Multi-crystal YAP:Ce detector system for position sensitive measurements

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Yttrium aluminum perovskite (YAP:Ce) scintillation crystal has a light efficiency of about 40% relative to NaI. Because of the yttrium atomic number (Z = 39) and the relatively high density (5.37 g/cm³) it has a good gamma-ray absorption. Furthermore it is not hygroscopic and is inert. Its peculiarity consists of material processing that provides us with crystal pillars down to 0.3 x 0.3 mm² aperture size and up to some centimeters in length. An array consisting of 11 x 22 YAP:Ce elements was made where each crystal has an aperture of 0.6 x 0.6 mm² and a length of 7 mm. Each scintillation crystal is optically separated by a reflective material resulting in a separation layer between elements of about 5 μm. The multicrystal detector was optically coupled to a Hamamatsu Position Sensitive Photomultiplier Tube (R2486). The intrinsic spatial resolution of the PSPMT is better than 0.3 mm but it is strongly dependent on the Point Spread Function (PSF) generated on the photocathode. The multicrystal detector very well matched the PSPMT characteristics resulting in a spatial resolution of about 0.7 mm at 140 keV (99mTc) gamma irradiation.

1. Introduction

The PSPMT R2486 was developed by Hamamatsu in 1985 [1] and commercially available some years later. It was the first position sensitive photomultiplier tube. It is worthwhile to remember that in the past the concept of high resolution position gamma ray measurement was bound mainly to solid state detectors (Si strip and more recently Ge strip) and to MultiWire Proportional Counters MWPCs [2] or gas scintillator proportional chambers [3] with severe limitations in gamma-ray detection efficiency. Then electronic device complexity of solid state position sensitive detectors together with high costs limited the use of large area detectors to MWPCs in the X-gamma ray energy range below 80 keV and to Anger cameras [4] for higher energies. Over the last years the multi-anodes photomultiplier tube seemed a good compromise between these position sensitive systems. Since the spatial resolution was related to the single anode dimension, reducing it to some millimeters, also the scintillation crystal was configured as a two dimensional array of pillars. In this way it is possible to obtain very high detection efficiency, a very high count rate and a spatial resolution comparable to a standard gamma-camera [5,6].

PSPMT (Hamamatsu R2486/87) [7] seems a combined system between a MWPC and an Anger camera, “MWPC without gas plus scintillator”, as defined by Del Guerra [8]. With such a system it is possible to obtain spatial resolution up to 0.1 mm [9] with gamma-ray detection efficiency depending on the scintillation detector [10] and an intrinsic high count rate capability. In addition it needs relatively simple electronic equipment and finally it allows large area assembling (a single PSPMT can reach 10 x 10 cm² of active area [11]). The spatial resolution of the PSPMT follows the rule of the Point Spread Function (PSF) depending on the light distribution on the photocathode [12,13]. The major limitations encountered by different authors using the PSPMT [14–16] was the use of very thin (< 3 mm thick) planar crystals with good scintillation light yield (as CsI or NaI) to obtain close PSF, but compromising the detector efficiency. For thicker scintillation detector better or similar spatial resolution values compared to those using a standard gamma camera were obtained [14,16]. To match the good intrinsic characteristics of the PSPMT a bundle of pillars of scintillation crystals are needed to create a light spot with less than 1 mm of aperture diameter and a greater number of photoelectrons than those obtained by BGO flat crystal. The goal seems to be obtained in this work by a multi-crystal detector of yttrium aluminum perovskite cerium doped (0.1%) (YAlO₃:Ce), so called YAP:Ce, developed by Preciosa Company, Czech Republic.
2. Equipment and method

2.1. The position sensitive photomultiplier tube

The PSPMT Hamamatsu Tube R2486-06 has a diameter of 75 mm with a measured effective area of 50 mm. The basic principle of the PSPMT consists of producing a shower of secondary electrons through the dynodes forming a charge cloud with a centroid related to the point on which the bi-alkali photocathode emitted the first electrons subsequently to an interaction with light photons. The electron multiplying process is obtained by 11 stages of proximity mesh dynodes that produce a spread of the charge cloud of 1.5 and 4.3 mm of FWHM between the first and the last dynode respectively. 16 × 16 crossed wires located between the last two dynodes are responsible for the collection of charge. The wires define a pitch of 3.75 mm and cover a circle of 60 mm of diameter.

Four output signals are collected through two external resistive chains connecting X and Y wires respectively. In this way the PSPMT utilizes a mean weighted by resistances to determine the position of the point originating the light photons. Starting from the four signals $X_a, X_b, Y_c, Y_d$ it utilizes the following formula to calculate the position:

$$X = \frac{X_a - X_b}{X_a + X_b},$$

where

$$X_a = \sum_{n=1}^{16} \frac{X_n}{n}$$

and

$$X_b = \sum_{n=1}^{16} \{ X_n / [16 - (n - 1)] \}$$

as calculated by the resistive chain. The same formula is utilized for the Y position. However, the linear position response of the resistive chain depends on the charge cloud spread and on the homogeneity of the photocathode response. The charge cloud spread depends mainly on the light distribution width striking the photocathode. It is related to the thickness of the planar scintillation crystal and to the distance between the photocathode and the positions in which the scintillation occurs. In Fig. 1 position linearity responses are shown for various measured charge spreads. The linearity responses were calculated applying, at different positions, formula (1) to the measured charge distribution collected by each wire of the anode array following a crystal gamma irradiation by a 0.4 mm spot in the center of the photocathode. In Fig. 1 the response obtained from a NaI(Tl) crystal of 50 mm diameter by 1 mm thick with a 3 mm glass window is compared with the one obtained from the YAP:Ce multi-crystal detector and with the intrinsic linear position response on the PSPMT. The following values of the charge distribution on the wire anode were considered: 22 mm, 7 mm and 4 mm for NaI(Tl), YAP:Ce and PSPMT respectively. The loss of linearity range is evident for NaI(Tl) demonstrating the important role the charge spread can play. On the contrary the close agreement of the YAP:Ce response with the PSPMT intrinsic one proves the good light guiding effect produced by the crystal pillars. Furthermore reflectors on the back side of the crystal, reflection inside the flat crystal and refractions due to optical coupling can strongly impair the spatial resolution. In Fig. 2 the effect of position linearity range loss is clearly visible comparing the images obtained by three small BGO crystals with the same surface area but with different thickesses. The image was obtained by parallel positioning and optical coupling of the three crystals on the PSPMT glass window. The crystals have the same face dimension of 7 × 30 mm$^2$ and thickness of 0.5 mm, 1 mm and 3 mm respectively from the upper to lower position on the image. The crystals were exposed to a $^{99m}$Tc source collimated just to irradiate the photocathode surface. The reduced range of values produced by formula (1) is particularly evident for the 3 mm thick crystal, due to the increase of the light spread.

The intrinsic spatial resolution values were measured by Hamamatsu [7] using a light spot with 1 mm of aperture diameter generating between 9 and 600 photoelectrons/event. The spatial resolution ranged between 0.9 and 0.12 mm FWHM respectively with a middle value of 0.3 mm at about 80 photoelectrons/event.

![Fig. 1. Calculated linearity responses for various measured charge distributions collected by the wire anode. (squared) 22 mm FWHM of the detector response function of NaI(Tl) planar crystal 50 mm in diameter by 1 mm thick with a 3 mm glass window. (rhombus) 7 mm DRF FWHM of YAP:Ce 22×11 crystal array, 7 mm thick with a crystal element 0.6×0.6 mm$^2$ aperture size. (triangle) 4 mm FWHM charge cloud measured by Hamamatsu.](image-url)
Recalling that the best value of light yield measured for NaI is about 10 photoelectrons/keV [17], at the photon energy of $^{99m}$Tc (140 keV) we should find the amount of photoelectrons needed to obtain spatial resolution values less 1 mm as well as other scintillation crystals commercially available. This is not confirmed experimentally, [14,16] demonstrating, as for position linearity range loss, the strong dependence of the PSPMT on the spread of the charge cloud produced by the light distribution width (PSF). The values measured by Hamamatsu are relative to 4 mm FWHM of the charge distribution, the minimum obtainable on the PSPMT.

As a consequence the reaching of the intrinsic spatial resolution values is bound to suitable crystal shapes with a capability to concentrate on an adequate number of light photons on an area less than 1 mm$^2$.

Fig. 2. Image of three BGO crystal strips with the same surface area ($7 \times 30$ mm$^2$) and 0.5 mm, 1 mm, 3 mm thick from upper to lower position respectively. The crystal strips were placed parallelly on the PSPMT glass window and irradiated by $^{99m}$Tc collimated source.

Fig. 3. YAP:Ce linear attenuation coefficients up to 10 MeV for the different interaction processes: photoelectric, coherent and incoherent scattering, pair production.

Fig. 4. The pulse height linearity response vs. photon energy for YAP:Ce and NaI(Tl) planar crystals. NaI(Tl) and YAP:Ce are 25 mm diameter by 1 mm thick and have the same housing: 2 mm of glass window and 0.1 mm Al entrance window.

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2.2. The scintillation detector

YAlO₃:Ce is a scintillation crystal with the structure of Perovskite. Because of its structure it has a density value of 5.37 g/cm³ (higher than the majority of scintillation crystals) and a relatively high atomic number (Z = 39) that makes it very interesting for gamma ray applications. In fact its radiation absorption characteristics are very similar to the ones of germanium. In Fig. 3 the calculated attenuation coefficients for YAP:Ce are shown. As in germanium at 140 keV the two principal interaction processes (Photoelectric and Compton) contribute equally. So at the gamma emission energy of ⁹⁹mTc we expect for YAP:Ce spectrum a contribution larger to the full energy peak of Compton photon reabsorption than for NaI(Tl) and CsI. On the contrary the low energy of Kα X rays (about 15 keV) of YAP:Ce and the low fluorescent yield (about 0.36) reduces the energy deposition spread due to fluorescent X-ray reabsorption. In fact for X- and gamma ray imaging systems, at photon energies below 140 keV, spatial resolutions less than 1 mm can be affected by the attenuation length of the fluorescent X-ray in the material.

As an example we can compare YAP:Ce with BGO where the Kα X-ray (80 keV average value, 0.6 of fluorescent yield) has 0.8 mm of attenuation length, vs. 0.13 mm in YAP:Ce. It means that at 140 keV we expect, in the material surrounding the primary interaction point, a mean fraction of energy of about 50 keV distributed within a radius of 0.8 mm and of 5.4 keV within 0.13 mm for BGO and YAP:Ce respectively. A detailed description of this phenomenon comparing YAP with other scintillation materials by a Monte Carlo method will be discussed in another paper. The scintillation emission maximum of YAP:Ce is situated at 370 nm with a decay time of about 25 ns, one of the fastest scintillation materials. Furthermore the absence of hygroscopicity can make for a simple crystal housing and the high hardness can make for a crystal machining into various shapes and geometries.

The multi-crystal scintillation detector realized and tested in this work consists of 11 × 22 YAP:Ce scintillation elements. Each element has an aperture of 0.6 × 0.6 mm² and a length of 7 mm. Each element has a thin dielectric reflective layer and is optically isolated by a thin metal layer. The elements are glued to one block. The total thickness of the layer is about 5 μm and the distance between the scintillation elements is about 10 μm. Because the arrangement of the scintillation elements is very close and the separation layers are thin, control of light tightness was reached. After removing the face layers, one scintillation element was excited by UV light (360 nm), and light from neighboring crystals was measured. As a conclusion of this measurement, less than 1% of light was measured, compared with the excited element.

2.3. Processing electronics

The PSPMT Hamamatsu R2486-06 is provided with dynode and anode divider resistors, wire anode resistive chains with ends directly connected to four input preamplifier stages. The four position signals from the resistive chains were connected to fast analog amplifiers, then summation and subtraction were performed analogically, sending the resulting signals to a linear gate and stretcher. The outputs were then processed to find the X and Y position signals. Eight bit FLASH ADCs were used to digitize summations and subtractions. The resulting digitized ratios for X and Y respectively were sent to a two-dimensional multichannel analyzer (64 × 64 channels). Such an electronic device allowed us to reach count rates up to 80 k events/s together with a real time visualization of the forming image. The digital image processing system utilized Digital 486 connected via RS232 to MCA and DEC 5000-240 workstation.

3. Results

To analyse the YAP:Ce light yield, crystals of YAP and NaI were made with the same housing. The crystals were both 25 mm in diameter, 1 mm thick with 2 mm of glass window and 0.1 mm aluminum as entrance window and light reflector.

The scintillation crystals were coupled to a standard bi-alkali photomultiplier tube EMI 9765B and irradiated by different calibrated radioactive point sources at different photon energies under the same geometrical irradiation condition i.e. at 10 cm source–detector distance. The pulse height linearity response for both crystals is shown in Fig. 4. Comparing the slopes obtained, a scintillation yield ratio of about 36–38%
results between YAP:Ce and NaI(Tl). The energy response of the YAP planar crystal was utilized to compare and evaluate the light yield of the YAP multi-crystal array. In Fig. 5 the energy spectra of $^{99m}$Tc measured by YAP:Ce planar crystal and multi-crystal under the same collimation condition are compared. At 140 keV photon energy the energy resolution resulted in 20% and 50% for the planar crystal and the multi-crystal array respectively. The energy resolution of the multi-crystal detector agrees with the strong reduction of light yield (four times) obtained demonstrating a fairly good homogeneous light response of the array elements. The loss of the light depends on the array element aperture size and length as well as on the light absorption by the crystal itself, by crystal impurities (Nd in this case) and by reflective layers.

The spatial resolution measurements were carried out utilizing a $^{99m}$Tc radioactive source with 28 mm collimator thickness and three different collimator aperture diameters: 1 mm, 0.4 mm and 0.2 mm. A scanning mechanical system with an accuracy of 10 μm allowed the alignment of the collimator axis with the array element axis. During the measurements a distance of less than 2 mm resulted between the multi-crystal entrance face and the collimator front.

To avoid unwanted irradiation to the neighboring crystal pillars the mechanical alignment procedure was performed irradiating the multi-crystal by progressively

Fig. 6. Two dimensional image of six light unshielded crystal elements of YAP: Ce 22×11 crystal array. The image was obtained irradiating the six crystal elements one at a time by 99 mTc a collimated source with a 0.4 mm collimation aperture diameter centered on a single element. The rows consist of three spots each separated from one another and two shielded elements respectively. The rows are separated by two shielded crystal elements. The nearest distance between the two light spot centers is 1.2 mm. The six spots cover an area of 2.4 × 3.6 mm$^2$ area of multicrystal detector.

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reducing the collimator aperture followed by a scanning of the crystal array at steps larger than the aperture size of the single element crystal. In this way it was possible to put in evidence the spatial resolution increase and peak shift due to the progressive irradiation of two crystal elements.

To investigate the response of single array elements the exit face of the multicrystal was light shielded by black ribbon leaving unshielded only few crystal elements. By this method measurements independent of the irradiation collimation were carried out. Light output measurements on each unshielded crystal were also performed and differences within a range of 10% were found.

The image of six light unshielded crystal elements is shown in Fig. 6. The crystal elements represent well known positions easily recognizable in the array. The six crystal elements were optically coupled to the PSPMT and irradiated one at a time by the $^{99m}$Tc collimated source with a 0.4 mm collimation aperture diameter centered on a single element.

Analyzing a row of three elements in the image, the first two spots represents two crystals separated by one shielded element. The distance between the two light spot centers is 1.2 mm. The third spot of the row represents the light output of a crystal element further away from the two shielded elements (1.8 mm). In the same way the distance between the two rows is 1.8 mm.

The best spatial resolution value measured on this image was 0.72 mm as results from the image cross-section shown in Fig. 7 where the two peaks are separated by 1.8 mm. An average spatial resolution value of 0.8 mm was also measured.

Some irregularities in position representation are present probably due to some crystal irregularities of the array or in the case of the upper right crystal due to an imperfect contact of the black ribbon.

During spatial resolution measurements some limitations on image digitizing appeared due to the capability of our two-dimensional histogramming memory buffer. In fact due to the very high spatial resolution values measured and because of the limited dimensions of the crystal array it needed to zoom the digitizing process to obtain a calibration factor of 0.17 mm channel. It implied an error of about ±0.08 mm on spatial resolution measurements.

An interesting effect was noted during the irradiation with the 0.2 mm collimation aperture diameter. One crystal element was scanned with the 0.2 mm irradiation spot at a 0.2 mm step between two crystal edges. A continuous peak position shifting resulted and a measurement of the peak resulting from the sum of all irradiations was carried out. The measured spatial resolution value of this peak was compared with the analogous one obtained by single irradiation with the 0.2 mm collimation diameter at the center of the crystal element. A difference of about 0.2 mm FWHM was found as shown in the Fig. 8.

The multicrystal detector was also irradiated by a free $^{201}$Tl source where Hg X-rays were only considered (about 73 keV). A decreasing of spatial resolution at 1.2 mm was observed, corresponding to the inverse

![Fig. 7. Cross-section of the two dimensional image shown in Fig. 6 where the peaks represent the light spots of two unshielded crystal elements separated by 1.8 mm. The spatial resolution value measured on this image by a Gaussian fit (line) was 0.72 mm.](image)

![Fig. 8. Spatial resolution peak obtained by single irradiation with 0.2 mm collimation diameter on the element center of the YAP:Ce crystal array (upper). The same crystal element after scanning with the 0.2 mm irradiation spot at 0.2 mm step between the two crystal edges (lower). A difference of about 0.3 mm FWHM results from Gaussian fits.](image)
of the square root of the photon energy. It has to be considered a good result because the detector efficiency of the investigated YAP multi-crystal at this photon energy is 98%.

Furthermore no position shift was detected with respect to the same image obtained by $^{99m}$Tc irradiation. It confirms the dependence of the position linearity on the width of the charge cloud collected by the PSPMT wire-anode. In this case we can also note that changing the interaction depth inside the YAP crystal element only slightly affects the output light spread.

On the same crystal array the light shielding was removed and all crystal elements were coupled to the PSPMT. A series of scanning measurements were performed by the same collimated radioactive source with a collimation aperture diameter progressively reduced from 1 mm down to 0.2 mm. The scanning by the 1 mm collimation aperture diameter put in evidence the irradiation of at least 4 crystal elements and an average spatial resolution value of 1.5 mm resulted. Finally the center of one crystal array element was determined and two irradiations, at a distance of 1.2 mm, by the 0.2 mm collimation aperture diameter were carried out. The value of the FWHM obtained by a Gaussian fit of the spatial resolution peak was about 0.7 mm (Fig. 9).

A more complete analysis of the spatial resolution values measured was performed by measuring the spread of the charge cloud on the crossed wire anode. The crystal array was light shielded leaving only one crystal element optically coupled to the PSPMT. The element was in the central portion of the multi-crystal detector and coupled approximately in the photocathode center. The crystal element was then irradiated by $^{99m}$Tc with a 1 mm collimation aperture diameter. The charge distribution spread produced by one array element was obtained by measuring the charge collected by each wire of the anode. The charge distribution obtained representing the Detector Response Function (DRF) [12] is shown in Fig. 10. As can be seen, the total charge width introduced by the light spread on the photocathode and by charge multiplication through the proximity mesh dynodes is confined within 8 mm FWHM. The integral of the DRF represents the number of photoelectrons generated by the photocathode. The evaluated number of photoelectrons at 140 keV was about 80 for the YAP:Ce multi-crystal detector. Such a value is quite close to that given by Hama-matsu, to obtain a spatial resolution value of less than 1 mm.

Details on Detector Response Function measurements and on photoelectron evaluation will be treated in an other paper.

4. Conclusions

The YAP:Ce multi-crystal detector investigated in this work demonstrated to match the PSPMT intrinsic characteristics very well carrying out 0.7 mm of spatial resolution. To date this result represents the best value for position sensitive measurements of 140 keV gamma rays with an intrinsic detection efficiency of 35%. This detection system could have, in the near future, important developments in medical applications in the near future where the actual spatial resolution of gamma cameras seems not improvable over 3 mm. At this moment we have in progress another work in which we are attempting to improve the spatial resolution values by different YAP:Ce multi-crystal detectors with different element aperture sizes and thicknesses up to 30 mm.

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Acknowledgments

This work was partially supported by National Institute for Nuclear Physics (INFN) of Italy, Italian Research Ministry MURST and by Digital Equipment ECP. The authors gratefully acknowledge the former financial support by UILDM section of Rome Italy.

The authors are very grateful to the staff of Preciosa for the technical support on crystal manufacturing, to Mr. G. Basti for his important contribution to the mechanical system, to Mr. S. Lamerti, and to Dr. N. Raffetto for CAT measurements and finally to Mr. C. Cerone and to Dr. R. Giallatini for their technical support during computers installation. We also would like to thank Dr. G. De Vincentis and Dr. M. Banci for their continuous and precious support during radioactive sources preparation.

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