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CALORIMETERS: GASEOUS READOUTS COMPARED TO ALTERNATIVES

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ABSTRACT

Calorimeter techniques are applied to a vast range of detection problems, measuring the energy and position of particles from keV-photons to TeV-nuclei. As a consequence, many different readout methods have been developed, among which gaseous techniques occupy a prominent place. First, we comment on our present understanding of the physics of the hadronic cascade, from which conditions on the response of the active material are derived. Secondly, we explain and compare the principal features of gaseous, liquid and solid readouts and describe examples of calorimeter systems, which exploit these properties in advantageous ways.

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1. INTRODUCTION

Modern calorimeters are among the most highly engineered and most finely instrumented detectors in particle physics. With experimentation crossing the 100 GeV scale, the performance of these devices - in energy and spatial resolution - approaches or surpasses that of traditional spectrometers. Increasingly frequently, the concept of 'jets' replaces the notion of 'individual' particles as a basic entity under investigation, for which calorimeters are emerging as the principal tool for our studies. Calorimeters offer perhaps the greatest discovery potential when configured to infer the production of 'invisible' particles - e.g. neutrinos - through precision measurements on the momentum balance of a multi-particle system: witness the W-discovery.

Progress has been achieved in several directions [1]. A great deal was learned about the physics of hadronic cascades, which formed the basis of the first generation of precision hadron calorimeters at colliders [2-4]. More recently, emphasis focused on achieving the potentially excellent performance - i.e. energy resolution of a few percent for ~ 100 GeV hadrons - at the new high-energy regime at the CERN and FNAL Colliders [5-7]. It required refining our sometimes too 'naïve' extrapolations to these high energies and considering 'second-order' effects, based on a better appreciation of the atomic and nuclear properties of the materials employed in the calorimeters.

The widespread use of calorimeters was facilitated through extensive work, by a large number of groups, on readout methods of the most diverse nature. Here we aim to elucidate the relative advantages and predominant areas of application of the commonly used methods.

First, aspects of the intrinsic performance of electromagnetic and hadronic calorimeters are reviewed which set the scale for the quality of readout methods. We indicate that the understanding of the shower processes and the response of the calorimeter at the atomic and nuclear level may lead to improved performance. A catalogue of major calorimeter facilities using gaseous readouts demonstrates some of the specific features inherent in this instrumentation technique, to which already several specialized workshops have been devoted [8].

2. PARAMETER SPACE FOR CALORIMETERS

The most important properties which determine the performance of electromagnetic and hadronic calorimeters (EMCs and HCs) are summarized in table 1.

2.1 Setting the absolute energy scale: "e/ μ "

The response of EMCs may be approximately described with, for example, 'Rossi's approximation B' [9], in which energy-independent cross-sections for the electromagnetic (e.m.) shower propagation (pair-production and Compton scattering) are assumed. For a more precise model - accurate to a few percent - this analytical description needs to be replaced by methods which better describe the absorption processes and, in particular, the low-energy part of the e.m. cascade. The most recent refinements in Monte Carlo simulation [10] reproduce for example, the absolute energy response to within a few per cent! Experimentally, the energy scale is conveniently established using relativistic muons and translating the observed signal [$S(\mu)$], i.e. the energy loss in the active readout, into an energy scale. This procedure is valid, provided a minimum of care is exercised, i.e. specifying the most probable or average energy loss and considering the relativistic rise of the energy loss [11]. One notes that in EMCs of the sampling type, the total absorption of electrons of energy $E(e)$ produces an observable signal $S(e)$, which is considerably reduced relative to the energy scale established with muons:

$$S(e)/E(e) < S(\mu)/[S(\mu) + \Delta E(\mu)(\text{absorber})].$$

This relative reduction, frequently attributed to 'transition effects', has its origin in the usually substantially different response of active and passive materials for the very low energy electrons, positrons, and photons characteristic of the later stages of the e.m. shower [12,13]. In Fig. 1 this 'e/ μ ' ratio is calculated [13] for three different sampling EMCs. With increasing depth, the e.m. shower is increasingly suppressed relative to the muons; this effect is more pronounced for devices with large differences in the atomic number of the active and passive materials, and consequently may be 'tuned' within limits through the choice of the calorimeter materials, and may be of interest for the performance of hadronic detectors (see section 2.2).

TABLE 1
Intrinsic Properties of Sampling Calorimeters

	Incident e, γ	Comments	Incident Hadrons	Comments
Energy resolution (intrinsic)	$< 0.01/\sqrt{E}$	Determined by lowest detectable energy of γ, e	$\sim 0.22/\sqrt{E}$ $\sim 0.45/E^\alpha$ $\alpha = \alpha(E) < 1/2$	$e/\pi \approx 1$ (if 'compensated') $e/\pi \approx 1.4$ (if non-compensated)
Energy resolution (sampling)	$> 0.04 \sqrt{\Delta E/E}$	Larger in very thin (gas) active readout	$\sim 0.09 \sqrt{\Delta E/E}$	
Linearity	Better than 1% in 0.01-100 GeV		Non-linear below ~ 2 GeV	Important effect for energy resolution of jets
Spatial localization	$> \frac{0.2 \langle X(\text{DET}) \rangle}{\sqrt{E^0}}$	$< \text{mm resol.}$ in 10-100 GeV range	$> \frac{0.25 \langle \lambda(\text{det}) \rangle}{\sqrt{E}}$	Showers separated if distance > 1 shower diameter

E is the energy of incident particle (GeV)

ΔE is the energy loss in one sampling cell (active + passive) (MeV)

While the absolute response of EMCs is considerably influenced by the fate of the low-energy particles, the effect on the energy resolution is more of principle than of practical consequence. In most detectors, the intrinsic resolution of EMCs, limited by the detectability of the very low-energy component, is well below the 1% level for 1 GeV particles. Sampling fluctuations in practical EMCs are always considerably larger (table 1) and represent the dominant contribution, particularly important for very thin active layers, e.g. in gaseous readouts [1,14,15].

2.2 Tuning the hadronic response: "e/π"

The very different particle composition in hadronic showers compared to that in e.m. cascades generally implies also a different detector response for these two types of showers. This difference is conveniently measured with electrons and hadrons, and the average behaviour is shown in fig. 2, with typical values for 'e/π' clustering around $e/\pi \sim 1.3$ to 1.5 for particle energies of ~ 10 GeV. We know that this substantial difference may be attributed to the nuclear-physics effects, invariably present in hadronic cascades, through which a large number of neutrons, protons, and photons in the few MeV energy range is produced. Fluctuations, event-by-event, in the number of these nuclear processes, and hence in the fraction of energy carried by these slow nucleons and soft photons, represent the principal physics limitation to the energy resolution of HCs. Various methods have been devised to balance these nuclear effects, the most effective to date being the 'fission compensation' using ^{238}U . In U-sampling calorimeters, additional detectable energy is derived from the fission processes, induced by the primary 'boil-off' neutrons. The intrinsic resolution for 'compensated' HCs is measured (table 1) to be approximately

$$\sigma/E (e/\pi = 1) \sim 0.22/\sqrt{E} \text{ (GeV)},$$

whereas for the non-compensated detectors one finds:

$$\sigma/\pi (e/\pi \sim 1.4) \sim 0.45/E^\alpha \text{ (GeV)}, \alpha < 0.5.$$

This deviation from the naïve $E^{-1/2}$ improvement for 'non-compensated' calorimeters may contribute in a very strong way to the energy resolution at very high energies.

The intrinsic properties of sampling calorimeters may be summarized as follows:

- i) the response towards electrons is depressed when measured on an absolute energy scale, e.g. set with muons. It is mostly caused by the difference in absorption cross-sections of the active and passive calorimeter materials, as well as by the detection properties for the low energy electrons, positrons and photons of the e.m. cascade.
- ii) The response towards:
 - a) low-energy hadrons ($E \leq 2$ GeV) is dominated by ionization loss and resembles that of muons ($e/\pi \sim e/\mu$). It produces a non-linear response, affecting the energy measurement of jets for example;
 - b) high-energy hadrons ($E > 2$ GeV) are strongly influenced by energy transferred into nuclear-collision processes, resulting in protons, neutrons, and photons of a few MeV. The level of this production and the response of the active medium may qualitatively change the characteristics of the detector ('compensated' versus 'non-compensated', $\sigma(E)/E \sim E^\alpha$, $\alpha \leq 0.5$).

3. PARAMETER SPACE OF READOUT METHODS

In the following, we compare the three types of readout methods, which are currently used in calorimetry, as summarized in table 2.

The most important performance parameters are listed in table 3. We note once more that the hadronic response is a complex superposition of the response towards the following:

- i) Charged particles leaving very different ionization densities in the calorimeter. 'Birk's' law parametrizes this response and fig. 3 demonstrates the importance of this effect for calorimeter response.
- ii) Photons.
- iii) Neutrons in the MeV range: see fig. 4, which demonstrates the possibility of 'tuning' the calorimeter response through a suitable

choice of the ratio of active to passive material thicknesses. In fig. 5 this concept is translated into a calorimeter, using gaseous CH_4 readout, and in fig. 6 it is compared with measurements on a related device [16]. One estimates that compensation may even be achieved in a lead - sampling device, provided care is exercised to detect the neutrons with adequate sensitivity [17].

TABLE 2
Calorimeter Readout Methods

Method	Active Medium	Signal Collection
Light collection	Scintillator	Light-guides or wavelength shifters read with photo - diodes, gain = 1; or photo-multipliers, gain $\geq 10^6$
	UV-emitting scintillators (e.g. BaF_2)	Readout using UV-sensitive wire chambers ^{b)}
Charge collection		
a) Ion-chamber mode	Liquids transporting electrons ($\text{Ar}, \text{Xe}, \text{TMS}^{\text{a}}$); high-pressure gas	multiple ion chamber, gain ≈ 1
b) Internal-gas-gain mode	Gases transporting electrons	Collection on wire electrodes suitable for charge amplification.

a) TMS stands for Tetra methyl silane, $\text{Si}(\text{CH}_3)_4$

b) D.F. Anderson et al., Nucl. Instrum. Methods 228 (1984) 33.

TABLE 3:
Characteristics of readout methods

Parameter/Type	Scintillator	Ion Chamber (liquids)	'Gain mode' (gases)
Response to charged particles	Signal response is non-linear versus ionization density Birk's law: $d(\text{signal})/dX = (dE/dX)/(1+KdE/dX)$ $K \sim 0.01 [\text{MeV}^{-1} \text{ g.cm}^{-2}]$ $K \sim 0.005 [\text{MeV}^{-1} \text{ g.cm}^{-2}]$ $K \sim 0.003 [\text{MeV}^{-1} \text{ g.cm}^{-2}]$ dependent on gas gain pressure, gas mixture		
Response to photons (keV to MeV)	Photo-ionization and Compton effect depend strongly on atomic number Z and density of absorber Choice of gas and pressure provide 'tunability'.		
Response to neutrons (MeV)	Strongly dependent on atomic number Z and density Hydrogen-rich sampling medium enhances contribution [LA vs TMS]		
Typical (mm)	1 to 10	1 to 10	0.5 to 5
Sampling (dE/dx)	1 to 60	6 to 60	2×10^3 to 2×10^4
Ratios			
Active/passive [λ]	5 to 50	5 to 50	2×10^3 to 2×10^4
Spatial subdivision	Limited by optical light-guides; for large systems $\Delta X \times \Delta Y > 10 \times 10 \text{ cm}^2$	Practical limitations imposed by signal connections (cable length; cross-talk) for large systems: $\Delta X \times \Delta Y > 1 \times 1 \text{ cm}^2$	

Table 3 (cont.)

Parameter/Type	Scintillator	Ion chamber (liquids)	'Gain mode' (gases)
Temporal response Transit time (ns)	20 to 50	<p>$\sim$ 200 per 1 mm gap</p> <p>$\sim$ 100 per 1 mm gap with CH₄ additive</p>	50 to 100
Measurement time (ns)	20 to 50 (100 ns for compensation with ²³⁸ U)	$\sim$ 400 (bipolar shaping) < 200 (with CH ₄ additive)	100 to 200 (bipolar shaping)
Timing resolution (ns)	2.5 for a few GeV deposit N.B.: reduced pulse width 2λ possible at the expense of signal/noise $\sim \lambda^\alpha$, $\alpha \sim 1$.	$\sim$ 2 for a few GeV deposit	< 10
Radiation Resistance	Depends on scintillator, dose rate, environment, > 10 ³ Gy achievable	Lifetime of on-detector electronics limited	Chamber lifetime adequate; lifetime of on-detector electronics may be limited
Uniformity within R/O segment	Light collection strongly non-uniform when averaged over shower size: 5 to 10%	Depends only linearly on mechanical tolerances of ratio active/passive of total cell	
Among different readout segments	Intercalibration required; dominated by photodetector	As above	See table 4
Suitability for calibration (energy scale)	Principal difficulty: needs reference light sources at all readout channels; typical: 2 to 4%	Electronically; typically at < 0.5%	Needs continuous monitoring of a reference (e.g. radioactive source)
Long-term stability	'Ageing' of optical components; typically 5% per year decrease; radiation damage likely to cause differential ageing	Control (or monitoring) of impurities affecting charge collection; more pronounced for room-temperature liquids	See above

An outstanding feature of readouts employing the 'gas gain' mode is the comparatively small amount of active material. It usually induces additional sampling fluctuations, which may be quite noticeable in EMCs [1,13,14] but are thought to be less important for HCs [18].

For instruments aiming to measure particles or jets in the 100 GeV energy range, the control of instrumental effects assumes preponderant importance. The intrinsic resolution may easily be spoiled unless the uniformity and the cell-to-cell calibration of the calorimeter is adequately controlled, typically better than 1% in high-precision instruments. This is one of the reasons why mostly ion-chamber techniques are being used for the present generation of precision hadron calorimeters, under preparation for several storage-ring experiments [6,7,19,20]. Optical methods are troubled by two complications: light collection is inherently non-uniform requiring elaborate correction methods [2,4]; photon detectors with internal multiplication (photomultipliers as opposed to vacuum photodiodes) require cumbersome gain calibration procedures. 'Gas gain' readouts have to be exceedingly carefully constructed to control those numerous effects (table 4), which contribute to non-uniformities and gain variations. From Table 4, however, one may conclude that there are, in principle, no obstacles for high-precision performance of gas-gain devices, supported by the results reported of several large calorimeter facilities under construction, summarized in table 5, and which call for a few comments:

- i) One of the most highly instrumented EMCs is the ALEPH e,γ calorimeter under construction at LEP [21]. The mechanical construction, fig. 7, allows for a projective tower geometry, each one consisting of 40 'pads', readout longitudinally threefold. The calorimeter is subdivided into approximately 75 000 towers, i.e. $\sim$ 225 000 readout elements. Exceptional care has been taken in the mechanical construction to ensure overall uniformity to better than 2%. One notes that the quoted resolution of $0.18/\sqrt{E}$ is about 80% worse compared to the intrinsic sampling fluctuation, which I evaluate at the 10% level. A complex monitoring system of temperature ($\Delta T \leq 0.5^\circ\text{K}$), pressure, and gas gain is planned to correct for the response at the 1% accuracy level.

TABLE 4
Sources of Gain Variation in 'Gas Gain' Mode

(Following M. Mishina, 2nd Gas Calorimeter Workshop, [8])

a. Mechanical Tolerances

- i) Wire diameter D for 50 μm wire:

$$\text{Gain } G \text{ variation } \Delta G/G = 6 \times \Delta D/D.$$

- ii) Wire displacement δ in 7 x 11 mm² cross-section tube:

$$\Delta G/G < 1\% \text{ for } \delta = 250 \mu\text{m}$$

- iii) Transverse gap variations for ALEPH channel ($t = 3.2 \text{ mm}$):

$$\Delta G/G \sim 10\% \text{ for } 0.1 \text{ mm changes}$$

- iv) Distance between proportional tube and resistive cathode pads is very critical!

$$\text{e.g: CDF find } \Delta G/G \sim 5\%.$$

b. Parameters affecting gas amplification

- i) High voltage V:

$$\text{e.g. CDF find: } \Delta G/G \sim 1\% \text{ for } \Delta V = 1 \text{ V.}$$

- ii) Temperature:

$$\Delta G/G \sim 2.5\% \text{ per } ^\circ\text{C.}$$

- iii) Pressure P:

$$\Delta G/G \sim 7\% \text{ for } \Delta P/P = 0.01.$$

It needs constant monitoring for corrections.

- iv) Gas composition and Impurities: they need control with 'calibration' chambers and gas analysis.

TABLE 5
Large Calorimeter Systems with Gas Readout

System	Passive absorber	Active medium	Resolution Electrons Measured (intrinsic)	Hadrons Measured (intrinsic)	Gas gain	Non-linearity	Uniformity	Gain control energy calibration
MAC	Pb : 0.5 X ₀ (first 18 X ₀) Fe : 1.5 X ₀ (last 55 X ₀) Pb: 0.25 X ₀	PCA) Ar : CH ₄ (80 : 20) Tubes Ar:NO ₂ :CH ₄ (91:2:7)	0.17/√E (0.10/√E)	0.90/√E (jets)				T,P,Ge)
PEP 4 ('TPC')			0.17 not ~ 1/√E	Geiger 50 pC/cell				mip ^d) energy scale set by Monte Carlo
MARK II Endcaps	Pb: 0.5 X ₀	Al tubes (9x15 mm ²) Ar : C ₂ H ₆ (50 : 50)	0.19/√E (0.09/√E)	2.5 x 10 ⁴	10% at 50 GeV	~ 1% (mech. tol.)		T,P,G (55Fe)
SLD 'WIC'	Fe: 2.84 X ₀	Pl tubes ^b) total t: 25 mm c) Ar : i-C ₄ H ₁₀	0.90/√E (0.90/√E)					
ALEPH e/γ	Pb: 0.36 X ₀ (first 12 X ₀) :0.72 X ₀ (last 10 X ₀)	Al tubes, Pads total t:6,5mm Xe : CO ₂ (80 : 20)	0.19/√E (0.1/√E)	proport. 0.1 pc/mip	5% at 40 GeV	< 2% (mech. tol.)		T,P
ALEPH hadronic	Fe: 2.84 X ₀	Pl tubes 9x9 mm ² Ar : CO ₂ : C ₅ H ₁₂ (25 : 50 : 25)	0.84/√E (0.90/√E)	'saturated' 3% at 50 GeV				

a) PC: proportional chamber; b) Pl tube: resistive plastic tube; c) Total t: total thickness of the active readout element
d) mip: minimum ionizing particle; e) T,P,G: implies that temperature T, pressure P, and gas gain G are being monitored.

Table 5 (cont.)

System	Passive absorber	Active medium	Electrons Measured (intrinsic)	Hadrons Measured (intrinsic)	Gas gain	Non-linearity	Uniformity	Gain Control energy calibration
DELPHI e/ γ	Pb: $\sim 0.55X_0$	TPC total t: 8 mm Ar: CH ₄ (80:20)	$\sim 0.16/\text{E}$ ($\sim 0.10/\text{E}$)			dominated by leakage	Att. lengths for drift: ~ 280 cm	
DELPHI Hadronic	Fe: $2.84 X_0$	P1 tubes		$\sim 1/\text{E}$ (behind coil and e.m. cal.) .55/ $\sqrt{\text{E}}+0.05$	Streamer (behind coil)			
L3	Cu/U238: $0.05/1.6 X_0$	Brass tubes $5 \times 10 \text{ mm}^2$ Ar : CO ₂ (80:20)			$\sim 0.5 \text{ p C/ mip}$			
OPAL End caps	Fe: $4.5 X_0$	PC + pads total t: 6.6mm C ₅ H ₁₂ : CO ₂ ($\sim 30 : 70$)		$1.2/\text{E}$	6 p C/ mip			
AMY	Pb : $0.63 X_0$ (first $9.4 X_0$) Pb : $1.26 X_0$ (last $5 X_0$)	P1 tubes total t: 10.3mm Ar : C ₂ H ₆ : CH ₃ CH ₂ OH (49 : 49: 2)	$\sim 0.25/\text{E}$ (0.11/ $\sqrt{\text{E}}$)		0.3 pC/mip	not known	$\sim 5\%$ for cathode pads	Monitor tubes with 55Fe sources
TOPAZ End cap	Pb: $\sim 0.45X_0$ (first $9 X_0$) Pb $\sim 0.63X_0$ (last $9 X_0$)	P1 tubes $12.5 \times 15 \text{ mm}^2$ Ar : CH ₄ (93 : 7)	0.19/ $\sqrt{\text{E}}$ (0.11/ $\sqrt{\text{E}}$)		$\sim 2 \times 10^4$		$\sim 5\%$	G,P,T, radioactive sources
CDF Endplugs	Pb: $0.5 X_0$ first $21 X_0$ Fe: $2.9 X_0$ last $58 X_0$	P1 Tubes Ar: C ₂ H ₆ (50 : 50)	0.24/ $\sqrt{\text{E}}$ (0.1/ $\sqrt{\text{E}}$)	$1.1/\text{E}+0.05$ (0.9/ $\sqrt{\text{E}}$)	3×10^5	$< 5\%$ at 200 GeV	3% before, 1% after beam calibr.	P, T, 24 Fe^{55} sources imbedded in cal. Test-beam measurement for absolute correction.

Table 5 (cont.)

System	Passive absorber	Active medium	Electrons measured (intrinsic)	Hadrons measured (intrinsic)	Resolution	Gas gain	Non-linearity	Uniformity	Gain control energy calibration
UA6 ($p/\bar{p}$ in H_2 jet)	Pb + stainless 0.8 X_0 + 0.06 X_0	Ar: CO ₂ (90 : 10)	0.28//E (0.13//E)		$\sim 10^3$	none below 100 GeV			Gain monitored by π^0 - reconstruction
E 733 v-cal.	Fe shot and sand: (340 t total weight)	'Flash chambers' (340 t total weight)	1.11//E (8% at 400 GeV)		200 to 400	5% at 400 GeV			T, P, 144 sources 109Cd
Charm II v-cal	Glass: 0.5 X_0 (700 t total weight)	Streamer tubes 10x10 mm ² + cathode strips	$\sim 0.20//E$						Gain stabilizers with 90Sr source and HV feedback system
FREJUS (nucleon- decay)	Fe: 0.17 X_0 (900 t total weight)	Flash chamber 5 x 5 mm ² Ne : He (70 : 30)	0.15//E	$\sim 20\%$ for 0.3 GeV π					
NUSEX (nucleon- decay)	Fe: 0.57 X_0 (150 t total weight)	Pl - streamer tubes + resist. cathodes Ar : CO ₂ -n-P (25 : 50 : 25)	$\sim 0.20//E$ ($\sim 0.17//E$)						
SOUDAN-2	Fe: 0.091 X_0 (1100 t total weight planned)	Pl-tubes TPC-type drift Ar : CO ₂ (85 : 15)							

- ii) The DELPHI e,γ calorimeter, at present under construction for LEP [22], demonstrates two powerful features of gaseous readout systems:
 - a) Great flexibility and adaptability of the readout wires: the Delphi geometry combines long drift channels with a detection plane similar in concept to 'TPC' tracking chambers and this calorimeter is aptly called a 'high density projection chamber' (HPC).
 - b) The chosen readout geometry provides a truly three-dimensional shower readout, which will allow unprecedented, detailed shower shape analysis. It will, for example, provide the necessary rejection of background in the study of rare-event topologies. It is noteworthy that the measured energy resolution improves when operated in a magnetic field [23].
- iii) The OPAL end-cap hadron calorimeter (and also the ALEPH e,γ calorimeter) exemplifies an important trend in gaseous readouts: the gap in the multiwire proportional chambers is only 3 mm large and the total thickness of the chamber structure (including 'pads') less than 7 mm. Thickness of the readout elements is of vital concern for hadron calorimeters at storage rings, where small radial dimensions imply enormous cost benefits [24].
- iv) The AMY group has carried out important studies on the uniformity of pad geometries, indicating that very tight dimensional tolerances have to be met, if uniformity of the 1-2% level is required.
- v) The CDF 'endplug' calorimeter is one of the very few operating storage ring calorimeters using the gas gain mode already in operation. The group exercised considerable care in calibrating each readout tower in a particle beam, and is using a rather elaborate system - including large numbers of radioactive sources - for stability monitoring.

Apart from storage-ring detectors, gaseous readout methods have found particularly useful applications, well matched to their principal advantage of high granularity, in large target calorimeters for neutrino-scattering experiments and nucleon-decay experiments. I will mention, in particular,

the 'SOUDAN-2' effort, aimed at constructing a very large (1100 t), very finely subdivided (1.5 mm Fe sampling) nucleon-decay experiment. The group will use the 'HPC' type readout, particularly powerful in the rejection of background events, and in the detailed reconstruction of possible nucleon-decay events [25].

4. SUMMARY

Calorimeters based on 'gas gain' readout methods have contributed in important ways to calorimeter applications in particle physics. From these efforts the following emerges:

4.1 Facts:

- i) The energy resolution of electromagnetic calorimeters is worse than the intrinsic one.
- ii) The performance of hadronic calorimeters may be close to the intrinsic one. It should be noted that high-performance devices are not yet operational (for storage rings).
- iii) The spatial resolution and pictorial reconstruction of showers is excellent.
- iv) Very careful engineering is required to achieve good uniformity: control of systematic effects at the few per cent level is difficult, but in principle achievable, given adequate monitoring procedures.
- v) The gas readout leads to low average density of the detector. It is not very suitable for high-performance hadron calorimeters at storage rings (radial space very expensive).

4.2 Trends (in the development of this method)

- i) The total thickness of readout chambers is constantly being reduced.
- ii) Gas gain is being lowered to improve linearity and chamber performance.

- iii) Mechanical tolerances are tightly controlled to have non-uniformity at the 1-2% level, including spacing of cathode pads.

4.3 Potential:

- The 'gas gain' mode offers the greatest tunability, which may be important for further progress in hadronic calorimetry (gas mixtures, geometry, signal level, sensitivity to specific ionization). It is conceivable to exploit the characteristic response to different particles (μ , γ , X-rays, UV photons, neutrons, slow protons, etc.)
- The 'gas gain' mode is particularly applicable to three-dimensional shower reconstruction (nucleon-decay; pion/muon discrimination inside jets, angular resolution of jets in neutrino experiments)
- The 'gas gain' mode will continue to be the technique of choice for a substantial segment of calorimeter applications.

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Figure Captions

- Fig. 1 The ratio ' e/μ ' (see text for definition) as a function of shower depth. Three different absorber/active medium combinations are evaluated, which were chosen to have constant thickness measured in radiation lengths $[X_0]$. This EGS-4 evaluation indicates for the low-energy part of the later stages of the cascade a smaller ' e/μ ' ratio compared to the early, energetic part. This ratio is seen to be influenced by the choice of active and passive calorimeter media [13].
- Fig. 2 The ratio of electromagnetic to hadronic energy response as a function of energy for different calorimeter systems. Below ~ 2 GeV, a considerable fraction of the energy is deposited by ionization and therefore the response towards hadrons tend to increasingly resemble that towards muons ($e/\pi \sim e/\mu$ for energy $\ll 2$ GeV). At high energies, the relative response is very different for 'compensated' and 'non-compensated' calorimeters [1].
- Fig. 3 Results of a 'Gedanken-experiment' using HETC to study the importance of the fission contribution and its manifestation in different readouts, with and without saturation (T. Gabriel et al., Nucl. Instrum. Methods 164 (1979) 609).
- Fig. 4 Energy deposition of neutrons of a hadron-initiated shower relative to minimum ionizing particles in 2.5 mm thick scintillator as a function of the thickness of the absorber plates normalized to the same energy of the incident particles. For uranium, compensation is obtained for plate thicknesses of approximately 3 mm, whereas approximately 10 mm thick Pb-plates are required in this calorimeter geometry to make the neutron flux sufficiently large to achieve compensation. In contrast, for Cu- and Fe-plates, the neutron contribution never reaches values adequate to achieve compensation [17].
- Fig. 5 An evaluation of the neutron contribution, similar to the one shown in Fig. 4. In this conceptual calorimeter the gas pressure in the active layer is varied to tune the neutron contribution relative to the contribution of minimum ionizing particles (thickness of metal plates 3 mm, thickness of gas gap 3 mm) [17].

Fig. 6 Response of a uranium/gas sampling calorimeter to pions and electrons versus incident energy. The absorber plates consisted of 4.5 mm U plates covered with 0.5 mm Cu plates on both sides. The data show the strong influence of the readout material (presence of hydrocarbons) on the hadronic response, reflecting the sensitivity towards neutrons in the MeV energy range [16].

Fig. 7 Exploded view of a section of the ALEPH $e\gamma$ calorimeter. Each individual pad of a tower is connected via readout lines to summing boards at the periphery of a module.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7