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TEST OF A BaF_2 -TMAE DETECTOR FOR POSITRON-EMISSION TOMOGRAPHY

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ABSTRACT

A detector consisting of BaF_2 scintillators and wire chambers has been tested for 511 keV gamma-rays. The wire chamber is filled with photosensitive tetrakis(dimethylamine)ethylene (TMAE) vapour and is operated at a pressure of a few Torr, using different gases at various temperatures. Energy, time, and position resolutions are given for BaF_2 crystals with sections of $10 \times 10 \text{ mm}^2$ and $5 \times 5 \text{ mm}^2$. We discuss the potential of this gamma detector for positron-emission tomography (PET) and compare it with other systems.

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1. INTRODUCTION

Barium fluoride is an inorganic scintillator with a radiation length of 20.5 mm and has two components in its scintillation light. The slow component, which peaks at 310 nm, has a decay-time constant of 620 ns, and the fast component, which peaks at 220 nm, has a decay-time constant of only 0.6 [1]. Hence, it is one of the fastest scintillators known. It is this unique combination of short decay-time constant and ultraviolet (UV) response which is exploited in the solid-state proportional counter (SSPC) [2–6].

In the SSPC the UV scintillation light is detected in a proportional wire chamber. This is achieved by adding a few Torr of tetrakis(dimethylamine)ethylene (TMAE) vapour to the chamber gas. In this way it is possible to combine the good detection efficiency characteristic of dense inorganic scintillators with the good spatial resolution of wire chambers. The SSPC has important potential applications in nuclear physics, in particle physics, and in nuclear medicine. In the present paper we are only concerned with the last one.

In nuclear medicine an obvious application of the SSPC is positron emission tomography (PET). In PET one has to detect the 511 keV photons from positron annihilation with the best possible efficiency and time resolution and with a spatial resolution of ≈ 2 mm. The more traditional approach to PET is to use a photomultiplier for each crystal. In this scheme a spatial resolution of a few mm and a large solid-angle coverage leads to a prohibitively expensive device. The commercially available systems use a compromise between these desirable features and the cost. With the SSPC one can envision a PET camera which contains many thousands of small BaF_2 crystals, all read by a few wire chambers. Moreover this camera would have an excellent time resolution: to reduce the rate of accidental events it is necessary to have a narrow coincidence window; BaF_2 is better than NaI or BGO, owing to the fast decay time of its UV component. A low-pressure wire chamber can take advantage of this speed, owing to its good timing properties and high gain [7].

Another possible solution for PET is the use of a conventional wire chamber with some sort of gamma converter [8–10]. These systems have good spatial resolution but suffer from poor detection efficiency and poor time resolution.

First results using $10 \times 10 \times 50 \text{ mm}^3$ crystals have been already described elsewhere [11]. Below we present more systematic measurements with $5 \times 5 \times 50 \text{ mm}^3$ crystals. This results in an improved spatial resolution. We also show that it is possible to operate the system continuously, without interruption for pumping and refilling.

2. DESCRIPTION OF THE DETECTOR

We have built two counters consisting of square matrices of 25 parallelepipedal BaF_2 crystals, $10 \times 10 \times 50 \text{ mm}^3$ for the first one and $5 \times 5 \times 50 \text{ mm}^3$ for the second one, followed by a multiwire proportional chamber (MWPC) (figs. 1 and 2). The crystals are optically separated and covered with reflective aluminium. On the side facing the MWPC they are in contact with a transparent grid, kept at fixed potential. The 511 keV gamma-rays are absorbed in the BaF_2 , with an efficiency of 90%. The MWPC consists of cathode planes of $100 \mu\text{m}$ diameter wires, grouped into 1 cm or 0.5 cm strips, in such a way that a strip faces a row of crystals, and an anode plane of $15 \mu\text{m}$ wires with a gap between planes of 3 mm. The wire spacing is 1 mm in all planes. The distance between the nearest cathode plane of the MWPC and the BaF_2 matrix—hereafter called the collection gap—can be varied from 0.5 mm to 4 cm, and a drift or amplification voltage can be applied, over this gap, in order to operate in the multistep mode. The SSPC is saturated with TMAE vapour at temperatures ranging from 20 °C to 55 °C. A few Torr of another gas are added and the temperature kept 5 °C higher to avoid condensation.

3. ENERGY RESOLUTION AND STABILITY

Unlike many other scintillators, the light yield of the fast component of the BaF₂ scintillator is insensitive to temperature [12, 13]. Variations in gain are hence entirely due to the wire chamber. We checked with a UV-sensitive photomultiplier that the light output of the BaF₂ matrix is the same as that of a single crystal of equivalent size. The energy resolution with the SSPC is measured with the anode signal fed into an ORTEC 142 preamplifier. The voltage in the drift space is kept at 30 V to avoid avalanche amplification, which could deteriorate the energy resolution. We obtain ¹³⁷Cs peaks ($E_\gamma = 662$ keV) with isobutane, CH₄, and CF₄, added to TMAE. Above 40 °C we also observe good working conditions with TMAE vapour alone. Our best signal is obtained with pure TMAE at 50 °C in a gap of 1.5 cm (fig. 3). The energy resolution is poor, owing to the small number of photoelectrons [3]. From the peak width we estimate their number to be of the order of 10. We deduce that the gain of the MWPC is about 2×10^4 without amplification in the collection gap, for a high voltage of 400 V on the anode. This gain is three times higher than what we measure at 20 °C with 3 Torr of isobutane.

The good working conditions we observe at high temperature are due to the rise of the TMAE vapour pressure. Our measurement of this quantity (fig. 4) follows the Clausius–Clapeyron relation, as in ref. [14].

If the chamber is filled and closed we observe a deterioration of the gain in 24 h. This is clearly incompatible with the routine work of a positron camera. The problem is probably caused by the chemical reaction of TMAE with some component or outgassing of the chamber. In an SSPC used in high-energy physics [15] we have tested a continuously flowing system. The TMAE bottle is constantly open on one side of the detector. The other side has a microleak, or a valve driven by a pressure transducer (MKS type 223BHA10), followed by a refrigerated bath to freeze the TMAE, and by a vacuum pump. With this system we have been able to keep the gain stable within a few per cent and to operate the apparatus continuously for three months.

4. TIME RESOLUTION

The time resolution is measured with a ²²Na source: the positrons emitted by this isotope annihilate in the source, producing two back-to-back photons of 511 keV. The start signal for the time measurement is provided by the detection of one of the photons in a small BaF₂ crystal coupled to a fast UV photomultiplier (XP2020Q). The stop signal is obtained from the anode of the SSPC. For the time-resolution measurements the electric field in the collection gap is increased until parallel-plate amplification is obtained. Under these conditions the anode signal shows a rise-time of 10 ns (see fig. 5). The drift velocity is measured by recording the delay between the photomultiplier and the chamber signals as a function of the collection gap. We find in pure TMAE a value of 3.8 cm/ μ s without amplification and 10 cm/ μ s with maximum amplification.

Results are shown in fig. 6: at 50 °C, with a 0.5 mm gap and a 130 V amplification voltage, we obtain 2.4 ns FWHM. The variation of the time resolution with the gap distance is compatible with a simulation assuming 10 UV photons detected by TMAE in an infinite collection gap and 10 cm/ μ s drift velocity (fig. 7). This simulation includes the Poisson statistical fluctuation in the ion-pair production mechanism by the incoming light. It assumes that the detection of the electron closest to the MWPC determines the timing.

There is clearly a conflict between the requirements of good time and good energy resolution. It seems to us that for PET a good time resolution is more important. A collection gap of 2 mm, corresponding to a time resolution of ≈ 4 ns at 50 °C, seems appropriate.

5. POSITION RESOLUTION

One possibility of measuring the position of the incoming gamma-ray is to have a large-diameter crystal and to use the Anger method. This method suffers from the small number of detected photons and cannot reach a value lower than 13 mm [6]. The other possibility, chosen in the present study, is to use a matrix of small closely packed crystals, optically separated, acting as light guides. A few photons are sufficient to identify the crystal which is hit. No attempt is made to localize the impact point inside the crystal.

Our previous measurement [11] of the position resolution was performed with a collimated ^{22}Na source. In the present study we avoid the difficult problem of collimation by using coincidences between two back-to-back 511 keV photons from a ^{22}Na source. The source, 1 mm in diameter, was placed at 12 cm from the crystals. The solid angle was defined by a BaF_2 crystal, $5 \times 5 \text{ mm}^2$ in section, viewed by a photomultiplier placed at 68 cm from the source, opposite to the SSPC. The uncertainties coming from this experimental procedure are the following (FWHM): 1 mm for the source diameter, 0.9 mm for the geometrical collimation, and 1 mm for the deviation from linearity of the two gamma-rays, as calculated for example by Derenzo and Budinger [16]. We measured the position resolution by moving the source perpendicularly to the axis from the SSPC to the photomultiplier. Each coincidence between the photomultiplier and the matrix was recorded, and no energy threshold was set on individual crystals. The position information was derived from the cathode signals, which were amplified and fed into analog-to-digital converters. Several values were tried for the gap width and the TMAE temperature. The results presented below were obtained with a 2 mm collection gap of 50 °C.

If the SSPC detects a 511 keV photon, all the signal is not necessarily confined to one single cathode strip. This is due to: a) Compton scattering in the BaF_2 such that the energy of the 511 keV photon is deposited in more than one crystal; b) spreading of the light in the collection gap; c) electronic noise and cross talk. If the impact point of the photon is assigned to the strip with the largest signal, one obtains a position resolution of 5.8 mm (fig. 8) and 11.5 mm (fig. 9) for $5 \times 5 \text{ mm}^2$ and $10 \times 10 \text{ mm}^2$, respectively. We also tested another method, to see if additional information can improve the performance: we determined the position by the centre-of-gravity method, using the highest signal and the two adjacent ones. This gives a continuous distribution with peaks located at the centre of the crystals (fig. 10). When we assign each measurement to the nearest centre, we find a resolution curve (fig. 11) as before. The FWHM is found to be 6 mm. Thus this method gives a similar but slightly worse result.

At 23 °C, with a 1 to 4 cm collection gap, the resolution was about 22 mm, which demonstrates the importance of keeping a narrow gap. In all the cases, we have checked that the amplification voltage of the PPAC has only a minor influence on the spatial resolution.

6. DISCUSSION

We find a position resolution which is almost equal to the size of the crystals. When we subtract quadratically the contributions due to source diameter, collimation, and non-linearity, we obtain 5.6 mm FWHM for 5 mm rods. This number, divided by 2, would correspond to a precision of 2.8 mm for the image, not including the degradation due to reconstruction. The resolution can probably be improved further by taking even smaller crystals, e.g. with a section of $3 \times 3 \text{ mm}^2$.

The performance can certainly be improved if the crystals are separated by lead or tungsten septa, to absorb Compton gamma-rays, at the expense of a decrease in the efficiency. On the other hand, one knows that the accuracy is deteriorated when the photon hits the detector with an angle different from 90°, as occurs for a source distant from the centre of the camera gantry. All these effects have been studied by different authors [17, 18]. They deserve a detailed analysis in our specific case, both experimentally and by simulation, which we plan to carry out in the near future.

7. POSSIBLE DESIGNS FOR A NEW PET CAMERA

Because of the parallax error, a PET camera based on BaF₂ and wire chambers must consist of a cylindrical detector where all crystals point towards the axis of the cylinder, or of a number of small plane detector modules assembled in a ring as illustrated in fig. 12. Each module should be less than $5 \times 10 \text{ cm}^2$ in section.

Figure 13 shows a possible detector module. The complete ring has 24 such modules. Each one contains 512 BaF₂ crystals, $3 \times 3 \text{ mm}^2$ in section. The wire chambers operate at low pressure in pure TMAE at 50 °C. The resolution on the time difference in such a system is expected to be between 3 and 6 ns FWHM, slightly better than a BGO ring camera. Below, this system is compared with a high-performance ring camera with 600 BGO crystals $3 \times 10 \text{ mm}^2$ in section [19]:

- The time resolution for the BaF₂ camera is better by a factor of 3 and, as a result, the rejection factor of the background from accidental coincidences is reduced by the same factor.
- The resolution in the plane of the ring is worse because of Compton scattering and the smaller density of BaF₂; the magnitude of this effect is difficult to evaluate without a detailed study, but it can be at least partly cured by the use of tungsten septa between the crystals.
- The axial resolution is better by a factor of 3.
- The solid angle is about 5 times bigger, and several sections can be imaged; a BGO camera having the same solid angle would be prohibitively expensive. An object the size of a human head can be completely imaged, in one go, as a three-dimensional object.
- The BaF₂ camera has almost no energy resolution; this will make the rejection of Compton scattered photons less effective; again only a detailed study will allow evaluation of the importance of this effect.

The solution looks attractive. It is simple and probably competitive in price with current commercial ring designs.

8. CONCLUSION

We have investigated the performances of an SSPC designed for 511 keV gamma-ray imaging. It is possible to operate this device constantly for several months at low pressure, if the TMAE is renewed by a continuously flowing gas system. To ensure good time and space resolution, it is necessary to have a small amplification gap. Consequently the system has to be operated at $\approx 50 \text{ °C}$ to save the efficiency of the light detection. This temperature and a 2 mm gap collection with amplification are appropriate working parameters.

We have measured a time resolution of 2.4 ns, which is too large for time of flight but gives a significant background reduction compared to NaI or BGO. The spatial precision with a matrix of small crystals is better than with a single large crystal. Despite the small number of photons, crystals with a section of $5 \times 5 \text{ mm}^2$ can be separated by the MWPC. A resolution of 5.6 mm FWHM for the photon detection with a single detector has been measured. This measurement suggests that the spatial resolution could be improved further by taking even smaller crystals. Our present result encourages us to work in more detail on the design of a full-size medical prototype. We expect that a medical PET camera based on an SSPC will have a high-rate capability and allow a dramatic improvement of the axial precision and of the acceptance.

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Figure captions

- Fig. 1** Schematics of the SSPC.
- Fig. 2** A photograph of the MWPC with the matrix of $10 \times 10 \times 50 \text{ mm}^3$ crystals.
- Fig. 3** 661 keV spectrum (^{137}Cs) obtained with pure TMAE at 50 °C and with a 1.5 cm gap collection.
- Fig. 4** TMAE vapour pressure as a function of the inverse of the absolute temperature, and the temperature in degrees Celsius, including points from ref. [14].
- Fig. 5** Signal showing the 10 ns rise-time.
- Fig. 6** Time spectrum for a 511 keV ^{22}Na source.
- Fig. 7** Time resolution for a ^{22}Na source, as a function of the collection gap (the curve is a simulation).
- Fig. 8** Probability of hitting a crystal (with a matrix of $10 \times 10 \times 50 \text{ mm}^3$ crystals) when the source is moved away from the centre.
- Fig. 9** Probability of hitting a crystal (with a matrix of $5 \times 5 \times 50 \text{ mm}^3$ crystals) when the source is moved away from the centre (two adjacent crystals are represented).
- Fig. 10** Continuous distribution obtained by the centre-of-gravity method ($5 \times 5 \times 50 \text{ mm}^3$ crystal).
- Fig. 11** Probability distribution obtained by the centre-of-gravity method.
- Fig. 12** Possible design of a PET camera with 24 MWPCs, to minimize the parallax error.
- Fig. 13** One of the 24 modules of the camera sketched in fig. 12.

Schematics of the SSPC

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Distance between the source and the crystal centre (mm)

Fig. 8

Distance between the source and the crystal centre

Fig. 9

Fig. 10

Distance between the source and a crystal centre

Fig. 11

Distance between the source and the crystal centre (mm)

Fig. 12

Fig. 13