CHAPTER 7

APPLICATIONS OF SCINTILLATION COUNTING AND ANALYSIS

7.1 Nuclear medecine

The information sought in most medical applications of scintillation detection is a clinically significant internal image of the body. Here we will treat only the imaging modality using photomultiplier tubes, i.e. nuclear medicine.

The radioactively labelled substances administered are chosen for their affinity to the specific organs or tissues to be studied. From the local radiation intensities registered by scintillation detectors it is then possible to construct images of the organs or tissues under investigation. In cardiac studies, for example, labelled substances injected into a vein enable dynamic images of the heart action to be obtained. A growing pharmacopoeia of radioactive tracers is steadily increasing the number of organs, tissues and functions that are accessible to this type of investigation.

An imaging system for nuclear medicine consists mainly of
- a collimator to select radiation emitted at a specific angle
- either one large scintillator covered by many large photomultipliers or many small scintillators read out by several smaller photomultipliers
- preamplifiers, pulse-shaping and analysing electronics, and discriminators
- a computer for constructing an image based on the information derived from the detected radiation.

Within this general framework there are numerous variations.

γ-cameras. The γ-camera invented by Anger offers dynamic information and has a fields of view up to 45 cm in diameter or 40 cm × 60 cm in rectangular format. In its usual form (Fig.7.1) it consists of a hexagonally or square close-packed array of photomultipliers coupled via a light guide (Fig.7.3) to a single, large scintillator. Radiation reaches the scintillator through a collimator of radiopaque material (e.g. lead, tungsten) with a dense, sieve-like array of parallel holes.

Apart from parallel-hole collimators, several other types exist, e.g. diverging and converging hole collimators to enlarge the field of view or increase the resolution at a specific depths within the body, slant-hole collimators to enable oblique imaging, and line-focused collimators for whole-body scanning.

Since all the photomultipliers view the scintillator, they all respond more or less to each scintillation, their signals being a function of their distance from the scintillation point and the total amount of light emitted by the scintillator, which is a function of

the energy of the γ-quanta. The coordinates of the scintillation point are calculated from summation signals obtained by passing the photomultiplier signals through a summation network incorporating weighting factors (resistors or capacitors). These weighting factors are chosen such that the summation signals either increase or decrease linearly with the x or y coordinates. As the photomultiplier signals are energy dependent, so too are the summation signals and hence the scintillation coordinates. To remove this energy dependence of the calculated coordinates the following algorithm is often used:

$$x = \frac{X^{+} - X^{-}}{X^{+} + X^{-}}$$

in which X = summation signals. The y coordinate is similarly calculated from the Y^{+} and Y^{-} summation signals.

Besides the summation signals defining position, there is also a fifth summation signal E or Z – the energy summation signal. Its function is to exclude (discriminate) undefined coordinate information caused by scattered radiation. This is necessary because the scattering process not only affects the direction but also lowers the energy of the γ-quanta.

The weighting factors for the energy summation signal are chosen such that the signal is virtually independent of the position of the scintillation. The energy signal is analysed by a multichannel analyser (MCA) in which, by appropriate choice of energy window, only so called *photo-peak events* are accepted while signals with other energies are excluded. This results in better contrast. The image is obtained by acquiring tens of thousands to millions of accepted events (counts).

Originally, the image was displayed on a cathode ray tube (CRT) with a long-persistence phosphor for direct viewing or integrated with a polaroid film cassette for recording. Nowadays, all γ-cameras are integrated with a computer. The position signals are digitized and the images are stored in memory and displayed via a monitor or sent to a hardcopy unit. The computer can be used for several forms of image processing and reconstruction (whole body, tomography). Its use is increasingly being extended toward providing total system control and user interfacing (Fig.7.1).

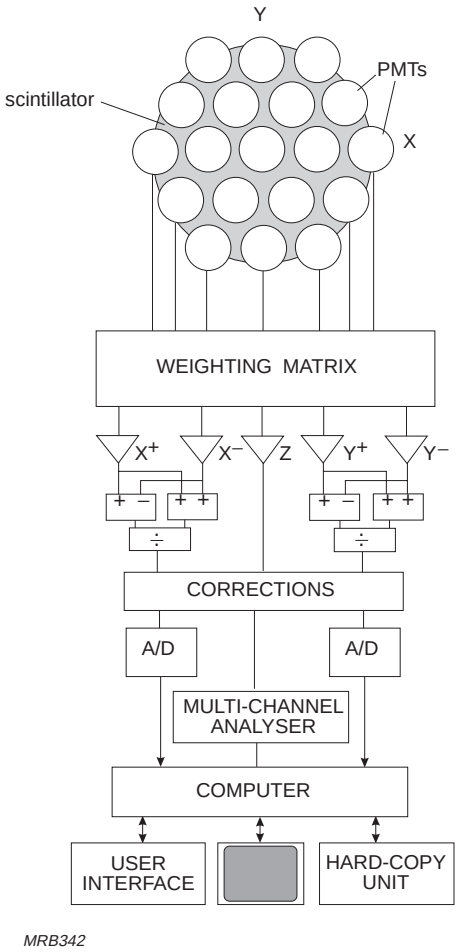

Fig.7.1 Operating principle of a γ-camera

The most important demands on photomultipliers for use in γ-cameras are
- uniform azimuthal response
- excellent pulse-amplitude resolution over a large dynamic range. γ-energies vary between 50 keV and 400 keV but the dynamic range is much larger due to the signal variation caused by the variation in distance to the scintillation point (by factors of between 30 and 100).
- very stable gain as a function of time, count rate and magnetic field.

The energy resolution of a photomultiplier varies inversely as the square root of the signal amplitude, which decreases as the distance of the scintillation from the photomultiplier axis increases. This decrease is commonly described by fall-off curves in which the photomultiplier response is plotted as a function of the off-axis distance (in any direction) of the scintillation. By designing the front end of the tube so as to favour the collection of distant light, it is possible to broaden the fall-off curve somewhat, and thereby improve the energy resolution of the tube for distant scintillations, improve the uniformity and linearity of the picture and, most important,

improve the camera's spatial resolution. Also, the use of hexagonal or square tubes, which can be close-packed with less dead space between them or with the dead space more uniformly distributed, makes it possible to obtain a larger sum signal and thus improve the energy resolution of the entire camera.

The interrelated aspects of azimuth response and tube energy resolution with picture uniformity, linearity and spatial resolution are the most important parameters for characterizing photomultipliers for γ-camera applications. The closer the scintillations are to the photocathode, the more critical these parameters are. They are less critical in cameras with thick scintillators and thick light guides between the scintillator and the photomultipliers, so here the use of hexagonal tubes may bring only minor advantages. Hence, different camera designs call for differently optimized tubes.

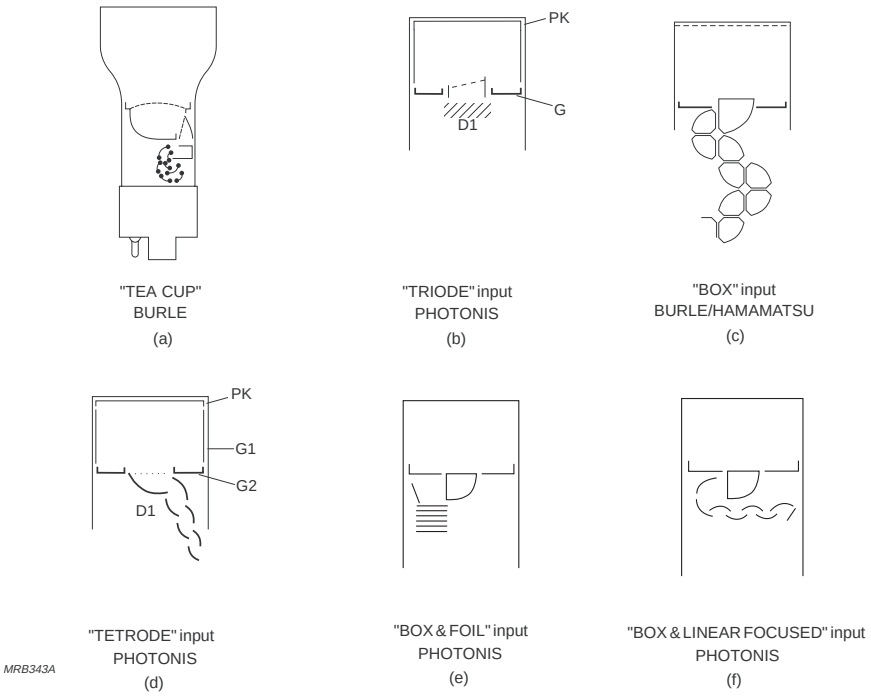

Fig.7.2 Examples of γ-camera tube input systems

The quest for improved azimuthal response and tube resolution has led to several developments in electron-optical input systems over the years. Amongst these are the 'teacup' first dynode of Burle, the asymmetric 'triode' input to venetian-blind dynodes and the 'tetrode' input to linear focusing dynodes of Photonis. Others include the 'box & grid' multiplier of Burle and Hamamatsu and the 'box & linear focusing' and 'box & foil' multiplier systems of Photonis (Fig.7.2). These newer multipliers have also enabled tube manufacturers to make much shorter tubes, resulting in thinner and, for the patient, less threatening γ-camera heads whilst simplifying the mechanical counterweights needed for rotating cameras. At the same

time, the quest for better energy resolution has led to improvements in cathode sensitivity, collection efficiency, and first-dynode multiplication statistics. And with present-day tubes, gain drifts can be kept well below 1% per month under the conditions prevailing in γ-cameras.

In modern γ-cameras, a whole palette of tricks and corrections is used to optimise the images. Important parameters are:
– spatial resolution
– uniformity
– energy resolution
– linearity (distortion)
– speed/temporal resolution
– stability (time, temperature, position).

Some of these properties result in conflicting parameter settings for the camera (e.g. resolution versus uniformity). Most of them, however, are more or less interdependent.

The shape of the response curve (fall-off versus distance) plays an important role in spatial resolution, linearity and uniformity. The shape is influenced by several factors (e.g. crystal and light-guide thickness and refractive index, shape and size of photomultipliers). Furthermore, it can be influenced by optical tricks (redistribution of light) and electronically (non-linear amplifier characteristics, threshold). It is also possible to introduce special processing for the signals contributing to the energy summation signals (to reduce noise).

During the last fifteen years, the γ-camera has seen many impressive improvements including the introduction of digital correction systems for controlling linearity, uniformity, energy uniformity and photomultiplier stabilization (off-line and on-line).

Traditionally it was common for cameras to contain 37, 61 or 91 circular tubes in a hexagonal array. Recently, the most popular and lowest-price concepts that still offer good spatial resolution make use of 55 circular tubes of 76 mm diameter with 6 elongated-hexagonal 40 mm tubes along the sides of the rectangular array, or simply 48 square 76 mm tubes forming a rectangular array. Large rectangular cameras have replaced rectilinear and hybrid scanners for whole-body scanning. Small-field-of-view cameras with thirty-seven 1.5 inch or 2 inch tubes are used for cardiac studies (sometimes as mobile cameras), an application in which gain stability as a function of anode current is critically important: count rates commonly go from background to as much as half a million for a few seconds and then down to background again.

For the tubes nearest the patient's heart, the variation in anode current is considerable. Here, a low gain hysteresis is also important.

A major application of γ-cameras is single-photon emission computed tomography (SPECT, Fig.7.3), in which cross-sectional images of the body are generated by one, two or even three rotating camera heads around the patient. This imposes a further demand on the photomultipliers used: insensitivity to variations of ambient magnetic field. The constructions shown in Fig.7.2 have proved themselves able to meet this requirement fully and at the same time provide good azimuthal response.

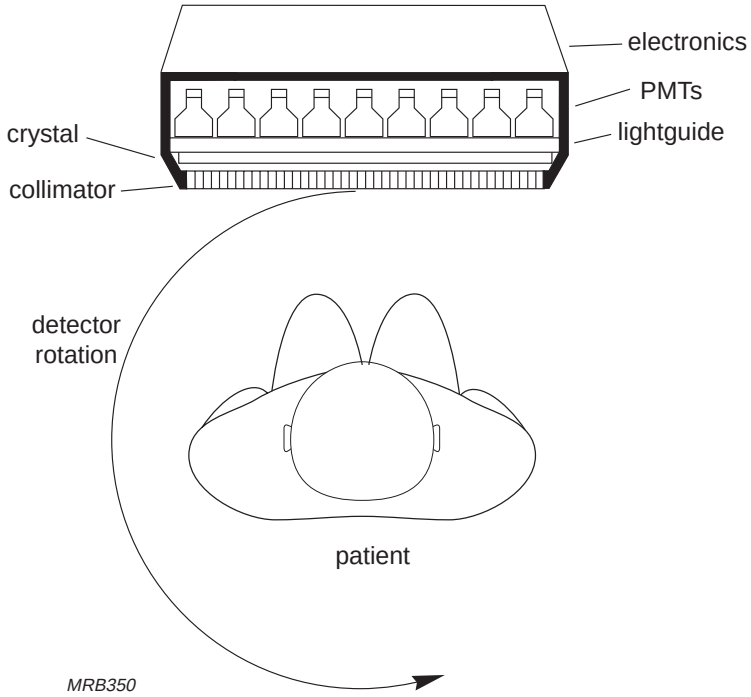

Fig.7.3 Principle of single-photon emission computed tomography (SPECT). The γ-camera head (sometimes 2 or 3) is moved around the patient and acquires projections from several angles. These are back-projected by computer to give transversal slices

Because of their inherently superior energy resolution, semiconductor radiation detectors appear to promise advantages over the scintillator and photomultiplier combination; theoretically at least, a γ-camera using high-purity germanium detectors should provide superior contrast and spatial resolution. So far, however, fulfilment of this promise has not been economically feasible. The low efficiencies of prototype systems, together with the technological difficulty of manufacturing large arrays of sufficiently uniform detectors, has discouraged serious ventures into production.

A further drawback of germanium is that it has to be cooled to liquid-nitrogen temperature. Two candidates for room-temperature detectors, CdTe and HgI_2, have been under investigation for many years but have yet to yield commercially usable results. Again, the stumbling blocks have been material quality and detector size. Detector polarization under radiation has also presented problems that have not yet been fully solved. At the moment, it looks as if semiconductor detectors have little chance of supplanting scintillators and photomultipliers in large field-of-view γ-cameras within the next ten years. However, new CdZnTe (CZT) room-temperature solid-state detectors may slowly become feasible for small, dedicated cardiac and thyroid γ-cameras with better spatial resolution. This will, however, require a significant reduction in the cost of growing and selecting useful (high-quality) single-crystal pieces out of a multi-crystal ingot.

Another idea that has been explored (and abandoned) is to combine a scintillator with a large image intensifier observed by a number of photomultipliers or other photo-sensors. Here, problems with the image intensifier (especially its size) have been the principal barrier to continued progress.

Experiments with gas-multiplication wire chambers have led to useful prototype cameras only for low γ-energies, where the efficiency of such a system is acceptable. Trials with the fast UV-emitting BaF_2 scintillator have recently raised the efficiency of such systems to useful levels. However, the UV-readout process involving a 'liquid' TMAE photocathode (not very stable over time) has so far been tried only on a laboratory scale, and new liquid photocathodes with greater overlap with the 190/225 nm fast BaF_2 peak have yet to be found.

Many ideas for replacing the photomultiplier by silicon or avalanche photo-diodes fall down on the basis of surface area, performance, price of the diode and the high number of electronic channels needed. Recently, however, a small camera has been commercialised based on an array of small CsI(Tl) scintillators plus silicon photodiodes for the niche market of local cardiac doctors.

Nevertheless, since large field-of-view γ-camera applications form a backbone of the world photomultiplier market, it seems likely that the scintillator-photomultiplier partnership will survive for many years yet, and that γ-camera developments, such as adding depth-of-interaction (DOI) corrections, will continue to motivate photomultiplier improvements as they have in the past.

Positron scanners. In positron emission tomography (PET), Fig.7.4, a positron-emitting isotope is administered to the patient and the body region under investigation

is surrounded by rings of small scintillators and photomultipliers. A computer constructs cross-sectional metabolic images based on detection of the two coincident 511 keV γ-photons which are emitted 180° apart when a positron annihilates with an electron in the patient's body. Owing to the very short half-lives of the four commonly used isotopes: ^{11}C (20 min), ^{13}N (10 min), ^{15}O (2 min) and ^{18}F (110 min), they must be produced and processed into labelled compounds on site. This calls for a dedicated cyclotron and radiochemistry facilities and for many years this has limited the use of PET to large, well-funded research hospitals. Scanners for measuring the blood flow in the coronary arteries were therefore the first to go into clinical use in hospitals. These make use of the long-lived isotope ^{82}Rb milked from ^{82}Sr (produced commercially by several accelerator centres around the world), eliminating the need for a cyclotron on site.

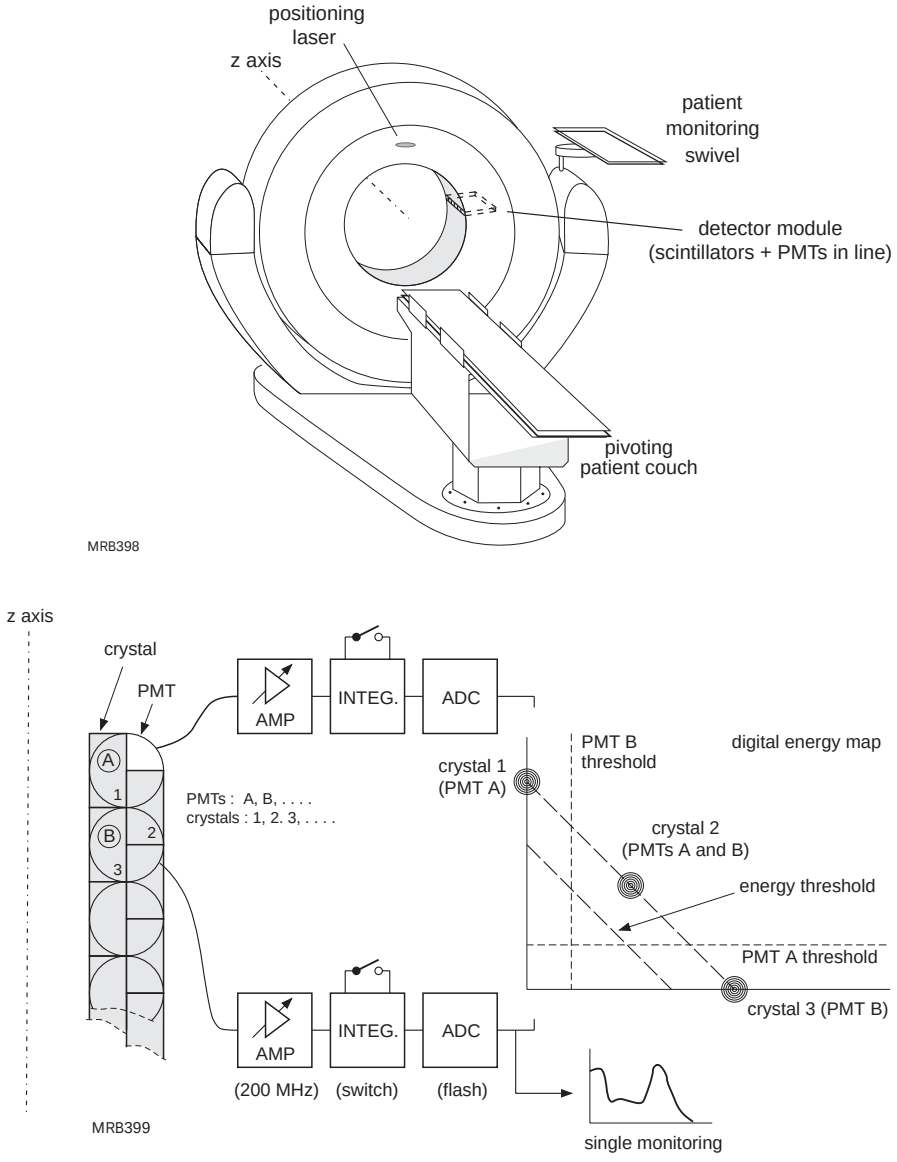

Fig.7.4 Principle of the PET scanner (courtesy of Positron Corporation, Houston, Texas). Light output from crystal 1 is primarily detected by PMT A, while light output from crystal 2 is detected by PMTs A and B equally

For some years, however, a few major medical-imaging companies have been investing heavily in PET scanner designs for clinical use, as the PET modality has been proven to be far superior to other modalities in clinical oncology. This has also been further promoted by the introduction of fluorodeoxyglucose (FDG) marked with the positron emitter ^{18}F, a type of sugar that concentrates in malignant tumours because of their faster growth than surrounding tissue. Owing to the 110 minute half life of the ^{18}F isotope, FDG can be transported from a cyclotron centre to several PET hospitals in densely populated areas offering better economy to the PET modality. Another approach that has recently become popular is to put the cyclotron in a van and visit several hospitals to a schedule of need. This market boom has resulted in PET applications becoming another backbone of the world photomultiplier market, further driving the development of new, dedicated PMT types.

The first PET scanners used NaI(Tl) scintillators and slow coincidence detection; the principal demands on the photomultipliers were good energy resolution and moderate time resolution. Later scanners use multiple detector rings with the green-emitting scintillator $Bi_4Ge_3O_{12}$ (colloquially, BGO). These scanners therefore require photomultipliers with good green sensitivity (which is provided by the introduction of green-extended bialkali cathodes), and improved time resolution, which calls for good collection efficiency in multi-electron mode. Note, however, that the time resolution is, in any case, limited by the slow decay time constant (300 ns) and dimensions of the BGO crystals.

A disadvantage of BGO as a scintillator is that it has a refractive index of 2.15, which makes it difficult to couple to the normal glass windows of photomultipliers (refractive index about 1.5), so the light gets trapped in the scintillator. Trials of other glasses have not yet led to a practical solution to this problem. Design effort has concentrated instead on trying to match the scintillators to the windows of the photomultipliers in such a way as to achieve the required dense rectangular packing of detectors without too much ‘geometrical’ light loss.

PET scanners with NaI(Tl) or BGO scintillators use slow coincidence detection. By using fast coincidence detection it becomes possible to ‘unfold’ a lot of noise from the picture. With this in view a number of scanners were developed around the fast scintillator compound CsF. This emits in the blue and ultraviolet and requires fast photomultipliers with UV-transparent windows. To attain the required efficiency for 511 keV γ-photons, CsF scintillators have to be several centimetres long. This sets a limit to the time resolution of the scintillator itself (as well as introducing parallax problems) and therefore puts severe demands on the time resolution of the photo-

multiplier. For multi-electron events, coincidence times below 400 ps can be resolved between two opposite channels.

The discovery of the fast 190/225 nm peak (decay time constant 0.6 ns) of BaF_2 has practically killed all interest in the highly hygroscopic CsF and directed most of the development effort in fast coincidence scanners toward BaF_2 and fast quartz window photomultipliers. Though PET scanners with two scintillators working with one photomultiplier (GSO as the fast channel and BGO as the slow channel) have been produced, GSO prices have so far limited further interest. Nevertheless, with a decay time constant of 35 ns and high stopping power, GSO now forms the basis of one of the new scanners. Others use blocks of many small BGO 'needles', a few millimetres in cross-section and about 25 mm long coupled to several 19 mm diameter photomultipliers or to two 24 mm square, dual photomultipliers. Future developments are expected to see the blocks read out with one single, quadrupole tube (four tubes in one envelop) developed by Photonis for decreasing the readout cost.

The recent introduction of the lutethium orthosilicate (LSO) scintillator by one major company, offering a slightly higher density than BGO, a decay time constant of only 42 ns combined with a refractive index of only 1.81 and a light output seven times that of BGO has contributed to a major leap in PET scanner performance. Several other new inorganic scintillators are under investigation to compete or further improve on the parameters of LSO.

Animal PET scanners. As a spin-off from PET scanners there has in recent years appeared a new market for photomultipliers for so called animal PET scanners. These are miniaturised PET scanners for studying the influence of new pharmaceuticals on rodents such as mice. Most profit from the new LSO scintillator forming narrow scintillator needles that are read out by multi-channel photomultipliers, sometimes via fibre light guides. The market, however, is still limited to pharmacological research.

Mamography scanners. The introduction of multi-channel photomultipliers has also stimulated a new market dedicated to mammography scanners based on different versions of the new scintillators, and some small companies have recently been created to promote such systems.

7.2 Analytical applications

Scintillation counting has opened the way to numerous techniques for measuring specific biochemical levels in body tissues and fluids with the aid of radioactive

tracers. Two of the most widely used are liquid scintillation counting and radio-immuno assay.

7.2.1 Liquid scintillation counting

The aim of liquid scintillation counting (LSC) is generally to trace the pathways of specific substances in the body or to measure their tendency to concentrate in specific tissues or fluids. For example a quantity of the substance in question is labelled with a radioactive tracer; after it has been assimilated, a sample is taken of the body tissue or fluid under investigation and the concentration of the labelled substance is determined by measuring its radioactivity.

Because of the organic nature of the samples to be measured, the radioactive tracer is usually an isotope of hydrogen or carbon. The most commonly used are the β-emitting isotopes ^{3}H and ^{14}C, with half-lives of 12.26 and 5500 years respectively, and maximum radiation energies of 18 keV and 156 keV (Fig.7.5). To detect such soft radiation it is necessary to incorporate the sample in the scintillation medium itself, hence the choice of a liquid. This not only prevents the β-particles from being stopped prematurely by air or detector windows, it also makes the response of the scintillator substantially isotropic (‘4π geometry’), which greatly improves counting efficiency at the very low energy levels involved.

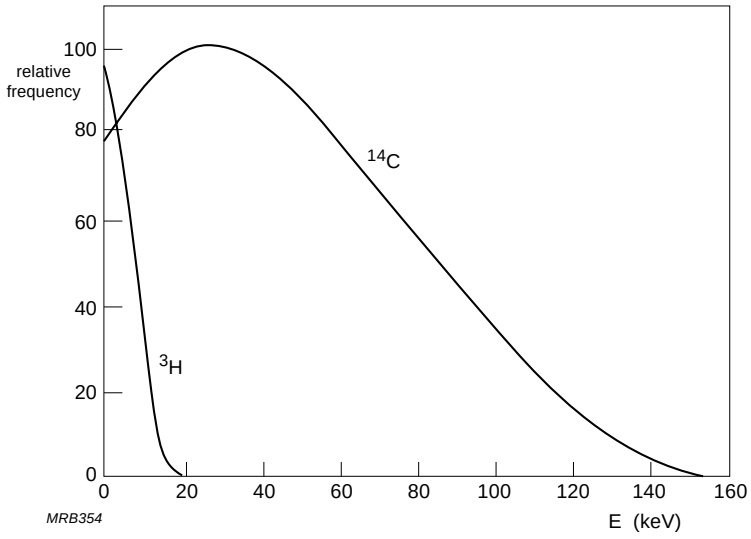

Fig.7.5 Relative spectral energy E of β emission from tritium (^{3}H) and carbon (^{14}C)

The liquid scintillator is a ‘cocktail’ consisting of at least one fluorescent aromatic solute in an aromatic solvent. One effective combination is PPO (2,5 diphenyl

oxazole) in toluene, which has a broad spectral emission peak at 370 nm. To avoid the use of a photomultiplier with a UV-glass or quartz window, a secondary solute that acts as a wavelength shifter may be added. A popular secondary solute is POPOP (1,4-bis-2-(5-phenyloxazolyl)-benzene) which shifts the spectral emission peak to 420 nm.

In a typical liquid scintillator, β-particles of 5 keV (mean energy for ^{3}H) will produce only about 50 photons, not all of which will reach the photomultiplier cathode. The resulting current pulses are therefore of the same order of magnitude as the dark pulses, so coincidence techniques must be used to distinguish them (Fig.7.6).

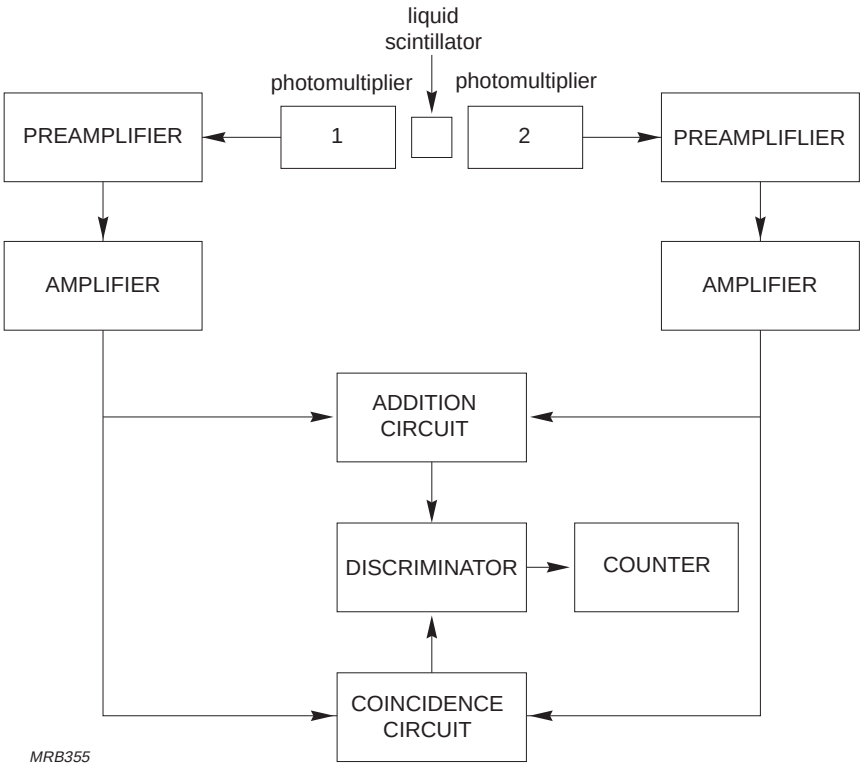

Fig.7.6 Schematic diagram of a liquid scintillation counter

The scintillator is observed by two photomultipliers 180° apart whose outputs are added together. Whenever a scintillation is observed by both tubes in coincidence, the added outputs are gated to a discriminator; provided their combined amplitude falls within a set window, the pulse is then passed to a counter. Except for chance coincidences, which are rare, random dark-current pulses from both tubes occur independently of each other and are rejected.

If n_1 and n_2 are the average dark pulse rates of the two tubes and τ is the resolving time of the coincidence circuit, the chance coincidence rate $n_f = 2n_1n_2\tau$. This usually amounts to less than one count per minute.

Besides the chance coincidences due to the dark pulse rates of the two tubes, however, other spurious coincidences also occur. One source is background radiation, for instance high-energy cosmic rays that penetrate to the scintillation sample. Another is crosstalk between tubes, which occurs when a light flash in one tube – due to the background radioactivity of its own glass, internal ionization, or a cosmic ray – is also seen by the other tube. The background count due to these causes can be minimized, but not wholly eliminated, by good shielding and careful setting of the discriminator window.

The counting efficiency E, in per cent, is

$$E = \frac{n_c - n_b}{N} 100$$

where n_c is the count rate, n_b the background count rate, and N the actual disintegration rate. A figure of merit combining the counting efficiency and background effects is E^2/n_b, where n_b is the background count rate measured under normal operating conditions but with no sample in the liquid scintillator. Though coincidence counting does reduce the counting efficiency E, it considerably increases the figure of merit by excluding nearly all the dark pulses due to thermionic emission and background radiation.

The sample chamber and vial must be designed to ensure maximum photon collection by both photomultipliers and equal division of photons between them. In present-day equipment the energy loss per photon in the scintillator, between point of origin and photocathode, averages 400 eV. Knowing this value and the energy spectrum of the radioisotope to be measured, one can calculate the efficiency for ^3H as a function of photocathode sensitivity, with photon energy loss as parameter (Fig.7.7).

The counting efficiency of present-day liquid scintillation counters is generally better than 60% for ^3H. Provided the sample chamber is well designed and well shielded, the background count rate n_b may be as low as 15 to 18 per minute, giving a figure of merit greater than 200. Modern counters with automatic sample changers can measure and register hundreds of samples in a single loading.

Photomultipliers for liquid scintillation counting require high quantum efficiency at the scintillation wavelength and low dark-count rate. Bialkali cathodes (SbKCs),

whose sensitivity is best toward the short wavelength end of the visible spectrum are generally preferred, sometimes with quartz input windows. The tube envelope should be of low ^{40}K glass to minimize background radiation, and the input window should be as thin as possible to minimize its volume.

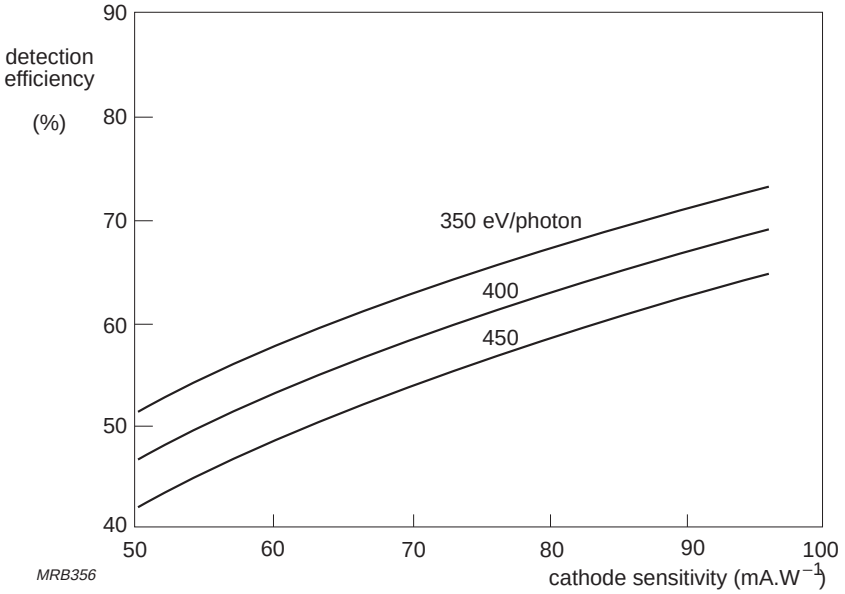

Fig.7.7 Detection efficiency as a function of photocathode sensitivity for ^{3}H, with energy loss as parameter

7.2.2 Radio-immuno assay

Radio-immuno assay (RIA) is a technique for measuring minute concentrations of specific substances, such as hormones, in biological fluids. A known quantity of the substance sought is labelled with a radioactive tracer and mixed with a specimen of the biological fluid under investigation. A comparatively small quantity of a binding agent (e.g. an antibody) with a specific affinity for the substance is then added to the specimen and allowed to react with both the labelled and unlabelled molecules of the substance. When the reaction has reached equilibrium the bound and the remaining free molecules of the substance are separated from each other, for instance by centrifuging. From the concentration of the radioactively labelled molecules in either fraction, as measured by scintillation counting, it is then possible to determine the concentration of the unlabelled molecules in the original specimen. In this way it has proved possible to detect and measure quantities as minute as picogrammes (10^{-12} g). Because it does not expose the subject to any radioactivity at all, RIA has become the method of choice for a large number of diagnostic tests – in fact the only practical method for some – and is now practised on a very wide scale as a routine procedure.

The tracers used in RIA are γ-emitters, and the detectors are well-type NaI(Tl) scintillators coupled to individual photomultipliers. Commonly used tracers are ^{125}I (35 keV γ-radiation) and, to a less extent (because it requires greater detection efficiency and has a shorter half-life) ^{131}I (360 keV γ-radiation). For determining the concentration of substances that contain cobalt but not iodine (e.g. vitamin B_{12}), one of the radioisotopes ^{57}Co, ^{58}Co or ^{60}Co may be used.

Counters for use in RIA are available as automatic sample changers, having one or more detectors, or as simple table-top equipment with up to 20 detectors in which the sample tray is changed by hand. Automatic sample changers, for which high capacity and therefore high efficiency are important, commonly use 2 inch scintillators coupled to similar-sized photomultipliers. Table-top models use 19 mm or 29 mm scintillators and photomultipliers.

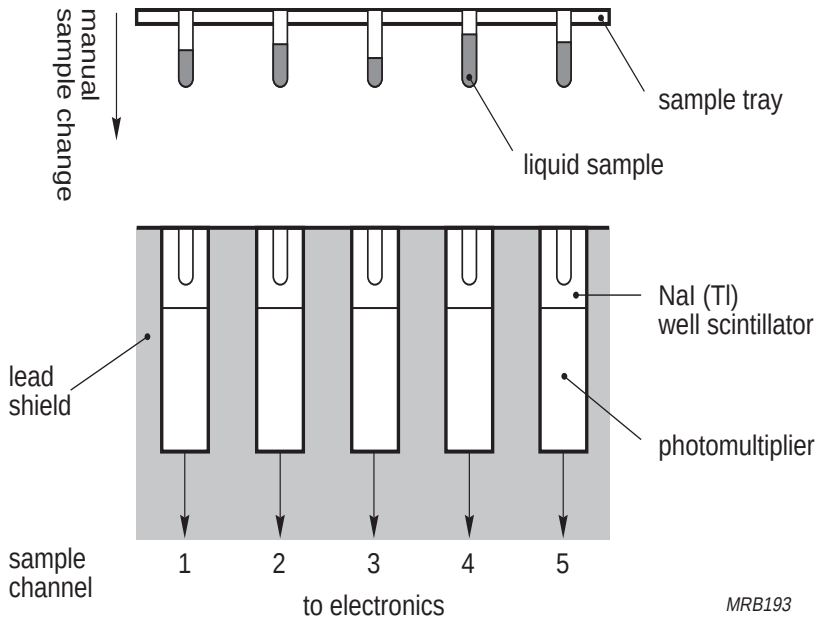

Fig.7.8 RIA counter with 5 channels

Because of the well in the scintillator the γ-interaction efficiency is high but the light transport to the photomultiplier is less than ideal. This puts demands on the photomultiplier energy resolution at the low γ-energies of some tracer isotopes (e.g. ^{125}I); it also imposes a requirement for low noise at those energy levels, plus good stability, to ensure that the detected energy peak remains within the discriminator window. Normally, 8- to 10-stage standard tubes afford sufficient gain and energy resolution, and are reasonably priced. The RIA technique is, nevertheless, currently experiencing serious competition from another technique known as chemiluminescence immuno assay (CLIA), see §8.1.2.

7.3 Industrial applications

Of the many industrial applications of scintillation counting, the three treated briefly here – non-destructive analysis of materials, thickness and density measurement, and oil-well logging – illustrate common principles and can be regarded as typical.

7.3.1 Non-destructive analysis

Two widely used methods of non-destructive analysis based on scintillation counting are:

- *Activation analysis*, in which the specimen is subjected to nuclear radiation so that the constituent elements become radioactive and can be identified and quantified by their own radiation
- *X-fluorescent analysis*, in which the specimen is exposed to γ, X or charged-particle radiation to stimulate emission of X-ray spectra characteristic of the constituent elements.

Activation analysis. Neutron irradiation is the most common means of activation; however, irradiation with high-energy γ-rays or charged particles, such as protons or deuterons, is also possible. The characteristics of the induced radioactivity that identify the constituent elements are its type (α, β, γ, X), its decay half-life, and its energy spectrum. As a rule these are sufficient for good analytical discrimination without supplementary chemical separation. The advantages of activation analysis are: speed; independence of the form in which elements are combined; preservation of the specimen; and great sensitivity, especially if the irradiation flux is large.

Short-lived radioisotopes can be identified by plotting their decay and determining the half-life. If the half-lives of constituent isotopes differ sufficiently they can be distinguished by a graphical breakdown; Fig.7.9 shows the decay of a mixture of ^{165}Dy and ^{152m}Eu as the sum of their respective half-lives. The greater the number of radioisotopes in the specimen and the more similar their half-lives, the less accurate the graphical method is.

For radioisotopes with very long half-lives it is more convenient to analyse the energy spectrum of the emitted radiation. Analysis by γ-spectrometry after irradiation with thermal neutrons can be done simply and quickly. There are several methods for distinguishing the characteristic energy peaks in a pulse-height spectrum; Fig.7.10 shows a subtractive analysis of the spectrum obtained from activated impurities in a specimen of natural calcium fluoride.

Neutron-activation analysis systems have recently been installed in baggage-handling departments of several major airports in an attempt to discover hidden explosives by detecting the nitrogen they contain. These systems are large, complex and expensive and, so far, they have met with only limited success. This is because they operate with thermal neutrons from a ^{252}Cf source. Only with fast neutrons from a dedicated particle accelerator would it be technically feasible to reliably detect the small amount of nitrogen present in explosives in a reasonable time (whilst the baggage is conveyed on a moving belt for instance). Cost and false alarms then become the limiting factors.

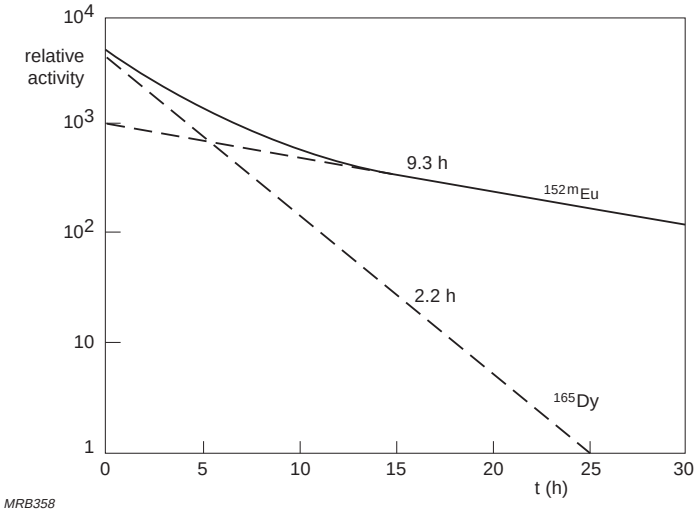

Fig.7.9 Illustration of the graphical separation of two half lives

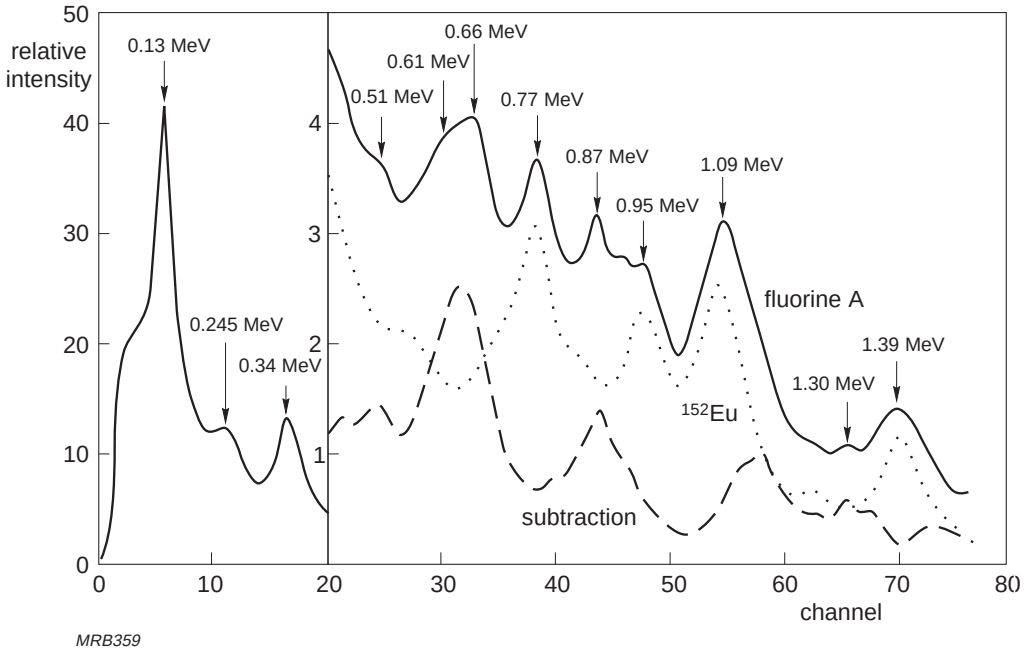

Fig.7.10 Subtractive analysis of a natural calcium fluoride spectrum

X-fluorescent analysis is based on the characteristic X-ray emission spectra of the elements constituting the specimen. The emission may be stimulated by bombardment with charged particles or irradiation with X- or γ-rays. Electron bombardment gives low emission efficiency (about 1%) and affects only the surface of the specimen. Proton bombardment gives good analytical sensitivity but requires the use of a particle accelerator; for most analyses X- or γ-irradiation is preferred.

High-power X-ray generators are available which yield an intense, highly penetrating flux capable of stimulating X-ray emission from far below the surface of the specimen. Radioisotope sources of X- or γ-radiation are also practical. They are highly stable, can supply a wide range of energies, and have the advantage of being small enough for use in portable instruments.

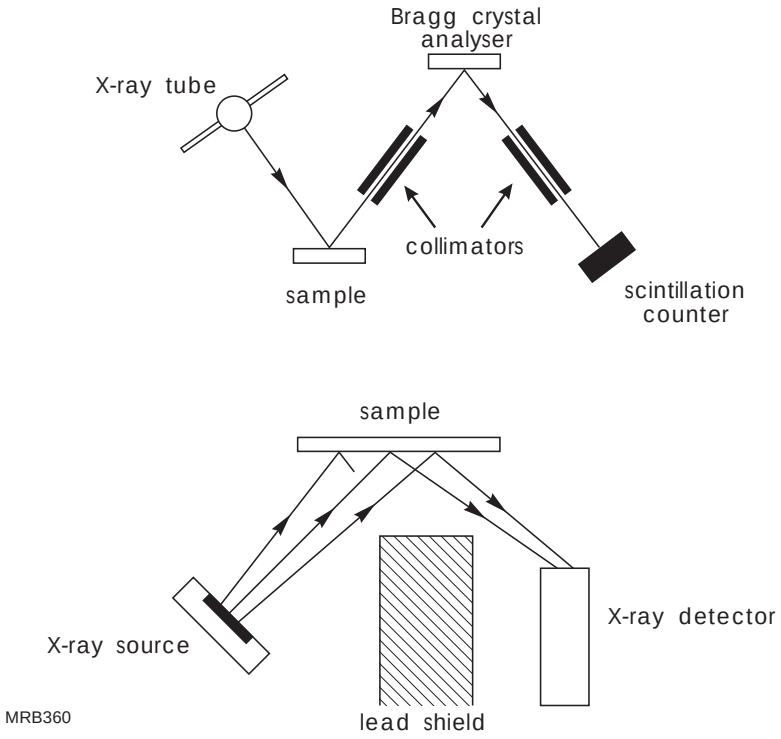

Fig.7.11 Schematic diagram of two X-ray spectrometers (a) dispersive, (b) non-dispersive

Two types of spectrometer are used, dispersive and non-dispersive (Fig.7.11). The efficiency of dispersive spectrometers is low, but this is compensated by the high intensity of the radiation; a multichannel dispersive spectrometer can identify a large number of elements simultaneously. In non-dispersive spectrometers the analysis is

based solely on pulse-height discrimination; owing to the low resolution of scintillation counters toward the low-energy end of the spectrum, this type of spectrometer is limited to analysis of spectra with comparatively few lines. The alternative is to use a high-purity germanium or Si(Li) detector.

7.3.2 Thickness and density measurement

Scintillation counters can also be used for measuring thickness and density by means of ionizing radiation. Though they require more complicated electronics than Geiger-Müller counters, they have the following advantages which are in many applications decisive: short resolution time, output pulse proportional to the radiation absorbed in the scintillator, and very high efficiency for X- and γ-radiation. The photomultipliers are usually general-purpose types with good shock and vibration resistance.

Thickness measurement can be either by transmission or backscatter (Fig.7.12), the choice being usually one of convenience. The radiation may be α, β or γ – each has advantages that suit it to some applications and limitations that exclude it from others.

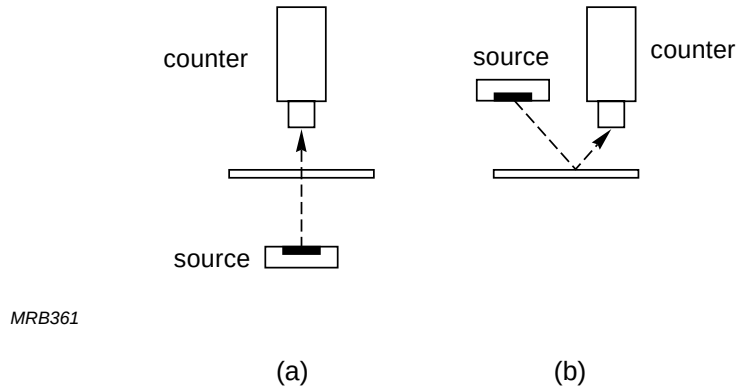

Fig.7.12 Principle of thickness measurement (a) by transmission, (b) by reflection

α-*radiation* has low penetration even in air and is therefore suitable for measuring only very small thicknesses, and then only by transmission, not backscatter. The detector should be spaced no more than a few millimetres from the source. Results are subject to variation due to environmental factors such as atmospheric pressure and humidity.

β-*radiation* has much greater penetration than α-radiation and can be used for backscatter as well as transmission measurements. Table 7.1 lists characteristics of some β-sources; those of low energy have the disadvantage that their radiation is too

quickly scattered away from the detector. On the other hand, some of the higher-energy ones emit radiation of more than one energy and type (e.g. β and γ), which complicates the interpretation of the results. Half-life is also a practical consideration: the longer it is, the less often the measuring set-up needs to be recalibrated.

Measurement by β-transmission is useful in the paper, rubber, plastics, metal and tobacco industries. The measurement may be continuous and is often integrated into an automatic process-control system. β-backscatter is useful for measuring the thickness of coatings.

Table 7.1 Some β-radiation sources

source	half-life	max. energy (MeV)	measurable thickness (mg/cm^2)
^{3}H	12.26 yr	0.018	small range
^{63}Ni	125 yr	0.067	small range
^{14}C	5568 yr	0.155	2 – 10
^{147}Pm	2.26 yr	0.223	4 – 15
^{85}Kr	10 yr	0.695	25 – 100
^{204}Tl	2.7 yr	0.770	20 – 150
$^{90}Sr(+^{90}Y)$	28 yr (64.4 h)	0.54 (2.26)	60 – 550
$^{144}Ce(+^{144}Pr)$	285 d (2.6 yr)	0.31 (3.10)	150 – 1250
$^{106}Ru(+^{106}Rh)$	1 yr (24 h)	0.039 (3.50)	200 – 2000

γ-*radiation* has sufficient penetration for measuring the thickness of dense materials. As the best results are obtained by Compton backscattering the γ-rays in the material, only sources with γ-ray energies from a few tens of keV to a few MeV are normally used; characteristics of some γ-sources are listed in Table 7.2.

Thickness measurement by γ-transmission has applications in metallurgy. With appropriate precautions against the high level of radioactivity required, it can be used to check the uniformity of, for example, aluminium ingots.

Surfaces that are conveniently accessible from only one side – for instance, tank walls, ships' hulls, pipes, and road paving – can be measured by γ-backscatter. With a 0.1 mCi ^{60}Co source it is possible to measure up to 15 mm of steel or 30 mm of aluminium by backscatter.

Table 7.2 Industrial γ-sources

source	half-life	energy (MeV)	half-thickness in steel* (mm)
^{55}Fe	2.94 yr	0.006	0.01
^{170}Tm	0.35 yr	0.084	1.0
^{85}Kr	10.6 yr	0.520	12.3
^{137}Cs	30 yr	0.662	16.5
^{60}Co	5.25 yr	1.17 & 1.33	33.8

* The thickness in which the radiation flux (photons/cm^{2}s) is halved

Density measurement involves the same principles as thickness measurement: the measured material absorbs or scatters radiation in proportion to its density.

An important application of density measurement by transmission is flow monitoring, with a radiation source and a scintillation counter disposed on opposite sides of the conduit. This is especially useful for monitoring high-pressure, high-temperature, or hazardous fluids. Detection of flow conditions such as the onset of turbulence is also possible.

Soil density can be measured in situ by Compton scattering. Portable instruments based on this principle are used to obtain continuous density profiles of road surfaces (Fig.7.13).

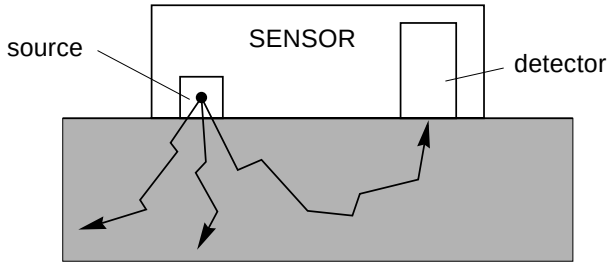

Fig.7.13 Soil density measurement by means of Compton scattering

7.3.3 Oil-well logging

In exploratory drilling, a bore-hole probe containing a γ-ray or neutron source and a scintillation detector can aid in assessing the probability of hydrocarbon deposits. The detector is shielded from the direct radiation of the source and responds only to

Compton scattering from the walls of the bore hole. By analysing the variations in count rate as the probe descends, an experienced operator can draw valuable conclusions about the structure and composition of the successive geological strata.

By the nature of the application, it is obvious that the photomultipliers used have to be extremely rugged, especially in the now popular activity of 'logging while drilling' (LWD). They also have to be able to withstand high temperatures without unacceptable loss of anode sensitivity. At the 10 km depths to which a bore-hole probe may be lowered, temperatures often reach 150 – 200 °C, far above the temperature (80 – 100 °C) at which the performance of most photocathodes seriously declines. The best choice of cathode material is bialkali SbNaK, without Cs. The cathode, as well as other materials in the tube, has to be specially processed for this application.

7.4 High-energy physics

7.4.1 Collider detectors

Scintillation detectors find extensive application in the very large installations used in high-energy physics to analyse the fragments generated in particle-particle collision experiments.

Designed to cover 4π steradians around the collision point so as to account for all the energy involved, such an installation (Fig.7.14) commonly includes:
- a vertex detector closely surrounding the beam pipe
- a tracking detector
- an electromagnetic calorimeter surrounding the tracker
- a hadron calorimeter surrounding the electromagnetic calorimeter
- a time-of-flight detector
- muon chambers.

A solenoid (usually many metres long and several metres in diameter) generates a strong (multi-tesla) magnetic field coaxial with the beam pipe to facilitate identification of charged fragments.

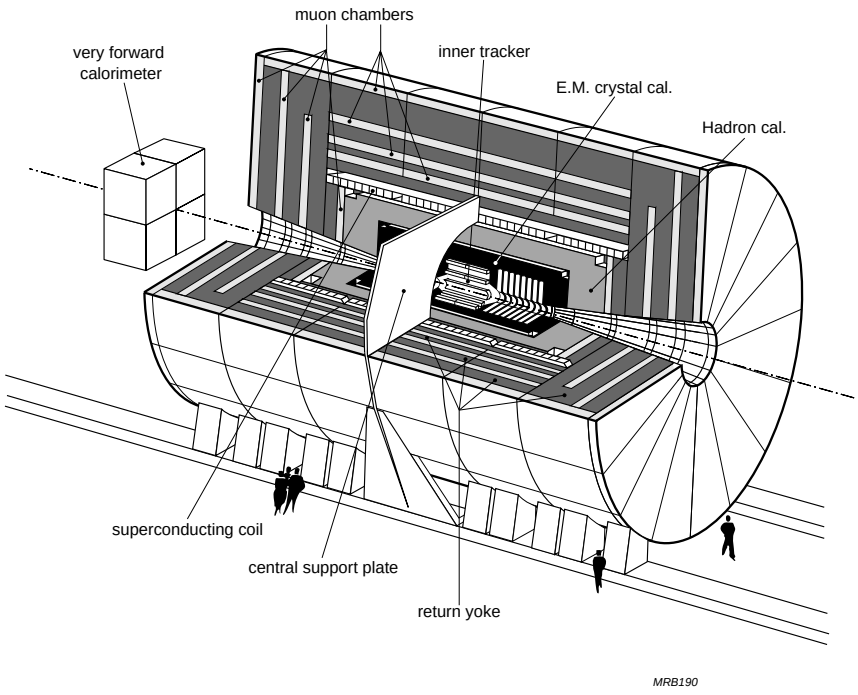

Fig.7.14 CMS 4π detector proposal (courtesy of CERN, Geneva)

Vertex detector. This may consist of thin organic scintillating fibres read out at one or both ends by photomultipliers. The energy deposited in the fibres is small and the attenuation of the light before it reaches the photomultipliers (located outside the magnetic field) is large; most events therefore give rise to only a few photoelectrons.

Today's designs are based on silicon-strip detector arrays or even CCDs with low-noise preamplifiers that eliminate the use of photomultipliers in vertex detectors.

Trackers. A central tracking detector traditionally uses many thousands of wires and gas multiplication. Its distinguishes between the tracks of charged and neutral fragments by means of the magnetic field generated by a solenoid. With the collision rates in proton-proton colliders increasing to 60 – 70 MHz, more advanced tracking techniques will be needed. In this respect, new scintillating fibres combined with multi-channel photomultipliers may be one solution. Since the light attenuation in these fibres is less for green wavelengths (especially if the fibres have suffered radiation damage), tubes with extended green response photocathodes should be used. As multi-channel photomultipliers cannot operate in magnetic fields of several tesla, the fibres have to convey the light out of the field. The resulting attenuation means that the tubes have to work in single photo-electron mode. Competing detectors include cooled silicon pixel arrays and avalanche diode arrays that can operate inside the field, thin-walled, small-diameter gas multiplication tubes ('straw tubes'), microstrip gas counters and even silicon-strip detectors.

Electromagnetic calorimeter. This is located outside the tracker and consists of a barrel detector with end caps to stop and analyse electromagnetically interacting fragments. The barrel and end caps often consist of plastic scintillators interleaved with some material with high atomic number (high stopping power) such as lead, iron, or uranium.

As the photons generated in the scintillators are in the ultraviolet, the scintillators are doped to shift the wavelength to around 400 nm. Wavelength shifting rods or plates that also act as light guides are often used to shift the light further towards the green-yellow part of the spectrum (Fig.7.15) where the attenuation length is very low (so that the photomultipliers can be located outside the magnetic field).

Such calorimeters often use thousands of 1 to 2 inch photomultipliers. Important requirements are that their gain must be very stable and, in view of the large dynamic range called for (1000 – 2000), their pulse amplitude linearity must extend at least to 100 – 150 mA. In addition, because of the large quantity involved, they must be reliable and reasonably priced.

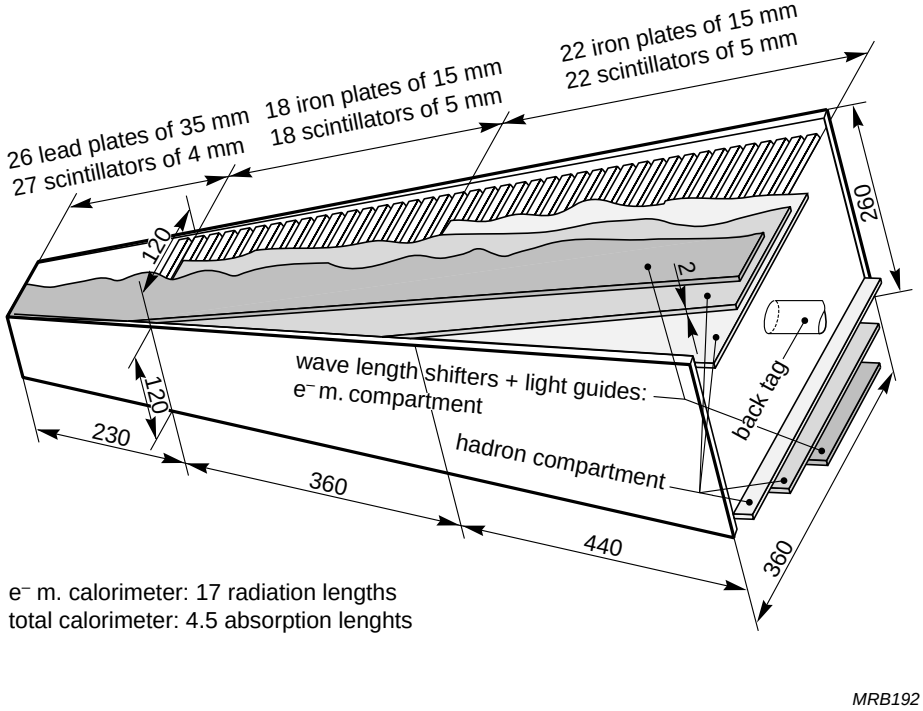

Fig.7.15 Calorimeter tower based on the wavelength shifter principle (courtesy of CERN, experiment UA 2)

The best choice of photocathode is extended green sensitive bialkali. The integral quantum efficiency with BBQ-, Y7- or K27-doped light guides is typically 12 – 20%.

Because of the large dimensions involved, it is never possible to derive accurate time information using calorimeter towers, so response time is not an important factor and most types of photomultiplier will be fast enough. Linearity and stability, however, are important. The severe demands on stability, in particular, have been a major stimulus to improving photomultiplier performance, leading to benefits in several other areas (gamma cameras for example).

Finally, mesh-dynode photomultipliers able to sustain reasonable gain in an axial magnetic field have been developed for situations where the electromagnetic calorimeter must remain inside the field. New HPDs (see §1.5.7) can work in an axial magnetic field of up to a few tesla.

Hadron calorimeter. The construction is similar to that of the electromagnetic calorimeter: a barrel with end caps in which e.g. organic scintillators (scintillating fibres) interleaved with high-atomic-number material are coupled to photomultipliers by BBQ-, Y7- or K27-doped wavelength-shifters/light-guides. Here though, the dynamic range required is usually lower, so tubes with pulse amplitude linearity up to 100 mA will be sufficient. The stability requirements are just the same. Other calorimeter designs also exist based on, for example, liquid argon without photomultipliers.

$PbWO_4$ calorimeters

As the next challenge in high-energy physics is to find the signs of the Higgs particle(s) that is supposed to define the mass of the other particles in the standard model, future Large Hadron Collider (LHC) experiments will be mainly directed at very-high energy particles. Therefore, with much efforts, a new inorganic scintillator, the $PbWO_4$ has been developed in cooperation with Chinese and Russian institutes and industry. Its high stopping power (density 8.28 g/cm^3) and short decay time constants of 2, 7 and 26 ns make it ideal for the huge CMS electromagnetic calorimeter. Its very low light output of only 0.8% of NaI(Tl) will easily be compensated by the very high energy of the particles of interest. Moreover, its peak emission wavelength of 480 nm makes possible to read it out with silicon avalanche photodiodes (APDs) that can operate in the perpendicular magnetic field of the calorimeter barrel. For the calorimeter end caps, where the radiation is very high close to the beam line, low-priced Russian vacuum phototriodes (VPTs) will be used.

This development will also increase the availability of $PbWO_4$ for lower-energy detectors in medium-energy physics experiments, where, however, owing to the lower energy of the particles, green-extended-response photomultipliers will be needed.

Lead-glass calorimeters. Alternative constructions for electromagnetic calorimeters placed outside of the magnetic field may use long lead-glass blocks instead of interleaved plastic scintillators. The photomultipliers, coupled direct to the blocks without light guides or wavelength shifters, are usually 2 or 3 inch tubes. As the light generated is due to Cherenkov radiation (§8.3) and is strongest toward the blue and UV end of the spectrum, normal SbKCs-cathode tubes are the best choice, for sensitivity as well as stability and price. The light output is sufficient for a 6- or 8-stage tube; in fact, even a gain of $10^2 - 10^3$ gives a signal large enough to be easily handled.

Fibre calorimeters. Instead of interleaving plastic sheets and high-Z material, calorimeters can also be produced from scintillating fibres uniformly stacked through the high-Z material. The signal from many fibres is then coupled to one photomultiplier. Other designs comprise scintillating tiles sandwiched between lead tiles, with the scintillating tiles read out via bundled wavelength-shifting fibres coupled to clear fibres that convey the light from all the tiles to a single photomultiplier tube. As the signal is composed of thousands of photoelectrons, only moderate gain is needed in the photomultiplier, but good stability and wide dynamic range are very important. For the best linearity, linear-focusing tubes are used, and since the light signal is in the green part of the spectrum to minimize light attenuation in the fibres, the best result is achieved with a green extended bialkali SbKCs photocathode.

Magnetic-field sensitivity: photodiodes, phototriodes. Because of the strong magnetic field surrounding the solenoid, the photomultipliers used require heavy shielding. This complicates design and limits the freedom with which the tubes can be placed.

As an alternative, detectors have been constructed with Photonis vacuum photodiodes (VPDs) that could be rendered reasonably immune to strong magnetic fields within 30° of axial. In conjunction with NaI(Tl) scintillators and special low-noise preamplifiers to compensate for their own unity gain, these have given good results. For use with lead-glass blocks (whose light output is very much lower than that of NaI(Tl)), vacuum phototriodes (VPTs) able to work in strong magnetic fields within 30° of axial with a gain of about 10 have also been used in end caps. Results are, again, excellent, when sufficiently low-noise preamplifiers are used. New glasses that give higher light output by scintillation may further advance this line of development.

Experiments have shown that BGO and CsI(Tl) scintillators in combination with large-area (1 cm^2) silicon photodiodes or avalanche photodiodes (APDs) and low-

noise preamplifiers can also achieve low enough noise levels to be feasible at high collision energies and moderate counting rates. Their advantages over photomultipliers are short length and immunity to magnetic fields.

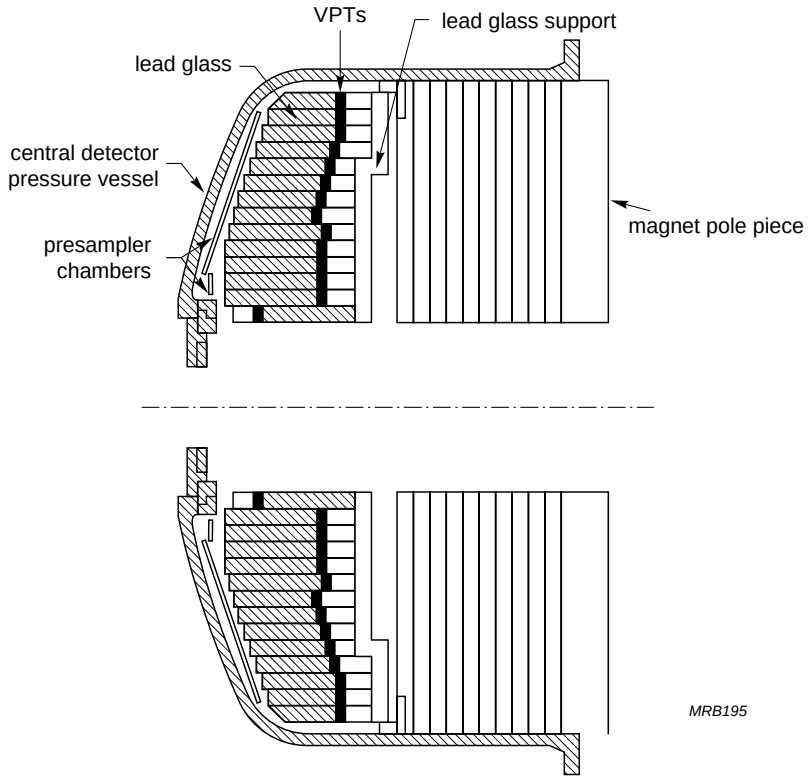

Fig.7.16 Lead-glass calorimeter end caps and Photonis VPTs (courtesy of OPAL collaboration, CERN, Geneva)

Disadvantages are high sensitivity to temperature variations, and high capacitance which induces preamplifier noise and makes the read-out channel slow to integrate all the charge in the pulse. They are fragile and their long term reliability is still not fully proven. This means placing several photodiodes per scintillator for redundancy reasons and/or to cover the required area. For these reasons, low-capacitance VPTs and VPDs could again become attractive alternatives for the next generation of 'fast' collider experiments.

Time-of-flight (TOF) detectors. In high-energy physics installations it is also important to obtain time-triggering information about the fragments generated. This is usually done with the aid of long rods of very fast plastic scintillators (e.g. Pilot-U, now replaced by BC418), with decay time constants of only 1 – 2 ns, observed from both ends by fast photomultipliers whose outputs are compared in time as well as

amplitude. TOF detectors often consist of a barrel placed inside or between the calorimeters.

When the photon emission of the scintillator and the electron emission of the photomultiplier cathode both obey laws of the type

$$f(t) = \left(\frac{\bar{n}}{\tau}\right) \exp\left(-\frac{t}{\tau}\right)$$

the variance of the time registered by the photomultiplier is

$$\sigma_t^{*2} = \frac{\tau^2 + \sigma_t^2}{\bar{n}_{k,s}}$$

where τ is the decay time constant of the scintillator, σ_t^2 is the transit-time variance of the photomultiplier, and $\bar{n}_{k,s}$ the mean number of photoelectrons per scintillation pulse. For optimum timing accuracy, therefore, the scintillator should be chosen for high scintillation efficiency and short decay time; and the photomultipliers, for high cathode sensitivity at the scintillation wavelength (to maximize $\bar{n}_{k,s}$) and small transit-time variance. Since the transit-time variance of fast photomultipliers is usually negligible compared with the decay time constant of even very fast scintillators, it is the latter and the length of the rod (different light paths) that mainly limit the time resolution in such detectors. It is therefore common to trigger already on the very first (directly arriving) few photons which demands a fast photomultiplier with high gain ($\approx 10^7$). Some years ago, to improve timing, Photonis developed a special tube with a 'screening' anode grid as proposed by Moszynski and this improvement is now being further explored to get the very best timing. Making the rods from scintillating fibre bundles can improve performance.

In some experiments, Cherenkov radiation in a gas-filled volume is used instead of scintillator rods to measure time-of-flight. Then, it is the photomultipliers that mainly limit the time resolution, since the Cherenkov radiation arrives at the photomultiplier practically instantaneously (§8.3).

Muon trackers. Until recently, muon detectors used wire/gas multiplication principles to determine the tracks of the muons penetrating the calorimeters. With the development of scintillating fibres, however, discussions now centre around the development of muon detectors comprising many layers of fibres read out by multi-channel photomultipliers incorporating extended-green bialkali photocathodes.

7.4.2. Fixed-target detectors

Hodoscopes. In experiments in which a beam of accelerated particles is focused onto a target, the resulting fragments scatter in various (forward) directions and are subsequently separated by a magnetic field. To trace their paths, hodoscopes are used consisting of crossed X-Y arrays of many flat, parallel, plastic scintillator strips or fibres coupled to photomultipliers. Apart from small size (19, 25 or 29 mm), the main photomultiplier requirement is high gain, for the typical scintillation excites only a few photoelectrons. In experiments in which pulse-height analysis is required this imposes demands on the linearity of the tubes. Usually, though, this is not the case; the usual information required from each scintillator is a simple yes/no.

Note: the hodoscope is also often used as a time trigger, in which case the principal demand on the tubes is narrow transit-time spread. Since most plastic scintillators emit at around 400 – 420 nm, a high-sensitivity bialkali SbKCs photocathode is necessary.

In the future, good spatial resolution is expected to become important, and here multi-channel tubes in combination with scintillating fibres are likely to be the best option. And since the attenuation of the fibres is lowest in the green part of the spectrum, these tubes should have extended-green photocathodes.

Veto and RICH counters

As modern veto counters and ring-imaging Cherenkov counters (RICH) do not use scintillators they are treated in Chapter 8.

7.5 Cosmic-ray detectors

Although some cosmic-ray detectors use liquid scintillators and some use the scintillation of the earth's atmospheric volume, these detectors are all treated in Chapter 8.