5 Electronics

5.1 Introduction

At the heart of the single photon counting instrument lies the time-to-amplitude converter, usually referred to as the TAC. This device achieves the time correlation between excitation and emission events that is the basis of the SPC experiment. It is common to measure this time difference in a commercial TAC NIM standard unit. In fact the electronic modules in most SPC instruments consist of little more than the basic TAC with, usually, one or two discriminators for noise reduction, and electronic delay lines for correct pulse synchronization. For data storing it is customary to have a pulse height multichannel analyzer (MCA) incorporating an analogue-to-digital converter and memory stores. Data analysis in a computer is now probably universal.

Other components may also be used if more sophisticated pulse processing is employed. Frequently the pulses from low gain PM tubes must be amplified, in which case an amplifier or preamplifier will be necessary. Dual discriminators, linear gates, single channel analysers, timing filter amplifiers, clock modules and many other components have been used in extensions or modifications of the basic experiment. Needless to say, the more components that are used the more difficulties are likely to be encountered in setting up the experiment. In this chapter we shall do little more than describe in some detail the basic equipment and give references to more complicated instruments.

5.2 Individual Electronic Components

5.2.1 NIM Bin

Most electronic components used in SPC equipment are standard Nuclear Instrument Modules (NIMs) and take their voltage, through a connection on the rear panel, from a NIM power supply which is normally incorporated in a mounting crate with a certain number of sockets (usually 12). The power supply and crate are called a NIM Bin. Sockets at each module position always provide four voltages, ± 12 V d.c. and ± 24 V d.c. In addition

± 6 V d.c. lines are usually wired but may have to be connected to a source external to the Bin. Since some modules do require either + or -6 V d.c. power a NIM Bin/Power Supply with ± 6 V d.c. direct wired is preferred. If a new NIM unit (particularly a discriminator) does not function correctly the NIM Bin should first be checked for the ± 6 V d.c. lines.

NIM Bins are not subject to many faults and do not require much attention. Occasionally, a Bin from one manufacturer may become overloaded if modules from different manufacturers are mounted in it. Test points are usually provided on the front panel of the Bin so that each power supply voltage level can be checked when all the modules are in place. Perhaps the only other serious fault associated with NIM Bins is overheating arising from the close proximity of modules in the crate. If the crate is mounted in a rack on which vacuum tube equipment is also mounted overheating may be a serious problem. Even without this extra heat source the modules themselves can generate enough heat to cause damage to resistors or capacitors. More commonly, intermittent malfunctioning of some component occurs; it can sometimes be corrected by placing the module in the Bin in a position with an unoccupied module position on each side.

Many manufacturers of electronic equipment supply NIM Bin/Power Supplies. The most popular manufacture is probably ORTEC Inc. but the components are also available from Canberra Industries, Inc., and from Nuclear Enterprises Ltd. Addresses for these companies can be found in Appendix 5.A1.

5.2.2 Discriminators

The output from the fluorescence photomultiplier consists of a broad distribution of pulse heights, some pulses being generated by dark noise, some by single photon events and others by multiple photon events. It is essential to route these pulses through a discriminator in order to improve the signal-to-noise ratio and to furnish the TAC with constant amplitude pulses that are independent of the PM pulse shapes. However, since photomultiplier pulses of different amplitudes will not cross a discriminator level at the same time, leading edge discrimination is not recommended for the fluorescence PM pulses. On the other hand, leading edge discriminators usually have less internal jitter than discriminators involving more complicated circuitry (Nemzek, 1975); they are therefore quite suitable for pulses with very little amplitude jitter, such as the trigger signals for the excitation pulse. Discrimination for the single photon pulses is usually of the constant fraction timing or snap-off timing variety.

Trigger pulses for the pump pulse are usually derived from a photomultiplier, photodiode, antenna or from a logic circuit in the pulsing electronics.

Logic pulses are generated with very little noise and are sometimes routed, without discrimination direct to the TAC. Many TACs however, accept only negative-going pulses so that the trigger pulses may have to be inverted. Feed-through inverting transformers of the BNC type are useful for this purpose. Elimination of the trigger channel discriminator, while removing one source of time jitter in the instrument, is not recommended for signals from photomultipliers, photodiodes or antennae which may have a significant noise component. Leading edge discriminators for this channel are available from many manufacturers and are sometimes called FAST or 100 MHz discriminators. They accept negative pulses of *c.* 20 mV amplitude and usually have the input connector terminated internally in 50 Ω. Output pulses from this discriminator should of course be compatible with the input pulse requirements of the TAC.

As Fig. 5.1 illustrates, the broad distribution of pulse heights in the PM signals can give rise to errors when timing is performed with a simple, leading edge discriminator. Pulses A and B may have their source in photons emitted the same time after excitation but are seen to cross the discriminator level at different times. This jitter with leading edge timing has been verified by Kinoshita *et al.* (1981). However, level timing goes some way towards correcting the timing error resulting from leading edge discrimination. In this type of discriminator, sometimes called a differential discriminator, timing is from a low voltage level where the time difference between pulses of different amplitudes is fairly small (see Fig. 5.1) but noise is excluded by timing only those pulses that cross an upper discriminator level $-(V_2 + \Delta V)$. A rather

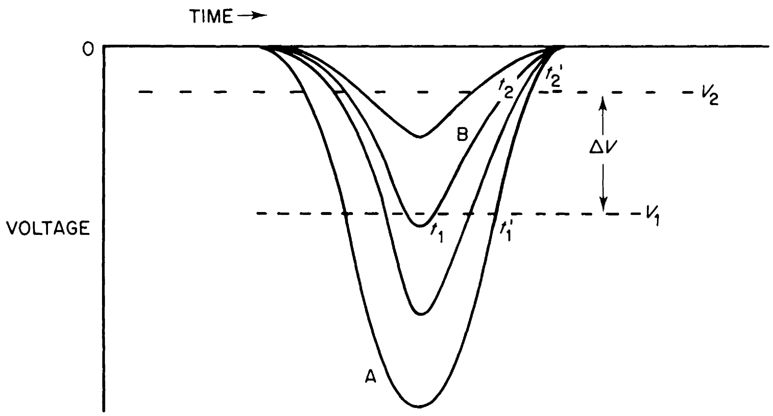

Figure 5.1 Schematic representation of timing errors associated with variable pulse amplitudes and leading edge discrimination. A, B, different amplitude pulses having the same time origin; $t_1 - t_1^1 = \Delta t_1$, timing error at high discriminator level, $-V_1$; $t_2 - t_2^1 = \Delta t_2$, smaller timing error at lower discriminator level, $-V_2$.

elaborate extension of this principle is described by Wild *et al.* (1977), who split the PM pulse into two channels, routing one channel to a leading edge discriminator and the other to a differential discriminator. Only pulses with amplitudes falling within a narrow range (set on the differential discriminator) are accepted and are timed at a low discriminator level by the leading edge discriminator. Although the jitter associated with this procedure is quite low the pulse rejection in the differential discriminator is probably so severe that the method can be used only for experiments in which the fluorescence count rate is extremely hgih.

In order to eliminate the timing errors occurring even in differential discriminators, discriminating with constant fraction timing is usually applied to the single photon pulses. As the name implies, with this type of discriminator the pulses are timed from a point on the leading edge that is a fixed fraction of the pulse height. For pulses of similar shape but varying amplitudes this timing point is constant. Figure 5.2 illustrates the way in which the constant fraction timing is achieved (Gedcke and McDonald, 1967, 1968). Suppose the input pulse has amplitude V_a and is to be timed at an amplitude fV_a on the leading edge. In the discriminator the output of the input buffer is fed through two paths, in one of which the pulse is delayed by an amount δ and inverted [Fig. 5.2(a)], while in the other the undelayed pulse is attenuated to a maximum amplitude fV_a. [Fig. 5.2(b)]. Both signals are then added to form the zero crossing signal [Fig. 5.2(c)]. Only pulses with amplitudes greater than a given threshold, set on the front panel, are timed.

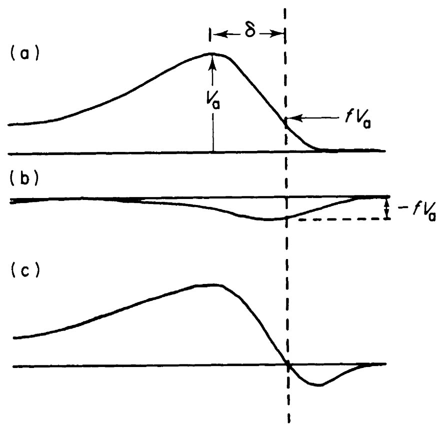

Figure 5.2 Schematic representation of constant fraction timing discrimination. Timing is from a position on the leading edge that is always a fixed fraction f of the input pulse height. Input pulse not shown. (a) Input pulse (amplitude $-V_a$) inverted and delayed by time δ. (b) Undelayed input pulse attenuated to maximum amplitude $-fV_a$. (c) Zero-crossing pulse (sum of (a) and (b)).

In Section 5.3 the setting of this threshold will be discussed. The most recent constant fraction timing discriminators (Bedwell and Paulus, 1976) seem to have much less internal jitter than earlier models and are therefore recommended. For example, Leskovar *et al.* (1976) developed a modified CFTD having a measured timing walk of only 35 ps. Commercially available components are now capable of equally good time resolution. Recently the ORTEC company has introduced a Model 934 Quad discriminator which includes four separate constant fraction discriminators in one NIM module. The Model 583 also incorporates an upper level discriminator and would appear to have excellent timing precision (Yamazaki *et al.*, 1982). It can be used for both the trigger and the fluorescence channels of the SPC instrument. Its main disadvantage is that it requires LEMO rather than BNC connectors, but as BNC to LEMO adapters are readily available this discriminator has become quite popular because of its good jitter characteristics and compactness. Simpler CFTD discriminators are also available from ORTEC Ltd and also from CANBERRA Ltd.

Instead of the CFTD discriminator a snap-off timing discriminator can be employed (Arbel *et al.*, 1974). This type, which is incorporated in one commercial SPC apparatus (Photochemical Research Associates), is available from the Elscint company.

5.2.3 Amplifiers

Amplifiers in SPC electronic arrangements are most commonly incorporated in three places, as illustrated in Fig. 5.3. With reference to the notation in this figure, A1, a preamplifier, may be essential if PM or trigger pulses are not of sufficient amplitude to trigger the discriminator. A2 is a timing-filter amplifier (TFA). It was once believed that the TFA, while improving signal-to-noise ratios, served as a filter for radio frequency interference (Lewis *et al.*, 1973). A3 is a bias amplifier (BA), and may be useful in the selection of the correct timescale. Otherwise it is not essential.

If possible, gain in the single photon pulses should be achieved in the PM, since the preamplifier (A1) may act as an antenna for r.f. interference. By introducing an additional time jitter it may also decrease the overall time

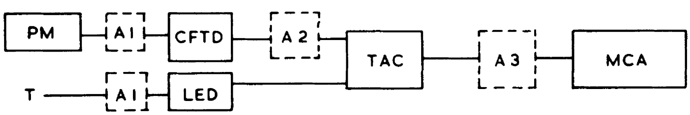

Figure 5.3 Position of amplifiers in SPC electronics. A1, A2, A3, amplifiers; T, excitation trigger. For other symbols, see Fig. 2.1.

resolution of the instrument, as Koester and Dowben (1978) have reported. It is also well established that the gross signal-to-noise ratio is improved if the amplification can be achieved in the photomultiplier (Kingston, 1978). However, when the current multiplication in the PM is small it is usually coupled to a preamplifier, which should have a fast rise time and an output pulse compatible with the input requirements of the discriminator. It should also be positioned as close to the PM tube as possible in order to minimize r.f. pick-up. A NIM module may not be suitable in this regard. A small preamplifier, which can be attached without support direct to a PM housing (if necessary through a plug-to-plug BNC adapter), is marketed by ORTEC Inc. (Lyke and Ware, 1977). This type of preamplifier usually derives its power from a NIM Bin Power Supply via some intermediate module (e.g., a Spectroscopy Amplifier), but the modification for direct wiring to the mains is easy to carry out. An advantage of this component is that it is easy to screen electrically. Excellent timing performance has been achieved with the Hewlett Packard Model HP 8447D 1 GHz preamplifier, which has outclassed the Ortec preamplifier when coupled to a microchannel plate PM tube (Yamazaki *et al.*, 1982). Another useful amplifier, available from Marconi Inc. (Robbins *et al.*, 1980), is powered without modification direct from the mains supply and is reported to have virtually insignificant time jitter and to improve instrument performance through correct pulse shaping. We have used this amplifier on the output pulses of an XP2020 Q photomultiplier and observed an improvement in performance of the instrument. However it should be recognized that spurious r.f. signals will also be amplified with such a system, and particular care must therefore be taken with screening when using a preamplifier. Our advice is that unless it is definitely necessary for pulse amplification a preamplifier may be more of a disadvantage than a benefit. The same remarks do not apply to the trigger side of the electronics where the discriminators threshold can be set high enough to exclude any r.f. noise picked up in the amplifier. Amplification of the trigger pulses is usually not necessary. Nor is there a need to amplify the output pulses from the single photon discriminator with a timing filter amplifier (TFA). It is an expensive and uncertain means of attenuating r.f. signals and can be difficult to adjust. Furthermore, there appears to be an advantage as regards r.f. suppression if gain is accomplished in the PM tube rather than in the electronics (Lyke and O'Connor, 1977), contrary to the belief of Lewis *et al.* (1973). When assembling a new SPC instrument, therefore, we would suggest that the added expense of purchasing a TFA is of doubtful value. As far as we know only one of three commercially available instruments incorporates this component (Applied Photophysics Ltd). In passing we should point out that the TFA can also be used on the PM side of the discriminator, where it serves as a preamplifier (Haugen *et al.*, 1979).

Although the correct placement of the decay curve in the analyser channels can be achieved by means of variable delay lines, a biased amplifier (BA) greatly facilities this operation and also provides in effect an increase in the number of time ranges available in the TAC. The mode of operation of this device will be described in conjunction with the details of the TAC.

Note: Some commercial manufacturers market photomultiplier tube bases that incorporate a preamplifier or a constant fraction timing discriminator. The latter is a very attractive feature, eliminating the cable connection between PM and discriminator, which may be an antenna for r.f. interference. However, we are aware of no reports of their use in a laboratory SPC instrument and are reluctant to make further comments beyond stating that this close coupling of preamplifier or discriminator to the PM anode will probably be a standard feature of future SPC instruments. At present these bases do not accommodate adjustments of the interdynode voltage divider and require some more development.

5.2.4 Delay lines

A variable delay line is an essential feature of every SPC instrument; it serves as a means of triggering the TAC MCA combination is such a way as to achieve optimum placement of the decay curve in the MCA channels. In addition, if the TAC is operated in "reverse" mode it is preferable to STOP the voltage sweep with a trigger pulse corresponding to the excitation cycle in which the signal that STARTED the sweep occurred (see Section 2.2.6). This synchronization of STOP and START pulses is best achieved by means of a variable delay line. Furthermore, coaxial cable delays have been reported to act as high frequency cut-off filters and to reduce the oscillations arising from r.f. pick-up in the photomultiplier (Lewis *et al.*, 1973). Our experience, on the contrary, inclines us to the opinion that long lengths of cable furnish rather effective antennae for r.f. signals.

Calibrated variable delays are available in NIM single-width modules from a number of manufacturers. They fit conveniently into standard NIM Bins, but because they usually consist merely of lengths of coaxial cable they require no power. In these modules the maximum delay attainable is about 70 ns and can be reached in 1 ns or 0.5 ns steps. Longer delays require a bigger housing but, if no power is required, the large housing should not be inconvenient. Accuracy in commercial delay boxes is quoted at ± 100 ps for each delay section, so that if such delays are used to calibrate the TAC–MCA combination an independent measurement of the delay should first be made.

Home-built delay lines should be made from 50 Ω coaxial cable, e.g. RG-58C/U, and very careful soldering or crimping carried out. BNC bulkhead connectors can serve to carry the signals into the delay lines which must be housed in an r.f. tight metal box. BNC connectors are open to criticism as regards poor r.f. filtering, earthing continuity and transmission of high frequency signals (Lytle, 1974), but since most of the NIM modules accept only BNC connectors there is little to be gained by using a different type on the delay line housing. Lengths of cable yielding delays of say 10, 25, 50, 100 and 200 ns, measured on the approximation that signals travel at 30 cm per ns, can be housed in a box that could be accommodated in a conventional NIM Bin rack.

All delay lines, whether home-built or commercial, should be checked for pulse reflections since multiple pulsing, which can seriously distort the collected data, sometimes results from impedance mismatches and faulty solder joints at connectors. We emphasize that r.f. tight housings are essential for delay cables since, although serving as attenuators for r.f. picked up in the PM, the coaxial cable is itself an antenna. As an added precaution the delay line should be placed between the PM or trigger pulse source and the discriminator, so that further r.f. suppression may be achieved.

When the required delay is too long for a convenient length of coaxial cable certain types of pulse generator can perform the same function (Haugen *et al.*, 1979).

5.2.5 The TAC

5.2.5(a) Function

In this instrument the time correlation between excitation and emission events is carried out as depicted in Fig. 5.4. Upon receipt of a START signal,

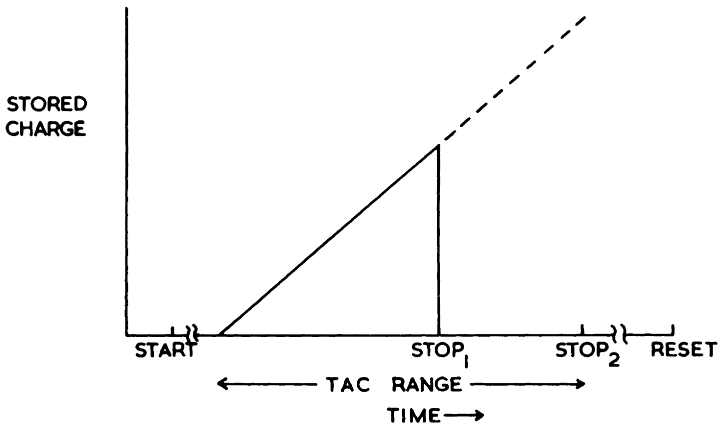

Figure 5.4 Schematic representation of TAC operation.

and after a certain fixed delay, a timing capacitor is charged linearly from a constant current source. The charging is discontinued ($STOP_1$) upon acceptance of a STOP pulse and an output pulse is generated with an amplitude derived from the final charge in the capacitor. Therefore the output pulse height is proportional to the time difference between START and STOP pulses. If no STOP pulse is received after a time called the TAC range, charging is automatically discontinued ($STOP_2$). Again a fixed time elapses before the capacitor is RESET, at which time the instrument is ready for another START pulse.

TAC ranges, usually from 50 ns to 80 μs, are switch selectable on the front panel. Hence if a range of 100 ns is selected the maximum output pulse amplitude, generally 10 V, corresponds to a 100 ns time difference between START and STOP signals.

In addition to the START and STOP inputs and the output (called the CONVERSION output) a standard TAC unit will generally possess a second CONVERSION, a TRUE START output, GATE and STROBE inputs and an INTERNAL STROBE facility. The TRUE START output can be used to monitor the number of signals that actually start the voltage ramp. A more useful monitor is that of the number of START signals converted to output signals (measured at one of the CONVERSION outputs) since this number can be taken as the number of "detected" photons and is adjusted to achieve single photon conditions (see Section 2.2.1). The GATE input in conjunction with the EXTERNAL STROBE is sometimes made use of to block TAC conversions that cannot be processed by the analogue-to-digital converter. In addition, pulses can be furnished through the EXTERNAL STROBE input to inhibit a converted output under certain conditions, e.g., when a multiple photon event has been detected. There may also be a BUSY output, from which pulses can be routed to other electronic equipment, for example, the repetition rate driver of the excitation source.

As discussed in Section 2.2.6, the TAC may be operated either in the conventional or the "inverted" configuration. If, as in most simple instruments, none of the additional options are chosen, the GATE is set at ANTICOINCIDENCE with no GATE input signal, the BUSY output is not used, and the STROBE option is set at INTERNAL. On some modules it is advised to terminate unused output connectors in 50 Ω. The relative advantages of conventional and inverted configurations have been thoroughly investigated by Haugen *et al.* (1979). They show that if the experiment is carried out under single photon conditions, the conventional configuration should not be used above START rates of *c.* 150 kHz. At higher repetition rates the "inverted" mode is necessary, and should possibly be used also at low repetition rates since it will always lead to some reduction in data acquisition times. However, in instruments that incorporate a pulse pile-up inspector the inverted mode of operation is not suitable (Haugen *et al.*, 1979). We have already stated that when operating the TAC in the "inverted" mode correct synchronization of START and STOP signals is advisable (Section 5.2.4). This synchronization is achieved by varying the delay between the START and STOP signals until the position of the curve in the MCA channels is independent of the excitation pulse repetition rate.

Perhaps the most serious source of distortion in the TAC is non-linearity associated with the sweep of the voltage ramp. Since the non-linearity is most severe at times corresponding to small charges on the capacitor the distorted decay curve is likely to show spurious oscillation in low-numbered MCA channels. Every TAC should be checked for differential non-linearity, if possible before purchase. One simple check entails the processing of uncorrelated signals; the START signals are taken from the excitation source or a pulse generator and random STOPs can be supplied by the PM, exposed if necessary to a small amount of room light. Counts should build up in the MCA in a horizontal line. With a 50 ns TAC range any non-linearity will be clearly evident when 2000–3000 counts have been accumulated in each channel. Alternatively, an experiment similar to time calibration with a variable delay line (*vide infra*) can be performed and the amplitude of the TAC conversion output pulse measured on an oscilloscope. A plot of delay against pulse height should be a straight line.

In our experience many commercial TAC modules suffer from severe non-linearity in certain time ranges. One instrument tested was actually non-linear over its entire range and was unusable (Roberts, 1982). It is therefore essential to characterize this fault and to determine which channels should be avoided when collecting (or analysing) the decays. For this purpose the variable delay lines are indispensable. Modern TACs, while apparently less subject to non-linearity associated with small timing capacitor charges than older instruments, may have a small non-random oscillation over the complete range. Usually this oscillation is of too low an amplitude to interfere with data analysis and can therefore be tolerated.

5.2.5(b) Pile-up inspection

Since pulse pile-up distortions are intimately connected with the mode of operation of the TAC we shall briefly discuss these effects in this section. Instrumental pile-up correction is based on one of two techniques – pulse discrimination or energy discrimination. In the former, the number of fluorescence-generated signals arriving at the TAC during a TAC cycle is monitored; the arrival of a second signal inhibits the transmission of the pulse associated with the first signal to the MCA. Energy discrimination assumes that a pulse height spectrum measured at a late dynode of the PM tube has a well-defined peak that corresponds to one photon events. If the sum of the amplitudes of all the pulses from this dynode during one excitation cycle exceeds the appropriate single photon level the TAC output for that cycle is inhibited.

An ingenious, if somewhat awkward, experiment that corrects for pile-up with pulse counting has been devised by Davis and King (1970). In it the PM pulse is split into two channels. One channel starts the TAC; the other is delayed and [because there elapses a fixed time before the TAC, having accepted a START pulse begins its voltage sweep (see Fig. 5.4)] can be timed so as almost but not quite to stop the TAC. An additional PM pulse occurring during a cycle will therefore stop the TAC. Also routed to the STOP input of the TAC are the excitation trigger pulses delayed by the TAC range. Data are now collected first for 10 seconds, say, with the MCA in ADD mode and both the PM and trigger pulses connected to the STOP input; then the trigger pulses are disconnected and data "collected" with the MCA in SUBTRACT mode. The MCA is cycled in this way between ADD and SUBTRACT until the desired number of counts have been accumulated. Random starting of the TAC is prevented by maintaining it in an inhibit mode until the beginning of each cycle. Techniques of pile-up correction, such as this, are difficult to implement correctly because of dead time in the inhibit circuit and precise timing requirements (Coates, 1972; Haugen *et al.*, 1979). Commercial components are available but are reported to be inefficient (Knight and Selinger, 1973). However, modifications that increase the data collection rate have been described (Knight and Selinger, 1973; Williams and Sandle, 1970).

Pile-up inspection employing energy discrimination depends for its success on a negligible or at least very small overlap between the peak corresponding to one and the peaks corresponding to multiple photon events in the pulse height spectrum of the photomultiplier tube. Some RCA photomultiplier tubes are particularly useful in this application (see Fig. 4.3). A typical instrument employing energy discrimination would include a PM with a well-resolved pulse height spectrum, a preamplifier with μs decay time, a spectroscopy amplifier and a timing single channel analyser. During the decay time of the preamplifier, multiple pulses from the dynode of the PM tube are converted to a single pulse with an amplitude proportional to the sum of the amplitudes of the original PM pulses. The spectroscopy amplifier shapes this pulse so that it is suitable for input to the single channel analyser, which is preset to output a gating pulse only when the input pulse is within the range of the single photon energy. Because of the rather slow decay time of the preamplifier (50 μs), this type of pile-up rejection is unsuitable for fast repetition rate sources.

Pile-up correction has been thoroughly investigated by Harris and Selinger

(1979). They concluded that avoidance of pile-up distortions is best achieved by reduction of the count rate (see Section 2.2.1). If a definite reduction in data collection times can be safely obtained by pile-up inspection, they recommend energy discrimination for excitation pulses with lifetimes less than 80 ns and pulse discrimination for other excitation sources. Therefore for the measurement of nanosecond lifetimes the former seems to be the method of choice.

A limitation on the maximum efficient count rate attainable with pile-up inspection is set by statistical considerations. Following the notation of Section 2.2.1 let $p_1(i)$ be the probability of emission of one photoelectron in the time interval $t_{i-1/2}$ to $t_{i+1/2}$ and let w_i be the average number of photoelectrons ejected from the photocathode in this time interval. Assume that all cycles corresponding to the emission of more than 1 photoelectron are excluded from the counting. The probability, $P_1(i)$ of detecting a pulse in the ith time interval is given by

$$P_1(i) = p_1(i) \prod_{j \neq i}^{\infty} p_0(j) \tag{5.1}$$

From Equations 2.4 and 2.5

$$P_1(i) = w_i e^{-w_i} \left[\exp\left(- \sum_{j \neq i}^{\infty} x_j \right) \right] \tag{5.2}$$

$$= w_i e^{-w}, \tag{5.3}$$

where

$$w = \sum_i w_i,$$

the average number of photoelectrons ejected during an excitation cycle. After N_E excitation cycles the number of counts in the ith channel is

$$N_i = N_E \beta z_i e^{-\beta z}, \tag{5.4}$$

where the notation is as in Section 2.2.1. It can be seen that this number is proportional to the intensity at time t_i, z_i, without any counting rate restrictions. If n is the number of analyser channels, the total number of useful counts, N_D, is given by

$$N_D = \sum_{i=1}^{n} N_i = N_E \beta \left(\sum_i z_i \right) e^{-\beta z}$$

$$= N_E \beta z e^{-\beta z} \tag{5.5}$$

For $\beta z = 1$, N_D is a maximum, so that $F_D = N_D/N_E = e^{-1} = 0.37$.

[Mathematical correction of pile-up distorted curves is described in Section 6.4.]

Commercially available SPC instruments do not offer pile-up inspection as a standard feature. Manufacturers would doubtless include the option if the customer requested it. However, with a well-aligned flash lamp apparatus and a ratio of converted counts to excitation events of 0.01 a decay curve should be measurable in at most 30 min. Considerable reduction in this time is standard of course, in instruments using a high repetition rate laser. Since data transfer and analysis must also be taken into account in an evaluation of time-saving, the actual reduction in data processing achieved by a pile-up inspector is likely to be quite marginal. In experiments where collection times are abnormally long the reason is usually a low count rate. A pile-up inspector might perhaps be suitable for experiments with high count rates in which the excitation source stability is not high or for experiments with biologically or chemically labile samples. Otherwise careful consideration of the actual time-saving expected is recommended.

5.2.5(c) Multichannel TAC

This component has been developed by the Research Institute of Applied Electricity, Hokkaido University, for Horiba Ltd (Hara, 1983). A schematic diagram is illustrated in Fig. 5.5. It consists essentially of several TAC units (channels) whose voltage sweeps are initiated by the same start

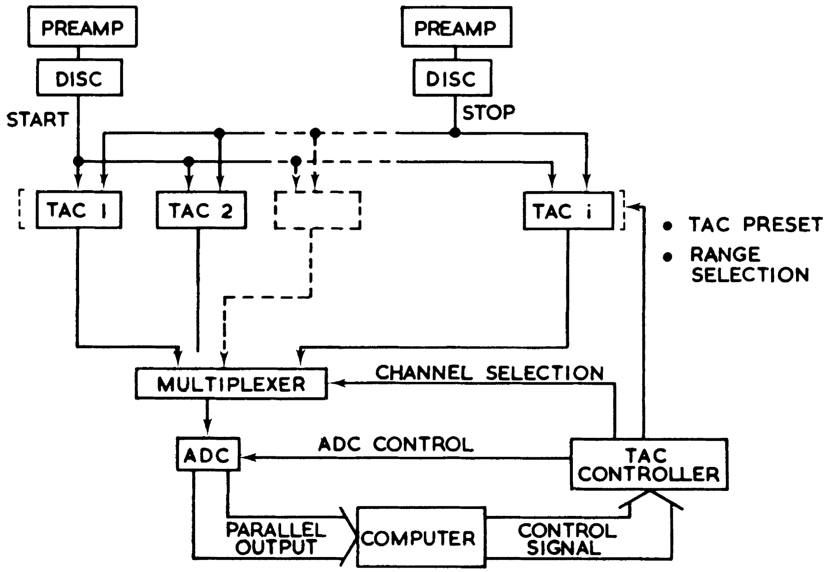

Figure 5.5 Schematic diagram of Horiba multichannel TAC operation (from Hara, 1983).

pulse. This allows a high stop count rate because the electronics can detect and time several photons for each exciting flash. With this component a count rate of 50% is possible for a 100 ns lifetime (Hara, 1983). The multichannel TAC has not yet been tested critically but it appears to offer a decided improvement over conventional TACs.

5.2.6 Biased amplifier

As was stated in Section 5.2.3, it is convenient to route the output pulses from the TAC to the MCA through a biased amplifier. This component amplifies the TAC output pulses yielding increased resolution and, through its ability to bias out time delays, helps to achieve suitable placement of the decay curve in the MCA channels. The effect of bias level and gain on the voltage of the TAC conversion output pulse is illustrated in Fig. 5.6. It can be seen that

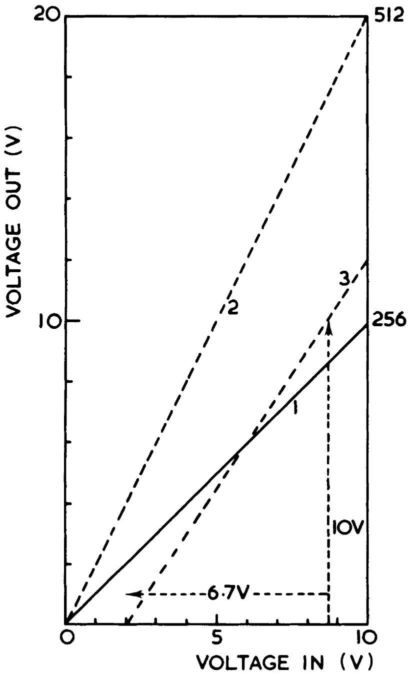

Figure 5.6 Effect of bias level and gain in biased amplifier used in conjunction with TAC:

(1) bias level 0, gain 1 $V_{out} = V_{in}$

(2) bias level 0, gain 2 $V_{out} = 2\ V_{in}$

(3) bias level 2 V, gain 1.5 $V_{out} = 1.5\ V_{in}$

voltages corresponding to short times can be biased out and a specific region of TAC voltage say 2 V–8.6 V (line 3) corresponding to say 20 ns–87 ns on a 100 ns TAC range, can be expanded to fill the N MCA channels ($V_{out} = 0$–10 V corresponds to 0–N channels). Gains of 15 above the bias level are standard in these components so that the usual minimum TAC range of 50 ns can be effectively reduced to 3.3 ns, allowing greater resolution of picosecond decays. Biased amplifier components may be purchased separately or be incorporated in the TAC. In either case time jitter in this amplifier appears to be negligible, TAC–BA combinations having less than 20 ps jitter (Ware, 1971; Koester, 1979). The BA is not an essential component of SPC electronics since even very short lifetimes are easily resolvable on a 50 ns timescale and delay generators or coaxial cables can be used to position the decay in the MCA channels. Nevertheless it can be a convenient component and the extra expense of a biased time-to-amplitude converter (TAC and BA combined in one NIM unit) over a standard TAC will probably be justified.

5.2.7 Multichannel analyser (MCA)

The variety of MCAs on the market is so large that we cannot hope to describe them all in this short section. We shall therefore give a brief description of a standard instrument and mention the features that we consider desirable for the SPC experiment.

A basic MCA has an analogue-to-digital converter, a memory consisting of channels for storing data and data input and output facilities. A standard instrument generally incorporates lower and upper level discriminators and two modes of data collection – pulse height analysis mode or multichannel scaling mode. It is usual and, in our opinion, essential to be able to display the contents of the memory store on a CRT screen, which may be a standard feature of the MCA, or an oscilloscope dedicated to the SPC experiment. Live 'scope display during data acquisition is preferable. MCAs may also possess the following features: PRESET TIME or PRESET COUNT which enables the operator to collect data to a certain peak height or for a certain time (useful but not essential); variable display scale (highly desirable); log display (useful but not essential); digital zero offset (sometimes useful); choice of data ADD or SUBTRACT (normally not used but can be convenient for background correction or pulse pile-up correction); internal clock (very useful); % dead time indicator (useful as a diagnostic); cursor for monitoring the counts in a particular channel (useful); region of interest integrator (useful for background estimation); multiple memory groups (very useful); AUTOMATIC ERASE (after readout) mode (useful in a computer controlled instrument but could be a disadvantage otherwise).

For pulse height analysis experiments 200 to 600 channels are sufficient in a decay curve. A smaller number may give less than satisfactory resolution in double exponential decays, especially if some channels are reserved for collection of background counts. Time resolution is increased with increasing number of channels but so also are data collection times. Five hundred to 600 channels are perhaps most common. Optical resolution in time-resolved spectroscopy is also dependent on the number of channels. Perhaps a suitable number for all types of experiment is about 1000 channels divided into 4 memory groups; in a single data collection one could use 250, 500 or 1000 channels. Calibration of the analyser channels is discussed in Section 5.4 and the effect of channel width on time resolution in Chapter 6.

Oscilloscope display of the accumulating data is necessary in order to judge visually whether the experimental conditions are correct. A log display is useful for judging exponentiality, but since convolution tends to mask the simple kinetics of the sample lack of this feature is not serious.

Data in the analyser must be transferred to a computer. Most analysers READOUT in several modes. For instance, standard MCAs will drive a paper tape perforator or cassette deck or will output data serially to an appropriate interface. Data transfer from analysers is sometimes tricky, especially when the instrument is hard wired to a computer. Most of the problems, however, can be solved with a reasonable knowledge of the appropriate electronics.

Many analysers have what the uninitiated might regard as a bewildering array of switches and knobs on the front panel. It is of course important to adjust the settings correctly, but this adjustment is quite simple to accomplish by consulting the user's manual, and the MCA is as easy to use as any of the other electronic components. Dead time in the MCA, which occurs while it is processing the converted output from the TAC, is not a limitation on data collection rates since it can accept input pulses at a rate faster than the TAC can supply them. Dead time in MCAs is discussed by Harris and Selinger (1979) and Bennett *et al.* (1965) among others. MCAs may be NIM units or independently powered components.

5.2.8 Rate meter

It is always essential to monitor the converted TAC signals so that a correct ratio, F_D, of detected photons to excitation events may be maintained (Section 2.2.1). This measurement (before decay curve collection) can be achieved by operating the MCA in multichannel scaling mode and by advancing a channel every second. For this purpose a cursor is useful. More convenient however is a rate meter. A counter, as such, merely accumulates counts; hence a counter that accumulates for one second, displays the total, resets to zero and repeats the cycle is necessary. Digital readout is more convenient although a dial readout may be less expensive. While a rate meter that can accept both positive and negative polarity input signals is most convenient, acceptance of only one polarity, that of the signals from the second CONVERSION output of the TAC, is quite satisfactory. This output signal is usually positive unipolar or positive bipolar. If it must be inverted to comply with the input requirements of the rate meter excessive attenuation may occur in a simple BNC-type inverting transformer. However, negative-going pulses may be taken from the discriminator in the fluorescence channel. If the excitation source repetition rate is very high (100 kHz–5 MHz) this count will be close to the TAC rate. If there is only one CONVERSION output from the TAC the signal to the MCA can be monitored before data collection. A rate meter for the trigger signals is convenient if the excitation pulse repetition rate is not displayed on the driving electronics for the excitation source (e.g., in a free-running flash lamp). This count can be used, with all sources, to monitor source stability. Input pulse polarity requirements are not critical for this rate meter since either positive-going or negative-going signals can be derived from the discriminator in the trigger channel.

Some rate meters incorporate a discriminator with adjustable threshold on the input. If the threshold is set too high or too low an incorrect count will be registered. The correct threshold can sometimes be set by monitoring the known trigger pulse count rate. Alternatively the signals to be monitored may be counted in the MCA, as outlined in the preceding paragraph, and the rate meter discriminator threshold adjusted until the count rate agrees with that measured in the MCA. In fact it is advisable to calibrate any counter before use since it is found that these components frequently perform less than satisfactorily.

5.2.9 Cables and connections

Electronic signals are usually transferred from one component to another along coaxial cable. Cable impedance is almost invariably 50 Ω. For standard BNC connectors RG 58C/U cable is suitable. Other connectors may accept coaxial cable of a different thickness. For instance, between LEMO connectors RG 174/U narrow width cable is satisfactory. Doubly-screened cable (e.g. RG 55/U, RG 71B/U) may act as an attenuator of r.f. signals. Signal transmittance has been discussed by Lytle (1974). Since pulse rise time increases with the square of the length of cable, lengths of greater than 1 m are not recommended. Soldering of cable cores to connector pins and crimping of screens to the connector bodies should be examined frequently, as dry solder joints are apt to break.

Inputs on NIM components are normally BNC bulkhead sockets (also called jacks), which accept BNC free plugs. Straight BNC adaptors (socket-to-socket or plug-to-plug) are very useful as also are, though less frequently, BNC elbow plugs. At least one BNC T-adaptor (with one plug and two sockets) should be available, especially if the TAC–MCA combination is to be calibrated by the simple method outlined in Section 5.4. Unused inputs on some components should be terminated in 50 Ω for which purpose BNC termination plugs are available; BNC 50 Ω THROUGH terminators will also suffice for this purpose. The latter are useful for signal transmission to a device whose input is not internally terminated in 50 Ω (inputs on some TACs require this type of termination). Trigger pulses are frequently of positive polarity; if so they must be inverted before input to most amplifiers, discriminators and TACs. A high frequency BNC type inverting transformer effects this polarity change in a most convenient way. BNC 50 Ω attenuators are useful when signals are monitored on an oscilloscope but may also be used to attenuate signals from, say, a fixed gain amplifier.

The 4-module CFT discriminator (Ortec Model 934) referred to in Section 5.2.2 possess LEMO type sockets for all input, output and internal connections. In this unit each of the four discriminators actually used requires, as an internal delay, about 10 cm of coaxial cable of external diameter 2.5 mm connected to two front panel sockets by 2 plugs of SUHNER type 11 QLA 01-2-2c. Adapters, BNC free socket to LEMO free plug, SUHNER type 33 QLA-BNC 01-1, can be obtained with which standard RG 58C/U cable can be connected to the input and output sockets of each discriminator. Details of these connectors, cables and adaptors can be had from the addresses given in Appendix 5.A1.

It is important to avoid earth loops when signals are transmitted from devices that are earthed independently. Good interdevice earthing should also help in the suppression of r.f. interference. Lytle (1974) advised connecting the chasis of the separate devices with a hollow wire braid threaded with a solid copper conductor. Conductor and braid are soldered together every 30 cm or so. With this technique a common d.c. and r.f. earth should be attained. Further discussion of r.f. attenuation can be found in the book by Morrison (1967).

5.2.10 Other components

Initial optimization of flash lamp performance is greatly aided by use of an oscilloscope with which the trigger pulse (and thyratron gating pulse, if used) is monitored while high voltage, arc gap etc., are adjusted. Pulse instability is easily observable by this means. The fairly common and relatively inexpensive Tektronix type 454 oscilloscope can be used for this purpose. Electronic components can also be tested on such an oscilloscope if a pulse generator is available. Pulses, of a type specified in the instruction manual for the component, are input to the component and its output is monitored on the 'scope. Frequently it is sufficient to monitor the response of the component to the pulses actually processed in the experiment thus dispensing with the need for a pulse generator. For many components this check is unnecessary until the instrument performance deteriorates, due to some unknown cause.

A convenient method of calibrating the TAC–MCA combination is by means of a commercial time calibrator. This is a NIM standard module with an internal crystal oscillator specifically designed for use with a TAC. It outputs START and STOP pulses, separated by an integral multiple of a precise time period, which are routed to the appropriate inputs of the TAC. One common model (ORTEC Model 462) has a facility (called a Dispersion Amplifier) for dispersing the peak over a number of channels so that its centroid can be calculated exactly. Some years ago a time calibrator of this type in our laboratory yielded different results when the Dispersion Amplifier was operated. For this reason, and also as a normal precaution, we recommend that time calibrators should themselves be calibrated against some known time period.

For time resolved spectral studies it is necessary, if the MCA does not possess an internal clock, to time the channel advance with an external clock. NIM standard modules are available that output a pulse after some chosen time interval. There is generally an input connection at the rear panel of the MCA to which the pulse can be routed so that the channel is advanced by one whenever a pulse is received.

As was stated in Section 5.6 commercial pile-up inspectors are now available. Before purchase, however, it is best to ascertain the efficiency of these devices. As Knight and Selinger (1973) pointed out, discussing earlier models, unless the device is gated to inspect pulses only during the TAC open period, it can be quite inefficient. For the other method of pile-up inspection, energy discrimination, a timing single channel analyser (SCA) can be employed. This device is also available as a NIM standard module. Pulses from the PM are routed to an integrating amplifier and, usually, a spectroscopy amplifier before input to the SCA. The integrating amplifier is also necessary in the determination of the pulse height spectrum of the PM. Suitable commercial components are (all ORTEC Models): 113 preamplifier, 451 spectroscopy amplifier and 420-A timing SCA.

Schuyler and Isenberg (1971) have described an SPC instrument which records two decay curves simultaneously through the use of COINCIDENCE modules and a LINEAR GATE. A block diagram of their instrument is shown in Fig. 5.7. It will be seen that energy discrimination pile-up inspection is employed in the two fluorescence channels while only a single

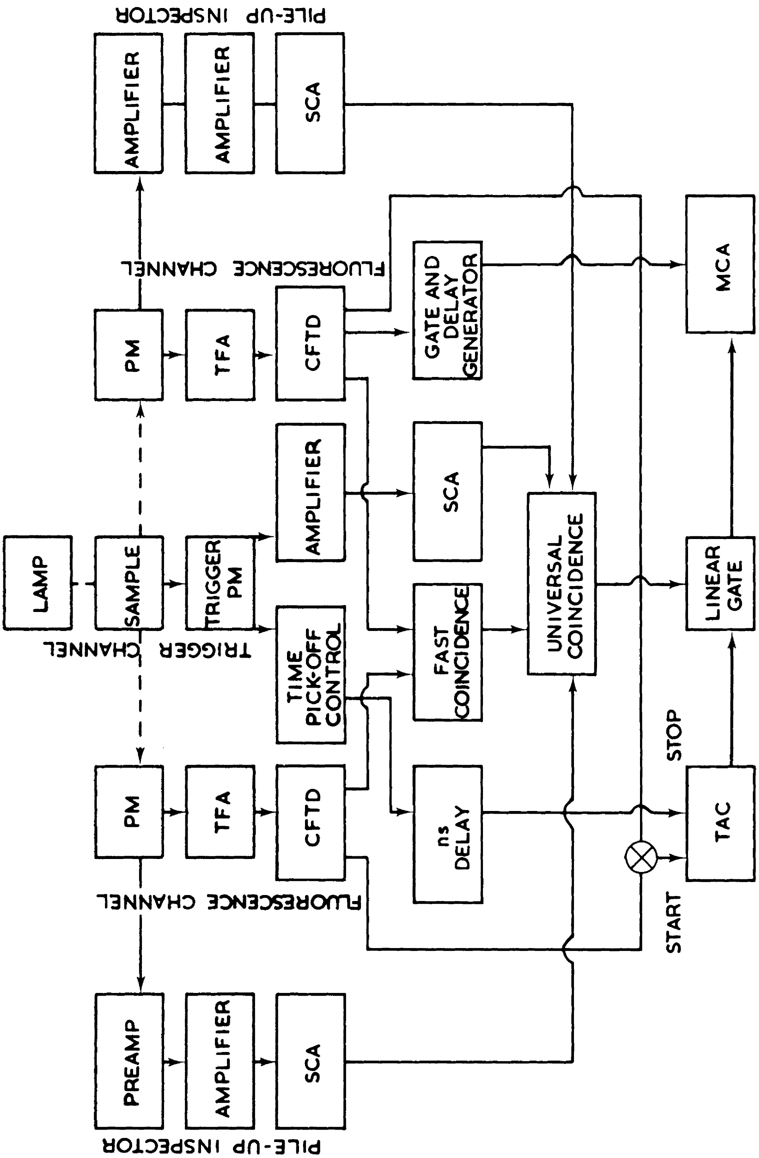

Figure 5.7 Block diagram of SPC instrument employing pulse pile-up inspection and alternation of data collection between two fluorescence channels. Symbols as in Fig. 2.1 and text (adapted from Schuyler and Isenburg, 1977).

TAC–MCA is necessary. The UNIVERSAL COINCIDENCE gates the timing information to the MCA while the FAST COINCIDENCE blocks data collection if the two PMs output anode pulses within 100 ns of each other. While the advantage of collecting two decay curves simultaneously is obvious in some experiments (e.g., when fluorescence polarized parallel and perpendicular to the direction of polarization of the exciting light is to be time-resolved), for most users the expense of assembling an instrument so sophisticated is possibly prohibitive. Close attention to the actual reduction in data collection and processing times should be paid before the components are purchased.

5.3 Setting Discriminator Levels

The discrimination level for the trigger pulses is not critical since these are usually of reasonably constant amplitude. The final setting is chosen by raising the level increasingly above threshold while the discriminator output is monitored with a rate meter. When noise has been discriminated against a region of constant output counts is reached. The operating level is then set about one third of the way along this plateau region.

Much more crucial in the success of the SPC experiment is the setting of the discrimination level on the fluorescence (usually constant fraction timing) discriminator. As the level is raised the FWHM of the instrument response function gets smaller, a distortion that must be clearly distinguished from increased time resolution. The effect has been explained on the basis of overlap of separate single photon anode pulses, which cause a multiphoton pulse with a much larger amplitude than a single photon pulse. Since this overlap is more severe at times close to the maximum of the photon distribution function, a high discriminator setting, which discriminates in favour of multiphoton events, biases the collected decay towards shorter times. The distortion is different for pump pulse and decay curve so that the convolution integral is no longer applicable.

Fluorescence PM pulses, as stated previously, have a wide amplitude distribution; there is no clear dividing line between pulses arising from dark noise and pulses arising from fluorescence photons. Increasing the discriminator level, however, seems to increase the signal-to-noise ratio and also to reduce somewhat the interference from spurious r.f. signals (Nemzek, 1975). Consequently the chosen discrimination level will be a compromise between acceptance of relatively more single photon pulses and rejection of dark noise and r.f. generated pulses. In order to adjust the level one should first try to find a signal plateau. If no clear plateau is observable the tedious but necessary adjust and deconvolve technique must be resorted to. A standard, preferably of short lifetime, is chosen and pump pulse and decay curves measured for various discrimination levels until the correct lifetime and acceptable fitting is obtained. An alternative to this procedure is collection of the instrument response function only and determination of its FWHM at different discriminator levels; an obvious narrowing of the function indicates excessive discrimination. While this procedure is certainly more convenient the final setting should always be tested by deconvolution using a compound with a known lifetime.

5.4 Time Calibration and Choice of Timescale

As discussed by Yguerabide (1972), the timescale in nanoseconds per channel can be estimated with a knowledge of the time range of the TAC, the gain of the BA, if used, and the input and output ranges of the MCA. Suppose the amplitude of the TAC output signal is V volts for a START–STOP time difference equal to the TAC range, TR ns, yielding a calibration of V/TR volts per nanosecond for the TAC pulse. The input range of the MCA, I volts, is determined by its upper and lower level discriminator settings and is usually about 10 volts for pulse height analysis. The output range, O, is sometimes referred to as the gain or conversion gain and is the number of channels corresponding to the input range. The calibration of the MCA range is therefore I/O volts per channel, yielding a time calibration C in nanoseconds per channel given by

$$C = \frac{TR}{V} \times \frac{1}{G} \times \frac{I}{O} \text{ ns per channel,} \tag{5.6}$$

where G is the gain of the BA ($= 1$ if no BA is used). Equation 5.6 gives only a rough estimate of the timescale. Owing to slightly variable internal settings in the TAC and MCA the actual timescale will usually be somewhat different.

One method of experimental time calibration has been outlined in Section 5.2.10. A much simpler method, requiring only accurately calibrated delay lines, is illustrated in Fig. 5.8. Pulses of constant amplitude, such as those from a pulse generator or from the trigger for the excitation source, are split into two channels. One channel is connected to the START input on the TAC and the other is routed through two delay boxes. With D_F switched out, D_V is adjusted until a spike appears on the analyser screen. D_F is switched in and the channel difference between the two spikes, N_{DF}, is noted. Then the spikes are erased, D_F switched out, D_V changed and a spike recorded. Again D_F is switched in and the resulting channel difference between the spikes noted. This process is repeated for various values of D_V and the resulting values of N_{DF} averaged, giving a time calibration of D_F/N_{DF} nanoseconds per channel.

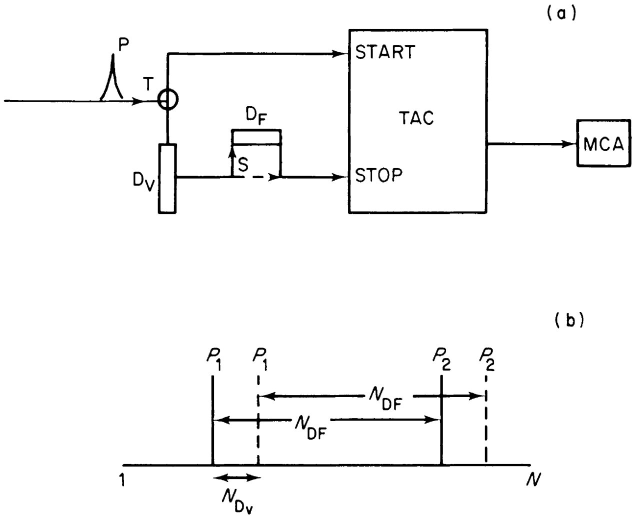

Figure 5.8 Illustration of time calibration of TAC–MCA combination. (a) Experimental arrangement P, constant amplitude pulse; T, BNC T-piece (pulse splitter); D_V, variable delay; S, switch; D_F, fixed delay.

(b) Peaks in MCA channels P_1, P_2, counts accumulated in narrow peaks; N, total number of channels; N_{DF}, number of channels corresponding to fixed delay, D_F; N_{DV}, number of channels corresponding to variable delay, D_V.

The advantage of this method is that if the spikes fall in a single channel the uncertainty in the position is reduced by the averaging. An alternative is to hold D_V constant and shift P_2 progressively across the channel range by increasing D_F. By drawing a straight line through a plot of channel number against delay added the time calibration is obtained. Whichever method of calibration is used, channels corresponding to a non-linear region of the TAC ramp should be avoided.

Calibration of longer TAC timescales cannot be achieved with small variable delays; perhaps the most satisfactory method of such calibration is a commercial time calibrator. Other methods employ a pulse generator with a precision variable delay (Ware, 1971) and, less satisfactorily, a fluorescence standard with a long lifetime. Hexafluoroacetone at 25°C and a pressure of 100 Torr has been suggested for this purpose (Knight and Selinger, 1973). Its lifetime is quoted as 84 ± 0.5 ns. This value should be confirmed before acceptance. We would recommend a method based on an accurately known and easily generated delay in preference to a decay time measurement.

Single exponential decay curves should be collected on a range that allows the curve to decay over 2 to 3 decades of intensity in the available channels. Multiexponentials are more difficult and may require two experiments on different time scales for adequate resolution. Although equations for choosing the TAC range have been suggested (Hall and Selinger, 1981) we feel that they introduce an unnecessary level of complication into what is really a matter of common sense.

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Appendix 5.A1

In this appendix we list names and addresses of manufacturers of SPC electronic modules. We would emphasize that the list is by no means exhaustive; only companies commonly referred to in the literature are listed. In order to conserve space only the address of the international headquarters of the company is given. If that is not known the address of the representative known to us is substituted.

A. General SPC equipment

(1) (EG and G) ORTEC Incorporated, 100 Midland Road, Oak Ridge, Tennessee 37830, USA.

(2) Canberra Industries Incorporated, 45 Gracey Avenue, Meriden, Connecticut 06450, USA.

(3) Nuclear Enterprises Limited, Sight Hill, Edinburgh EH11 4EY, Scotland.

(4) Elscint Incorporated, P.O. Box 297, Palisades Park, New Jersey 07650, USA.

B. Preamplifiers (as in A, also)

(5) Marconi Instruments Division, Marconi Electronics Incorporated, 100 Stonehurst Court, Northvale, New Jersey 07647, USA.

C. Calibrated delay units (as in A, also)

(6) Hamamatsu TV Company Limited (see Appendix 4.A2).

D. Time-to-amplitude converters (as in A, also)

(7) Societa Industriale per L'Elettronica Avanzata (SILENA), Via Negroli, 10/A, 20133 Milano, Italy.

(8) Le Croy Research Systems Corporation, 126 North Route 303, West Nyack, New York 10994, USA.

E. Multichannel Analysers (as in A, also)

(9) Hewlett Packard Company, 150 Page Mill Road, Palo Alto, California 94304, USA.

F. Connectors

BNC cables and connectors from any electronic components supply company. Lemo connectors and adaptors from (*inter alia*):

(10) Lemo S.A. Electrotechnique, 1110 Marges, Switzerland.

(11) Huber and Suhner AG, 9100 Herisau, Switzerland.

(12) Kings Electronic Company Incorporated, Tuckahoe, New York 10707, USA.

In-line inverting transformers, attenuators and terminators:

(13) Tektronix Incorporated, P.O. Box 500, Beaverton, Oregon 97077, USA.

G. Oscilloscopes

Tektronix Incorporated (see 13)
Hewlett–Packard Company (see 9)

(14) Fabri–Tek Incorporated, 5901 South County Road 18, Minneapolis, Minnesota 55436, USA.

H. Time calibrator

(EG and G) ORTEC Incorporated (see 1)

(15) Tennelec Incorporated, P.O. Box 601, Oak Ridge Turnpike, Oak Ridge, Tennessee 37830, USA.