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Z. G. T. Guiragossián and R. F. Schilling

High Energy Physics Laboratory

W. W. Hansen Laboratories of Physics

Stanford University

Stanford, California 94305

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Abstract

Signal shaping properties are demonstrated with a large NaI(Tl) crystal assembly, 20 in. thick and 30 in. in diameter. Correlated energy resolution responses are shown for total energy absorption in the crystal from 580 MeV electrons. Light collection optics by diffuse reflection most likely determined the 10% - to - 90% rise-time of signals of 80 nsec, connected with the transit time of trapped light, before it reaches a photocathode surface. Using a signal clipping technique, the trailing edge of pulses are shaped to have base-lines entirely restored to zero. Providing good energy resolution, signals are obtained which are shaped to have 200 nsec full-width at base. The energy resolution responses from signal pulse-height measurement are demonstrated. Further improvements to obtain shorter pulse-widths are discussed and the capability of these crystals to handle several types of background is shown.

I. Introduction

Signal shaping is required in the use of large NaI(Tl) total absorption shower counters (TASC), especially for experiments at new generation proton accelerators. The large duty cycle of these accelerators, the expected abundant low energy background and the need of detecting high energy signals free of pile-up effects are some of the reasons why it is important to remove long time constant components in the overall signal processing chain. Similarly, because of the use of other detectors with TASC spectrometer arrangements, such as multi-wire proportional chambers (MWPC), it is important to have NaI(Tl) signal recovery and gating times matching those of MWPC's. The scintillation light pulse from NaI(0.001 Tl) has a sharp rise time[1) of the order of 5 - 10 nsec, after which the light decays exponentially with two constants:[2) a decay time constant of 0.22 μsec with a coefficient of 98% and 1.35 μsec with 2% . It is shown that the energy resolution response obtained from encoding the pulse-height of TASC signals is equally good as the response derived from the integration of these pulses. These properties have made it possible so that NaI(Tl) signals are shaped to have short time widths at the processing electronics and also provide good energy resolution in the energy measurement of gamma-rays or electrons from high energy collisions. From such collisions and with shaped pulses, pulse pile-up effects in the energy pulse-height linearity relation would begin to appear at a data rate of 5 - 10 MHz, only if all of the signals have about the same pulse heights.

The expected signals in high energy physics experiments,[3] observed from large NaI(Tl)/MWPC spectrometers, have a rate of 0.5 MHz. Mostly, these are due to low energy background gamma-rays and neutrons. The high energy signals from physical processes under investigation, the triggered events in such experiments, arrive at a rate which is several orders of magnitude lower than low energy background rates. Typically, desired event signals would have pulse heights which are 10 - 200 times larger than background signal heights. Therefore, it is important to shape NaI(Tl) TASC signals so that pile-up effects are eliminated. Under these conditions, in only a small fraction of triggered events, signals would have a base-line shift which can be recognized in almost all of the cases.

II. NaI(Tl) Crystal Assembly Configuration

The signal shaping tests are made using a NaI(Tl) crystal assembly, 20 in. thick and 30 in. diameter, as shown in Fig. 1. The cylindrical assembly contains two optically coupled crystals, each 10 in. thick and 30 in. in diameter. Except at the back face of this assembly, crystal external surfaces are ground by a sanding process to remove the possibility of total internal reflection of light and MgO light diffusing reflectors are applied on these surfaces. A sheet of clear glass is used at the back face and the entire assembly is encapsulated having a front face thin window. Light is collected at the back face by twelve slow 5 in. photomultiplier tubes of the type RCA 8055. A supporting back plate with viewing ports is painted white and mounted on this are photomultiplier assemblies arranged in two concentric rings. Using 2 nsec signal cables, all photomultiplier anode pulses are mixed directly to form a common sum signal.

The above light collection optics was designed earlier to provide, as a function of particle entrance positions, as much as possible uniformity of NaI(Tl) light signal response. In this configuration light is dispersed by diffuse reflectors to make the energy measurement response mostly insensitive to particle entrance coordinates, by having only a small fraction of the observed light collected directly. Using a reflectivity figure of 97% for MgO, it is seen that several tens of traversals could occur before light reaches a photocathode surface, where each traversal has a transit time of up to 5 nsec. Therefore, slower signal rise times are expected as a result of providing uniform signal responses.

III. Signal Shaping and Energy Resolution

Signal shaping is achieved by clipping[4)] directly mixed anode pulses. As shown in Fig. 1, a 50 Ω clipping cable is used, terminated by an adjustable resistance of $R < 50\ \Omega$. For a given delay cable length, this termination is set to a value such that the base-line is restored to zero, with no undershoot on the trailing edge of pulses. In this manner a shaped signal is obtained which is the difference of a direct signal and, the attenuated and delayed shape of the same direct signal.

The Stanford University Mark III electron linear accelerator is used to provide a steady low intensity beam of 580 MeV electrons, incident at the center of the NaI(Tl) crystal assembly. Each of the 12 photomultiplier tubes is equalized in gain at slightly different individual high voltage values. At this energy, a typical high voltage setting is 1.1 kV with a spread of about 10% among individual values. TASC signals of about 200 mV are obtained directly, without the use of preamplifiers.

The rise-time property of these photomultipliers at such high voltage settings is about 25 nsec. The actual observed 10% - to - 90% rise-time of signals is 80 nsec. Most if not all of this difference can be attributed to transit time of trapped light by diffuse reflection light collection optics.

Directly mixed and shaped signals are processed by the following electronics. The signals are accepted by either a linear amplifier for pulse height measurement (ORTEC 410) or an integrating amplifier for pulse area measurement (ORTEC 451). Amplified signals are fed to a linear gate and stretcher (ORTEC 442). Above a given discriminator level, this module is sensitive to the occurrence of following pile-up signals. In these cases the stretched and amplified output is due to the initial linear pulse and the second pile-up pulse is rejected. The signal stretched output is accepted by a multi-channel pulse height analyzer ADC, under a valid gating condition. A triggering gate is provided by the signal from a 2 cm diameter beam defining counter placed in front of the crystal assembly, in coincidence with the accelerator pulse duration gate.

Oscilloscope traces of individual pulses are shown in Fig. 2. These are unclipped signals representing 12 directly mixed anode pulses. The observed signal width is 2100 nsec full-width at base. The energy resolution response from 580 MeV incident electrons is also given in this figure. Using a linear amplifier for pulse height measurement of these signals, a value of 2.35% FWHM is obtained for the energy resolution. In Fig. 3 the insert shows an oscilloscope trace representing signals which are shaped and have base-line restored to zero by the clipping technique. A 64 nsec clipping cable is used to prcduce shaped signals of 360 nsec full-width at base. There is no significant difference in energy resolution and a value of 2.4% FWHM is obtained. It should be remarked that the energy resolution is 2.2% FWHM when a similar spectrum is derived, using pulse area measurement of shaped signals. In this case signals are processed by an integrating amplifier. In Fig. 4 the inserted oscilloscope trace demonstrates that a shaped signal of 210 nsec full-width at base is achieved, using a 24 nsec clipping cable. A good and only slightly degraded energy resolution response is obtained with a value of 3.10% FWHM for pulse height measurements of shaped signals made with a linear amplifier.

Any further reduction in shaped signal pulse-width, sharply degrades the energy resolution response due to the fact that signal pulse-heights are reduced and fewer photo-electrons are sampled. This effect is demonstrated in Fig. 5. In Fig. 5 (a) a measured correlation is displayed showing that the pulse-height of shaped signals is reduced linearly as function of the pulse-width at base values of these signals. In Fig. 5 (b) the corresponding measured energy resolution response is given also as function of pulse-width at base values of shaped signals. Thus, to obtain good energy resolution responses it is required that shaped signals have a pulse-width at base value of not less than 2.5 t, where t is the actual 10% - to - 90% rise-time of unclipped signals.

At new generation proton accelerators, the energy of incident particles on such a detector is higher by 2 or 3 orders of magnitude than the energy of electrons used for this study. Correspondingly, the high energy gamma-ray or electron induced signals have larger pulse-heights so that sensitivity to photo-electron statistics as seen in Fig. 5 becomes less important. Thus, even with the present light collection geometry, pulse widths of less than 2.5 t could provide good energy resolution in these applications.

IV. Improvements and Background Signals

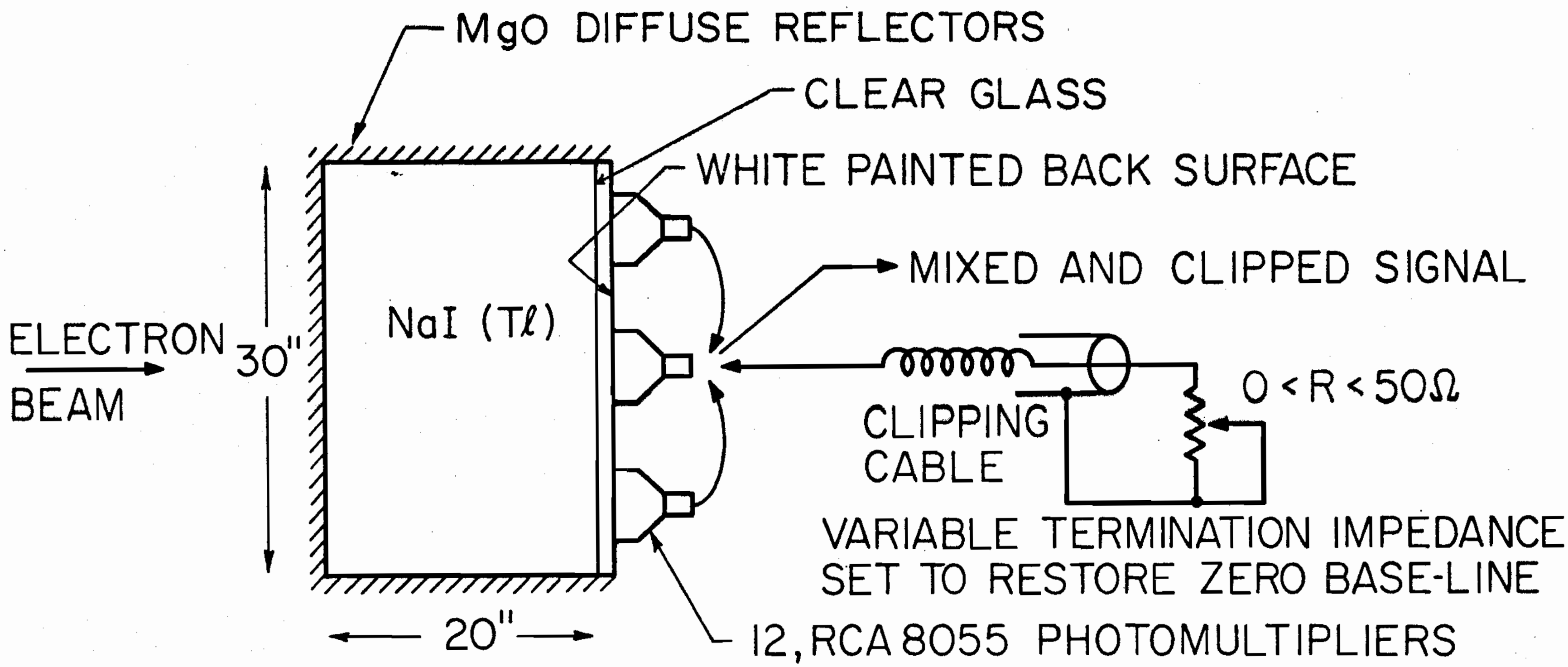
Further improvements can be made to obtain smaller signal pulse-widths which also provide good energy resolution. However, this requires, modification of the light collection optics where total transit time of trapped light is reduced, and use of faster photomultipliers in a different configuration. A study in this direction is in progress, based on the use of an extensive Monte Carlo program[5)] which will simulate several different configurations. The aim is to match the available fast NaI(Tl) signal rise-time with the best energy resolution and also with a uniform energy response as function of spatial coordinates of incident particles.

The viewing of only direct NaI(Tl) TASC light produces a large spread in the energy resolution response because in this case the light collection efficiency factor becomes geometrically variable. This variation is due to fluctuating amounts in the ratio of direct to indirect light, caused by longitudinal fluctuations in the maxima of energy deposition during electromagnetic shower developments. Thus, the principle for fast light collection with good energy resolution is mostly based on total internal reflection optics, instead of the present diffuse reflection optics. In this case, a major part of the light reaches photocathode surface indirectly, by total internal reflection off of smoothly polished crystal surfaces. Because of fewer light reflections much shorter total light transit times are achieved, resulting in sharper signal rise time and narrower shaped signal widths. A possible smooth variation in TASC signal response, as a function of particle entrance position, can be compensated by available information of space coordinates from associated multi-wire proportional chambers which are part of the spectrometer system.[3] After a calibration with high energy electron beams, such a response function is mapped and stored in an on-line computer.

The above need of achieving narrower shaped pulse-widths is connected with the capability of handling higher background rates in a given experimental arrangement. With beams of energies at the scale of 200 - 300 GeV, typically 1 - 5 GeV gamma-rays and neutrons are the experimental background, at production angles of 50 - 200 mrad. Desired triggered events are expected to produce TASC signals which are 10 - 200 times larger than background signals. So that, with these detectors instead of pile-up, the condition of zero base-line shift occurs in a small fraction of triggered events. Other limiting saturation effects[6] are prevented by the use of a properly designed voltage divider network for photomultipliers.

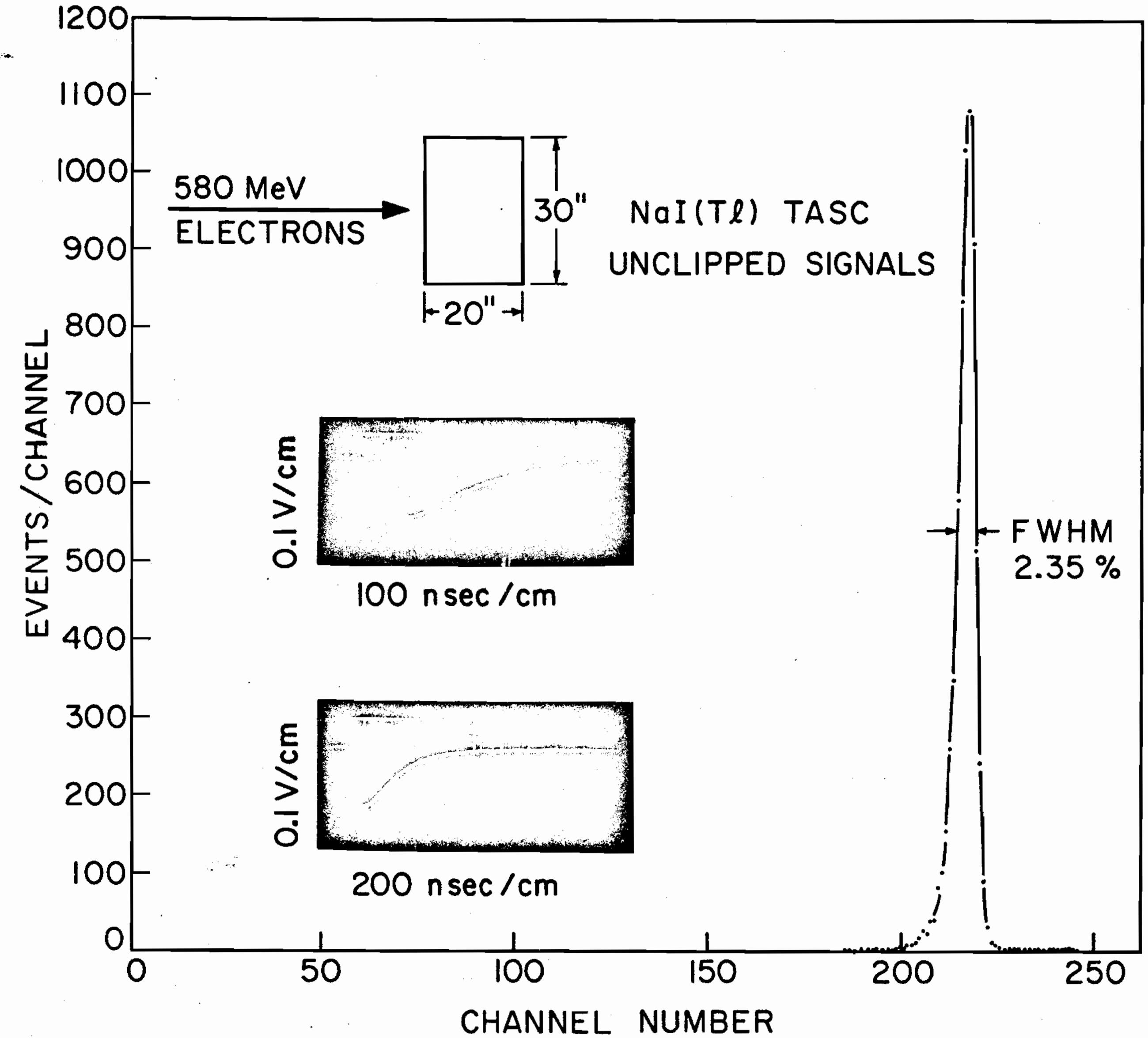
Thus a NaI(Tl) TASC with signals shaped to have 200 nsec full-width at base, as is shown here, provides good energy resolution and can handle a background rate of 5×10^5/sec. In this case, 10% of valid events have a zero base-line shift which is a recognizable condition almost 100% of the time, by the use of associated plastic scintillators.

The authors wish to thank Professor R. Hofstadter for his encouraging guidance, constant interest and several illuminating discussions. One of us (Z.G.T.G.) is pleased to acknowledge stimulating discussions with Professors V. L. Fitch and O. E. Chamberlain indicating the need of this study for high energy physics experiments.



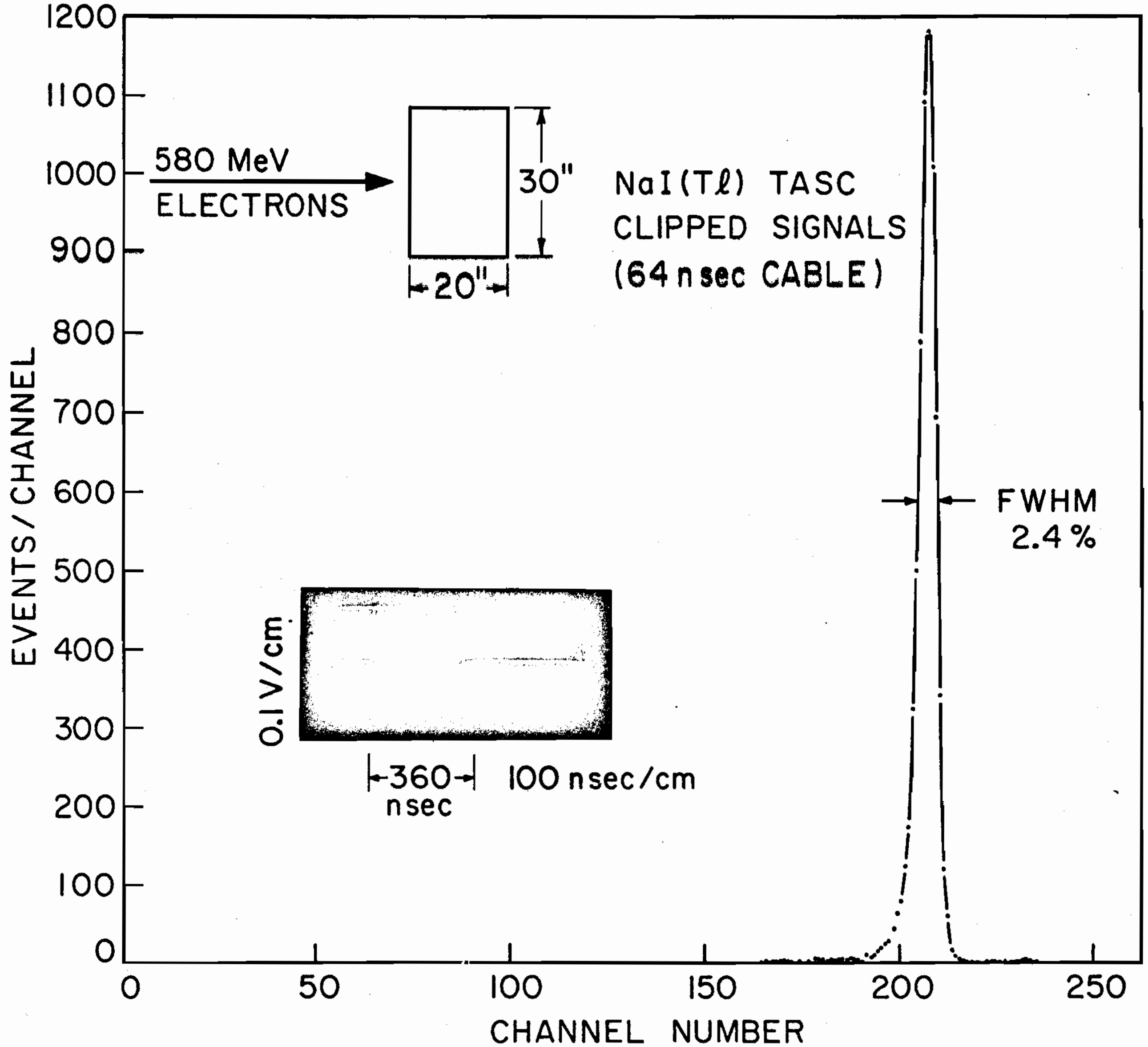
NaI (Tℓ) LIGHT COLLECTION BY DIFFUSE REFLECTION

Figure 1



1200
1100
1000
900
800
700
600
500
400
300
200
100
0
EVENTS/CHANNEL
580 MeV
ELECTRONS
30"
20"
NaI(Tℓ) TASC
UNCLIPPED SIGNALS
0.1 V/cm
100 nsec/cm
0.1 V/cm
200 nsec/cm
FWHM
2.35 %
0
50
100
150
200
250
CHANNEL NUMBER

Figure 2



580 MeV
ELECTRONS
30"
20"
NaI(Tℓ) TASC
CLIPPED SIGNALS
(64 nsec CABLE)
FWHM
2.4 %
0.1 V/cm
360
nsec
100 nsec/cm
EVENTS / CHANNEL
CHANNEL NUMBER
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
0
50
100
150
200
250

Figure 3

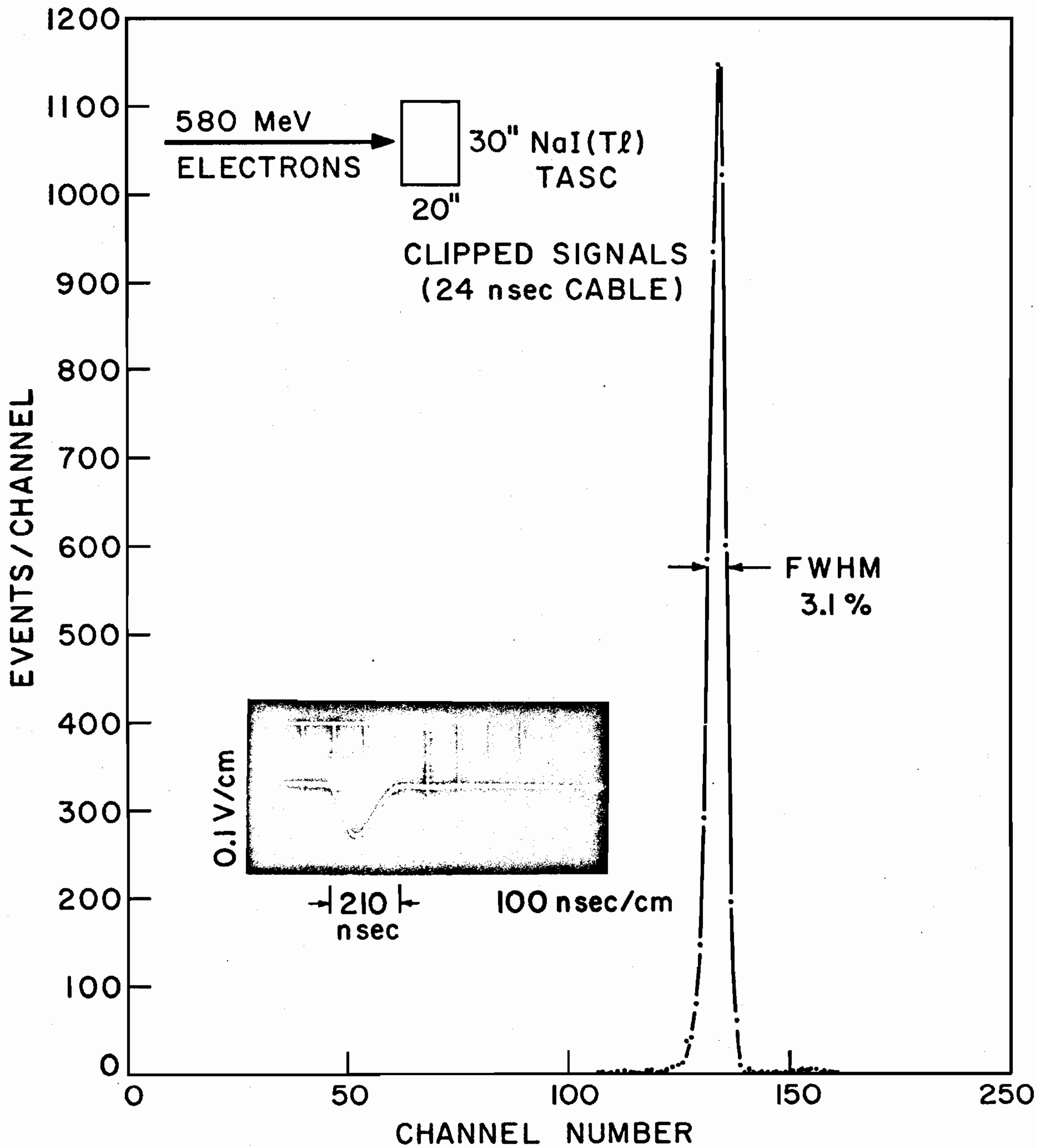

1200
1100
1000
900
800
700
600
500
400
300
200
100
0
EVENTS / CHANNEL
580 MeV
ELECTRONS
30" NaI(Tℓ)
TASC
20"
CLIPPED SIGNALS
(24 nsec CABLE)
FWHM
3.1 %
0.1 V/cm
210
nsec
100 nsec/cm
0
50
100
150
250
CHANNEL NUMBER

Figure 4

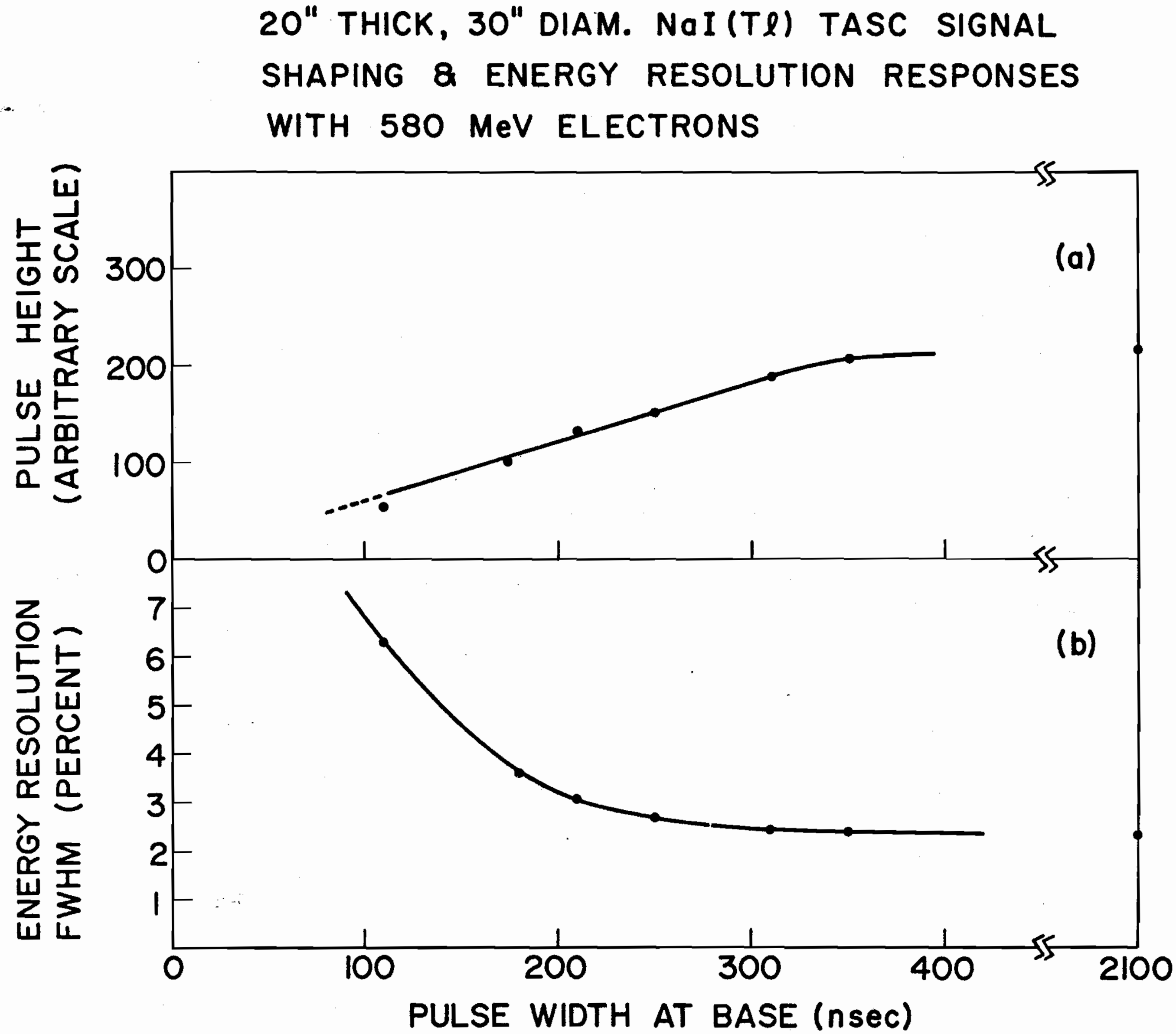

20" THICK, 30" DIAM. NaI(Tℓ) TASC SIGNAL
SHAPING & ENERGY RESOLUTION RESPONSES
WITH 580 MeV ELECTRONS
PULSE HEIGHT
(ARBITRARY SCALE)
300
200
100
0
(a)
ENERGY RESOLUTION
FWHM (PERCENT)
7
6
5
4
3
2
1
(b)
0
100
200
300
400
2100
PULSE WIDTH AT BASE (nsec)

Figure 5

References

* Work supported by the National Science Foundation, Grant No. GP-28299.

1) Confirmed in observation of signals from a NaI(Tl) crystal of 4 in.× 4 in.× 10 in. dimensions, encapsulated with clear glass windows and viewed by a pair of 58 AVP photomultiplier tubes; J. F. Crawford (Stanford University) private communication.

2) J. B. Birks, The Theory and Practice of Scintillation Counting, Pergammon Press, 1964; L. M. Bollinger and G. E. Thomas, Rev. Sci. Instr. 32, 1044 (1961); L. E. Peterson (University of California, San Diego) private communication.

3) Z. G. T. Guiragossián, R. Hofstadter, R. F. Schilling, M. R. Yearian, E. V. Hungerford III, G. S. Mutchler, G. C. Phillips and B. W. Mayes, NAL Proposal No. 192 and No. 193 (1972).

4) C. Brassard, Nucl. Instr. and Meth. 94, 301 (1971).

5) An IBM 360/91 program developed by J. F. Crawford (Stanford University) for this study.

6) Limiting saturation effects could occur internally within the photomultiplier tube structure. Space charge limitation could cause non-linearity in gain. With a properly designed voltage divider network, the gain and standing current can be set to maintain the average internal currents which are expected under actual experimental conditions. In a given experiment, the level of these internal currents is defined by the anticipated average energy deposition expected in the crystals. The clipping of anode pulses has no effect on such a limitation because these currents are being dissipated in the terminating resistor.