Notes for Nuclear Physics Laboratory

Y. K. VIJAY and SARDAR SINGH

Q. What are scintillations?

Ans.➢ Scintillations are flashes of light excited by absorption of nuclear radiations in certain materials.⮜

(Comments: Scintillator is a substance that converts some of the energy of incident radiation into detectable photons (i.e., it converts energy lost by ionizing radiation into pulses of light). In most scintillation counting applications, the ionizing radiation is in the form of X-rays, γ-rays and α- or β-particles ranging in energy from a few thousand electron-volts to several million electron-volts (keV's to MeV's). Scintillators fall into two main classes, inorganic and organic, which differ not only chemically but also in the processes by which they release photons.)

Q. Give some examples of inorganic materials used as scintillators.

Ans.➢ Inorganic scintillators are either mono-crystals or polycrystalline powders. Mono-crystals are transparent to their own luminescence; the polycrystalline powders are less so.

The principal mono-crystalline scintillators are alkali halides, mostly doped with heavy metals such as thallium or europium: NaI(Tl), CsI(Tl), CsI(Na), KI(Tl), CaI_2(Eu) and CaF_2(Eu). Crystals of pure (undoped) alkali halides like NaI and CsI are also useful. Other, more recently adopted mono-crystalline scintillators are $CaWO_4$, $CdWO_4$, $PbWO_4$, $ZnWO_4$, BaF_2, CsF, CeF_3, $Bi_4Ge_3O_{12}$ (called BGO), and the Ce-doped Gd_2SiO_5:Ce (gadolinium orthosilicate or GSO), Lu_2SiO_5:Ce (lutethium orthosilicate or LSO), Y_2SiO_5:Ce (yttrium orthosilicate or YSO) and $YAlO_3$:Ce (yttrium aluminium perovskite or YAP).

Polycrystalline powders include the doped sulphides ZnS(Cu), ZnS(Ag) and CdS(Ag), ZnO(Ga), and the oxide ZnO. NaI(Tl) is also sometimes used as a polycrystalline powder. Being partly opaque to their own luminescence, polycrystalline powders are mostly used as thin screens that detect only heavy and highly ionizing particles with good efficiency.⮜

(Comments: The list of inorganic scintillators grows yearly. NaI(Tl), CsI(Tl), CsI(Na), CsF, KI(Tl) and ^{6}LiI(Eu) are all hygroscopic and have to be sealed hermetically encases. BGO and BaF_2, which are not hygroscopic, have high absorption coefficients for X- and γ-photons and very low delayed fluorescence. In some applications, such as medical PET scanners, these properties compensate for the relatively low scintillation effectiveness of these materials. The new non-hygroscopic LSO scintillator, with a much shorter decay time constant than BGO and with similar stopping power, shows considerable improvements and therefore is the recent scintillator choice for PET scanners.)

(Comments:

NaI(Tl) scintillation crystals are used in most standard applications for detection of γ-radiation because of their unequalled high light output and the excellent match of the emission spectrum to the sensitivity of photomultiplier tubes, resulting in a good energy resolution.

CsI(Tl) has the advantage that it is non-hygroscopic, does not cleave and can be read out using silicon photodiodes instead of photomultiplier tubes. These so-called *Scintillator Photodiode Detectors* are compact, very stable, do not require any high voltage, are rugged, and can be operated in high magnetic fields. These detectors are frequently used in arrays or matrices in particle physics research.

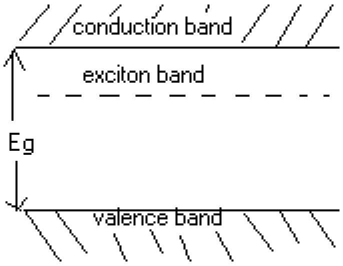
CsI(Na) is a non-hygroscopic, high light output scintillator mainly used for applications where mechanical stability and good energy resolution are required. Below 120 ^{o}C it is an alternative to NaI(Tl).

BGO has the extreme high density of 7.13 g /cm^3 and has a high Z value which makes these crystals very suited for the detection of *natural radioactivity* (U, Th, K), for high energy physics applications (high photofraction) or in compact Compton suppression spectrometers.

YAP:Ce is a high density (5.5 g/cm^3) oxide crystal with a decay time about 10 times shorter than NaI(Tl). It is used in detectors for high-count rate (up to several MHz) X-ray spectrometry. The non-hygroscopic nature of this material allows the use of thin mylar entrance windows and guarantees a long lifetime of the detector.

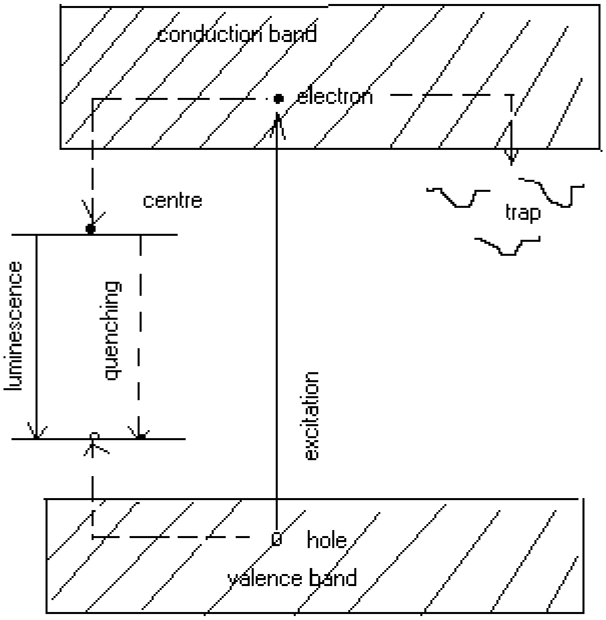
CaF_2(Eu), Europium doped calcium fluoride is a low density scintillation crystal with a high light output. Due to its low Z value it is well suited for the detection of electrons (beta particles) with a high efficiency (low backscatter fraction). CaF_2 (Eu) is a crystal that is also used in *phoswich* scintillation detectors in combination with NaI(Tl).

Q. Discuss the process of luminescence in inorganic scintillators.



Energy Bands in inorganic crystal

Ans.➢ Luminescence in inorganic crystals is mainly a crystal property. In crystalline compounds luminescence originates from emission centers in the compounds themselves or formed by activating agents introduced in controlled amounts. Scintillator crystals are usually insulators or semiconductors having an energy gap of a few electron volts between the valence and conduction bands. Under the influence of ionizing radiation, electrons in the valence band can acquire sufficient energy to reach the conduction band, leaving behind charge deficiencies (positive 'holes') in the valence band. The crystal is then ionized and photoconductive. If the energy imparted to an electron is insufficient to raise it to the conduction band, it remains bound to a hole, at an energy level just below the conduction band. The electron-hole pair is called an 'exciton'. This description applies only to a perfect crystal.



Descrete levels within the forbidden gap caused by impurities in the crystal

Imperfections due to lattice dislocations or impurities in the crystal create additional energy levels in the energy gap into which excitons in the gap or electrons in the conduction band can move. These levels correspond to activation centers of three types:

Luminescene centres, at which recombination of an electron-hole pair brings the center to an excited state from which it returns to the ground state by photon emission (this is called fluorescence). The electron-hole recombination that excites the center can be due either to capture of an exciton or to simultaneous capture of an electron from the conduction band and a hole from the valence band.

Quenching centers, which are like luminescence centers except that the excitation energy is dissipated as heat (phonons) instead of light.

Traps, which are metastable levels at which electrons and holes, or excitons, can remain for a long time before acquiring sufficient thermal energy to return to the conduction and valence bands or to move to a luminescence or quenching center. When they do move to a luminescence center the delayed emission that results is called phosphorescence.∢

Q. What is response time of a scintillator?

Ans.➢ Response time is a measure of the width of the scintillator pulse, which is usually much greater than the stopping time of the ionizing particle or photon that causes it. After rising abruptly, the pulse falls according to a composite law in which at least two components can be distinguished:

– a fast exponential decay (fluorescence) with a time constant τ

– a slower decay (phosphorescence, delayed flurescence) following a more complex law.

The time constant τ is called the response of the scintillator. ∢

Q. Mention the factors on which shape of the scintillation pulse depends.

Ans.➢ The shape of the scintillation pulse depends on the factors such as the type of crystal, the nature and concentration of the activator, the type of radiation detected, and the temperature. In general, the rise time is very fast: a few tenths of a nanosecond, and the fall time can be resolved into two components – (i) a prompt, exponential component with a time constant from a few hundred nanoseconds to a few microseconds, (ii) a delayed component lasting several microsecond.

In NaI(Tl) the prompt component has a decay time constant of about 350 ns at very low concentration of Tl, decreasing to 230 ns at normal concentrations (0.1% to 0.5%). The fact that the delayed component may account for as much as 20% to 40% of the total emission of inorganic scintillators sets a limit to their usefulness in high-count-rate applications. ∢

Q. Define *scintillation effectiveness* and *scintillation efficiency*.

Ans.➢ Scintillation effectiveness ε_S is the ratio of the number of photons emitted per unit time (n_P) to the energy of the radiation absorbed in the scintillator (E_a),

$$\varepsilon_S = \frac{n_P}{E_a}.$$

It is usually expressed in photons per MeV.

Scintillation efficiency η_S is the product of scintillation effectiveness ε_S and the energy $h\nu$ of the emitted photon,

$$\eta_S = \varepsilon_S h\nu = \frac{n_P h\nu}{E_a}.$$

It is usually expressed as a percentage.

The efficiencies of monocrystalline scintillators NaI and CsI are among the highest known. NaI(Tl) has an efficiency of about 13 %, emitting four or five photons (or 3 eV average energy) per 100 eV of absorbed energy. ≺

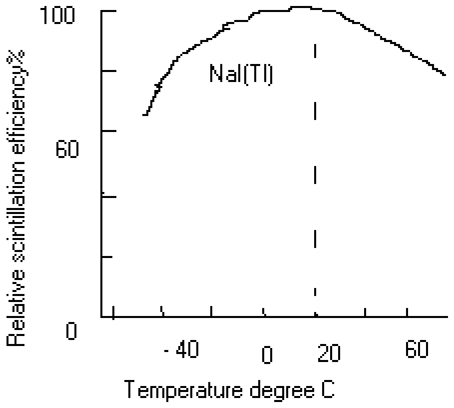
(Comments: ZnS has higher efficiency than any monocrystalline scintillator. ZnS(Ag) and ZnS(Cu) have efficiencies of about 25% and 30% for α-particles, regardless of the energy of the particles, and about half that for β-particles.)

Q. What are the advantages of using inorganic scintillators?

Ans.➢ (i) High absorption for X- and γ-photons and nuclear particles such as α and β, (ii) Good matching with the spectral sensitivity of general-purpose photo-multipliers, (iii) Practically linear scintillation effectiveness over a wide energy range, and (iv) decay time constants mostly in the region of a microsecond or less. ≺

Q. Does temperature influence scintillation efficiency?

Ans.➢ Yes, temperature influencies scintillation effectiveness, pulse decay time and emission spectrum. The temperature dependence of the relative scintillation efficiency fro Nai(Tl) is shown here. It has a broad maximum around 20 °C (convenient for normal lab usage).≺



Q. Write properties of NaI and NaI(Tl) crystals relevant to their use as scintillators.

Ans.➢Material	NaI	NaI(Tl)
Density g/cm^3	3.67	3.67
Index of refraction	1.78	1.85

Wavelength of maximum emission (nm)	303	410
Decay time constant 1/e (ns)	60	250
Scintillation pulse height	190 (relative to NaI(Tl) at 80 K)	100
Hygroscopic	Yes	Yes

Because of their high density and high atomic number of iodine (Z=53), monocrystals of alkali halide are well suited for detecting X- and γ-photons. They are also highly absorbent fro electrons and heavy charged particles (α , p etc). Inorganic scintillator usually have two emission bands; one due to the activator and another, at shorter wavelength, due to the crystal lattice. The relative intensity of the emission due to the crystal lattice decreases as the concentration of the activator increases; at high enough concentrations (e.g. 0.1% to 0.5% Tl in NaI) only the emission due to the activator is practically significant. ≺

Q. Define energy resolution of a γ –ray scintillation spectrometer.

Ans.➢

$$Energy\ resolution = \frac{FWHM \text{ of the full energy peak}}{Energy \text{ corresponding to the peak maximum}} \times 100 \,.$$≺

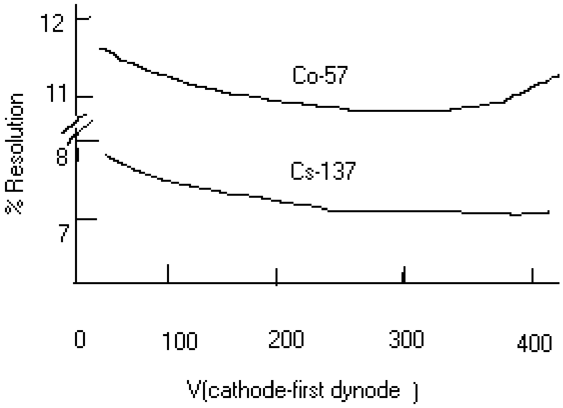
(Comments: Commercial diameter 50 mm × 50 mm and 38 mm × 38 mm aluminium encased NaI(Tl) scintillators used in combination of present-day photomultipliers give resolutions of 6 – 7 % for 662 keV γ –radiation of ^{137}Cs, and 8 – 9 % for the 122 keV γ –radiation of ^{57}Co.)

Q. What are the factors that influence the energy resolution of a γ –ray spectrometer?

Ans.➢ The γ –ray energy resolution is influenced by (i) the light output of the scintillator, (ii) the size of the scintillator (light collection) and (iii) photomultiplier characteristics (quantum efficiency and photocathode homogeneity).≺

(Comments: The energy resolution of a scintillator is a true detector property, limited by the physical characteristics of the scintillator and the PMT. At low energy photoelectron statistics dominate the energy resolution and it is roughly inverse proportional to the square root of the γ-ray energy. At low energies Si(Li) or HPGe detectors have better resolution.)

Q. Does the energy resolution depend on the cathode to first dynode voltage?



Ans.➢ Yes. Because electron collection and multiplication in the photo multiplier input stages is a dominant statistical factor in the conversion of incident photon energy to electrical energy, the energy resolution also depends strongly on the voltage applied to those stages. See Fig. which shows energy resolution variation as a function of cathode to first-dynode voltage obtained with radiation sources ^{57}Co, and ^{137}Cs. From these it is apparent that energy resolution is best when the cathode to first dynode voltage is between 200 V and 300 V.

Q. The narrowness of the peaks is a measure of the energy resolution of the scintillator-photomultiplier combination. What causes widening of the peak and hence loss of resolution.

Ans.➢ The following effects always cause some widening of the peaks, and hence loss of resolution:

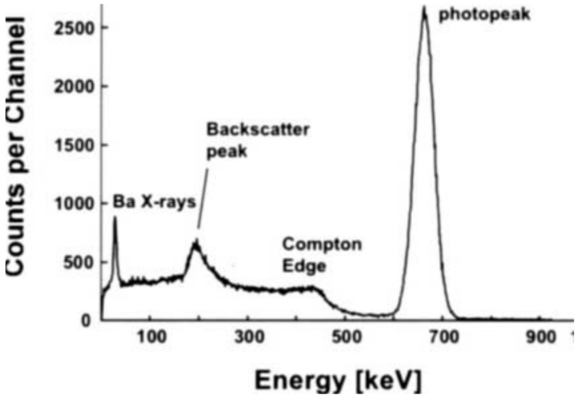
- Photon emission in the scintillator fluctuates from one monoenergetic interaction to another, mainly because of inhomogeneities in the scintillator and an inherent resolution-degrading component originating from the non-proportionality of the light yield, typical for each scintillator.

- Photon collection at the cathode fluctuates from one scintillation to another because of variation of the points of origin of successive scintillations, consequent variations of photon path lengths and angles of incidence, and local variations of scintillator window, coupling compound, and cathode window transparency and refractive index.

- Photon-electron conversion efficiency fluctuates because of local variations of cathode sensitivity.

- Electron collection and multiplication fluctuate, mainly because of variations in photoelectron points of origin. ≺

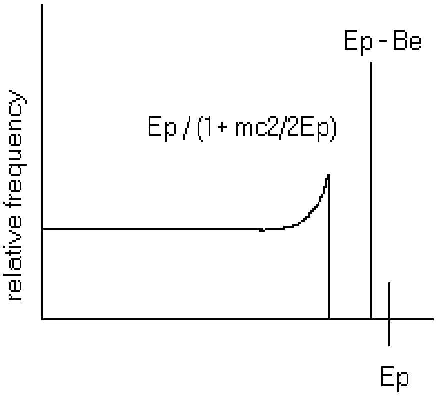
Q. Why there are so many different peaks in the γ ray spectrum for ^{137}Cs source detected with NaI(Tl) ?



Ans.➢ The proportionality between the primary photon energy E_P absorbed in the scintillator and the mean number of scintillation photons received at the cathode, $\bar{n}_{P,S}$, depends on the interaction processes by which radiation absorbed in the scintillator liberates electrons and thereby excites fluorescence. There are three primary processes, photoelectric effect, Compton effect, and pair production by which radiation is absorbed in the scintillator. Each of these processes leaves its own signature on the spectrum.

The *photopeak* arises because many incoming γ-photons deposit their energy in the scintillator through photoelectric effect. A γ-photon undergoes a photoelectric absorption and liberates an electron of energy $E_{S,P} = E_P - B_e$. Here, B_e is the binding energy of the liberated electron, which is usually ejected from a K or L shell. The liberated electron excites fluorescence and gives rise to a peak in the spectrum corresponding to energy $E_{S,P}$ (For a NaI(Tl) crystal B_e = 28 keV). Apart from this, when the vacancy left by the ejection of electron is again filled, the energy B_e reappears as characteristic X-rays or Auger electrons. If these occur within the response time for the primary photoelectric event, the fluorescence they excite also contributes to the photo-peak corresponding to that event. In this case the photo peak becomes equivalent to a full energy E_P peak.

The continuous spectrum up to *Compton edge* arises due to deposition of γ-energy by Compton effect. When the incoming γ-photon undergoes Compton effect, the recoil electron acquires energy



Spectrum of primary electron energyies produced in a scintillator by monoenergetic gamma radiation of energy Ep, showing the Compton continuum. the Compton edge and the photoelectric line.

$$E_{S,C} = \frac{E_P}{1 + {m_e c^2}\Big/{(1-\cos\theta)E_P}}$$

Besides this electron, Compton interaction yields a secondary photon of energy

$$E'_P = \frac{E_P}{1 + (1-\cos\theta)\dfrac{E_P}{m_e c^2}}$$

where θ is the angle between the path of the secondary photon and the original γ-photon. If the secondary photon is absorbed within the scintillator, the Compton interaction contributes to the full-energy peak. Otherwise, it yields a continuous spectrum (the 'Compton continuum') extending from zero up to the 'Compton edge' corresponding to the energy $(E_{S,C})_{max} = {E_P}\Big/{(1 + m_e c^2/2E_P)}$.

The *backscatter peak* arises due to the scattering of low energy photons of energy E'_P with ($\theta \approx \pi$) back into the scintillator from the surroundings. These may produce an observable photo-peak in the Compton continuum, usually centered at energy slightly greater than $E_P/(1+2E_P/m_ec^2)$.

The peak around 30 keV is due to the *Ba X-rays* emitted by the source. ≺

(Comments: Apart from the above-mentioned peaks, the following peaks may also arise:

Peaks due to *Pair production*: In pair production an electron-positron pair may be created by the absorption of a γ-photon. The energy of the resulting electron is $E_{S,PP} = E_P - 2m_ec^2$ .The contribution of pair-production events to the spectrum depends on whether both, one, or neither of the photons due to subsequent annihilation of the positron escapes from the scintillator without further interaction. If both escape, the pair production event contributes to a spectral peak at $E_P - 1.02$ MeV, which is usually superimposed on the Compton continuum. If only one escapes, it contributes to a peak at $E_P - 0.511$ MeV. And if neither escapes, it contributes to the full-energy peak E_P. All three of these possibilities may appear in a single spectrum.

Annihilation peak: Pair production interactions in the immediate surroundings (or in the radiation source itself) may scatter annihilation photons into scintillator. These produce a spectral peak at 0.511 MeV.

X–escape peak: If an X-photon due to a photoelectric interaction escapes from the scintillator, the scintillation energy for that interaction will be correspondingly diminished. In an

NaI(Tl) scintillator the loss amounts to some 28 keV. In the spectra of low energy radiation sources this gives a secondary peak 28 keV to the left of the photo-peak. In higher energy spectra the X-escape peak is so close to the photo peak that it is indistinguishable.

Sum peaks: Sources that emit γ-radiation of two distinct energies E_{P1} and E_{P2}, produce a spectrum with two corresponding full energy peaks. However, when the two radiations are emitted simultaneously within the response time of the scintillator photomultiplier combination, they produce a third spectral peak corresponding to $E_{P1} + E_{P2}$. Examples of sources that produce such a peak are ^{60}Co and ^{24}Na. The latter produces a sum peak corresponding to its 1.274 MeV γ-radiation pulse plus the 0.511 MeV due to annihilation of a pair-production positron.

In general, the larger the scintillator, the more prominent is the full energy peak relative to such features as the Compton continuum and pair production, back scatter and X-escape peaks.)

Q. What is photoelectric efficiency of a scintillator?

➢ The fraction of the total recorded pulses that appears under the full-energy peak is called the photoelectric efficiency, ε_{ph} , of the scintillator. ≺

Q. Discuss qualitatively the general principle of energy spectroscopy using a scintillator?

Ans.➢ The general principle of energy spectroscopy using a scintillator is as follows:

Pulses of light emitted by the scintillating material can be detected by a sensitive light detector, usually a photomultiplier tube (PMT). The photocathode of the PMT, which is situated on the backside of the entrance window, converts the light (photons) into so-called photoelectrons. The photoelectrons are then accelerated by an electric field towards the dynodes of the PMT where the multiplication process takes place. The result is that each light pulse (scintillation) produces a charge pulse on the anode of the PMT that can subsequently be detected by other electronic equipment, analyzed or counted with a scaler or a rate meter. The combination of a scintillator and a light detector is called a *scintillation detector*.

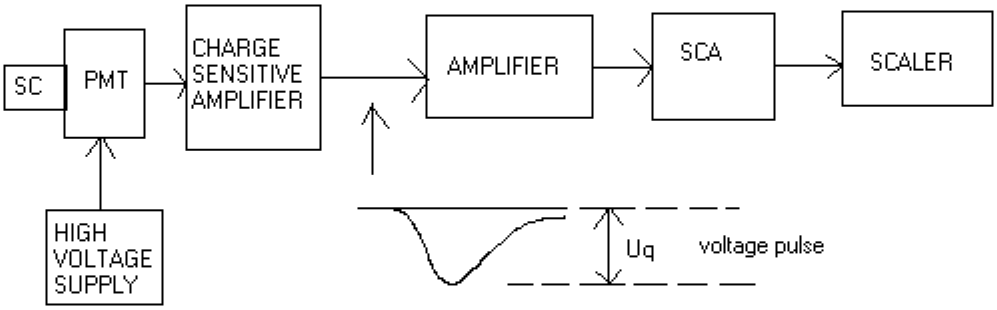
Since the intensity of the light pulse emitted by a scintillator is proportional to the energy of the absorbed radiation, the latter can be determined by measuring the pulse height spectrum. This is called spectroscopy. To detect nuclear radiation with a certain efficiency, the dimension of the scintillator should be chosen such that the desired fraction of the radiation is absorbed. For penetrating radiation, such as γ-rays, a material with a high density is required. Furthermore, the light pulses produced somewhere in the scintillator must pass the material to reach the light detector. This imposes constraints on the optical transparency of the scintillation material. When increasing the diameter of the scintillator, the solid angle under which the detector "sees" the source increases. This increases detection efficiency. Ultimate detection efficiency is obtained with so-called *"well counters"* where the sample is placed inside a well in the actual scintillation crystal.

The thickness of the scintillator is the other important factor that determines detection efficiency. For electromagnetic radiation, the required thickness to stop say 90 % of the incoming radiation depends on the X-ray or γ -ray energy. For electrons (e.g. β-particles) the same is true but different dependencies apply. For larger particles (e.g. α-particles or heavy ions) a very thin layer of material already stops 100 % of the radiation.

The thickness of a scintillator can be used to create a selected sensitivity of the detector for a distinct type or energy of radiation. Thin (e.g. 1 mm thick) scintillation crystals have a good sensitivity for low energy X-rays but are almost insensitive to higher energy background radiation. Large volume scintillation crystals with relatively thick entrance windows do not detect low energy X-rays but measure high energy gamma rays efficiently.

Q. Draw a schematic diagram of energy spectrometer.

Ans.➢ The basic principle of pulse height spectroscopy is that the light output of a scintillator is proportional to the energy deposited in a crystal. The standard way to detect scintillation light is to couple a scintillator to a photomuitiplier. A γ-ray energy spectrometer usually consists of a preamplifier, a main (spectroscopy) amplifier and a multichannel analyzer (MCA) or Single Channel analyzer (SCA) with a counter. The electronics amplify the PMT charge pulse resulting in a voltage pulse suited to detect and analyze. Figure below illustrates an energy spectrometer using a single channel pulse height analyzer. Each interaction in the scintillator gives rise to a photo-multiplier anode charge $q_{a.s}$,which is proportional to the energy spent in the interaction. The charge amplifier converts the charge into a proportional voltage pulse u_q which is then amplified and applied to the single channel analyzer and counted by the counter. By selecting appropriate LLD and window, an energy ($\propto$ pulse height) spectrum is obtained.



ENERGY SPECTROMETER

For pulse counting, the time constant is usually made as short possible to be compatible with the high resolution of the detector system. For energy spectrometry it must be long enough to integrate all the charges due to a single event; however, if is too long there is a risk of pulse pile-up.

The SCA selects pulses that are between a set minimum and maximum (the amplitude window), and passes them to the counter. The pulse frequency registered by the counter is a measure of the radiation intensity to which the scintillator is exposed. ≺

Q. What is peak-to-valley ratio?

Ans.➢ A sensitive way to check the energy resolution of a scintillation detector is to define a so-called peak-to-valley (P/V) ratio in the energy spectrum. This criterion does not depend on any possible offsets in the signal. Either the peak-to-valley between two gamma peaks is taken or the ratio between a low energy peak and the PMT / electronics' noise. A good P/V ratio for a 76 x 76 mm NaI(Tl) crystal is 10 : 1. This is equivalent to an energy resolution of 7.0 % at 662 keV. At 5.9 keV, a high quality X-ray detector can have a P/V ratio of 40: 1. ≺

Q. Define resolution time.

➢ *Resolution time* is the least interval between successive scintillations that the counter can distinguish. It is determined either by the decay time constant of the scintillator or the time characteristics of the electronics. With present-day scintillators resolution times of the order of 1 ns can be obtained. ≺

(Comments: If the dead time of the counter, τ_d , is comparable with the mean interval separating successive scintillations, the counting error may be appreciable. If n_e is the observed count rate, the true count rate corrected for the dead time is

$$n = \frac{n_e}{1 - n_e \tau_d} .$$

Environmental effect may increase or decrease the count rate. Background radioactivity increases it. Absorption between the source and the scintillator decreases it. Absorption can be a significant cause of counting error for highly ionizing radiations such as α and soft β-rays, especially if their free path in the ambient medium is short compared with the distance between source and scintillator. Scatter may increase or decrease the count rate, depending on whether the net deflection of radiation is into or away from the detector.

Statistical considerations also affect counting accuracy. Even when the dead time of the counter is small compared with the mean time interval between scintillations (and environmental effects are negligible), the accuracy of the count is limited by the stochastic nature of the phenomena observed. For example, when measuring radiation intensity (nuclear particles or photons), the measured value of the count rate will have no fixed level but will vary from observation to observation. An estimate of the accuracy of the count rate measured can be made on a statistical basis.)

Q. Explain the formation of current pulse and voltage pulse.

Ans.➢ *Current Pulse:*

The light emission L(t) of a scintillator excited at time t = 0 can be approximated by

$$L(t) = \frac{\overline{n}_{p,s}}{\tau} \exp(-\frac{t}{\tau})$$

where $\overline{n}_{p,s}$ is the mean number of photons per scintillation and τ is the decay time constant of the scintillator. The convolution product gives the resulting number of electrons at the photo-multiplier anode

$$S(t) = L(t) * R_\delta(t)$$

where $R_\delta(t)$ is the photo-multiplier pulse response. If the photo-multiplier response-pulse width t_w is negligible compared with τ , this reduces to

$$S(t) = \frac{\overline{n}_{a,s}}{\tau}\exp(-\frac{t}{\tau})$$

where $\overline{n}_{a,s}$ is the mean number of anode electrons per scintillation; or, in terms of the anode current I_a and anode charge $q_{a,s}$

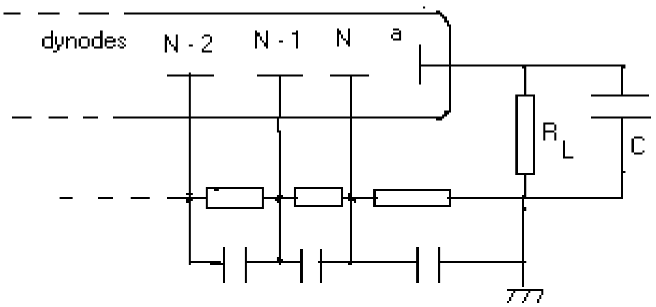
$$I_a(t) = \frac{\overline{q}_{a,s}}{\tau}\exp(-\frac{t}{\tau}) \qquad \text{(Eq. 1)}$$

*Voltage Pulse:*In the circuit of Fig given here the current pulse of Eq.1 gives rise to a voltage pulse

$$V_a(t) = \frac{\overline{q}_{a,s}}{C}\frac{\theta}{\tau-\theta}\left\{\exp(-\frac{t}{\tau}) - \exp(-\frac{t}{\theta})\right\}$$

……..Eq. 2

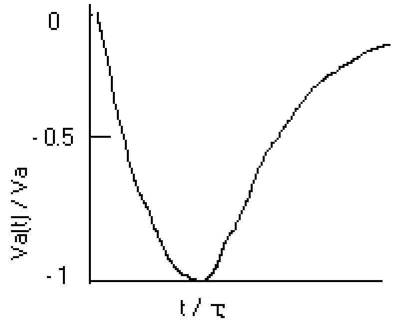
where θ = R_LC. The second Fig. shows the pulse shape; the amplitude is given by



Anode circuit with anode load

$$V_a = \frac{\overline{q}_{a,s}}{C}\left(\frac{\theta}{\tau}\right)^{1/(1-\theta/\tau)}$$

As θ/τ tends toward infinity, V_a tends toward the limit $\overline{q}_{a,s}/C$.



voltage pulse shape at anode RC

Special cases

When θ << τ, Eq.2 approaches the limit

$$V_a(t) = \frac{\overline{q}_{a,s}}{C}\frac{\theta}{\tau}\left\{1 - \exp(-\frac{t}{\theta})\right\}\exp(-\frac{t}{\tau})$$

corresponding to an amplitude

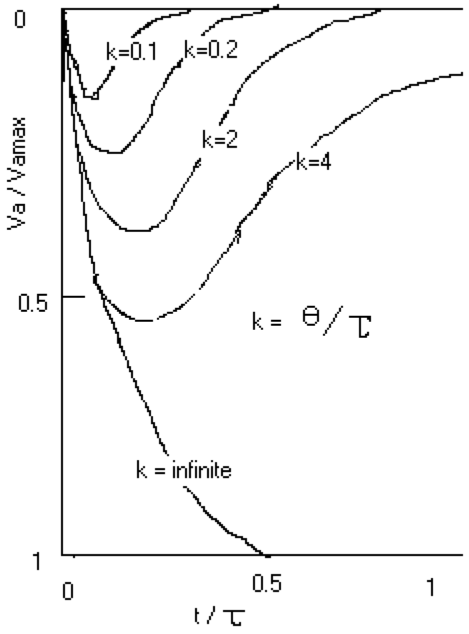
$$V_a = \frac{\overline{q}_{a,s}}{C}\frac{\theta}{\tau}$$

attained at a time $t_m = \tau\ln(\tau/\theta)$, which tends towards zero as θ/τ does. When θ = τ, Eq.2 reduces to

$$V_a(t) = \frac{\overline{q}_{a,s}}{C}\frac{t}{\tau}\exp(-\frac{t}{\tau})$$

corresponding to an amplitude

$$V_a = \frac{\overline{q}_{a,s}}{C}\times\frac{1}{e}$$



Relative pulse amplitude shapes for an anode load RC with parameter k attained at a time $t_m = \tau$.

When $\theta >> \tau$, Eq.2 approaches the limit

$$V_a(t) = \frac{\overline{q}_{a,s}}{C}\{1 - \exp(-t/\tau)\}\exp(-t/\theta)$$

corresponding to an amplitude

$$V_a = \frac{\overline{q}_{a,s}}{C} = V_{a\,max}$$

attained at a time $t_m = \tau \ln(\theta/\tau)$, which tends towards infinity as θ/τ does. The Fig. above shows the effect of θ/τ on pulse shape.

Low values of θ/τ allow high-count rates and lessen the risk of pulse pile-up, but, because of the larger bandwidth of the circuit, they worsen the signal-to-noise ratio. ≺

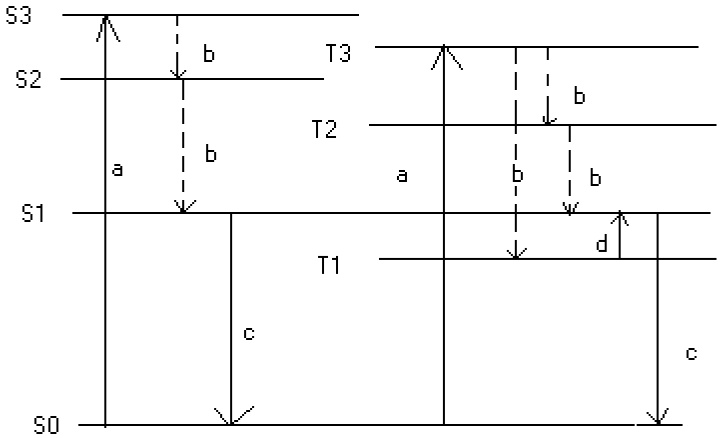
Q. What is a plastic scintillator?

Ans.➢ *Organic (plastic) scintillators* consist of a transparent host material (a plastic) doped with a scintillating organic molecule (e.g. POPOP : p-bis [2-(5-phenyloxazolyl)] benzene). Radiation is absorbed by the host material, mostly via Compton effect because of the low density and Z-value of organic materials. Therefore, plastic scintillators are mostly used for the detection of β- and other particles. Furthermore plastic scintillators are mainly used when large detector volumes are required e.g. in security or health physics applications. The cost of large plastic scintillation detectors (per volume) is much lower than that of equivalent size NaI(Tl) detectors; plastic scintillators can be manufactured in meter long slabs. ≺

Q. Explain the process of luminescence in organic scintillators.

Ans.➢ Luminescence in organic substances is a molecular phenomenon, which can occur in the solid, liquid or vapour phase as well as in liquid or solid solutions and plastic and glassy states.

Organic compounds form molecular crystals in which the occurrence of luminescence is associated with transitions between different energy levels of the electron systems: the singlet levels S_0, S_1, ..., S_n; and the triplet levels T_1,T_2, ..., T_n (see Fig. below). In the ground state the electrons are at the S_0 level. Incident radiation can either excite a molecule, raising its system of π electrons to a high singlet level (S_n), or ionize it, forming a free electron and a positive ion. Fast recombination of the electron and ion produces an excited molecule at a triplet level T_n or, less probably, a singlet level S_n. Non-radiative internal conversion phenomena then quickly return the excited levels to the lowest triplet or singlet levels, T_1 or S_1; these phenomena take about 10 to 100 ps.



a = excitation, b = non-radiative transition, c = radiative transition, d = activation T1 ---> S1

In organic compounds, luminescence is associated with electron transitions between different energy levels (singlet and triplet states)

The S_1 excited state, which lasts for about a nanosecond, can return to the ground state S_0 by either of two processes: thermal degradation (inhibition) or photon emission. The latter is called prompt fluorescence.

The T_1 excited state lasts much longer, and the molecule may return from it to the ground state by either of two routes. A direct return from T_1 to S_0 with photon emission is called phosphorescence. The emission is at a longer wavelength than fluorescence and the decay, which is exponential, is also longer – sometimes approaching a millisecond. Alternatively, interaction between two molecules in excited triplet states may raise one of them from the T_1 to the S_1 state, from which it can then return to the ground state; as before either by thermal degradation or photon emission. In this case the emission is of the same wavelength as fluorescence but the decay is non-exponential. ≺

(Comments: The mechanism of visible light photon emission that forms the basis of liquid scintillation counting is: (a) Passage of radiation through the solution produces a trail of ionized and electronically excited solvent molecules (b) Excited solvent molecules transfer their energy to solute molecules producing electronically excited solute molecules (c) Electronically excited solute molecules lose their excitation energy by collisional de-excitation or by photon emission.)

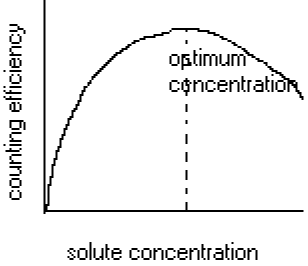
Q. What are the main components of liquid scintillators?

Ans.➢ The main components are: (1) a solvent; (2) a primary 'solute' - the scintillator material, and may contain (3) a secondary solute. The nature and functions of each component are considered below.

(1) The solvent: The solvent's functions are to keep the scintillator or solute in solution, and to absorb the decay energy of the radioisotope for subsequent transfer to the solute. Changes to the solvent, such as dilution with other material, may have a marked effect on the efficiency with which the solvent fulfils these roles. Solvents fall broadly into three categories:

(i) Effective solvents, e.g. the aromatic hydrocarbons, of which toluene and xylene are by far the most widely used. (ii) Moderate solvents, e.g. many non-aromatic hydrocarbons. With appropriate scintillator these may result in counting efficiencies of 15-40% of that of toluene. (iii) Poor solvents; unfortunately this is virtually everything else including most common laboratory solvents such as alcohols, ketones, esters and chlorinated hydrocarbons. Poor solvents usually give solutions with counting efficiencies of 1% of that of toluene.

(2) The primary solute: This is the name given to the scintillator material in the solution. The solute acts as a trap for the radioactive decay energy initially converted into electronic excitation energy by the solvent molecules. The earliest solutes were naphthalene, anthracene and p-terphenyl, and large conjugated systems are still the most widely used, and indeed the most efficient. Modern scintillator solutes often have lengthy chemical names and are most frequently known by simple abbreviations. Among the commonest are: p-terphenyl (PT), PPO (1-phenyl, 4-phenyloxazole), BPD (2-phenyl, 5(4-biphenyl) oxadiazole), PBO (2-phenyl, 5(4-biphenyl) oxazole), PPD (1-phenyl, 4-phenyl oxadiazole), BBOT (2,5 di-(5-t-butyl-2-benzooxazoyl) thiophene). As the concentration of primary solute in a scintillator solution increases, the counting efficiency initially increases, as shown in *Figure*. However, a scintillator solute, being an efficient photon emitter, is also a good photon absorber, so that a concentration is reached at which the number of photons escaping from the solution begins to fall. As a result there exists an optimum solute concentration at which maximum counting efficiency occurs. *Table* shows primary solute concentrations generally used in popular scintillator solutions.



Solute	*Concentration* (g per *l*)
p-terphenyl	5
PPO	3-7
PBD	8-10
BBOT	7

(3) The secondary solute: The photons emitted by PPO - probably the most popular primary solute – have wavelengths in the range 300-400 nm, a region of the spectrum which is ideal for detection by modern photomultiplier tubes. Unfortunately a large number of molecules have inconvenient photon absorptions in this region of the spectrum, particularly molecules of interest in biochemistry and medicinal chemistry, and samples containing such molecules would be counted with a lowered counting efficiency. When high counting efficiency is important the absorption of photons by either the sample or the primary solute may be reduced by using a secondary solute, which traps the excitation energy from the primary solute and emits photons of a longer wavelength. The most important secondary solutes are POPOP and its dimethyl derivative. Dimethyl POPOP is 1 ,4-di-2-(4 methyl, 5 phenyl oxazoyl) benzene and emits photons in the 400~500 nm range. Both materials have rather low solubilities in common scintillator solvents and are normally used in concentrations of 0.05-0.2 g l^{-1}. The combination of solvent and solutes, together with additives, which are sometimes used to improve miscibility of the sample material with the solvent, is referred to as a scintillator cocktail. Although an excellent range of scintillator cocktails is available from commercial suppliers, some laboratories find it worthwhile to mix their own and a selection of commonly used recipies is given in *Table below*. Note that purified materials, including the solvent, should be used to make these cocktails if problems such as chemiluminescent photon emission are to be avoided. 'Scintillation grade' solvents and solutes are available from many suppliers, and the slightly higher cost than the laboratory reagent grade is usually worthwhile.

Table: Typical scintillator cocktails (concentrations in g l^{-1})

Solvent	*Primary solute*	*Secondary solute*	*Additives*	*Sample type*
Toluene	PPO (4-6)	Me_2 POPOP (0.05-0.2)	--	organic soluble
Toluene	butyl PBD (8-12)	- -	- -	organic soluble

p-Xylene	butyl PBD (8-2)		Ethanol (100)	aqueous
1,4 Dioxan	PPO (4-6)	Me_2 POPOP (0.2)	Methanol (100) Ethylene glycol (20) Naphthalene (60)	aqueous ≺

Q. Give some examples of organic scintillators.

Ans.➢ Most organic scintillators are either monocrystalline compounds or liquid or plastic solutions. Among the most efficient monocrystalline compounds are naphthalene, anthracene, fluoranthane, p-terphenyl (PT), p-quaterphenyl (PQ), and trans-stilbene. Liquid scintillators are usually binary or ternary systems consisting of a solvent and small concentrations of one or two solutes that alter the emission wavelength. The most widely used solvents are alkyl benzenes such as xylene, benzene, toluene, etc. Common primary solutes are p-terphenyl, DPO, and PBD; common secondary solutes are POPOP, BBO, and BPO. Chemically, plastic scintillators are very similar to liquid ones. Just as the alkyl benzenes are the most effective liquid solvents, their polymers, such as polyvinylbenzene, polyvinyltoluene, etc., are the most effective plastic ones. PT, DPO, and PBD are useful primary solutes for both liquid and plastic scintillators; common secondary solutes include BBO, TBP, POPOP, and DPS. An advantage of plastic scintillators is the ease with which they can be formed into a variety of shapes and sizes: the large scintillator sheets used in high-energy physics experiments are an example. ≺

(Comments: *Anthracene* ($C_{14}H_{10}$): Traditional organic scintillator, finds use in a number of special applications. Important properties: Crystal anisotropy (high light output anisotropy Application comments: beta radiation detection and spectrometry.

Stilbene($C_{14}H_{12}$): Used for selective registration of fast neutrons (n) on the gamma radiation background in scintillation pulse-shape discrimination techniques, as well as for alpha/beta-, n/beta-, proton/beta-selection. It makes possible to perform neutron field spectrometry. The largest dimension is dia. 120x100 mm. Important properties: High structural perfection and performance stability. Selection of fast neutron on the gamma radiation background. Application comments: Fast neutron spectroscopy n/gamma, alpha/beta-discrimination.

Doped crystals of p-terphenyl ($C_{18}H_{14}$) : Undoped p-terphenyl crystals are of limited use because of their low light output. Introduction of special dopants ensures the light output to be increased by 4-5 times. Doped p-terphenyl crystals retain all basic advantages of organic scintillators, i.e. short decay time (t ~ 3-4 ns), temperature-independent light output values in a wide temperature range (-80...+150 °C). The p-terphenyl single crystals are translucent, knotty over the whole volume, plastic, water-insoluble, and poorly soluble in organic solvents. Scintillators based on doped p-terphenyl crystals are used in β-radiation spectrometry, where they are the most effective organic scintillators, α-radiation one, as well as for fast neutrons detection on the γ-radiation background in schemes for radiation discrimination by the scintillation pulse shape. Due to short decay time, p-terphenyl can be used in the spectrometry of high-intensity radiation. Important properties: High light yield. The lowermost light output anisotropy. Application comments: Detection and spectroscopy of alpha-, beta-radiations.)

Q. Mention some physical properties of organic scintillators:

Ans.➢ *Physical Properties of Organic Molecular Single Crystals :*

	Anthracene($C_{14}H_{10}$)	Stilbene($C_{14}H_{12}$)	Doped p-terphenyl($C_{18}H_{14}$)
Molecular weight	178	180	230
Density, g/cm^3	1.25	1.22	1.23
H/C – ratio	0.174	0.857	0.778
Melting point, °C	216	124	214
Wavelength of emission maximum, nm	445	390	420
Refractive index at emission maximum	1.62	1.64	1.65
Light output, 10^4 photons/Mev	2.0	1.4	2.7
Decay time, ns	30	3.5	3.7
A ratio of ranges in the crystal and anthracene for:			
a) heavy charged particles	1	1.002	0.997
b) electrons	1	1.014	1.012
Radiation degradation, Mrad	2	4.0	4.5

Q. What are the advantages of plastic scintillators?

Ans.➢ Plastic Scintillators offer high performance, ease of handling, mechanical stability at a relatively low cost. The versatility of plastic scintillators makes them the ideal choice for large area and specially shaped detectors.

Due to low effective atomic number organic materials in contrast to nonorganic ones are characterized by negligible back scattering effect for the process of charged particles absorbtion. Due to high concentration of hydrogen atoms they are used in fast neutron spectroscopy. Scintillators on the base of organic crystals are non-hygroscopic and fast. ≺

(Comments: Detectors based on organic crystals (doped p-terphenyl, stilbene, anthracene) are used for the detection and spectrometry of beta, gamma radiation, discriminative n/gamma - measurements, and in detectors for discriminative measurements of low-energy beta radiation. Since stilbene crystals have the most stable properties, detectors with these crystals are used as the reference ones in light output measurements. Detectors and assemblies with organic crystals are similar in design to those with alkali halide crystals. In the detectors (assemblies) intended for beta radiation measurement, the input window is made of aluminum-coated polyethylene-terephtalate film having a thickness less than 2 mg cm $^{-1}$.)

Q. Mention some isotopic neutron sources.

Ans.➢ Isotopic neutron sources produce continuous fluxes of neutrons. Typical isotopic sources are Californium-252 (^{252}Cf), with a half-life of about 2.64 years (Type of decay: α (97%) with 6.076 MeV 15%, 6.118 Mev 82% and fission (3%) with ≈ 20 γ's / fission, 80% < 1 MeV and ≈ 3 neutrons/fission, $<E_n>$= 2.14 MeV) (one mg ^{252}Cf$_{98}$ produces about 2.3×10^6 n/s), or Americium-Beryllium (AmBe), which produces neutrons via the ^{9}Be(α, n)^{12}C reaction (^{241}Am$_{95}$ has a half-life of 432.2 years and yields 6×10^{-5} neutrons (4–8 MeV) and 4×10^{-5} γ's (4.43 MeV) per Am decay). Isotopic neutron sources have the advantage of having a long useful life and producing a relatively constant flux of neutrons. They are relatively inexpensive for low flux (<10^8 neutrons per second) sources. However, isotopic sources have several disadvantages. The neutron output can not be turned off; requiring that they be contained within bulky shielding at all times. Isotopic neutron sources cannot be pulsed and the energy spectrum of the emitted neutrons is broad and peaks at energies below the threshold for some important reactions. ≺

Q. From where do you quote the range energy relation $R = 412\ E_0^{1.265 - 0.0954\ln E_0}$ (mg/cm^2)?

Ans.➢ The range energy relation $R=412\ E_0^{1.265 - 0.0954\ln E_0}$ (mg/cm^2) appears in the paper titled " Range-Energy relations for Electrons and the Determination of Beta-Ray End-Point Energies by Absorption" by L. Katz and A.S. Penfold in Rev. Mod. Phys. 24, 28 – 44 (1952). The abstract of the paper contains the following:

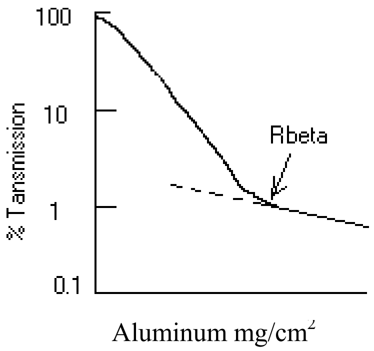
"It is shown that for aluminum absorbers, a single range-energy equation $R=412\ E_0^{1.265 - 0.0954\ln E_0}$ (mg/cm^2) will fit the most reliable published values of practical ranges of mono-energetic electrons and the maximum ranges of nuclear beta-rays in the energy region $0.01 <\sim E_0 <\sim 2.5$ MeV……………. There are few ranges for energies above 2.5 MeV. All the higher energy values found in the literature and four new measurements on mono-energetic electrons are presented and are shown to be consistent with the range-energy equation $R = 530\ E_0 - 106$ (mg/cm^2) for $E_0 \geq 2.5$ MeV. ……………….. All the methods commonly used to determine the ranges of beta rays from absorption curves are discussed and a new method developed by the authors is presented." ≺

Q. What is the inspection method of determining the range?

Ans.➢ Inspection Method: This method is the simplest and perhaps the least reliable. The range is determined from an inspection of absorption curve. In order to find where the curve meets the background many accurate experimental points are required close to the range thickness. If the curve approaches the background very slowly, then it is difficult to obtain good accuracy. Thick sources tend to have an overabundance of slow electrons because of self-absorption, thus giving rise to this difficulty. Hence thick sources should be avoided. A high γ –ray background will also cause the gradual merging of the absorption curve and the background. In this case there is little one can do. ≺

Q. How do you define range of β-particles? What is the advantage of the absorption method?

Ans.➢ If the fractions of the incident betas, which pass through given thickness of aluminum, are plotted against that thickness an absorption curve is obtained (Fig. a). At high filter thickness the curve passes into the background. This

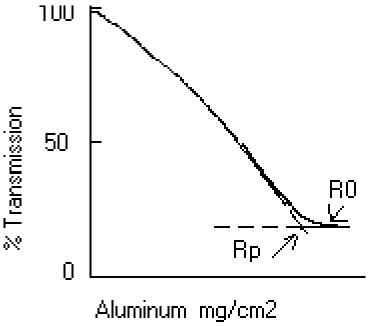


(a) Percent of nuclear β-rays transmitted by various thickness of aluminum absorber. The background is the result of cosmic rays, natural radioactivity, and Compton electrons from γ –rays, when present. The point at which the absorption curve meets the background is called the range (R_β) of the betas.

background is usually due to cosmic rays, and γ-rays when they are present. The point at which the absorption curve meets the background is called the range. Once the range has been measured, the end-point energy can be determined from the range energy-relation.

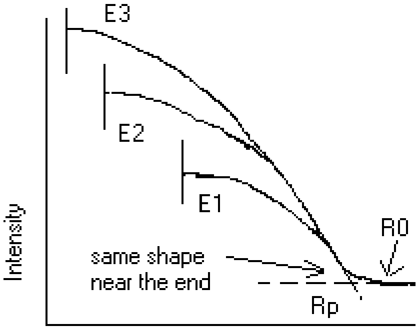
The absorption method has the advantages of simplicity, speed, and, above all, sensitivity, it does not present the "picture" of the spectrum. Conversion peaks (particularly if they occur near the end-point) and Compton recoil electrons are hidden factors, which may lead to a value for the range that is in considerable error.

RANGE ENERGY RELATIONS



(b) Characteristic absorption curve of homogeneous electrons in aluminum. Point where extension of the linear portion of the curve meets the background is called the practical range R_p. The maximum range R_0 is the point where the absorption curve runs into the background.

Early range energy measurements were made mainly with nearly homogeneous (mono-energetic) beams of electrons. The absorption curves for these have a long straight portion down to fairly low intensities (intensity potted to a linear scale) and then a considerable tail, going into the background (Fig. b). After the electrons have penetrated a certain fraction of their range the beam becomes completely diffuse and so all the absorption curves have the same shape near the range thickness as shown in Fig(c). Because of this similarity in shape writers have defined the point at which the extension of the linear region meets the background as the practical range (R_p), whereas the point where the tail meets the background is known as the maximum range (R_0). For, homogenous electrons one have, in R_p, a consistent definition of range.



(c) Sketch to show how absorption curves of homogeneous electrons of different initial energy have the same shape near the end of their range. Curves of initial energy E_1, E_2, and E_3 are drawn with their practical ranges, R_p, coincident.

However no linear region exists for β-ray absorption curves, and the definition of the range is more arbitrary. An analysis by Katz and Penfold shows that there is no discernable difference in the ranges of homogeneous electrons and β-particles. Therefore it seems that the definition of the practical range (R_p) in the case of homogeneous electrons is compatible with the range of β-rays (R_β) as determined by methods involving absorption curve analysis. ≺

Q.Give a summary of Katz and Penfold determination of range – energy relation.

Ans.➢ For approximate computations of the absorption of nuclear β-rays it has been customary for some workers to assume that over a limited region the intensity of the beam varies exponentially with absorber thickness,

$$I = I_0 \exp(-\mu x / \rho)$$

where μ/ρ is an apparent mass absorption coefficient expressed in cm^2/mg and x is the absorber thickness in mg/cm^2.

This equation may be related to the range-energy curve through the following analytical, though experimentally unrealistic formulation. Suppose the range is defined in principle as that thickness which reduces the intensity I_0 to some small fraction kI_0, where k is a small number of the order of 0.0001 or less depending on the sensitivity of the detector and the energy of β rays involved. Then

$$k = \exp(-\mu R/\rho)$$

or

$$\mu/\rho = -\ln(k) / R = -\ln(k) / a(E_0)^n$$

where the following range –energy relation is assumed

$$R(mg/cm^2) = a\,(E_0)^n$$

with both "a" and n as unknown parameters. From the experimental points the value of R at $E_0 = 1$ was chosen as 412. The value of n was then determined for each of the experimental points. The best straight line through the data (for n versus $\ln E_0$ graph) gave

$$n=1.265 - 0.0954 \ln E_0 .$$

The final equation for the range energy relation was thus

$$R(mg/cm^2) = 412(E_0)^{1.265 - 0.0954 \ln E_0}$$

where the energy is in MeV. A remarkable fit to the experimental values is obtained for energies up to about 3 MeV. For $0.1 < E_0 < 3.0$ MeV, the value of n as obtained from $n = 1.265 - 0.0954 \ln E_0$ varies from 1.16 to 1.48 having an average value of 1.32.

The authors further proposed that the range energy curve in the region of energies between 2.5 and 20.0 MeV be represented by

$R(\mathrm{mg/cm^2}) = 530\ E_0(\mathrm{MeV}) - 106$ (for $2.5 < E_0 < 20.0$). ∢

Q. Reproduce the Katz – Penfold Range - Energy Graph.

Ans.➢ See next page. The Fig. 2 is taken from the original paper. Suggestion: Use this graph to estimate the energy once you determine the range experimentally.

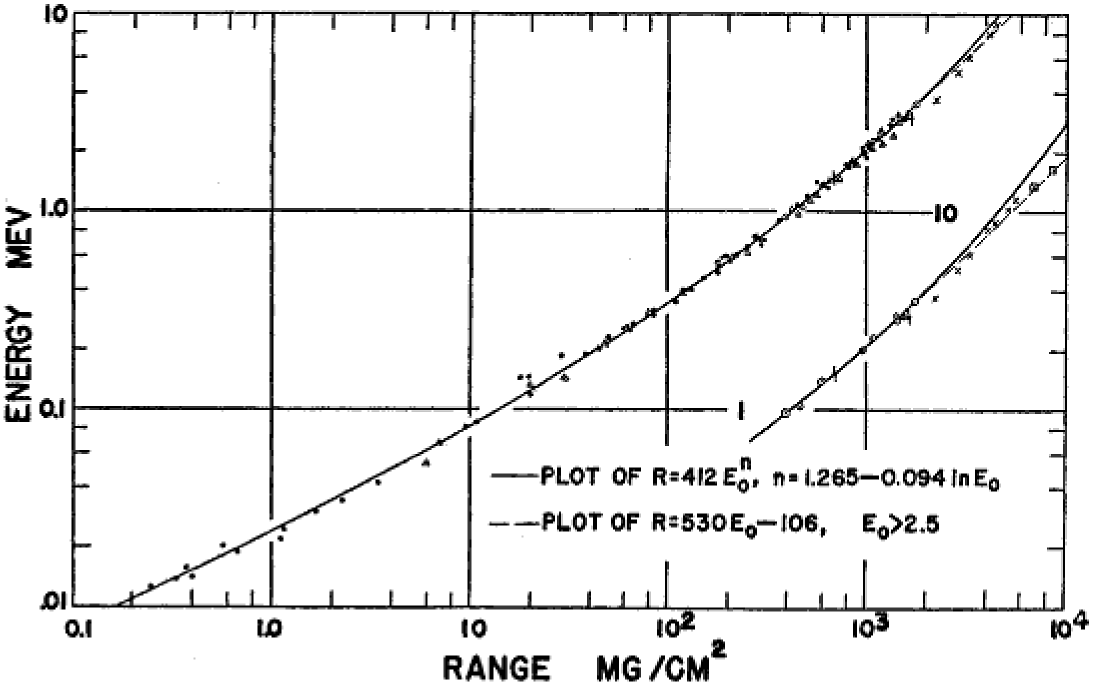


FIG. 2. Range-energy curve. The experimental points are those listed in Table I. ● Practical range of homogeneous electrons as measured by Varder, Schonland, Madgwick, Eddy, Marshall and Ward. ⊗ Practical range of homogeneous electrons according to Trump, Wright, and Clarke. △ Ranges of beta-rays according to measurements of Widdowson and Champion, Moore, and Glendenin; energies are the best accepted values from N.B.S. circular 499. ⊙ Ranges of beta-rays measured by the authors; energies are the best accepted values from N.B.S. circular 499. ⊡ Ranges of beta-rays from B^{12} (range—Hereford and Swann, energy—Fowler, Lauritsen, and Lauritsen) and N^{12} (Alvarez). —●— Two practical range points due to Bleuler and Zunti. × Practical range measurements from Hereford and Swann. The solid line represents the empirical equation $R=412\ E_0^{1.265-0.0954 \ln E_0}$ and is a good fit below 2.5 Mev. The dashed line represents the Feather relation $R=530\ E_0-106$ and is a good fit above 2.5 Mev.