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Test Results from a Position-Sensitive NaI Detector*

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Abstract

Results are reported for a position-sensitive NaI detector of 25.4 cm length and 5.1 cm thickness. Position resolutions as good as 1.0 cm FWHM for electrons and 1.4 cm FWHM for gamma rays have been obtained using left-right energy signals. Data for gamma rays and electrons of various energies are presented.

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1. Introduction

NaI has long been the standard for the detection of gamma rays of energies greater than a few MeV. It provides high conversion efficiency, a reasonably short decay time and energy resolution as good as 3% at 15.1 MeV¹) and 2% at 4 GeV²). While the energy of high-energy gamma rays can easily be measured to the above accuracy it is difficult to determine the direction of the gamma rays with corresponding accuracy. However, many physics experiments such as rare pion or muon radiative decays, pion single charge exchange ($\pi^{\pm}, \pi^0$), and radiative pion capture either require or could be significantly improved if angular as well as energy information could be obtained.

One approach to obtaining position information for gamma rays consists in using a lead converter followed by a scintillator hodoscope or multi-wire proportional chamber (MWPC) and then a large volume NaI detector. In order to achieve reasonable conversion efficiencies, however, the thickness of converter causes a significant loss in energy resolution.

A second approach³) consists in cutting up the large volume NaI detector into many smaller bars and orienting their axes parallel to the direction of the gamma rays. In this way a position resolution equal to 7.5 cm FWHM or one-half the size of the module has been obtained.

A third approach to this problem consists of a set of position-sensitive NaI bars oriented perpendicular to the direction of the gamma rays and placed in front of a large volume detector. The bars convert the gamma rays and measure their position; the total energy can be determined by summing the pulse heights from the large volume detector

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and the bar. Each of the bars has two phototubes, one at either end. The bars are specially treated so that the pulse height from each tube varies approximately inversely with the distance between the point of interaction and the tube. From the measured ratio of the pulse heights at the two ends, the position along the bar can be determined thus yielding angular information.

For this purpose we tested such a position-sensitive detector in order to find out the accuracy with which the position along the bar could be measured for high-energy gamma rays or electrons ($E > 20$ MeV). Data are already available⁴⁾ from tests on a positron camera which show that such a technique can yield position accuracies of ≈ 1.5 cm FWHM over the length of a 17 cm cylindrical bar for 511 keV annihilation photons. However, no data exist at higher energies where the shower is not fully contained in the bar. In the present paper both source data ($E < 3.5$ MeV) and beam data ($E \leq 90$ MeV) are presented and the results show that the technique can be usefully applied in high-energy physics research.

2. Detector and set-up

The detector described and tested in the present paper was made by Harshaw Chemical Co. and had the following dimensions: 25.4 cm length, 6.35 cm height and 5.1 cm depth. One RCA 6342A photomultiplier was mounted at each end. The anode signals were used for pulse height information after being fed through an ORTEC 454 timing filter amplifier with a 20 ns integration time constant to reduce high-frequency noise. The pulse height was digitized in a LRS 2249W charge sensitive CAMAC ADC

using an 800 ns gate length and recorded on magnetic tape for later analysis. Timing signals were also derived from the anode signals by means of ORTEC 934 constant fraction discriminators. The gain of the two phototubes was equalized for events occurring in the centre of the detector by varying the high voltage and the gain of the timing filter amplifiers. Data were taken with various radioactive sources (see sec. 3) and also with electrons from the stopped π/μ channel at TRIUMF (see sec. 4). They were written on tape via a PDP 11/40 system and analysed off-line using the UBC Amdahl computer system.

3. Results from γ and e^- sources

We used ^{137}Cs and ^{60}Co as γ -ray sources and also electrons from a ^{106}Ru source. All sources were collimated to about 5 mm with two lead bricks. Fig. 1 shows the position dependence of the pulse heights measured at the two ends, left (EL) and right (ER), and also their sum (ER+EL). The strong position dependence is achieved by a special surface treatment of the NaI bar. The total variation in pulse height over the length of 25 cm is about a factor of three. As a result of the non-linearity of the individual pulse height signals the summed energy is $\sim 15\%$ higher at the edges than in the centre of the detector. In future applications this can easily be compensated for during off-line analysis once the response has been determined. The measured energy resolution for ^{137}Cs and ^{60}Co is given in fig. 2(a). It is almost position independent (at 10% for ^{137}Cs and 8% for ^{60}Co) except for the points within 2.5 cm of the edges, i.e. close to either phototube where it deteriorates quite rapidly and drastically (to $\sim 30\%$ and 20% , respectively). Fig. 2(b)

shows the ^{60}Co γ -ray spectrum obtained for one of the central positions along the bar using the summed energy signals.

The actual position determination along the bar can, in principle, be done by calculating various combinations of the measured individual pulse heights E_L and E_R . We calculated the pulse height ratio $\frac{E_L}{E_R}$ (or equivalently $\frac{E_R}{E_L}$), the relative difference $\frac{E_R - E_L}{E_R + E_L}$ and also the relative pulse heights at either end $\frac{E_R}{E_R + E_L}$ and $\frac{E_L}{E_R + E_L}$, respectively. All these quantities give a strongly peaked distribution for a given position along the NaI bar. The straightforward calculation of the ratio, $\frac{E_L}{E_R}$ (or its inverse $\frac{E_R}{E_L}$), however, is not as useful as the others because the width of the peak in this distribution changes with position, as shown in fig. 3 for a ^{60}Co γ -ray source. The reason for this change in width is the change in the absolute width of a given pulse height distribution measured at each end, as a function of position.

The other three quantities $\frac{E_R - E_L}{E_R + E_L}$, $\frac{E_R}{E_R + E_L}$ and $\frac{E_L}{E_R + E_L}$ proved to be of equal significance, as will be seen below. Fig. 4 shows data for $\frac{E_R - E_L}{E_R + E_L}$ obtained using the 1.17 and 1.33 MeV gammas from ^{60}Co . It demonstrates the narrow peak distribution obtained for any given position. Very similar results showed up in the relative pulse-height distributions $\frac{E_R}{E_R + E_L}$ and $\frac{E_L}{E_R + E_L}$.

The essential results, i.e. the position resolution calculated from the width of the individual peaks in the $\frac{E_R - E_L}{E_R + E_L}$ distribution are displayed in fig. 5. Different sources were used in order to check the energy dependence of the position sensitivity. Only events with a certain total energy were analysed, as indicated in fig. 5. There is an improvement in the position resolution with increasing energy, i.e.

going from ^{137}Cs to ^{60}Co or taking higher energy electrons from ^{106}Ru . The best position resolution achieved was 1.0 ± 0.1 cm (FWHM) for electrons from ^{106}Ru . Table 1 gives the measured average position resolutions (excluding the 2 outer values) as a function of energy.

The tendency of the position resolution to improve with increasing energy is, however, not expected to continue for higher energy γ 's because of the large spatial distribution of the shower that these γ 's create in the detector.

The position determination based on the relative pulse heights $\frac{E_R}{E_R + E_L}$ and $\frac{E_L}{E_R + E_L}$ gave the same position resolution within statistical errors as did $\frac{E_R - E_L}{E_R + E_L}$.

The linearity of the calculated quantities $\frac{E_R - E_L}{E_R + E_L}$ and $\frac{E_L}{E_R + E_L}$ with position is shown in fig. 6. Small deviations occur towards the edges of the detector. These can easily be compensated for by fitting the measured position dependence of the individual pulse heights with a polynomial (see fig. 1).

4. Results from beam data

Data were also taken at the stopped π/μ channel at TRIUMF with scattered electrons of about 90 MeV kinetic energy. A 2.5 cm wide defining scintillator was placed in front of the NaI bar. Because of the width of this counter the true position resolution had to be unfolded.

Fig. 7 shows the measured position resolution for five positions along the bar. Again the quantity $\frac{E_R - E_L}{E_R + E_L}$ was used. The measured resolution is 2.6 ± 0.13 cm FWHM at the centre of the bar and 3.0 ± 0.13 cm near the edges.

in fig. 8 we have plotted the function $\frac{ER-EL}{ER+EL}$ for the position 18 cm from the left edge of the bar. The solid line is a calculated curve obtained by convoluting a rectangular distribution of width 2.5 cm with a Gaussian having a FWHM of 1.5 cm. This Gaussian distribution represents the intrinsic NaI resolution. Very good agreement is found between the calculated curve and the measured data points. Thus we are quite confident that an intrinsic position resolution for high-energy γ 's or electrons of 1.5-2.0 cm will be obtainable using this technique.

5. Position sensitivity using left-right timing signals

Timing signals were also recorded from the two photo-tubes by means of ORTEC 934 constant fraction discriminators. The left-right timing resolution for the high-energy electron beam ($E > 25$ MeV) was 1.5 ns FWHM. However, for the ^{60}Co γ rays only 5.0 ns FWHM was obtained. The position resolution for the beam data based on left-right timing had a FWHM of 3.6 to 4.6 cm depending on position, i.e. 25-50% worse than the position resolution based on $\frac{ER-EL}{ER+EL}$. No useful position information could be obtained for the source data using the timing technique (FWHM ~ 15 cm).

The sum of T_{left} and T_{right} was constant, i.e. position independent within 1.3 ns. The CFD's were not carefully tuned for this measurement and therefore it is likely that the timing performance could be improved slightly but not significantly. However, for high-rate applications both timing and pulse height could be used to determine the position in order to eliminate pile-up events.

6. Conclusion

We have demonstrated that good energy resolution and rather accurate position determination is possible with a specially prepared NaI detector. A position resolution of 1-2 cm FWHM was easily obtained in the present measurements with a NaI detector of 25 cm length. Thus it seems quite feasible to use a system of several such position-sensitive detectors to form a large area active converter in combination with a large volume NaI crystal to determine the energy and position (angle) of high-energy γ 's. An angular resolution of 2.5° over a flight path of 1 m should be obtainable. Such a system is planned as a gamma-ray converter at TRIUMF in combination with the large volume detectors - TINA (46 cm $\phi \times 51$ cm) and MINA (36 cm $\phi \times 36$ cm).

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Table 1

Average position resolution (excluding the 2 outer values) for the various sources and energies.

Source	FWHM (cm)
^{137}Cs	1.8 ± 0.1
$\text{ER+EL} \geq 0.56 \text{ MeV}$	
^{60}Co	1.4 ± 0.1
$\text{ER+EL} \geq 1.1 \text{ MeV}$	
^{106}Ru	
$0.7 \text{ MeV} \leq \text{ER+EL} \leq 1.4 \text{ MeV}$	1.6 ± 0.1
^{106}Ru	
$\text{ER+EL} \geq 1.4 \text{ MeV}$	1.2 ± 0.1

Figure Captions

1. Position dependence of individual and summed pulse heights for ^{137}Cs data. The solid lines are merely to guide the eye.
2. (a) Position dependence of measured energy resolution for ^{137}Cs and ^{60}Co . The resolution refers to the summed energy ER+EL .
(b) ^{60}Co -spectrum measured at the centre of the NaI bar.
3. The ratio ER/EL for several positions along the bar. The peak separations correspond to a 5 cm displacement of the ^{60}Co source. The solid line is merely to guide the eye.
4. The ratio $\frac{\text{ER-EL}}{\text{ER+EL}}$ for several positions along the bar. The peak separations correspond to a 5 cm displacement of the ^{60}Co source.
5. Measured position resolution for various sources as a function of position along the bar. The solid lines are merely to guide the eye.
6. Position dependence of the ratios $\frac{\text{ER-EL}}{\text{ER+EL}}$ and $\frac{\text{EL}}{\text{ER+EL}}$, based on ^{60}Co data. The solid lines are merely to guide the eye.
7. Position resolution measured with electrons of about 90 MeV in coincidence with a 2.54 cm wide scintillator in front of the NaI bar. The solid line is merely to guide the eye.
8. The ratio $\frac{\text{ER-EL}}{\text{ER+EL}}$ measured at the centre of the bar for high energy beam electrons. The solid curve is the convolution of a rectangular distribution of width 2.5 cm with a Gaussian of width 1.5 cm (FWHM).

Fig. 1

Fig. 2(a)

Fig. 2(b)

Fig. 3

Fig. 4

Fig. 5

Fig. 7

Fig. 6

Fig. 8