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THE RESPONSE OF A 10 in $\times$ 12 in NaI(Tl)
SPECTROMETER TO 130 MeV TO 387 MeV γ -RAYS

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ABSTRACT

A method is described which improves the energy resolution of a NaI(Tl) crystal 25 cm in diameter and 30 cm in length by the use of a thick plastic scintillator surrounding the crystal. The method was tested at the Bonn synchrotron with a parallel photon beam (diameter ~ 7 cm, $E_\gamma = 130$ -387 MeV) and at the CERN Proton Synchrotron (PS) with 129 MeV γ -rays illuminating nearly the whole crystal. For these photon energies the energy resolutions obtained are of the order 7-8% (FWHM) without loss of efficiency.

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1. INTRODUCTION

In order to detect intermediate-energy photons ($E_\gamma \gtrsim 100$ MeV) with good energy resolution, very large (50 cm $\times$ 50 cm or more) NaI(Tl)-crystal spectrometers are coming progressively into use [1]. These spectrometers consist either of one large block (or a few large blocks) of NaI(Tl) or of an assembly of many (up to several hundred) smaller optically independent modules. The first solution has the merit of simplicity but, owing to the large volume, the single rates and the probability for multiple hits in high multiplicity experiments may become prohibitive. These drawbacks are very much attenuated in the second solution (small modules); but then electronics, data acquisition, and data analysis become very complex. Both solutions are expensive and may exceed the possibilities of a small laboratory.

We propose here a solution which uses a NaI(Tl) crystal of moderate size (25 cm $\times$ 30 cm). Several laboratories already possess such crystals [2], mainly for the study of radiative capture reactions in the giant resonance region ($E_\gamma \sim 20$ MeV). They can be produced with good uniformity of light output ($\sim 1\%$). The detection solid angle is of course rather small (some percent of 4π) which reduces the problems of multiple hits in high-multiplicity experiments. Because of the limited volume, the energy resolution of the bare crystal is rather poor owing to the fluctuations in shower energy leakage [3,4]. A straightforward solution to improve the resolution is to select showers for which the escaping energy is relatively small by the use of a plastic anticoincidence scintillator surrounding the crystal [2]. However, we present a method which substantially improves the energy resolution without loss of efficiency or solid angle.

The basic idea of this method is to recapture in the plastic scintillator which surrounds the crystal a fraction of the energy escaping from the crystal. Owing to the statistical nature of the escaping shower products one can assume in first order that the energy deposited in the plastic scintillator is an approximately constant fraction of the energy missing in the crystal. If then, one adds the output of the plastic scintillator, multiplied by an experimentally determined

coefficient, to the output of the crystal, one can hope to obtain a pulse height corresponding to the full energy of the incident photon.

In order to test this idea, we have measured the response of the first Strasbourg 25 cm $\times$ 30 cm NaI(Tl) spectrometer [5] at the Bonn 500 MeV electron synchrotron using tagged photon beams of energies ranging from 137 to 387 MeV [6]. In addition, the spectrometer was tested at CERN with 129 MeV γ -rays produced by radiative capture of π^- at rest in hydrogen. The results presented after the brief description of the spectrometer show that the method described above is justified.

2. THE SPECTROMETER

Figure 1 shows the Strasbourg NaI spectrometer. The intrinsic energy resolution (FWHM) of the NaI(Tl) crystal (25 cm in diameter and 30 cm in length)*) for low-energy γ -rays is 14% at 0.66 MeV, 7.5% at 2.62 MeV, and 3% at 20.5 MeV. The uniformity was measured with a collimated 2.62 MeV source and was of the order of 1% except for the last 5 cm near the 60 AVP photomultiplier. The plastic scintillator completely surrounds the NaI crystal and is composed of three pieces: the front plastic (FP) 6 cm thick, the main plastic (MP) at least 10 cm thick, and the rear plastic (RP) 10 cm thick. The gains of the photomultipliers viewing these three plastics were adjusted so that each scintillator had the same energy calibration. For the main plastic the calibration varies by a factor of two over its whole length.

Figure 1 also shows schematically the associated electronics. The output of the 60 AVP photomultiplier associated with the NaI crystal is analysed in the conventional way. The mixed plastic scintillator signal passes a fast linear gate and stretcher opened when there is a high-energy photon interacting with the crystal. Slow pulses corresponding to energies deposited in the crystal and in the plastic scintillator are analysed separately by two ADCs gated by an external device (tag counter in Bonn, or telescope identifying a stopped π^- at CERN) and stored in event mode on magnetic tape by the use of a computer.

*) Manufactured by Quartz et Silice, St.-Pierre les Nemours, France.

3. RESULTS AND DISCUSSION

3.1 Measurements using the tagged photon beam

The incident photons were produced by the tagged photon facility of the Bonn 500 MeV electron synchrotron [6]. The diameter of the photon beam is approximately 7 cm (see fig. 1). Twenty tag counters make available 20 different photon energies for the same electron energy. Two series of measurements were done with electron energies of 300 MeV ($138 \text{ MeV} \leq E_\gamma \leq 257 \text{ MeV}$) and 450 MeV ($206 \text{ MeV} \leq E_\gamma \leq 386 \text{ MeV}$). The number of the tag counter in coincidence with a NaI pulse was written for each event identifying the incident photon energy. For the sake of clarity the results which will be presented correspond to some selected photon energies only.

The raw results were analysed in the following manner. Each event corresponding to an incident photon energy E_0 was classified in one of five subgroups according to table 1 depending on the fraction of E_0 deposited in the plastic scintillator.

Figure 2 gives the fraction of the total number of counts in the peak for the different subgroups. One sees that these fractions are rather independent of the photon energy E_0 . Also, a high fraction ($\sim 80\%$) corresponds to low ($< 0.02 E_0$) plastic energies. Of course, the energy deposited in the plastic scintillator corresponds only to a certain fraction of the energy escaping from the crystal. Results from Monte Carlo shower calculations [4,7] and shower measurements [8,9] show that for our crystal dimensions the mean energy leakage should be 5 to 10% of E_0 . In order to have an idea of the value of the fraction of escaping energy deposited in the plastic scintillator, we determined the coefficient k by which one has to multiply this energy in order to fulfil the relation

$$E_0 = E_{\text{NaI}} + k E_{\text{plast}} . \quad (1)$$

Figure 3 shows the position of the peak obtained by applying relation (1) to the raw data for different values of k , for three different energies and for the subgroups defined in table 1. It can be seen that the peak position is independent of the subgroup, i.e. of the energy deposited in the plastic scintillator, only for $k = 1.5$. As a matter of fact, k contains the leakage energy spectrum, the

corresponding plastic scintillator efficiency, and the exact plastic scintillator energy calibration. Since they are only approximately known, a Monte Carlo prediction of the absolute value of k is irrelevant.

Another interesting feature shown by fig. 3 is that, for the optimum value of k , the results are independent of the photon energy and the energy deposited in the plastic (subgroup). To further illustrate this point, fig. 4 shows spectra obtained by performing the operation $E_0 = E_{\text{NaI}} + 1.5 E_{\text{plast}}$ on the raw data and by classifying the resulting spectra in subgroups according to table 1. For a given E_0 the peaks in the different subgroups occur at the same position. On the other hand, the distribution of intensities in the different subgroups is very characteristic for photons. Indeed, high-energy charged particles give rise to a completely different kind of distribution.

Figure 4 also shows that the energy resolutions (FWHM) of the peaks in the different subgroups are similar. This is a further positive test of the mixing procedure implied by relation (1). Under these conditions it is clear that adding up all subgroups results in a peak with FWHM of the same order as the one of the peak in subgroup 1.

In order to illustrate this point, fig. 5 shows the energy resolution (FWHM) as a function of incident photon energy E_0 . In determining the FWHM the contribution due to the energy spread of the incident photon beam was taken into account.

The data points for $k = 0$ and all subgroups added (open circles) correspond to the bare crystal. At $E_0 \sim 130$ MeV the energy resolution ($\sim 11\%$) measured under these circumstances is worse than the one measured (7%) from a NaI(Tl) crystal 27 cm in diameter and 33 cm in length [3]. The difference may be due to the somewhat bigger dimensions of the crystal and the tighter photon collimation in the experiment of ref. 3. Results of Monte Carlo calculations [4] (open squares) performed by using approximately the photon flux dimensions of our experiment (fig. 1) are in satisfactory agreement with our experimental results (open circles). The same method [4] was used to calculate the response curve of the crystal to 20.6 MeV γ -rays. Again, the agreement with the measured response curve [5] is very good.

Applying relation (1) with $k = 1.5$ to the experimental data (closed circles in fig. 5) improves the energy resolution by approximately 20%. This result is obtained without any loss of intrinsic efficiency since all subgroups are added. A very similar result (triangles in fig. 5) can be reached by using data only contained in subgroup 1, i.e. the energy deposited in the plastic scintillator is lower than $0.02 E_0$, but in this case the loss of efficiency is approximately 20% (see curve 1 in fig. 2). Applying relation (1) with $k = 1.5$ and using data only contained in subgroup 1 does not further improve the energy resolution.

3.2 Measurements using photons from the $\pi^- + p \rightarrow n + \gamma$ reaction

The 129 MeV γ -rays were produced at the CERN PS by stopping negative pions in a liquid-hydrogen target. Figure 1 shows the target-detector geometry. A lead collimator 15 cm in diameter and 20 cm in length was placed between the target and the spectrometer. The same arrangement was used for the study of γ -ray decay of the $\bar{p}p$ system at rest [10]. Electronics, data acquisition, and data analysis were the same as those described previously.

Table 2 gives the total number of counts in the 129 MeV peak in the different subgroups defined in table 1. As could be expected, these values are different from those shown in fig. 2. Owing to the very open geometry, nearly the whole crystal is now illuminated by γ -rays from the extended target (fig. 1). As a consequence more events are associated with greater leakage energies detected by the plastic scintillator. For example, the fraction contained in subgroup 1 ($E_{\text{plast}} < 0.02 E_0$) drops from 80% (central incident photons, fig. 2) to 63%.

The coefficient k of relation (1) determined in the same manner as previously (see fig. 3) has again the value 1.5.

Table 3 gives the energy resolutions at FWHM measured for $E_\gamma = 129$ MeV in the geometry of the CERN experiment. These measurements were done twice under different experimental conditions. During a first period (which corresponded to the experiment described in ref. 10) a high neutron flux during the 400 ms long beam burst of the CERN Proton Synchrotron resulted in a 300,000 counts/s rate, which

produced a deterioration of the energy resolution by pulse pile-up and gain shifts. In a later stage, this background was reduced to a very low level (some kHz) and thus the energy resolution reached the expected value (table 3).

4. CONCLUSIONS

It has been shown that the use of a plastic scintillator surrounding a 25 cm $\times$ 30 cm NaI(Tl) crystal brings a substantial improvement to the performances of such a crystal for the detection of 130 to 400 MeV photons. In particular, the energy resolution is improved without loss of efficiency even in the case where the incident photons are not tightly collimated, which often happens in practice. In addition, the plastic scintillator is very useful in distinguishing non-photon background. Of course, even with the compensation method described here, the performances of such a spectrometer cannot reach those obtained with very large NaI(Tl) crystals (modularized or not), but may in some cases be sufficient to perform interesting experiments at moderate cost.

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Table 1

Definition of the subgroups

Subgroup number	1	2	3	4	5
Energy deposited in the plastic scintillator	$< 0.02 E_0$	$\geq 0.02 E_0$ $< 0.04 E_0$	$\geq 0.04 E_0$ $< 0.06 E_0$	$\geq 0.06 E_0$ $< 0.08 E_0$	$\geq 0.08 E_0$

Table 2

Fraction (in per cent) of the total peak in the different subgroups for $E_0 = 129$ MeV and open geometry (CERN)

Subgroup number	1	2	3	4	5
Fraction (in %)	63	14	6	3	14

Table 3

Energy resolution (FWHM in per cent) for $E_0 = 129$ MeV and open geometry (CERN).
The case $k = 0$ and all subgroups added corresponds to the bare crystal.

	$k = 0$	$k = 1.5$
Subgroup 1 (first period)	13%	12%
All subgroups added (first period)	16%	14%
Subgroup 1 (second period)	9%	

Figure captions

- Fig. 1 : Schematic physical layout of the spectrometer and simplified diagram of electronic pulse-processing circuit
- PM = fast photomultiplier
- FP = front plastic scintillator
- MP = main plastic scintillator
- RP = rear plastic scintillator
- AT = calibrated attenuator
- A = amplifier
- FA = fast amplifier
- FD = fast discriminator
- LG = linear gate
- FLG = fast linear gate and stretcher
- SS = spectrum stabilizer
- HV = high-voltage power supply
- ADC = analog-to-digital converter interfaced to computer
- Fig. 2 : Fraction (in per cent) of the total number of counts in the peak for different incident energies E_0 and for the different subgroups defined in table 1 (subgroup number indicated for each curve).
- Fig. 3 : Position of the peak obtained by applying relation (1) to the raw data for different values of k , for the different photon energies E_0 , and for the subgroups defined in table 1.
- Fig. 4 : Examples of spectra obtained after applying relation (1) to the raw data for $k = 1.5$, for four different photon energies E_0 and for the subgroups defined in table 1.
- Fig. 5 : Energy resolution of the spectrometer (FWHM in per cent) as a function of incident photon energy E_0 . The different symbols are explained in the inset. The open circles and open squares ($k = 0$, all subgroups added) correspond to the bare crystal.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5