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S. Bartalucci, G. Bellettini, S. Bertolucci, M. Cordelli, R. Dini, L. Giacomelli, P. Giromini, A. Rutili, A. Sermoneta and M. Spadoni: HIGH PERFORMANCE, LOW COST SHOWER DETECTORS FOR LOW ENERGY γ-RAYS.

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HIGH PERFORMANCE, LOW COST SHOWER DETECTORS FOR LOW ENERGY γ-RAYS

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SUMMARY: We describe the performance of three NaI(T1) multicrystals in silicon oil assemblies and of one fluorescent SCG1 glass block exposed to 60 MeV monochromatic photons. The purpose of the work was to find the cheapest element that would still allow to achieve the ultimate energy resolution allowed by systematics, when implemented into a large modularized detector. The results point at the merits of such counters when operated as low energy photon detectors.

1. - INTRODUCTION.

Large arrays of NaI(T1) or lead glass counters are presently in use as γ-ray spectrometers in a number of high energy experiments. The attainable energy resolution is illustrated in Fig. 1. Lead glass (SF5 type) is relatively cheap and easy to handle, but its energy resolution below 300 MeV deteriorates rapidly and can be only slightly improved by using more transparent flint glasses like F2(6). In contrast, NaI(T1) single crystals promise a beautiful resolution at any energy ($\Delta E/E \approx 2\%/E^{1/4}$(GeV) FWHM), but are very expensive (about 5-8 times more than lead glasses) and delicate to handle (in particular, since hygroscopic, they need to be encapsulated in metal housings). This situation brings one to swing between two very unpleasant alternatives, when planning a large coverage multicell detector for low energy photons : either one fits within the budget with a marginal or insufficient resolution, or one plans for an excellent resolution but cannot fit within the budget. However, one important observation to be made in Fig. 1 is that, when dealing with a large number of counters, the resolution obtainable in practice tends to move into the 5-10% range even for sodium iodide. This phenomenon has to do with shower sampling fluctuations brought about by dead space between counters, electronics noise and by errors in monitoring the relative gain of the photomultipliers in a large counter array. In our specific experiment(13) the required energy resolution was $\lesssim 20\%$ FWHM for $E_\gamma \lesssim 500$ MeV, and an attempt was made to find a practical compromise solution with cheaper NaI(T1) or scintillating glass which would still allow a detector with ultimate energy resolution not qualitatively worse than a large assembly of NaI(T1) crystals. We believe that the conclusions of our work are of some general interest, in as much as the four detectors

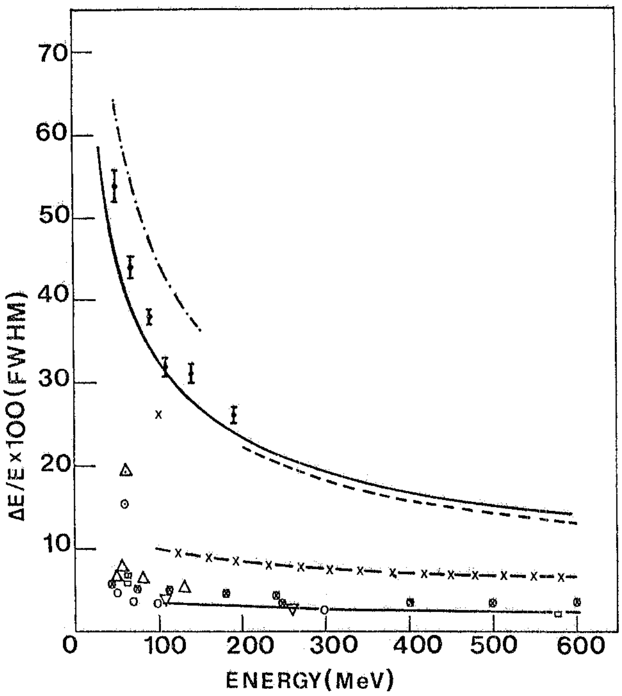

FIG. 1 - Energy resolution (FWHM) of a number of NaI and Pb-glass detectors. Full, broken, broken-dotted curves show the resolutions of the Pb-glass SF5 detectors of refs. (1), (2), (3) and (4) respectively. I SF5 data(5); x F2 flint glass data(6); o resolution of a single NaI(Tl) crystal(7); Δ resolution of an array of 45 NaI(Tl) crystals(8); □ resolution of a single NaI(Tl) crystal(9); ▽ resoltution of an array of 19 NaI(Tl) crystals(10); ⊠ resolution of an array of 54 NaI(Tl) crystals (prototype of crystal ball)(11); -x-x- approximate resolution achieved so far (1979) by the crystal ball detector (672 NaI(Tl) crystals)(12); □ , ⊡ , Δ , ⊙ this experiment, counters shown in Figgs. 2b, 2c, 4 and SCG1 counter respectively.

that we have studied fall at various steps within tha gap in resolution between NaI(Tl) and Pb-glass, such that one or another can be more or less suited to the needs of a specific experiment.

We describe in Section 2 the studies made on three types of NaI multicrystals assemblies, and in Section 3 the study of a scintillator-loaded heavy glass. In Section 4 the measurements made on a 60 MeV photon beam are described.

2. - STUDY OF NaI(Tl) ASSEMBLIES.

Several attempts have been made in the past(14) to produce NaI(Tl) counters by filling cans with NaI(Tl) chunks of random size and quality, using some liquid as optical coupling medium. This is in principle a good idea if one wants to reduce strongly the cost of single crystals. Indeed, much of this cost arises because one has to pay for off-cut losses (which are large because usually one also selects the ingot part of the raw crystal where the Tl concentration is more uniform), for the crystal polishing and eventually for controlling the crystal surface texture and the sorrounding optical reflector to give uniform response. Multicrystals counters were found to work satisfactorily as heavy anticoincidence shieldings of low energy photons(14): however, their energy resolution (measured with ^{137}Cs and ^{60}Co) was found to be poor. This effect was qualitative attributed to the short attenuation length of the scintillation light(14). As a matter of fact, we will show that counters of this type, when properly designed, can still provide an appealing energy resolution in the energy range below ~1 GeV. We have made the entrance window of our counters 10x10 cm^2 wide (constrained by the needed angular resolution and the photon source distance in the experiment (13)) and we have chosen the thickness to be only 10 X_0. The argument leading to this choice was as follows. With respect to thickness of a high resolution crystal (~20 X_0) the counter volume is reduced by a factor of two (even more for tower-shaped counters), while the fluctuations associated to back-leakage of showers with energy smaller than 1 GeV are still below 10%. In addition, with such a short length nearly the full counter volume is illuminated for $E_\gamma \gtrsim 50$ MeV such that the energy resolution is determined only by the convolution of shower shape fluctuations and the dependence of the light collection on the position inside the counter. We show later that for 50 MeV $\lesssim E_\gamma \lesssim$ 500 MeV this effect can also be kept within 10%. Notice the difference from the case where a ^{137}Cs or ^{60}Co photon is absorbed in small areas but over the all counter volume. In such a case the resolution would be determined directly by the counter opacity. We have studied this effects in our counters using the 662 keV γ-lines of ^{137}Cs and a 60 MeV photon beam.

A sketch of the three counters employed$^{(15)}$ is shown in Fig. 2. Counter A is an assembly of raw chunks in silicon oil, counter B contains three polished crystals, counters C containes 24 raw-cut crystals hold together by silicon resin (see figure caption fore more details).

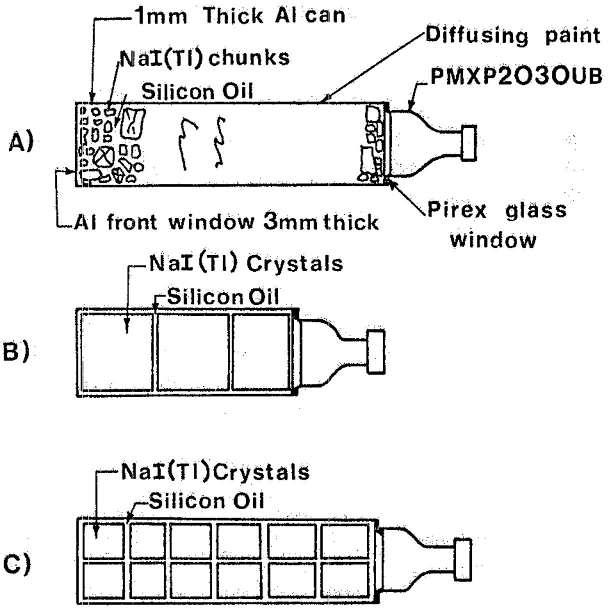

FIG. 2 - Sketc of the NaI(Tl) assemblies. Counter A is an assembly of row chunks (average linear dimensions ~3 cm) in silicon oil (NaI filling factor ~70 %). The counter volume is 10 x 10 x 37 cm^3, this thickness corresponding to 10 X_0. Counter B contains three polished crystals of dimensions (front to back) 10 x 10 x 9 cm^3, 10 x 10 x 9 cm^3 and 10 x 10 x 8 cm^3 (total thickness 10 X_0). The optical contact is made by silicon oil (NaI filling factor ~99 %). The inside of the can is mirror like Aluminum coated. Counter C containes 24 rough-ground crystals 4.5 x 4.5 x 5.5 cm^3 in size, assembled in a raw-aluminum can of 10 x 10 x 35 cm^3. The crystals are glued together by silicon resin (n = 1.5), to a total NaI filling factor of ~76 %.

Counter A was exposed to a ^{137}Cs source, which was moved from the front to the back along one side. The pulse height was found to vary by a factor of ~15. The dependence on the distance x from the photomultiplier was well fitted by the formula

$$I(x) = I(o)\, e^{-\frac{x(cm)}{13.5}} \quad . \qquad (1)$$

The counter was found to be insensitive to lateral displacement of the source at fixed x. A resolution (FWHM) of 70 % was found in calibration runs with 60 MeV photons, as discussed later. This was precisely the resolution predicted by Montecarlo calculations incorporating the light attenuation function (1). Since the Montecarlo computed shower leakage fluctuations were only about 25 %, it was clear that the resolution was dominated by non-uniformity of the assembly. In order to get $\Delta E_\gamma / E_\gamma$ down to < 20 % as required in our experiment, we needed to understand the origin of these non-uniformities better. This was achieved by studying assemblies of easier geometry, counters B and C. The light-output yields obtained when moving a ^{137}Cs source along side these counters are shown in Fig. 3. The result for counter C

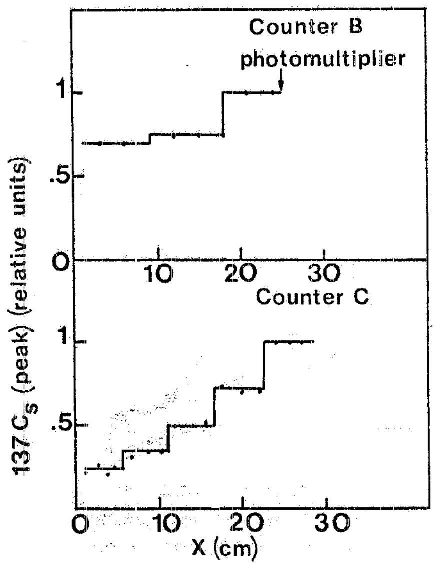

FIG. 3 - Output of counters B and C viewing a ^{137}Cs source, as a function of the source distance x from photomultiplier.

suggests very clearly that each time the light passes from one crystal to the adiacent one through the silicon oil it is attenuated by ~ 30 %, while no appreciable dependence is seen on the position of the source along a single crystal. We take this wafer factor (WF) as a basic empirical number and check wether the performancies of all assemblies could be explained on the basis of this number only. When considering that counter B has reflective walls (reflectivity ~ 80 %) the results of Fig. 3 are immediately interpreted on the basis of the same WF. Since crystals have rough sides in C and are polished in B, this result suggest that the WF is independent of the surafce texture. Under this assumption one can predict the average attenuation in counter A as a function of x:

$$I(x) = I(o)\, e^{-0.3\left[n(x) - 1\right]} , \qquad (2)$$

where n(x) is the number of chunks between the photomultiplier and the source position. If one computes function (2) based on the actual average chunk size of 3 cm, one obtains a result which is nearly identical to what found experimentally (formula (1)). We conclude that we have a good model to explain the performance of any assembly on the basis of a WF = 0. 3 in each crystal / optical coupling medium/ crystal transition.

Since our Montecarlo calculation predicts a resolution $\lesssim$ 10 % FWHM provided the attenuation along the counter does not exceed a factor of two, we conclude that one cannot use more than three crystals in series if one aims at a resolution of this order of magnitude. Therefore counter B was retained as basic prototype and the study was furthered to explore the reproducibility of performances in a sample of many similar counters.

Nine "second generation" counters of the B type were built$^{(16)}$ each one containing three crystals with 10 x 10 cm^2 section and various thicknesses totalling to 37 cm. The crystals were immersed in silicon oil and contained in raw aluminium cans. Can walls were 1 mm thick and had a 3" diameter glass window at the photomultiplier end. All crystals were of the "fast grown and cut" type, i. e. were rather yellow with many bubbles, cracks and bands inside. For all counters the attenuation factor from back to front was measured and found to be about a factor of two, as expected by considering the wafer factor attenuation only.

The ultimate cost of counters of type B is fixed by the fact that they still contain crystals of rather large size, ~ 10 x 10 x 12 cm^3. On the other hand, if one wants to reduce the crystal size without spoiling the resolution one must find other ways of making the counter response independent of its depth. This problem was addressed by enclosing the crystals of counter C in a different can having a 3 mm thick pirex glass window on one side, and collecting the light from this window with a BBQ doped bar as shown in Fig. 4.

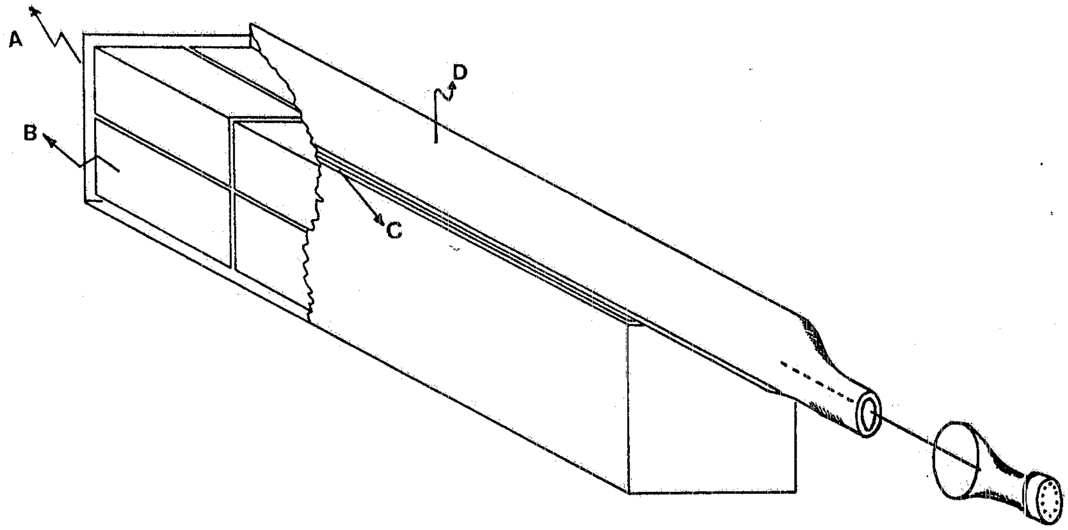

FIG. 4 - Sketch of the NaI crystal assembly with uniform response over the counter volume. A: aluminum can (NE581 coated); B: inner crystals; C: 3 mm thick pirex glass window; D: BBQ doped (150 mgr/litre) read-out bar. The bar is 4 mm thick and is bent from a flat to an annular shape at the photomultiplier side.

Crystals were cleaned in a dry room from silicon resin and restored to the original raw-cut surphaces. In order to eliminate the non-uniformity brought about in the transverse direction by one WF, good light reflectivity (as for counter B) was assured by coating the inner can walls with NE581 TiO_2 paint. The can was 10 x 10 x 35 cm^3, and was filled with silicon oil (24% of the total volume). A scanning of the counter volume with a ^{137}Cs source showed an uniform response within ± 5%. The amount of light lost by wave shifting was also measured. While counter B gives 8×10^5 photoelectrons/GeV, this counter provided 6.8×10^4 photoelectrons/GeV. Indeed one sees that although the matching among emission and absorption spectra is not particularly good (see Fig. 5) the overall production of photoelectrons is only ~12 times less abundant than in a standard counter and it remains quite large.

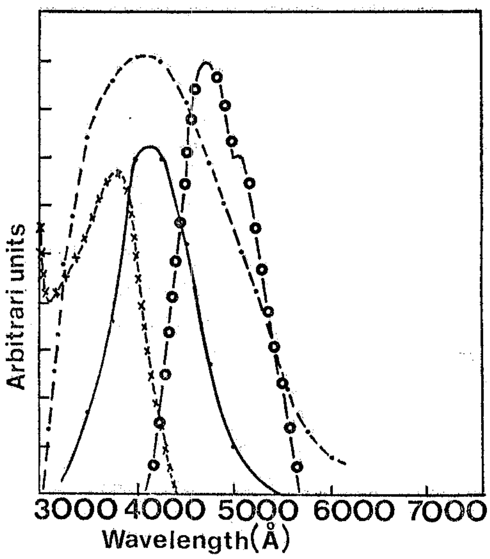

FIG. 5 - Emission and absorption spectra in an NaI counter, read-out with a BBQ doped bar. ——— NaI scintillation spectrum; -·-·- bialcaly photocathode spectral quantum efficiency; -x-x- BBQ absorption spectrum; -o-o- BBQ emission spectrum.

3. - STUDY OF A FLUORESCENT GLASS WITH SHORT RADIATION LENGTH.

We have analyzed the result of previous experiments(1, 2, 3) in order to understand to what extent the resolution in Pb-glass counters is determined by photoelectron statistics. We write the number of photoelectrons in any counter (per GeV) as :

$$N = 500 \sin^2\theta \; \alpha_1 \alpha_2 \alpha_3 L , \qquad (3)$$

where $\theta = \cos^{-1}\frac{1}{n}$ is the angle of emission of the Cerenkov light, α_1 is the quantum efficiency of the p.m. photocathode (we take $\alpha_1 = 0.11$ in the following, corresponding to the average quantum efficiency of a bialcaly or S11 photocathode), L = 200 cm is the total charged track length in a 1 GeV shower(17), α_2 is the ratio between photocathode and counter exit face area, and α_3 takes into account the reduced efficiency in collecting Cerenkov light which is emitted over a broad band of directions in a shower, relative to light emitted by particles going towards the photomultiplier. If E_μ is the energy deposit faked by an high-energy muon traversing the full counter length one can write $\alpha_3 = \frac{\ell}{L} \frac{1}{E\ (GeV)}$ where ℓ is the counter length. If all shower electrons were directed towards the p.m., one would have $\alpha_3 = 1$. In general, $\alpha_3 < 1$. The value of α_3 can be derived from the experimentally measured μ's pulse height in each particular case. For a 15 x 15 x 35 cm^3 SF5 Pb-glass block seen by a 5" photomultiplier(1, 2) ($\alpha_2 = 0.42$) we derive $\alpha_3 = 0.35$, and correspondingly N ~ 1000. The statistical contribution to the resolution is then ~7%, while experimentally the resolution was measured to be 10% (FWHM at 1 GeV). In another case(3), $\alpha_2 = 0.59$, $\alpha_3 = 0.44$, and the resolution that we would predict on the basis of photon statistics is 5.4% while the overall resolution was found to be 8.6% (FWHM at 1 GeV). Actually in this particular experiment the contribution of photon statistics to the resolution was directly measured and found to be 5.5%. The agreement with our estimate is remarkalble and supports the validity of our approach.

In order to gain confidence on the validity of the above procedure, we also made a specific measurement. We took an F2(18) Pb-glass counter 8 x 8 x 40 cm^3 in size viewed by a 3" XP2030 photomultiplier and set it on a 60 MeV photon beam (see below). The measured energy resolution was $9\%/\sqrt{E}$ (GeV) FWHM. The corresponding pulse height was simulated with a high frequency light pulses, and 1640 photoelectrons/GeV were measured on the basis of the photocathode first dynode current. On the other hand, since $\alpha_2 = 0.56$ and taking $\alpha_3 = 0.40$ (average of experiments 1, 2, 3) one expects N ~1600 photoelectrons (statistical contribution = 5.7% FWHM). Our conclusion is that, out of the typical energy resolution of Pb-glasses of 10 % at 1 GeV, about 7 % is due to photoelectron statistics while the rest is due to fluctuations in collection efficiency of Cerenkov light (whose average value is typically 40 %).

Based on the above considerations, the fluorescent glass with short radiation length described in ref. (19) would look very much suited for low energy photons. This is a cerium activated SiO_2-BaO-Li_2O glass in which cerium is excited by ultraviolet Cerenkov light and re-emits in the blue region. Being the emission of light isotropic, one expects no deterioration in resolution like the one contributed by fluctuations in the direction of the Cerenkov light. In addition, since the light output in the p. m. useful spectral region is increased by ~ 4(19) one would expect a purely statistical energy resolution of 3-4 % at 1 GeV. It looked therefore surprising to us that measurements reported in ref. (19) do not show anything like such an improvement over normal flint glasses. We therefore decided to repeat those measurements.

A fluorescent SCG1 glass block with size 10 x 10 x 50 cm^3 with properties similar to those of ref. (19) was prepared for us by Ohara(18). The properties of this glass(20) are listed in Table I. The sides of this block were polished as for the above F2 block, and an identical reflecting aluminum wrapping was used.

TABLE I - Characteristic data of glass SCG1.

Chemical composition (by weight)	SiO_2 43% + BaO 44.2% + MgO 4% + + Li_2O 4.3% + K_2O 3% + Ce_2O_3 1.5%
Radiation length (cm)	4.22
Density (g/cm^3)	3.41
Refractive index	1.608
Linear coefficient of expansion (100-300°C) ($10^7/°C$)	115
Exciting wavelength peak (nm)	378
Fluorescent wavelength peak (nm)	428
Fluorescent life time (ns)	70
Light output	about four times as high as Cerenkov light of SF 6

The block was glued to a 3" XP2030 photomultiplier (α_2 = 0.36) and exposed to the 60 MeV photon beam. The pulse-height was found to correspond to 4750 photoelectrons/GeV. After correcting for the different α_2-values one finds :

$$\frac{\text{SCG1 light output}}{\text{F2 light output}} \sim 4.5 .$$

To see wether one could save the cost of polishing, we rough ground the block and had it painted with NE580 TiO_2 reflector. This procedure when applied to flint glasses produces a loss of about a factor of two in the collected Cerenkov light(3). We found a pulse-height of 3760 photoelectron/GeV, corresponding to a loss of only 20 %. This can be understood because the reflector efficiency is much higher in the blue region of scintillation light. We retained this SCG1 configuration, expecting a resolution ~ 3.8 %$\sqrt{E}$ (GeV) (FWHM).

4. - TESTS ON A 60 MeV PHOTON BEAM.

The pulse-heights and resolutions at 60 MeV already quoted in the previous Sections for a number of counters were measured using the LADON beam which has been recently put into operation at Frascati. The beam is produced by back-scattering a laser beam on the ADONE electron beam operating at 1300 MeV. The beam energy spectrum is shown in Fig. 6. The response of the counter to be calibrated was measured in a matrix arrangement as shown in Fig. 7, by setting the counter at the center of a ring of 8 guard counters. As a first measurement, the nine B-type counters described in Section 2 were used. The signals from all counters were treated according to the electronics scheme of Fig. 8, the outer counters serving to rescue the shower fraction leaking out of the central one. Counter gains were equalized to ±2 % on the main beam and to ±0.7 % off-line. The nine signals are added off-line, after correcting for ACD non-linearities.

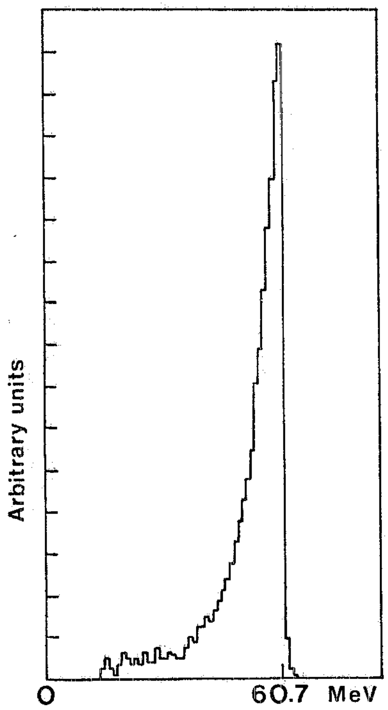

FIG. 6 - Ladon beam energy spectrum, as measured with an electron pair magnetic spectrometer (1 % accuracy).

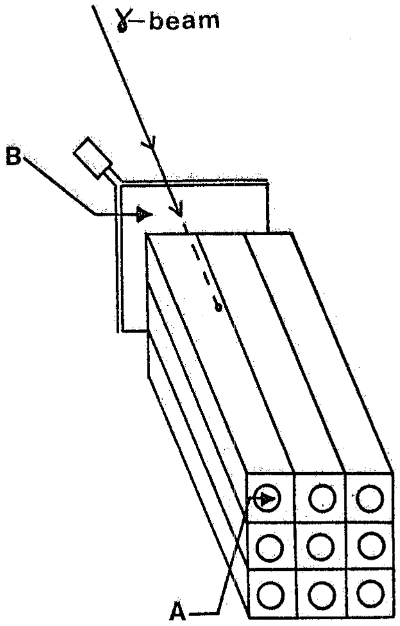

FIG. 7 - Counter arrangement as used in the beam test, in a 30 x 30 cm^2 matrix. The counter under test is set at the center. A: photomultipliers; B: veto counter for charged track accompanying the photon beam.

Fig. 9 shows the result of this measurement: 9a gives the spectrum of the central counter only, 9b the overall spectrum including the guard counter information. Fig. 9c shows the overall resolution (7 % FWHM) expected in shower development Montecarlo calculations in which one accounts for the matrix size and the light attenuation in each counter according to the WF. No account was made for counter imperfections or sampling fluctuations in the cans. After folding this resolution to the beam spectrum, one obtains the full curve of Fig. 9b, which fits the data very well. The expected dependence of the resolution of these counters on energy is shown in Fig. 10.

The resolution of the various prototypes was measured by inserting them successively in the array central position. Their gain was adjusted until the total pulse-height provided by the array was equal to the original one. The results obtained for counter B of Fig. 2 are shown in Fig. 11. The Montecarlo computed matrix resolution is shown on the right hand-side. The full curve on the left hand side is the resolution folded on the beam spectrum, and again fits the data

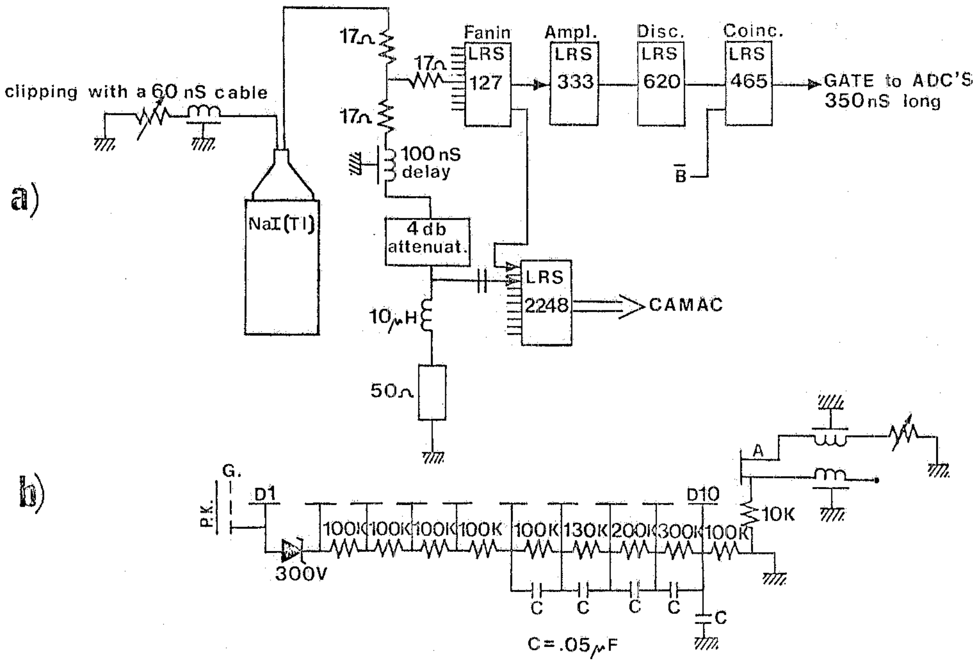

FIG. 8 - a) Electronic circuitry associated to the counter array of Fig. 7. b) Voltage divider for the Philips XP2030UB photomultipliers. With such chain the tubes were linear within ± 1 % up to pulses equivalent to 1 GeV photon showers in NaI(Tl). Signals were clipped to provide 300 ns wide square pulses(9).

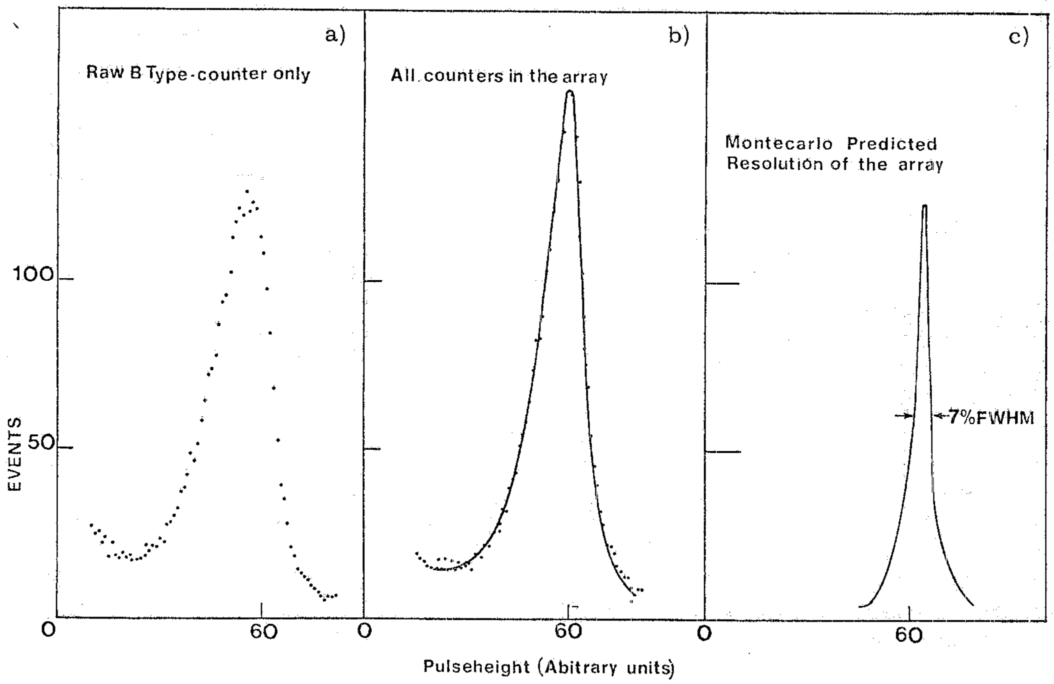

FIG. 9 - Calibration of the 3 x 3 array of raw "type B" counters with 60 MeV photons. a) Pulse height spectrum of the central counter. b) Total pulse height spectrum of the array. The solid line represents the spectrum predicted by folding the beam energy spectrum with the computed resolution. c) Montecarlo computed resolution (7 % FWHM).

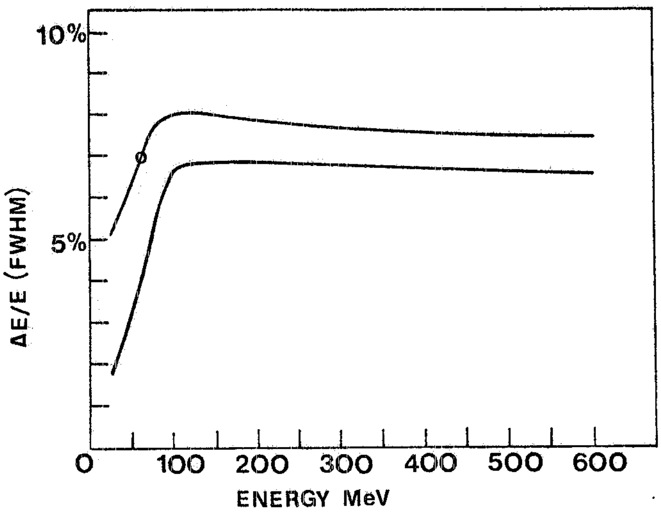

FIG. 10 - Expected dependence (Montecarlo) of the resolution (corresponding to the data shown in Fig. 9) on energy. The measured point at 60 MeV is also shown. The lower curve shows the resolution contributed by fluctuations in shower leakage from the array.

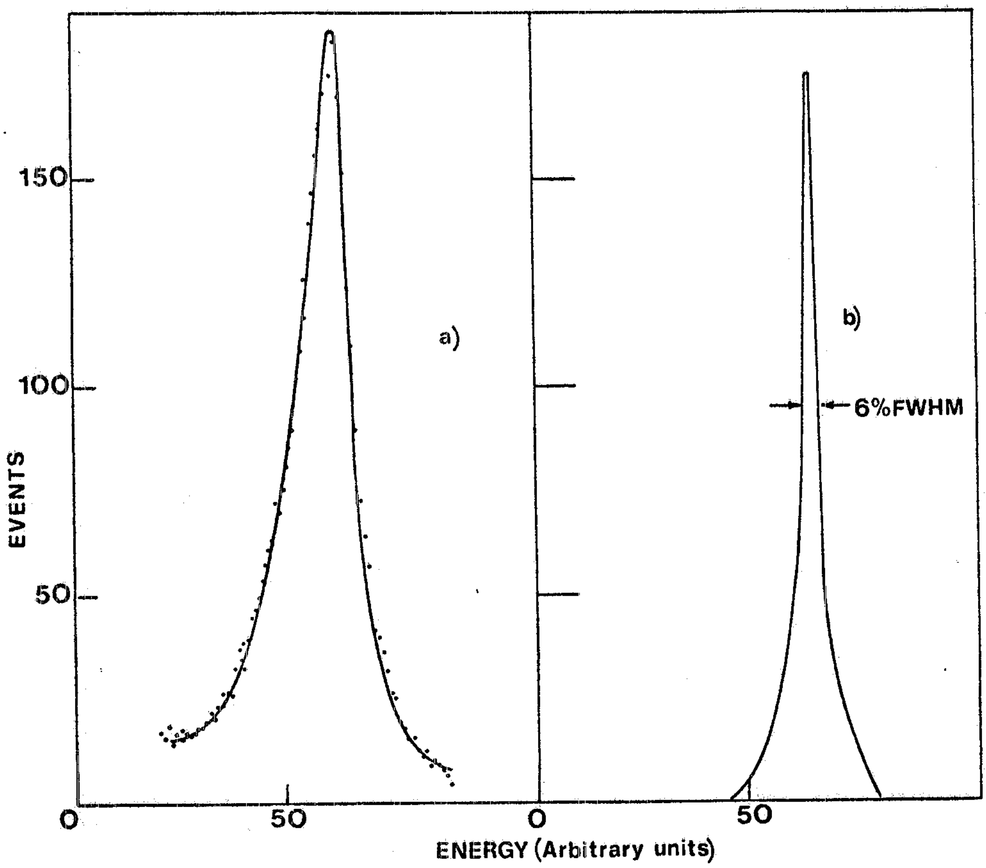

FIG. 11 - As Fig. 9b) and 9c), when counter B of Fig. 2 is used as central element.

very well. Notice that the resolution (6 % FWHM) is expected to be better in this case (even if the matrix length is defined by the central element to be only 10 r. l.) than in Fig. 9, because of the better counter uniformity (as shown in Fig. 3).

The measured pulse-height distribution, when the counter with BBQ bar side read-out (Fig. 4) is inserted in the matrix, is shown in Fig. 12. In order to reproduce the data with the Montecarlo calculation we had to "ad hoc" spread energy deposit in the central counter with a gaussian distribution with 19.5 % FWHM. Being the response of the central counter very uniform, one could at a first guess the resolution to be determined by statistics only. With about 4000 photoelectron at 60 MeV, even accounting for a factor of two loss because of signal clipping, one still expects a resolution of ~ 7.5 %, which is much better than the measured (19.5 %). The difference should be attributed to fluctuations in energy loss in the glass window, in the BBQ bar and in the 1 cm thick oil layers sorrounding the crystals on two sides of the counter. These layers were left in order to simulate qualitatively the effect of the several light guides that would be crossed by a shower in a realistic multicell detector based on this technique. Unfortunately our Montecarlo calculation is too naive to properly take these effects into account.

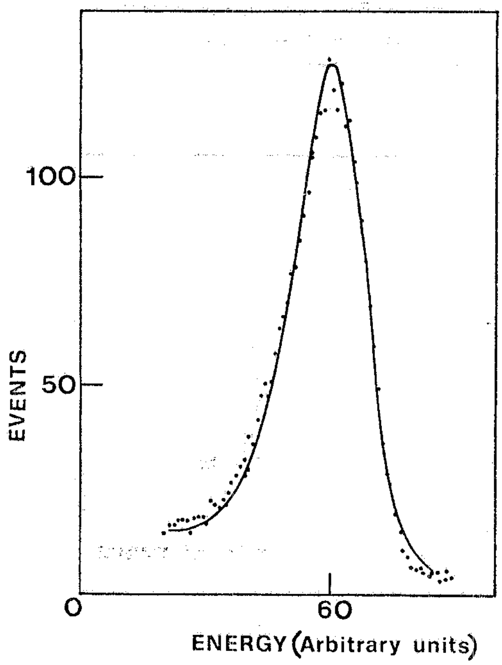

FIG. 12 - Total energy spectrum measured by the matrix when the counter of Fig. 4 is inserted as central element. The solid line is the spectrum obtained by folding the beam shape and the detector resolution. The resolution which fits the data was obtained by spreading the energy deposited in the central counter with a 19.5% FWHM gaussian. The computed pulse height in the remaining neighbouring counters is subsequently added in.

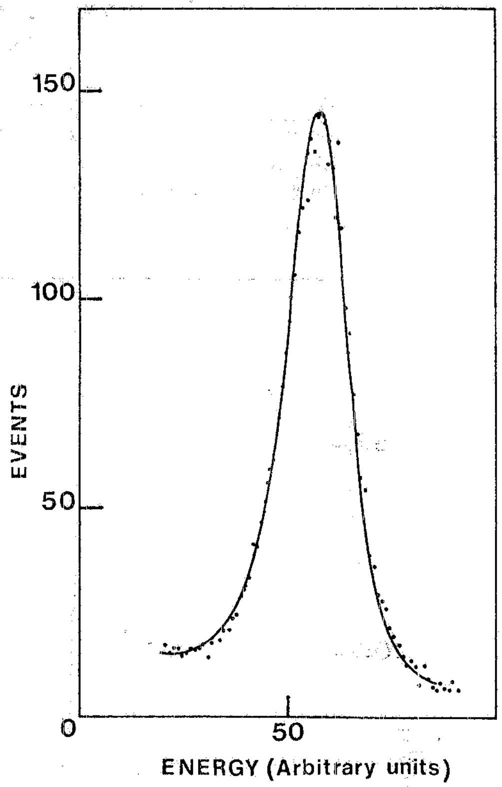

FIG. 13 - Energy spectrum measured by the matrix with the SCG1 block inserted as central element. The solid line is the spectrum obtained by folding beam shape and detector resolution. The resolution which fits the data was obtained by spreading the energy deposited in the SCG1 block with a $3.8\%/\sqrt{E}$ FWHM gaussian distribution. The energy deposited in the neighbouring counters is subsequently added in.

The array pulse-height spectrum with the SCG1 glass as central element, shown in Fig. 13, is well fitted by spreading the energy deposited in it with a gaussian distribution with 15.3% FWHM.

This result agrees with the prediction (15.5 %) at this photon energy done in Section 3, where the resolution of the central counter was calculated to be $3.8\,\%/\sqrt{E}$ (GeV).

It is natural to expect that performances of such glass, if needed, could be improved, by better matching the counter size to the tube dimensions (e.g., $8 \times 8\ \mathrm{cm}^2$ onto a 3" tube gives $\alpha_2 = 0.56$) and by polishing the block sides (20 % more photoelectrons), to about $2.7\,\%/\sqrt{E}$ (GeV).

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