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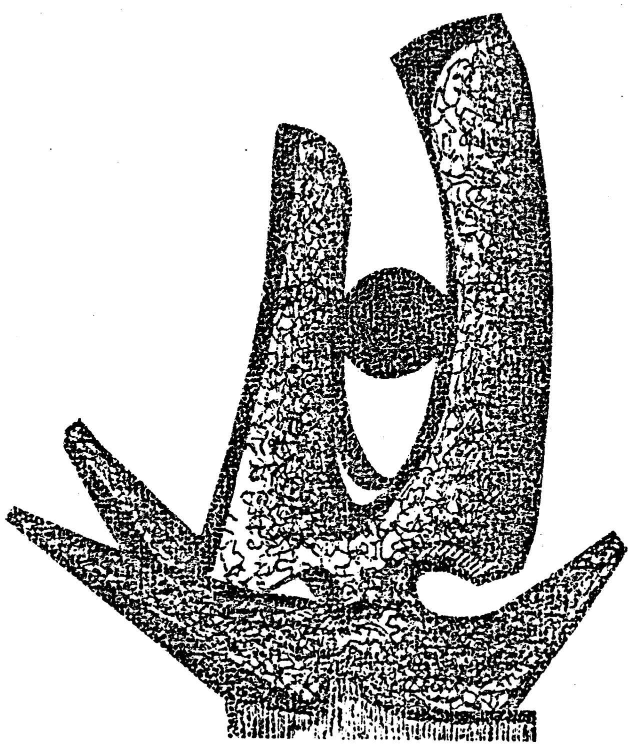
N. MATSUSHITA, J. KASAGI, and WM. C. McHARRIS



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The Pulse-Height Correction Technique for Improving γ-Ray Spectra from Coaxial Ge Detectors

N. Matsushita, J. Kasagi, and Wm. C. McHarris*
National Superconducting Cyclotron Laboratory
and
Departments of Chemistry and Physics
Michigan State University
East Lansing, Michigan 48824, U.S.A.

*On leave at Lawrence Berkeley Laboratory (Nuclear Science Division), Berkeley, Calif. 94720, U.S.A.

Abstract:

We demonstrate that the pulse-height correction technique can be used for coaxial as well as planar Ge γ-ray detectors. Pulses from the detectors are analyzed according to their rise-times, and an improved spectrum is obtained by correcting the incompleteness of charge collection, using the relation between rise-time and pulse-height defect. Geometrical effects in coaxial detectors require at least a three-parameter correlation, in which the rise-times of the pulses are analyzed for two time segments. We have been able to improve the energy resolution of neutron-damaged Ge detectors by more than 50% and their peak-to-Compton ratios by almost as much, all without significant loss in detector efficiency.

1. Introduction

The pulse-height correction (PHC) technique [1] is a means by which one can improve both the energy resolution and the peak-to-Compton ratios of γ-ray spectra taken by Ge detectors. To do so, one performs a detailed analysis of the rise-times of the pulses coming from the detectors. In general, the pulses having slower rise-times are associated with damaged or defective portions of the detector; consequently, these pulses suffer from incomplete charge collection. Thus, merely by "throwing away" such slower rise-time pulses, one can immediately improve the resolution, albeit with a significant loss in detector efficiency.

With PHC one can circumvent this loss in efficiency in the following manner: The spectra can be sorted into bins or slices as a function of the pulse rise-time. If a correlation can be found between the rise-time and the degree of incompleteness of charge collection, then a correction can be made to compensate for the incompleteness of charge collection. Each bin or slice can be corrected in turn, and many or most of the corrected slices can be reassembled to produce an improved spectrum characteristic of a superior detector. And this can be done without any significant loss in detector efficiency.

As might be expected, the PHC method produces its most dramatic results with Ge or Ge(Li) detectors whose resolution has deteriorated, most often because of neutron damage. For such detectors

we have obtained resolutions improved by 40-50% -- and this was done more or less routinely, using electronics that are available in most nuclear science or counting laboratories. For pristine, state-of-the-art, highest-resolution intrinsic Ge detectors, results from the PHC technique are much less dramatic -- indeed, they can become marginal to the point that it is not worth the bother of applying the technique. However, most laboratories have γ-ray detectors that are no longer of the highest quality, yet which are too good to discard or to send back for refurbishing. Since the PHC technique is basically a straightforward process, it can be quite useful in improving the quality of the spectra obtainable from these middle-quality detectors.

In our initial paper [1] we applied the PHC technique primarily to spectra obtained with planar detectors. Most planar detectors tend to be rather small, and in planar detectors the electric field is basically uniform; therefore, essentially all the variation in rise-time of a pulse of given energy can be attributed to traps or inhomogeneous portions of the detector. As a result, the correlation between rise-time and pulse-height defect is linear, and a simple one-parameter correction is sufficient to correct the spectra.

In this paper we extend our procedures to spectra produced by coaxial detectors. In coaxial and trapezoidal detectors (or detectors of more complex geometry) the rise-time of the pulse is affected strongly by the position where the electron-hole pair is created, much more so than in a small planar detector. This variation in rise-time is geometrical in origin and can occur even with pulses having "perfect" or complete charge collection. This results in a significantly more complicated relation between the rise-time and the pulse-height defect. However, we have found that this complicated relation can be simplified by observing <u>two</u> rise-time segments of the pulse along with the pulse height. Using the deduced correlation between these two rise-time segments and the pulse height, the spectrum can again be corrected to yield improved energy resolution and peak-to-Compton ratios -- again with no appreciable loss in detector efficiency.

2. Rise-Time Considerations

Since Ge and Ge(Li) detectors have found widespread use in γ-ray spectroscopy, many studies have been made of the effects of radiation damage, particularly damage caused by fast neutrons, on the resolution and other characteristics of these detectors [2-6]. These studies have demonstrated that neutron fluences approaching 10^{10} n/cm^2 severely degrade the resolution of the detectors, primarily through the creation of defects in the crystals that act as hole traps. This led to a demonstration [5] that a high-purity coaxial Ge detector with "reversed" electrodes (i.e., negative contact on the periphery and positive contact on the central core) was less susceptible to degradation from neutron damage than a detector with "normal" electrodes, the reason being that on the average electrons travel farther than holes during the course of charge collection in a detector with "reversed" electrodes. The most recent extensive study [6] of the actual mechanism for fast neutron damage of Ge detectors makes it clear, however, that radiation-induced defects can be quite complex, varying from simple relaxation products of interstitials to gross disordered regions extending some 20 nm or more. Experiments with resolution transients, induced by biasing the detectors off/on, indicate that details of charge trapping can depend on a number of different mechanisms.

Cumulative results from these studies show that a simple linear relationship between pulse rise-time and completeness of charge collection (hence, between rise-time and pulse-height defect), such as we observed [1] for planar detectors, is fortuitous, implying as it does a single dominant trapping mechanism or similar rates for two or more mechanisms. Thus, in general, we should be prepared to deal with more complicated relationships between rise-time and pulse-height defect. Hopefully, the techniques for coping with such relationships will not be so cumbersome as to render them worthless for routine use.

For coaxial, trapezoidal, and other detectors having "nonsimple" geometries, a further complication arises: The electric field in such detectors is no longer uniform, and this in itself introduces a variation in the rise-time of a pulse that is geometry dependent, i.e., depends on where in the detector the photon interaction took place. Thus, even undamaged, highest quality coaxial detectors, in which there is complete charge collection for each and every event, still exhibit a range of pulse rise-times.

An experimental illustration of the problems incurred in correlating rise-times with pulse-height defects is given in fig. 1. Here the pulse-height spectrum of the ^{60}Co 1332.513-keV peak is shown as a function of rise-time (the time difference between 0.1 and 0.5 constant-fraction discriminator outputs). The detector was an ORTEC true-coaxial Ge(Li) detector, 44.4 mm long, 49.6 mm ϕ, and with a drift depth of 19.3 mm. Its operational bias was 4800 V, and its original resolution of 2.0 keV fwhm (for the ^{60}Co 1332.513-keV peak) had deteriorated to 4.92 keV fwhm because of neutron damage before this

measurement. As the gate number increases in fig. 1, the rise-time becomes progressively slower -- a total of $\simeq$50 nsec in rise-time range is covered.

It can be seen that not only does the peak broaden with increasing rise-time, but also it splits into a doublet, the lower-energy component of which shifts in position. No longer can one make a straightforward assignment of the lower-energy component to incomplete charge collection and the higher-energy component to relatively complete charge collection. Obviously, another effect is also at work, most likely the geometrical rise-time variation intrinsic to a coaxial detector. (Although the existence of more than one type of defect can also potentially complicate the rise-time correlation.)

Since a complete analysis of these rise-time and trapping phenomena are beyond the scope of the present experiments, what we are seeking is a moderately simple, <u>empirical</u> approach to the correlation between rise-time and pulse-height defect. This can be found by analyzing the rise-times of two pulse segments: Suppose we were to use three constant-fraction timing discriminators to analyze the pulse rise-times, setting them, for example, at 0.1, 0.5, and 0.7 fractions of the rise-times. Now, a "good" pulse having complete charge collection but originating from a portion of the detector with a geometrically slow rise-time just might have, say, the same 0.1-0.5 fraction rise-time as a "poor" pulse slowed down by trapping and with incomplete charge collection but originating with a geometrically faster rise-time. The two pulses can accidentally have the same rise-time over one fractional interval, but it is highly unlikely that they would have the same rise-time over another interval, for example, that of the 0.1–0.7 fractions. Thus, a double analysis could separate and sort such pulses.

In fig. 2 we show such a correlation between the rise-times in the 0.1–0.5 fraction and the 0.1–0.7 fraction for a coaxial detector. If there were no trapping, i.e., the variations were all geometrical, the solid line should be expected from the model calculation reported in ref. [7]. Slowing down the rise-times by trapping (or, since this is purely an empirical procedure, by any mechanism whatsoever) will smear the line out in such a way that the rise-times of both intervals will increase, as indicated by the shaded area in fig. 2. One can now use "areas" within fig. 2 as time gates to effect the pulse-height corrections.

Of course, one can always add more and more fractions to "improve" such an analysis. (The asymptotic limit would be a complete computer analysis of each and every pulse shape!) We have found that this three-parameter analysis gives a good mean between results and complexity. (Also, one can try varying the fractional settings on the constant-fraction timing discriminators, perhaps improving the analysis for a particular spectrum.)

3. Experimental Techniques and Results

The same ORTEC true-coaxial Ge(Li) detector that produced the spectra in fig. 1 was used for our three-parameter rise-time experiments. It was ≈16% (with respect to a 7.6×7.6-cm NaI(Tl) detector) and had a degraded resolution of 4.92 keV fwhm and 8.98 keV fwtm for the ^{60}Co 1332.513-keV peak. Standard ^{60}Co, ^{137}Cs, and ^{152}Eu sources were used for the measurements.

We used a standard fast-slow "megachannel" multi-coincidence circuit with certain modifications. Its block diagram is shown in fig. 3. (The NIM electronics were all ORTEC modules.) Branched signals from the single detector were used for the coincidence inputs. The 0.1-fraction level of the constant-fraction timing discriminator (CFTD) was used to start both time-to-amplitude converters (TAC's); the 0.7- and 0.5-fraction levels were used to stop them. Thus, the output of the left-most ADC in fig. 3 is proportional to the rise-time difference between the 0.1- and 0.7-fraction levels of the CFTD's; that of the middle ADC is proportional to the difference between the 0.1- and 0.5-fraction levels; and that of the right-most ADC provides the pulse-height signal. (Single "pulse-shape analyzer" modules could replace a number of the modules in fig. 3, thereby simplifying the outward appearance of the block diagram. However, the effective circuits would remain the same.)

All data were recorded event by event on magnetic tape for later recovery and off-line analysis. This was done as follows:

Because of limitations in the sizes of computer memory, it is necessary to choose limited portions of the spectra for analysis in a given pass. As an example, for a single analysis we first sorted those portions of the pulse-height spectrum that contained the 244.692- (^{152}Eu), 661.649- (^{137}Cs), 1173.238- (^{60}Co), and 1332.513-keV (^{60}Co) γ-rays and obtained them as a function of both rise-time segments. For the 0.1-0.5-fraction TAC output (hereafter referred to as t_1) we set windows in 1.5-nsec steps, and for the 0.1-0.7-fraction TAC (t_2) in 3.3-nsec steps.

An example of the variation of the pulse-height spectrum of the 1332.513-keV γ-ray with the t_1 window centered at 37 nsec and the t_2 window progressing from 58 to 84 nsec is shown in fig. 4. The lowest spectrum in the figure is the one without t_2 windows, and it shows two broad peaks. The lower of these peaks corresponds to incomplete charge collection from neutron-damaged portions of the detector. As can be seen, this component can be easily separated from the "nondamaged" component by including the t_2 windows. The centroid channel of this component decreases with increasing t_2 value. Thus, it is demonstrated that one can distinguish between "damaged" and "nondamaged" events that have the same rise-time over one fraction by setting gates on another rise-time fraction.

In fig. 5 we show the overall correlation between the centroid channel number of the 1332.513-keV γ-ray and the two rise-time segments. Here the centroid channel number is plotted on the vertical axis, while

the rise-time windows are plotted on the horizontal axes. The events with small t_2 values at a given t_1 produce the largest pulse heights. These "nondamaged" events are distributed on a rather narrow line. This corroborates the qualitative results shown in fig. 2, in which the "nondamaged" events make a line distribution, while the "damaged" events lie on a slower rise-time area.

The relative yields for the 1332.513-keV peak vs the two rise-time segments are shown in a similar fashion in fig. 6. Two ridges can be clearly seen in this figure, one corresponding to "nondamaged" events, the other to "damaged" events. On the average, the energy resolution from the "nondamaged" area is about 2.6 keV fwhm, while that from the "damaged" area is about 3.0 keV fwhm. The fact that the total yield of "damaged" events is much larger than that of "undamaged" events and that the peak centroid position of "damaged" events is strongly affected by the t_1 and t_2 positions explains the 4.92-keV resolution of the raw spectrum.

Of course, the simplest method for obtaining an improved spectrum is merely to discard the "damaged" events by setting the appropriate two-parameter windows on the rise-time segments. We have done this, with the result that the energy resolution was improved to 2.6 keV fwhm by retaining 10% of the events and to 3.0 keV fwhm by retaining 28% of the events. However, since the energy resolutions of the individual gated spectra, even the "damaged" portions, are in general considerably better than that of the raw spectrum makes it possible to obtain the improved spectra without any appreciable loss in efficiency, as was demonstrated for the simpler case of planar detectors in our previous work [1].

The amount of pulse-height defect resulting from the incompleteness of charge collection is expected to be proportional to the energy of a γ-ray [1]. In other words, the gains of the individual gated spectra are no longer all the same but depend on the two rise-time segments. Therefore, we can fit the centroids of the γ-ray peaks, sorted according to the two rise-time segments, by the simple equation,

$$\mathcal{E}_\gamma = \alpha(t_1, t_2)x + \beta,$$

where $\mathcal{E}_\gamma$ is the energy of the γ-ray, x is the channel number of its centroid, and α and β are parameters to be determined empirically. As expected, the distribution of the values of α vs t_1 and t_2 shows the same characteristics as that of the centroid of the 1332.513-keV peak in fig. 5.

In order to generate the improved spectrum, the values of the matrix $\alpha(t_1, t_2)$ and the constant β were stored in computer memory, and the corrected energy of each event was calculated using these values. The final reconstructed spectrum is shown in fig. 7, along with the raw spectrum for comparison. An expanded portion is shown in fig. 8 in order to display the peak shapes more clearly. The energy resolution of

the 1332.513-keV peak was improved from 4.92 to 2.91 keV fwhm and from 8.98 to 6.21 keV fwtm. The peak-to-Compton ratio was improved by about 43%. We emphasize that these improvements were obtained without significant loss in detector efficiency.

4. Conclusion

We have demonstrated that the pulse-height correction technique can be extended from planar Ge detectors and applied to detectors having more complex geometry. In doing so, however, one must relinquish the simple linear correlation between the pulse-height defect and the corresponding pulse rise-time. This comes about because geometrical effects caused by the nonuniform electric fields in detectors having complex shapes can affect the rise-times of the pulses. In other words, neutron damage and the consequent incomplete charge collection are not the only factors that slow down a pulse's rise-time. Instead, one has to resort to at least a three-parameter analysis and determine the correlation between the pulse-height defect and the rise-times of two different segments of the pulse -- the linear correlation becomes an area-type correlation. Using the deduced correlation, the correction of the pulse height for each event can be done in a more or less straightforward manner. By this method we have improved energy resolution by more than 50% and the peak-to-Compton ratios by almost as much.

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Figure Captions

Fig. 1 Correlation between pulse rise-time and pulse height for the ^{60}Co 1332.513-keV peak in a spectrum taken by a ≈16%-efficient true-coaxial Ge(Li) detector. The spectra shown are time-gated slices, with the fastest rise-time in the first gate, then progressively slower ones until the slowest is reached in the fifteenth gate.

Fig. 2 Correlation diagram of the rise-time in the 0.1-0.5 fraction vs that in the 0.1-0.7 fraction of pulses from a coaxial Ge detector. The solid line at the left would be the expected correlation if geometrical variations in rise-time due to variations in the position of interaction in the detector were the only effects. The addition of trapping smears this out into the shaded area.

Fig. 3 Block diagram of the circuit used for rise-time discrimination on γ-ray pulses from a single detector. The three ADC's, from left to right, yield, respectively, the analyzed 0.1-0.7-fraction TAC signal, the 0.1-0.5-fraction TAC signal, and the pulse-height signal to be listed on magnetic tape for later off-line three-parameter analysis.

Fig. 4 Example of triple correlation between the pulse height for the ^{60}Co 1332.513-keV peak and the rise-times for two separate pulse segments. For these spectra the window of the 0.1–0.5 fraction was held constant, while that of the 0.1–0.7 fraction was varied. The bottom spectrum has no gate at all included for the 0.1–0.7 fraction; the second spectrum has the fastest rise-time from this fraction, and this rise-time becomes progressively slower toward the top spectra.

Fig. 5 Correlation between the centroid of the ^{60}Co 1332.513-keV peak ($\mathcal{E}_\gamma$ on vertical scale) and the two rise-time windows as determined by TAC signals.

Fig. 6 Correlation between the relative yield for the ^{60}Co 1332.513-keV peak (vertical scale) and the two rise-time windows as determined by TAC signals.

Fig. 7 γ-ray spectra for ^{60}Co + ^{137}Cs + ^{152}Eu sources taken with a ≈16%-efficient true-coaxial Ge(Li) detector. *A*) The raw spectrum, with energy resolution of 4.92 fwhm for the ^{60}Co 1332.513-keV peak. *B*) Pulse-height corrected spectrum, with energy resolution improved to 2.91 keV fwhm and the peak-to-Compton ratio improved by ≈43%, all without significant loss in detector efficiency. (Vertical scales arbitrarily displaced for clarity of display.)

Fig. 8. Expanded portion of fig. 7 in the vicinity below the ^{60}Co 1332.513-keV peak to show the peak shapes more clearly. (Vertical scales arbitrarily displaced for clarity of display.)

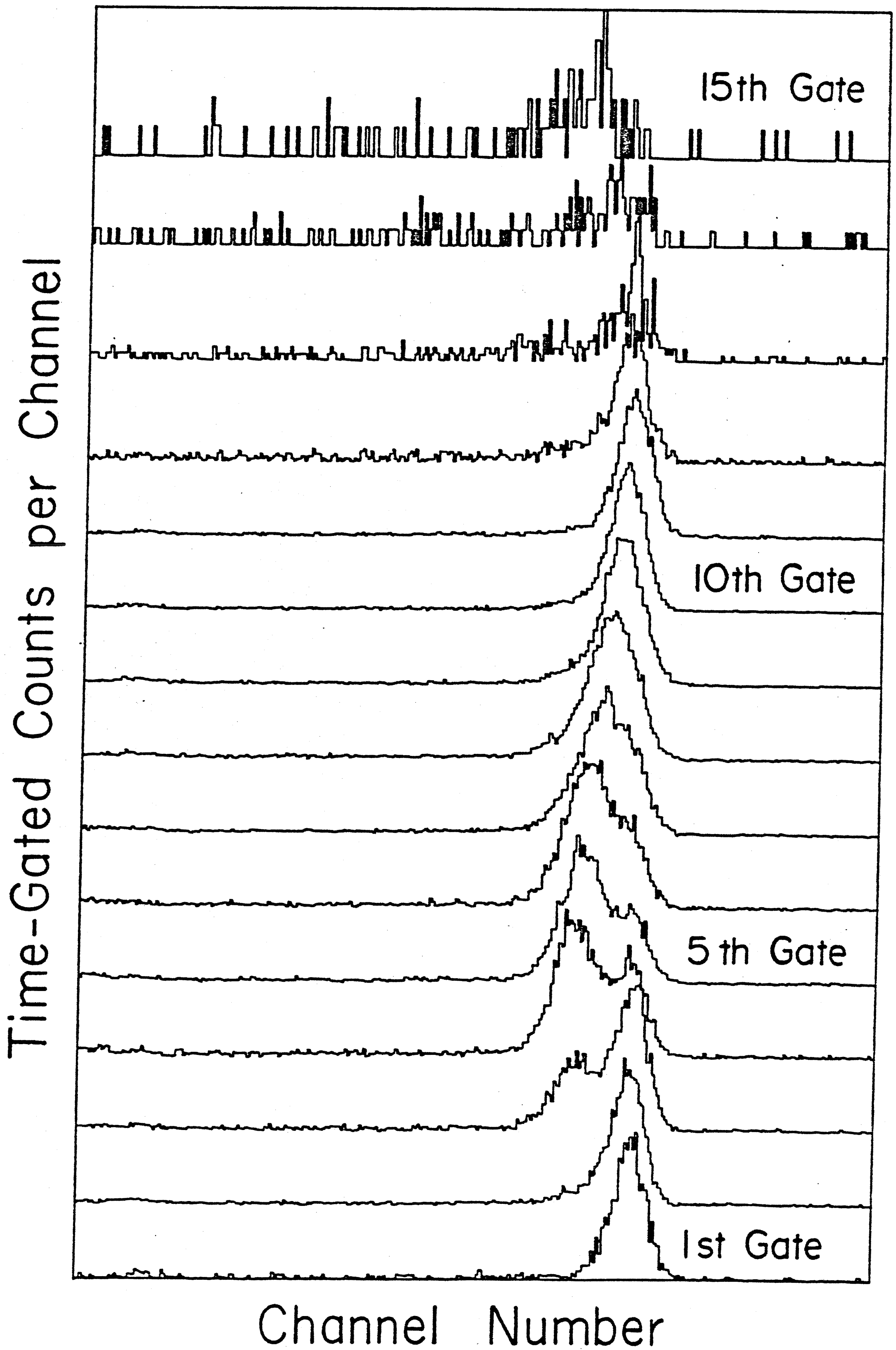
15th Gate
10th Gate
5 th Gate
1st Gate
Time-Gated Counts per Channel
Channel Number

Fig. 1

MSUX-81-464

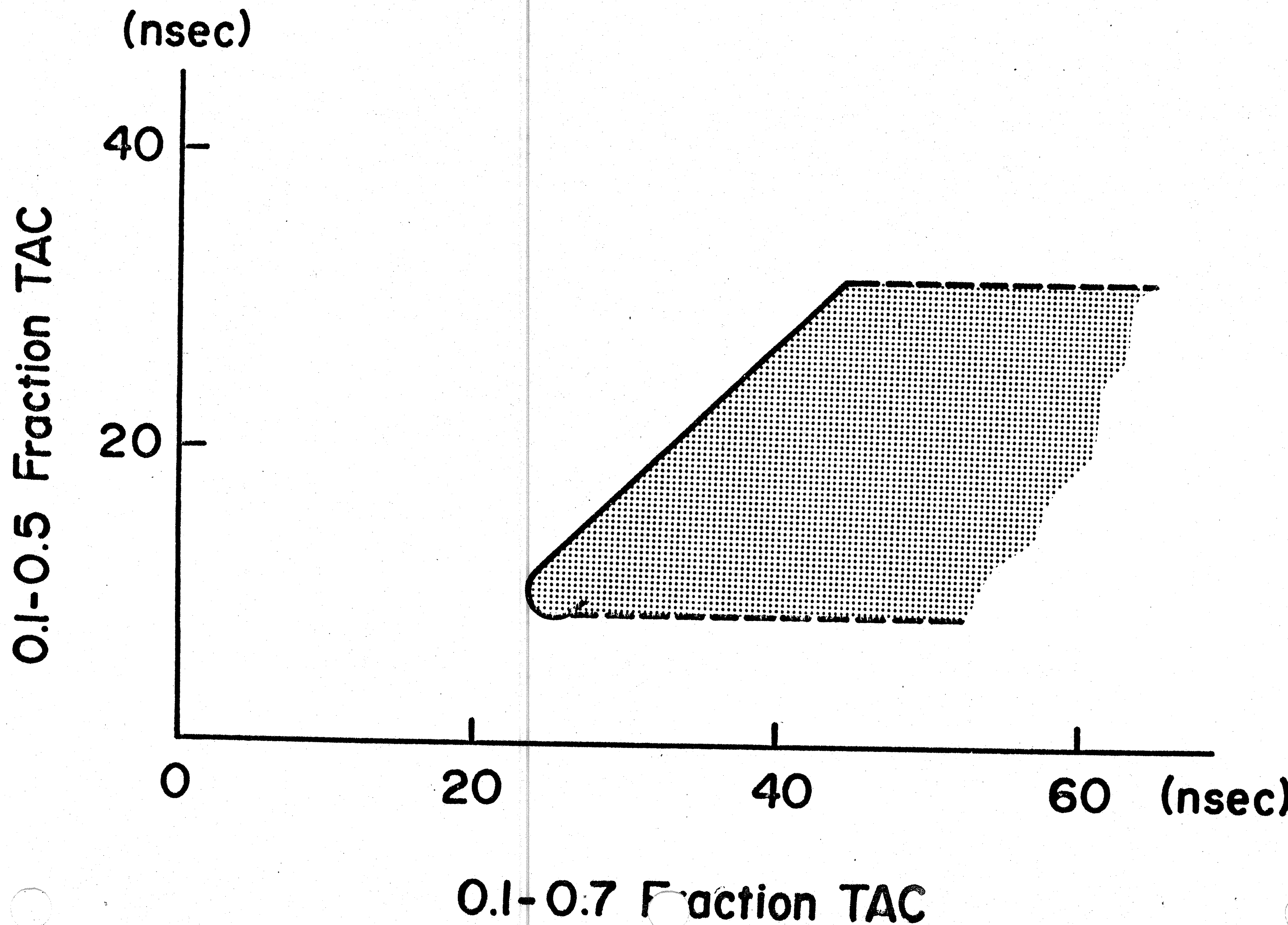

Fig. 2

MSUX-81-455

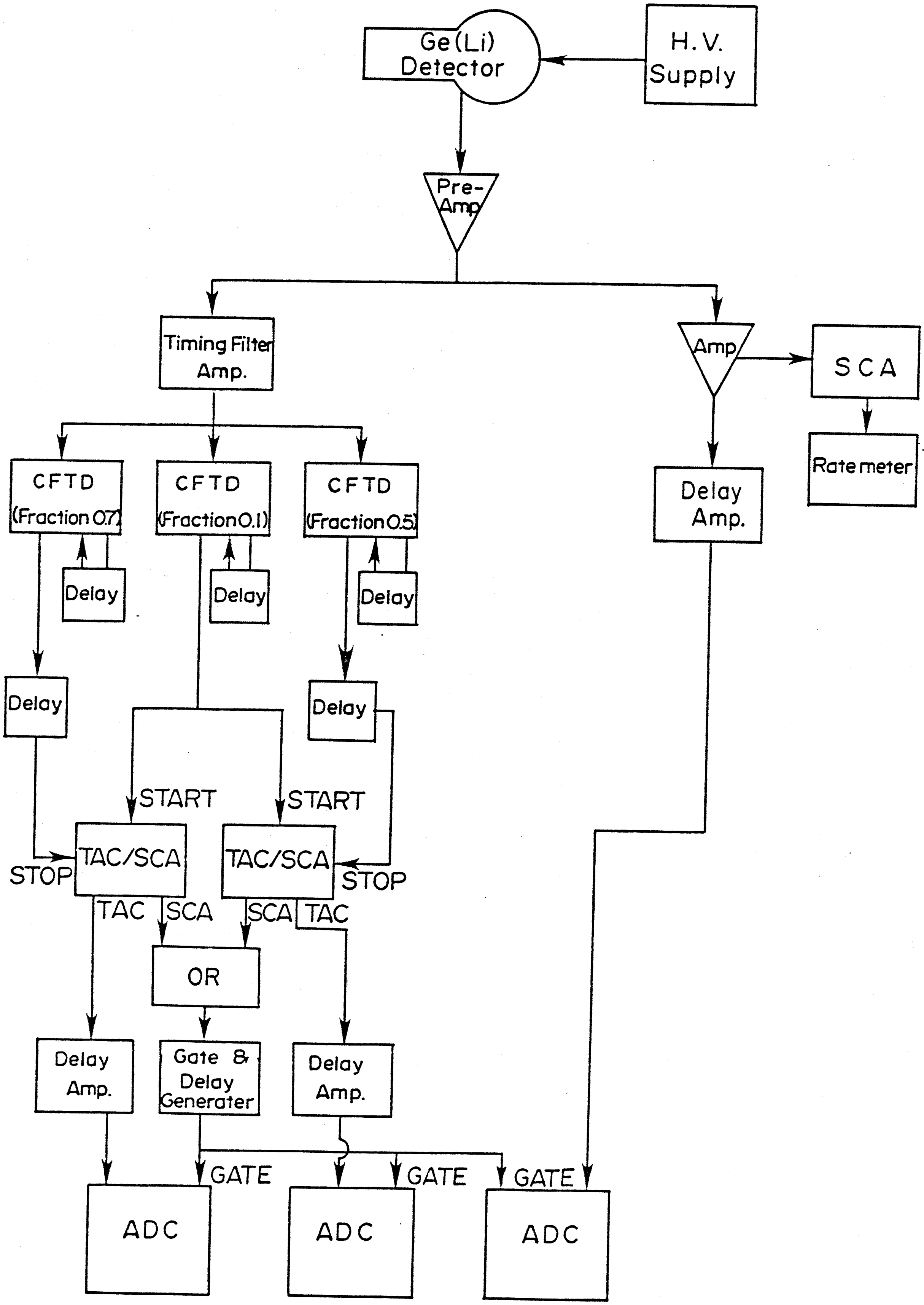

Fig. 3

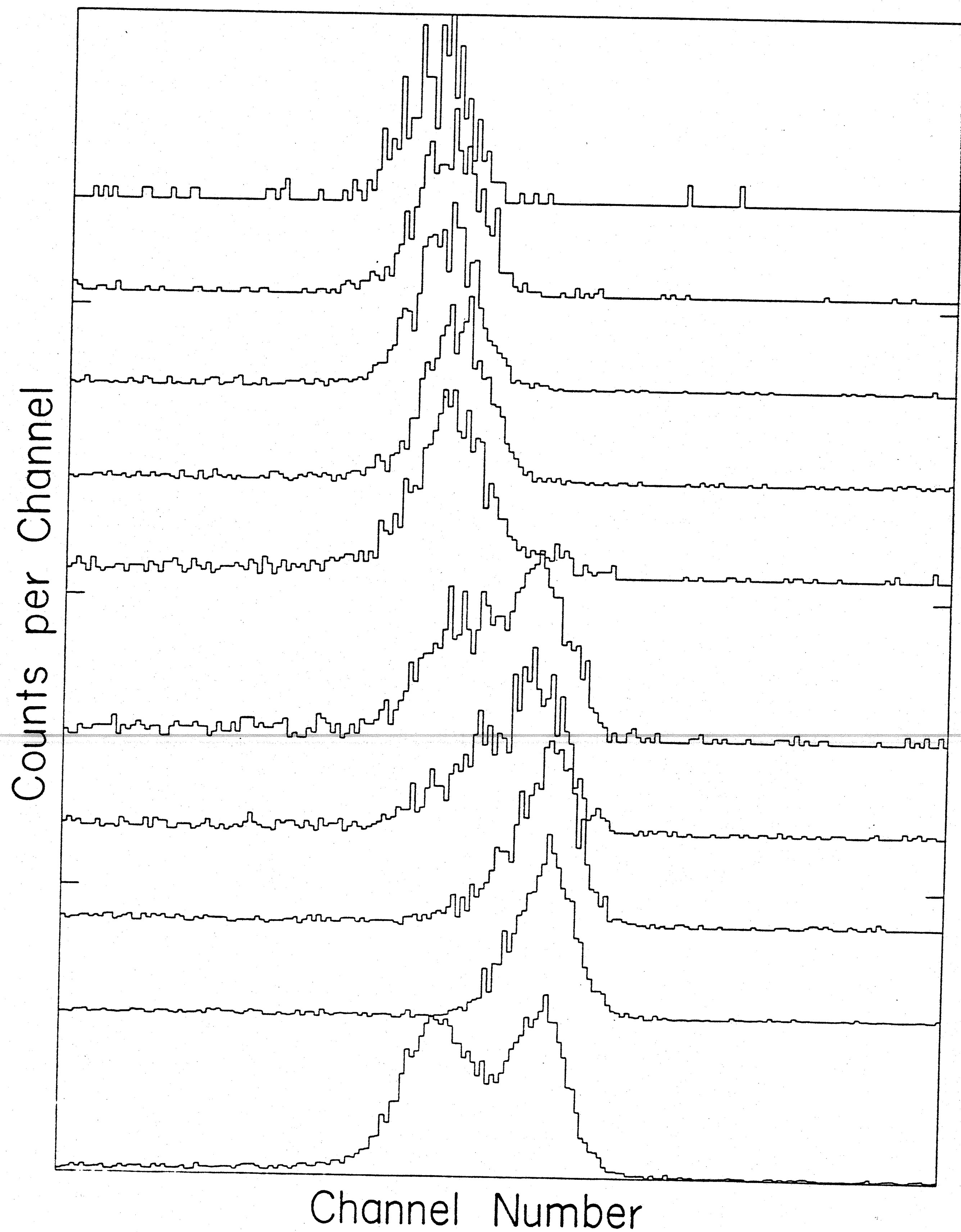

Fig. 4

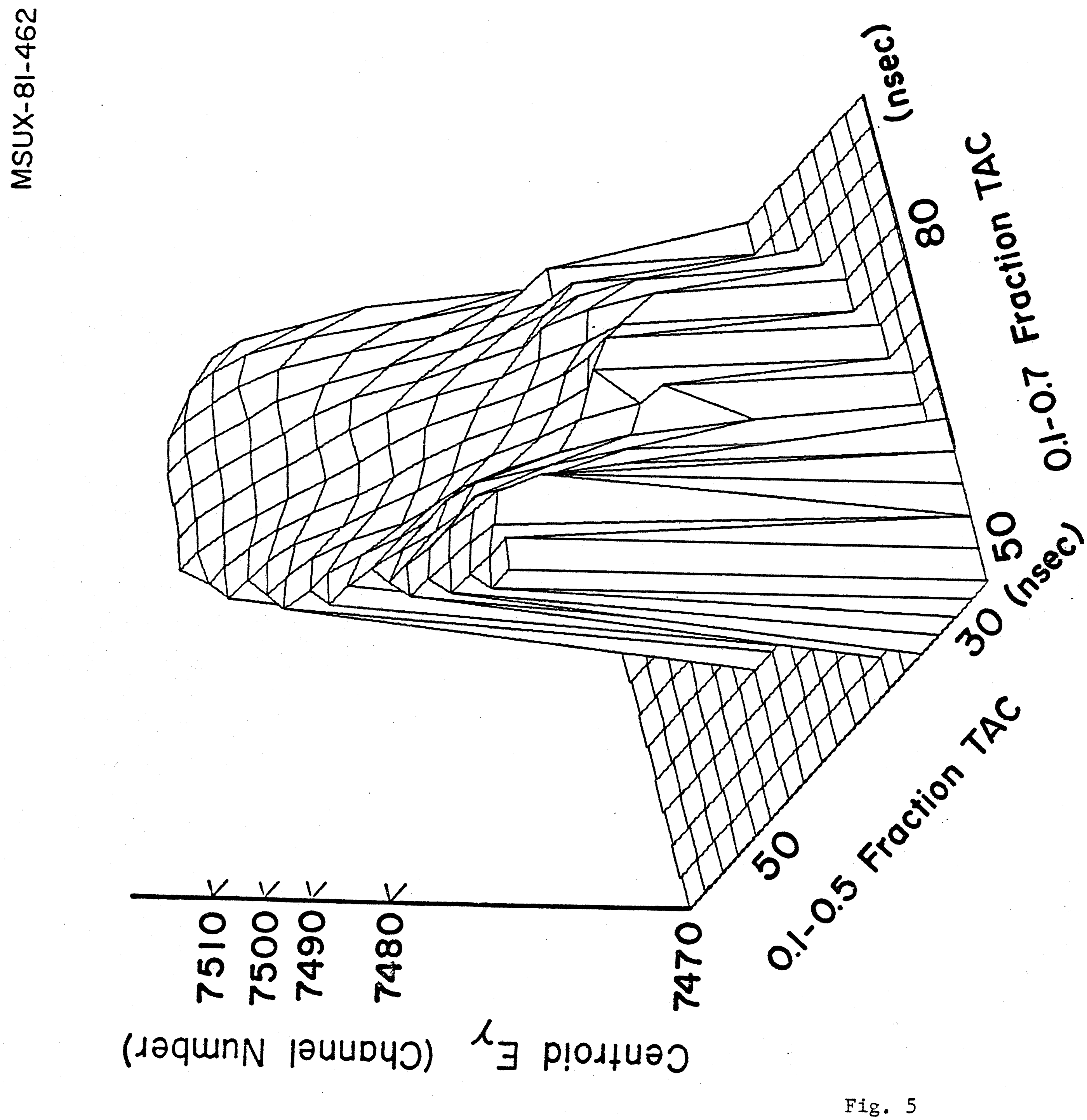
MSUX-81-462
(nsec)
80
Fraction TAC
0.1-0.7
50
30 (nsec)
50
0.1-0.5 Fraction TAC
7510
7500
7490
7480
7470
Centroid Eγ (Channel Number)

Fig. 5

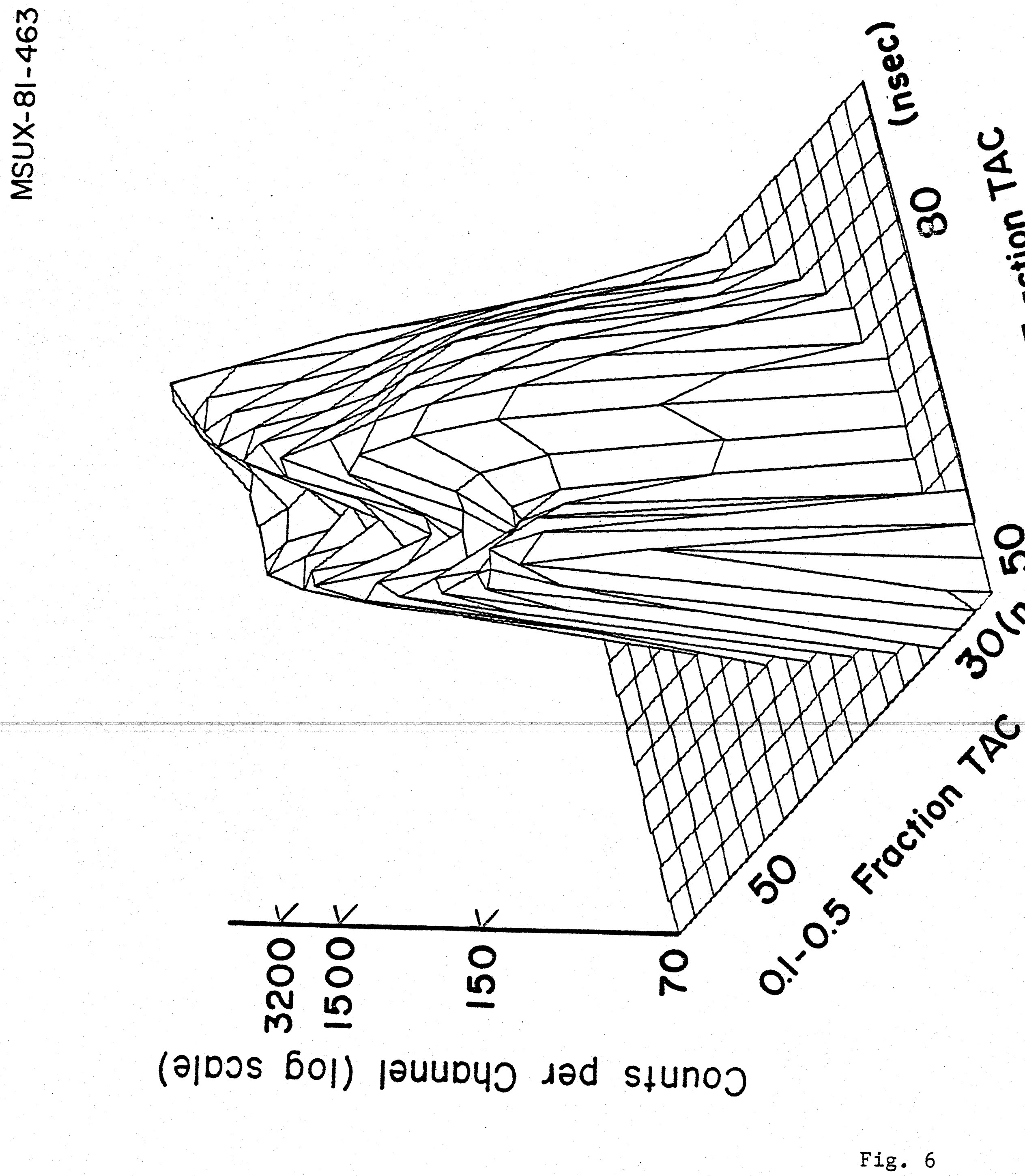
MSUX-81-463
Counts per Channel (log scale)
3200
1500
150
70
0.1-0.5 Fraction TAC
50
30 (nsec)
50
0.1-0.7 Fraction TAC
80
(nsec)

Fig. 6

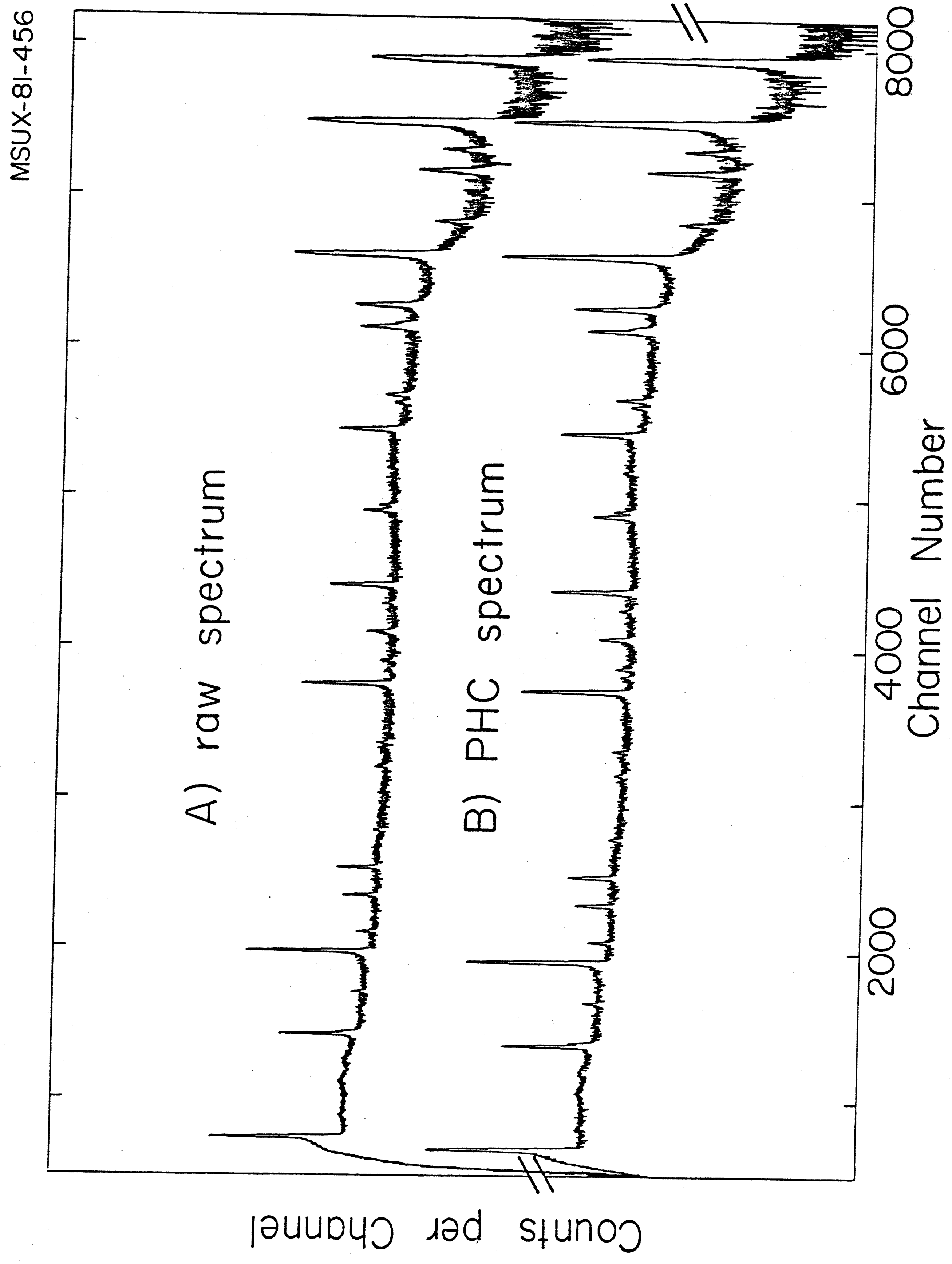
MSUX-81-456
A) raw spectrum
B) PHC spectrum
2000
4000
6000
8000
Channel Number
Counts per Channel

Fig. 7

MSUX-81-459

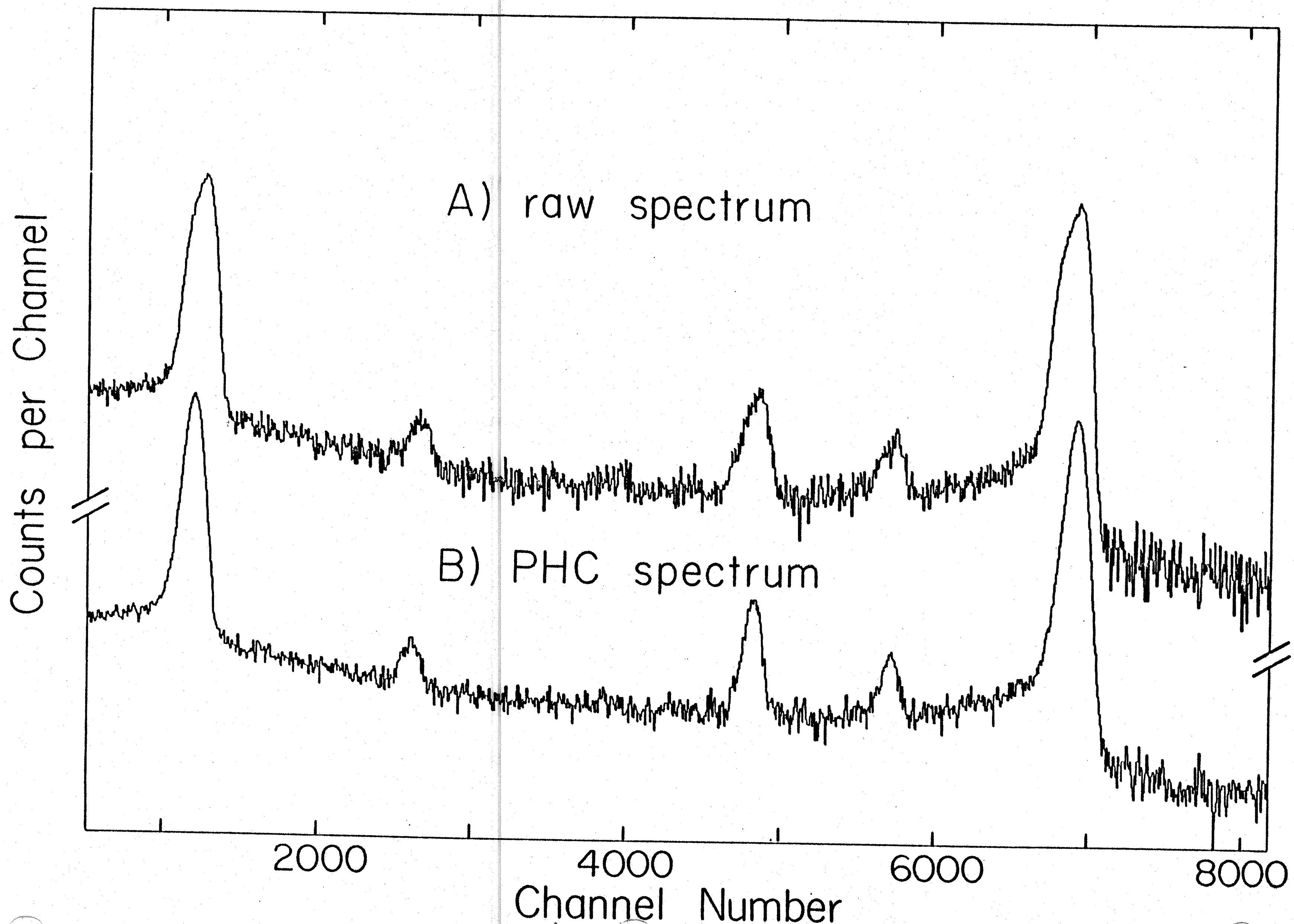

Fig. 8