Calorimeters in HEP, I

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Aims

• To give a broad appreciation of the physical processes in calorimetry.
• To discuss the energy and position resolution of calorimeters in fundamental terms.
• To describe a variety of techniques for constructing practical calorimeters.
• To examine a few real calorimeter systems.
Information sources

Six good sources of information on ECAL and HCAL (there are many others)

1. T Ferbel “Experimental techniques in high-energy nuclear and particle physics” Addison-Wesley, 1987
5. ATLAS, CMS, BaBar, LHCb, D0 etc. TDR reports (various dates)
Why calorimeters

• Calorimeter
  – A device to measure *Energy*

• Current and future collider based experiments are based on an “onion” like arrangement of tracking (mass-less) and energy measuring (massive) detector systems.
  – Momenta of charged particles are determined by hits in silicon (or gaseous) detectors in a high magnetic field region.
  – Particle energies are measured by calorimeters (they also measure position)
  – Muons and neutrinos penetrate through with minimal interaction.
Calorimetry

• Neutral and charged particles when incident on a block of material deposit energy through creation and absorption processes.
• The deposited energy can be determined in a variety of ways:
  – ionisation, scintillation, Cerenkov light, bolometry
• The dense medium may be active or passive
  – Homogeneous calorimeters, e.g. CsI(Tl), BGO, Pb-glass, PWO, Xe(liq) etc,
  – Sampling calorimeters, e.g. Pb-scintillator or Pb-Ar(liq) etc.
Why are calorimeters important?

- Energies of neutral and charged particles
- Relative energy resolution *improves* with energy as
  \[
  \frac{\sigma}{E} \propto \frac{1}{\sqrt{n}} \propto \frac{1}{\sqrt{E}}
  \]
  Where \( n \) is the number of secondary cascade particles and is proportional to the incident energy \( E \)

Contrast this with the *decreasing* momentum resolution from tracking systems with *increasing* particle momentum.
Features

• Longitudinal depth to contain the cascades increases logarithmically with energy.
• Jet energies can be measured.
• Missing transverse energy, $E_T$, can be measured (if hermetic coverage). This can be a signature of neutrinos or other weakly interacting particles.
• Longitudinal and lateral development of electromagnetic cascades is different for electrons, photons, hadrons and muons.
• Calorimeters are intrinsically fast.
• If the calorimeter has good lateral and longitudinal segmentation then efficient triggering on $e/\gamma$, jets and missing $E_T$ is possible.
Electromagnetic cascade

- A high energy electron or photon incident on a thick absorber produces a cascade of secondary electrons and photons via bremsstrahlung and pair production.
- As the depth increases the number of secondary particles increases, but their mean energy decreases.
- When the energies fall below the critical energy $\varepsilon$, the multiplication process ceases and energy is now dissipated via the processes of ionisation and excitation.
Simple model

- $\varepsilon$ is defined as the energy when the ionisation loss and radiation are equal. It can be calculated approximately as $560/Z$ (in MeV).

- Radiation length, $X_0$, is the distance in which, on average, an electron loses $1-1/e$ of its energy. It is also the length in which a photon has a pair conversion probability of 7/9. $X_0$ can be approximated as $180A/Z^2$ g.cm$^2$.

- Define two scaled variables

\[
t = \frac{x}{X_0} \quad y = \frac{E}{\varepsilon}
\]

Taking $1 \cdot X_0$ as the generation length then the particle energy $e(t)$ and the number of particles $n(t)$ are given by

\[
e(t) = \frac{E}{2^t} \quad n(t) = 2^t
\]

At shower maximum

\[
n(t_{\text{max}}) = y \quad t_{\text{max}} = \ln y
\]
## Properties of some dense elements

<table>
<thead>
<tr>
<th>$Z$</th>
<th>Density</th>
<th>$\varepsilon$</th>
<th>$X_0$</th>
<th>$\lambda$</th>
</tr>
</thead>
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<tr>
<td></td>
<td>g.cm$^{-3}$</td>
<td>MeV</td>
<td>cm</td>
<td>cm</td>
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<tr>
<td>Fe</td>
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<td>7.9</td>
<td>24</td>
<td>1.76</td>
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<tr>
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<td>0.56</td>
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<tr>
<td>U</td>
<td>92</td>
<td>19.0</td>
<td>6</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**Note:**

$\lambda$ is the *hadronic* interaction length
Shower containment

Figure 3 from Fabjan C in Ferbel 1987

Longitudinal containment

Lateral containment
Lateral shower development

- As the shower develops it broadens laterally due to multiple scattering of electrons and low energy photons.
- This can be characterised by the *Moliere radius*, \( R_m \).
- \( R_m \) is approximately 7A/Z g.cm\(^{-2}\).
- The shower starts (and persists) with a narrow core surrounded by a soft halo of scattering particles. An infinite cylinder of radius 1 \( R_m \) contains 90% of the shower energy.
Lateral shower development

Calorimeter cells are typically one Moliere radius in size. Some lateral shower sharing between cells improves the position resolution.

Figure 4 from Fabjan C in Ferbel 1987
EM Simulation

- https://www.mppmu.mpg.de/~menke/elss/home.shtml

150 GeV electron shower in PbWO$_4$

CMS Homogeneous ECAL. The green lines show the approximate location of a single crystal.
Hadronic calorimetry

- High energy hadrons interact with nuclei resulting in the production of secondary hadrons (pions, kaons).
- The hadronic analogue of $X_0$ is the interaction length $\lambda$ which varies as $A^{1/3}$.
- The strong interaction results in a developing shower of particles. There are two distinct components
  - Electromagnetic arising mainly from $\pi^0$ production
  - Hadronic
- Multiplication continues until the pion production threshold is reached. The average number of secondary hadrons grows like $\ln(E)$. Their transverse momentum is fairly low (of order 300 MeV)
• Using scaled variables

\[ \nu = \frac{x}{\lambda}, \quad E_{th} \approx 2m_\pi = 0.28 \text{ GeV} \]

• The energy and number of the secondary particles can be modelled as

\[
e(\nu) = \frac{E}{\langle n \rangle^\nu}
\]

\[
e(\nu_{\text{max}}) = E_{th}
\]

\[
n^{\nu_{\text{max}}} = \frac{E}{E_{th}} \implies \nu_{\text{max}} = \frac{\ln(E/E_{th})}{\ln\langle n \rangle}
\]

Note that the number of independent particles is smaller than in an EM shower by the ratio \( E_{th}/\epsilon \). Thus the intrinsic energy resolution will be poorer by about a factor of 6 in most materials.
Shower containment

- About $9\lambda$ are required for longitudinal containment
- Lateral development
  - Secondary hadron $p_T$ is about 300 MeV
  - This is comparable to energy lost in $1\lambda$ in most materials
  - At shower maximum (where the characteristic particle energy = 280 MeV) the radial extent will have a characteristic scale of $1 \lambda$
  - High energy showers have a pronounced core surrounded by an exponentially decreasing halo
Figure 28.21: Nuclear interaction length $\lambda_I/\rho$ (circles) and radiation length $X_0/\rho$ (‘+’s) in cm for the chemical elements with $Z > 20$ and $\lambda_I < 50$ cm.
Hadron shower simulations

32 GeV pions in the CALICE “digital” HCAL (1 m³, 8000 channels)

- http://www.ast.leeds.ac.uk/~fs/showerimages.html