Particle Physics Phenomenology

May 4, 2004
Detectors

• Interaction of Charged Particles and Radiation with Matter
  - Ionization loss of charged particles ✓
  - Coulomb scattering ✓
  - Radiation loss by electrons ✓
  - Absorption of γ-rays in Matter ✓

• Detectors of Single Charged Particles
  - Pictorial Detectors: Cloud Chambers, Emulsions, Streamer Chambers, Spark Chambers, Bubble chambers ✓
  - Proportional counters, Spark and streamer chambers, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters,

• Shower Detectors and Calorimeters
  - Electromagnetic-shower detectors
  - Hadron-shower detectors

• References: Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition
  Particle Data Group: 24. Detectors (multiple-authors)
Electronic Detectors

- Scintillators
- Proportional counters
- Multi-wire proportional counters
- Wire drift chambers
- Time projection chamber
Scintillators

- Certain materials scintillate when excited by ionizing particles
- Rutherford had his grad students counting the scintillations from zinc-sulfide
- Plastic or polystyrene are in common use today, but other material scintillate as well
- Organic
  - crystalline
  - liquid
  - plastic
- Inorganic
Scintillator Mechanism

• Scintillation:
  - Molecules are excited by a passing charged particle.
  - Certain molecules will release a small fraction (~3%) of this energy as optical photons, in a process known as scintillation.
  - Scintillation is particularly important in organic substances which contain aromatic rings, such as polystyrene, polyvinyltoluene, and napthalene.
  - Liquids which scintillate include toluene and xylene.
Scintillator Mechanism

- Fluors
  (a) increase wavelength,
  (b) extend range of photons, and
  (c) speed up decay time
Fluorescence

• Fluorescence:
  - In fluorescence, the initial excitation takes place via the absorption of a photon, and de-excitation by emission of a longer wavelength photon.
  - Flours are used as "wavelength shifters" to shift scintillation light to a more convenient wavelength.
  - Occurring in complex molecules, the absorption and emission are spread out over a wide band of photon energies, and have some overlap, that is, there is some fraction of the emitted light which can be re-absorbed.
  - This "self-absorption" is undesirable for detector applications because it causes a shortened attenuation length.
**Organic Scintillators**

- Most applications in HEP are plastic or liquid
- Wide range of applications, extremely versatile

<table>
<thead>
<tr>
<th></th>
<th>Pulse height (relative to anthracene)</th>
<th>Decay time, ns</th>
<th>λ_{max}, Å</th>
<th>Density, g cm^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>polystyrene + p-terphenyl</td>
<td>0.28</td>
<td>3</td>
<td>3550</td>
<td>0.9</td>
</tr>
<tr>
<td>polystyrene + tetraphenylbutadiene</td>
<td>0.38</td>
<td>4.6</td>
<td>4800</td>
<td>0.9</td>
</tr>
<tr>
<td>sodium iodide (+ thallium)</td>
<td>2.1</td>
<td>250</td>
<td>4100</td>
<td>3.7</td>
</tr>
<tr>
<td>anthracene</td>
<td>1.0</td>
<td>32</td>
<td>4100</td>
<td>3.7</td>
</tr>
<tr>
<td>toluene</td>
<td>0.7</td>
<td>&lt;3</td>
<td>4300</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Plastic Scintillators

- Plastic scintillators are reliable, robust, and convenient, but there are issues that must be dealt with
  - aging and handling
    - exposure can reduce light yield, and surface crazing destroys light transmission
  - attenuation length
    - care must be taken to ensure good transmission
  - afterglow
    - long-lived luminescence
  - atmospheric quenching
    - decrease light yield
  - magnetic field
    - small effects on light yield
  - radiation damage
    - reduced light yield, and attenuation length
Non-linear Response

- Plastic scintillators do not respond linearly to the ionization density.
  - Very dense ionization columns emit less light than expected on the basis of $dE/dx$ for minimum ionizing particles.
  - A widely used semi-empirical model by Birks' posits that recombination and quenching effects between the excited molecules reduce the light yield.
  - These effects are more pronounced the greater the density of the excited molecules.
  - Birks' formula is

$$
\frac{d\mathcal{L}}{dx} = \mathcal{L}_0 \frac{dE/dx}{1 + k_B dE/dx}
$$

- where $\mathcal{L}$ is the luminescence, $\mathcal{L}_0$ is the luminescence at low specific ionization density, and $k_B$ is Birks' constant, which must be determined for each scintillator by measurement.

PDG
# Inorganic Scintillators

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$X_0$ (cm)</th>
<th>$r_{\text{Molière}}$ (cm)</th>
<th>$dE/dx$ (MeV/cm)</th>
<th>$\lambda_I$ (cm)</th>
<th>$\tau_{\text{decay}}$ (ns)</th>
<th>$\lambda_{\text{max}}$</th>
<th>$n_D$</th>
<th>Rel. output*</th>
<th>Hygro?</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>2.59</td>
<td>4.5</td>
<td>4.8</td>
<td>41.4</td>
<td>250</td>
<td>410</td>
<td>1.85</td>
<td>1.00</td>
<td>very</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>1.12</td>
<td>2.4</td>
<td>9.2</td>
<td>22.0</td>
<td>300</td>
<td>410</td>
<td>2.20</td>
<td>0.15</td>
<td>no</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>4.89</td>
<td>2.05</td>
<td>3.4</td>
<td>6.6</td>
<td>29.9</td>
<td>$0.7^f$</td>
<td>$220^f$</td>
<td>1.56</td>
<td>0.05$^f$</td>
<td>slightly</td>
</tr>
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</tr>
<tr>
<td>CsI(Tl)</td>
<td>4.53</td>
<td>1.85</td>
<td>3.8</td>
<td>5.6</td>
<td>36.5</td>
<td>1000</td>
<td>565</td>
<td>1.80</td>
<td>0.40</td>
<td>some</td>
</tr>
<tr>
<td>CsI(pure)</td>
<td>4.53</td>
<td>1.85</td>
<td>3.8</td>
<td>5.6</td>
<td>36.5</td>
<td>$10,36^f$</td>
<td>$305^f$</td>
<td>1.80</td>
<td>0.10$^f$</td>
<td>some</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tr>
<tr>
<td>PbWO$_4$</td>
<td>8.28</td>
<td>0.89</td>
<td>2.2</td>
<td>13.0</td>
<td>22.4</td>
<td>5–15</td>
<td>420–440$^\dagger$</td>
<td>2.3</td>
<td>0.01</td>
<td>no</td>
</tr>
<tr>
<td>CeF$_3$</td>
<td>6.16</td>
<td>1.68</td>
<td>2.6</td>
<td>7.9</td>
<td>25.9</td>
<td>10–30</td>
<td>310–340</td>
<td>1.68</td>
<td>0.10</td>
<td>no</td>
</tr>
</tbody>
</table>

* For standard photomultiplier tube with a bialkali photocathode. See Ref. 27 for photo-diode results.

$^\dagger$ Emission $\sim$ 500 nm also possible due to crystal defects.

$f =$ fast component, $s =$ slow component
Photomultiplier Tubes

- Light from scintillator is usually recorded by photomultiplier tubes
- photocathode coated by alkali metals
- amplification through dynode chain
  - $10^8$ for 14 dynodes
- transit time $\sim 50$ nsec
- jitter $\sim$ nsec
- quantum efficiency $\sim 25\%$
Typical Phototube - 931A

931A, 931B
Photomultiplier

28-mm (1-1/8 inch) Diameter 9-Stage, Side Window PMTs

- Anti-Hysteresis Design
- Narrow Range of Anode Sensitivities
  931A: 30 A/Im - 600 A/Im
  931B: 100 A/Im - 1000 A/Im
- Low Dark Current

Figure 1 - Typical Photocathode Spectral Response Characteristics
Super K Phototubes

- Super Kamiokande
  - 11,146 tubes (20-inch diameter)
Photodiodes

- Higher quantum efficiency
- Lower power consumption
- More compact
- Improved ruggedness
- Immune to magnetic fields
- Good time response
Light Path in Scintillator

- Light may be extracted from scintillator to phototube by internal reflection (multiple reflection down light guide)
- Alternative approach - wavelength shifter bars along edge of scintillator
  - blue light from scintillator re-emitted as green
Proportional Counter

- Developed over a century ago
- Gas-filled cylindrical tube of radius $r_2$ at negative potential, with central anode wire of radius $r_1$ at positive potential
Proportional Counter

- For potential difference $V_0$, the electric field is
  \[ E(r) = \frac{V_0}{r \ln(r_2/r_1)} \]
- Liberated electrons drift toward anode, gaining energy.
- An avalanche is initiated if energy gain exceeds ionization energy.
- Gas amplification of $\sim 10^5$ is typical, but independent of the number of primary ions "proportional counter"
Multiwire Proportional Counter (MWPC)

- Around 1968, Charpak developed the MWPC
- Many parallel anode wires in a plane between two cathode planes
- Each wire is an independent detector
- Typical: 20 μm diameter wires, 5/cm, 12mm between cathodes, 5kV, argon-isobutane gas
**Multiwire Proportional Counter (MWPC)**

- Electric Field Lines
Multiwire Proportional Counter (MWPC)

- Fast rise time (0.1 nsec) arising from first arriving electrons
- Positive ions are slower, resulting in pulses of ~30 nsec duration
- Spatial resolution ~ 0.7 mm from anode pulses
- Cathode strips can be used to measure spatial coordinate of the avalanche (with about 0.05 mm precision)
Wire Drift Chambers

- MWPCs require large number of wires and are limited to resolutions of about 1 mm and time resolutions of about 30 ns
- By drifting the charge, the number of wires can be significantly reduced, and the resolutions improved.
- Drift in field of ~ 1 kV/cm over 10 cm, amplify at anode
  - arrival time give measure of position
Wire Drift Chambers

- SLD Drift Chamber
Wire Drift Chambers

- SLD Drift Chamber

~100 μm resolution
Wire Drift Chambers

- SLD Drift Chamber
Time Projection Chamber

- Uniform electric field drifts ionization electrons to a 2D array of detectors at the end.
  - drift along the magnetic field direction to eliminate $v \times B$ force

![Aleph TPC Diagram]
Cerenkov Counters

- Threshold detectors
- Differential detectors
- Ring Imaging detectors
Cerenkov Counters

- Part of the light emitted as a particle passes through a dielectric medium at a velocity exceeding the speed of light in the medium appears as a coherent wavefront.

\[
\cos \theta = \frac{ct}{\beta ct} = \frac{1}{\beta n}, \quad \beta > \frac{1}{n}
\]
Cerenkov Counters

- **Cerenkov radiation**
  \[
  \frac{d^2 N}{dxdE} = \frac{\alpha z^2}{\hbar c} \left( 1 - \frac{1}{\beta^2 n^2} \right)
  \]

- blue light predominates
  - well known blue glow from reactor

- **Total rate of energy loss:**
  \[
  \frac{dW}{dx} = \frac{\alpha z^2}{\hbar c} \int \left( 1 - \frac{1}{\beta^2 n^2} \right) EdE
  \]
  \[
  = \frac{\alpha z^2}{2\hbar c} \left[ (h\nu_1)^2 - (h\nu_2)^2 \right] \left( 1 - \frac{1}{\beta^2 n^2} \right)_{av}
  \]
  - a small fraction of the energy loss
**Cerenkov Counters**

- The angle of emission of radiation is a measure of the velocity of the particle

\[
\cos \theta = \frac{ct}{\beta ct} = \frac{1}{\beta n}, \quad \beta > \frac{1}{n}
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<th>Medium</th>
<th>(n - 1)</th>
<th>(\gamma) (threshold)</th>
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<tr>
<td>helium (NTP)</td>
<td>(3.3 \times 10^{-5})</td>
<td>123</td>
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</tr>
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<td>aerogel</td>
<td>0.075 → 0.025</td>
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<td>H(_2)O</td>
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Threshold Cerenkov Counters

- If two particles of different mass carry the same momentum, the lighter particle may emit Cerenkov radiation, while the heavier does not.

- For example, in helium at NTP, the threshold for radiation is $\gamma = 123$.

- A 100 GeV/c pion has a $\gamma \approx 700$, above the threshold while a 100 GeV/c proton has a $\gamma \approx 106$, below threshold.

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Differential Cerenkov Counters

- Since the angle of emission of radiation is a measure of the velocity of the particle, by measuring the angle, one can determine velocity

\[
\cos \theta = \frac{ct/n}{\beta ct} = \frac{1}{\beta n}, \quad \beta > \frac{1}{n}
\]

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</table>
Ring Imaging Cerenkov Counters

- eg. SLD and DELPHI

light at angle $\theta_c$ is focussed by mirror of radius $R$ on ring CD
Ring Imaging Cerenkov Counters

Muon in liquid ($C_6F_{14}$)  
Muon in gas (87% $C_5F_{12}$ 13% $N_2$)
Ring Imaging Cerenkov Counters

CRID final performance for gas and liquid rings for simple events such as di-muons [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gas rings</th>
<th>Liquid rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fraction of photoelectrons contributing to the “final efficiency” compared to the “starting efficiency”</td>
<td>0.70</td>
<td>0.53</td>
</tr>
<tr>
<td>Mean photon energy (eV)</td>
<td>6.70</td>
<td>6.50</td>
</tr>
<tr>
<td>Mean refractive index</td>
<td>1.001646</td>
<td>1.27202</td>
</tr>
<tr>
<td>Mean Cherenkov angle (mrad)</td>
<td>57.33</td>
<td>666.24</td>
</tr>
<tr>
<td>($\beta = 1$ particle)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated for radiator length (cm)</td>
<td>45</td>
<td>1</td>
</tr>
<tr>
<td>$N_o$ [cm$^{-1}$]</td>
<td>80</td>
<td>42</td>
</tr>
<tr>
<td><strong>Expected</strong> average number of photoelectrons per full ring ($\beta = 1$ particle) [11]</td>
<td>11–12</td>
<td>16</td>
</tr>
<tr>
<td><strong>Measured</strong> average number of photoelectrons per full ring (di-muons) [34]</td>
<td>10</td>
<td>16–17</td>
</tr>
</tbody>
</table>
Solid State Detectors

- Silicon detectors in nuclear physics
- Microstrip detectors
- Hybrid pixels detectors
- Silicon drift detectors
- CCDs
- CMOS detectors
- Diamond detectors
Detectors

- Interaction of Charged Particles and Radiation with Matter
  - Ionization loss of charged particles
  - Coulomb scattering
  - Radiation loss by electrons
  - Absorption of $\gamma$-rays in Matter

- Detectors of Single Charged Particles
  - Pictorial Detectors: Cloud Chambers, Emulsions, Streamer Chambers, Spark Chambers, Bubble chambers
  - Proportional counters, Spark and streamer chambers, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters

- Shower Detectors and Calorimeters
  - Electromagnetic-shower detectors
  - Hadron-shower detectors