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C.A. Heusch

<u>Page</u>	<u>Line</u>	<u>Correction</u>
1	24	change 9000 t to 8000 t
1	27	change 200 cm to 400 cm
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4	5	change "when" to "where"
9	2	delete the g in Yelling - should be Yellin
10	2	delete the r in trajectory - to read trajectory
16	8	change 13000 A to 3000 A
17	26	change 50 m to 40 m
17	29	change 9000 t to 8000 t
17	30	change 3000 t to 3300 t
18	1	change $n \rightarrow K^+ \mu^-$ to $n \rightarrow \pi^+ \mu^-$
18	23	change planes to plans
23	9	delete paper contributed to the Int. Europhysics Conf. on High-Energy Physics, Brighton, 1983, and references therein. Reference 21) should read: R.M. Bionta et al., PRL <u>51</u> (1983) 27. B.C. Cortez et al., PRL <u>52</u> (1984) 1092.
23	11	add to reference 22); should read: E. Fiorini, Proc. Int. Lepton-Photon Symposium, Cornell, 1983 (Cornell Univ., Ithaca, New York, 1983), p. 405. L. Sulak, Proc. 5th Workshop on Grand Unification, K. Kang, ed., Brown Univ. (1984).
30	19	change $n \rightarrow K^+ \mu^-$ to $n \rightarrow \pi^+ \mu^-$

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THE USE OF CHERENKOV TECHNIQUES FOR TOTAL ABSORPTION MEASUREMENTS

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THE USE OF CHERENKOV TECHNIQUES FOR TOTAL ABSORPTION MEASUREMENTS

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This article is dedicated, with all good wishes,
to Academician P.A. Cherenkov on the occasion of
his eightieth birthday on 28 July 1984

1. CHERENKOV CALORIMETRY, A SEMANTIC EXCURSION

It has become a common practice to designate as calorimeters those particle detectors that measure the total energy of high-energy particles by stopping them and yielding a signal approximately proportional to that energy.

For many years now, P.A. Cherenkov's original observation¹⁾ that, when passing through matter, relativistic charged particles induce the characteristic radiation which now bears his name, has provided us with a tool which, among other uses, will be able to effect such a total energy measurement. Are we therefore justified in speaking of Cherenkov calorimeters -- i.e. literally, of instruments that measure total energy deposition in terms of caloric change?

The present report spans energies from about 100 MeV to some 10 TeV, and detector volumes from table-top arrays to some 10^6 t of water. For an illustrative example, take a total absorption measurement of a nucleon decay event

$$p \rightarrow \pi^0 + e^+$$

in a 9000 t water Cherenkov detector [such as the Irvine-Michigan-Brookhaven (IMB) detector, Section 6]. The all-showering final state will dissipate 0.94 GeV in the water, generating a total charged track length of some 200 cm; if we assume constant photon emission of some 200 photons per centimetre of track, with energies of order 1 eV, even full absorption of the photons will deposit only a few 10^4 eV in the volume, or $\sim 10^{-15}$ cal. With this energy, the temperature of the 9000 t of water can be raised by

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$$\Delta T \approx 10^{-25} \text{ deg.}$$

The change in temperature would be unnoticeable to the most sensitive instrument. Clearly, therefore, Cherenkov calorimetry is a misnomer: in fact, little of the energy contained in the Cherenkov radiation of a cascade will be absorbed in the radiating medium of the detectors we choose. These should properly be named Cherenkov shower counters or Cherenkov hadrometers.

Having said this, we can proceed to detail the features that may make their use preferable to that of more conventional calorimeters, owing to the specific process of total track measurement they employ for particle detection. The purpose defined by a physics problem at hand will have to decide on their applicability.

In Sections 2 and 3 we briefly review electromagnetic and hadronic cascade features as they pertain to Cherenkov detection. Sections 4 to 6 will highlight, by a sample of devices, the design and performance of detectors that make use of these features in various ways, through a large range of applications to various physical phenomena, and of total energies measured.

2. PROPERTIES OF ELECTROMAGNETIC SHOWERS

Electrons and photons in the energy range of interest here, when passing through matter, dissipate their energy principally by bremsstrahlung emission and pair creation, respectively. They build up electromagnetic 'showers', the main charged-particle components of which are electrons and positrons. If we disregard angular properties, Cherenkov photon emission is virtually constant per unit track length for all $e^\pm$ energies, owing to their low rest mass, until well below the 'critical energy' ϵ_0 (see later), below which cascades do not propagate. This feature of Cherenkov detection, very unlike the ionization features used in scintillator or gas-amplification-based devices, makes Cherenkov shower counters uniquely useful in a number of applications where hadron/electron rejection is vital. To illustrate the point²⁾, we show in Fig. 2.1 the response of a Cherenkov versus a scintillation radiator of identical geometries at 1000 MeV/c: π and electron, fully relativistic, look the same in lucite; in a scintillator,

the π distribution has the characteristic 'Landau tail' (Fig. 2.1a). In a lead/lucite Cherenkov sandwich counter, 0.5 and 1.0 GeV electron showers are seen to differ, decidedly from the 0.8 GeV $\pi^\pm$ and p distributions (Fig. 2.1b).

To see how these radiator properties translate into shower counter use, we briefly review relevant features of shower physics in a utilitarian way³⁾. Figure 2.2 schematically shows the longitudinal development of an electron- or photon-initiated shower. Longitudinal penetration into an absorbing medium is parametrized by the quantities

$$t_{1/2} \approx \ln \frac{E}{\epsilon} + \begin{cases} 0.4 & \text{for } e^\pm \\ 1.2 & \text{for } \gamma \end{cases} X_0 ,$$

$$t_{\max} \approx t_{1/2} - 1.5 X_0 ,$$

$$t_{0.98} \approx 3t_{1/2} ,$$

in terms of the quantities

$$\epsilon \approx 550 \frac{1}{Z} \text{ MeV} ,$$

critical energy, where $dE/dx|_{\text{radiation}} = dE/dx|_{\text{ionization}}$, and

$$X_0 \approx 180 \frac{A}{Z^2} \text{ g/cm}^2 ,$$

radiation length, where an electron beam has been attenuated by $1/e$, so that

$$\frac{dE}{dx}_{\min} = \frac{\epsilon}{X_0} \approx 3 \frac{Z}{A} \text{ MeV/(g/cm}^2\text{)} ;$$

$t_{\max}$ is more respectably derived from the approximate differential distribution

$$\frac{dE}{dt} = E_0 \frac{b^{a+1}}{\Gamma(a+1)} t^a e^{-bt} ,$$

which leads to $t_{\max} \approx a/b$. Note that the penetration depth is determined by ϵ : the lower ϵ , the larger the percentage of energy lost by pair creation, giving a more successful total track measurement.

Lateral shower extent will be dominated by multiple scattering for the radiative range when transverse momenta are mostly negligible. Thus there are two components: Fig. 2.3 indicates the radiative regime and a broad halo due largely to photon propagation around and below ϵ . A typical containment parameter may be

$$R_{0.95} \approx 2R_M \approx 14 \frac{A}{Z} \text{ g/cm}^2 ,$$

where R_M is the 'Molière radius' ($\approx 2 X_0$ for a high-Z nucleus).

For Cherenkov detection, the central component, which comes at fixed direction and fixed velocity, permits a directional measurement inaccessible to other total-absorption detectors: Figure 2.4 indicates the directional imaging possibilities open to a device that does not simply integrate over the total light output -- a possibility much used in proton decay detectors (Section 6).

This directionality possibility exists much less for other techniques: Figure 2.5 (taken from Amaldi, Ref. 3) indicates that, for a scintillation device, not only does the isotropic light emission vitiate such information to be optimally used; but also, the slowest electron component, which has the highest dE/dx values, is closer to isotropic in angular distribution.

Thus we measure energy, one or more 'points' along a trajectory and direction of a shower within the limits set by the shower fluctuations. For energy measurement, the total track length $T(X_0)$ is again a function of E/ϵ :

$$T \sim \int_0^{\infty} n(t) dt \quad \text{at given } E_{\text{cut-off}} \quad [= E_c] ;$$

$E_{\text{cut-off}}$ depends on the detection method employed -- for Cherenkov detection of $e^\pm$, $E_c \approx 1 \text{ MeV}$. We can set

$$T = F(E_c) E/\epsilon [X_0] ,$$

where a good approximation for the function $F(E_c)$ is

$$F(E_c) = F[z(E_c)] = e^z \left[t + z \ln \frac{t}{1.54} \right] \quad \text{and} \quad z = 4.6 \frac{Z}{A} \frac{E_c}{\epsilon} .$$

For all practical applications, the proportionality counts:

$$T \propto E .$$

We will see that various types of homogeneous and sampling shower counters utilize these features to give information about all four components of γ or $e^\pm$ four-vectors.

3. PROPERTIES OF HADRONIC CASCADES

For energy dissipation through hadronic interactions, we purposely use the term 'cascade' to stress the much more discontinuous types of elementary processes involved, and the larger transverse momenta. Here, the appropriate scale parameter is the nuclear absorption length λ . Note that, except for very light nuclei, $\lambda \gg X_0$, and that

$$\lambda \approx 35 A^{1/3} \text{ g/cm}^2 .$$

The elementary processes contributing to it are manifold, and do not permit an analytical treatment; the fact that $\lambda \gg X_0$ and that the inelasticity η of each interaction is often small (whereas $\eta = 1$ for $\gamma \rightarrow e^+e^-$) leads to large fluctuations and a slow build-up of this cascade, as indicated in Fig. 3.1.

Monte Carlo simulations using the best available cross-section input lead to disparate results (Fig. 3.2). Among the elementary processes contributing, there are several that do not usually lead to secondaries that will produce Cherenkov radiation: binding energy loss in nuclei, nuclear de-excitation, heavy fragment or neutron emission, and μ, ν emission (where the μ often escapes). All of this leads to the large fluctuations indicated in Fig. 3.1, and to a characteristic cascade profile schematically shown in Fig. 3.3, in comparison with the electromagnetic shower.

To further develop the analogy, we mention the scaling behaviour of the hadron cascade (with x = penetration depth):

$$x_{1/2} \approx (0.54 \ln E + 0.4)\lambda ,$$

$$x_{\max} \approx x_{1/2} - 0.6 \lambda ,$$

$$x_{0.95} \approx 2.5 x_{1/2} .$$

The transverse containment is clearly subject to bad fluctuations; but, as Fig. 3.3b shows, 90% containment will demand a detector size of transverse dimension $> 2 \lambda$.

Hadron total absorption devices based on Cherenkov light measurement will be of limited use at lower energies, save in those cases where individual final states are investigated, as in p or n decay (see Section 6); at high energies, the fact that, in each generation of cascade build-up, one third of the produced π 's will be π^0 , leads to an ever-increasing share of showers in the energy deposition balance. Figure 3.4 illustrates the effect, which dramatically makes 'hadrometers' more useful as energies increase --- and Cherenkov hadrometers particularly so. This leads to the great interest in Cherenkov detection of ultrahigh-energy cosmic-ray events (see Section 6). Notwithstanding this 'silver lining' in total absorption Cherenkov hadron detection, we should remember that it is mostly suited to rather special cases; and to those where great accuracy is not essential: transverse size and a lack of fine angular definition analogous to Fig. 2.4 for showers limit its use.

4. CONTINUOUSLY SAMPLING DEVICES: LEAD-GLASS SYSTEMS

Among dense, homogeneous 'calorimeters' (NaI , 'BGO', BaF_2) there is only one based on a bona fide application of Cherenkov techniques: the lead-glass detector. From many commercial variants, we pick the highly successful Schott SF5 for typical parameters (for comparison, see Table 1):

Contents: 38% SiO_2	parameters:	$X_0 = 2.54 \text{ cm}$
55% PbO		$n(4 \mu\text{m}) = 1.673$
5% K_2O		$\rho = 4.08 \text{ g/cm}^3$
1% N_2O_2		$\epsilon = 11.8 \text{ MeV}/X_0$

The first literature reference I find is M. Jester's unpublished Berkeley report (1955)⁴⁾. There has been a remarkable progression from very simple lead-glass blocks of modest size to giant systems with many readout channels; we will choose a few illustrative examples (see below), out of a wealth of successful developments. My own first efforts in this field were directed at precise kinematical reconstruction of π^0 photoproduction events. The lead-glass cylinder shown in Fig. 4.1 was designed⁵⁾ for the detection of high-energy $\pi^0 \rightarrow 2\gamma$ decays along an axis determined by two-body kinematics in the photoproduction process $\gamma p \rightarrow p\pi^0$. (I well remember the indignant objections of the engineer at the Schott Optical Company in Mainz when I suggested that it would be all right to furnish us with the relatively large glass cylinder even if there were 'Schlieren' inhomogeneities in the volume: Schott made optical quality glass, and would not stoop to selling inferior products even to physicists who put them to unaccustomed use!)

Lead-glass total absorption counters, when thick enough to fully contain a shower, have a resolution in E_γ limited by photoelectron statistics (depending on phototube choice, counter material, and geometry, there are approximately $1000 \text{ e}^\pm/\text{GeV}$) and by the aspect ratio R -- the phototube coverage of the readout face (at best some 0.5):

$$\frac{\sigma(E)}{E} \underset{t \rightarrow \infty}{=} [0.6 + 3R^{-1/2} E^{-1/2}] \%$$

which, with the assumed R factor of 0.5, leads to a typical $\sigma/E = 5\%$ at 1 GeV and $\sim 1\%$ at 100 GeV. For most practical applications this resolution is quite sufficient. More serious limitations are due to the following factors:

- i) the technical problems and cost of forming/grinding and polishing to exacting specifications;
- ii) the need for good phototube coverage, often in the presence of magnetic fields;
- iii) the difficulty and cost of fine segmentation, both longitudinal and transverse, and of providing a solid support structure;

- iv) radiation damage: the yellowing under prolonged exposure to larger doses of radiation, with loss of uniformity and transmissivity.

We will illustrate these points by a look at a few indicative systems that exhibit telling features:

4.1 A successful system with early transverse segmentation
[M. Holder et al.⁶⁾]

This system well illustrates several of the above points: built to investigate the rare decay mode $K_L \rightarrow \pi^0 \pi^0$ in the presence of heavy backgrounds from, for example, $K_L \rightarrow \pi^0 \pi^0 \pi^0$, it was necessary to have precise information about the trajectory and energy of the four photons of the final state.

Figures 4.2a,b show two views of the lead-glass array, consisting of 61 blocks of hexagonal cross-section adapted to the best coverage by 5-inch phototubes, 15 X_0 long, tightly packed in a honeycomb geometry. The longitudinal extent was sufficient for a 90% containment of 7 GeV showers; the phototubes were axially mounted on the back of each column. At 1 GeV, the energy resolution was tested to correspond to the above expectation.

The need for precise trajectory information was met by the insertion, upstream of the honeycomb structure, of a sequence of six thin converters (0.1 to 0.25 X_0 thick), each followed by a set of wire chambers for track localization, as shown schematically in Fig. 4.2c.

Clearly, such a system with passive converters has its drawbacks: efficiencies are small for four-photon conversion; the air and gas gaps between converters and honeycomb lead to a blow-up of the lateral size of the shower, in addition to multiple scattering, spraying its energy over several lead-glass cells.

Notwithstanding these limitations, the performance criteria were impressive, as evidenced by the π^0 mass determination from $\gamma\gamma$ pairs, and K^0 masses from $\pi^0 \pi^0$ combinations (Fig. 4.2d). The $\eta_{\pi\pi}$ parameter measured by the experiment has stood the test of time well⁷⁾.

4.2 A compact system with active converters [Heusch, Kline, Prescott, Yelling⁸⁾]

The lower the energy, the more serious the problems of photon conversion efficiency and trajectory localization, due both to low shower multiplicities with large fluctuations and to multiple scattering. Furthermore, energy measurement will be seriously compromised by passive converters such as the lead sheets mentioned in subsection 4.1. An example of a system that uses active lead-glass converters for total energy measurement plus interspersed wire chambers for track definition is shown in Figs. 4.3a,b. This apparatus was built to detect photons effectively from the reaction $pd \rightarrow {}^3\text{He}\gamma$, with a precision permitting the rejection of the hundred-fold more copious process $pd \rightarrow {}^3\text{He}\pi^0$; while photon energies were only in the few hundred MeV range, tight coplanarity cuts on the ${}^3\text{He}\gamma$ system were needed in order to permit a sensitive test of T invariance in the electromagnetic interaction.

The salient features are visible in Fig. 4.3: two lead-glass converters, each $2 X_0$ thick, are followed by four wire chamber planes for each converter. If a photon converts, the conversion point is determined as indicated in Fig. 4.3b. The need for both converters is seen in Fig. 4.3c: the detection efficiencies would be low in the energy region of interest if we demanded conversion at any one sampling depth (curves 1 and 2), but are satisfactory if we demand one or the other. An instructive look at the value of pulse-height measurement in the converters is given, for 500 MeV electron-induced showers, in Fig. 4.3d: broad pulse-height distributions in the two converters and in the main lead-glass block, if added together event by event, lead to the good narrow definition of the added signal (upon proper calibration). Note, again, that the Cherenkov techniques which provide effective separation from non-radiative final-state particles were crucial to the success of the time-reversal test⁹⁾.

4.3 A large planar array for photoproduction studies

Over the years, a number of large shower calorimeter systems have been built using lead-glass elements for containment. Experimentation involving photons and electrons in the 100 GeV energy range found the techniques to be well adaptable. As an example, we mention the shower spectrometer OLGA¹⁰⁾ (at CERN), which was originally built for use with the Omega Spectrometer (Expt. WA4), and has since been adapted to use with the NA14 apparatus in a high-intensity beam line.

Requirements for such spectrometers include adequate transverse segmentation, a highly resolving hodoscope for trajectory definition, some longitudinal segmentation for e/γ -hadron rejection, a readout scheme capable of distinguishing multiple showers -- all this covering a large solid angle, possibly including a central hole for the passing of the non-interacting beam.

The general scheme, including a $3 X_0$ thick active converter, two fine-grained scintillator hodoscope planes, and a $14 \times 14 \times 47 \text{ cm}^3$ ($18.5 X_0$ thick) total absorption block, is schematically shown in Fig. 4.4a. The fractional energy deposition in the converter was measured to decrease from $\sim 30\%$ at 5 GeV to $\sim 5\%$ at 50 GeV. The units of the converter wall, consisting of 38 units, each 150 cm long and 14 cm wide, are read out (just as in subsection 4.2 above) by one phototube, with appropriate absorption corrections, taking the separately determined shower location into account. The same holds for the 150 cm long, $1 \times 1.5 \text{ cm}^2$, hodoscope fingers that cover its area as position detectors. The transverse dimension of the 337 identical elements of the total-absorption wall is adapted to phototube sizes, and is commensurate with the opening angle of a 30 GeV $\pi^0 \rightarrow 2\gamma$ decay in the NA14 geometry. Resulting 2γ invariant mass distributions are shown in Figs. 4.4b.

Figure 4.4c indicates that, for the large solid-angle to be covered in NA14, a fine-grained hodoscope such as OLGA can be complemented, at larger angles, by a less highly segmented device, still sufficient for the region it covers. The total coverage in the longitudinal momentum variable x_L is indicated, for an incident 100 GeV photon, in Fig. 4.4d.

4.4 An attempt to beat the high cost of highly segmented lead-glass arrays: extruded elements [R. Engelmann et al.¹¹⁾

In an attempt to reduce the cost of grinding and polishing the large number of lead-glass units that are needed for appropriate segmentation, a Stony Brook group¹¹⁾ has conducted interesting tests with an array (shown in Fig. 4.5a) of unpolished, extruded, lead-glass elements, 140 cm long and $6.5 \times 6.5 \text{ cm}^2$ in cross-section. Consisting of Ohara F2(W) optical glass (density 3.61 g/cm^3 , $X_0 = 3.22 \text{ cm}$), the extension process left these elements with $\sim 1 \text{ mm}$ ripples, thus prohibiting perfectly dense packing, but making a big saving in equipment costs possible.

Using the excellent 12-layer longitudinal segmentation (but, in the absence of a crossed arrangement, transverse segmentation in only one direction) shown in Fig. 4.5a, the authors¹¹⁾ were able to produce, after appropriate gain optimization in the phototubes, an energy resolution quoted as

$$\frac{\sigma}{E} = \left(\frac{4.2}{\sqrt{E}} + 0.6 \right) \% ,$$

quite compatible with the values mentioned for a homogeneous detector.

The power of fine longitudinal segmentation is shown by the comparison of electron energy deposition in each of the eight layers (Fig. 4.5b) with hadron cascade development. Including lateral spread, the authors define a 60 x 60 matrix from the response of all 60 elements to N electron showers:

$$M_{ij} = \frac{1}{N} \sum_{n=1}^N (E_i^n - \bar{E}_i) (E_j^n - \bar{E}_j) .$$

Using the inverse matrix $H = M^{-1}$, they then introduce a variable ζ that expresses how much a cascade is like the one initiated by an electron, for each event m:

$$\zeta_m \equiv \sum_{i,j=1}^{60} (E_i^m - \bar{E}_i) H_{ij} (E_j^m - \bar{E}_j) .$$

For the energy region between 15 and 45 GeV, they find an electron likeness, for pions, of $\sim 10^{-3}$, permitting good hadron-electron rejection. The relative ζ distributions for electrons and pions are shown in Fig. 4.5c.

4.5 A large cylindrical calorimeter for use at LEP -- OPAL¹²⁾

Notwithstanding the difficulty of assembling large arrays of lead-glass cells in complicated geometries, one of the four LEP detectors will contain an almost 4π solid-angle shower counter coverage of this type. The well-known exigencies of 'hermeticity', target-pointing 'tower structure', and coexistence with a solenoidal magnetic field were not considered by the OPAL Collaboration to be a hindrance to the adoption of such a scheme for their detector.

It may be seen as significant in the framework of this Cherenkov Symposium that, for the purpose of having one detector that would be certain to function at LEP turn-on time, the LEP Committee chose one that bases its shower detection on the Cherenkov effect. This comes at considerable expense: the mechanical and readout needs of the giant lead-glass array place the barrel shower spectrometer outside the $1.5 X_0$ thick conventional coil, thus vitiating some of the high resolving power of shower energies. Also, the target-pointing geometry with minimal cracks necessitates the grinding and polishing, for the barrel alone, of 9,600 lead-glass blocks of 30 different, slightly flaring geometries (Fig. 4.6a,c), of a weight totalling some 200 t! All of these will have to be separately calibrated, as well as the 1,250 units for each of the two end-caps.. These latter have the added problem of being exposed to the full magnetic field; for their readout, conventional phototubes will have to be replaced by specially developed vacuum phototriodes. On individual units (made of heavy SF6 glass, with $X_0 = 1.7$ cm) and mounted as in Fig. 4.6a, Bhabha events have been measured to yield the energy resolution shown in Fig. 4.6b. Note, however, that the $1.5 X_0$ thick coil will significantly degrade the resolution of the barrel section.

For an over-all impression of this largest and most ambitious lead-glass array ever conceived, see the OPAL quadrant depicted in Figs. 4.6b,c. (The latter also makes clear that the barrels are not truly target-pointing, and that there is no really small-angle lead-glass detector -- for fear of radiation damage.)

4.6 Trouble in lead-glass land: radiation damage

It has long been known that continued exposure to high radiation doses causes a 'yellowing' of lead glass; the use of lead-glass total absorbers close to electron or photon beam lines has been abandoned long ago. The formation of radiation-induced colour centres in the near UV, the visible region, and the near IR, has recently been studied in more detail. The growth of absorption coefficients in several energy bands could be lethal in the hostile environments we expect for new-generation high-luminosity machines.

An interesting study was performed by a Brookhaven-based Collaboration¹³⁾ investigating the possibility of preparing a type of lead-glass

that would not be subject to the effects of these radiation-induced changes. Figure 4.7a shows the change in the absorption coefficient for the main absorption bands in [Ohara F2(W)] lead glass, with increasing radiation dose. Up to a dose of over 3000 rad, the growth is clearly a linear function of the dose that induces impurities and defects in the glass.

Adams et al.¹³⁾ then systematically investigated the effects of adding CeO_2 to the lead glass. This doping has been known to induce new absorption bands near the ultraviolet transmission limits, but also to inhibit the formation of the defects that cause radiation-induced absorption. Figure 4.7b shows the photoelectron yield calculated from the measured absorption coefficients for various levels of CeO_2 doping: clearly, at integrated doses of more than 500 rads, CeO_2 doping at the 1% level, albeit reducing the photoelectron yield for unirradiated glass by a factor of 2, leads to results that are much preferable. The 'equivalent doses', for which the resolution loss due to doping is equal to that induced by radiation, is given in Fig. 4.7c. It appears, then, that lead-glass shower counters with $\sim 1\%$ CeO_2 doping, although with a light yield considerably reduced with respect to undoped glass, will be able to operate without serious degradation in high-radiation-level environments.

Other attempts have been made to obtain continuously sampling shower detectors that are resistant to radiation damage; we mention the development of 'Helicon' liquid devices by a Japanese group¹⁴⁾. Testing ZnI_2 and thallium formate $\text{Tl}(\text{HCO}_2)$, among other solutions, they find encouraging performance on the level of SF5 glass; radiation resistance is apparently good. However, no functioning systems are yet available to bolster the expectations held out by this group.

5. DISCONTINUOUS SAMPLING: LEAD/LUCITE SANDWICHES

Total absorption devices based on the sampling technique have several advantages: they permit the use of less expensive materials (e.g. lead sheets) for absorbers; they are mechanically more easily adapted to various geometrical requirements; they permit the use of radiators with excellent light transmission, and with good radiation resistance.

On the negative side, sampling calorimeters are subject to the statistical fluctuations of shower development (see Sections 2 and 3) and low photoelectron yield at low energies. It becomes crucial to ask: How many samplings? and at what cascade depths?

5.1 Compact lead/lucite shower counters

To answer these questions for low-energy electromagnetic showers, Heusch and Prescott¹⁵⁾ measured the average number of Cherenkov-radiating particles, as a function of energy, at various sampling depths (Fig. 5.1), using a lucite radiator behind lead converters. They then built¹⁶⁾ sandwich counters as shown in Fig. 5.2, where 1 X_0 lead plates alternated with 1/2-inch lucite sheets; feeding all the light from six layers onto one 5-inch phototube, they found that the response from a 12 X_0 device not only gave a good linear energy response (Fig. 5.3a) but also a much flatter response over the face of the counter when compared with a lead-glass block of identical geometry (Fig. 5.3b).

Counters of this type were sufficiently easy to build and operate so as to be used quickly in a number of experiments where electron or photon energy measurement was vital, but not necessarily with the highest resolution. Shower fluctuations, which could be beaten only by a large increase in samplings (and a resulting loss in compactness and readout simplicity) and photoelectron statistics (typically, a Cherenkov sandwich would yield a factor of 40 fewer photons than a similar scintillator sandwich, albeit with greater uniformity) limited the resolution to the values indicated in Fig. 5.4. One of the early applications of these detectors involved electron identification in the experiment that (re-)established the validity of QED in the photoproduction of wide-angle electron pairs¹⁷⁾.

5.2 A large planar lead/lucite sandwich with hodoscope

The real limitation at lower energies, for energy measurement with lead/lucite counters, was the relatively low photon yield. At high energies (say, $E > 20$ GeV), shower multiplicities are high enough to counteract the effects of sampling.

For a photon scattering experiment (Expt. 152) at Fermilab, the Santa Cruz group¹⁸⁾ therefore built a large shower hodoscope out of lead/lucite

sandwiches, the elements of which are shown in Fig. 5.5. It is conceptually somewhat akin to the OLGA spectrometer mentioned above, but with some notable differences: the total absorption counter units are subdivided into a seven-layer front part (with an active area of $0.75 \times 0.185 \text{ m}^2$ each) and a 10-layer back section; these two parts are called the U and V sections, respectively. Each of these units is viewed by one 5-inch phototube only. The response of this system to 135 GeV electrons is seen in Fig. 5.6. At 100 GeV, σ/E of $\leq 2\%$ was achieved.

The total array of 16 such units was mounted, as seen in Figs. 5.7a,b, on a movable platform that could be displaced up-beam/down-beam for a change in subtended solid angle, or sideways for a different t range. A fine-grained hodoscope made out of low-grade scintillator was placed between the U and V banks, somewhat behind the shower maximum for good statistical accuracy. Its elements are 3 cm wide (in the centre, 2 cm) and ~ 158 cm long. There are two planes, one vertical, one horizontal.

The modest segmentation of the U and V banks assigns an important task to these crossed hodoscopes: they provide information not only about the trajectory of showers but also about their energies, as indicated in Fig. 5.8. With shower widths of some 5 cm (from 30 to 135 GeV), their location can be determined to ~ 1 mm.

Note that this system -- which covers an area of $1.5 \times 1.5 \text{ m}^2$ and has only 32 elements of total-absorption counter made of inexpensive acrylic-based UVT plexiglas -- involves the careful monitoring of the performance of only 32 phototubes (by LEDs, ^{241}Am sources, and halo muons). The system's success can be gleaned from Figs. 5.9a,b, where π^0 , η^0 , and ω^0 signals are prepared out of multishower final-state data.

6. THE CHEAPEST OF ALL: WATER CHERENKOV COUNTERS

Even prior to Cherenkov's definitive findings, L. Mallet had, in 1926, observed¹⁹⁾ bluish light when immersing a γ -ray source (Ra) in water. In recent years there has been much interest in the use of large volumes of water for total absorption measurement by way of Cherenkov radiation. The advantages are obvious: even highly purified water is a cheap substance, so that even very large volumes can be envisaged. Good uniformity can be

reached; light transmission is excellent; any geometry can be fitted; lastly, leakage constitutes no danger. Also, the physical parameters are interesting:

$$\left. \begin{array}{l} \lambda = 78.8 \text{ cm} \\ X_0 = 36.4 \text{ cm} \end{array} \right\} \lambda \approx 2 X_0$$

$$dE/dx|_{\min} = 2.03 \text{ MeV/cm}$$

$$n \approx 1.33 \quad \text{for visible wavelengths}$$

$$\begin{array}{ll} \text{attenuation lengths:} & 12.5\text{--}30 \text{ m } (4000 \text{ \AA}) \\ & 1.5\text{--}3 \text{ m } (13000 \text{ \AA}) . \end{array}$$

Clearly, the lack of compactness makes good phototube coverage problematic. Water Cherenkov systems are therefore most easily adapted to relatively low-resolution studies that need large volumes, such as nucleon decay experiments, or the investigation of cosmic-ray interactions up to very high energies. Cherenkov angles tend to be small, as is multiple scattering: this permits the use of the Cherenkov cone for important directionality information.

6.1 Accelerator energies: a modest-sized system for μ -hadron separation [B.C. Brown et al.²⁰⁾]

For certain accelerator-energy problems, total absorption of hadron energies can be usefully effected with water Cherenkov counters. This was demonstrated by B.C. Brown et al.²⁰⁾, who designed a simple and effective system for μ -hadron separation in a high-luminosity two-arm experiment at Fermilab. For each arm, they built a simple plywood box covered with black vinyl; one of these is shown in Fig. 6.1. With a depth of ~ 8 interaction lengths, they successfully contained much of the hadronic cascades. The sides were lined with acrylic mirrors; the end-plane was covered with wavelength shifter light-guides, so that the entire light output was measured in only nine phototubes. In this experiment, where charged-particle momenta p were known in each arm, the water hadrometers were preceded by a $24 X_0$ (1.5λ) thick lead-glass wall for electron energy measurement. Adding signals from these walls and the water counters, a total-energy quantity F was formed. The ratio F/p thus determined a characteristic hadron signature,

as indicated in Fig. 6.2: $F/p = 1$ for electrons; $F/p > 0.16$ safely excludes μ 's. The range in between is seen to be populated by hadrons; their energy resolution is limited by the fluctuations of secondaries that will emit radiation. (Note that this entire water Cherenkov system cost about \$20,000!)

6.2 Low-energy hadronic cascades: Nucleon decay detectors

In the last few years, the need to test theories that predict the non-stability of nucleons on a time scale of some $10^{30 \pm 2}$ years has led to great interest in detectors that, whilst containing at least 10^{30} nucleons, should lend themselves to the detection of individual N-decay final states, such as

$$\begin{aligned} p &\rightarrow e^+ \pi^0 \\ &\rightarrow K^0 \mu^+, \text{ etc.} \end{aligned}$$

Water Cherenkov detectors offer obvious attractions: they can be made large; they contain a considerable fraction of 'free' protons; they are largely transparent to Cherenkov light. Another important feature is the easy definability of track directions by the well-known structure of the Cherenkov cone. No bona fide nucleon decay events have been reported to date, but the facilities lying in wait for them are impressive. We mention two of them:

6.2.1 The Irvine-Michigan-Brookhaven (IMB) experiment²¹⁾

This is the largest active water Cherenkov device; its basic layout is schematically seen in Fig. 6.3. Located deep in a salt mine, at 1570 m water equivalent (mwe) and well protected from most charged cosmic rays, an almost cubic volume ($22.5 \times 17 \times 18 \text{ m}^3$) filled with purified water (absorption length for visible light: $\sim 50 \text{ m}$) is viewed from close to the surface by a total of 2048 phototubes (special EMI 5-inch tubes, mounted in buoyant housing as seen in Fig. 6.3b). Note that the Cherenkov detector volume houses some 9000 t of water; the 'fiducial volume' for contained events, away from the walls, holds $\sim 3000 \text{ t}$. The engineering task to build such a structure deep in a mine is a formidable one; we give a little illustration in Fig. 6.3c. The phototube housings are strung on nylon lines, and

are read out in 8×8 patches. A decay of a neutron might, if $n \rightarrow K^+ \mu^-$, look roughly as in Fig. 6.4. Note that the kinematics as well as the particle type can be inferred from the size and width of the Cherenkov rings. The width of the rings will indicate the range of the parent particle; relative timing between different parts of a skew ring will permit a measurement of the particle's direction. A fuzzy ring means an electron, a smeared circle means a photon (or π^0), etc.

For details of performance, I refer the reader to any of the recent conference contributions²²⁾. The IMB Collaboration has set the best limits so far on the $e^+ \pi^0$ mode of proton decay, and may well have ruled out SU(5) Grand Unification.

6.2.2 Kamioka nucleon decay experiment²³⁾

This project, which is in many ways similar to the IMB experiment above, has some notable differences. While situated 1000 m underground in the Kamioka Mine in central Japan, the volume of ~ 3000 t of water is viewed from all six sides by a total of 1,000 phototubes which permit a particularly good aspect ratio: the consequent good photoelectron statistics puts the experiment in an excellent position to extract a maximum of information out of the ~ 1000 t of fiducial volume (see Fig. 6.5). The new 20-inch diameter Hamamatsu phototubes²⁴⁾, the photocathodes of which can be immersed in the water tank (see Fig. 6.6a), cover some 20% of the detector surface area, i.e. they supply about an order-of-magnitude better coverage than that of the IMB detector above (for which improvement planes exist). Their high quality (gain: 10^7 at 2000 V, 90 μ s transit time, with quantum efficiency as in Fig. 6.6b) assures a light collection efficiency for good pattern recognition. Since the large size of the phototube does not permit relative timing of the order of the IMB experiment, the position and the direction of tracks are determined from the intensity patterns on the phototubes hit. Note that a typical event is observed by a large number of phototubes, say > 100 , so that such patterns should be easily distinguishable. From voluminous Monte Carlo studies, we show here (Table 2) the expectations for the number of photoelectrons for several possible nuclear decay modes, and in Fig. 6.7 the separation of various of these modes by photoelectron yield alone. The real power of the apparatus is demonstrated

by the simulations reproduced in Figs. 6.8a,b. They show two of the principal expected decay modes of the proton, into $\pi^0 e^+$ and $K^0 \mu^+$, in an unfolded geometry, as the phototube pulse heights would respond to them. In Fig. 6.7a, the fuzzy circle is clearly due to the showering positron, the broad patch of higher pulse heights to the overlapping $\pi^0 \rightarrow \gamma\gamma$ showers. Figure 6.7b sees three clear annular populated patterns, each due to one of the charged secondaries μ^+ and $(K^0 \rightarrow) \pi^+ \pi^-$.

Suffice it to say that these (and several other) beautiful water Cherenkov arrays are expected to provide not only proof or disproof of some of our present theoretical credos, but can also be trusted to provide much novel information on cosmic-ray problems hitherto not within experimental reach.

6.3 'Think Big, Sink Deep': deep underwater cosmic-ray detectors (DUMAND and Baikal)

If thousands of tons were needed in the previous section for a sensitivity to minuscule decay rates, much greater detector masses are desirable for a number of neutrino interaction studies. The only media that are at our disposal in such quantities are air and water. The weak scintillation of air is used for extensive air shower studies by large earthbound telescopes [e.g. the Fly's Eye Detector in Utah²⁵]. For neutrino studies in the 100 MeV range, owing to extragalactic gravitational stellar collapse we expect fluxes of 10^5 – 10^6 /cm² whereas reactor fluxes may go up to 10^{15} /cm² s, and even high-energy accelerator-generated neutrino beams have fluxes of up to 10^8 /m² and pulse. High-energy (> 10 TeV) cosmic-ray fluxes may even be of the order of one neutrino per square metre and hour. Consequently, deep under-surface volumes of water have been seen as the only radiator material possible: at 1000 m below surface, no skylight penetrates, and the background due to charged cosmic-ray particles (mostly μ 's) subsides at several kilometres depth. The DUMAND (Deep Underwater Muon and Neutrino Detector)²⁶ project has therefore been suggesting detector masses between 10^6 and 10^{11} t, to be appropriately instrumented.

Detection of muon tracks, of electron showers, and of hadron cascades is thus indicated through the emission of Cherenkov light. The principal

limitations to its low-level detection in this environment are the occurrence of natural biological luminescence, and the presence of radioactive nuclides in sea water down to great ocean depths (creating backgrounds in the visible region), as well as the absorption of Cherenkov light before it can reach one of the detector elements. Fortunately, at great ocean depths, attenuation lengths for visible light of more than 20 m are not uncommon, making $100 \times 100 \times 100 \text{ m}^3$ and even larger instrumented volumes entirely thinkable.

Detailed studies about hadron cascade characteristics²⁷⁾ and about the generation and detection of Cherenkov radiation²⁸⁾ have been made, and signatures have been determined for hadrons versus electrons or muons (see, for example, Figs. 6.9a,b and 2.4). The design of instrumentation that can be afforded is of vital importance. Figure 6.10 demonstrates the sensitivity of a minimal ('muon string') and a large DUMAND array to various high-energy neutrino events, when compared with an underground laboratory of feasible proportion. Figure 6.10a makes it clear that neutrino interaction studies at energies beyond $\sim 1 \text{ TeV}$ will be a proper domain for DUMAND; Figure 6.10b shows the sensitivity of DUMAND to events that might become observable by neutrino fluxes in this energy range, as a function of their distance from Earth. The power of a large underwater detector is evident.

How would a Cherenkov array be built? ²⁶⁾ Analogously to that of the IMB detector, by the suspension of appropriately mounted and shielded phototube arrays hung on strings. Linscott's suggestion²⁸⁾ of a 1 km^3 detector instrumented throughout with a cubic lattice of phototubes with a lattice spacing of 40 m, and, for muon detection, with a wall coverage of 20 m spacing between phototubes, would involve some 31,000 large photomultipliers. Since rare events due to high-energy (10 TeV) neutrinos are among DUMAND's principal aims, total energy containment, with both hadronic cascades and long (about 1 km) muon tracks, may make such detectors desirable. For efficient light collection, one may need light traps and multiple phototubes mounted in 'sea urchins' (Fig. 6.10) for efficient light detection. Bioluminescent and naturally occurring ^{40}K decay backgrounds may have to be suppressed by multiple coincidence requirements. Initial experience is soon to be gained from the tests with one muon string that are being prepared by the Hawaii DUMAND Center.

Lastly, we mention the parallel work that is being carried out at the Lake Baikal Laboratory of the Nuclear Physics Institute, USSR Academy of Sciences, which is being separately reported on at this conference²⁹⁾. Although only 1.4 km deep, this site has the considerable advantage of essentially no bioluminescent backgrounds of short period; an absence of underwater currents and the availability of a thick ice blanket in early spring, for precise placing of equipment, make array assembly in situ much simpler than for a deep ocean site. Again, a simple initial array should soon give further feasibility indications.

7. CONCLUSION

In discussing the total absorption devices that are using P.A. Cherenkov's discovery as their principal tool for particle detection, we have seen its application to a great variety of burning particle-physics questions. From rare decay events at low energies, through large solid-angle energy containment or more specialized tasks at accelerator energies, to neutrino studies at energies beyond the reach of man-made sources, our quest for an understanding of the laws of nature is being much aided by methods based on the original work of our distinguished colleague: It is fitting that we recognize this at the Seminar that marks both his 80th birthday and the 50th anniversary of the discovery which made his name a household word to every physicist around the globe.

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Table 1
Some physical properties of various kinds of
commercially available lead glass

Schott	Ohara	Ref. Index	Density g/cm ³	PbO (%)	Rad. Len. (cm)	Int. Len. (cm)	IL/RL
F2	PEMG2A	1.6200	3.63	45.0	3.22	28.0	8.7
-	PEMG2	1.6200	3.63	45.0	3.22	28.0	8.7
SF2	PEMG1	1.6477	3.85	50.0	2.84	27.3	9.6
SF5	PEMG4	1.6727	4.08	55.0	2.54	25.6	10.1
SF1	PEMG5	1.7174	4.47	61.0	2.17	24.9	11.5
SF6	PEMG3A	1.8052	5.20	71.0	1.68	22.7	13.5
-	PEMG3	1.8052	5.20	71.0	1.68	22.7	13.5

Table 2

Kamioka nucleon decay experiment:
simulation of response to various decay modes (from Ref. 23)

Decay mode	Mean No. of photoelectrons	Energy resolution (4)
$p \rightarrow e^+\pi^0$,	2520	3.5
e^+	1221	10.6
$\pi^0 \rightarrow 2\gamma$	1299	9.5
$n \rightarrow e^+\pi^-$,	1608	15.2
e^+	1228	12.2
π^-	380	67.4
$p \rightarrow e^+\eta^0$,	2530	3.2
e^+	794	12.4
$\pi^0 \rightarrow 2\gamma$	1736	5.8
$n \rightarrow e^+\rho^-$,	1689	11.1
e^+	422	55.8
$\rho^- \rightarrow \pi^-\pi^0$	1267	20.2
$p \rightarrow e^+\rho^0$,	894	35.6
e^+	417	62.3
$\rho^0 \rightarrow \pi^+\pi^-$	477	65.1
$p \rightarrow \mu^+\pi^0$,	1900	4.7
μ^+	610	20.4
$\pi^0 \rightarrow 2\gamma$	1290	10.5
$n \rightarrow \mu^+\pi^-$,	1009	28.0
μ^+	628	25.1
π^-	381	81.0
$p \rightarrow \mu^+K_S^0$,	1913	3.6
μ^+	296	26.3
$K_S^0 \rightarrow \pi^0\pi^0$	1617	6.2
$p \rightarrow \mu^+K_S^0$,	516	36.6
μ^+	291	24.3
$K_S^0 \rightarrow \pi^+\pi^-$	225	83.5
$p \rightarrow \nu K^+$,	131	9.5
$K^+ \rightarrow \mu^+\nu$		
$p \rightarrow \nu K^+$,	701	12.0
$K^+ \rightarrow \pi^+\pi^0$		
$n \rightarrow \nu K_S$,	1639	7.2
$K_S \rightarrow \pi^0\pi^0$		
$n \rightarrow \nu K_S$,	218	85.1
$K_S \rightarrow \pi^+\pi^-$		

Figure captions

- Fig. 2.1 : a) Integrated pulse-height distributions for 1 GeV e , π in scintillator and lucite Cherenkov radiator of identical geometry: in lucite, π and e look alike; in scintillator, the π distribution has a long tail. b) Lead/lucite sandwich: Cherenkov radiation output is considerably lower for 0.8 GeV/c protons than for 0.8 GeV/c π^- . Typical shower distributions emerge for the 0.5 and 1 GeV e distributions.
- Fig. 2.2 : Schematic picture of longitudinal development of electromagnetic showers. Note the differences between γ, e -initiated showers.
- Fig. 2.3 : Schematic view of lateral shower development. A central hard component has a width due to multiple scattering; the soft component is largely due to slow $e^\pm$ in the minimum-absorption range.
- Fig. 2.4 : Schematic representation of a showering track distribution in a plane intersecting the Cherenkov cone at right angles. It mirrors Fig. 2.3.
- Fig. 2.5 : Angular distribution of the $e^\pm$ at a sampling of a high-energy shower: a) for all $e^\pm$ energies, the sharp forward peak prevails, b) for energies below 3 MeV, there is a trend towards isotropy (from Amaldi, Ref. 3).
- Fig. 3.1 : Schematic representation of a hadronic cascade's longitudinal development. Note slow build-up, large fluctuations.
- Fig. 3.2 : Model-dependent Monte Carlo calculations of the principal processes that mediate energy dissipation in hadronic cascades. The various models give widely varying results for π , p cascades (from Amaldi, Ref. 3).
- Fig. 3.3 : Longitudinal cascade development and lateral containment for three different materials: a) 6 GeV electromagnetic showers show scaling with E/ϵ , and are well contained within $\sim 1 R_M$; b) hadron cascades exhibit approximate scaling in absorption length λ . Lateral containment is maintained for the core (FWHM), but does not extend to the slower large-angle component (from Fabjan, Ref. 3).

Fig. 3.4 : a) Fraction of total energy dissipated as electromagnetic showers in iron. Shaded area: ± 1 r.m.s. band; b) number of π^0 in the hadronic cascade in iron, as a function of hadron energy (from Amaldi, Ref. 3).

Fig. 4.1 : Lead-glass cylinder for π^0 detection along a given direction, with lead-glass hodoscope (Ref. 5).

Fig. 4.2 : Lead-glass hodoscope wall of Holder et al. (Ref. 6): a) front view of honeycomb structure; b) side view of same; c) system side view including six lead converter sheets and wire chambers for track definition; d) invariant-mass plots show clean signals for $\pi^0 \rightarrow \gamma\gamma$ and $K_L^0 \rightarrow \pi^0\pi^0$.

Fig. 4.3 : Use of 'active' lead-glass converters by Heusch et al. (Ref. 8); a) side view (total lead-glass thickness for low-energy photons: $12 X_0$); b) details of reconstruction of photon trajectory from secondaries; c) conversion efficiencies as a function of photon energy, for both converters (4), either one (3), or for one given converter; d) pulse-height distributions are seen to be broad and diffuse in all three sections, well-defined in the summed signal.

Fig. 4.4 : The OLGA detector at CERN: a) schematic view of basic array components: $3 X_0$ active converters, position detectors, and total absorber; b) π^0 and η^0 signals are easily reconstructed from $\gamma\gamma$ distribution; c) OLGA and its 'crown' of lead-glass blocks (note beam hole); d) angular span of detector inside NA14 experiment, as seen by 100 GeV photons (Ref. 10).

Fig. 4.5 : BNL extruded lead-glass array of Engelmann et al. (Ref. 11): a) side view of test array; b) energy deposition in $Z X_0$ thick segments for 41 GeV e^- ; c) 'electron-likeness' parameter ζ (see text) for electrons and pions, showing efficient separation.

Fig. 4.6 : OPAL detector for LEP (Ref. 12): a) individual lead-glass unit; note slight flaring toward photo-tube; b) energy resolution measured in test block for 17 GeV electrons; c) layout of one quadrant of barrel calorimeter. Different-sized units are numbered 1, ..., 30; d) quadrant section including end-cap.

- Fig. 4.7 : a) Growth of absorption bands with radiation dose in Ohara F2(W) lead-glass. b) Effect of radiation doses on two levels of CeO_2 doping of lead glass, compared with undoped glass. Crossover at ~ 500 rad (see text). c) 'Equivalent dose' for given CeO_2 doping percentage (Ref. 13).
- Fig. 5.1 : Cherenkov radiation in lucite at various sampling depths for 0.1-1.0 GeV electrons: a measurement of longitudinal shower development (from Ref. 15).
- Fig. 5.2 : Section through a six-layer lead/lucite counter stacked with lead so as to subtend a fixed angular aperture toward a close-by target (example of geometrical adaptability).
- Fig. 5.3 : Lead/lucite shower counter: a) linearity with energy at low E_e , E_γ ; b) pulse height versus shower location; good uniformity for lucite, poor for lead glass of identical geometry.
- Fig. 5.4 : Resolution σ/PH for lead/lucite counters. Upper curve: poor aspect ratio, one phototube; lower curve: good aspect ratio with two phototubes. This underlines the importance of good photoelectron statistics at low energies (from Ref. 16).
- Fig. 5.5 : Sketch of elements for large lead/lucite shower spectrometer at Fermilab. The U module precedes the V module in beam (Ref. 18).
- Fig. 5.6 : Shower distributions in U,V banks of lead/lucite spectrometer for 135 GeV electrons (beam width not unfolded). Added signal shows precise definition.
- Fig. 5.7 : Shower spectrometer for Fermilab Exp. 152: a) Schematic sketch in perspective. The cart can move on rails to change the solid angle with respect to the fixed target; sideways motion on the cart permits a change in the t-values spanned. b) Beam's-eye view of U bank. Note beam hole in centre.
- Fig. 5.8 : Shower definition in position hodoscope for 135 GeV shower: a) pulse-height distribution over 11 counters, giving Δx (Δy); b) energy deposition in hodoscope; c) mean position (accurate to 1 mm); d) determination of shower width (~ 5 cm over a wide range of high energies).

- Fig. 5.9 : Consistency measurement of shower energy in low-grade scintillator hodoscope installed after U-section of lead/lucite spectrometer: energy calibration is linear (notice difference between photon and electron showers, see Fig. 2.2). The σ/E is broad, but gives important help in disentanglement of multishower states.
- Fig. 5.10 : Extraction of radiatively decaying meson signals from multishower samples: a) π^0 and η^0 from $m_{\gamma\gamma}$; b) ω from $m_{\pi^0\gamma}$ (Ref. 18).
- Fig. 6.1 : Fermilab water Cherenkov total absorption counters (Ref. 20): acrylic mirrors project light onto back face, which reads out with nine phototubes (see text).
- Fig. 6.2 : Pulse-height spectra for η 's (a) and hadrons (b) and (c) in water Cherenkov counter; hadron energy measurement is normalized to momentum determination by upstream system (see text).
- Fig. 6.3 : Large water Cherenkov tank of IMB nucleon decay experiment: a) almost cubic volume is viewed by 2,048 phototubes; b) buoyant housing and a lifeline keep phototubes operable inside water; c) a glimpse at the civil engineering for the detector.
- Fig. 6.4 : Schematic sketch of how a two-charged-particle final state of nucleon decay (say, $n \rightarrow K^+\mu^-$) will appear in the phototube array of the IMB detector.
- Fig. 6.5 : Sketch of Kamioka nucleon decay detector in its underground housing. Suspension of phototubes along inner perimeter is indicated (Ref. 23).
- Fig. 6.6 : a) New 20-inch diameter phototube used by Kamioka experiment. Waterproof seals provide pressure resistance to 6 kg/cm²; b) quantum efficiency for 20-inch tube.
- Fig. 6.7 : Good aspect ratio gives the total number of photoelectrons observed on the detector surface, distinguishing power between groups of decay modes.
- Fig. 6.8 : Monte Carlo simulation of surface appearance of principal expected proton decay modes: a) $p \rightarrow e^+\pi^0$; b) $p \rightarrow \mu^+K^0$ ($\rightarrow \pi^+\pi^-$). Notice characteristic patterns on the unfolded wall geometry.

Fig. 6.9 : Appearance of principal components of very high energy neutrino interaction in large ocean detector: a) long μ tracks will illuminate entire plane; b) hadron showers of effective length λ will illuminate an annular region.

Fig. 6.10 : Sensitivity of large and minimal ('muon string') DUMAND detectors to high-energy neutrino interactions: a) expected yearly events due to E_ν greater than the values indicated; b) flux of neutrinos due to putative extraterrestrial sources, as a function of their distance from Earth (see text).

Fig. 6.11 : Underwater phototube mounting for protection and maximum efficiency: a) 'Sea urchins': a phase-space matching array which collects light by means of radial spines, then transmits it onto a hemispheric phototube. b) Multiple phototube optical sensor modules. (The devices used at the Lake Baikal Laboratory are similar in concept to these.) Their length is 6 m, diameter 0.33 m.

Fig. 2.1a

Fig. 2.1b

Fig. 2.2

Fig. 2.3

Fig. 2.4

Fig. 2.5

Fig. 3.1

Fig. 3.2

Fig. 3.3a

Fig. 3.3b

Fig. 3.4a,b

Fig. 4.1

Fig. 4.2a

Fig. 4.2b

Fig. 4.2c

Fig. 4.2d

Fig. 4.3a

Fig. 4.3b

Fig. 4.3d

Fig. 4.3c

Fig. 4.4a

Fig. 4.4b

Fig. 4.4c

Fig. 4.4d

Fig. 4.5a

Fig. 4.5b

Fig. 4.5c

Fig. 4.6a

Fig. 4.6b

Fig. 4.6c

Fig. 4.6d

Fig. 4.7a

Fig. 4.7b

Fig. 4.7c

Fig. 5.1

Fig. 5.2

Fig. 5.3a

Fig. 5.3b

Fig. 5.4

Fig. 5.5

Fig. 5.6

Fig. 5.7a

Fig. 5.7b

Fig. 5.8

Fig. 5.9

Fig. 5.10a

Fig. 5.10b

Fig. 6.1

Fig. 6.2a

Fig. 6.2b

Fig. 6.2c

Fig. 6.3a

Fig. 6.3b

PROTON DECAY LABORATORY

Fig. 6.3c

Fig. 6.4

Fig. 6.5

Fig. 6.6a

Fig. 6.6b

Fig. 6.9a

Fig. 6.9b

Fig. 6.10a

Fig. 6.10b

SEA URCHIN

Fig. 6.11a

Fig. 6.11b