals with the standard fast photomultipliers described in the section above. For the large $CeBr_3$ our preliminary results are comparable to $LaBr_3$(Ce) crystals of similar volume, with FWHM time resolution 148±3 ps using the XP20D0 PM tube. A significantly worse result is of 175±3 ps FWHM is obtained with the XP2020URQ PM tube. The time resolution obtained with a smaller $CeBr_3$ crystal is worse than with a larger crystal. This must be attributed to a poor quality of the smaller crystal, since smaller crystals as a rule provide better time resolutions than larger ones. A summary of the results is given in Table 1 below.

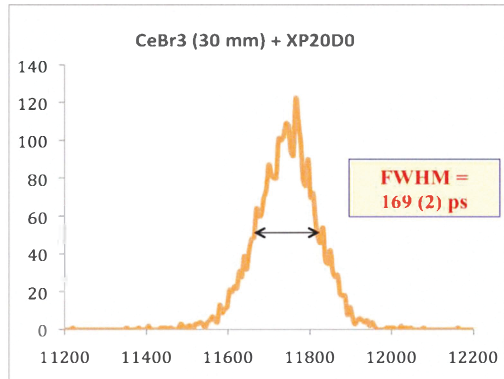

Figure 6: Time spectrum for a *Scionix* 30 mm × 30 mm $CeBr_3$ coupled to the XP20D0 Photonis photomultiplier.

VI. Conclusions

We have shown that R9779 is a competitive photomultiplier for use with $LaBr_3$(Ce) and similar scintillators for fast timing applications. This allow for replacement of the XP20D0 photomultipliers, which production has been stopped.

The $CeBr_3$(Ce) scintillator is found as a promising and an inexpensive competitor to $LaBr_3$(Ce) for fast timing. A digital system could be well suited for energy analysis purposes. The time response is very good for one of the samples. Tests will be continued with $CeBr_3$ and R9779.

Table I. Summary of time measurements with $CeBr_3$ crystals coupled to XP2020URQ and XP20D0 photomultipliers.

Crystal	PMT	FWHM (ps)	Error (ps)
Small $CeBr_3$	XP2020URQ	194	5
Large $CeBr_3$	XP2020URQ	175	3
Small $CeBr_3$	XP20D0	168	2
Large $CeBr_3$	XP20D0	148	3

Acknowledgments

We kindly acknowledge support from Comunidad de Madrid (ARTEMIS S2009/DPI-1802), and from the Spanish Ministry of Science and Innovation (FPA2010-17142 and CPAN, Centro de Física de Partículas, Astropartículas y Nuclear, CSD-2007-00042, Ingenio2010).

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