Scintillation Detectors

Introduction
Components
- Scintillator
- Light Guides
- Light Sensors
  - Photomultiplier Tubes
  - Silicon Photomultipliers
Formalism/Electronics
Application to Particle Identification
**Experiment basics**

- **B field**: \( \sim 5/3 \, T \)
- **R**: \( 3 \, m \)
- **L**: \( \frac{1}{2} \pi \, R = 4.71 \, m \)
- **\( p = 0.3 \, B \, R = 1.5 \, \text{GeV/c} \)**

\[ \beta_\pi = \frac{p}{\sqrt{p^2 + m_\pi^2}} = 0.9957 \]
\[ \beta_K = \frac{p}{\sqrt{p^2 + m_K^2}} = 0.9496 \]

\[ t_\pi = \frac{L}{\beta_\pi c} = 15.77 \, \text{ns} \]
\[ t_K = \frac{L}{\beta_K c} = 16.53 \, \text{ns} \]

\[ \Delta t_{\pi K} = 0.76 \, \text{ns} \]

**Particle Identification by time-of-flight (TOF) requires Measurements with accuracies of \( \sim 0.1 \, \text{ns} \)**
Measure the Flight Time between two Scintillators

Start
Disc

Stop
Disc

TDC

Particle Trajectory

450 ns

20 cm

300 cm

100 cm

400 cm
Propagation velocities

- \( c = 30 \text{ cm/ns} \)
- \( v_{\text{scint}} = \frac{c}{n} = 20 \text{ cm/ns} \)
- \( v_{\text{eff}} = 16 \text{ cm/ns} \)
- \( v_{\text{pmt}} = 0.6 \text{ cm/ns} \)
- \( v_{\text{cable}} = 20 \text{ cm/ns} \)

\( \Delta t \sim 0.1 \text{ ns} \)
\( \Delta x \sim 3 \text{ cm} \)
CLAS detector with FC pulled apart
Start counter assembly
Scintillator types

- Organic
  - Liquid
    - Economical
    - Messy
  - Solid
    - Fast decay time
    - Long attenuation length
    - Emission spectra

- Inorganic (crystals)
  - Anthracene
    - Unused standard
  - NaI, CsI
    - Excellent $\gamma$ resolution
    - Slow decay time
  - Lead Tungstate ($\text{PbWO}_4$)
    - High density and resolution
Light Spectrum

The graph shows the radiant sensitivity (mAW) as a function of wavelength (nm) for different scintillator materials. The curves represent the UV response of the quartz window options for various compounds:
- NaI(Tl): 410 nm
- BGO: 440 nm
- ATP: 582 nm
- HeNe: 633 nm
- BeF$_2$: 325 nm
- Plastic: 370-545 nm
- CsI(Tl): 565 nm
- GaAs Laser: 680-900 nm

Lighter colored sections indicate the UV response of the quartz window options.
Light Collection: Light guides

- Goals
  - Match (rectangular) scintillator to (circular) pmt
  - Optimize light collection for applications

- Types
  - Plastic
  - Air
  - None
  - “Winston” shapes
Reflective/Refractive boundaries

Scintillator
n = 1.58

acrylic

PMT glass
n = 1.5
Reflective/Refractive boundaries

\[ R_{\text{air}} = \left( \frac{1 - n}{1 + n} \right)^2 \approx 4 - 5\% \]

(reflectance at normal incidence)
Reflective/Refractive boundaries

Scintillator
n = 1.58

air

PMT glass
n = 1.5
Reflective/Refractive boundaries

Acceptance of incident rays at fixed angle depends on position at the exit face of the scintillator.

Rule of thumb: Acceptance is given by the ratio of output/input areas.
Winston Cones - special geometry

**Fig. 2.** Construction of an ideal light collector for the case of constant index of refraction. In this example, $\theta_{\text{max}} = 16^\circ$. 
Photomultiplier tube, sensitive light meter

Gain ~ $V^{\alpha N} \sim 10^6 - 10^7$

- Photocathode
- N Dynodes
- Electrodes
- Anode

56 AVP pmt
High voltage

- Positive (cathode at ground)
  - low noise, capacitative coupling

- Negative
  - Anode at ground (no HV on signal)

- No (high) voltage
  - Cockcroft-Walton bases
Housing
Compact divider design
Single photoelectron signal
PMT single p.e. spectra (noise)
Signal for passing tracks

![Graph showing signal for passing tracks]
Energy deposited in scintillator

Photons and “corner clippers”

Minimum-ionizing peak pions, electrons

Geometric Mean

(ADC channels)
Effect of magnetic field on pmt

Figure 32

Demostrating how a wrapped mu-metal shield reduces the sensitivity of a 9106 photomultiplier to external magnetic fiel. Solid line: unshield; grey line: wrapped shield; shaded region: earth's field. Field aligned across the first dynode, X axis.
Hall D – GlueX detector

Hermetic detection of charged and neutral particles in solenoid magnet

Initial Flux $10^7 \gamma/s$
18,000 FADCs
4,000 pipeline TDCs
20 KHz L1 trigger
300 MB/s to tape

What to do in a Magnetic Field?

Superconducting 2 T solenoid

Barrel Calorimeter (Bcal)
Time-of-flight (tof)

Pb-glass detector (Fcal)

Future PID detector

Tracking
Cathode strips
Drift chambers
Straw tubes
Some history in photos
Multipixel Limited Geiger mode APD

- 20-100 µm Geiger APD pixel
- Incident photon initiates avalanche
- Quenched by resister $\rightarrow$ device reset
- Sum the pixels $\rightarrow$ photon counter

Insensitive to Magnetic Fields!
Hamamatsu S12045 arrays

4x4 array of 3x3 mm$^2$ sensor
Area = 12.7 x 12.7 mm$^2$
57600 pixels
Figure 5: Examples of typical QDC data for one cell (3x3 mm\(^2\)) from a SiPM array.
Measure the Flight Time between two Scintillators

Particle Trajectory

450 ns

Start Disc → TDC → Stop Disc

20 cm

300 cm

100 cm

400 cm
Formalism: Measure time and position

\[ T_L = T_L(0) + \frac{x}{v_{eff}} \quad \quad T_R = T_R(0) - \frac{x}{v_{eff}} \]

\[ T_{ave} = \frac{1}{2} (T_L + T_R) = \frac{1}{2} (T_L(0) + T_R(0)) \]

Mean is independent of position!

\[ x = \frac{v_{eff}}{2} \left[ (T_L - T_R) - (T_L(0) - T_R(0)) \right] \rightarrow \frac{v_{eff}}{2} \left[ T_L - T_R \right] \]
Experiment basics

- B field $\approx \frac{5}{3}$ T
- $L = \frac{1}{2} \pi R = 4.71$ m
- $p = 0.3 \ B \ R = 1.5 \text{ GeV/c}$

- $\beta_{\pi} = \frac{p}{\sqrt{p^2 + m_{\pi}^2}} = 0.9957$
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- $t_{\pi} = \frac{L}{\beta_{\pi} c} = 15.77$ ns
- $t_{K} = \frac{L}{\beta_{K} c} = 16.53$ ns
- $\Delta t_{\pi K} = 0.76$ ns
Particle ID by "tof": $\beta$ vs p plot
Summary

- Scintillation counters have a few simple components
- Trigger and time-of-flight systems are built out of these counters
- Fast response allows for accurate timing
- New solid-state light sensors are now available, which allow use in high magnetic fields
- Combining the timing information from scintillator detectors with momentum measurements from tracking detectors, one can determine the mass of passing particles.
Backup slides
Electronics

- **Anode**
- **Dynode**
- **Trigger**
- **Measure pulse height**
- **Measure time**
Formalism: Measure energy loss

\[ P_L = P_L(0) e^{-x/\lambda} \quad \quad P_R = P_R(0) e^{+x/\lambda} \]

Energy \[= \sqrt{P_L \cdot P_R} = \sqrt{P_L(0)P_R(0)} \]

*Geometric mean is independent of position!*
Example: Kaon mass resolution by TOF

\[ P_K = 1 \text{ GeV} \]
\[ E_K = \sqrt{m_K^2 + P_K^2} = \sqrt{0.495^2 + 1} = 1.1161 \text{ GeV} \]
\[ \beta_K = \left( \frac{P_K}{E_K} \right) = 0.896 \]
\[ \gamma_K = \left( \frac{E_K}{m_K} \right) = 2.26 \]

For a flight path of \( d = 500 \text{ cm} \)
\[ t_K = \left( \frac{500 \text{ cm}}{0.896 \cdot 30 \text{ cm/ns}} \right) = 18.6 \text{ ns} \]

Assume experimental resolutions of
\[ \delta t = 0.15 \text{ ns} \]
\[ \frac{\delta p}{p} = 0.01 \]

\[ \left( \frac{\delta m}{m} \right)^2 = 2.26^4 \left( \frac{0.15}{18.6} \right)^2 + (0.01)^2 = 0.042^2 \]
\[ \rightarrow \delta m_K \approx 21 \text{ MeV} \]

\[ \left( \frac{\delta m}{m} \right) \rightarrow \infty \quad \text{for } p \rightarrow \infty \text{ and fixed } \frac{\delta \beta}{\beta} \]