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COMPARATIVE STUDY OF NEW 130mm DIAMETER FAST PHOTOMULTIPLIERS FOR NEUTRON DETECTORS

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Abstract :

The present paper is a summary of the test measurements carried out using new 130 mm diameter fast photomultiplier tubes manufactured by Philips (France), EMI (England) and Hamamatsu (Japan), along with a comparison to the results obtained with the well known XP 2041 Philips model. These tubes will be used in large size neutron detectors.

1. INTRODUCTION

In a french-belgian multidetector, called DEMON**, 96 individual large size neutron detectors will be available[1]. These detectors consist of 16 cm in diameter and 20 cm in length liquid scintillator cells each associated to 130mm diameter photomultiplier tube. For neutron detection, employing liquid scintillators with pulse shape discrimination, fast photomultipliers with a high linearity of the output current pulse are preferable. In the past an XP2041 photomultiplier was the choice [2,3]. At present, a number of new photomultipliers have entered on the market based on a new technology, mainly associated with new dynode material and structure.

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Table 1 shows the basic parameters of the new photomultipliers proposed recently by Philips, Hamamatsu and EMI, gathered from their data sheets, in comparison to those of the XP2041. Due to a new dynode material high gain of the photomultipliers is achieved with a lower number of stages, typically with 10 dynodes instead of 14, as is the case for XP2041. Moreover a high gain first dynodes are applied too. This improves the stability of the photomultipliers and can increase accuracy in time and energy measurements. Note the newest XP4512B photomultiplier developed recently by Philips for the DEMON array. According to the manufacturer the efficiency of photoelectron collection in this photomultiplier was improved over the parent XP4502B type. In turn three samples of the EMI D658B photomultiplier were tested. In the first one the serious prepulse effect was observed. The next two samples redesigned by the manufacturer were free of this effect. However, thay exhibited very high noise levels and the other characteristics were rather poor.

The effectivness of particle identification due to the pulse shape discrimination technique depends strongly on the quality of the photomultiplier used. The method being based on the analysis of the pulse shape from the scintillator, the distortion introduced by the photomultiplier should be limited. Thus the speed of the photomultiplier reflected in the rise time of the output pulse and its time jitter are of great importance.

The effectiveness with which different kind of particles can be separated depends on the statistical fluctuations of the slow component of the scintillation pulse. Note that its intensity for neutrons is of the order of 10 to 20 % of the total light pulse [4]. Thus high quantum efficiency and good photoelectron collection at the first dynode are the critical parameters. The latter quantity is very rarely specified by the photomultiplier manufacturers.

In modern experiments using large arrays of counters a large dynamic range of particle energies of the order of 100 is of importance. This can be limited by the linearity and dynamic range of the output current pulse of the photomultiplier used.

With the large dynamic range of particle energies the perturbing effect of prepulses and afterpulses on the timing and pulse shape discrimination is increased. Thus in this respect the precise inspection of the photomultiplier output signal is of importance before final acceptation of a given photomultiplier.

The aim of this work was to make a comparative study of the new photomultipliers delivered to us as test samples. Special attention was focussed on the items discussed above because some of these photomultiplier parameters are not specified by the manufacturers. In particular the photoelectron yield for a large liquid scintillator and that for a smaller one coupled to the center of the photocathode and at its edges were measured. The time jitter of the photomultipliers was determined using Cherenkov radiation produced in the glass window of the photomultiplier by Compton electrons generated by γ–rays. Finally each photomultiplier was tested by a timing study with ^{60}Co source and by measurements of n–γ discrimination carried out by means of digital charge comparison method [4] with an Am + Be source.

Although the reported measurements were addressed to the future application of the photomultipliers in the neutron detectors the conclusions concerning the capabilities of the new photomultipliers are more general and they can be taken into account in projects of any future experimental arrangement.

Moreover, in spite of the fact that this study was carried out with the testing samples of each type of photomultiplier they can be considered as being representative. In general only two parameters are varied within different photomultipliers of the same type, i.e. photocathode sensitivity and gain. Both these quantities of the tested photomultipliers were "typical" according to data quoted by the manufacturers. Other parameters as for example photoelectron collection efficiency or time jitter, depend on the design of the photomultiplier and should vary very weakly. This is correct in the measure that all the tested photomultipliers are still in the development phase. Thus one can expect further improvements of their parameters and this is certainly true for EMI photomultiplier.

2. Experimental details

2.1. Scintillators

The main part of the study was carried-out with a large BC501 liquid scintillator 16 cm in diameter and 20 cm in depth designated to be used in the "DEMON" arrangement. The liquid scintillator, delivered by Bicron Co., was encapsulated in a "bulb free" aluminum can with the white reflecting paint applied inside.This scintillator was used to measure the photoelectron yield of the photomultipliers, to check time resolution of the counters with ^{60}Co source and finally to observe the quality of n–γ discrimination with an Am + Be neutron source.

To test the photoelectron collection efficiency at the edges of the photocathode a small 2.5 cm diameter and 1 cm thick Pilot U plastic scintillator was chosen. The polished plastic, coated with a teflon tape, was used in the measurements.

2.2. Photomultipliers

All the photomultipliers except for the XP4502B type were studied with the voltage dividers recommended by the manufacturers with the last dynodes operated at progressively increasing voltages. This ensures good linearity of the current pulse at the anode.

In the case of the XP4502B photomultiplier the focalisation voltages was greatly modified to improve efficiency of photoelectron collection and the shape of single photoelectron pulse height spectrum. The new voltage distribution at the focalisation system of the XP4502B is shown on Fig. 1.

The photocathode – first dynode voltage was increased from 4 V_O to 6 V_O and the voltage at the accelerating electrode G_2 was increased from that of D6 to that of D8. Moreover the optimum G_1 potential found experimentally deviated strongly from that recommended by the manufacturer. The adjustment of D_1–D_2 and D_2–D_3 voltages was found to be critical as they affect the shape of the single photoelectron spectrum.

Note that for the newest XP4512B photomultiplier in Philips recommendation the photocathode – first dynode voltage was increased even up to 10 V_0. The critical adjustement of D_1–D_2 and D_2–D_3 voltages was not observed too.

3. Results

3.1. Photoelectron yield and efficiency of photoelectron collection

The photomultiplier photoelectron yield for a given scintillator depends on quantum efficiency of the photocathode and photoelectron collection efficiency. As for all the studied photomultipliers quantum efficiency is comparable, the photoelectron collection is the critical parameter as the liquid scintillators designated to be used in the final DEMON array have a larger diameter than that of the photocathode. A serious reduction of the photoelectron collection from the edges of the photocathode may thus be troublesome.

The measurement of the photoelectron yield was carried out first with the BC501 liquid scintillator. The measured numbers represent the mean photoelectron yield of the photomultipliers as it depends on both the quantum efficiency of the photocathode and the efficiency of photoelectron collection. The next series of measurements was performed with the small Pilot U plastic scintillator coupled to the center of the photocathode. In this case it was assumed that the measured number of photoelectrons is not affected by limited photoelectron collection. Then moving this small scintillator around the edges of the photocathode one can determine the efficiency of photoelectron collection in these critical conditions.

Measurements of the photoelectron yield were made using the method described by Bertolaccini et al. [5] and applied further in Ref. 6 for example. The number of photoelectrons per energy unit lost by γ–rays in the scintillator is measured directly by comparing the mean value of the peak position of the single photoelectron pulse height spectrum, which determines the gain of the photomultiplier, with the characteristic point of the energy spectrum of detected γ–rays. The edge of Compton spectrum of 662 keV γ–rays from ^{137}Cs

source was used. The linearity of the photomultiplier response was checked by means of ^{22}Na γ–lines.

Fig. 2a presents the example of the single photoelectron pulse height spectrum as measured with an XP4512B photomultiplier. Note a very well defined peak in the spectrum reflecting a high gain of the first dynode. Fig. 2b represents the corresponding spectrum of γ–rays from ^{137}Cs source measured with the gain of the amplifier reduced by factor of 200. The Compton edge used to calculate the photoelectron number is defined at 66 % of the trailing–edge of the Compton peak, following Ref. 5.

The results of the photoelectron yield measurements are collected in Table 2 for both the scintillators. The highest photoelectron yield was measured for XP4512B and EMI D658B photomultipliers. All the others photomultipliers show comparable photoelectron yield within ± 5 % accuracy, as measured with the BC501 scintillator. The photoelectron number measured for the small Pilot U plastic coupled to the middle of the photocathode follows mainly photocathode sensitivity except for the XP4512B photomultiplier which showed about 20 % higher photoelectron yield.

Fig. 3 shows the positions of the small Pilot U scintillator coupled to the edge of the photocathode with respect to the dynode plane. The numbers quoted at each position represents the relative photoelectron yield measured with the XP4512B photomultiplier in relation to that in the central position of the photocathode where it is assumed to be equal to 100 %. Fig. 3 reflects the serious non–uniformity of the collection efficiency for different positions around the photocathode which are so characteristic for the linear focused dynode structure. This affects pulse height resolution and it stresses that a diffused reflector for the scintillator is of the great importance in the measurement of energy spectra. In this respect the best is the EMI D658B photomultiplier which showed variation of the collection efficiency in the external region of the photocathode within ± 9 % only.

The mean values of the photoelectron collection efficiency for the tested photomultipliers are collected in Table 2. The mean efficiency varied from ~ 60 % for the XP4502B to ~ 76 % for the XP2041 photomultipliers. These numbers seem to be reasonable compared to the photoelectron collection efficiency observed for smaller diameter photomultipliers [7, 8] and which are equal to about 70 %.

In the last column of the Table 2 the ratio of the photoelectron yield measured with the BC501 scintillator to that of the Pilot U and divided by the photoelectron collection efficiency, ∈ was calculated. This quantity depending mainly on the ratio of the light yield of both the scintillators should be constant, independent of the tested photomultiplier, if the measured photoelectron collection efficiency from the external part of the photocathode is a reliable parameter of the photomultipliers. The data presented in Table 2 seem to confirme well the above statement. The larger value of this quantity found for R4144 photomultiplier reflects the bigger diameter of the photocathode which covers about 20 % more of the BC501 scintillator exit than the other tested photomultipliers.

In the Table 3 the photoelectron numbers measured with the small Pilot U scintillator are compared to the so called "blue" sensitivity of the tested photomultipliers. The blue photocathode sensitivity is measured with a tungsten filament lamp with a colour temperature of 2856 ± 5° K. Light is transmitted through a blue filter, Corning CS N° 5–58, polished to half stock thickness. This measurement of the photocathode sensitivity corresponds very well to the emission spectra of typical scintillators. In third column of Table 3 the photoelectron yield normalised to the blue photocathode sensitivity is listed. This quantity depends mainly on the photoelectron collection efficiency from the central part of the photocathode, in general, assumed to be close to 100 %. The calculated numbers do not confirm this assumption.

Taking arbitrarly that for the XP4512B 100 % of the photoelectrons are collected, the efficiency of photoelectron collection in the other tested photomultipliers is only about 80 %. This indicates a very important advantage of the XP4512B photomultiplier.

The observed effect again confirms conclusions of earlier works [7,9] that it is not enough to characterise photomultipliers by their photocathode sensitivity. The efficiency of the photoelectron collection has to be specified too. Moreover this measurement showed that even in the most favorable conditions when light strikes the photocathode centrally one observes a reduction of the photoelectron collection. It means that the focalisation system of photomultiplier is not able to collect all the photoelectrons emitted at different angles from any point at the photocathode. This effect has to be taken into account by designers of modern fast photomultipliers.

3.2. Linearity of the anode current pulse

Although the parameter describing the linearity of the photomultipliers is given by the manufacturer, (see Table 1), it was considered useful to recheck these data in well controlled conditions. Note that the linearity range of the photomultiplier depends on a high voltage at the photomultiplier or more precisely on the voltages at the last dynodes. Therefore one will observe a different linearity range for let us say 1 MeV, 10 MeV or 100 MeV detected radiation energy as they need different gains to reach a full pulse height.

The linearity range was determined for ^{60}Co γ-rays detected in a BC501 liquid scintillator. This corresponds to about 1000 photoelectrons in the integral of the photocathode current pulse. Fig. 4 shows, in turn, the shape of the anode current pulse from the XP4502B photomultiplier observed with the large bandwidth Tektronix 2467B scope. Note that this relatively slow pulse is mainly due to the slowing-down process occuring in the light collection process in such a large scintillator. As the FWHM of single photoelectron pulse is equal to 3 ns, the scintillator pulse is weakly affected by the photomultiplier bandwidth.

The criterion of the linearity range was defined as that for which the signal due to γ-rays from ^{60}Co source is still linear within ± 10 % (estimated accuracy from the scope measurements for continous energy spectrum).

Experimentally the linearity measurement was done by observing the height of the current pulses due to γ-rays from ^{60}Co and ^{137}Cs sources. Independently the energy spectra of integrated current pulses were measured by means of a multichannel analyser. The ratio of the pulse heights and that of the positions of Compton edges at the multichannel analyser were compared to the theoretical ratio of Compton edges i e. 2.18. For ^{60}Co γ-rays the mean value of the Compton edge due to 1.175 MeV and 1.332 MeV γ-quanta was adopted.

In Table 4 the maximal linear current pulses for the Compton edge of ^{60}Co γ-rays and the corresponding high voltages are listed for all the photomultipliers. The measurements showed a poor linearity range for the EMID658B photomultiplier which can limit seriously its application in measurements with a wide dynamic range of particle energies. In turn the linearity range of the XP4502B and XP4512B seems to be much better than that quoted by the manufacturer, however, given with higher accuracy. The measured linearity range of the R4144 photomultiplier for ^{60}Co γ-rays was limited by the low gain of this 8 stage photomultiplier at the maximum high voltage.

3.3. Time jitter of the photomultipliers

The time jitter of fast photomultipliers is determined experimentally by the measurement of the single photoelectron time distribution spectrum. To obtain a measurement of the time jitter accurately enough needs a light pulse of a very short duration. Therefore, very often, Cherenkov light generated by Compton electrons in the glass window of the photomultiplier is used [7, 10 – 13].

This method was applied in this study. This was carried out with a ^{60}Co source placed on the axis of the studied photomultiplier at 10 cm from the photocathode to ensure uniform production of Cherenkov light over the whole photocathode. The time spectra of coincidences between Cherenkov events under the single photoelectron peak and γ-rays detected in the reference counter were recorded. The reference counter consisted of the 2.5 cm diameter and 2.5 cm thick Pilot U plastic coupled to a XP2020 photomultiplier. The anode pulse of this counter was sent to a constant fraction discriminator ORTEC 934 and the upper 30 % of the Compton spectrum was accepted by the discriminator threshold to insure that the time resolution of the counter to be better than 150 ps. The anode signal of the studied photomultiplier was amplified using a Phillips 777 fast amplifier and sent to ORTEC 934 constant fraction discriminators. In the parallel side channel the peak of single photoelectrons was selected to reject the contribution of multiphotoelectron Cherenkov events.

Fig. 5 shows the time spectrum measured with the R4144 photomultipliers. In Table 5 the collected results of the time jitter measurements are represented by FWHM and FWTM of the time spectra.

Table 5 shows that the new generation of timing photomultipliers proposed by Philips and Hamamatsu have a lower time jitter than the former best XP2041. These good results are correlated with the lower number of dynodes and the high gain of the first one in these modern photomultipliers. Note that there is no a real difference in the advanced focalisation system of the XP4512B, XP4502B and that of the XP2041.

The best FWHM of the single photoelectron time spectrum measured with the XP4512B confirms an excellent focalisation system of this photomultiplier. In turn the best FWTM of the time spectrum measured with the R4144 may reflect the reduced photoelectron collection observed in sect. 3.1 for this photomultiplier. It may suggest that "delayed" photoelectrons are rejected by the focalisation system.

Time jitter of the EMI D658B photomultiplier is larger by a factor of 3 than those of the XP4502B, XP4512B and R4144 which again limits its application in experiments involving timing.

3.4. Time resolution study with ^{60}Co source

All the timing studies for γ-rays from ^{60}Co source were carried out with the BC501 liquid scintillator coupled to the tested photomultipliers. Measurements were done using the coincidence experiment method described in sec. 3.3. but with the ^{60}Co source placed at 20 cm from the scintillator. The electronic setup was also similar. using an ORTEC 467 time-to-pulse height converter for coincidence time-spectra. For the tested counters the threshold of the CFD was set at 100 keV and at 20 keV. The first measurement represents the standard timing test for a typical spectroscopy range where timing weakly depends on adjustment of CFD. The other measurements with the threshold set at 20 keV was considered as that representing limitation in timing with a very large dynamic range of energy. In this case the walk adjustment of the CFD was found to be critical.

Fig. 6 present the time spectrum measured with R4144 photomultipliers for the energy threshold set at 20 keV. Note the good time resolution FWHM = 1.15 ns and FWTM = 3.12 ns for such a large dynamic range of energy measured with the BC501 liquid scintillator 16 cm in diameter and 20 cm in depth.

The results of timing studies with the XP2041, XP4502B, XP4512B and R4144 photomultipliers are collected in Table 6. It shows comparable time resolution for all the tested photomultipliers. This result is understandable taking into account that the dominant source of the time jitter in the studied scintillation counters is the time spread of the light collection process in such large scintillators [10,14]. Somewhat worse time resolution measured with the XP2041 photomultiplier is probably associated with the old 14 stages dynode structure.

3.5. n–γ discrimination

The final comparative test of all the studied photomultipliers were done observing n–γ discrimination spectra measured with an Am + Be neutron source by means of the charge comparison method [4, 15]. The measurements were carried out with the BC501 liquid scintillator. The block scheme of the experimental arrangement is shown on Fig. 7. The anode signal from photomultiplier is split and sent to an ORTEC 934 constant fraction discriminator and to a two-fold charge-to-voltage converter [16]. The QV converters are gated by the reshaped signals from the CFD to integrate the total charge and that due to the slow component of the scintillation pulse. Both the output signals from the QV converters are send to the ADC's of the two-parametric data acquisition system. All the details of the method and arrangement are given in Ref. 4.

Fig. 8 presents the comparison of two-dimensional spectra of the charge under the slow component versus the total charge measured with the XP2041, XP4502B, XP4512B and R4144 photomultipliers. A very good separation of neutron and γ-events is achieved with the applied method. It indicates also the high quality of the tested scintillation counters. The best discrimination is observed with the XP4512B photomultiplier due to the sharpness of the γ-component. Somewhat poorer separation was obtained with the XP2041. Fig 9, in turn, shows a comparison of the n–γ discrimination spectra for energy gates corresponding to 300 keV recoil electron energy. To quantify of the n–γ discrimination at a given energy the figure of merit, M, was used as proposed in ref. 17 :

$$M = \frac{\text{(peak separation)}}{(\gamma \text{ peak width}) + (\text{n peak width})} \qquad (1)$$

According to the eq (1) the quality of the separation, expressed by the figure of merit M, relates inversely to the pulse height resolution of the signals due to the slow components of both neutron and γ light pulses. Thus the photoelectron yield of the counter and the contribution to the pulse height resolution coming from the electron multiplier structure are essential.

This is reflected in Table 7 where the figure of merits, M, determined for all the studied photomultipliers at 300 keV and 1 MeV recoil electron energy are listed. This confirms quantitatively that the best n–γ discrimination is achieved with the XP4512B photomultiplier because of its highest photoelectron yield, see sect. 3. 1.. A similar good separation is observed with the first photomultiplier of the D658B type, however, the separation was destroyied for high energy events by serious prepulses, see sect. 3. 6.. The next photomultipliers delivered by EMI were free of prepulses, however, much poorer n–γ separation was measured, see Table 7. A worse separation observed with the XP2041 is certainly associated with a larger gain dispersion of the old dynode structure as the photoelectron yield of this photomultiplier was comparable to those of XP4502B and R4144, see Table 2.

3.6. Prepulses and afterpulses

The application of the photomultipliers in experiments with the wide energy range involving timing and analysis of the scintillation pulse shape makes it imperative to check photomultipliers for prepulses and afterpulses.

Moreover, this study was prompted by the strange effect observed in the two-dimensional spectrum of n–γ discrimination measured with the D658B photomultiplier, see fig. 10. A serious discontinuity in the γ–ray component corresponding to increased charge under the slow component is seen for high energy events. Careful tests excluded effects associated with the electronic arrangement.

3.6.1. Prepulses

To understand the effect observed with the D658B photomultiplier a carefull inspection of the anode pulse corresponding to neutron and γ–rays from Am + Be source was carried out by means of a scope. The anode pulse is sketched in Fig. 11. The pulses due to high energy events are preceded by a sort of pedestal about 15 ns to early. The height of the pedestal corresponds to ~ 2 % of the anode pulse.

This form of the anode pulse with the preceding pedestal helps us to understand the distortion of n–γ discrimination seen on fig. 10. The pedestal at the anode pulse triggers earlier the constant fraction discriminator for the events above a certain threshold. Thus the gate for the slow component is advanced in time. The result is that the gate overlaps a tail of the fast component and an excess of charge is integrated (see time relation in Fig. 7). This is reflected in the jump of pulse height due to the slow component seen on Fig.10.

The above discussion suggests strongly that these prepulses are produced by a direct interaction of the light from scintillator with the first dynode. The pedestal character of the preceding part of the anode pulse can be understand taking into account the large width of the anode pulse which is equal to 17 ns. Thus there is no separation in time between prepulse and the main component of the anode pulse.

This conclusion seems to be confirmed by the measurement done within the time jitter study of the D658B photomultiplier (see sec. 3.3.). The time spectrum measured in coincidence with all the Cherenkov events, generated in the photocathode glass window, showed an earlier spike shifted by 15.6 ns (see Fig. 12). Note the good agreement for the shift with that estimated from the scope (Fig. 11). The FWHM of the spike (equal to 2.2 ns) is much better than that of the main component of the time spectrum. This is understable as the prepulses generated at the first dynode by the direct interaction of the light are not affected by the dominant component of the photomultiplier time jitter arising from the transit time dispersion between a photocathode and a first dynode.

The intensity of the earlier spike which is equal to 2.2 % of the main time spectrum is rather low. However, Cherenkov events produced by ^{60}Co γ–rays in the photomultiplier glass window are distributed only to about 30 photoelectrons [18]. Thus for the high energy γ–rays this effect starts to be of great importance as it can be seen on Fig.10.

It has to be pointed out that the observed prepulses in the first D658B photomultiplier were eliminated in the next tubes delivred by the manufacturer. However, a very high noise level and the rather poor other characteristics of the new photomultipliers (see Table 7 for example) suggest that this photomultiplier is still in an early phase of development.

A similar careful inspection of the other tested photomultipliers did not show any existence of prepulses. Therefore the effect presented above seems to be a very good example of the real discovery of prepulses in the photomultiplier. Fortunately, in fact, this is a very rare effect in modern photomultipliers.

3.6.2. Afterpulses

A close look at the anode pulses done by means of Tektronix 2467B scope with a high brightness permitted us to observe directly afterpulses in R4144 and D658B photomultipliers. Philips photomultipliers XP2041, XP4512B and XP4502B were found to be free of this effect at least within the accuracy of the inspection.

The photomultipliers with the BC501 liquid scintillator were tested by means of γ–rays from a ^{60}Co source and then with γ and neutron radiation from an Am + Be source. In the case of Hamamatsu R4144 two groups of afterpulses delayed by about 800 ns and 1.5 μs are distributed over about 50 ns and 100 ns respectively. The height of pulses in both groups was about 5 % of that of primary anode pulse observed with a ^{60}Co source. Taking into account that FWHM of afterpulses is lower than that of scintillator pulse, thus it corresponds to about 10 – 20 photoelectrons or 10 – 20 keV recoil electron energy. It is interesting and important to note that the pulse height of the afterpulses in both groups was independent of the energy of primary radiation. This was checked with the Am – Be source which emits hard γ rays with energy up to about 4 MeV.

The origin of afterpulses in photomultipliers is explained [19] by the interaction of the primary electron beam with remaining traces of molecules of different gases. It suggests that the height of the afterpulse in the group corresponds to that produced at the photocathode by a single ion of gas. The larger energy of primary radiation detected in the counter may only increase the probability of interaction with gas molecules and thus increase the probability of occurrence of the afterpulses. This was estimated to be below 10 % for ^{60}Co source γ–rays.

A similar effect of the afterpulses was seen in the D658B photomultiplier except that only one group of afterpulses was observed with a delay 2.3 μs. This may suggest that they are due to traces of heavier molecules.

The appearance of afterpulses is not bothersome. The pulse height of afterpulses in the groups is below 20 keV electron recoil energy, thus it is well below the expected energy threshold in most of the predicted experiments with the DEMON array. The estimated probability of occurrence of afterpulses showed that it will not increase significantly the noise level of the scintillation counters.

4. Conclusions

The comparative study of 130 mm diameter photomultipliers showed that for experiments involving timing or pulse shape discrimination techniques two photomultipliers are recommended Philips XP4512B and Hamamatsu R4144.

The Philips XP4512B ensures the best photoelectron collection efficiency about 20 % larger than the other tested photomultipliers. This is of great importance for n–γ discrimination as the quality of separation depends on the statistical fluctuation of the number of photoelectrons in the slow component of the scintillating pulse. This feature as well as good gain makes it a choice for low and moderate energy experiments. There is no doubt that the XP4512B will replace the parent XP4502B photomultiplier.

The Hamamatsu R4144 photomultiplier is preferable in the experiments with high energy radiation because of its lower gain and good timing properties.

All the modern photomultipliers are significatly better than the old XP2041. This is reflected in the better timing and higher precision of the pulse height measurements. This confirms the improved quality of the dynode structure in the modern photomultipliers, mainly associated with the high gain first dynode.

The EMI D658B photomultiplier is still in the development phase. The first D658B photomultiplier tested was excellent for general purpose nuclear spectroscopy due to high quantum efficiency and a good and most uniform photoelectron collection from external regions of the photocathode. However its application in timing and pulse shape discrimination was seriously limited by prepulses. More recent versions of the D658B photomultiplier were free of prepulses but they proved to have poor performances.

The studies of the photoelectron yield and the photoelectron collection efficiency suggest that more attention should be paided to the last problem. The photoelectron collection efficiency in the XP4512B was improved by about 20 % over the parent XP4502B and the other tested photomultipliers. This shows again that this is not enough to qualify photomultipliers by their photocathode sensitivity only. The photoelectron collection efficiency should also be quoted by the manufacturers.

The afterpulses observed in R4144 and D658B photomultipliers have, in general, negligible consequence in typical experiments. Their pulse height estimated to be about 10 ÷ 20 photoelectrons is independent of the energy of detected radiation. They occur with an estimated probability of less than 10 % for ^{60}Co γ-rays.

Finally the spectacular effect in the first tested D658B photomultiplier is a nice demonstration of prepulses. Fortunately, in fact, this is not commonly observed in the modern photomultipliers.

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Figure Captions

Fig. 1 : The modified voltage distribution at the focalisation system of the XP4502B photomultiplier used in the experiments.

Fig. 2 : The single photoelectron pulse height spectrum measured with the XP4512B photomultiplier (a) and the ^{137}Cs γ–rays spectrum measured with the BC501 liquid scintillator (b). Note that the gain of the amplifier was lowered by factor of 200 to observe the γ–spectrum.

Fig. 3 : The positions of the small Pilot U plastic scintillator at the photocathode used to measure the photoelectron collection efficiency. The positions of the Pilot U are oriented towards the dynode plan. The numbers quoted at every position correspond to the collection efficiency determined in relation to the central position of the Pilot U as measured with the XP4512B photomultiplier.

Fig. 4 : The anode current pulse observed with the BC501 liquid scintillator coupled to the XP4502B photomultiplier for ^{60}Co γ–rays.

Fig. 5 : Single photoelectron time spectrum measured with the Cherenkov light produced by γ–rays from ^{60}Co source in the glass window of the R4144 photomultiplier. Time calibration : 1 ch = 90 ps.

Fig. 6 : Time spectrum of coincidences measured for γ–rays from ^{60}Co source with the BC501 liquid scintillator coupled to the R4144 photomultiplier. The energy threshold was set at 20 keV. Time calibration : 1 ch = 65 ps.

Fig. 7 : Block scheme of the experimental arrangement used to measure the n–γ discrimination by the charge comparison method. Time relations between gates and photomultiplier pulse at the inputs of QV converters are presented in the lower part of the figure.

Fig. 8 : Two–dimensional spectra of charge in the slow component vs total charge measured with the BC501 liquid scintillator coupled to the XP2041, XP4502B, XP4512B and R4144 photomultipliers respectively. Measurements were carried–out with Am–Be neutron source.

Fig. 9 : n–γ discrimination spectra measured at 300 keV energy of recoil electrons for XP2041, D658B, XP4512B and R4144 photomultipliers.

Fig. 10 : The same as fig. 8 measured with the first tested D658B photomultiplier. Note the strange distortion of the spectrum due to prepulses.

Fig. 11 : Sketch of anode pulse from the BC501 liquid scintillator coupled to the EMI photomultiplier observed with Am–Be source (a). The same extended to show the pedestal proceeding the pulse interpreted as prepulses (b).

Fig. 12 : Time spectrum of coincidences measured with Cherenkov light produced in the photocathode glass window of the D658B photomultiplier by ^{60}Co γ–rays (a). The same extended (b). Note an earlier spike at the time spectrum shifted by 15.6 ns which represents the effect of prepulses. Time calibration : 1 ch = 0.44 ns.

TABLE 1

COMPARISON OF THE PARAMETERS OF THE STUDIED PHOTOMULTIPLIERS

PHOTOMULTIPLIER	XP2041	XP4502B	XP4512B	R4144	D658B
Photocathode	bialcali	bialcali	bialcali	bialcali	bialcali
Quantum efficiency [%]	26	25	25	22	26
Photocathode diameter [mm]	110	110	110	120	110
Type of dynodes	Cu Be	D_1 : High gain CsSb	D_1 : High gain CsSb	D_1 : High gain CsSb	D_1 : High gain CsSb
Number of stages	14	10	10	8	10
Gain at HV	$3x10^7$/2200V	$3x10^7$/2000V	$5x10^6$/1700V	$1.4x10^6$/2000V	$1x10^6$/1250V
Dark current at gain [nA]	30nA/$3x10^7$	30nA/$3x10^7$	10nA/$5x10^6$	10nA/$1.4x10^6$	1nA/$1x10^6$
Anode pulse linearity [mA]	280	40	80	250	-
Anode pulse risetime [ns]	2	2.1	2.1	2	4
Transit time spread [ns]	1	-	-	1.1	-

TABLE 2

PHOTOELECTRON YIELD AND PHOTOCATHODE COLLECTION EFFICIENCY

PHOTOMULTIPLIER	Blue photocathode a) sensitivity [μA/lmF]	Photoelectron yield,N [phe/MeV]		$\in$ b) [%]	$\frac{N_{BC501}}{N_{Pilot\ U} {}^{*} \in}$
		Pilot U	BC501		
XP2041	-	1390 ± 70	828 ± 40	75.7 ± 2	0.79 ± 0.06
XP4502B	10.9	1660 ± 80	856 ± 45	58.5 ± 2	0.82 ± 0.07
XP4512B	10.6	2000 ± 100	1070 ± 54	65.4 ± 2	0.82 ± 0.07
R4144	10.2	1443 ± 70	900 ± 45	68.7 ± 2c)	0.91 ± 0.08
D658B	12.4	2045 ± 100	1143 ± 60	67.1 ± 2	0.83 ± 0.07

a) according to the manufacturer data, measured with Corning blue filter CS 5-58 polished to the half stock thickness

b) mean value measured at 85 mm diameter in relation to the center of the photocathode

c) 95 mm diameter

TABLE 3

PHOTOELECTRON COLLECTION EFFICIENCY IN THE CENTER OF THE PHOTOCATHODE

PHOTOMULTIPLIER	Blue photocathode a) sensitivity, S_{pc} [μA/lmF]	Photoelectron b) yield, N [phe/MeV]	N/S_{pc} [phe/MeV/μA/lmF]	ϵ_M c) [%]
XP4502B	10.9	1660 ± 80	152 ± 7.3	80 ± 5.6
XP4512B	10.6	2000 ± 100	189 ± 9.4	100 d)
R4144	10.2	1443 ± 70	141 ± 6.9	75 ± 5.3
D658B	12.4	2045 ± 100	165 ± 8	87 ± 6.1

a) according to the manufacturer data, measured with Corning blue filter CS 5-58 polished to the half stock thicknesss

b) for Pilot U scintillator in the middle of the photocathode

c) calculated in relation to the XP4512B, according to : $[N/S_{pc}] / [N/S_{pc}]_{XP4512B}$

d) arbitrary assumed to be equal to 100 %

TABLE 4

LINEARITY RANGE OF THE ANODE PULSE a)

Photomultiplier	Linearity range b) [mA]	High voltage c) [V]
XP2041	300	2350
XP4502B	200	2000
XP4512B	240	2080
R4144	200	3000
D658B	80	1850

a) for ^{60}Co γ – rays detected in BC 501 liquid scintillator.

b) measured with the fast scope. The accuracy of the linearity is ± 10%

c) high voltage applied to the photomultiplier.

TABLE 5

TIME JITTER[a)] OF THE PHOTOMULTIPLIERS

PHOTOMULTIPLIER	Time jitter	
	FWHM [ns]	FWTM [ns]
XP2041	2.0 ± 0.1	4.3 ± 0.2
XP4502B	1.56 ± 0.08	4.1 ± 0.2
XP4512B	1.38 ± 0.07	3.9 ± 0.2
R4144	1.53 ± 0.08	2.9 ± 0.15
D658B	5.1 ± 0.25	9.5 ± 0.5

a) measured with single photoelectrons due to Cherenkov radiation. Whole photocathode was irradiated by ^{60}Co γ – rays from 10cm distance.

TABLE 6

TIME RESOLUTION FOR $^{60}Co\ \gamma$ – RAYS a)

PHOTOMULTIPLIER	Energy threshold E ≥ 100 keV		Energy threshold E ≥ 20 keV	
	FWHM [ns]	FWTM [ns]	FWHM [ns]	FWTM [ns]
XP2041	1.0 ± 0.05	2.38 ± 0.12	1.51 ± 0.07	3.7 ± 0.2
XP4502B	0.91 ± 0.05	2.17 ± 0.1	1.30 ± 0.06	3.5 ± 0.2
XP4512B	0.89 ± 0.04	2.13 ± 0.1	1.17 ± 0.06	3.27 ± 0.16
R4144	0.85 ± 0.04	2.25 ± 0.1	1.15 ± 0.06	3.12 ± 0.15

a) measured with BC501A liquid scintillator. The contribution of the reference counter is ≤ 150 ps. The ^{60}Co source is 20 cm far from the BC501A scintillator

TABLE 7

FIGURE OF MERIT M (see eq.(1)) OF n – γ DISCRIMINATION AT 300 keV AND 1 MeV RECOIL ELECTRON ENERGIES a)

Energy [keV]	XP2041	XP4502B	XP4512B	R4144	D658B PM1 b)	D658B PM2c)
300	1.20 ± 0.06	1.54 ± 0.08	1.73 ± 0.09	1.63 ± 0.08	1.78 ± 0.09	0.89 ± 0.05
1000	1.61 ± 0.08	1.90 ± 0.1	2.02 ± 0.1	1.93 ± 0.1	1.97 ± 0.1	1.38 ± 0.07

a) measured with Am – Be source.

b) First D658B photomultiplier with prepulses.

c) Second photomultiplier, free of prepulses.

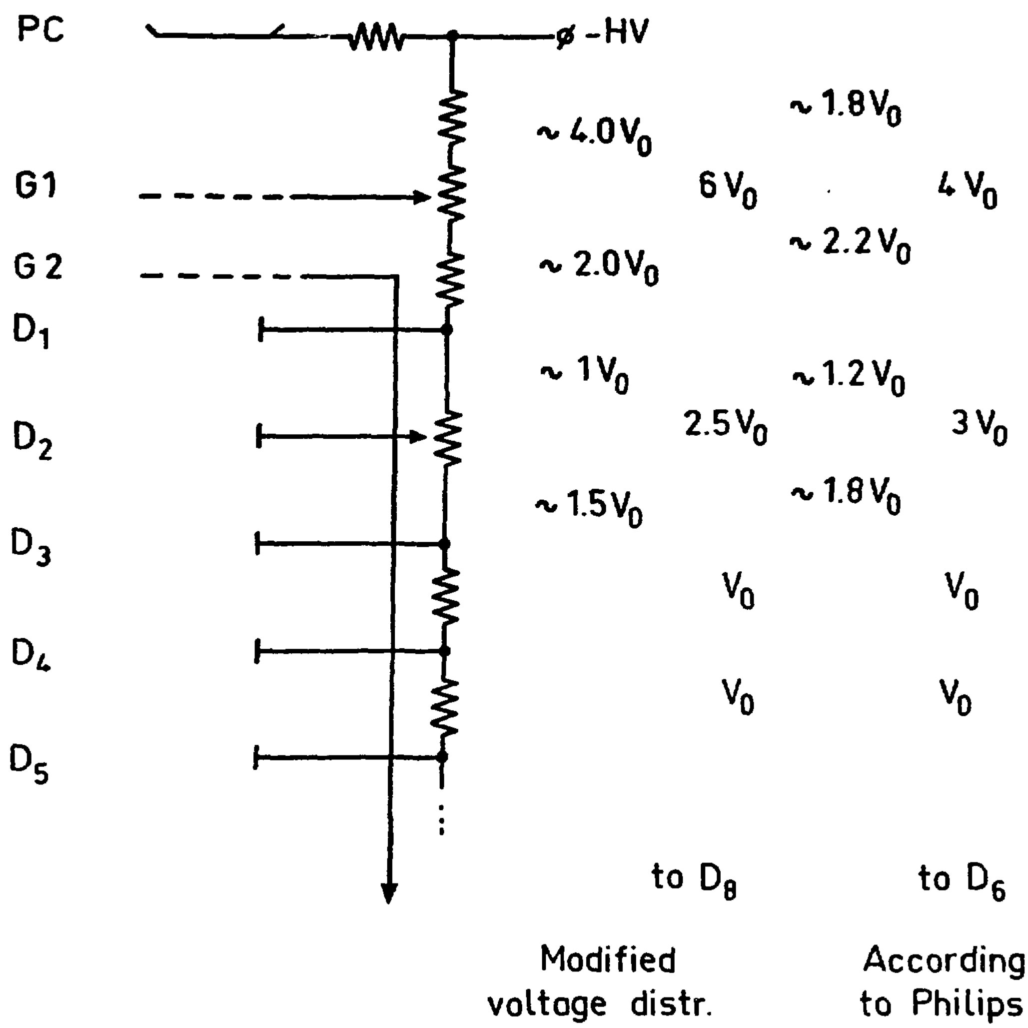
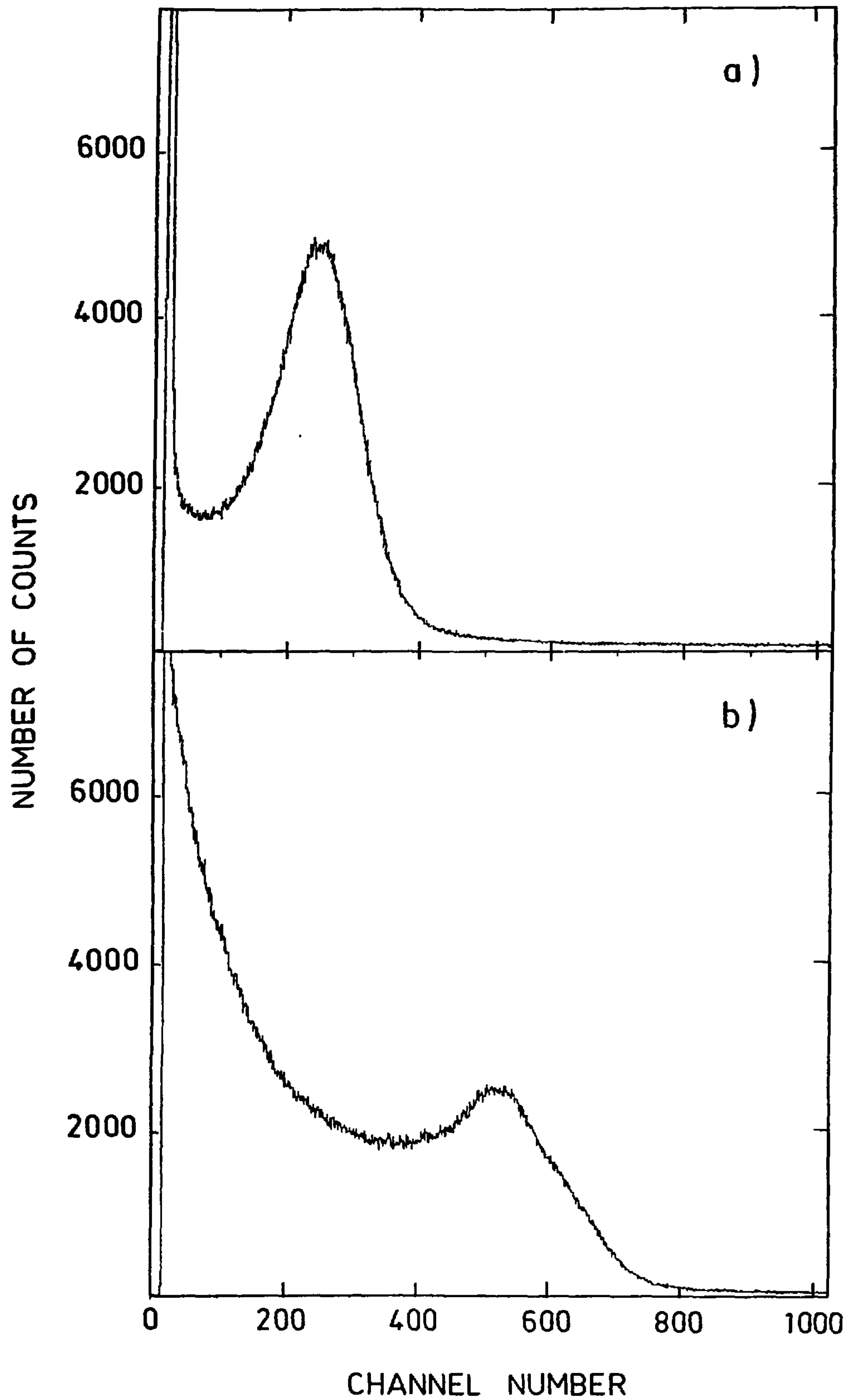

PC
-HV
G1
G2
D1
D2
D3
D4
D5
~4.0V0
~2.0V0
6V0
~1V0
~1.5V0
2.5V0
V0
V0
to D8
~1.8V0
~2.2V0
4V0
~1.2V0
~1.8V0
3V0
V0
V0
to D6
Modified
voltage distr.
According
to Philips

Fig. 1



a)
b)
6000
4000
2000
NUMBER OF COUNTS
0
200
400
600
800
1000
CHANNEL NUMBER

Fig. 2

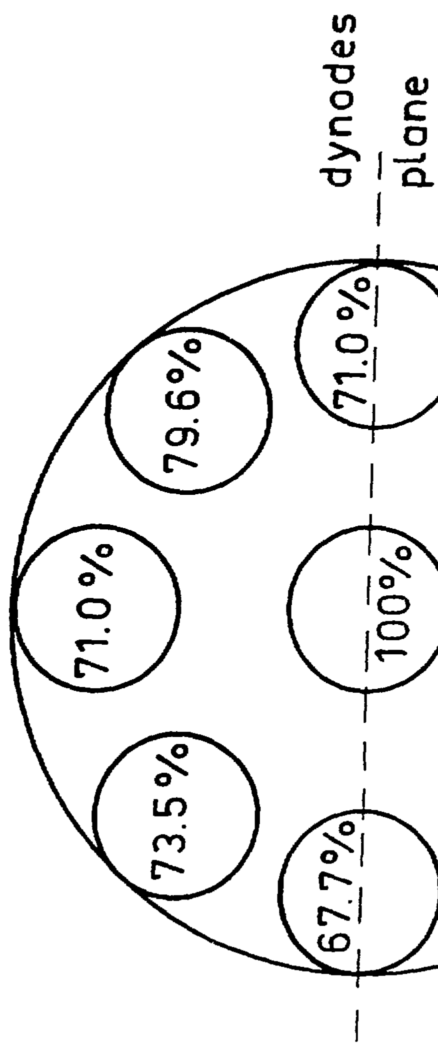


Fig. 3

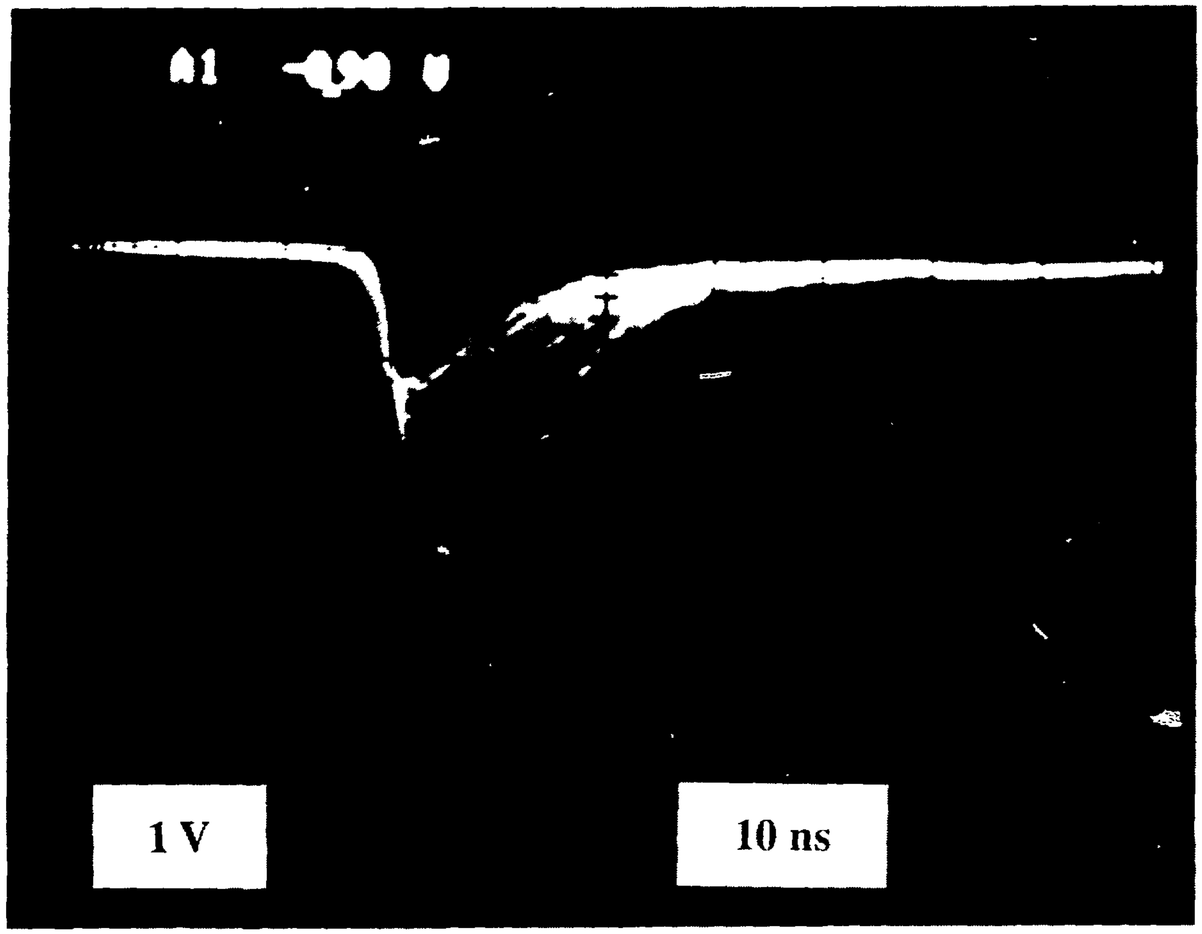


Fig. 4

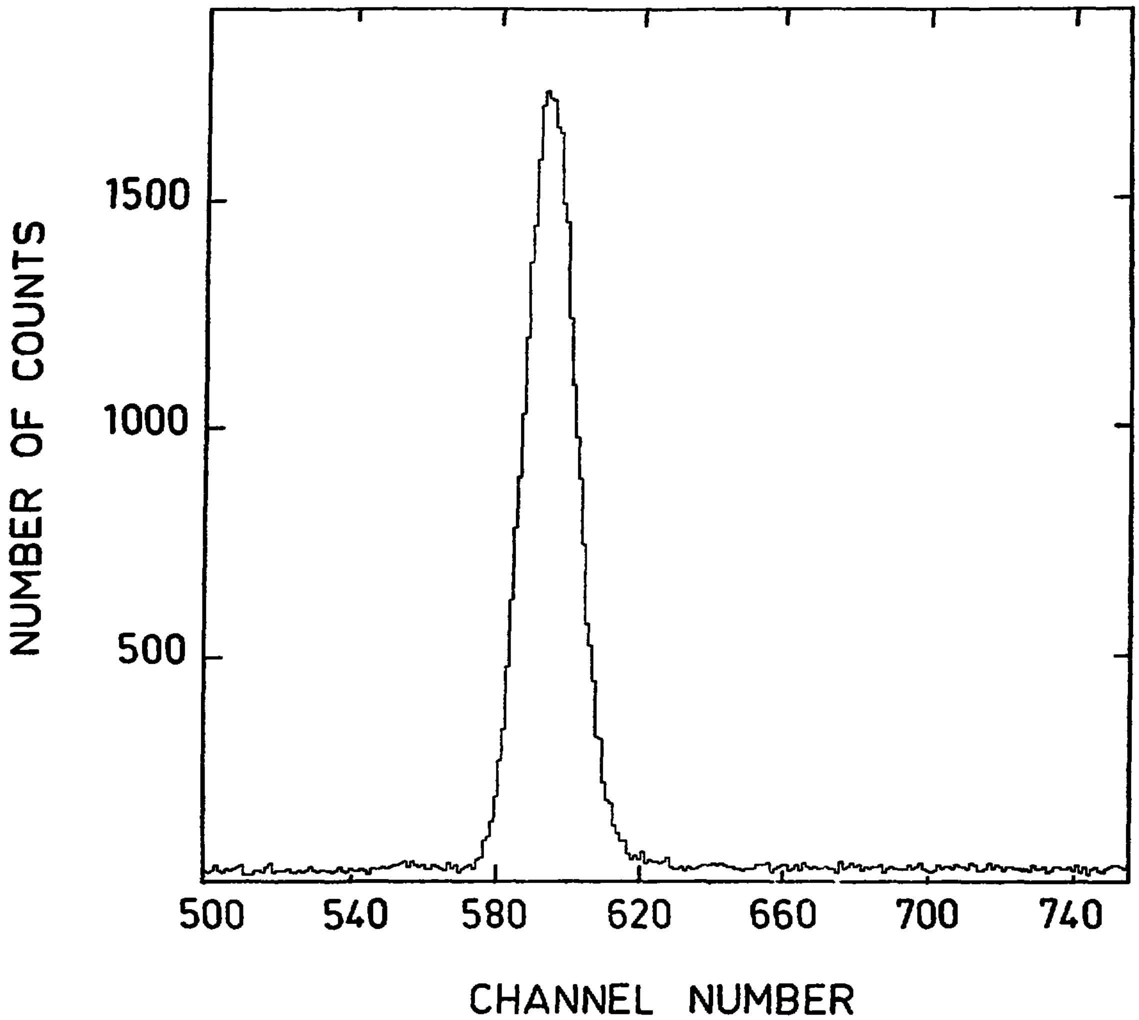

1500
1000
500
NUMBER OF COUNTS
500
540
580
620
660
700
740
CHANNEL NUMBER

Fig. 5

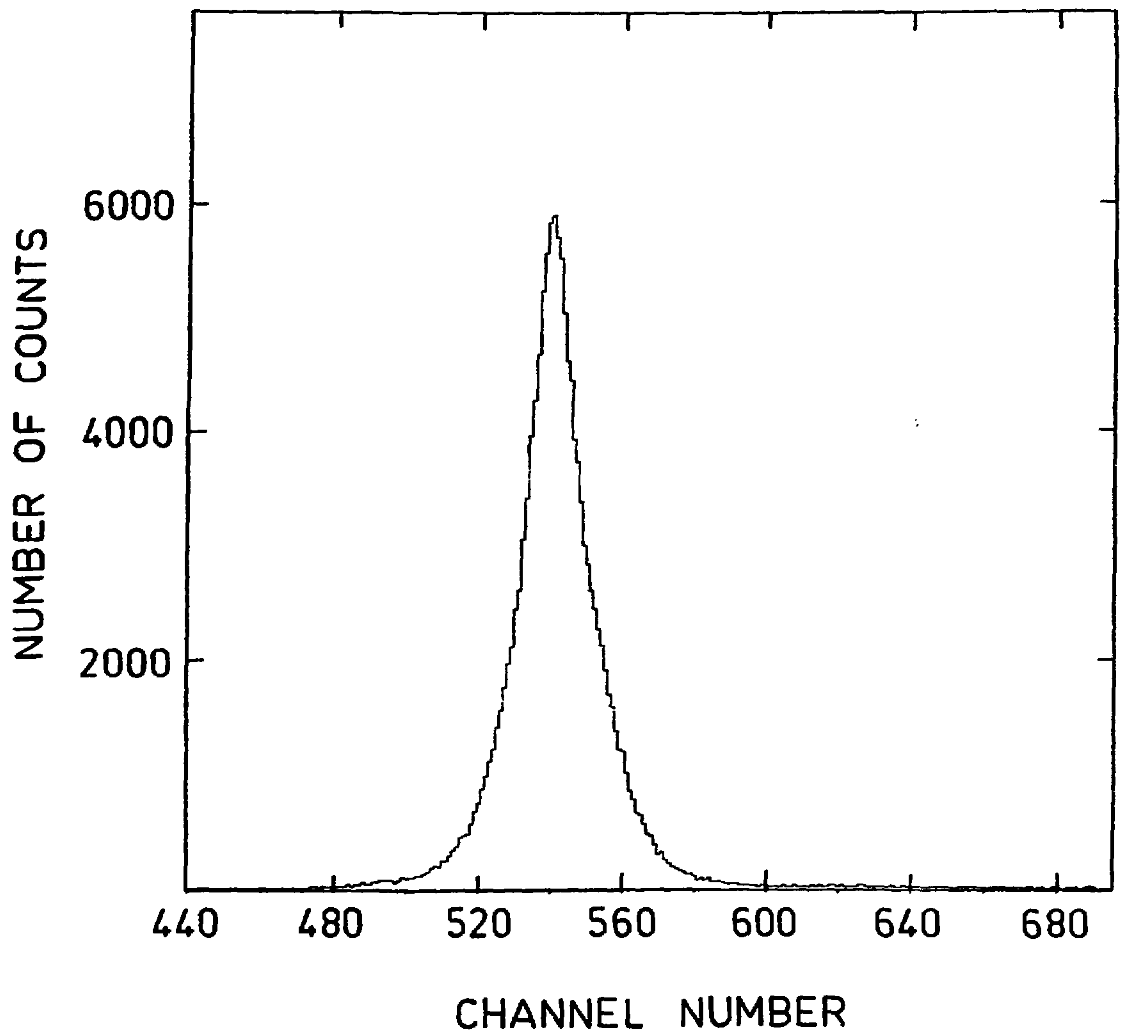
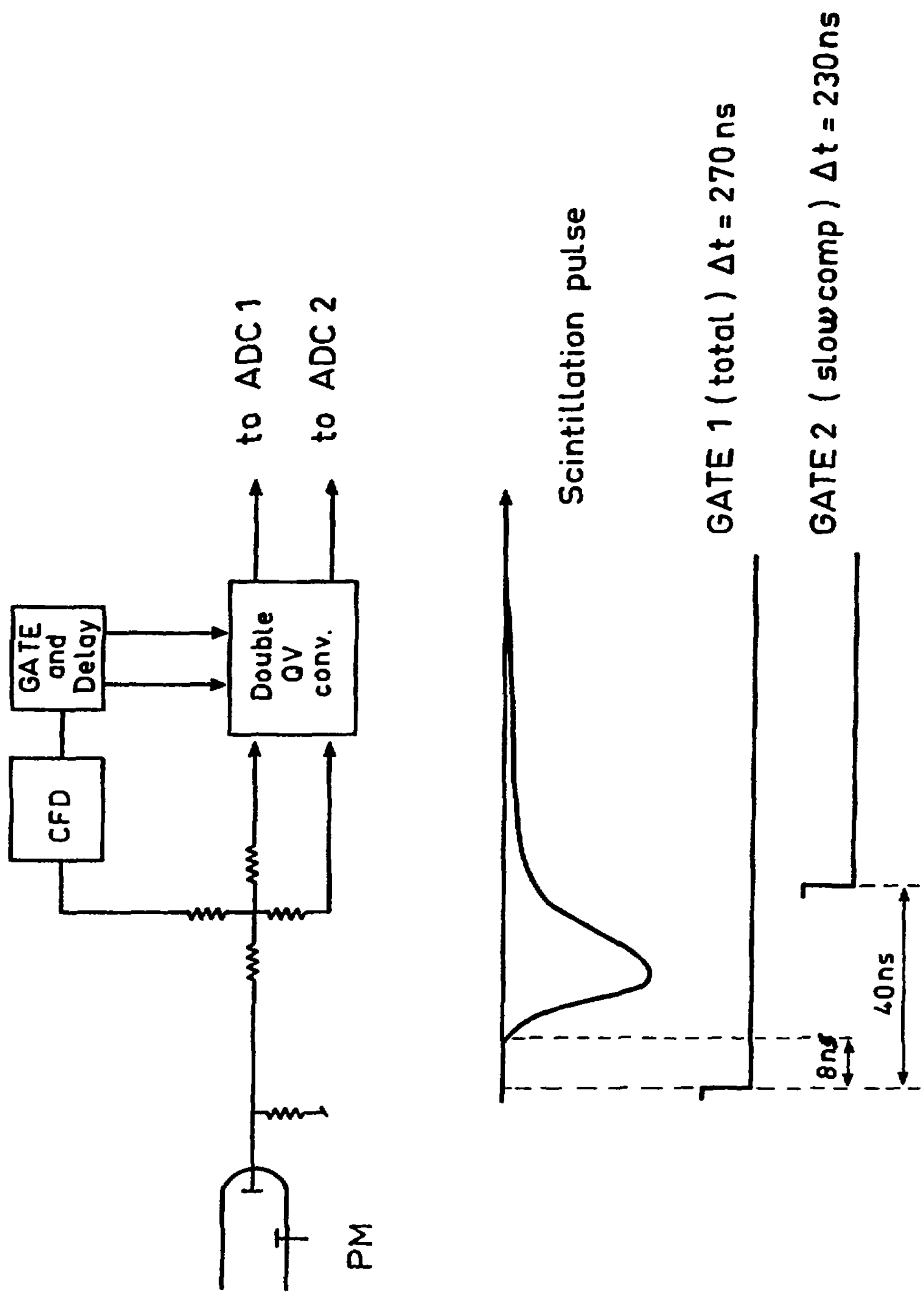

6000
4000
2000
NUMBER OF COUNTS
440
480
520
560
600
640
680
CHANNEL NUMBER

Fig. 6



to ADC 1
to ADC 2
Scintillation pulse
GATE 1 (total) Δt = 270ns
GATE 2 (slow comp) Δt = 230ns
GATE and Delay
Double QV conv.
CFD
PM
8ns
40ns

Fig. 7

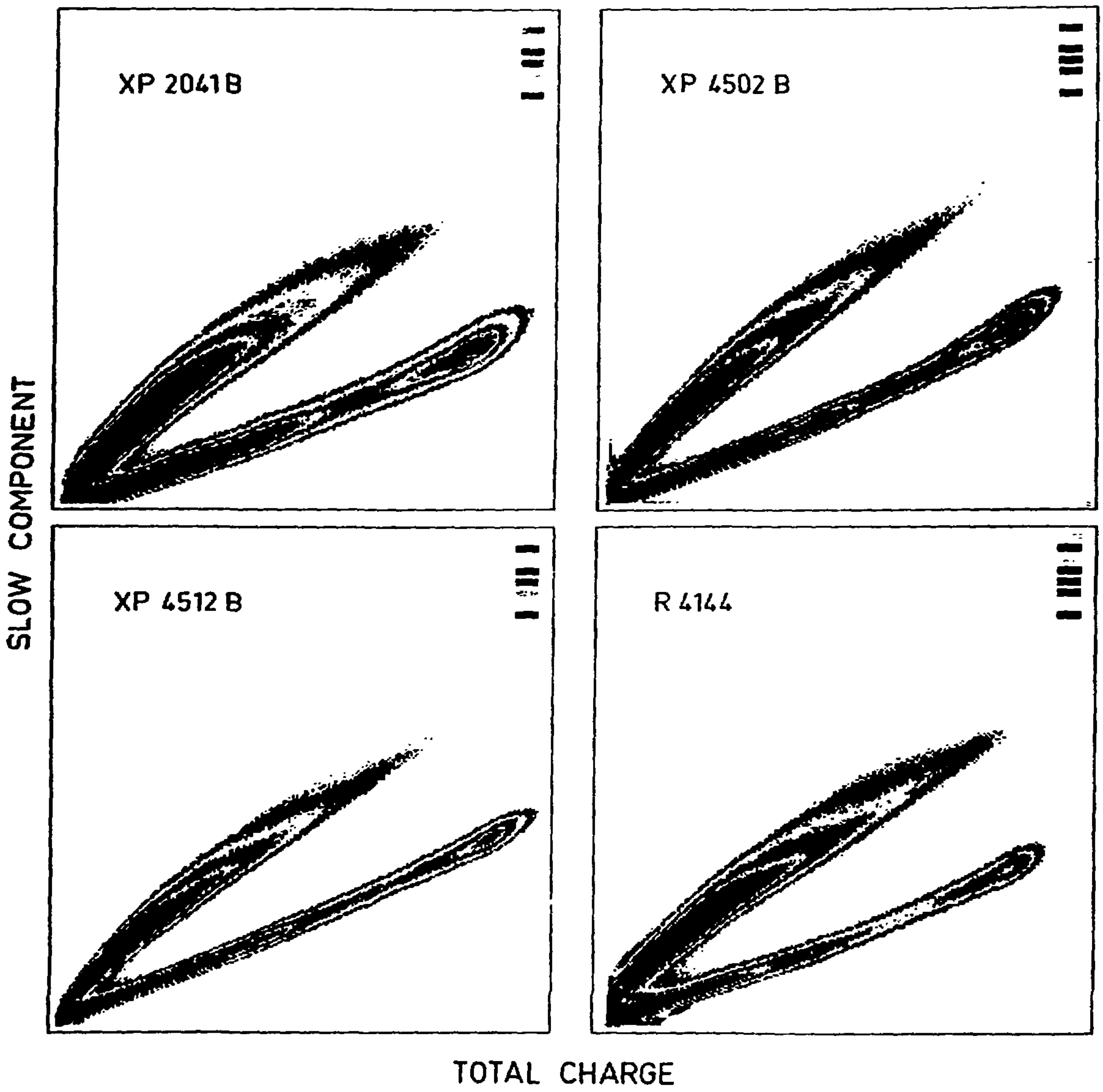
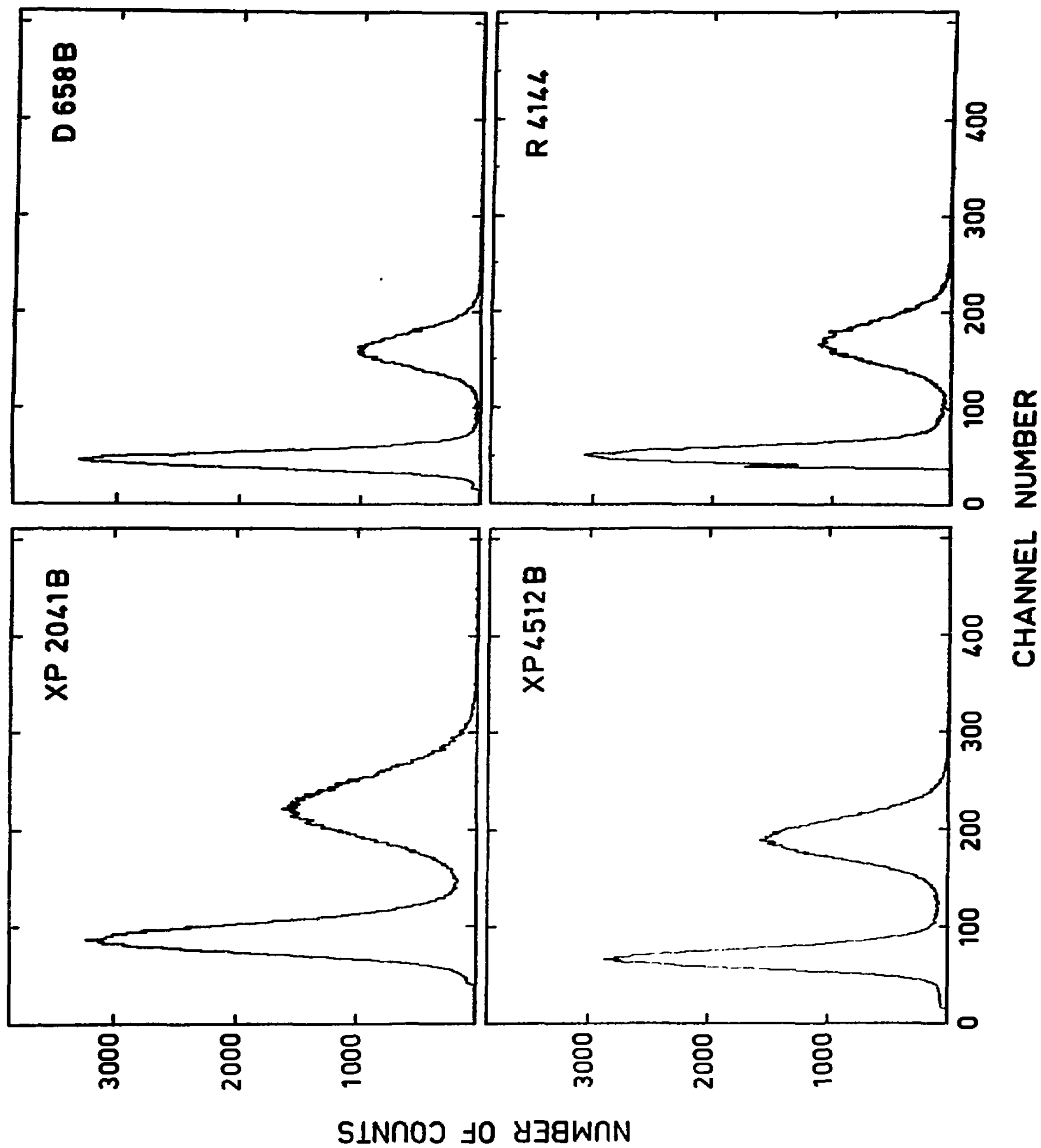

XP 2041B
XP 4502 B
XP 4512 B
R 4144
SLOW COMPONENT
TOTAL CHARGE

Fig. 8



D 658 B
R 4144
XP 2041 B
XP 4512 B
NUMBER OF COUNTS
CHANNEL NUMBER
0
100
200
300
400
1000
2000
3000

Fig. 9

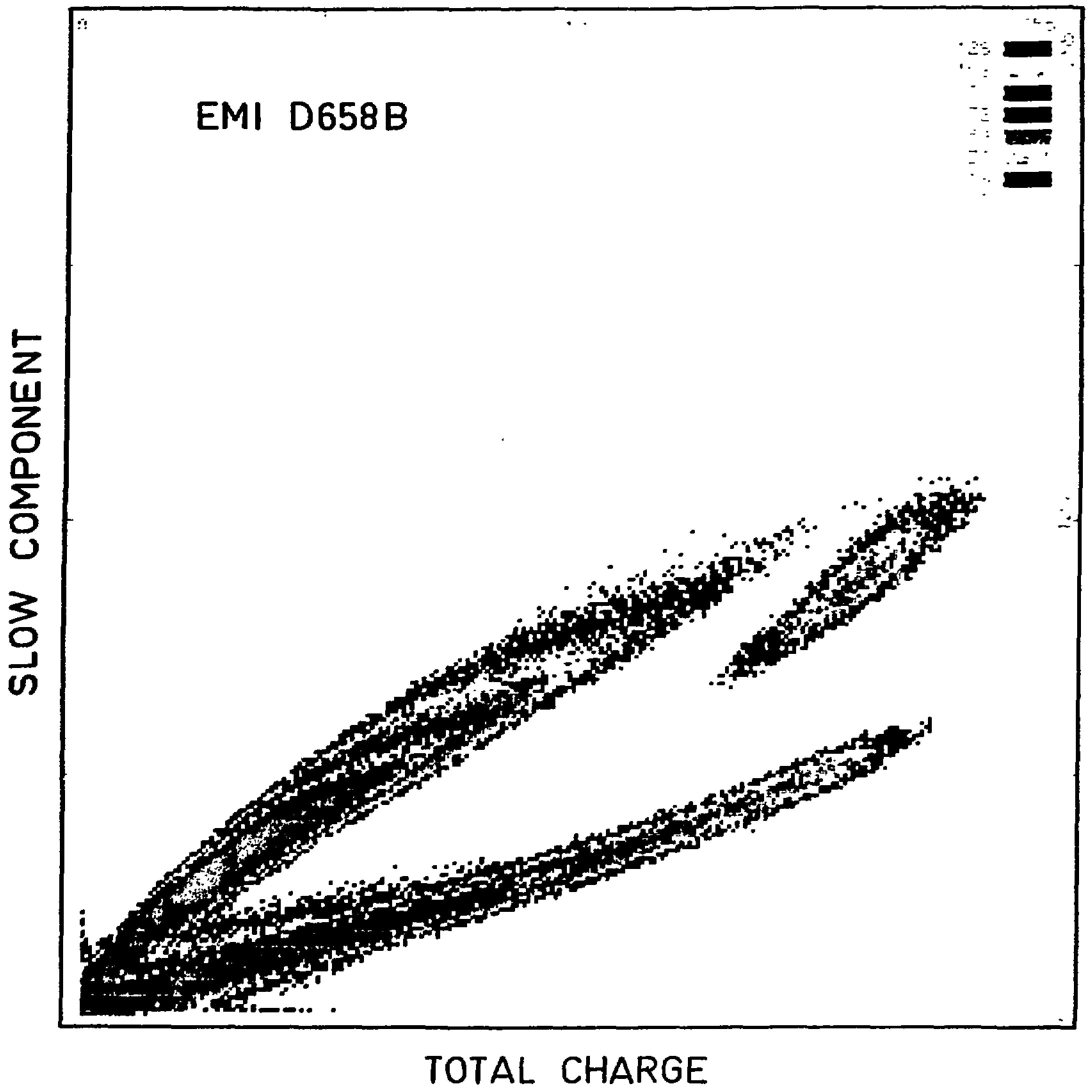


Fig. 10

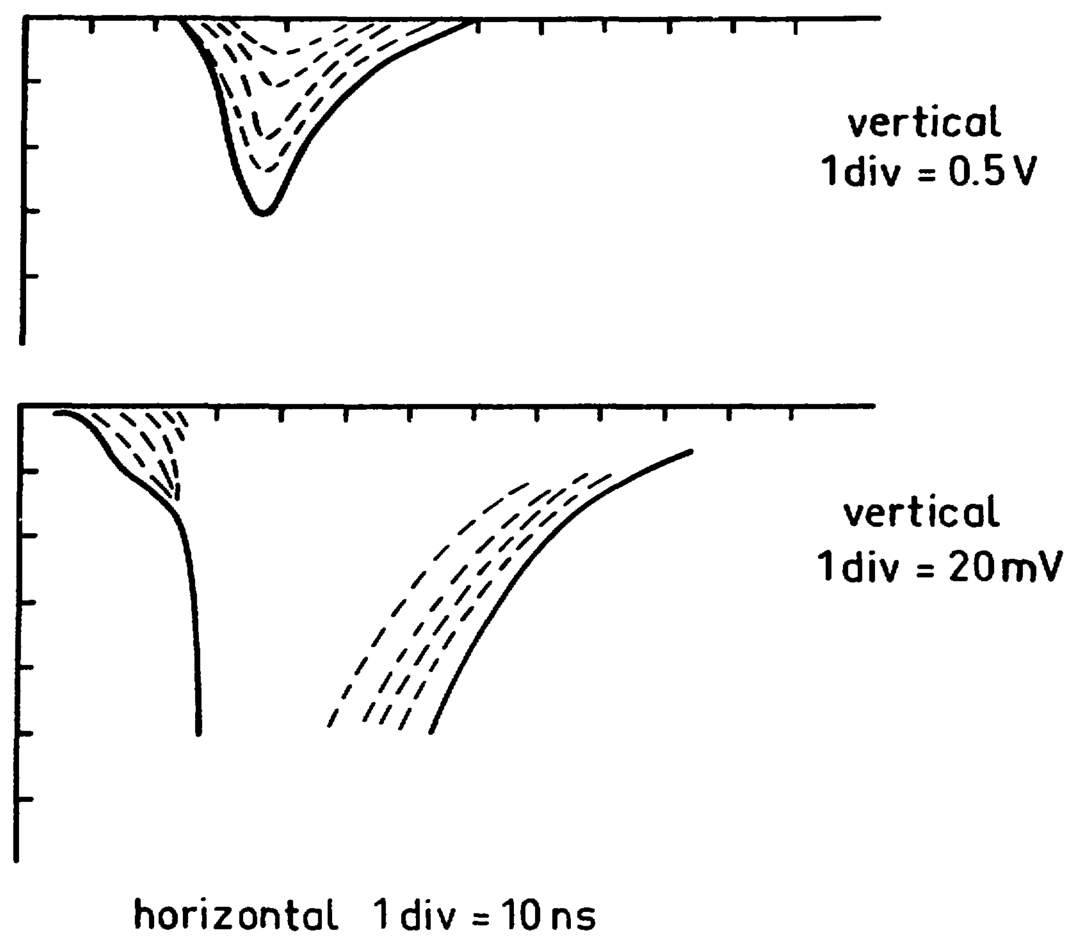


Fig. 11

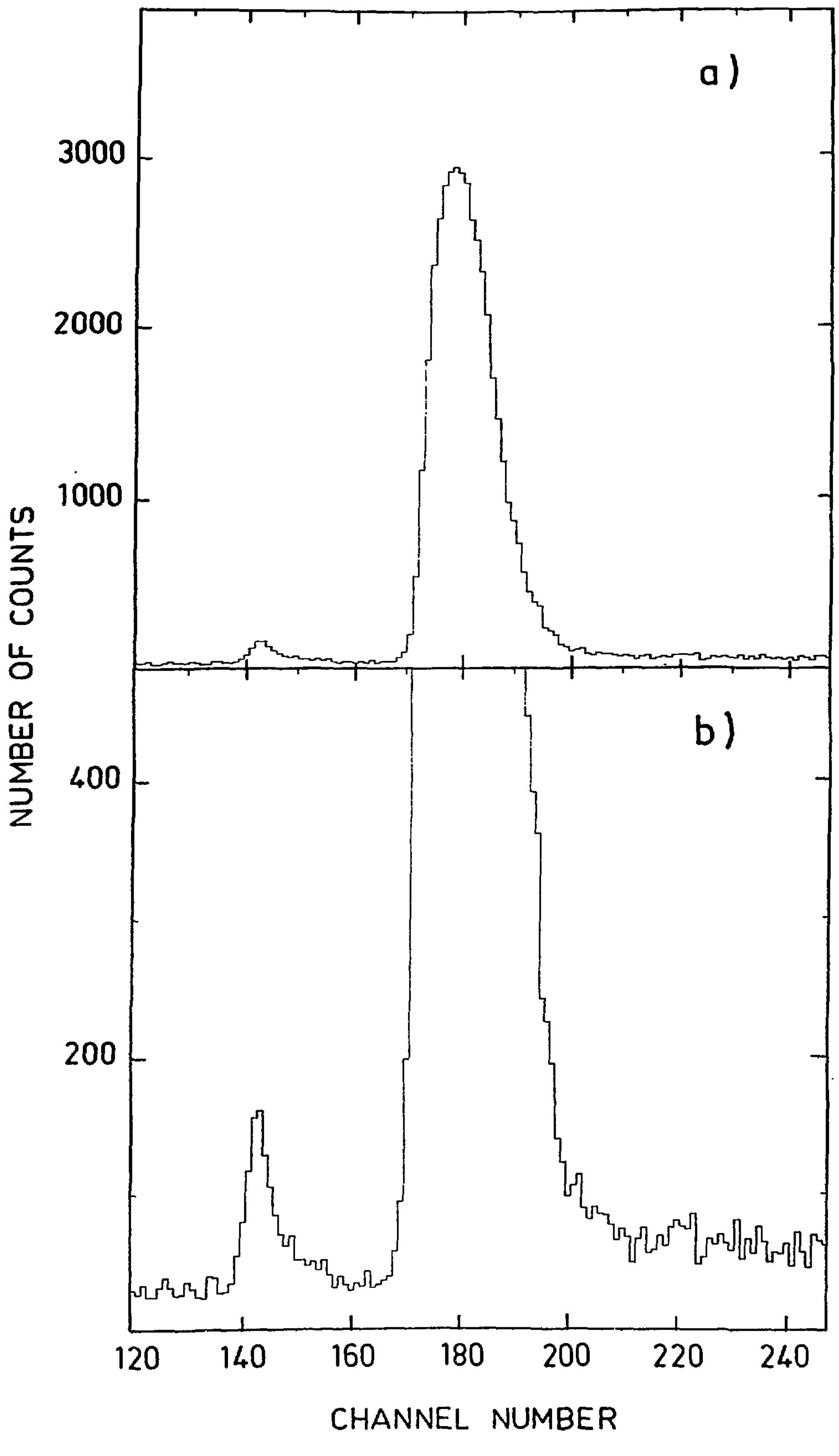

a)
b)
3000
2000
1000
400
200
NUMBER OF COUNTS
120
140
160
180
200
220
240
CHANNEL NUMBER

Fig. 12

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