Particle Physics Phenomenology

April 29, 2004
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

## Spatial and Temporal Resolutions

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Accuracy (rms)</th>
<th>Resolution Time</th>
<th>Dead Time</th>
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</thead>
<tbody>
<tr>
<td>Bubble chamber</td>
<td>10 to 150 (\mu m)</td>
<td>1 ms</td>
<td>50 ms(^a)</td>
</tr>
<tr>
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<td>300 (\mu m)</td>
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<td>100 ms</td>
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<td>(\geq 300 \mu m)(^{bc})</td>
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<tr>
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<td>1 (\mu m)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Silicon strip</td>
<td>Pitch (^e)</td>
<td>(f)</td>
<td>(f)</td>
</tr>
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<td>3 to 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon pixel</td>
<td>2 (\mu m)(^g)</td>
<td>(f)</td>
<td>(f)</td>
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\(^a\) Multiple pulsing time.
\(^b\) 300 \(\mu m\) is for 1 \(\text{mm}\) pitch.
\(^c\) Delay line cathode readout can give \(\pm 150 \mu m\) parallel to anode wire.
\(^d\) For two chambers.
\(^e\) The highest resolution ("7") is obtained for small-pitch detectors (\(\leq 25 \mu m\)) with pulse-height-weighted center finding.
\(^f\) Limited at present by properties of the readout electronics. (Time resolution of \(\leq 25 \text{ns}\) is planned for the ATLAS SCT.)
\(^g\) Analog readout of 34 \(\mu m\) pitch, monolithic pixel detectors.
Pictorial Detectors

- **Cloud chamber**
  - condensation on track
- **Emulsions**
  - enhanced silver content, reveals (after development) particle tracks with extreme precision
- **Streamer chambers**
  - ionization of gas generates light through recombination which is photographed
- **Spark chambers**
  - breakdown through electrodes
- **Bubble chambers**
  - liquid is expanded to superheated condition
Cloud Chamber

- Invented by C.T.R. Wilson for study of formation of rain in clouds
- Perfected around 1912
- Expands moist air in a closed container
  - Expansion cools the air
  - It becomes supersaturated
  - Moisture condenses on dust particles
  - ............or paths ionized by charged particles
- Example: beta particles
Cloud Chamber

A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.
Emulsions

- Photographic film contains tiny crystals (or “grains”) of very slightly soluble silver halide salts such as silver bromide.

- The grains are embedded in gelatine which is melted and applied as a thin coating on a substrate.

- Light or radiation striking a silver halide crystals initiates a series of reactions which produce a small amount of free silver in the grain.

- Free silver produced in the exposed emulsion constitutes the “latent image,” which is later amplified by the development process.

- The free silver grains are easily reduced by “developers” to form relatively large amounts of free silver; the deposit of free silver produces a dark area on the film.

- Emulsions have superb spatial precision (~ 1 µm) but poor time precision, being continuously active.
Emulsions

- Historical example:
  - Discovery of the pion, announced in 1947 by Powell et al

Four examples of $\pi$-$\mu$-$e$ decays recorded in photographic emulsions
Emulsions

- Example:
  - Chorus experiment at CERN
  - Searched for tau-neutrino interactions

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Physics 663, lecture 6
Emulsions

- DONUT (Direct Observation of NU-Tau)
  - Discovered tau neutrino interactions
  - Search for

\[
\nu_\tau + N \rightarrow \tau^- + X \\
\tau^- \rightarrow (\mu^- \text{ or } e^-) \nu_\mu \nu_\tau \text{ or } \tau^- \rightarrow h^- \nu_\tau
\]
Emulsions

- DONUT

Tau neutrino interaction
Spark Chambers

- Extremely high voltages across gaps lead to breakdown, and emission of light
- Space charge within an avalanche is strong enough to shield external field
  - recombination occurs, and emission of light
- Often multiple gaps were employed
Spark Chambers

[Diagram of a spark chamber with labeled parts: Scintillation Counter, Photomultiplier Tube, Base Plate, and 16 modules.]

[Diagram showing a track passing through the scintillation counter and photomultiplier tube, indicating the detection of a particle path.]
Streamer Chambers

- If a short (10 ns) high-voltage pulse (10-50kV/cm) is applied between parallel plate electrodes, a short (2-3 mm) streamer discharge develops

- Good multi-track efficiency and spatial resolution
- triggerable
- long recovery time
- processing of optical images required

- Fermilab experiment, triggered on muons, scanned for $V^0$s (search for charm)
Bubble Chamber

- Invented in early 1950’s by Glaser
- Dominant detector for decades
- Superheated liquid begins to boil along path of charged particle
- Superheating achieved by maintaining liquid at high pressure (5-20 atmospheres), and sudden expansion.
- Bubble grow for a period of time (ms typically)
- Photograph and recompress
Bubble Chamber

- Several cameras provide stereo image
  - very detailed measurements following reconstruction
- Disadvantages
  - low repetition rate (1-20 Hz)
  - analysis of film complicated
  - very low duty cycle (~ 10^{-2})
  - not matched to colliding beam geometry
Bubble Chamber

- Liquids used
  - hydrogen - most elementary target material (proton)
  - deuterium - most elementary form of neutron targets
  - heavy liquids - short radiation length, or higher interaction rate

Table 2. Properties of bubble chamber liquid.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Temperature [K]</th>
<th>Density [g/cm³]</th>
<th>Radiation length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>25</td>
<td>0.0645</td>
<td>968</td>
</tr>
<tr>
<td>D₂</td>
<td>30</td>
<td>0.14</td>
<td>900</td>
</tr>
<tr>
<td>Ne</td>
<td>35</td>
<td>1.02</td>
<td>27</td>
</tr>
<tr>
<td>He</td>
<td>3.2</td>
<td>0.14</td>
<td>1027</td>
</tr>
<tr>
<td>Xe</td>
<td>252</td>
<td>2.3</td>
<td>3.9</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>333</td>
<td>0.43</td>
<td>110</td>
</tr>
<tr>
<td>CF₃Br</td>
<td>303</td>
<td>1.5</td>
<td>11</td>
</tr>
<tr>
<td>Ar</td>
<td>135</td>
<td>1.0</td>
<td>20</td>
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<tr>
<td>N₂</td>
<td>115</td>
<td>0.6</td>
<td>65</td>
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SLAC 1-meter Bubble Chamber
Bubble Chamber

- BEBC at CERN, 3.7 m diameter,
  - with EMI (MWPCs)
  - $B = 2-3.5$ Tesla
Bubble Chamber
Hybrid Bubble Chamber

- Combine bubble chamber with a downstream system
- Example was the Fermilab 30-inch hybrid bubble chamber system
- Upstream measurements to tag beam particle
- Downstream measurement needed to achieve good momentum resolution on high energy tracks (beam momentum ~ 150 GeV/c)
Triggered Bubble Chamber

- Use downstream system to trigger bubble chamber flash
- Only take picture when event, or selected event, occurs in BC
- Example was the SLAC Hybrid Facility (1 meter BC)

- $\pi^p \rightarrow K^X$
- Flash in 2.5 msec
- 40% of photos had event
- $\sim 15/1$ reduction in photos
Triggered Bubble Chamber

- Event detected at SLAC 1 meter bubble chamber.

- Careful analysis shows this event is

\[ \bar{p} p \rightarrow p \pi^+ K^- \pi^- \pi^0 K^0 \bar{n} \]
High Resolution Bubble Chamber

- Special optics were developed to improve resolution
  - Run bubble chamber “hot” (29K) to slow bubble growth and increase bubble density
  - Achieved bubble size of <50 μm (compared to standard ~300 μm)
  - Example, charm lifetime measurements in SLAC Hybrid Facility

Decay lengths of 0.86 mm and 1.8 mm

FIG. 1. An event showing the decay of a positive charmed particle into three charged tracks after 0.86 mm and the decay of a neutral charmed particle after 1.8 mm. Both decays contain missing neutrals and cannot come from strange particles. The quantities $d_{max}$ and $d_2$, the largest and second-largest impact distance for three-prong decay, are indicated.
Holographic Bubble Chamber

- In a conventional optics system the depth of field is coupled with the resolution:
  - \( \text{DOF} \sim \frac{\lambda}{D^2} \)
  - Resolution \( \sim \frac{\lambda}{D} \)

- Therefore, high resolution implies limited depth of field, reducing useful volume of bubble chamber

- A holographic system uncouples DOF and resolution
  - \( \text{DOF} \sim \) laser coherence length
  - Resolution \( \sim \frac{\lambda}{D} \) where \( D \) is the size of the recording medium

- Applied in two experiments at Fermilab in search of tau neutrino interactions in 1980s
  - Sensitive to large volumes - critical for neutrino experiments
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