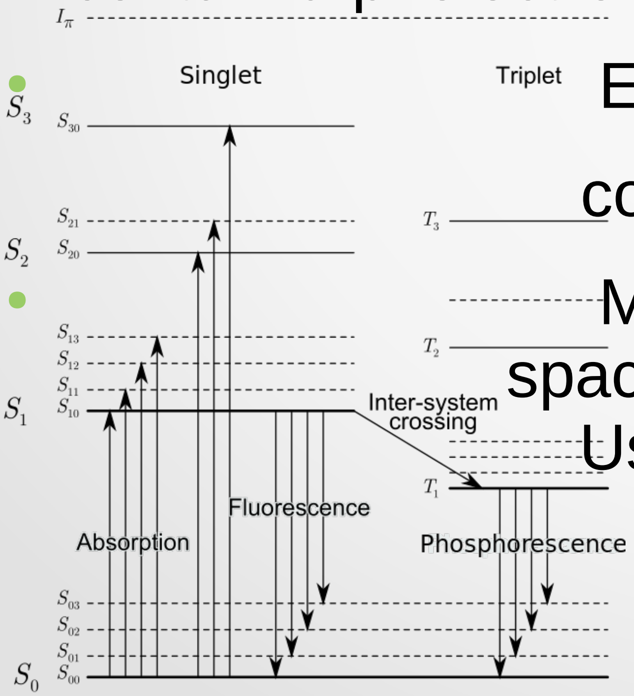
Ideal Scintillator Properties

- Convert K.E. of charged particles into detectable light with high efficiency
- Energy conversion should be linear; light yield proportional to deposited energy
- Medium should be transparent to wavelength of its own emission
- Decay time of luminescence should be small to allow fast signal pulses
- Material is of good optical quality and can be made in sizes for practical detectors
- The index of refraction should be near 1.5 (glass) to allow easy use of the light with a photomultiplier tube or other light sensor

Organic Scintillator Mechanism

- A fluorescence process which can occur whether material is solid, vapor or part of a solution.
- Caused transitions in energy levels of a single molecule.
- Most practical organic scintillators based on molecules that contain a pi-electron structure



- Energy can be absorbed and excite the configuration into singlet or triplet states.
- Most molecules used have an energy spacing between S0 and S1 of 3 or 4 eV. Usually smaller for higher states.

Con‘t

- Subcategories of levels are vibrational states. Usual spacing is order of 0.15 eV.
- Average thermal energies are 0.025eV and thus most molecules at room temperature are in the S00 state.
- Higher singlet states de-excite to the S1 state on the order of picosecond through internal conversion, as do states with excess vibrational energy (not in thermal equil.)
- This means a large population in the S10 state in a short period of time.
- Scintillation light is emitted by transition from S10 to S0#.

Con‘t and Phosphorescence

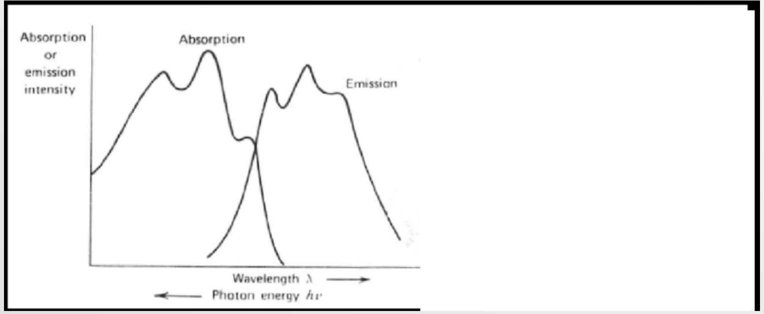
- T is the fluorescence decay time for S10. The intensity at a time t after excitation is:

  I = i * exp(- t / T)

- Most organic scintillators, T is a few nanoseconds.
- Some singlet states may convert to triplet states. This process is called intersystem crossing.
- Lifetime of T1 can be as high as 1e-3 sand the radiation from T1 → S0 is delayed light emission. This is called phosphorescence.

Delayed Fluorescence and Transparency

- Some molecules, while in the T1 state, can be thermally excited back to S1 and then decay as normal fluorscence.
- This is delayed fluorescence and sometimes is observed in organic scintillators.
- Since the fluorescent transitions are lower in energy than the required excitation energy, there is litle overlap in the emission and absorption spectra.
- This is sometimes called Stokes shift and results in low self-absorption.



Scintillation Effeciency

- The scintillation effeciency is the fraction of incident particle energy converted into visible light
- Quenching is the term for all other de-excitation processes that do not emit radiation.

Inorganic Scintillators

- Based on energy states of crystal lattice of the material.
- The electrons in a lattice only have discrete bands of energy (insulators and semiconductors). These include the valence band (lower energy -bound) and the conduction band (higher energy-free electrons)
- Excitation from the valence to conduction band is a pure crystal is inefficient and the resulting photon is outside the visible range.
- To allow for visible photon emission, impurities are added to the crystal. These are called activators.
- The activators create locations in the scintillator where the energy levels are allowed between the band levels.
- The locations of impurities are called luminescence centers or recombination centers.

Mechanism

- Many electron-hole pairs are created when a charged particle passes through the detection material.
- The ionization energy for the impurites are smaller than the crystal lattice and the holes will ionize these locations. The free electron will roam and bind with an ionized impurity location.
- These activator locations now have their own excited states. For an allowed de-excitation to the ground state, the emission happens on the order of 30-500 ns. Electron roaming times is much smaller meaning that these excited states occur at essentially the same time.
- This decay determines the time characteristics of the scintillator light. Some scintillators can be fully characterized by one decay time, an exponential.

Types of Organic Scintillators

- Pure organic crystals: Anthracene has the highest effeciency of any organic scintillator.

  These materials are relativlely fragile and difficult to obtain large sizes.

  The effeciency depends on the orientation of the ionizing particle and thus many incident directions spoils the energy resolution up to 20-30%.

Con‘t

- Liquid organic solutions

  Made by dissolving an organic scintillator into an appropiate solvent.

  Most practical in terms of cost when a large volume detector is needed.

  Must be sealed and dissolved oxygen removed as it acts as a quencher.

  More resistant to radiation damage than solid scintillators.

  Counting radioactive material that can dissolve into the solution and the counting effeciency can be 100%.

Con‘t

- Plastic scintillators

  Easily shaped and fabricated

  Many sizes, including large scintillator sizes

  Can be rods, cylinders and flat sheets

  Relatively inexpensive, used when large volume solid scintillators are needed.

  Attention to the attenuation properties must be given as the self absorption is no longer negligible.

- Can be small diameter fibres and can be grouped as bundles or ribbons and used for position of particle interactions with good spatial resolution.

  Large gamma ray exposures degrade light yield significantly

Con‘t

- Thin Film scintillators

  Very thin films of plastic

  Easy to create a detector that is thin compared to the range of weakly penetrating particles such as heavy ions.

  Response time does not follow directly from energy loss of ions, but as a more complex function of ion velocity and atomic number.

- Can be placed directly on the face of a photmultiplier tube

  Light yield per energy loss increases with decreasing atomic number and are useful for transmission detection of protons or alpha particles.

  Scintillation decay time is several ns and useful in fast timing measurements

Con‘t

- Loaded organic scintillators

  Low Z-number (H,C,O) means there is virtually no photoelectric cross section for gamma rays.

  Organic scintillators show no photopeak and will give rise to comptom continuum

  To provide photelectric conversion,attempts to add high Z elements have been made

  These cause decreased light output and energy resolution.

Inorganic scintillators

- NaI(Tl)

  Exceptionally high light output.

  Available in large volumes at low cost

  Large ingots can be grown and thalium added as an activator

  Unusual size and hsape scintillators cna be made by pressing small crystallines together

  Crystals will deteriorate due to water absorption if exposed to the atmosphere and thus must be in an arirtight container

  Light yield for fast electrons is about 38000 photons per MeV
- Nonproportionality with scintillator response, common with inorganics.
- 230 ns pulse is too long for fast timing or high counting rate.
- 0.15s phosphorescence decay contributes to 9% of the yield.

  Low counting rates are single electron pulses .
- Phosphorescence afterglow is undesirable at high counting rates that build up due to overlap.
- Sometimes need at different temperatures than room and the response time increases at high temperatures The light yield also drops off.
- Pure sodium iodide is fast but weak at room. Low temperatures cooled with liquid nitrogen, it outputs higher than NaI(Tl)

Con‘t

- CsI(Tl) and CsI(Na)

  Larger gamma ray absorption coefficient per unit size

  Important for applications in space instrumentation

  Less brittle than NaI and can be subjected to ore extreme shoc and vibration

  Thin sheets can be bent into shapes without fracture

  Malleable

  CsI(Tl) has a variable time decay for various exciting particles.

  Pulse discrimination can be used to differentiate types of radiation

  Colum microstructure can be created for better spatial resolution and layering can be used for x-ray detection

  Higher yield in the red region due to the emission spectrum peaking at longer wavelengths

  Unusual high rise time of 20ns. Decay is among the slowest . Best energy resolution at long shaping times to include all prompt scintillation light

  Afterglow inteference in high counting rates
- CsI(Na) similar spectrum to NaI and light yield, but very slow decay.

Con‘t

- Bismuth Germanate

  High density is an advantage (7.13g/cm^3)

  Large atomic number (83)

  Large probability pr unit volume for photoelectric absorption of gamma rays

  Not as fragile, easy to handle

  High refractive index (2.15) makes effecient collection for difficult

  Light yield is low

  Interest for high gamma ray counting effeciecy over energy resolution

  Much worse timing resolution
- No activator needed

  Self absorption low as the emission and absorption spectra have a large shift

Con‘t

- Cadmium Tungstate

  High z number (74)
- Good for gamma ray and x ray photelectric absorption

  Very long decay times. Pulse mode applicatiosn are limited.

  2.3 index of refraction

  Calcium Tungstate ha a better decay time.
- Zinc Sulfide

  Powder only: limited use to thin screens and alpha particle or heavy ion dtection

  Thickness grater than 25mg/cm^2 are unusable as it is opaque to its own luminescence
- Calcium Fluoride

  nonhygroscopic and inert. Useful in severe environmental conditions.

  Fracture resistant

  Can be used under vacuum conditions (low vapor pressure)

  900 ns decay times

Response of Organic Scintillators

- Remainder of energy not used in fluorescence is tranferred to heat or vibrational energy
- Fraction that is converted is dependent on type of particle and energy
- Possible to be independent of energy, thus a linear dependence light yield
- Many organic scintillators, response to electrons is linear above 125keV
- Heavy charged particles, protons, alpha particles, response is less for similar energies and nonlinear for higher energies
- Due to dependence of light yield of type of particle, MeV electron equivalent (MeVee) is used to describe the absolute light yield.
- 1 MeVee is 1 MeV for electrons and several MeV for heavy charged particles
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Con‘t

- Strontium Iodide

  High resolution in gamma ray spectroscopy

  Very high light yield (100000 ph per MeV)

  Easier crystal to grow

  1.2 micro s decay time

con‘t

- He response can be described by a relation of dL/dx (fluorescent energy emitted per unit path) and dE/dx (specific energy loss)
- High ionization density along the track leads to quenching and lowers the efficiency
- Density of damaged particles proportional to ionization density,B(dE/dx) is thier density.
- Absence of quenching, light yield is proportional to energy loss dL/dx = SdE/dx
- Birks formula accounts for probability of quenching

  dL/dx = SdE/dx (1 + kBdE/dx)^-1
- A fraction of the density, k, leads to quenching

Con‘t

- Excited by fast electrons, dE/dx is small for large E

  dL/dx at e = SdE/dx (incremental light output per unit energy loss is constant)
- DL/dE at e = S
- Regime where the light output is linearly related to inital particle energy E
- Alpha particle: dL/dx = s/kB
- kB = dL/dE(e) / dL/dx (alpha)
- Other formulas have been proposed to matc experimental data
- Alpha to beta ratio is a parameter used to describe the difference in light outputfor electrons and charged particles of the same energy
- For plastic scintillators, there is a variablility in the measurements due to diffrences in purity and history of the material. Absolute values should be used with caution
- Some organics, the partial overlap of the spectra leads to size dependence of the apparent efficiency.

Time response

- It can be assumed that luminescent states are formed instantaneously and prompt flurescence is only observed
- Time profile should then be very fast leading edge for the light pulse followed by exponential decay
- Models should take into account the finite time to populate states and slower compnetns of scintillation for delayed phosphorescene and fluorescence
- Half a ns are needed to populate. Fast scintillators, decay time 3 or 4 times greater.
- One approach assumes population is alos exponential and the overall shape of the light pulse is

  $I = i\,(e^{-t/T} - e^{-t/T1})$
- T1 is the constant describing population of optical levels and T is the decay
- Overall light versus time profile is

  $I/i = f(t)\, e^{-t/T}$
- Usually the FWHM is used to characterize the profile.