Techniques in Experimental Nuclear Physics

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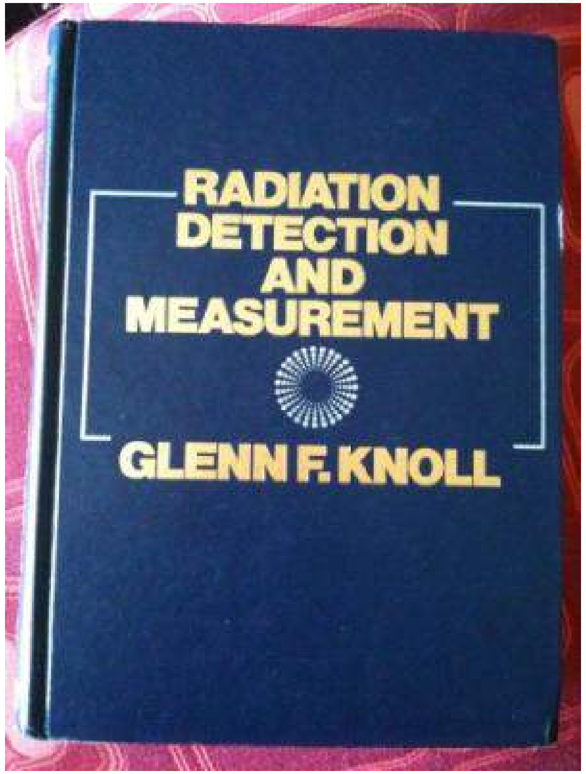
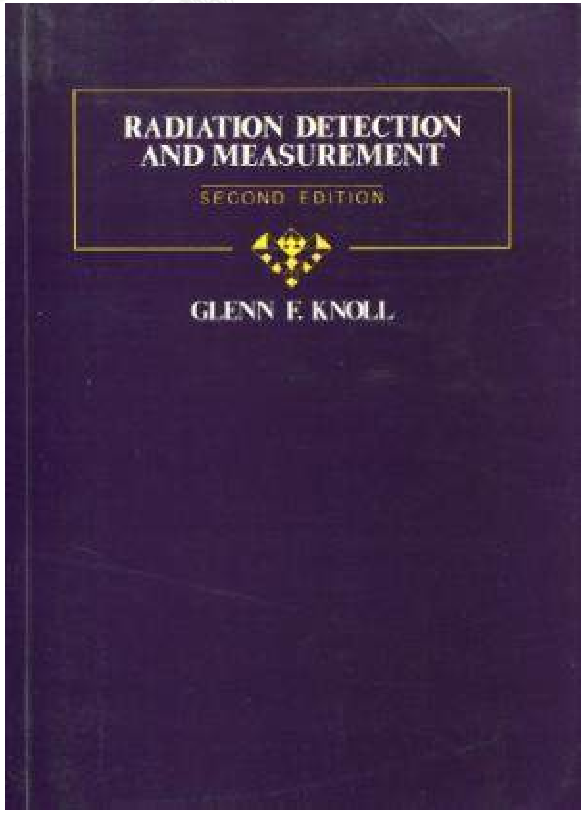
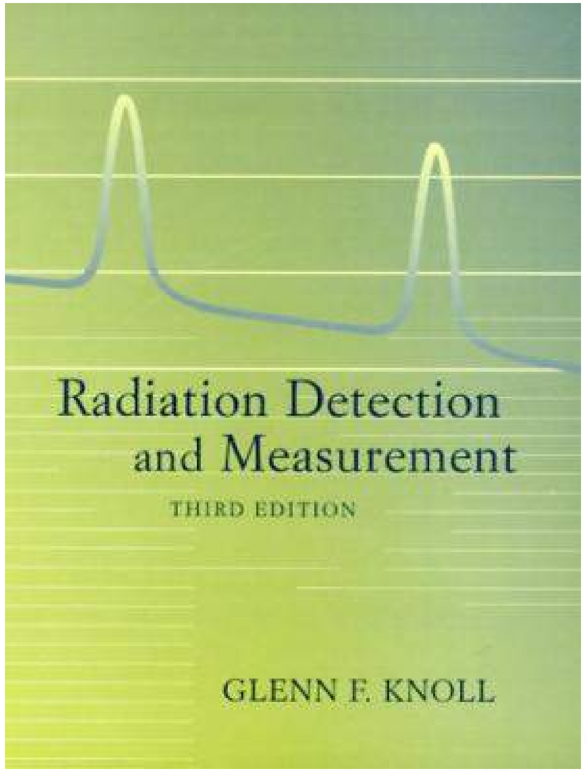
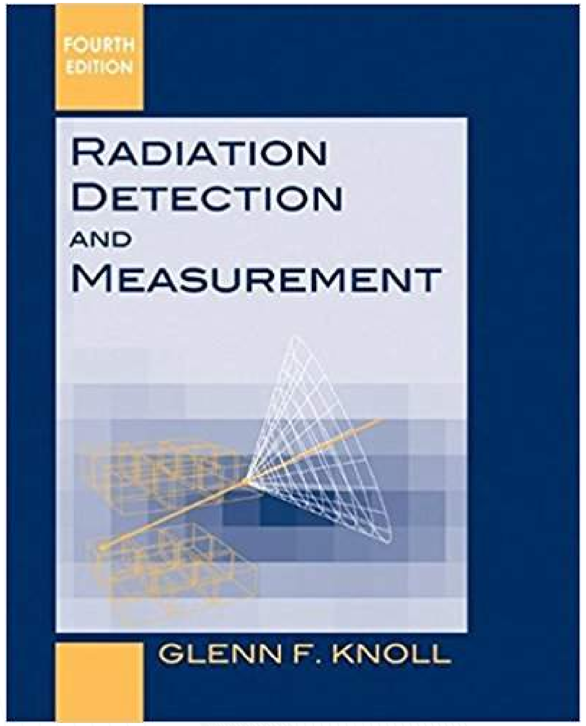
Lesson #0: you're not a nuclear physicist unless you own this book









...ok, maybe you're a theorist, but you should still own the book

Topics

- Detector operational principles
  - Semiconductor
  - Scintillator
  - Gas-filled

- Experimental setup and techniques
  - Electronics – pulse generation, amplification, timing, logic
  - Data acquisition – analog vs digital

- Analysis techniques
  - Coincidences
  - Pulse shape analysis/discrimination
  - ...

Where do we start?

What we want to measure:
→ energy, velocity, momentum, mass
→ time
→ position
→ cross section
→ correlations (angular, feeding)

We then want to infer (with theory):
→ spin/parity
→ angular momentum transfer
→ spectroscopic factors

What we actually measure:
→ charge or light (pulse)
→ time (wrt a defined clock)
→ segment ID (pixel hit)
→ number
→ true/false logic gates

Things we can optimize:
→ resolution
→ efficiency
→ rate capability
→ selectivity

Where do we start?

Let's begin with detectors, with which we measure these

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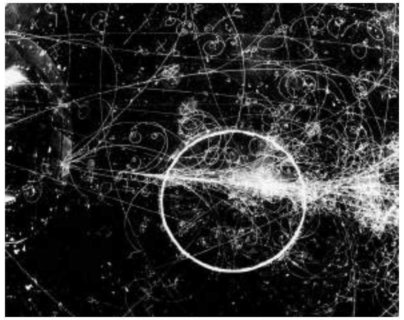
Detector basics



We need some sort of device that converts incoming radiation (charged particle, gamma, neutron, beta…) into a usable signal.

“Back in the day” we had photographic plates, cloud chambers, emulsions → visual indication of particle tracks as signal

Semiconductor detectors → ionization (electron-hole pairs) collected into current or charge signal

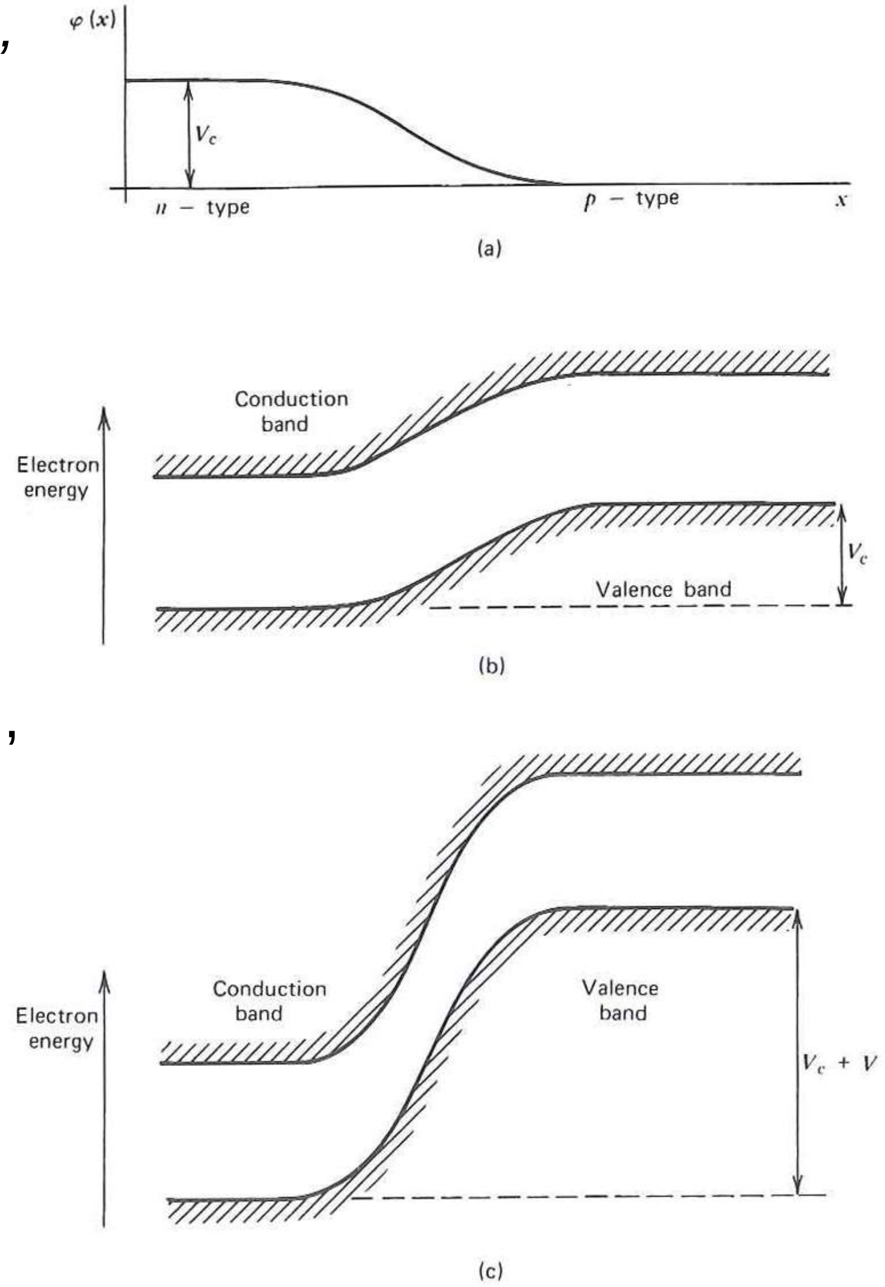
Scintillation detectors → deexcitation (photons), converted to electrons via a photocathode/photodiode and collected into current or charge signal

Gas-filled detectors → ionization (electron-ion pairs) collected into current or charge signal

Semiconductor Detectors

aka “semiconductor diode detectors” or “solid state detectors”

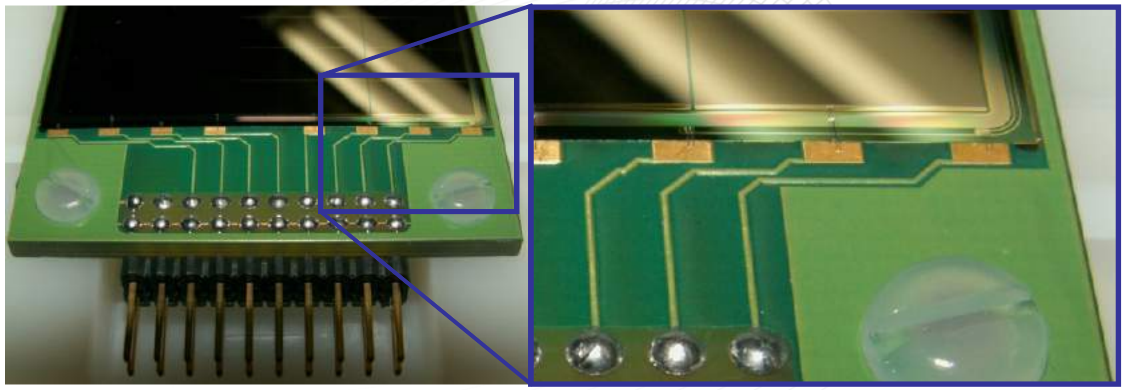
- Silicon, Germanium = semiconductors
  - **Hands-on: HELIOS, Gammasphere**
- “intrinsic” semiconductors are not just rare (can't get the purity), but also a bit useless – we want to dope the semiconductor to tailor its response to our needs
- n-type: donor electrons from doping (pentavalent dopant in the case of silicon), lie very close to conduction band, net effect is to create far more conduction electrons than holes
- p-type: donor holes (or “acceptors”) from doping (trivalent dopant in the case of silicon), lie very close to valence band, net effect is to create more conduction holes as the charge carrier
- incoming radiation creates electron-hole pairs along track (roughly 3 eV per pair), these charge carriers are migrated through the material with an applied electric field and the current signal, proportional to energy, is read out from electrical contacts

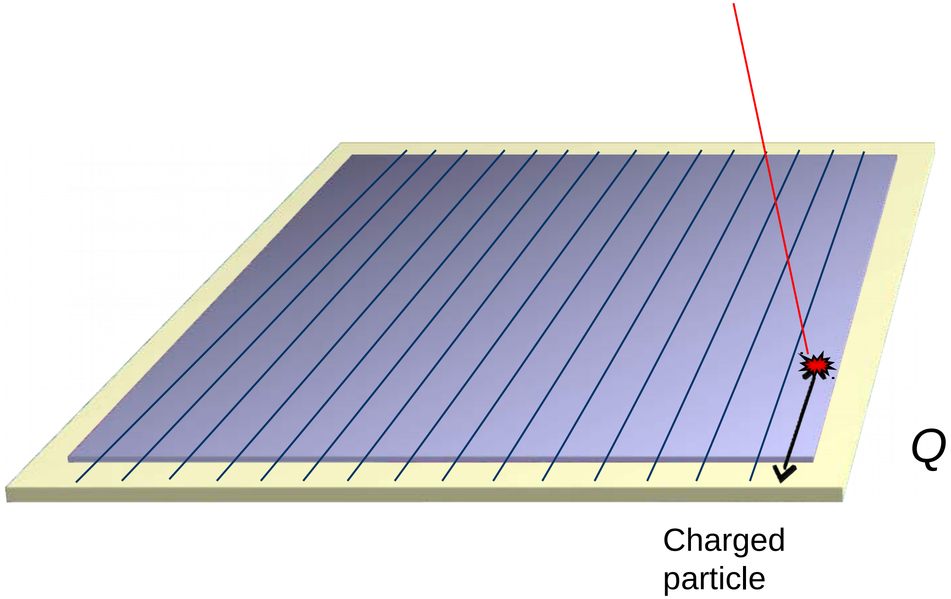


Semiconductor Detectors

- in practice, most useful semiconductor detector takes advantage of a junction between p- and n-type doped regions (a diode) – this represents a discontinuity in the conduction electron density → net diffusion of charge carriers until a small “space charge” is created = “depletion region” where electron-hole pairs are created by incoming radiation and quickly swept up
- apply a reverse bias to the p-n junction and nearly all of this voltage appears across depletion region (much higher resistivity than rest of material) – “partially depleted” = depletion region inside detector volume; “fully depleted” = depletion region reaches to surfaces of detector
- capacitance of detector varies with applied voltage (changing the depletion region), so “charge sensitive preamps” are required; small capacitance = good resolution
- because the depletion region is the only real “active volume” of detector, heavy or low E ions can lose a lot of energy in the bulk material prior to reaching it (this is called the “entrance window” or “dead layer”) - important in some circumstances
- masks can be used to purposely create dead regions → segmentation!

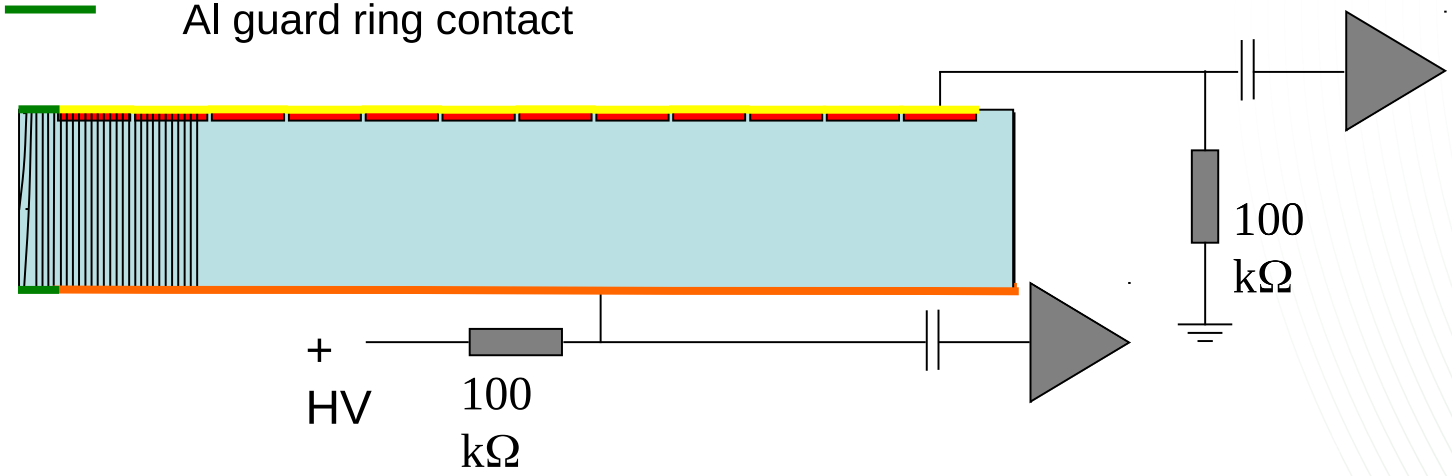
Semiconductor Detectors





- Energy = Q
- Position = strip location
- Many channels required to achieve high spatial resolution

🟨 Al contact
🟥 p-type Si
▭ residual n-type Si
🟧 Al contact
🟩 Al guard ring contact



Scintillator Detectors

There are two main categories of scintillation materials:

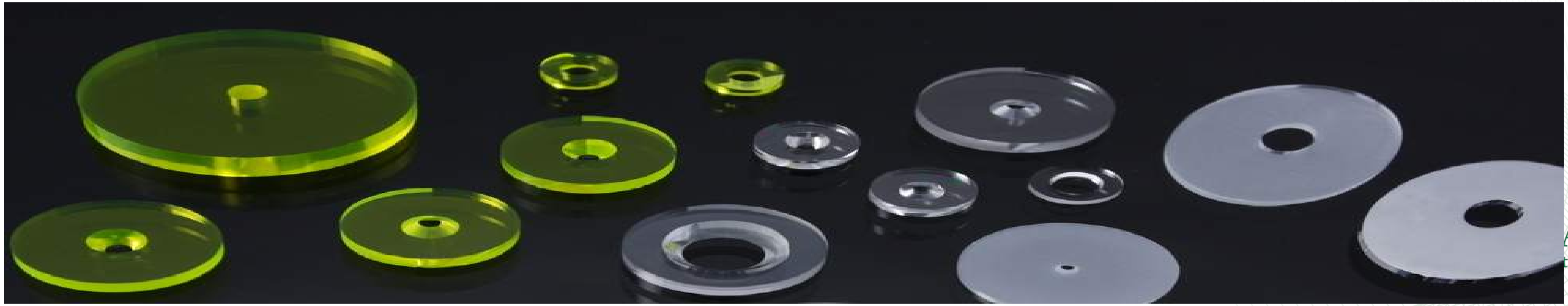
→ inorganic scintillators: NaI(Tl), BGO, BaF2, also noble gases
→ organic scintillators: plastics (solid and liquid)

These differ in how the scintillation light is produced, so we will address them separately.

Note that scintillation light will be produced by nearly any incident radiation (not just gammas or neutrons), but gammas and neutrons (and other uncharged particles) do so through elastic scattering of the scintillator material, which then loses energy and produces the light

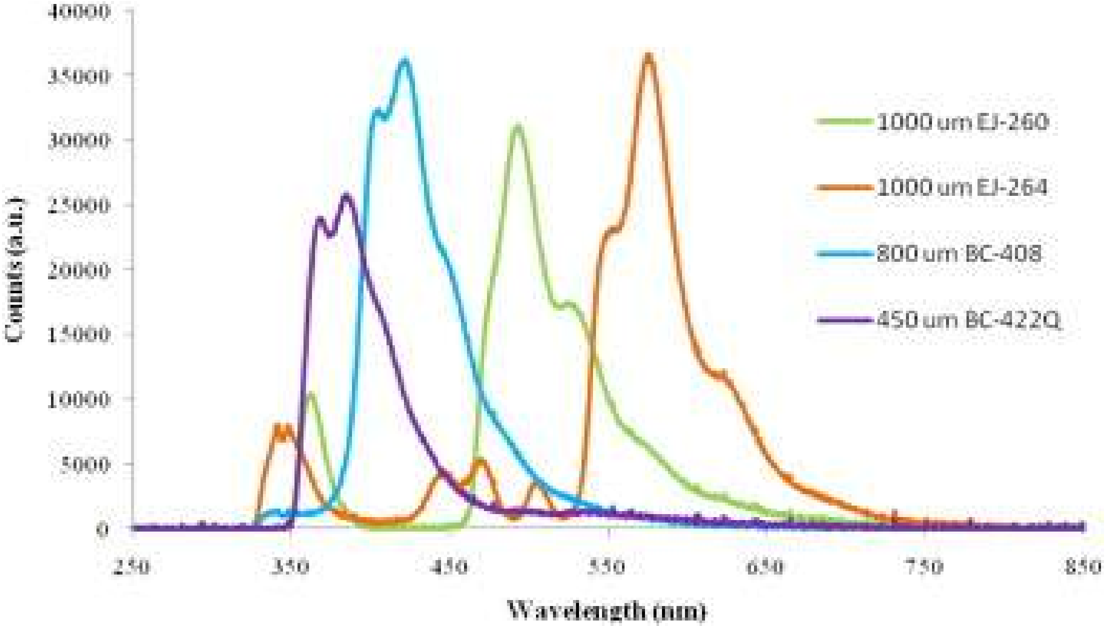
Inorganic Scintillator Detectors

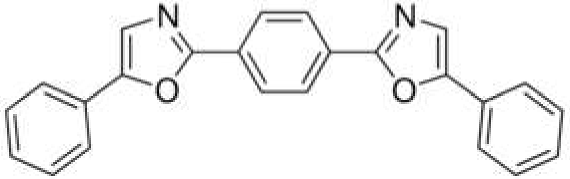
- in inorganic scintillators, light production process depends on energy states of material crystal lattice
- inorganic scintillators can be classed as alkali halides (NaI, CsI…), unactivated fast (BaF2, CsI…), cerium-activated fast (GSO, YAP, LSO, LaBr3…), slow (BGO, ZnS…), and activated glasses (Ce-activated Li glass, Tb activated glass)
- in pure crystals, deexcitation through a photon across the crystal band gap is inefficient (and can cause self-reabsorbtion), so impurities (called "activators") are purposely added to create "recombination centers"
- incident radiation creates electron-hole pairs within inorganic scintillator, which quickly migrate to these recombination centers and ionize them, often putting them in an excited state which deexcites through photon emission
- if recombination center is put in an excited configuration with a disallowed transition, no photon results, until thermal energy can provide the extra "boost" needed to move into an allowed transition → phosphorescence, or "afterglow"



Organic Scintillator Detectors

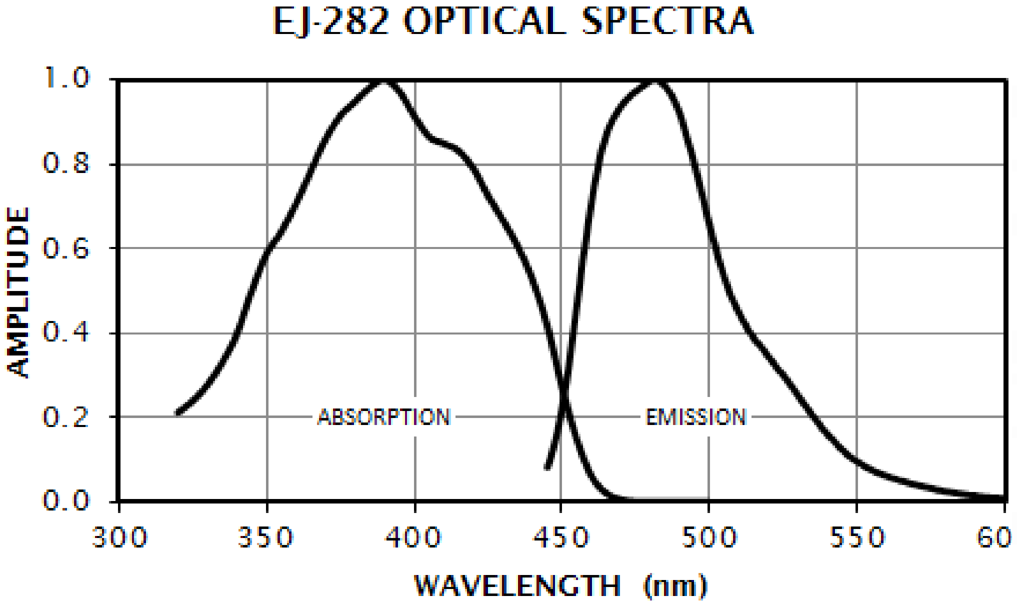
- in organic scintillators, fluorescence process is due to transitions within a single molecule, so doesn't depend on chemical/physical state (solid, liquid, solution…)
- alternate deexcitation modes, such as vibrational energy lost to heat, are referred to as “quenching”
- additional dopants in solution may be used as wavelength shifters, to adjust scintillator emission spectrum into something more closely matched to photon collection (PMT or photodiode)
- if scintillator and wavelength shifters can be dissolved in a polymerizable solvent, we can make them into solid plastics (styrene, PVT, PMMA...)

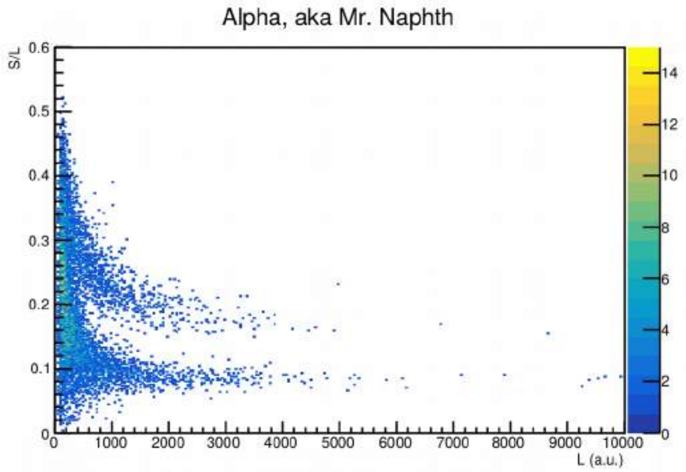


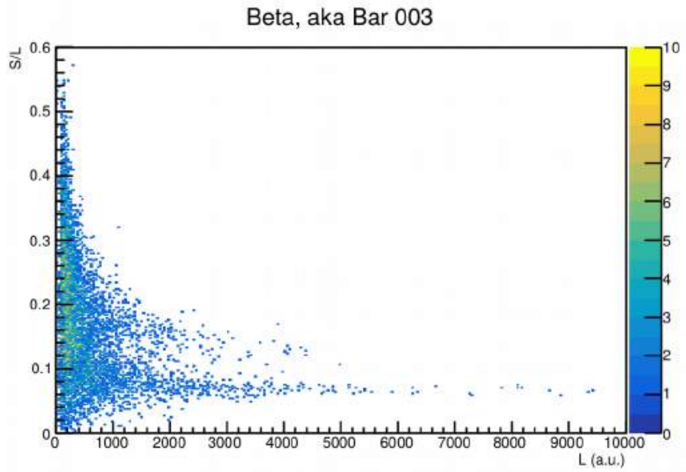


Organic Scintillator Detectors

- key to PSD is “singlet states” and “triplet states” within molecule:
  - singlet states deexcite through fluorescence (mostly at much different energies to that required to excite the states, so material is transparent to its own emission: “Stokes shift”)
  - triplet states, excited via intersystem crossing, deexcite through phosphorescence
  - population modes and decay times for two processes can be vastly different, creating potential for pulse shape differences



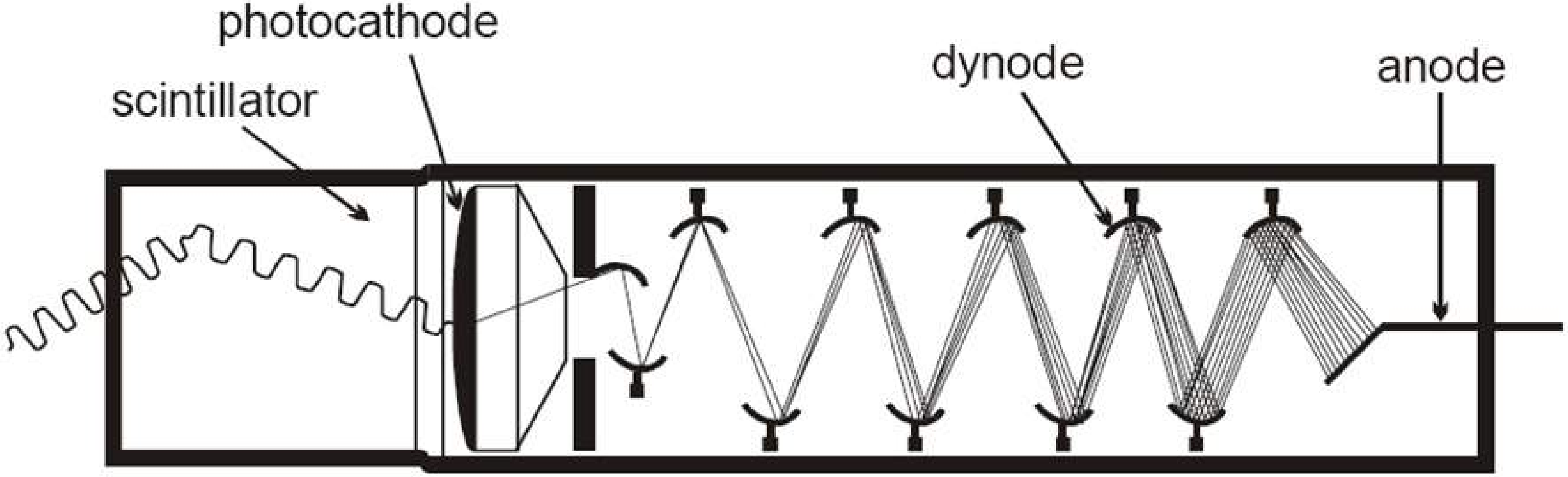




Scintillator Detectors – conversion of photons to electrons

Regardless of whether the scintillator is organic or inorganic, we need to convert the light pulse into a measurable signal.

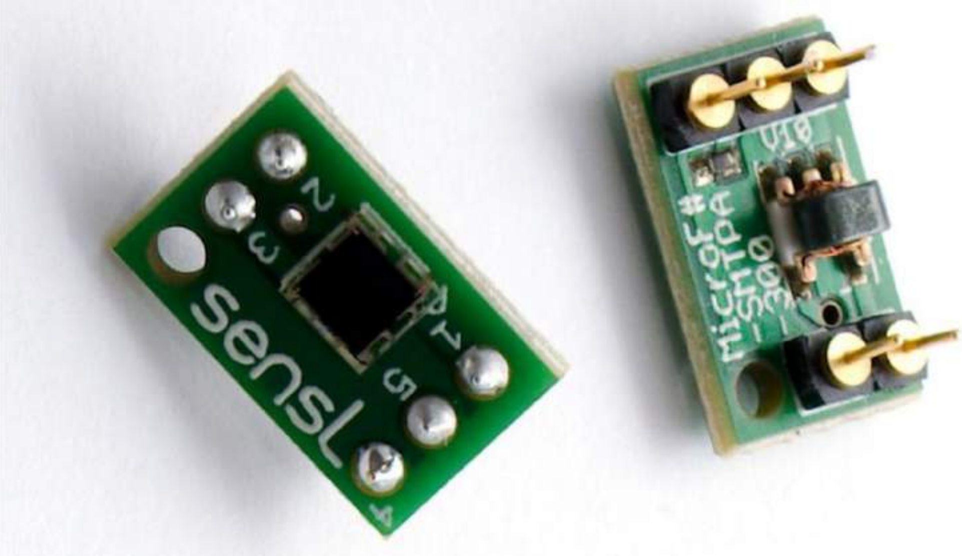
→ use a photoelectric material (photocathode) to generate electrons from the incident photons
→ because just a few photons are “detectable,” but just a few electrons aren't, we need electron multiplication (gain): various methods (microchannel plate, dynodes, etc) – all require high voltages



Scintillator Detectors – conversion of photons to electrons

Regardless of whether the scintillator is organic or inorganic, we need to convert the light pulse into a measurable signal.

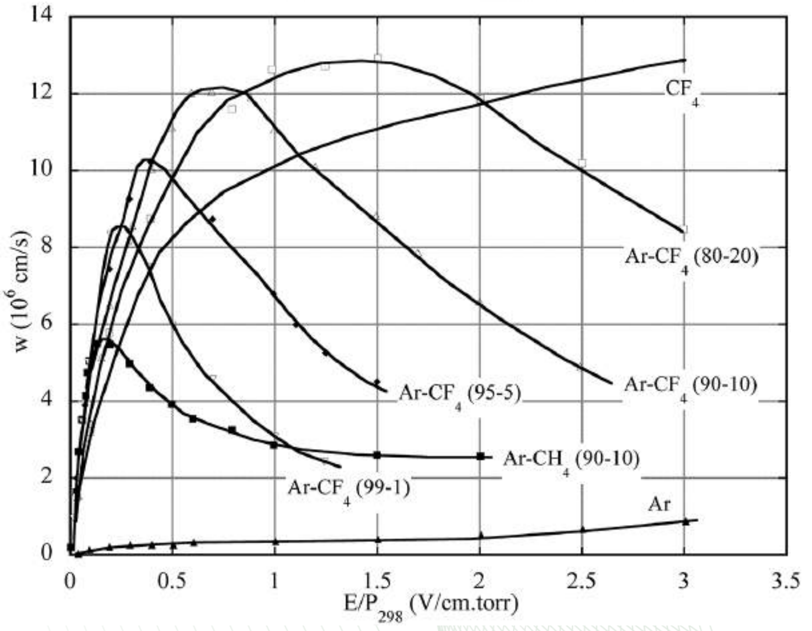
→ use of silicon photomultipliers/avalanche photodiodes (basically the same as solar cells) allow creation of electron-hole pairs easily in the bulk material (we don't have to help them “escape”), but there is no gain so signals are small compared to PMTs; SiPMs also noisier than PMTs (higher dark current and smaller signals); SiPMs are not sensitive to magnetic fields, as PMTs are (bends electron trajectories through the multiplication chain)



Gas-Filled Detectors

Again, we're working with ionization as the means to convert incident radiation into a measurable electrical pulse.

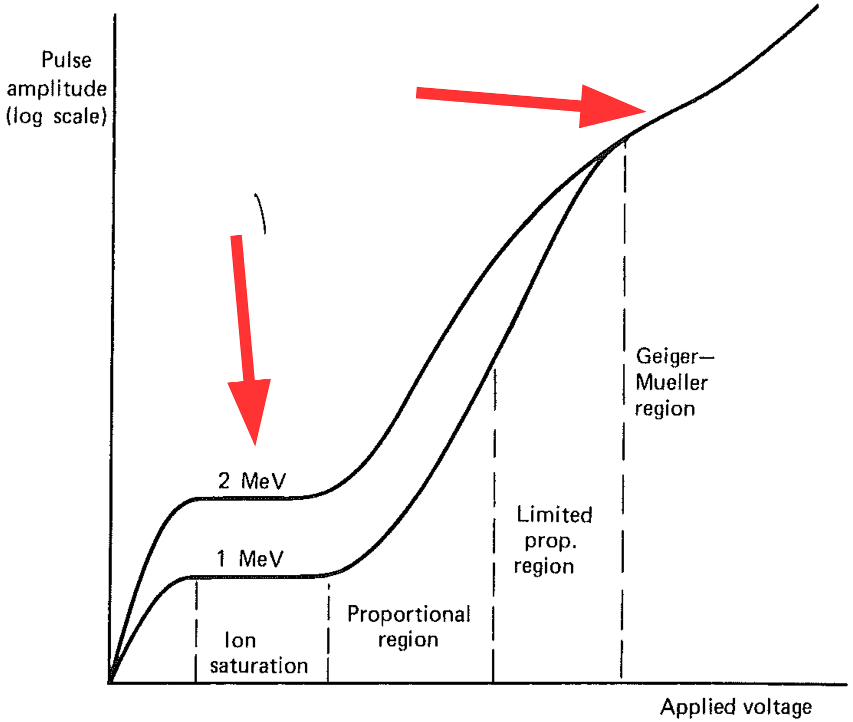
- W value (~30 eV/ion pair) of a gas describes average energy lost by incident radiation in the production of an ion pair (several mechanisms other than just ionization at work)
- Fano factor is empirical number describing observed variance in number of ion pairs produced (since it's actually a statistical process: no statistical fluctuation = Fano factor of zero)
- pure gas ok (noble gases); addition of “quench” gas protects proportionality
- for our purposes, we want gas-filled detector operated in “pulse mode” (as opposed to current mode) so we can examine individual events instead of event rate
- we apply an electric field to move the electron-ion pairs to the anode/cathode
- segmentation of the anode or cathode can provide info on position (how much of track was covered by that anode?) and energy loss (what portion of total energy deposited along track was detected by that anode?)

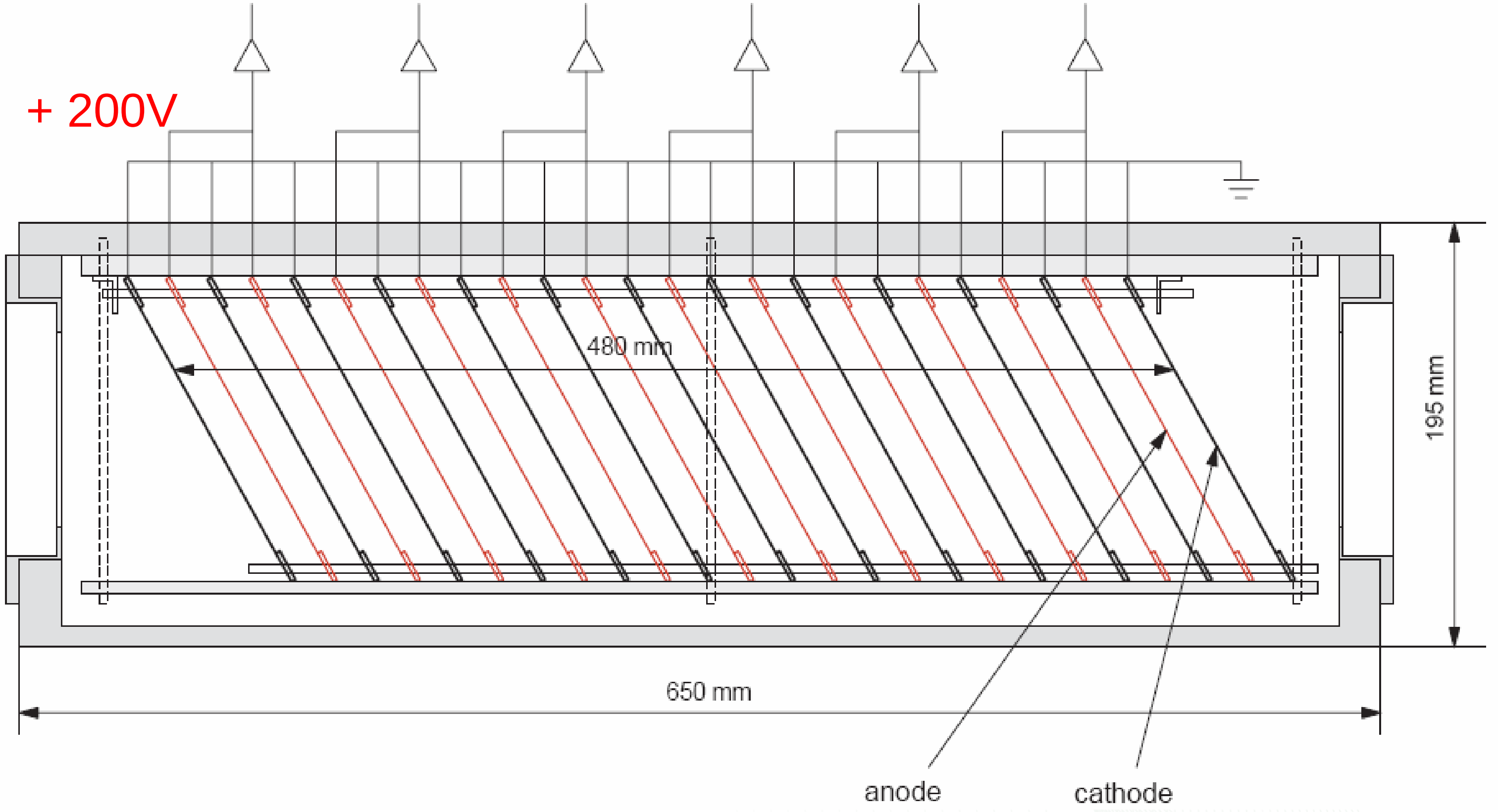


Gas-Filled Detectors

- electron drift velocity in the specific gas and detector dimensions dictate length of signal; statistics of electron/ion pair production dictate best possible energy resolution
- introduction of a Frisch grid shields the anode until electrons are close (within spacing between grid and anode) – removes position sensitivity of anode to incident radiation
- known drift velocity and signal time can be used to reconstruct the track of the ionizing radiation parallel to anode plane; segmentation (as mentioned previously) can give position information on anode plane → all three dimensions! (this is the operational principle behind a TPC)
- a wire grid/cage can also shield an “active” area from an area where considerable charge could build up (such as along track of incoming beam, when reaction products are what's desired); TACTIC and ANASEN use this technique to make their detectors insensitive to deposited beam
- using segmentation of anode to measure energy loss as a function of position (for particle identification) is essentially Bragg curve spectroscopy
- **Hands-on: MUSIC, FMA focal plane PGAC**

Gas-Filled Detectors





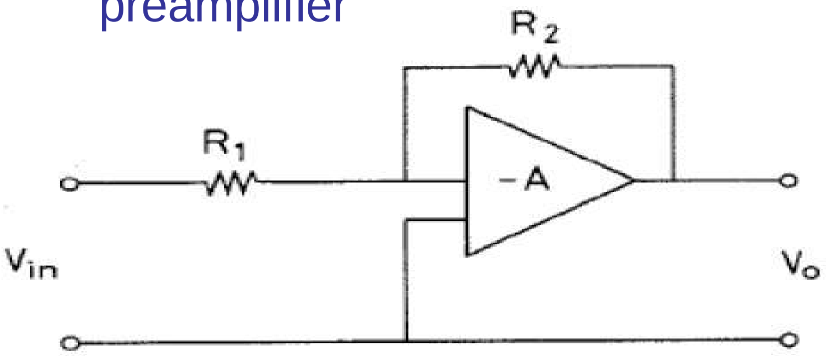
K. Kimura et al. / Nuclear Instruments and Methods in Physics Research A 538 (2005) 608–614

Common attributes of detectors

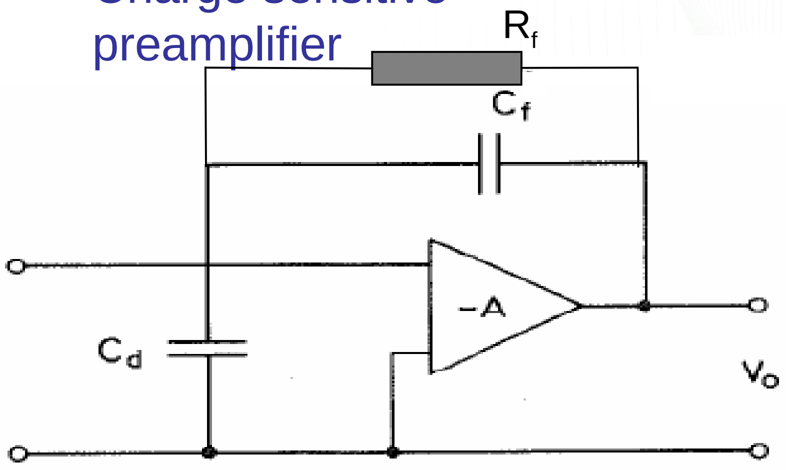
Detection mode:

- pulse mode preserves info on amplitude and timing of individual events
- properties of pulse depend on input characteristics of signal-reading circuit (usually a voltage-sensitive preamplifier)
- usually operate with large RC, so time constant of external circuit >> detection time → this results in max voltage output of circuit being directly proportional to collected charge from detector ($V_{max} = Q/C$)
- assumption that capacitance is constant is ok except for semiconductors, where C depends on operating parameters → require charge sensitive preamps

Voltage sensitive preamplifier



Charge sensitive preamplifier



Common attributes of detectors

Pulse height spectra:

- we are most accustomed to viewing a differential pulse height spectrum, which displays incremental number of pulses within a given height "bin" (range) divided by the width of the range
- can also display integrated pulse height spectrum – gives plateau instead of peak, but both contain same basic info and can be derived from one another

Energy resolution:

- energy resolution is formally defined as the FWHM of a peak (in differential pulse height spectrum, assuming poisson statistics) over its centroid: $R = FWHM/H_0$
- one should generally be able to resolve two energies (H) that are separated by more than one FWHM
- many things can affect resolution, including drift in operational parameters, random noise (eg spurious electronics pulses), and statistical noise (eg variations in number of charge carriers produced for a given incident radiation – irreducible!)

Common attributes of detectors

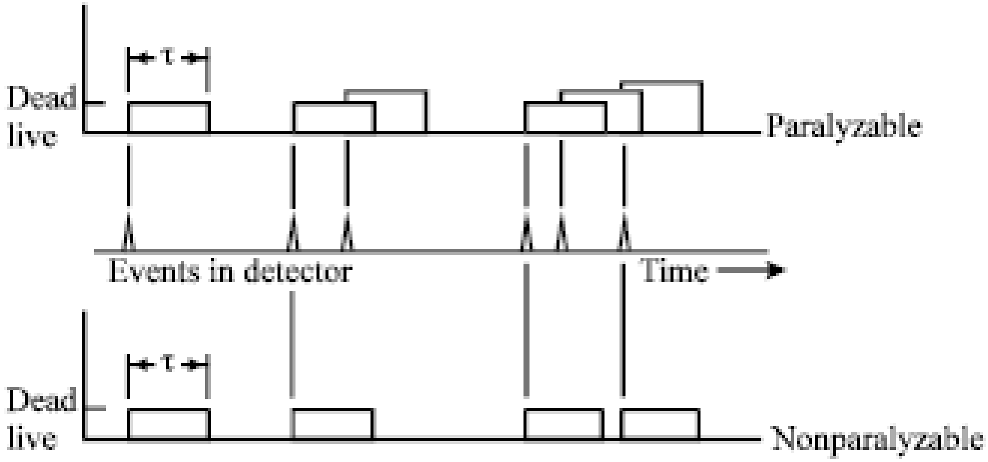
Detection efficiency:

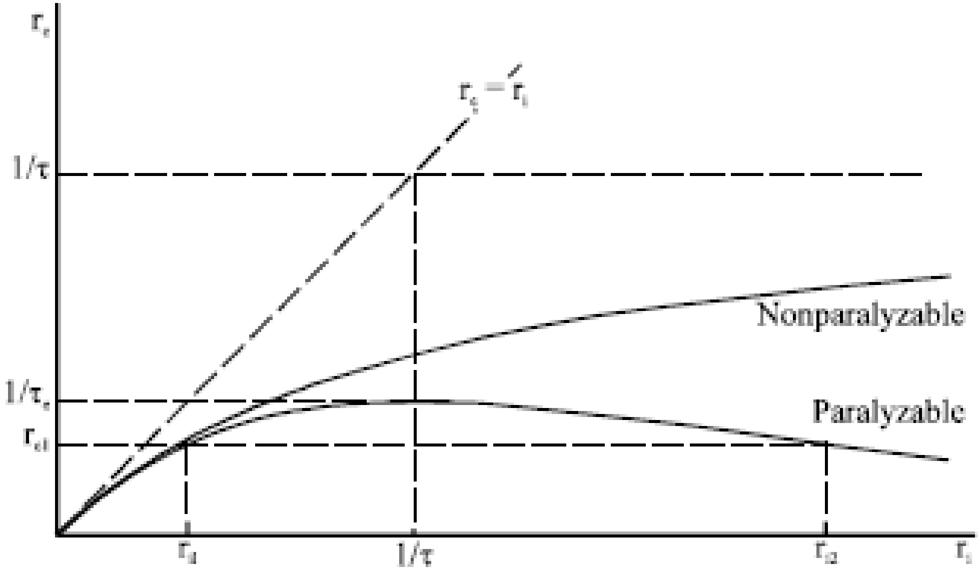
- ionizing radiation (charged particles) inside a detector based on collection of ionization (gas, semiconductor) will have essentially a 100% detection efficiency
- losses would be due to dead regions (entrance window, undepleted areas) where ion pairs created are not collected
- for gammas and neutrons (and detectors based on conversion of light to charge), many processes at work so losses far more likely → detection efficiency <100%
- absolute efficiency is number of pulses recorded over number of radiation quanta emitted by source – accounts for losses in detector, geometry, data acquisition, etc
- intrinsic efficiency is number of pulses recorded over number of quanta incident on the detector, and is a property of the detector itself
- peak efficiency = full height pulses only (not the lower energy stuff)
- efficiency can be a function of incident energy as well, due to various processes such as Compton scattering

Common attributes of detectors

Dead time:

- dead time, or time after an initial pulse that a system cannot detect additional pulses, can be due to pulse generation in detector or limitations in associated electronics and data acquisition
- two models: nonparalyzable (incoming pulse completely “shuts down” system for a set time) and paralyzable (pulses coming during dead time of previous pulse are not recorded, but extend the dead time)
- only differ significantly at very high rates
- empirical measurement of dead time usually relies on this nonlinearity





Additional things to consider

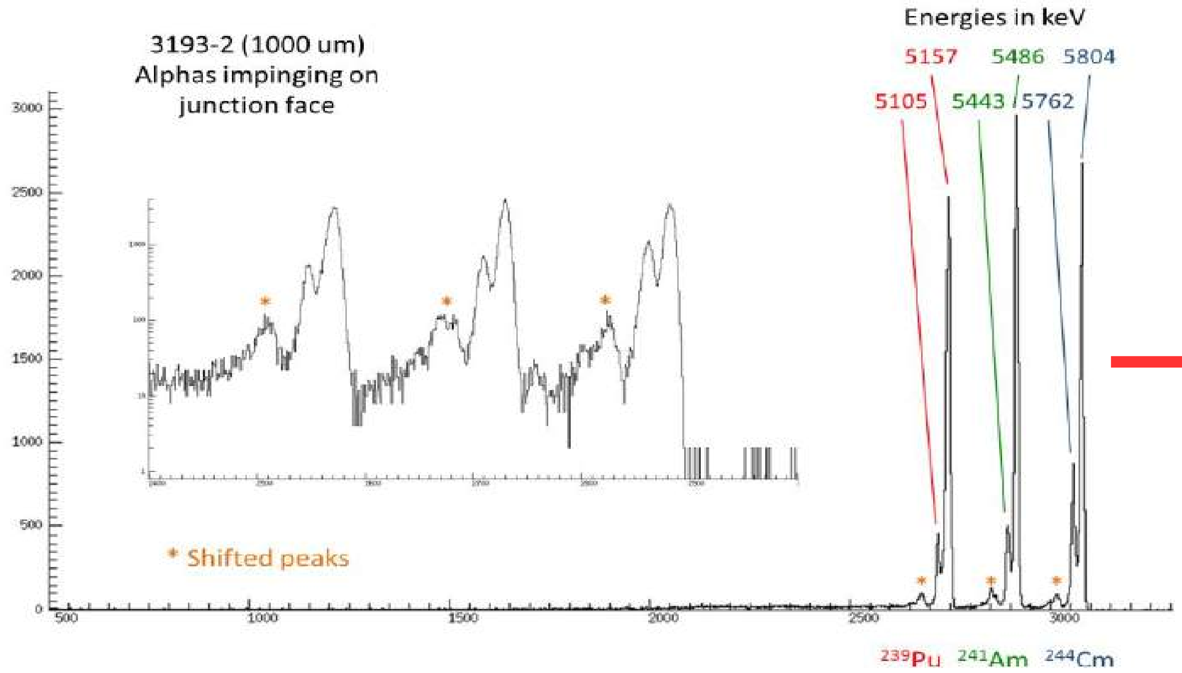
Not all detectors are sensitive to all types of radiation, but some are sensitive to several, so care needs to be taken in choosing the right detector for the job

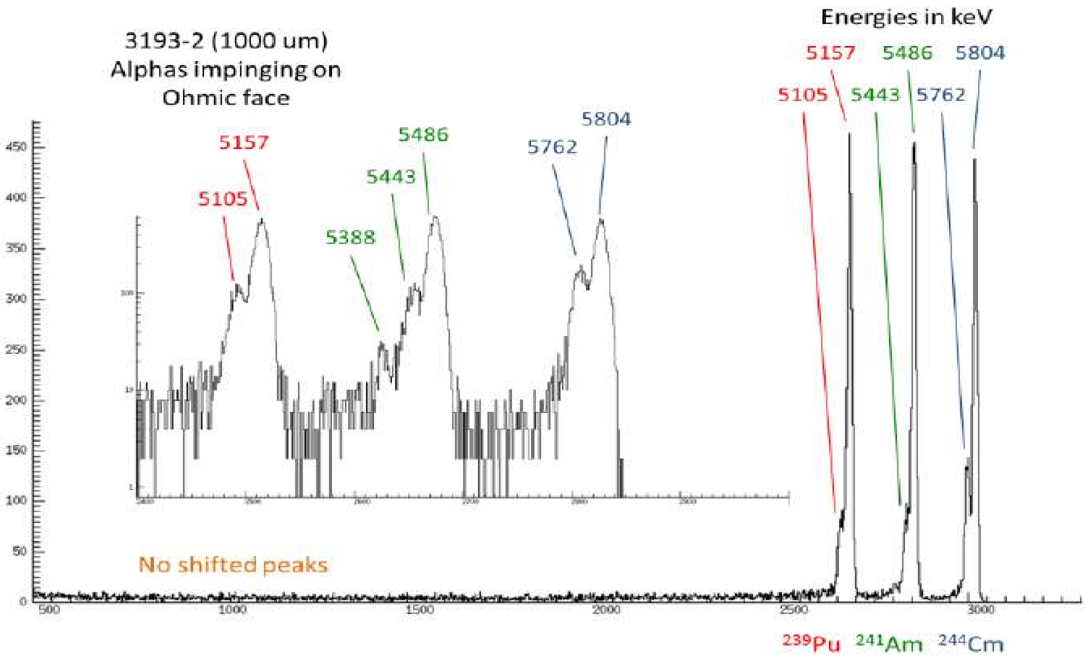
→ consider eg use of silicon detectors with a gamma beam

Gas detectors can be much more robust to radiation damage, but some crystalline detectors (eg HPGe) can be regenerated through annealing

→ radiation damage can occur from things other than what you're measuring

Things like guard rings or uneven depletion regions can cause spurious peaks





Additional things to consider

Dead time can usually be approximated by some set time (τ), so the event rate matters, therefore things which alter event rate also matter

→ consider a DC beam vs a pulsed beam: instantaneous rate matters!

Note that if the incident radiation doesn't impart all of its energy to the detector, we don't have a measure of E

→ why in some cases we need ToF, in order to calculate E

Many detectors display variations (in resolution, timing, etc) due to temperature or other operating conditions

Impedance mismatch between detector and rest of system can cause attenuation

Signals also subject to pileup, jitter, walk...

It is imperative to know your detector!

A Basic Setup

Or, how do we get from the detector to the DAQ?

This differs slightly based on whether we are using an analog or digital data acquisition system – not because the basic premise differs, but just the order of operations:

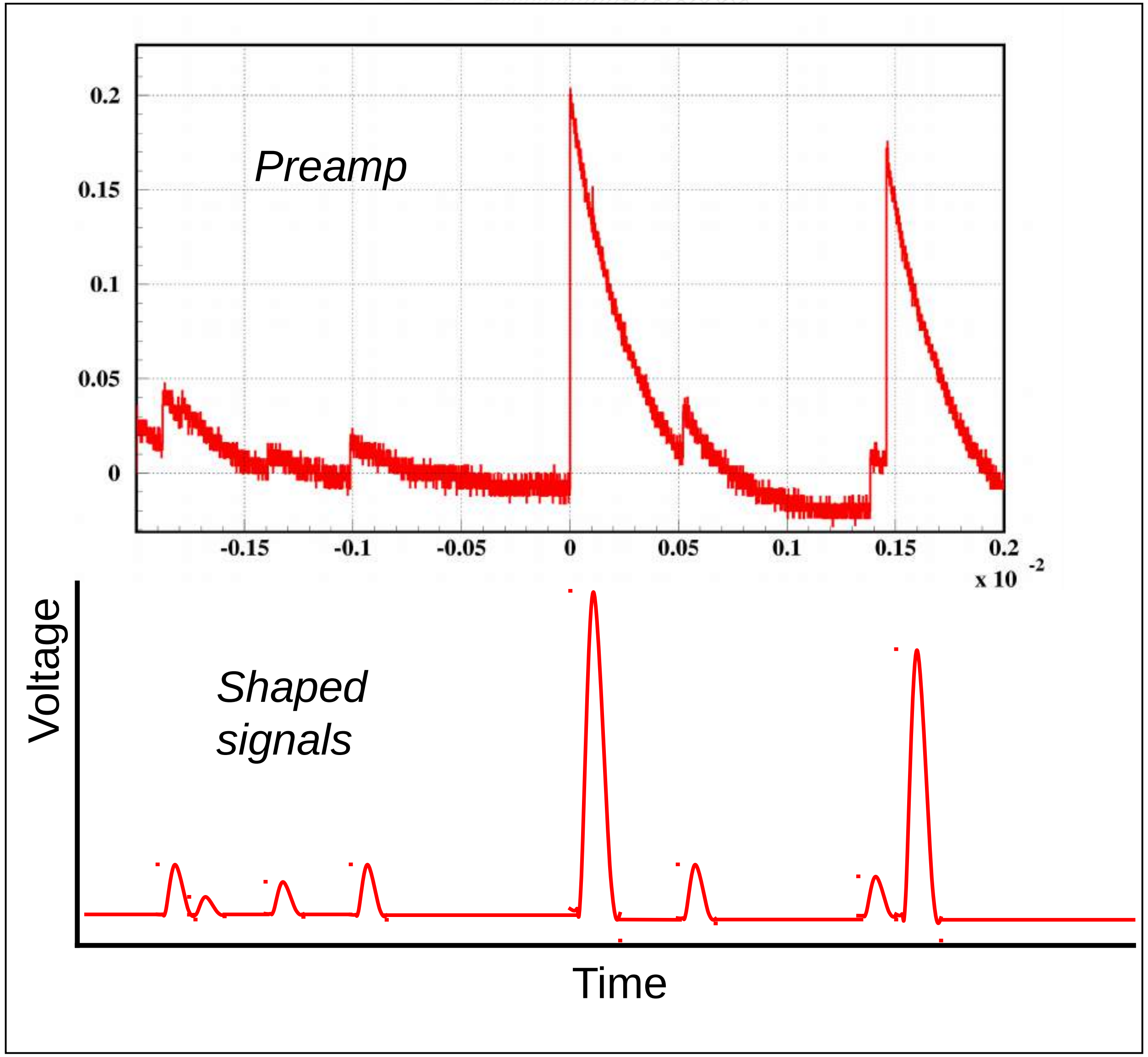
analog DAQ: signal → shaping → discrimination → logic → event recording
digital DAQ: signal → some filtering → event recording → more filtering → logic

Let's start with analog...

Analog DAQ: shaping

- a train of pulses from a preamp, with long tails from the RC circuit (necessary to ensure the full charge is collected), might overlap, and randomly
- this overlap can cause the amplitude of a given pulse (sitting on the background of the tail of the previous pulse) to appear larger than it really is
- this is bad since the amplitude carries the energy information, and the time at which a given pulse height threshold is passed gives the signal time
- we need to "shape" the preamp pulses to remove the long tails but preserve the energy and timing information
- this is done through a CR-RC (differentiator-integrator) circuit, which often also includes an amplification stage
- the time constant of a shaping amp in practice can be chosen from several values with a dial (for example, 0.25, 0.5, 1, 2 μs)
- the CR-RC circuit will produce a slight "undershoot" (or non-unipolarity) due to the finite decay time of the input pulse – pole-zero cancellation adds a resistor in parallel with the capacitor of the CR network, removing this undershoot
- baseline shift (non-true-zero) can be overcome with bipolar shaped pulses

Analog DAQ: shaping



- in order to get the energy information out of these shaped pulses, we have to tell our DAQ how long to hold a peak voltage before conversion through the use of a gate
- use a discriminator (next slide) to create a “start” signal, which is fed to a gate generator
- length of gate is set with potentiometer on module (check against signals on a scope!)
- gate and shaped signals are sent to an ADC

Analog DAQ: discrimination

- for logic and timing, shaped and amplified pulses must be converted into logic pulses, and for this we use discriminators
- there is generally a tradeoff between being able to count fast and getting precise timing information (sometimes we discriminate on fast, unshaped pulses for speed)
- for example, a leading edge discriminator, very basic, compares the incoming signal to a set voltage
  - when leading edge of signal crosses threshold, logic pulse is created
- another example, a CFD (constant fraction discriminator) creates a logic pulse when incoming signal reaches some predefined fraction of the total pulse height
  - achieved through creation of delayed and flipped input pulses which are then compared
- we now have 1) a time-of-event signal and 2) a logical event=true/false signal
- other things we may need: a TAC (time to amplitude converter) which takes two time input signals (start/stop) and converts the duration between them to a pulse with a given amplitude, or a TDC (time to digital converter) which takes the duration signals directly into the DAQ

Analog DAQ: discrimination

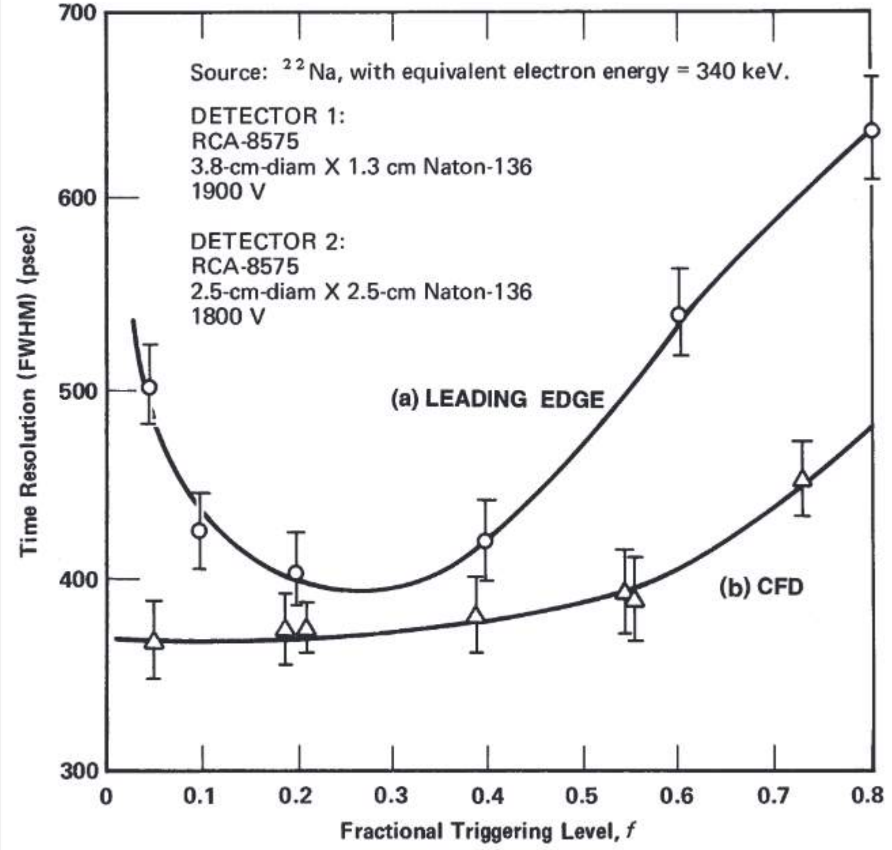
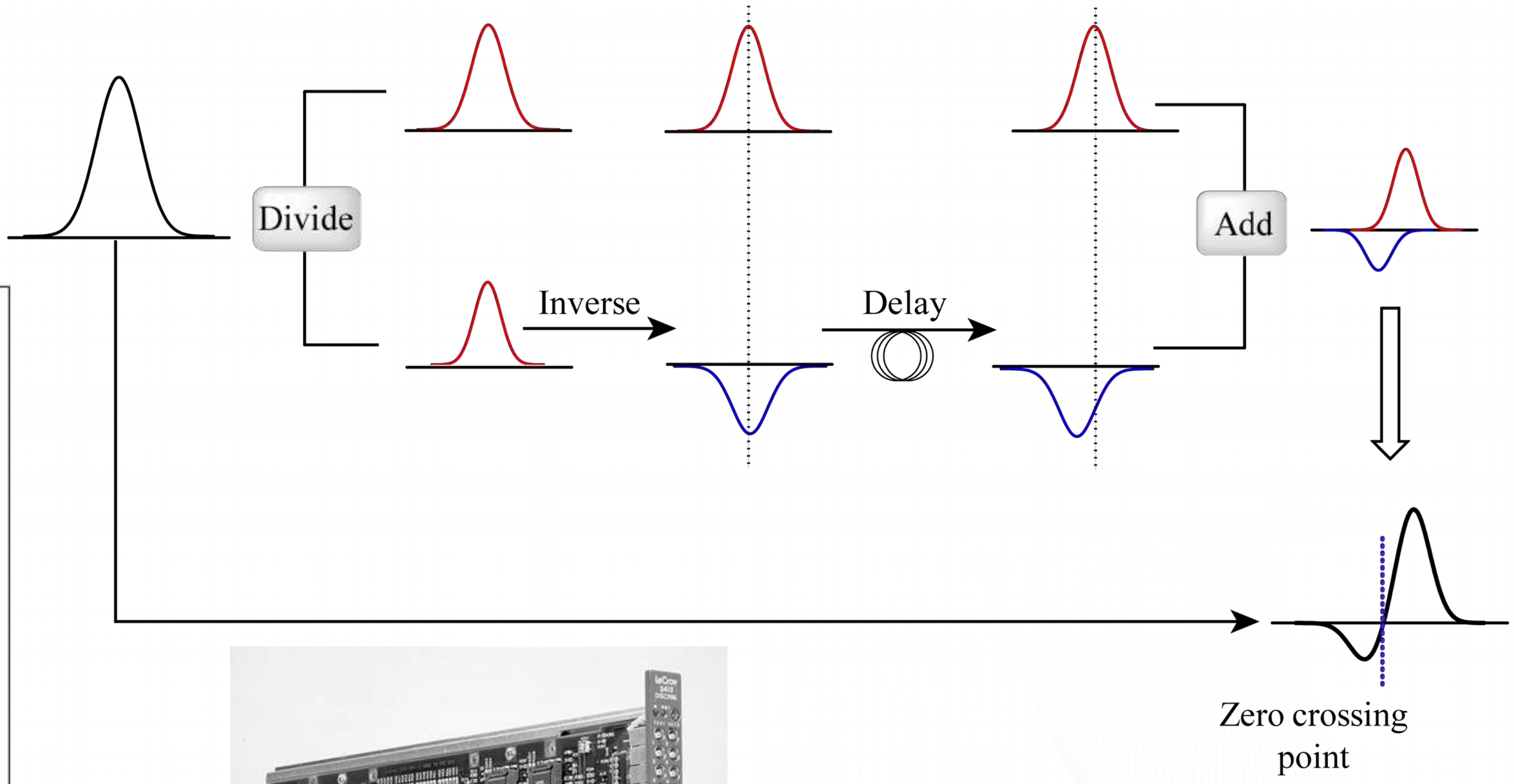
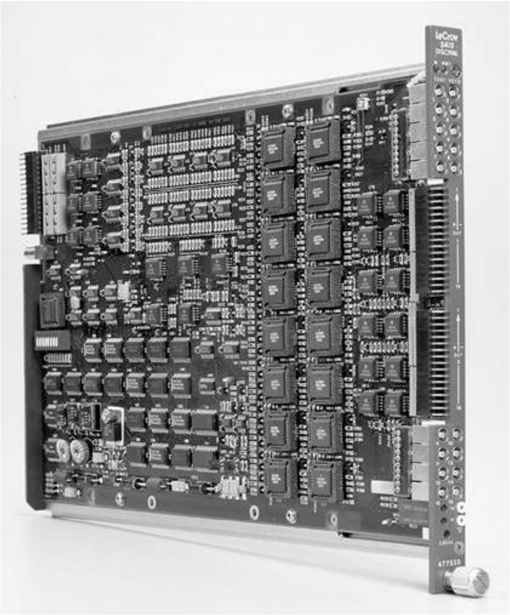


Fig. 2. A Comparison of Leading-Edge Timing with Constant-Fraction Timing for a Narrow Pulse-Height Range. The source was ^{22}Na, with the selected equivalent electron energy in the scintillator = 340 keV. The time resolution (FWHM) is Δt.





Analog DAQ: logic

- once we have true/false and timing info, we can build “events” through the use of coincidences
- for example, an event might be defined as any signals which fall within some predefined time window (coincidence) – outputs a new logic pulse
- anticoincidence outputs a logic pulse only if one input appears within predefined time window
- anything possible with electronics logic is possible here: ANDs, ORs, NORs, etc
- these can determine our “trigger” - that is, our signal to open the DAQ and start recording an event
- we may also wish to use a “scaler” or “prescaler” to cut down the total number of counts registered by some factor (if we're doing a high-stats counting experiment and only need to know how many thousands of events we had, for instance)
- finally, we need a clock signal (usually in the form of a known frequency) and probably a “busy” signal (fed to the DAQ from our logic to tell it when an event is in progress and another event cannot be accepted → one way of assessing dead time, among others)

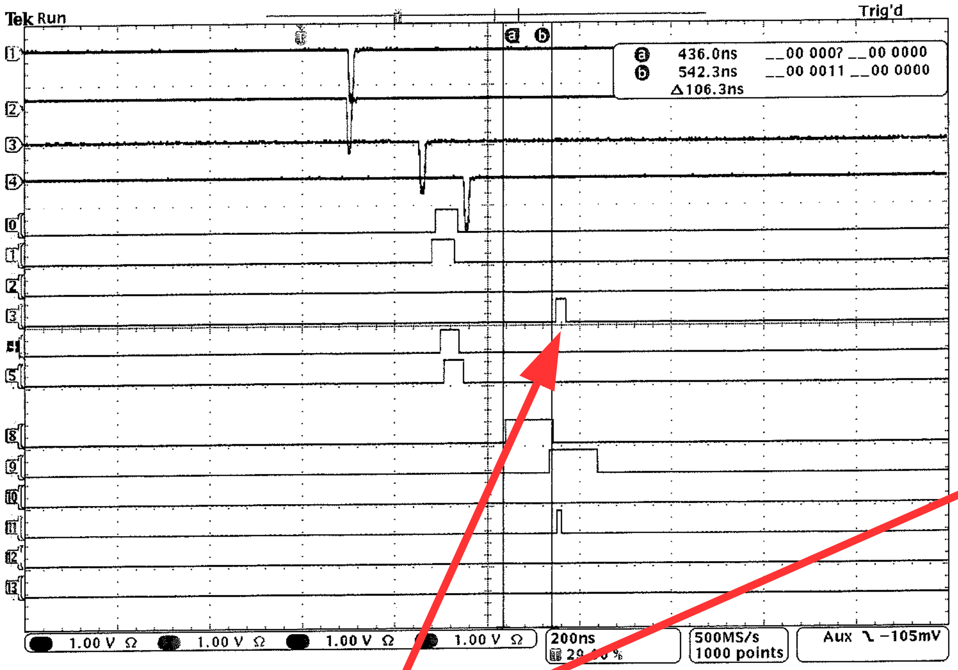
Digital DAQ

As mentioned, in the case of a digital data acquisition system, the basic premise is the same, but the order is somewhat changed.

- signal from preamp is generally sent straight into the data acquisition system
- DAQ is “self-triggering” (doesn't require the trigger/logic generation of analog DAQ, though there is some fast preliminary logic and filtering that happens when a signal first arrives)
- signal is digitized into a series of amplitude vs time points (it's now referred to as a “trace”) based on the specific digitizer specs
- on-board programmable filters can parse digitized traces to extract energy and time info (eg trapezoidal filter)
- full traces can be written out for later filtering (shaping and discriminating)
- instead of being physical modules, the shaping, discriminating, and logic are all handled virtually – this can be a big benefit because signals aren't split
- digital is especially useful when in-depth pulse shape analysis is desired, but it can be very rate limited (both on front end and back end)

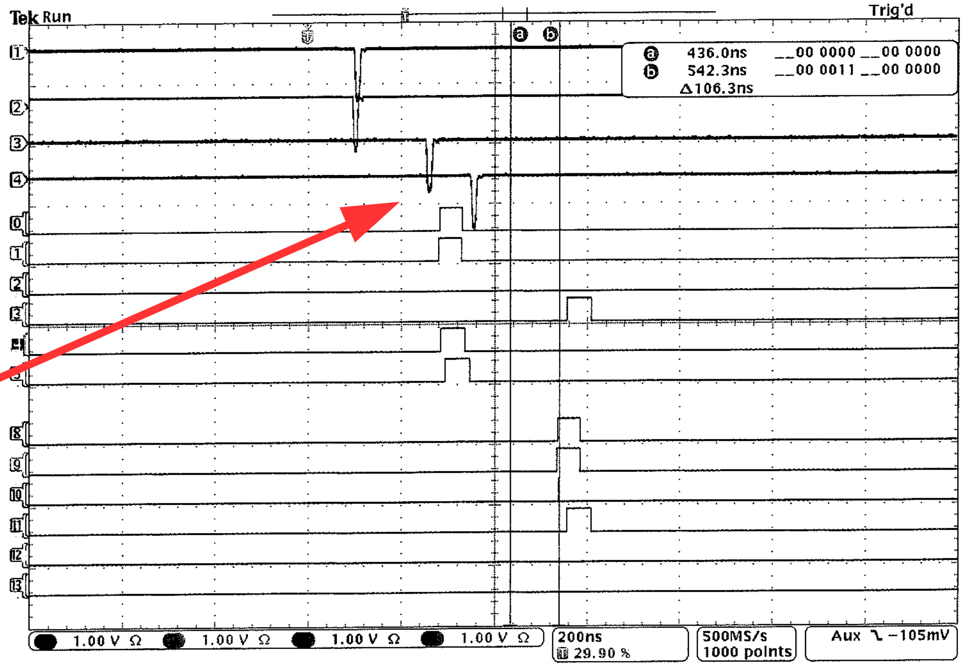
Digital DAQ

We see that D11 has vanished as D8 and D9 are no longer overlapping. Changing the `FASTTRIGBACKLEN` to 104 ns we now see a small overlap in D11.



computationally-created logic pulses
(instead of through circuitry)

We can reset `FASTTRIGBACKLEN` to 0.048 and change the `FtrigoutDelay` to 0.104 for module 0, channel 0.



Switching to test pin group 0 (by modifying bit 31 of `TrigConfig3`). You see that D12 shows the VANDLE pairwise coincidence trigger of channel 0 and 1, `VANDLE PWA[0]`. In addition, we

A few words on analysis techniques

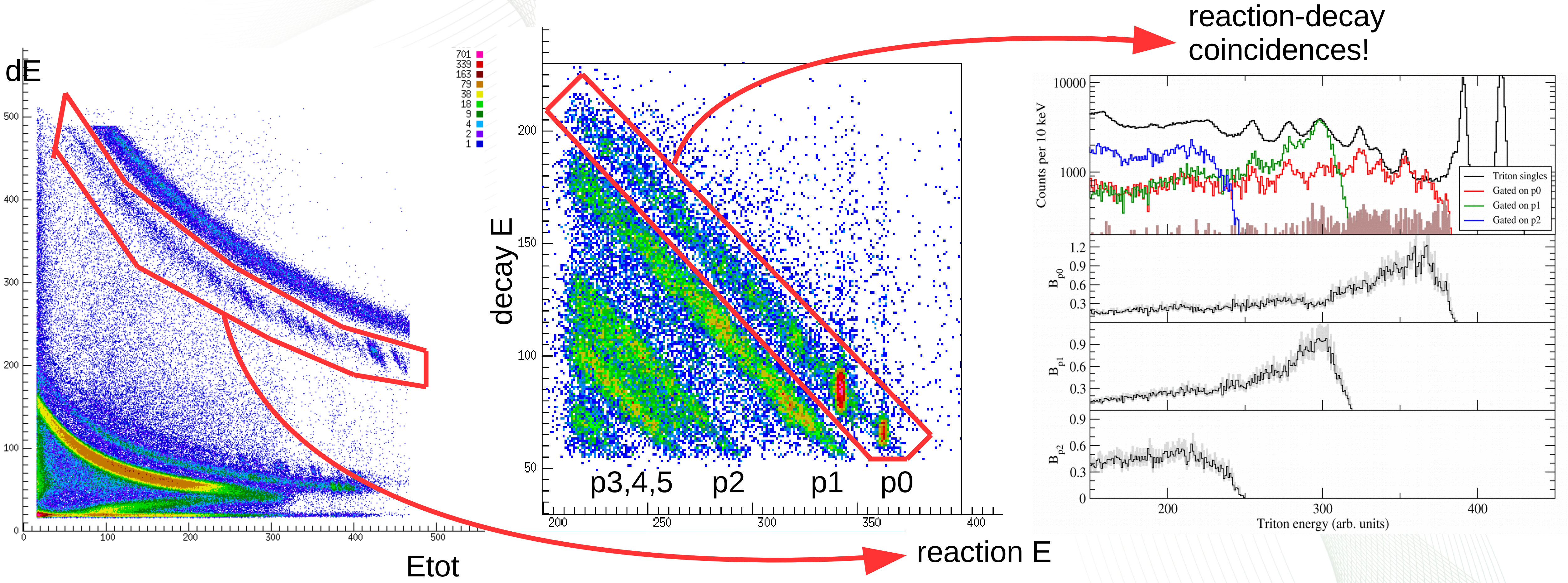
There are many nuances to the way analysis can be undertaken.

Tricks we can play:

- → combination detector systems
- → coincidences
  - branching ratios
  - active shielding
  - angular correlations/DCOs
- → pulse shape discrimination
  - n/γ separation
  - beam γ/reaction γ separation
  - intrinsic radiation suppression

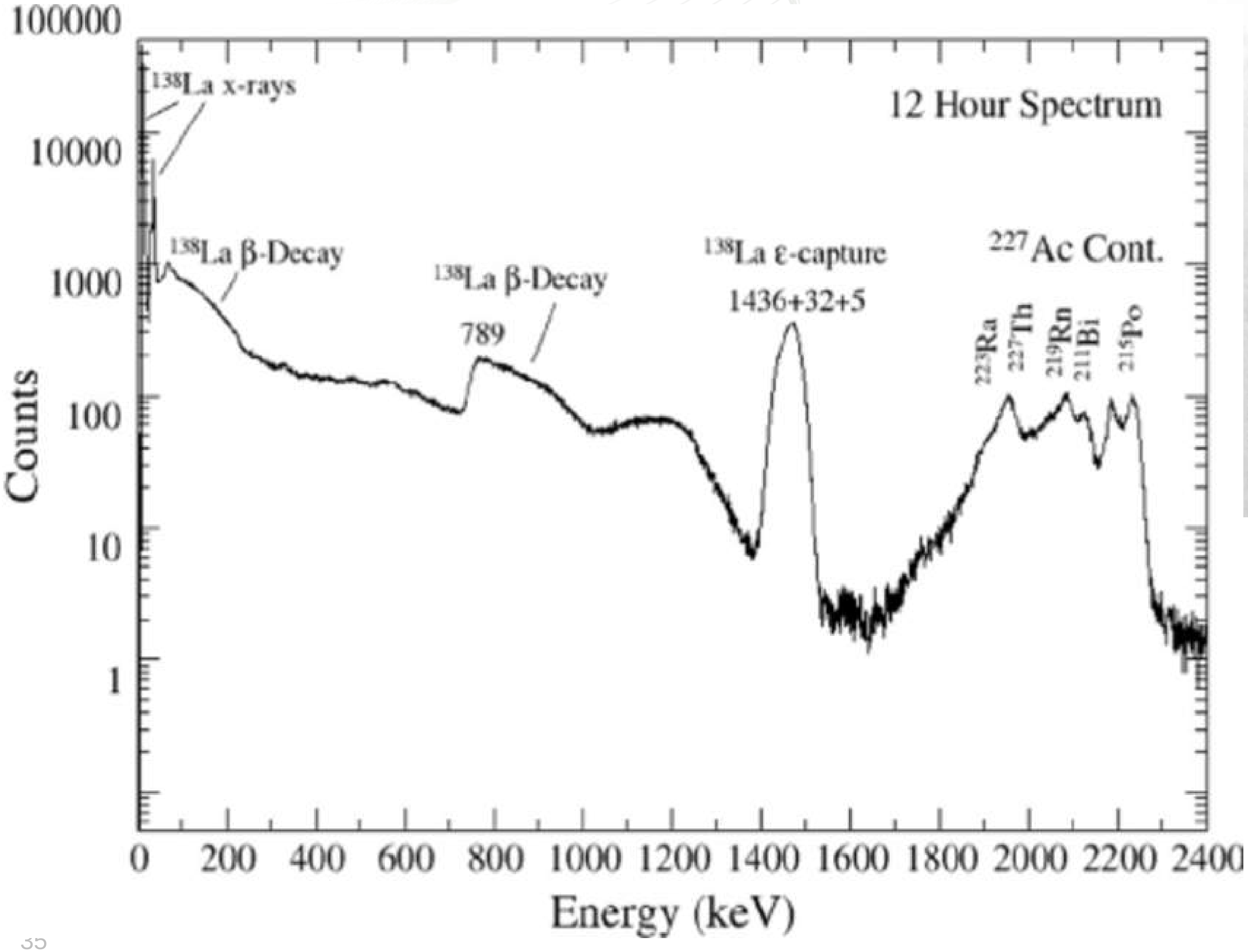
Branching ratios

Just because we set up one experiment doesn't preclude another result from hiding in our data.



Pulse shape analysis to discriminate intrinsic backgrounds

Different incident radiation produces different signals – the same is true of intrinsic radiation.



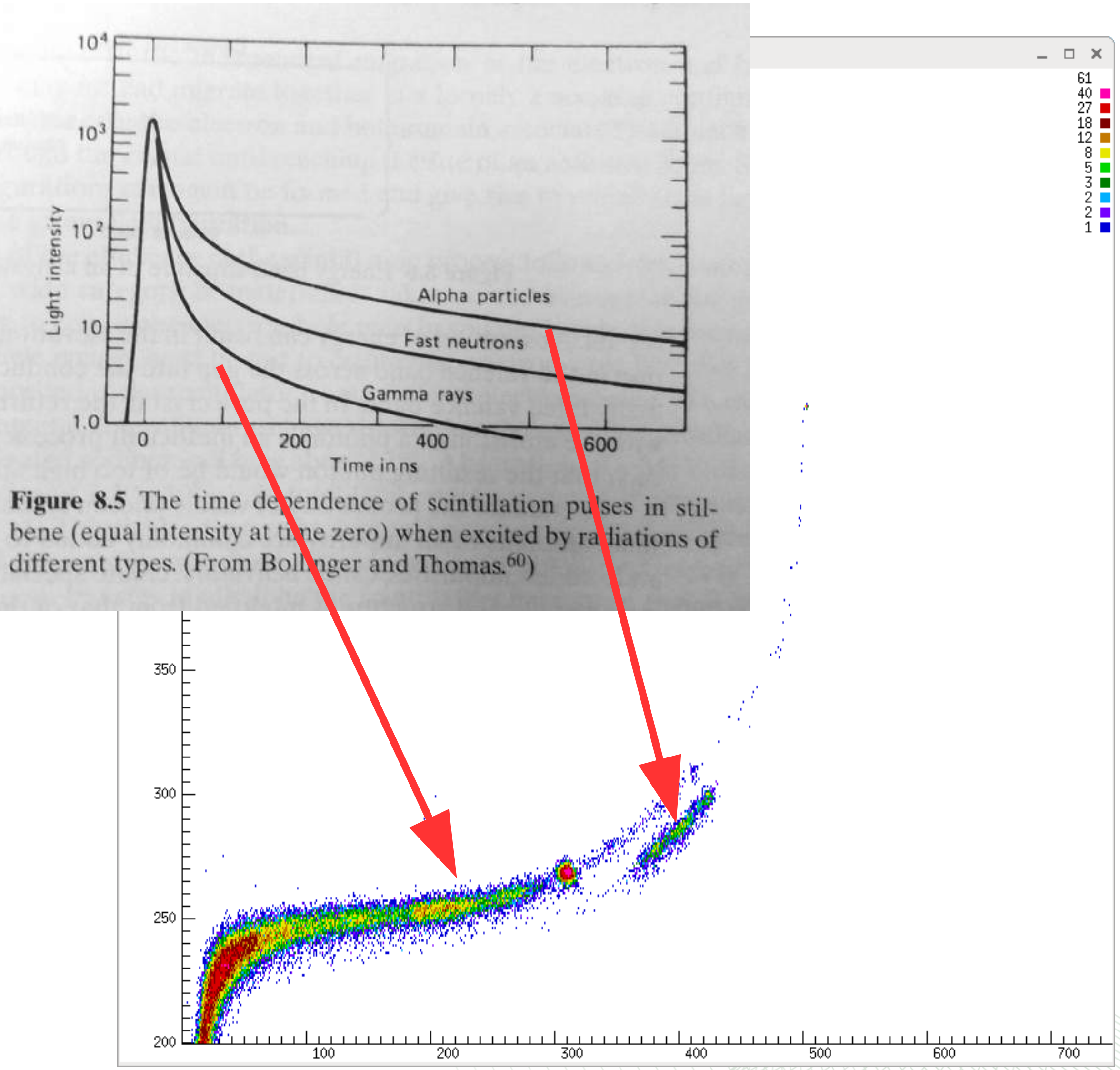


Figure 8.5 The time dependence of scintillation pulses in stilbene (equal intensity at time zero) when excited by radiations of different types. (From Bollinger and Thomas.^{60})

A sample experiment

Pretend we want to measure ^{100}Sn(d,p) at 10 MeV/u to examine spectroscopic strengths of neutron states in ^{101}Sn.

What do we need?

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→ charged particle detection for protons
  - use large solid angle silicon detector array (want broad angular coverage)
  - thickness depends on energy of protons (need about 1mm total thickness)
  - detector telescope for particle identification
  - detector placed to measure elastic scattering for absolute normalization
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→ gamma detection
  - help determine level energies to high precision
  - decay information

Closing thoughts

Know thy detector!

Know thy system!

Think outside the box to solve analysis problems!

READ KNOLL!