Calorimetry play an increasingly important role in high-energy experiments. In order to be able to optimize the performance of these detectors, it is absolutely necessary to understand in detail how they work. This is the subject of these lectures.

We will review the processes through which particles lose energy in dense matter (shower development), and the factor determining the response of an instrumented block of dense matter.

Emphasis will be put on sampling calorimeters, although homogeneous devices for electromagnetic shower detection will be treated as well. The so-called compensation mechanisms, crucial for the performance of hadron calorimeters, will be discussed in detail.

Finally, some attention will be given to current R & D work carried out in view of the very demanding requirements of experiments at future supercolliders.
CALORIMETRY IN HIGH-ENERGY PHYSICS

Richard Wigmans
CERN

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OUTLINE:

- Principles of calorimetry
- Comparison of different techniques
- Limitations
- Research and development

NO emphasis on details of specific detectors.

Lecture 1: Principles, EM Calorimeters
Lecture 2: Techniques, HADRONIC Calorimeters
Lecture 3: Compensation, R&D

LITERATURE:

- Proc. ICFA School on Instrumentation in Elementary Particle Physics, Trieste 1987, p. 41-149
• Experimental particle physics
  → want to measure 4-vectors

METHODS:
- Bubble chamber
- "Electronic" bubble chamber (c, b quarks)
- Calorimetry
WHAT IS A CALORIMETER?

A block of matter (< 1 kg - > 1000 tons) in which the particle gets absorbed, and from which one gets a signal.

Some (constant!? ) fraction of the initial particle energy is transformed into a measurable signal, e.g. light or electric charge.

The energy resolution is determined by fluctuations in the measured charge.

2 TYPES OF CALORIMETERS:

- Homogeneous calorimeters
- Sampling calorimeters
WHY CALORIMETERS?

→ CALORIMETER PROPERTIES

• Sensitive to charged and neutral particles
• Particle identification \( (h/e/\mu/\nu \text{ separation}) \)
• \( \sigma/E \) improves with increasing \( E \) (as \( c/\sqrt{E} \) if properly designed)
• Size \( (\equiv \text{ cost}) \) goes as \( \log(E) \)
• Fast (response times < 100 ns) — high rates
• They don't need a magnetic field
• Granularity — good measurement of particle direction

→ PHYSICS REASONS

• Interest shifted from hadron to quark level — measure jets
• Measure global event properties (E-flow): \( \Sigma E_T, E_T^{\text{miss}}, E_{\text{tot}}, E_{\text{miss}}^{\text{tot}} \)
• Trigger on extremely rare events

Calorimeter performance crucial for experimental successes

Increasingly true at higher energies: SLD, ZEUS, D0, UA1, UA2, HELIOS. H1 spent a major fraction of their budget on calorimetry.

Optimal design — need detailed understanding of factors that limit the calorimeter performance.
Figure 2
Jet-jet invariant mass distribution, measured in $p\bar{p}$ collisions at $\sqrt{s} = 630\text{GeV}$. Data from ref. 1.
Figure 3

$\bar{p}p \rightarrow W \rightarrow e\nu$
CALORIMETERS FOR DETECTING EM SHOWERS

- CALORIMETRY AT VERY LOW ENERGIES

Used by nuclear physicists since more than 50 years (γ detection)

Best results obtained with semiconductor crystals: Ge, Ge(Li), Si(Li)

It takes only ~ 3 eV to create an electron-hole pair

\[ \sigma/E = \frac{\sqrt{350,000}}{350,000} = 0.17\% \text{ at } 1 \text{ MeV} \]

Confirmed in practice

Already at these very low energies we may have quite complicated showers

Example illustrates some characteristic aspects of calorimetry:

- Shower development
- Effect of fluctuations on the signal distribution
- Leakage
HIGH RESOLUTION NUCLEAR γ CALORIMETRY

100 cm³ Ge(Li) crystal detector.

\[ \frac{J}{E} = 0.17\% \text{ at } 1\text{ MeV} \]

Figure 6
SHOWER DEVELOPMENT BY

LEAKAGE

Figure 7
SCINTILLATION COUNTERS

Other nuclear $\gamma$ detectors are based on the detection of scintillation light, e.g. NaI(Tl), CsI, BGO.

COMPLICATIONS COMPARED TO SEMICONDUCTOR CRYSTALS:

- Scintillation light spectrum
- Sensitivity photocathode
- Light isotropically emitted $\rightarrow$ losses

$\rightarrow$ Signal fluctuations do not only depend on statistics in primary processes (emission scintillation light), but also on e.g.

- What kind of light is produced
- Where is it produced

Fluctuations largely $E$-independent $\rightarrow \frac{\sigma}{E} \neq c/\sqrt{E}$

EXPERIMENTAL RESULTS:

$8 \text{ keV} \rightarrow \frac{\sigma}{E} \approx 15\% \ (200 \text{ eV/p.e.})$

$1 \text{ MeV} \rightarrow \frac{\sigma}{E} \approx 5\%$
MECHANISMS OF ENERGY LOSS IN HIGH-ENERGY EM SHOWERS

\( eV, \text{keV, MeV} \rightarrow \text{GeV, TeV} \) (1 cal \( \approx 2.6 \times 10^7 \) TeV)

**ALREADY SEEN:**
- Ionisation for \( e^+, e^- \)
- \( \gamma \rightarrow e^+e^- \)
- Compton scattering \( \gamma \rightarrow e^- + \gamma^* \)
- Photo-electric effect \( \gamma \rightarrow e^- \)

At high energies one new process: **Bremsstrahlung**

\( e \rightarrow e^+ + \gamma \) in nuclear Coulomb field \( \rightarrow \) **Particle multiplication**

**- Bremsstrahlung principle source of energy loss high-E electrons**
**- Bremsstrahlung spectrum soft**
**- Multiple scattering**
Part of an EM shower recorded in a bubble chamber

- Overwhelming majority shower particles very soft
- $<E>$ shower particles decreases in time (depth)
EM SHOWER DEVELOPMENT

- Governed by laws of QED
- Electron density in matter $\sim Z$

**CRITICAL ENERGY** $\rightarrow$ shower particle multiplication stopped

- $E > E_c$: $\gamma \rightarrow e^+ e^-$, $e \rightarrow e^\prime + \gamma$
- $E < E_c$: $\gamma \rightarrow e^-$, $e$ stopped.
- $E_c \sim 1/Z$

![Diagram](image)

- Number of different shower particles increases with $Z$
  - $\gamma \rightarrow e^+ e^-$ continues until lower energies
  - $e \rightarrow e^\prime \gamma$ continues until lower energies.

Physics of em shower development well-understood and relatively simple
$\rightarrow$ Monte Carlo simulations reliable: EGS 4
ENERGY LOSS $e^\pm$

a) $^6\text{C}$
- Energy loss by ionization
- Energy loss by radiation

b) $^{26}\text{Fe}$

28 MeV

c) $^{92}\text{U}$

9 MeV

$E_e$ (MeV)
CROSS SECTIONS FOR PHOTONS

(a) $^{6}\text{C}$

(b) $^{26}\text{Fe}$

(c) $^{92}\text{U}$

$E_{\gamma}$ (MeV)

$\sigma$ (b/atom)

30 MeV

10 MeV

0.7 MeV

4.6 MeV
EM SHOWER CHARACTERISTICS

MATERIAL-INDEPENDENT DESCRIPTION

Shower dimensions scale with:

- **Radiation length** $X_0$ (longitudinal)
- **Molière radius** $\rho_M$ (radial)

\[
X_0 \approx 180 \frac{A}{Z^2} \text{g/cm}^2 \quad \rho_M \approx 7 \frac{A}{Z} \text{g/cm}^2
\]

Scaling in $X_0$ and $\rho_M$ approximately correct

Deviations due to low-$E$ peculiarities ($X_0$ defined at $E = \infty$)

Reasonable fit: 
\[
N = N_0 X_0^a \exp(-bX_0) \quad a, b = f(Z), \quad a = f(E)
\]

Shower max: 
\[
a/b \sim \log(E)
\]

CONTAINMENT:

- 10 GeV → 25 $X_0$ for 99%
- 20 GeV → only 1.3 $X_0$ extra!

→ Need ~ 15 cm Pb to contain 20 GeV γ showers

- Need **more** for 1 Curie $^{60}$Co source (1 MeV γ's)

$X_0$ has no meaning for low energies. Low-energy gammas may easily travel many radiation lengths, especially in high-Z materials
LONGITUDINAL DEVELOPMENT EM SHOWERS

LONGITUDINAL DEVELOPMENT EM SHOWERS (EGS4, 10 GeV e⁻)

(%o) Xp/Ep

X₀
LATERAL SHOWER SPREAD

2 EFFECTS:

a) Multiple scattering electrons

b) $\gamma$'s around 1 MeV may travel many $X_0$

- A dominates before shower maximum
- 2 components clearly visible (Pb)
- B much less important at low $Z$ → shower more narrow (in $\rho_M$)
- Very good position resolution in first few $X_0$ ($\leq 1\text{mm}$)
LATERAL DEVELOPMENT EM SHOWERS

Figure 12

\[ \text{E}_\text{cm} = \text{E} \times 10^7 \]

\[ f_M(T) = 1.7 \times 10^7 \]
THE ENERGY RESOLUTION OF EM CALORIMETERS

HOMOGENEOUS (FULLY SENSITIVE) DEVICES:

- **NaI(Tl):** 60 cm (24 $X_0$) crystal $\rightarrow \sigma/E = 0.9\%$ at 1 GeV.
  
  Limit: Fluctuations in light collection, not production

- **BGO ($X_0 = 1.1$ cm):** Similar properties

- **Lead Glass:** Detection Čerenkov light.
  
  If $E_e > 0.7$ MeV $\rightarrow$ Čerenkov light, $\sim 1400$ photons/GeV.

  Č-light directional $\rightarrow$ good collection efficiency.

  At 1 GeV: $\sigma/E \sim \sqrt{700}/700 \sim 5\%$ $\rightarrow \sigma/E \sim 5\%/\sqrt{E}$ [GeV$^{-1/2}$]

  Energy resolution limited by fluctuations shower development

SAMPLING CALORIMETERS:

- Measure energy loss charged shower particles in **active layers**

- Which fraction of $E$? Mass ratio active/passive (rough estimate)

- Solid or liquid active layers: 1-10%, **gases:** $10^{-4} - 10^{-5}$
THE ENERGY RESOLUTION OF EM SAMPLING CALORIMETERS

All sampling calorimeters based on abundant primary processes
(scintillation, ionisation charge collection, > $10^6$/GeV

Nevertheless, (photo-)electron statistics may contribute to $\sigma/E$:

- Scintillator: $1000$ p.e./GeV is very good $\rightarrow 3%/\sqrt{E}$ from photon statistics.
- Wire chambers: $10^{-4}$ sampling fraction $\rightarrow 100$ ionizations per GeV in active layers $\rightarrow 10%/\sqrt{E}$ contribution to $\sigma/E$
- In addition, Landau fluctuations

\[
\frac{\sigma(N)}{N} > \frac{\sqrt{N}}{N}
\]

# ionizations/layer

Major contribution to resolution of sampling calorimeters comes from fluctuations in the number of shower particles contributing to signal: Sampling fluctuations


**ANALYSIS SAMPLING FLUCTUATIONS**

Distinguish 3 types of contributions:

1. Fluctuations determined by $\sqrt{v^2}$.
   Only dependent on $t_{obs}$ if $t_{obs} > 1/\Delta t$.
   $\sigma_{\text{sam}}/E = c \sqrt{t_{obs}}$.
   Independent on $t_{act}$.

2. $\sigma_{\text{sam}}/E = c \sqrt{t_{obs}}$.
   Independent on $t_{act}$.

3. $\sigma_{\text{sam}}/E = c \sqrt{t_{obs}}$ for fixed $t_{act}$.
   $I_{\text{sam}}/E = c / \sqrt{t_{act}}$ for fixed $t_{obs}$.
ANALYSIS SAMPLING FLUCTUATIONS

EGS 4 $\rightarrow$ (3) dominating: WHY?

- Only $\sim 65 \, \text{e}^+$ produced per GeV in U, less for low-Z

- **Electrons softer than 1 MeV** deposit 25 - 40% of ionisation energy
  (Compton, photo-electrons) $\rightarrow$ 1000/GeV!

  N.B. Most of these electrons are not detected because of their **short range**
  (in U: 0.4 mm at 1 MeV, 0.02 mm at 0.1 MeV)

Relative contribution (3) and (5) strongly dependent on configuration

- **Fe/LAr $\rightarrow$ (3) dominates**

- **Gas calorimeters** $\rightarrow$ No contribution from (3) Much less particles contribute to signal $\rightarrow$ larger fluctuations

- **High-Z calorimeters $\rightarrow$ (3) suppressed by photo-electric effect ($\sim Z^6$) $\rightarrow$ resolution worse than for Fe at same sampling fraction.**
ENERGY DEPOSIT IN 10 GeV $e^-$ SHOWER (EGS 4)

Fraction of ionization energy (%) vs. $Z_{\text{absorber}}$

- Deposited by $e^+ < 4 \text{ MeV}$
- Deposited by $e^+ < 1 \text{ MeV}$
- $^{238}\text{U}$
- Al
- Fe
- Sn
- Pb
- Deposited by $e^+ > 20 \text{ MeV}$

Figure 13
RESOLUTION Fe/LAr
EM SHOWERS

![Graph showing resolution for Fe/LAr EM showers]

$\frac{\sigma(E)}{E} \%$

$x_a$ (LIQUID ARGON) (mm)

Figure 14
RESOLUTION EM SHOWERS

![Graph showing resolution in em showers for different elements and materials with symbols for Scint, LAr, Gas, and others.](Image)

Figure 15
PATH LENGTH FLUCTUATIONS

More refined analysis of em calorimeter energy resolution

Fluctuations in amount of energy deposited by individual particles

Angular distribution → Path length fluctuations

Contribution depends on range of typical electrons contributing to signal, compared to the thickness of the active layers.
RESOLUTION EM SHOWERS IN Pb/gas

\[ \frac{\sigma(E)}{E} \] (\%)

\[ E \text{ (GeV)} \]

Figure 16
SUMMARY YESTERDAY

WHY CALORIMETRY?

- Calorimeter properties (high E)
- Physics (E-flow)

CALORIMETERS FOR DETECTING EM SHOWERS

- Nuclear energies: \( \sigma/E = c/\sqrt{E} \)?
- Mechanisms of energy loss
- Dimensions of em showers \((X_0, \rho_M)\)
  Deviations scaling \(\rightarrow\) low-energy phenomena
- Energy resolution em calorimeters
  Homogeneous calorimeters: \( \mathcal{C} \) vs scintillation light
  Sampling calorimeters: \( \sigma/E \) dominated by fluctuations in number of particles. Very configuration-dependent.
READOUT TECHNIQUES FOR SAMPLING CALORIMETERS

Chosen solution depends on performance requirements + cost

REQUIREMENTS USUALLY CONCERN:

- Energy resolution
- Signal linearity + line shape
- Electron/pion separation
- Position resolution (granularity)
- Hermeticity
- Rate capability
- Radiation resistance
- Signal uniformity
- Electronic stability + calibration
- Operation in a magnetic field
- Compactness
READOUT TECHNIQUES SAMPLING CALORIMETERS

**Plastic Scintillator**

HELIOS, ZEUS, UA2, CDF (all using WLS readout)

**ADVANTAGES SCINTILLATOR:**

- Minimizes dead space (hermetic)
- Compact construction
- Easy (cheap) technology
- Fast → high rate capability

**DISADVANTAGES SCINTILLATOR:**

- Granularity
- Signal uniformity
- Radiation sensitivity
- Stability (PM)

- Interesting new development: Scintillating plastic fibres
READOUT TECHNIQUES FOR
SAMPLING CALORIMETERS

Figure 17
**READOUT TECHNIQUES SAMPLING CALORIMETERS**

**CHARGE COLLECTING DEVICES** *(solids, liquids, gases)*

**Silicon**

*(not yet applied in large scale experiment)*

**ADVANTAGES:**

- Compactness
- Granularity
- Rate capability
- Stability

**DISADVANTAGES:**

- Small sampling fraction
- Radiation damage (neutrons)
- Cost
LIQUID ARGON (HELIOS, SLD, D0, H1)

ADVANTAGES:
- Long term stability
- Granularity

DISADVANTAGES:
- Hermeticity (cryogenic)
- Slow

WARM LIQUIDS (UA1)

ADVANTAGES:
- Hermeticity

DISADVANTAGES:
- Signal/noise ratio
- Technologically difficult

GAS GAIN CALORIMETERS (LEP experiments)

ADVANTAGES:
- Cost
- Granularity

DISADVANTAGES:
- Very small sampling fraction
- Rate capability
- Alinearity (saturated mode)
HADRON CALORIMETERS

GENERAL CHARACTERISTICS

- Conceptually, hadronic shower development similar to em, but
- **Strong interaction** → wide variety of reactions
  - **Meson** production ($\pi$, $K$, but also $\pi^0$, $\eta$ → em!)
  - **Nuclear** reactions ($p$, $n$, $\alpha$)
  - **Energy losses**: Binding energy, target recoil, $\mu$, $\nu$

- **DIFFERENCES EM/HADR. SHOWERS RELEVANT TO CALORIMETRY**:
  - **Shower dimensions**
  - **Invisible energy**
  - **Non-relativistic shower particles** (→ sampling, saturation)
  - **Neutrons** (not subject to em interaction)

- Strong interaction → scaling with nuclear interaction length $\lambda_{\text{int}}$

- **Electron/hadron separation**
  - $\lambda_{\text{int}}/X_0 \sim Z$ → high-$Z$ absorbers
  - possible with **longitudinal and lateral shower information**
  - **Granularity**

- Monte Carlo simulations **much less reliable** than EGS 4
Figure 18
NUCLEAR INTERACTION INDUCED BY 3.8 GeV II

Early example of the nuclear interaction of a meson of energy 3.8 GeV

Figure 30
IONIZATION BY NON-RELATIVISTIC PROTONS

![Graph showing ionization by non-relativistic protons](image)
SATURATION OF SCINTILLATOR RESPONSE TO LOW ENERGY PROTONS

(b) Birk's law

\[ \frac{dL}{dx} = \frac{dE/dx}{1 + KB \cdot dE/dx} \]

\[
\begin{array}{c}
\text{SCSN-38} \\
\text{PMMA}
\end{array}
\]

\[
\begin{array}{c}
0.8 \\
0.6 \\
0.4 \\
0.2 \\
0.01 \\
0.1 \\
1 \\
10 \\
100
\end{array}
\]

L/E

E_p (MeV)
HADRONIC SHOWER LEAKAGE

![Graph showing the fraction of energy beyond the calorimeter depth for different energy levels.](image-url)
Particle Identification: $\lambda / x_0$
CONSEQUENCES $e/h \neq 1$

- Signal distribution not Gaussian
- Fluctuations fraction $\pi^0's \rightarrow \sigma/E \neq c/\sqrt{E}$
- Signal $\neq E$ (alinearity, $f_{em}$ function of $E$)
- Measured $e/\pi$ signal ratio function of $E$

Experimentally confirmed

$e/h = 1 \rightarrow$ "Compensating" calorimeter, i.e. equal em and non-em calorimeter response

CONSEQUENCES $e/h \neq 1$ FOR DETECTORS AT SUPERCOLLIDER

- $\sigma/E$ factor $\sim 5$ worse
- Trigger biases
- Problems unfolding $E_T$

How can we make a calorimeter compensating?

(works only for sampling calorimeters)
ENERGY RESOLUTION OF HADRON CALORIMETERS

Energy resolution worse than for em shower detection

- **Sampling fluctuations larger** than in em showers
- Correlated hits (1 π may ionise 50 active layers)
- Fewer hits for same signal (non-relativistic particles)

- Fluctuations in the fraction of $E$ going into ionizing particles ($\Delta B$)

  $< \Delta B >_{\text{non-em}} = 40\% \pm 30\%/\sqrt{E}$

- Effect of $e/h \neq 1$ (non-compensation)
Figure 1

Signal Decomposition: Hadronic Shower

(Scattered pions $\pi^0$ not Gaussian)

$\pi^0, K, p$ (had) → $\pi^0$ component

purely hadronic component

Number of counts (arb. units)

Signal/GeV (arb. units)
Figure 24

EFFECT OF e/n ON ENERGY RESOLUTION AND SIGNAL LINEARITY (EXPT.)

{ NIKHEF 57-63 }
{ NIM 180 (1981) 429 }
{ DESY 87/27 }
RELATION $e/h$ vs $e/\pi$
HOW TO ACHIEVE COMPENSATION?

- **Naive expectation:** $e/h = 1/0.6 \sim 1.6$

- Lesson from em calorimeters: Calorimeter response *decisively* determined by details of *last stages* shower development.

3 **MECHANISMS EXPLOITED TO BRING $e/h \rightarrow (1) 1.0$$

a) **Boost** $h$ by using $^{238}$U absorber plates (nuclear fission). *Neither essential nor sufficient*

- **Relative** contribution of the different shower components ($\pi^0$, ionizing hadrons, $n$, $\gamma$) to calorimeter signal can be *varied* within certain limits $\rightarrow$ $e/h$ can *be tuned*

b) **Reduce** $e$ ($\pi^0$-response) using low-$E$ peculiarities of em shower development *(photo-electric effect) $\rightarrow$ high-$Z$ absorber, low-$Z$ active material.*

  Effect *amplified* by low-$Z$ passive shielding active layers.

c) **Boost** $h$ by *amplifying the relative response to neutrons* through the sampling fraction

- 10 – 15% of non-em energy carried by low-$E$ neutrons.

  Compensation: $\sim 40\%$ of signal comes from low-$E$ neutrons

- **Hydrogenous** active material *essential*

- **Saturation** properties *crucial*