comparable for both systems, but due to the above listed complications of a semiconductor detector its damage is more likely than that of an NaI crystal. Also the vacuum system of the semiconductor crystal area in the detector head underlies deterioration over the length of the usage time and this is also true for the isolating properties of the liquid nitrogen Dewar storage vessel. No definite lifetime can be stated for both kinds of detector since, especially for germanium detectors, it is contingent upon many parameters of material and the care of the user of the equipment.

A significant factor is the total financial effort for both kinds of detector. First, the purchase price for a standard semiconductor detector including liquid nitrogen storage vessel and preamplifier is about one order of magnitude higher than that of a quasi-comparable standard NaI detector. Second, continuous costs for the above mentioned maintenance of the germanium detector must be taken into account whereas NaI detectors do not require more financial effort than the purchase price.

Finally one special application should be mentioned which combines both detector systems, namely the anti-Compton spectrometer. It is not too often used in activation analysis because of its large instrumental effort. However, it is extremely useful for multicomponent activity measurement since very favouable signal-to-Compton ratios can be achieved. In this arrangement, a germanium detector is surrounded by a large volume annular NaI crystal. If the escape of a Compton-scattered photon from the germanium detector is registered by the scintillation crystal the coincident Compton signal of the germanium detector is discarded with help of an electronic anti-coincidence unit. Although a loss of the total counting efficiency is effected by this arrangement a significant improvement of the analytical sensitivity can be achieved by the gain of the signal-to-Compton ratio in the resulting spectrum[200,494-507].

Table 4-2: Comparison of the NaI(Tl) scintillation detector[1] and the Germanium high resolution detector[2]

Characteristic	Scintillation crystal	Semiconductor detector
Detector material	Sodium iodide, thallium-activated	Germanium, lithium-drifted or high-purity germanium
Material density (g/cm^2)	3.67	5.35
Hygroscopic	yes	no
Maximum active volume[3] (cm^3)	quasi-unlimited	about 150
Maximum measurable count rate[4] (s^{-1})	>200,000	about 50,000
Energy resolution[5]		
FWHM (keV)	90	1.9
FWTM (keV)	160	3.5
FWHM, relative (%)	6	0.14
Photopeak counting efficiency[6] (%)	100	up to about 40
Peak-to-Compton ratio[7]		
signal integral	0.85	0.28
signal height	7	up to about 60
Linearity	linear in the energy range of interest for activation analysis	

Table 4-2, continued

Characteristic	Scintillation crystal	Semiconductor detector
Lower energy measuring limit[8] (keV)	10 ([9]) 90 ([10])	about 4 ([11]) 90 ([10])
Upper energy limit	quasi-unlimited	
special maintainance requirements	no	liquid nitrogen cooling during operation[12]
Laboratory space requirement	negligible	considerable[13]
Purchase price[14]	DM 2,500 or $1,000	DM 25,000 or $10,000
continuous costs	no	yes[15]

Explanations to Table 4-2

1 Data are valid for a 3" x 3" plain crystal unless specified otherwise

2 Data are valid for a large volume germanium detector with coaxial drift configuration unless specified otherwise

3 Inquired from several producers in December 1985

4 Obtained using comparable standard electronic counting equipment for both systems; frequencies above the named limit cause significant deterioration of the energy resolution.

5 Measured at 1332.5 keV (^{60}Co) at an integral input pulse rate of 1,000 s^{-1}

6 Measured at 662.3 keV with a calibrated sample (^{137}Cs, point source geometry) at a distance of 20 cm from the front of the detector housing; the value is given relative to a standard NaI(Tl)-scintillation crystal (3" x 3").

7 Measured at 662.3 keV (^{137}Cs)

8 The given value is the lower energy limit recommended for analytical application; the "real" measuring limits are somewhat lower (see Para. 4.1.4.6).

9 Valid for a thin (about 2 mm) NaI-crystal equipped with a thin beryllium window

10 Valid for normal detector housing

11 Valid for a planar low energy photon diode with a thin (about 0.2 mm) beryllium window

12 Li-drifted Ge-detectors must be cooled continuously.

Explanations to Table 4-2, continued

13 The typical size of a standard Ge(Li)-detector including the liquid nitrogen Dewar storage vessel is about 60 cm diameter and about 80 cm total height (horizontal cryostat configuration).

14 Average as inquired from several producers in Dec. 1986

15 The continuous costs of a semiconductor detector (e.g. charge for liquid nitrogen supply) cannot be exactly quantified.

4.2 Photon counting electronics

In this paragraph the electronic devices necessary for photon spectrometry are discussed comparatively briefly, since, for the analytical practice, the choice among the different units is limited. Moreover, one part of the electronics usually is quasi-integrated in the detector, namely the preamplifier of a semiconductor detector. Also, the electronic partition of a photon spectrometer used for activation analysis mostly is basically comparatively simple. As already mentioned in the introduction of this chapter, a photon spectrometer, besides the detector plus preamplifier, contains a bias voltage supply, a linear pulse height amplifier and a pulse discriminating device, mostly a multichannel analyser. More electronic equipment is necessary for special spectrometer configurations, of course, but these will not be discussed extendedly since for activation analysis purposes no more than the above described devices are used in the most cases. Other options designed for special analytical purposes are mentioned briefly. Among the above named units, multichannel analysers are those which are available with the largest variety in performance and special features. Therefore, major attention will be directed to these devices. As mentioned several times, the electronic pulse processing system has a great influence upon the integral performance of a photon spectrometer; as will be demontrated, this is particularly true for the energy resolution of high-resolution spectrometers. It was already noted that frequently the entire resolution capacity of a semiconductor detector cannot be fully exploited because of poor performance data of the preamplifier and the spectroscopy amplifier. In the authors' laboratory it was observed several times that the energy resolution of old gamma spectrometers dramatically improved with the application of modern electronic pulse-processing devices.

The two main sources of deterioration in performance are the electronic noise of the whole spectrometer and the instability of the pulse amplifying units. Therefore, parallel to the development of the detectors, major attention has been paid to the development of the necessary stable and low-noise electronics.

All in all, nuclear electronics have shown a dramatic development in the last twenty to thirty years. This is especially true for multichannel analyser systems. For instance, quasi-pocket-sized multichannel analysers are available now, equipped with battery power supply units, liquid crystal displays, memories containing many thousand channels and a lot of spectrum processing software included for full in-field analysis of spectra taken on-site with portable semiconductor detectors. While linear amplifiers are improved in details of

their performance only, more and more sophisticated multichannel analysers are offered by the manufacturers in completely new series every few years and there is no limit in their development visible as yet.

4.2.1 Linear amplifiers

Important early work on linear amplifiers was performed by Jordan and Bell[518], Moody et al.[519] and Kelly[520]. An extended review about linear amplifiers and their development is gived by Chase[521]. See also Ref's.[522-530].

4.2.1.1 Preamplifiers

The primary purpose of the preamplifier is to optimise the coupling of a detector output to the rest of the spectrometer. More exactly, it provides the accurate analog conversion of the burst of electrons resulting from the absorption of the radiation energies in the detector, into a signal which can be conveniently transmitted to the measurement system. Another task of the preamplifier, especially its pulse entrance unit, is to minimise any source of noise which may degrade the energy resolution capacity of the spectrometer. Briefly summarised, the preamplifier is to derive a stable, precise, reproducible and undisturbed output signal from the detector. In the case of preamplifiers for semiconductor detectors this is accomplished primarily by virtue of field effect transistors as a noise-suppressing signal input unit. Preamplifiers for NaI scintillation counting will not be discussed here; their circuits are comparatively simple. The major source of poor energy resolution of a scintillation detector is the nature of the radioluminescence process and the stability behaviour of the photomultiplier rather than the noise activities of other sources (see paragraph 4.1.1). Therefore, special noise suppression at the preamplifier entrance as necessary in those for semiconductor detectors is of no use in scintillation spectrometers. The stability of the high voltage supply unit is of much more importance for a scintillation spectrometer since the gamma energy/pulse-height conversion function by the photomultiplier tube is contingent upon the high voltage level. This is not the case in semiconductor spectrometers in the proper operating voltage range. Along with the availability of field effect transistors fully transistorised preamplifiers became superior to all other systems which had been in use until then (see e.g. Ref.[531]). Nowadays, field effect transistors with an extremely high quality standard are available, so that they do not have to be cooled by integrating them into the cryostat system of the detector; earlier on, this had to be done in order to yet improve the signal-to-noise ratio of the spectrometer[532]. In the case of

failure, however, it was very complicated to replace the field effect transistor.

More information about preamplifiers can be found in Ref's.[414,533-544].

4.2.1.2 Spectroscopy amplifiers

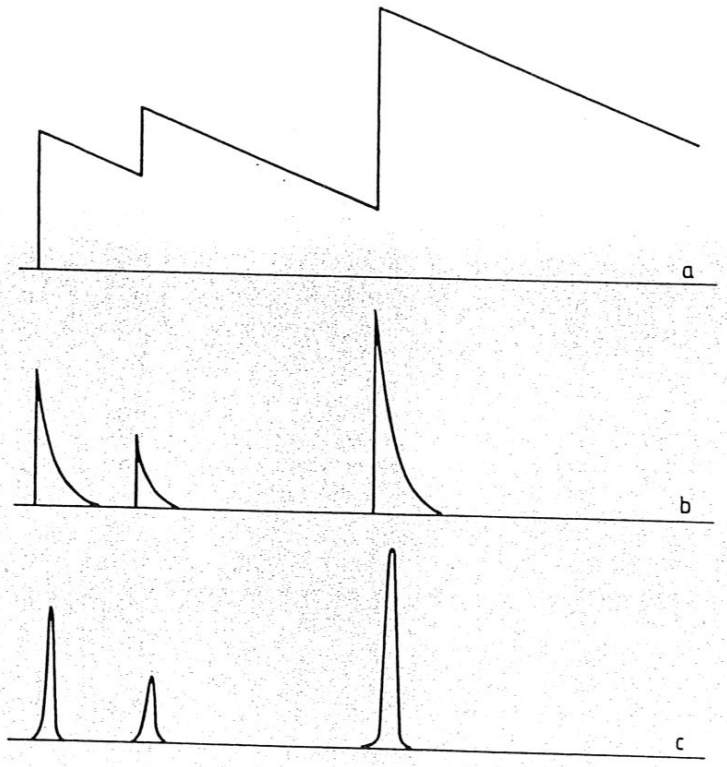

Fig. 4.28: Pulse shapes produced by a Ge(Li)-spectrometer; a: at the preamplifier output, b: differentiated signal, c: at the spectroscopy amplifier output

Amplification is actually a purpose of minor priority within all the tasks of a linear spectroscopy amplifier; The amplification rate usually is continuously adjustable and typically goes up to a factor of several thousand. The best fitting term for the unit would be "signal processor". The major role of the instrument is to convert the preamplifier output signal into a form which is most

suitable for the subsequent multichannel analyser signal input. Since there is a large variety of applications so there are as many amplifier versions to best meet the requirements. At this point, since in photon spectroscopy an optimum resolution linear amplifier is the most commonly used one, these devices will be discussed. In the following, the features of a modern high resolution, high count rate spectroscopy amplifier will be summarised.

a) Baseline restoration

Fig.4.28 illustrates a preamplifier output signal sequence whose leading edge contain both timing and pulse height (or energy, respectively) information. The tailing edge of the preamplifier signals decays comparatively slowly back to the baseline ("long-tailed pulse"). Since each new pulse will be "riding" on the tail of the previous one the amplifier has to restore a baseline reference-level for each pulse (Fig.4.28). Usually the baseline level is zero volts DC, but in modern spectroscopy amplifiers it may be adjusted to other values. The baseline restoration is accomplished by pulse differentiation with help of a complicatedly designed circuit containing a high-pass filter unit [545-548].

b) Pole/zero adjustment

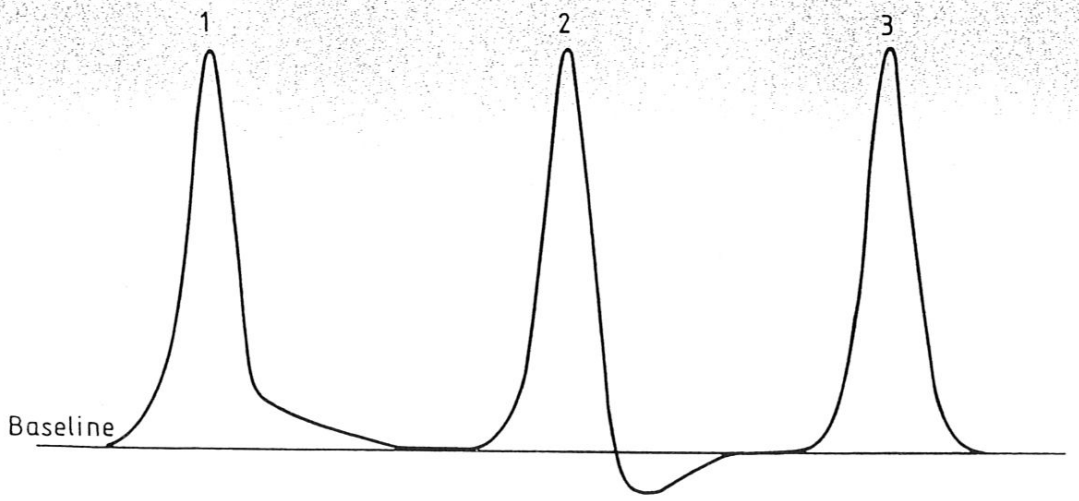

Fig. 4.29: Output pulse shapes from the spectroscopy amplifier; 1: pulse overshoot, 2: pulse undershoot, 3: pulse at correct pole/zero cacellation

To avoid undesired influence of over- or undershoot of the output pulse upon the height of a subsequent one, a pole/zero cancellation is provided which enables monotonic return of the output pulse to zero baseline reference level (Fig.4.29). The setting of the pole/zero cancellation must be adjusted to the actual decay time of the preamplifier output signal[549-551].

c) Pulse shaping

Optimum system energy resolution requires a quasi-Gaussian-shaped amplifier output signal (Fig´s.4.28 and 4.29)[545,552-556]. The half-width of the resulting pulse may be varied, in modern amplifiers usually from 0.25 up to 12 microseconds in fixed steps. The user, according to his requirements, has to optimise the pulse shape to an acceptable compromise value regarding the following limitations: if the time-constant of the amplifier is shortened to provide rapid return to the baseline for high count rate processing, it deteriorates the signal quality by allowing higher noise level to pass the amplifier. Conversely, if the integration time-constant is prolonged, to improve the resolution by favourable signal-to-noise ratio, the possibility of baseline shift and - in the case of higher count rate - pile-up appearance is introduced. In high-quality spectroscopy amplifiers a significan signal-to-noise enhancement is achieved by Gaussian-shaping of the pulse and special baseline stabilising units which are adjustable for various measurement conditions (e.g. different output impedance values).

d) Pile-up rejection

When dealing with high count rates, one of the most embarrassing appearances is the pile-up process, where sequential pulses interfere with previous ones. Thereby severe degradation of the integral performance of the spectrometer is entailed. Pile-up rejection and live-time correction are included in high-quality amplifiers[557]. The pile-up rejection works thus: when an incoming pulse has reached its maximum, subsequent pulses are automatically inhibited until the output pulse has recovered to the baseline. This is achieved by a very complex electronic circuit which is not discussed here (the reader might refer to Ref´s.[545,558-580]), the more since recently their basic principles have been rediscussed critically and promising new systems of pulse processing - especially the handling of high count rates - have been suggested[581-586].

To summarise, linear spectroscopy amplifiers are to convert incoming pulses from the preamplifier into, ideally Gaussian-shaped, noise-free pulses, whose heights are proportional to the photon energy incident to the detector. These pulses should arise on a stable, adjustable baseline. The amplifier should be

able to process a count-rate range from zero to at least 10^5/sec without any kind of pulse quality degradation[338,396,420,421,587,588].

In the photon activation analysis context, one other spectroscopy amplifier version among the large number of available units is worth mentioning, namely the biased amplifier. With help of this, parts of a pulse amplitude spectrum may be expanded to a smaller scale. Usually the desired portion can be selected arbitrarily by continuous bias level adjustment. However, in many cases, the expanding of spectral regions of interest can be achieved more efficiently by setting a digital offset in the multichannel analyser. This is explained further in the following paragraph.

Further recommended literature about spectroscopy amplifiers can be found in Ref's.[589-595].

4.2.2 Pulse height measurement

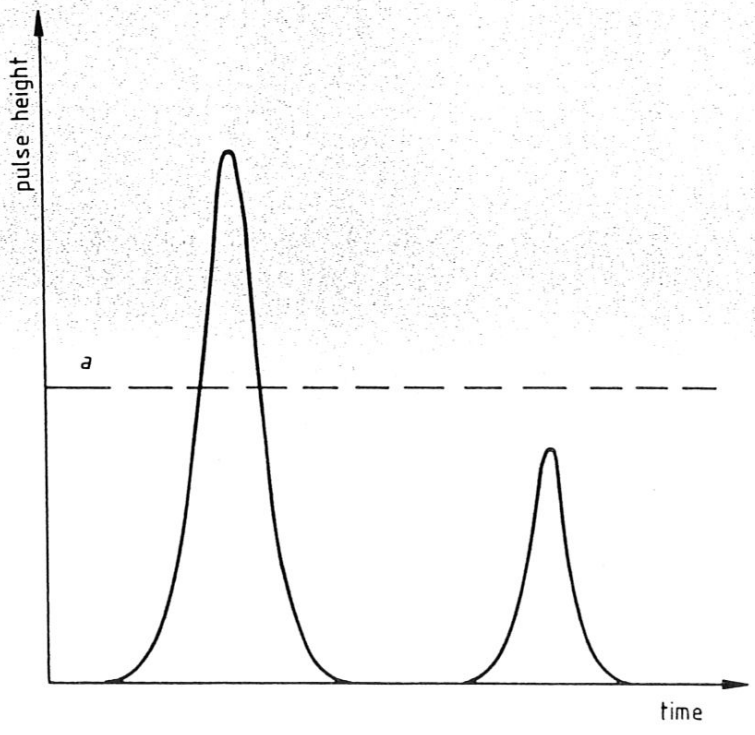

Fig. 4.30: Function principle of an integral discriminator; pulses, whose maxima are located beneath the threshold level (a) are discarded

Since, as noted above, pulse heights of solid state detectors are proportional to the incident photon ray energies a pulse-height discriminator is required to keep track of the spectral distribution of the radiation. The simplest one, namely the integral discriminator, is due to the basic idea of Schmitt[596], whose diagram includes a threshold which rejects all electric pulses lower than an adjustable level (see Fig.4.30). Thus it was possible to "cut" off lower parts of a radiation spectrum sequentially. Many circuits of integral discriminators have been developed since then (Elmore[597], Westcott and Hanna[598], Parsons[599], Moody et al.[519], Francis et al.[600]).

The differential pulse height discriminator - also called single channel analyser - was developed almost simultaneously. Different working principles were used to trigger the data output device by pulses whose heights fall within an adjustable "window" between two pulse height levels (see Fig.4.31); mostly an anti-coincidence mechanism was used. The first one was reported by Roberts[601]. Later but as well fundamental work was performed by Glenn[602,603], Watkins[604], Fairstein[522-526], Gatti and Piva[605]. Special devices including linear amplifiers and window discriminator with high window-width and level stabilities were developed by Gatti[606] and Colombo et al.[607]. Using a single channel analyser all signals outside the window are discarded. This wastefulness is only acceptable if the radiation source is strong and long-lived enough to offer a satisfactory high count rate within the window area throughout the integral spectrum counting period. The extension of the single channel analyser towards an integrated device with several windows with adjacent pulse height levels was straightforward. By this multichannel analyser a large part of the pulse hight spectrum (and thereby of the radiation spectrum to be analysed) is processed simultaneously. This is of special advantage and frequently unalterably necessary in the case of short-lived activity measurements.

The first multidiscriminator analyser systems were reported in the late 1940s (Freundlich et al.[608], Westcott and Hanna[598], Kelly[609]), although apparently there were earlier developments which have not been published explicitely (Wilkinson[610]). The largest multidiscriminator analyser contained 120 channels (Chase[521]). Multidiscriminator analysers suffered from frequent breakdowns and window width and level instabilities, whereas other pulse height analyser systems, e.g. grey-wedge analysers and photographic systems (Maeder and Medicus (Ref's.[611,612], Bernstein et al.[613]) had insufficient resolution.

Both problems were overcome and all other systems became obsolete by the invention of the Wilkinson type pulse-height-to-time analog to digital converter

(ADC; see below, 4.2.2.2) (Wilkinson[610]). Fundamental work on ADC systems of various kinds was performed by Fulbright and McCarthy[614], Gatti[606], Byington and Jonstone[615], Schumann and McMahon[616], Chase[618], Colombo et al.[607], Koch and Jonston[619], Russell and LeFèvre[620], McMahon and Gosolowitch[617], Schulz[621]. See also Ref's.[622,623]. A storage memory of any kind is required to keep track of the acquired data and to make them processable. The first multichannel analyser with a computer memory was developed by Hutchinson and Scarrot[626]; see also Franck et al.[627]. Different storage systems were reported by Gallagher and McKibben[624] and Wells and Page[625]; see also[628]. Wells and Page were the first to use a magnetic core memory to store the accumulated data. With help of these mentioned improvements special spectrometry techniques like anti-Compton counting and others became possible (Michaelis and Schmidt[501,629]) and the time of the first availability of improved high resolution photon spectrometers can be considered the date of birth of instrumental multielement activation analysis. A review of pulse discriminating devices is given in Ref.[675].

A counting of the pulses from a spectroscopy amplifier could be accomplished with help of a simple digital scaler; in this case not even a measure of the integral radiation activity of the counted sample could be obtained. It is not only the inability of the pulse counter to discriminate the different energies within a photon spectrum which makes the application of pulse discriminators unalterable. Both pulses due to electronic noise and signals due to various interaction effects of the radiation in the detector (e.g. Compton signals, see paragraphs 4.1.3ff) cannot be recognised as such with help of only pulse counting devices.

4.2.2.1 Single channel analysers

As touched on above, the integral discriminator is the simplest among all pulse height analysers. Since only a lower threshold can be set by an integral discriminator (Fig.4.30), an integral of the spectrum can be measured only. Differential spectrum analyses can be performed by the use of single channel analysers, also called differential discriminators(see Fig.4.31). A whole spectrum can be measured by scanning a constant window over the entire pulse height distribution. Pure differential discriminators are offered by several manufacturers, but in analytical photon spectroscopy units are in use almost exclusively which combine a linear amplifier and a discriminator. These devices are called "amplifier/single channel analyser" or window amplifier. Nowadays they are mostly used for scintillation spectroscopy since usually only one or very few photon energy lines are processed during activation analysis using scintillat-

tion counting. In photon activation analysis the most prominent example is the analysis of the light elements (C,N,O,F) where only the 511 keV annihilation line is processed after chemical separation of the mentioned elements from the matrix (see chapter 6.1). In this case, the window is permanently positioned to measure the 511 keV line. Instead, in higher resolution photon specroscopy, primarily multicomponent spectra are processed, and the use of a single channel analyser is not practical.

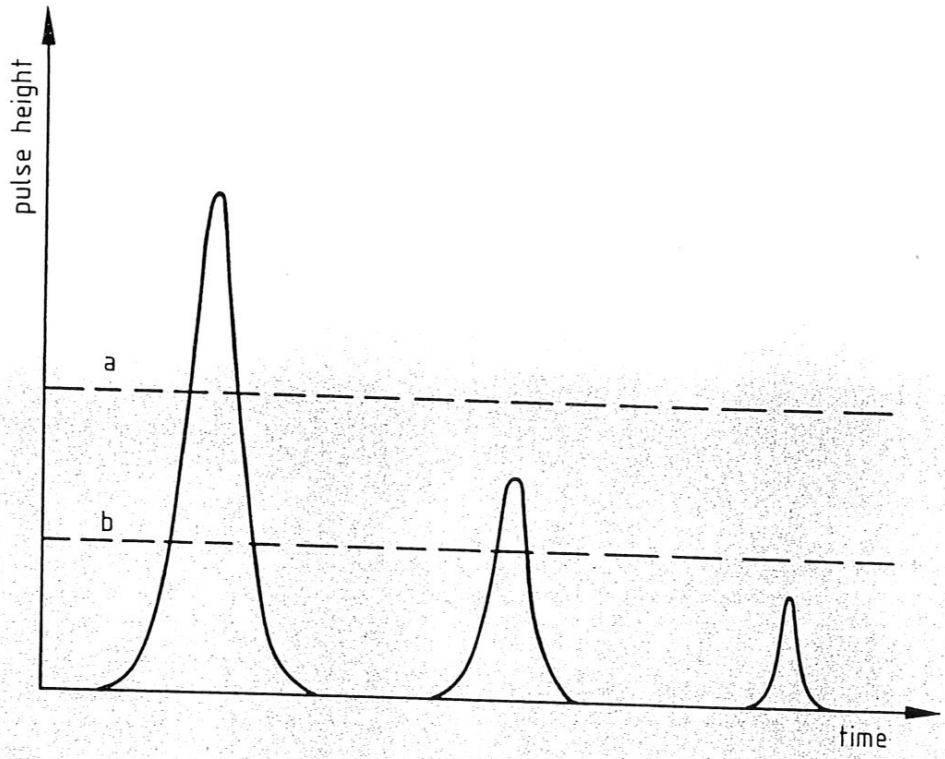

Fig. 4.31: Function principle of a differential discriminator; only those pulses whose maxima are located between the window levels (a and b) are registered

4.2.2.2 Multichannel analysers

To summarise: all multichannel analysers contain the following elements:

- A quantising and digitising device (analog to digital converter) that associates each incoming signal with a specific amplitude channel,

- A data storage device (memory) which keeps track of the number of signals which fall in each of the amplitude channels,

- A display service (cathode ray tube) which allows immediate visual inspection of the collected data,
- A data output facility of any kind which allows either data storage on any carrier or immediate data processing by computer,

Modern multichannel analysers with help of microprocessors and more and more expanding associated available software are extended to entire spectrum analysing, processing and evaluating systems, with help of which, theoretically, the data processing work could be performed without external computers involved. However as yet, these systems are not flexible enough to meet all the different requirements of an analytical laboratory performing various analysis of different material kinds and classes and thereby very different analysis procedures. Hence, freely programmable, flexible computers are still necessary in these cases. Anyway, the "pretreatment" of the spectral data in microprocessor-equipped multichannel analysers can be very useful for the reduction of the data passed on to the computer, saving both computing time and memory space as already noted.

In the following, the different operating units of a modern multichannel analyser, including the most common data processing options will be discussed. No difference is made between standard and optional units; this is very much due to the individual policy of the manufacturer.

Inputs

Besides the input for the analog pulse from the linear spectroscopy amplifier output various other signal inputs are available, namely:

a) An input intended for sequential multichannel scaling. Mostly logic rectangular pulses are used, but usually any other pulse shape exceeding a certain height and duration is accepted.

b) A gate input is provided for the case that any kind of data acquisition, processing or output is to be gated by logic pulse.

c) Several remote control inputs are provided for remote initialising and terminating of various operations by logic pulse, e.g. data collect trigger, multichannel scaling sweep start, channel advance and sweep stop trigger, data readout etc..

The execution of these functions might also be initialised by computer using a connection through a suitable data input/output (I/O) interface. This is the next item to be explained.

I/O - units

I/O units are combined input/output facilities. For fast and convenient data processing several I/O units are provided, equipped with suitable electronic interfaces to provide data formats acceptable by any peripheral unit.

a) On-line computer I/O unit; with help of this data may be transferred to the computer where they are processed immediately or stored intermediately on a secondary data carrier. Conversely, the multichannel analyser may be controlled automatically by computer with help of adequate software using the mentioned I/O unit.

b) I/O unit for terminals; cathode ray tube terminals or printers may be used for data input/output and multichannel analyser remote control.

c) I/O unit for disc recorder; either solid or flexible discs are used mostly for immediate fast data dumping but may also serve for the above described correspondence with the multichannel analyser. This is also true for

d) I/O for paper tape and magnetic tape recording and reading devices.

Data outputs

Most of the data outputs operate as I/O units mentioned above. Besides the internal cathode ray tube display which might also be considered as a data output device, following outputs are usually provided:

a) Single channel analyser logic pulse output; the pulse rate might be acquired from any region of interest of the spectrum, selectable through a built-in single channel analyser.

b) X/Y and graphic plotter output for spectrum processing and documentation

c) Line printer output; usually this is used for fast digital dump of memory partitions.

Processor

The processor is the "heart" of the multichannel analyser. It has to fulfill many tasks, e.g. direct the signals from the analog-to-digital converter output into the proper memory location; enact the commands from the controls either initialised manually by the user or remotely by computer, and many more. The most important operation unit within the processor is the memory. It is, as noted above is divided into channels, each representative for a certain range of incident pulse heights; this means that the resolution of the multichannel analyser is linearly dependent upon the number of channels available in the memory.However, this resolution capability is limited by the operating range (conversion gain) of the analog-to-digital converter as is explained below. Anyway, channel blocks exceeding this maximum are useful, too; they might serve as intermediate storage memory for visual inspection during undelayed collection of the next spectrum or internal data processing which will be discussed in detail later on. To provide optimal energy resolution of the entire spectrometer, a photopeak in a spectrum should contain at least five channels. Hence, due to the poor intrinsic resolution capability of a scintillation crystal, only camparably few channels are necessary for NaI-spectrometry, typically several hundreds. For high-resolution spectra, however, if they cover an energy range from say 100 to 2000 keV, at least 4000 channels would be required to provide optimum energy resolution. Nowadays, by virtue of semiconductor storage units available, memory sizes up to 64000 channels are optionally available in multichannel analysers. Usually, 1024 is the mimimum total memory size which can be extended in binary increments i.e. 2048,4096, etc.. This is due to the binary operations logic of the multichannel analyser memory (the operation mode is the same as that of computer memories; all in all, due to its logic architecture, a modern multichannel analyser may be regarded as a computer with a fixed basic program, which usually is called the "firmware"). The total count capacity is mostly 2^{20}-1 or 1048575 counts per channel. The maximum standard offered, as far as the authors know, is 2^{24}-1 or 16777215 counts per channel. According to the desired number of channels per entire spectrum, partitions of the total memory can be addressed from the analog-to-digital converter or other sources, normally starting with 2^8 or 256. In the case of pulse height analysing, in the first channels (0 and 1) counting time data are stored and cannot be addressed from any other source but the internal clock. The memory can be cleared entirely or in partitions selectable manually at the panel control (or, as noted above, remotely by any remote control unit, e.g. computer program). In many modern multichannel analyser models data clearance and many other operations, especially concerning the memory contents, require the operator's confir-

mation to avoid accidental loss of data.

Groups of adjacent channels may be marked as regions of special interest to facilitate later spectrum processing (see below, analysis options). The contents of groups of channels - usually starting with 256 as the smallest block and its binary increments - may be transferred into other locations within the memory. Unlike in magnetic core memories which had been used earlier, semiconductor memory data must be protected against failure of the main power supply. This is accomplished by an internal intermediate battery power unit which usually does not enable any multichannel analyser operation but is only intended to protect the memory contents.

Analog to digital converter

As noted above, Wilkinson-type pulse-height-to-time analog-to-digital converters almost exclusively used for photon spectroscopy. There are also other principles in use, but for spectroscopy the Wilkinson-type device is superior due to its excellent linearity. The operation principle is as follows: A pulse is digitised by charging a capacitor to the amplitude of the input and then discharging the capacitor at a constant discharge rate. During the discharge a crystal timer-controlled pulse sequence is counted in a register until the capacitor charge is decayed to zero. The number in the register then is proportional to the input signal height and corresponds to a specific channel whose contents is increased by one unit.

Important factors of the analog-to-digital converter are the conversion gain, the dead time and the linearity.

The conversion gain, given in channels per input voltage range, or just channels, refers to the slope of the analog to digital converter capacitor discharge function described above; it determines the number of channels in the memory which are addressed (or triggered) by the analog to digital converter, again usually starting with 2^8 normally selectable in binary increments up to a maximum of 2^{14} (16384). The quartz timer frequencies are 50-400 MHz.

The dead time refers to the time the analog-to-digital converter is busy while processing a pulse and cannot accept another. The dead time can be accounted for since it can be exactly calculated. Compensation for dead time is accomplished by data acquisition for "live time" periods, rather than "clock" or "true" time. The live time is obtained by gating off the internal clock with the dead

time. However, the dead time correction during operation of multichannel analysers is somewhat problematic; see Ref's.[630-633].

Normally, the timing mode of data acquisition may be selected by the operator, and usually both counting period information are available in the memory (normally in channels 0 and 1 as touched on above). It is important to note that the contribution of the electronic system to the total dead time of the spectrometer can be compensated, but not the dead time of the detector crystal itself; this dead time is not explicitely determinable. Therefore, in order to avoid measurement errors in high-precision measurements, it is of use not to exceed a certain integral count rate.

The linearity of the analog-to-digital converter is given in terms of differential and integral nonlinearity. Integral nonlinearity may be described as the deviation from a linear function of pulse height versus channel number, or energy versus channel number, respectively. Differential nonlinearity is the variation of the width of the single channels. Typical values are 0.025% for integral nonlinearity (1 channel per 4096) and 1% for differential nonlinearity. Usually in activation analysis application of multichannel analysers, linear calibration functions are sufficient for energy calibration.

A digital offset can be set by the operator. This is the capability of subtracting a selectable channel number (usually in increments of 1 in modern multichannel analysers) from the number of converted channels (see above, conversion gain) before the memory is accessed. This is equivalent to the use of a biased amplifier (see above), but has the advantage of being digital and thus more exact. It is mostly used to cut off lower energy ranges and expand higher ones across the full memory size.

An offset can also be set by shifting the baseline output level of the spectroscopy amplifier (see 4.2.1.2) but this is recommended in exceptional cases only since both the amplifier and the multichannel analyser operate optimally at approximately zero pulse baseline voltage.

For more information about analog-to-digital converters Ref's.[512,634-642] are recommended.

Mixer/router

Mixer/router inputs for data acquisition from multiple sources, typically up to 8, can be used for both pulse height analysing and multichannel scaling; some multichannel analyser models allow both kinds of pulse processing simultaneously. This unit, on the one hand, is extremely useful in the case that it provides a pseudo-multiple analog-to-digital converter pulse processing, i.e. all operation functions can be directed and executed independently in all selected partitions of the analog-to-digital converter; on the other hand, in the case of excessive integral pulse frequency incident to all inputs spectra might be distorted since the dead times of the single partitions of the analog-to-digital converter are added up. In high-quality multichannel analysers the optional use of more than one analog-to-digital converter is provided; these usually are available as NIM-module plug-ins.

Multichannel analysers can be used not only for pulse height analysing but also for multichannel scaling as shortly touched on above in the paragraph on the inputs. In this case the channels are activated or opened to the signal input (usually it is a separate input) sequentially at selectable dwell times. During the dwell time (selectable from microseconds to hours) incoming pulses are collected in the activated channel without regarding their heights as they exceed a predetermined threshold height. This application is particularly useful for analysis of decay functions for half-life determinations.

In early multichannel analysers only a data acquisition with clock timing, optionally plus dead time correction, was possible. In modern, microprocessor-equipped ones the data acquisition can be terminated by various other criteria as well, namely number of counts in any specific channel, overflow of any channel contents, integral in a specified region of the memory, net area or its statistical error of a specific peak and other criteria.

Internal display

Cathode-ray tube display units are used in most multichannel analysers. CRT screens in modern units are considerably large, typically about 30 cm in diagonal, to accomodate the operator's data inspection, operation setting and control. The display should be non-flickering and have high contrast. Frequently, different groups of data can be displayed in different colours to enhance the contrast of the displayed image. The primary task of the display is to allow immediate visual inspection of the data which have been collected and stored in

the memory, but it is not its only function. The display should enable the operator to keep track of all analyser functions which have been initialised also of those which are in operation and finally of those which are intended to be initialised, i.e. functions whose execution is initialised by an internal or remote computing device within a sequential operation program. Usually a lot of information can be displayed on the CRT. In order not to overload the screen with information, groups or logical blocks of data are displayed on the CRT upon the operator's request. The different features of the display in modern multichannel analysers are summarised in the following.

The memory contents or parts of it can be displayed, usually starting with 256 channels covering the horizontal full scale, increasing in binary increments up to a displayable maximum, typically 2^{14} or 16384 channels. Normally also smaller channel blocks may be expanded separately over the full horizontal scale. Single channels or blocks of adjacent channels may be identified and marked with single or dual markers. Different parts of the memory may be displayed simultaneously to allow immediate comparison, e.g. of two gamma-ray spectra. In some analysers it is possible to scan a window which covers a selectably sized part of the memory contents over the whole range to allow detailed inspection of the entire spectrum by displaying the screened part separately, expanded over the entire horizontal scale.

The vertical scale display mode may be selected linear or logarithmic, in some models also at a square root scale. In the case of linear display mode, the vertical full scale range may be selected in different steps up to the maximum capacity of a channel, as mentioned above usually being 2^{20} counts.

Following further information should be displayed, either permanently or upon the operator's request: preset counting time or other data acquisition limitations, actual horizontal and vertical full scale range, time and date, actual ADC dead time, input pulse frequency, number and contents of the cursor-located channel, in the case of dual markers integral channel contents between the markers. In some analyser models extra memory space is provided for any individual identification code or name of the data set; this code can be entered into the memory from any outer data I/O-device (see above, data inputs and outputs), and is then displayed on the CRT to allow immediate data set identification.

Finally, all operations are traced by the display, mostly in a dialog mode, including command checks, warnings and comments, e.g. request for confirmation, to avoid missettings and accidental damage of data, as mentioned in the above

paragraph on the multichannel analyser processor.

More about information to be displayed on the CRT is mentioned in the following paragraphs about the data analysis and computing units of the analyser.

Analysis options

The analysis software other than the above described components mostly is supplied optionally upon the users request since it serves very special demands. For instance, a nuclide library may be helpful if the spectrometer is primarily used for analysis of radioactive wastes or effluents or other contamination whereas it is of no use for those who mainly perform multiscaling measurements. Therefore, the user should be able to select the offered software options according to his special requirements. Some of these analysis options are not urgently necessary if - as is usual in activation analysis - the multichannel analyser is coupied on-line to a computer, but they might be helpful in reducing the data to a conveniently processible minimum and thus help to save computer memory space and computing time. Following analysis options are usually offered:

- Internal energy calibration function computation
- Peak centroid location
- Net peak area calculation
- Peak search
- Spectrum smoothing
- Spectrum stripping
- Spectrum normalisation and ratio computation
- Isotope identification by internal isotope library
- Spectrometer efficiency calibration and quantitative activity analysis

and others.

Additionally frequently learn/execute facilities are available to allow sequential operation step execution, e.g. including sample changing, data processing or transfer etc..

As yet, due to the limited size of a multichannel analyser software capacity, some of these analysis routines operate with limitations, e.g. usually no peak multiplet unfolding is possible, and it is not possible to perform a complete activation analysis evaluation. Therefore, as already stated, an external com-

puter is still a must in multielement activation analysis. However, regarding the advances in nuclear electronics, this might change in the near future.

4.2.2.3 Miscellaneous options

In the following, several electronic devices are briefly described which are not necessarily imperative for a photon spectrometer but have proved useful for photon activation analysis work.

- Coincidence unit; especially in the case of the light element analysis, as is explained in detail in chapter 6.1, a pulse coincidence unit may enhance both the sensitivity of the method and the accuracy of the results. Pulses originating from two sources (usually NaI crystals) are fed into the coincidence unit. All pulses falling in non-simultaneously are then gated off and discarded. In the case of coincidence, a signal is passed on to a following counting or analysing device.

- Spectrum stabiliser; this unit fulfills serveral tasks. It compensates for gain shifts due to any instability source within the spectrometer (detector, high voltage supply, preamplifier, spectroscopy amplifier); it also compensates for baseline level shift in the spectroscopy amplifier which often occurs at excessively high count rates. To summarise, the spectrum stabiliser ensures drift-free data acquisition over quasi-unlimited counting time.

- Reference pulser; due to the complexity of a photon spectrometer it is of use to provide a monitoring device which tests the proper operation of the spectromemter and investigates malfunctions. With help of a high-precision pulser, quasi-"ideal" pulses can be fed into any of the electronic specrometry devices to simulate ideal input conditions in the electronic system. A verification or, if necessary, an adjustment of the corresponding output signal can be made with use of known input which is free of detector limitations. Thus, the reference pulser can be used for stability or linearity checks on the equipment, to determine contamination by electronic noise, to calibrate and monitor the pulse height analysis system and finally, to check the proper operation of the whole electronic part of the spectrometer. Moreover, the dead time of the electronic part of the spectrometer can be accounted for by feeding the constant reference pulser frequency into the appropriate preamplifier input and measuring the area of the corresponding pulser peak.

4.3 The spectrometers used for the present work

In this paragraph, the photon spectrometers are described which have been used for the present work, especially for the determination of the data given in Ch.5. Fig.4.8 shows the shielding configuration of the detector, the detail figure 4.32 represents the detector head plus sample positioner.

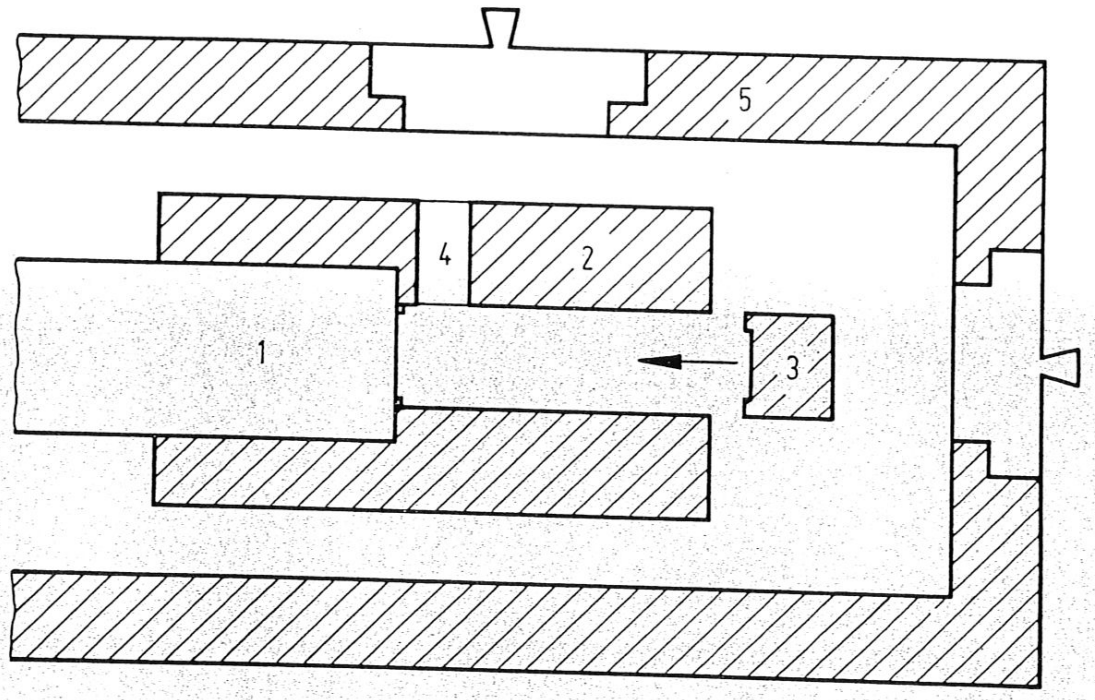

Fig. 4.32: Sample position setup used in the present work; 1 = detector head, 2 = plastic cylinder, 3 = sample holder, 4 = inlet for test-tube sample holder, 5 = lead- or iron shielding

Low energy spectra ($E \lesssim 90$ keV) were taken with an intrinsic planar germanium diode with the following parameters:

active area: 300 mm^2
active thickness: 7 mm
operating voltage: -1400V
energy resolution: 180 eV FWHM at 5 keV
500 eV FWHM at 121 keV

High energy photon spectra (E=90-3000 keV) were measured with a standard coaxial lithium-drifted germanium detector. The parameters were as follows:

active volume: 50 cm^3
counting efficiency: 18% of a 3" by 3" NaI (Tl) crystal at 662 keV at a distance of 20 cm from the detector housing
operating voltage: +4800 V
peak-to-compton signal height ratio: 42 at 662 keV
energy resolution: 2.0 keV FWHM at 1333 keV

Both detectors had a horizontal cryostat configuration as demonstrated in Fig. 4.8. Bias voltage supply NIM plug-in units were used as operating voltage source. The spectroscopy amplifiers were equipped with baseline restorer, pulse shaping and pile-up rejection units. However, the latter one was not used since in no case an input rate of 10000 pulses per second was exceeded during spectrum counting. Spectra were stored in 2048 channels of a multichannel pulse-height analyser. This analyser was equipped with a 8192 channel memory and with all the analysis options described above. For spectra evaluation, however, a computer was used.

4.4 Preparation of semiconductor photon spectrometers for analysis

Once the complete spectrometer is properly installed, the first step of gamma spectrometry is the energy calibration, i.e. the determination of the channel number versus photon energy function. This is either performed using several gamma-emitting radionuclide reference samples (usually ^{133}Ba, ^{22}Na, ^{137}Cs, ^{60}Co etc.) or one gamma-emitting reference sample containing a radionuclide which emits many photon energies covering the entire energy region of interest (^{152}Eu, ^{226}Ra etc.). As noted in paragraph 4.1.4.5, the pulse height versus photon energy function in the region of analytical interest, i.e. from 5 to 90 keV for low energy photon spectrometers and from 90 to 3000 keV for conventional gamma spectrometers is linear[414,492,513,514,643-646]. Therefore there is no point in fitting a function of higher order as is frequently optionally provided in the spectrum analysis software within modern multichannel analysers (see paragraph 4.2.2.2). It is important to note that the gamma reference samples have to be measured keeping the same geometry as used in later analysis since shifts of the energy calibration function at different counting geometries have been observed (see Ref's.[647,648].

A very important factor is the number of channels of the full spectrum (or the single peak, respectively), which can be selected by proper setting of the conversion gain of the ADC as noted in 4.2.2.2. For different reasons it is of use to demensionate the total spectrum memory size so that each peak at least contains five to six channels. A smaller number would entail significant loss of energy resolution of the spectrometer. Moreover, it is easier for computer programs to process peak which contain a good number of information points, e.g. in the case of multiplet unfolding (Reimers et al.[649]). During practical laboratory work it was found that 2048 channels is an acceptable number for a spectrum in photon activation analysis, covering about 2000 keV in total. The determination of the detector efficiency versus photon energy function is not discussed here since in photon activation analysis (as in all other activation analysis methods) no absolute radionuclide activities are determined but gamma emission rates of identical photon lines of an analysis sample and a reference material are compared. This is explained further in chapter 6.

The next step is the proper positioning of the activated sample at the detector and the data acquisition. Details on these procedures are also presented in chapter 6 on the applications of photon activation analysis.

The qualitative analysis of the photon spectrum is then performed by determinat-

ion of the photopeak energy and comparison with tabulated energy values either using compilations, e.g. as presented in chapter 5, or in the gamma-ray catalogues cited in chapters 5 and 6, or with help of an internal library in the multichannel analyser (see 4.2.2.2) or in an external processing device. Sometimes it might be necessary to analyse the half-lives of some photon emitting activities, e.g. in the case of spectral interference by other nuclides. However, this is necessary in exceptionally disadvantageous cases only (see chapter 6.1), since almost all product nuclides after bremsstrahlung exposure emit a characteristic photon spectrum as is the case in all other nuclear activation analysis techniques, too (see chapters 2 and 5).

The quantitative evaluation of the acquired spectra is performed by net area determination of the full energy photon peaks. An "ideal" photopeak can be adequately described in terms of a Gaussian curve[650] superimposed upon the background which is primarily due to Compton effects. To determine the pulses which are due to the full energy signals exclusively, the background has to be subtracted (see Fig.4.33).

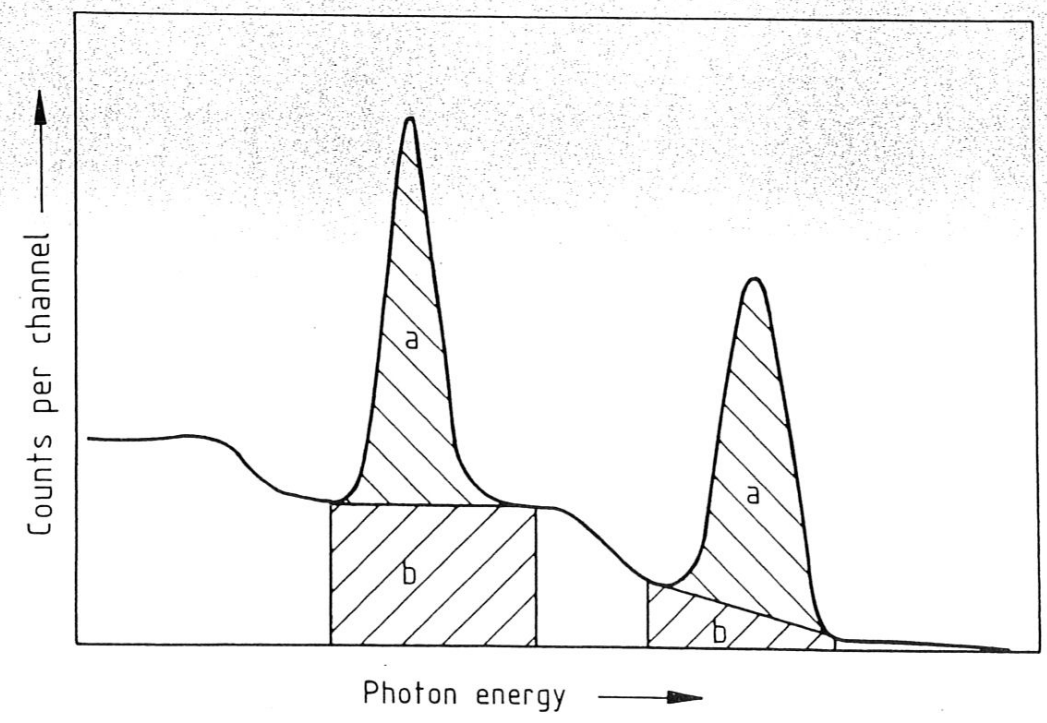

Fig. 4.33: Net area (a) and background (b) of γ-ray peaks

The integration limits can be calculated with help of the peak data; it should be assured that these limits at least fall within the unification points of the photopeak with the background line. It is of advantage to somewhat enlarge the integration limits since even with highest quality electronic spectrometry components minute shifts of the calibration function cannot be avoided for sure, especially over long data acquisition periods. An excellent extended description of peak analysis including algorithms for precision peak integration is given by Debertin[651]. It was found in practice that special additional spectrum treatment like smoothing does not ensure improved accuracy and precision of the obtained data. Moreover, the safest way to ascertain non-erroneous net peak area determination is the evaluation using interactive computer programs which allow visual control of the spectrum processing (Reimers et al.[649]).

More information on the quantitative spectra processing can be found in the above cited report of K. Debertin and will be given in Chapter 6.2 of this book. See also Ref's.[652-673,676,677].