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Nuclear Instruments and Methods in Physics Research A 420 (1999) 181–188

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Optimizing performances of CsI(Tl) crystals with a photodiode readout

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Received 17 July 1998

Abstract

Tests are described concerning the performances of CsI(Tl) crystals. Particular care was dedicated to the study of the light production and collection of the crystals, that appear to be significantly affected both by the choice of the wrapping materials and by the details of the binding technique. A functional relation between the light pulse height and the coupling of the crystal + photodiode system was deduced. Finally, the influence of this coupling on the energy resolution of the detector is discussed. © 1999 Elsevier Science B.V. All rights reserved.

PACS: 29.40.Mc

Keywords: Heavy-ion; Scintillation detectors; Photodiodes

1. Introduction

The complexity of physical events produced in intermediate-energy heavy-ion reactions require experimental apparata able to detect reaction products over a large solid angle in a wide range of kinetic energies and masses. Since no single detector is capable of similar performances, the use of ΔE–E telescopes becomes necessary. Moreover, the need to identify the reaction products in a high dynamical range makes one use a three-stage detectors which are necessary to reach the best compromise between low-energy thresholds and proper identification triggering [1–4].

On the other hand, it has been recently shown [5,6] that it is possible to identify both light charged particles and heavy fragments using a telescope with only two stages: microstrip gas chambers (MSGC) as low-energy threshold transmission detectors and CsI(Tl) crystals to stop the reaction products.

The choice of CsI(Tl) arises from the fact that, since the maximum available thickness for silicon detectors is a few millimeters, they become

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0168-9002/99/$ – see front matter
PII: S0168-9002(98)01136-X

unsuitable as stopping detectors for higher energy light ($Z \leq 2$) particles when the incident particle energy becomes larger than ~ 10 MeV. Even though the energy resolution of CsI(Tl) crystals with a photodiode (PD) readout is worse than an order of magnitude, these detectors are more suitable because of their high stopping power and relatively low cost, and also because they have, with respect to Si diodes, the advantage of being mechanically stronger, easily cut, and machined. Finally, this choice is also supported by the fact that in this energy region, arrays with a large number of detectors are necessary to detect and identify the reaction products with a good granularity and sufficient coverage of the solid angle, so Si diodes are not a suitable choice because of their high cost and susceptibility to radiation damage.

This paper describes procedures to optimize such a kind of detectors, mainly concerning the search for the best value of the light output and of the energy resolution. In particular, the effect on these quantities of the adopted wrapping materials and of the thickness and area of the employed photodiodes is investigated in detail.

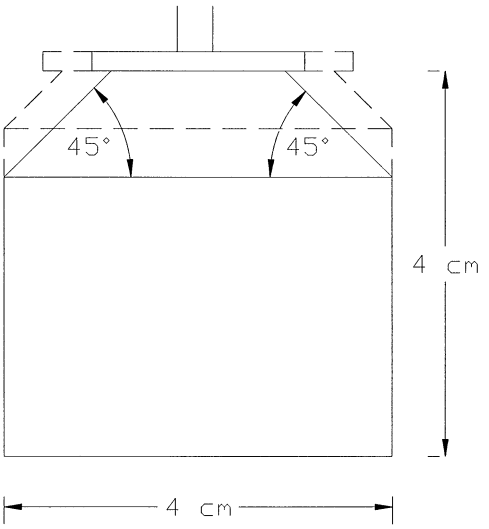

Fig. 1. Schematic picture of the CsI(Tl) crystals used in the present work. The two profiles of the truncated pyramid shapes used to fit the crystals to the PDs keeping the total thickness and the pyramid angle constant (4 cm and 45°, respectively) are indicated by the dashed and full lines for the 28×28 mm^2 and 18×18 mm^2 PDs, respectively.

2. Experimental

The tests have been performed by using cubic CsI(Tl) crystals, $4 \times 4 \times 4$ cm^3, with a side of truncated pyramid shape in order to allow the matching of the PDs: that is why no light pipes were used. The crystal was directly coupled to the PD by means of a siliconic glue[1] that allowed both a good optical quality of the glueing and the possibility of removing and cleaning the crystals and the PDs easily. A schematic picture of the crystal-PD array is shown in Fig. 1.

The experimental setup consisted of a 45 cm diameter, 30 cm deep vacuum chamber for detector and source lodging. Radioactive sources were placed in front of the CsI(Tl) crystals, without any kind of collimation, at a distance of 5 cm. The outgoing pulses fed a Canberra 2003BT FET preamplifier and, through an ORTEC 572 amplifier using a shaping time of 3 μs, were recorded in an ORTEC 918A multichannel buffer operated by an IBM PC. A precision pulse generator (ORTEC 448) was used to check the linearity and the stability of the amplifiers and the ADC.

In a procedure mainly devoted to the optimization of the light response and the energy resolution of the detector, the best attention must be used in order to avoid possible errors due to modifications in the performance of the electronics, such as changes in offset and conversion factor of the energy scale. So, a completely self-consistent protocol was adopted throughout all measurements. The first step was the determination of the energy scale of the multichannel analyzer. The tests began by exposing the crystal to be studied to a three-peak multiple α source (^{239}Pu [7], $E_\alpha = 5148.8$ keV; ^{241}Am [8], $E_\alpha = 5478.7$ keV; ^{244}Cm [9], $E_\alpha = 5794.9$ keV (the reported values of E_α being the weighted mean values from the single nuclide α emissions)). Even though the light output of CsI(Tl) detectors is not linear with the energy, this

[1] Glue model SILGEL 612, supplied by Walker-Chemie Italia SpA

effect can be completely neglected in the relatively small energy range involved in our tests: the linear correlation coefficient between the measured centroids of the peaks and their energies was in fact close to one.

The multiple peak spectrum furnished a careful energy calibration. A typical calibration spectrum is shown in Fig. 2 (full lines). This calibration was then used to measure the various parameters of interest by using a ^{241}Am α source (the resulting spectrum is indicated with a dotted line in the same figure). For the major part of the measurements performed during the tests, it stemmed out that the overall energy resolution was good enough to well separate the peaks of the multiple source allowing in this way the energy resolution to be obtained directly from this run. But the whole procedure was adopted since, for worse resolution (as in the case of the smallest size of the PDs), the separation between the peaks is sufficient to obtain their centroids and, consequently, the energy calibration, but not the shape of the single components of the spectrum without a multiple Gaussian fit introducing remarkable uncertainess connected to the fitting procedure. Finally, in order to assure the maximum reproducibility and uniformity of the analysis, a fully automatic method was employed for peak identification and fitting [10].

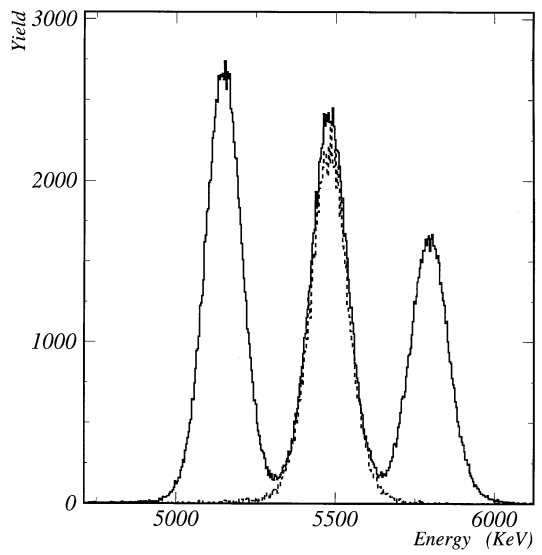

Fig. 2. Multiple peak α source spectrum from a $4\times4\times4$ cm^3 CsI(Tl) crystal coupled to a 28×28 mm^2, 500 μm Hamamatsu photodiode (full line) and ^{241}Am α source spectrum from the same detector (dotted line).

On the other hand, it is necessary to underline the importance of such an accurate working protocol, because the light output changes with any modification of the crystal preparation procedure and detector geometry. This self-consistent calibration method with the multiple source enables us to control all the experimental conditions throughout the long time necessary for all the tests (about 6 months).

3. Results

3.1. Light pulse and wrapping material

The hint for the tests described in this paper arose from the experimental evidence that the light response of CsI(Tl) crystals prepared in a classical way (typically 2 or 3 layers of teflon tape followed by a thin (1.5 μm) aluminized mylar window and finally wrapped round by some other teflon layers [11] increases remarkably if one or more teflon layers are replaced by a foil of reflective material. More than 20 tests performed in successive runs with different crystal and photodiode systems prepared according to the two methods showed a relative gain of about 20% in the pulse height if reflective foils are used. So, we decided to deepen this subject to get information on the best reflecting materials [12].

To carry out these tests, two different $4\times4\times4$ cm^3 crystals were used, the first one (A) coupled to a 28×28 mm^2, 300 μm thick photodiode, the second one (B) to a 18×18 mm^2, 500 μm photodiode.[2] In all the measurements described in this paper, the 300 and 500 μm PDs were biased at 100 and 150 V, respectively. To preserve the crystals from possible chemical reactions with the reflecting materials, they were initially wrapped with one layer of Teflon tape, 0.1 mm thick, externally of which the reflective material was applied. The binding was completed by the 1.5 μm monoaluminized

[2] Supplied by HAMAMATSU Italia SRL.

Table 1
Light output for different wrapping materials

Wrapping material	Peak CH. ("A")	Gain (%)	Peak CH. ("B")	Gain (%)
"Bare" crystal	880	–	582	–
Millipore IPVH	1071	22	771	32
Millipore HAWP	1106	26	813	40
Millipore GVHP	1051	19	753	29
Dupont TYVEK L-1057D	971	10	699	20
Dupont TYVEK L-1059D	1065	21	780	34
Dupont TYVEK L-1073D	1022	16	711	22
Dupont TYVEK L-1082D	1040	18	737	27

"A": the crystal is coupled to an $28 \times 28\ mm^2$, 300 μm photodiode.
"B": the crystal is coupled to an $18 \times 18\ mm^2$, 500 μm photodiode.

mylar window and by further 3 layers of Teflon tape. The examined reflective materials were Millipore foils (IPVH, HAWP and GVHP)[3] and Dupont TYVEK foils (L-1057D, L-1059D, L-1073D and L-1082D).[4] Table 1 reports the results for all the examined materials, indicating in particular the channel number corresponding to the barycenter of the ^{241}Am α peak, that is of course related to the light output from the detector, and the relative gain

$$\left(\frac{\text{Wrapped crystal peak barycenter} - \text{Bare crystal peak barycenter}}{\text{Bare crystal peak barycenter}}\right)$$

due to the use of the various reflecting materials with respect to the response of a "bare" crystal, namely a crystal with simple Teflon + mylar + Teflon preparation. The results of the measurements referring to the crystal labeled "A" in Table 1 are shown in Fig. 3. Throughout all measurements, the reproducibility in the value of the barycenter of the peaks was better than 1%.

[3] Supplied by MILLIPORE Italia SpA.
[4] Supplied by Dupont de Nemours International SA through Augusto Berni SpA.

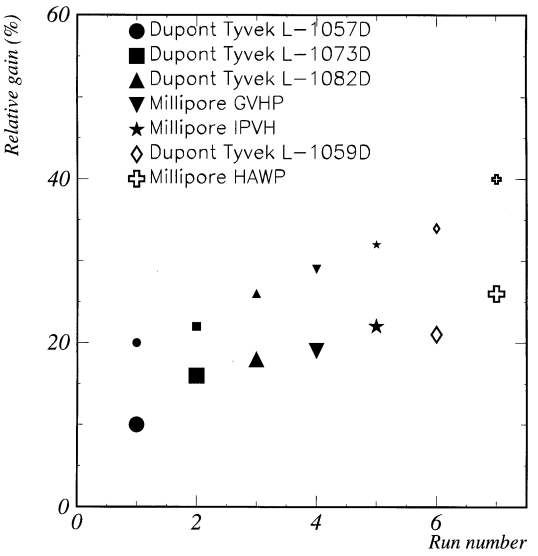

Fig. 3. Relative gain (% with respect to a "bare" crystal) in the pulse height from the crystal + PD array for the various employed reflecting materials. The two sets of data identify crystals "A" (large symbols) and "B" (small symbols).

It stems out from Table 1 and Fig. 3 that the use of the various reflecting materials improves the light response of the detector with a relative gain ranging from 10% to 40%. On the other hand, it is also necessary to take into account other parameters such as, for example, the extreme fragility of the Millipore HAWP foils, the difficulty of obtaining a good wrapping with a thick paper such as Tyvek L-1082D, and similar related problems. The best combination of reflecting performances and easiness in preparing the crystals was achieved, in our opinion, with Millipore IPVH foils and relatively thin Dupont TYVEK foils (L-1059D).

Fig. 3 also shows that the trend of the pulse height value is the same for both the crystals. It also appears from Table 1 that the gain in the value of the absolute position of the centroid of the peak is the same (∼ 300 channels) in both the cases.

3.2. Light pulse and photodiodes

Another choice affecting the output light pulse is the geometrical configuration of the CsI(Tl) + photodiode detector. In order to search for an analytical expression connecting the output pulse height to these geometrical quantities, two identical CsI(Tl) crystals ($4 \times 4 \times 4$ cm^3) were used, in order to avoid that the results were affected by a better or worse quality of the rough material. In successive steps, both the crystals were coupled to six pairs of Hamamatsu photodiodes, three 300 μm thick (10×10 mm^2, 18×18 mm^2, 28×28 mm^2) and three 500 μm thick (9×9 mm^2, 18×18 mm^2, 28×28 mm^2). The measurements were performed according the same protocol described in Section 3.1. In all the tests, the Millipore IPVH foils were used as wrapping material.

The results of these measurements are summarized in Fig. 4. In this figure, the relative gain in the value of the barycenter of the ^{241}Am peak due to the change of the thickness of the PD from 300 μm to 500 μm

$$\left(\frac{\text{500 μm peak barycenter} - \text{300 μm peak barycenter}}{\text{300 μm peak barycenter}}\right)$$

is shown for the aforementioned sizes of the PDs and for both the crystals, wrapped in the "classical" [11] and "present work" way. Only in the case of the largest PDs there is a gain in the output, whereas in the other cases there is either no influence (18×18 mm^2 PDs), or a diminution of the output pulse for the smallest PDs, even though this fact can be related to their different sizes (the 500 μm PDs have an area about 20% smaller than the 300 μm ones).

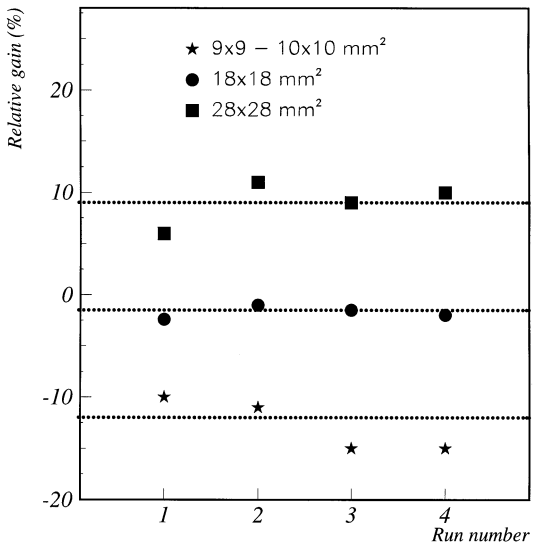

Fig. 4. Relative gain in the value of the barycenter of the ^{241}Am peak due to the different thicknesses of the PDs. Run numbers 1 and 2 identify the crystal "A" with a "classical" and "present work" wrapping, respectively; run numbers 3 and 4 refer to the same data but for the crystal "B". The dotted lines are drawn in correspondence with the mean values of the relative gain for the different PD sensitive areas.

A second point concerns the dependence of the output pulse height from the geometrical configuration of the crystal + photodiode detector. We start by simply assuming that if dN is the number of photons impinging on the element dS of the surface of the photodiode in unit time, a linear relation

$$dN = K\, dS \tag{1}$$

holds, where K is a proportionality constant. This assumption can be considered reasonable since we experimentally observed the independence of the light output both from the position in which the α particles hits the surface of the crystal and from the volume of the crystal itself. Of course,

$$dN = \frac{\varepsilon_{PD} S}{\eta e d}\, dV, \tag{2}$$

where η is the quantum efficiency of the photodiode, ε_{PD} its dielectric constant, S and d, respectively,its area and thickness, dV the corresponding infinitesimal pulse height and e the elementary charge. Then

$$dV = \frac{\eta e d K}{\varepsilon_{PD} S}\, dS \tag{3}$$

and, integrating,

$$\int dV = \frac{\eta e d K}{\varepsilon_{PD}} \int_{A_0}^{A} \frac{dS}{S}, \tag{4}$$

where the photodiode area A_0 is a lower limit for which it is possible considering as a constant the inner photodiode electric field. So, the output pulse of a photodiode with area A coupled to a crystal

and exposed to a monochromatic source can be given by

$$V(A) = V_0 + B \ln(A/A_0) \quad (5)$$

with

$$B = \frac{\eta e d K}{\varepsilon_{PD}}$$

that represents the pulse height of the PDs. We then fitted the available experimental data to a relation like

$$PH = C + D \ln S \quad (6)$$

where PH is the output pulse height, S the area of the photodiode and C and D fitting constants.

For the eight studied cases (two crystals with two photodiode thickness and two kinds of wrapping) the values of the C and D parameters remain in a reasonable range of values. The results of the fits are $C = -1048 \pm 53$ and $D = 620 \pm 19$ for the 300 μm PDs and $C = -1178 \pm 36$ and $D = 678 \pm 26$ for the 500 μm PDs (in both the cases the linear correlation coefficient ranged from 0.997 to 0.999). Fig. 5 shows the comparison between the experimental points and the fitted lines. In this case also, the data refers to the crystal labeled "A" in the tables.

This logarithmic dependence holds true also for data on the light output from CsI(Tl) tapered crystals viewed by PDs with a sensitive area smaller than the cross section of the scintillator [13]. A ratio greater than 2 between the signals from CsI(Tl) coupled to 400 and 100 mm^2 was also reported [14] in full agreement with our results.

3.3. Energy resolution

The last set of tests concerned the study of the possible dependence of the energy resolution of the detector from the overall crystal/photodiode geometry. For this reason, the data measured as described in Section 3.2. were used to extract the required quantities, where the energy resolution is classically defined as the ratio of the FWHM of the ^{241}Am α peak to the energy of its barycenter. It should also be noted that the energy loss in the entrance window was measured by covering a Si detector with a foil of the same thin (1.5 μm) aluminized mylar used for reparing the window. The measured energy loss was 189 keV for the ^{239}Pu peak ($E_\alpha = 5148.8$ keV), 178 keV for the ^{241}Am peak ($E_\alpha = 5478.7$ keV), and 170 keV for the ^{244}Cm peak ($E_\alpha = 5794.9$ keV). These values are in fairly good agreement with those evaluated by means of the TRIM97 code [15] (176, 166 and 160 keV, respectively): thus, the small variation of this value in the α particle energy range involved in these measurements allows this effect to be completely neglected.

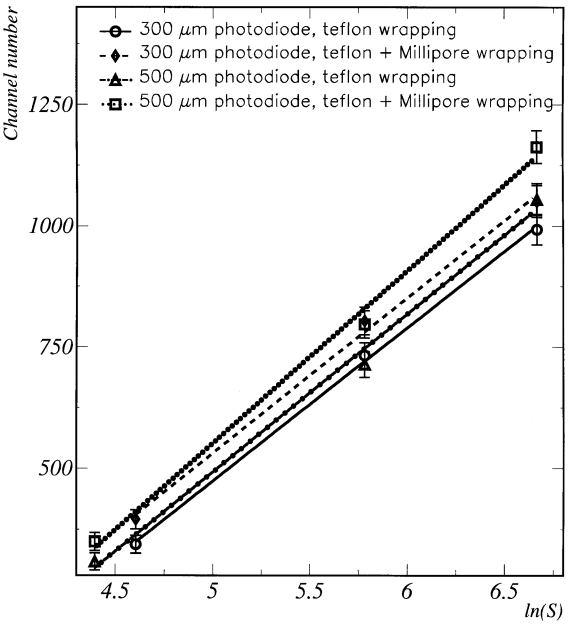

Fig. 5. Functional dependence of the height of the light pulse from the logarithm of the sensitive area for various photodiode thicknesses and wrapping techniques.

The results are reported in Table 2 and show a systematic worsening of the energy resolution with the decrease of the area of the PD's. It must be finally underlined that these energy resolutions were obtained without any kind of collimation of the α particles, which means that the detector was seen by the source on the whole subtended solid angle.

The results of the above-described tests is the choice of the final configuration of the crystals: we selected reflective IPVH Millipore foils and

Table 2
Energy resolution of CsI(Tl) plus photodiodes detectors

(*)	Photodiode	Energy resolution (%)
A	28×28 mm^2, 500 μm	2.6
B	28×28 mm^2, 500 μm	2.8
A	28×28 mm^2, 300 μm	3.1
B	28×28 mm^2, 300 μm	3.0
A	18×18 mm^2, 500 μm	3.0
B	$18 \times$ x18 mm^2, 500 μm	3.2
A	18×18 mm^2, 300 μm	3.2
B	18×18 mm^2, 300 μm	3.2
A	9×9 mm^2, 500 μm	6.5
B	9×9 mm^2, 500 μm	7.0
A	10×10 mm^2, 300 μm	4.4
B	10×10 mm^2, 300 μm	4.2

(*) The two crystals are identified by the letters "A" and "B".

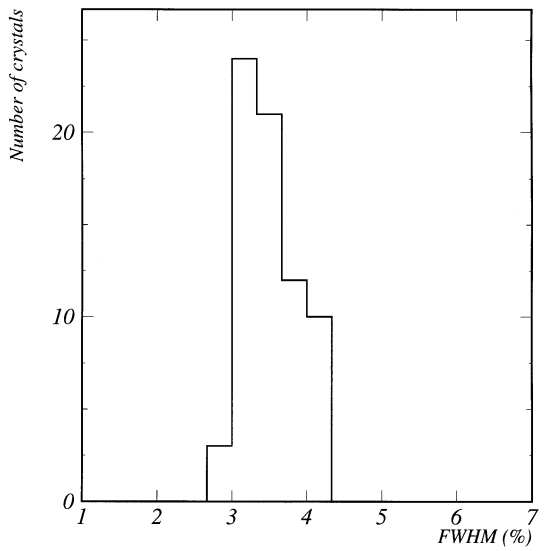

Fig. 6. Distribution of the energy resolution values for the test of a set of 70 CsI(Tl) crystals.

500 μm, 18×18 mm^2 Hamamatsu PDs. A test was performed concerning a set of 70 CsI(Tl) crystals prepared for the forward part of the GARFIELD apparatus [5]. The energy resolution values remained close to an acceptable value of $3.5 \pm 0.7\%$ and his distribution around this value is shown in Fig. 6.

4. Summary and conclusions

Some tests were carried out in order to optimize the performances of CsI(Tl) crystals to be used in a new 4π apparatus under construction [5].

First of all, a systematic study was made about the wrapping techniques and, in particular, about the choice of reflecting materials to be used in preparing the crystals. Both paper foils and biological membranes were tested, in order to achieve the best compromise between the reflective properties and the mechanical resistance and workability.

Then, a functional relation was extracted concerning the dependence of the photodiode light pulse height from geometrical parameters such as the area of the photodiode itself. A logarithmic dependence was found and has been explained by simple physical and geometrical assumptions.

Finally, energy resolution was measured for all the possible crystal + photodiode combinations. The best resolution was obtained for relatively large photodiodes, whereas the resolution becomes suddenly worse if the area of the photodiode is much smaller (a typical factor is 20 times) than the area of the entrance window.

Acknowledgements

The authors would like to thank Arialdo Moroni for his friendly encouragement and stimulating discussions. The help of Roberto Baccomi and Claudio Becciani in preparing and testing the crystals is gratefully acknowledged. Thanks are also due to all the members of the GARFIELD collaboration that encouraged and stimulated this work.

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