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LARGE APERTURE GAS CHERENKOV COUNTERS WITH GOOD REJECTION OF SLOW PARTICLES

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Several mechanisms limiting the rejection in large aperture gas Cherenkov counters and their implications for the design of such counters are discussed Gas scintillations, one of these mechanisms, were investigated experimentally and measurements of relative scintillation yields of various gases are reported A counter which was used in an experiment on leptonic K-decays is described in detail

1. Introduction

In well collimated particle beams, a good rejection of unwanted particles by means of Cherenkov counters is usually obtained using a perfect optical system for the focalisation of the Cherenkov light or by cascading several Cherenkov counters Both methods become impracticable if particles emitted from an extended source into a large solid angle have to be identified In connection with experiments on electronic decays of hadrons[1–4]) we studied the problem of how to obtain a good rejection of unwanted particles in such applications which require a large aperture gas Cherenkov counter

In the paper presented here, this problem is discussed and the design of the counter which was used recently in an experiment on K_{e2} decay[3 4]) is described in detail The Cherenkov counter which our group used earlier in experiments on hyperon β-decay has been briefly discussed in ref 1

In these experiments, the aim was to identify electrons with energies of 50–300 MeV in the presence of many pions and muons in the velocity range $\beta = 0\ 85$–$0\ 92$ and in the presence of a large general machine background The results of our investigations may also be useful in other situations

2. Rejection in large aperture gas Cherenkov counters

We consider several mechanisms by which particles with velocities below the Cherenkov threshold can be counted in large aperture gas Cherenkov counters

2 1 Nuclear reactions

Nuclear reactions in the material of the Cherenkov counter may produce particles with velocities above the Cherenkov threshold from particles below threshold Most effective is charge exchange of pions with subsequent conversion of one π^0 γ-ray In order to reduce this effect, large aperture gas Cherenkov counters should be operated at atmospheric pressure, since otherwise thick windows are imposed

At atmospheric pressure, however, the number of photons produced by Cherenkov effect is rather small Consequently, a focussing counter is indicated in view of a reasonable efficiency

2 2 δ-rays

The production of knock-on electrons (δ-rays) is a second mechanism by which particles of lower velocity may produce secondaries with higher velocity The Cherenkov threshold should be above the maximum velocity of the δ-rays produced by the background particles

2.3. Scintillations

Many gases scintillate In focussing gas Cherenkov counters of the type used in collimated beams, this scintillation light is usually not seen In the counters discussed here, the large aperture optics and the need to work with few Cherenkov quanta tend to make the counter sensitive to scintillation light of particles below the Cherenkov threshold Since little is known about gas scintillations, the relative scintillation yield of various gases has been measured using 90 MeV protons from the CERN synchro-cyclotron† A 58 AVP photomultiplier in contact with the gas was used to detect the scintillation light quanta The reduction of the measured scintillation yield to the case of minimum ionizing particles was made under the assumption that

* Now at CERN, Geneva, Switzerland

† These measurements were carried out in 1967 and 1970 by one of the authors (H R)

TABLE 1

Scintillation of gases (1) Number of scintillation light quanta emitted into the full solid angle in the S11 spectral range from 1 cm path of a minimum ionizing particle at 20 °C and 1013 mbar A systematical error of ± 20% has to be attributed to all values (2) The values given here are from the Landolt–Bornstein tables for $\lambda = 436$ nm at 20 °C and 1013 mbar, unless noted otherwise If no table value was found, or if there was a big difference between the table value and the value measured by us, the latter is also given and denoted by (M) For all fluorinated hydrocarbons our measured value differs from the calculated value given in the DuPont Technical Bulletin B-32 For gas mixtures, the value was calculated from the components and denoted by (C)

Gas	Formula	(1) Scintillation intensity	Scintillation decay time (ns)	(2) Refractive index $\eta = (n-1) \times 10^5$	Purity	Supplier
Helium	He	3.6×10^{-1}	14	3.27	purum	Linde
Neon	Ne	6.2×10^{-1}	19	6.29	puriss	Messer Grieshm
Hydrogen	H_2	4.1×10^{-4}	< 3	13.22	purum	Carba
Oxygen	O_2	2.2×10^{-3}		25.74	purum	Carba
Nitrogen	N_2	2.7×10^{-1}	< 3	28.24	purum	Carba
Air		5.0×10^{-2}	< 3	27.6		
Carbon dioxide	CO_2	2.1×10^{-2}		42.5	purum	Carba
Freon 12	$C\ Cl_2F_2$	2.4×10^{-2}	6	110 (M)		Du Pont
Freon 22	$CH\ ClF_2$	6.6×10^{-2}		77 (M)		Du Pont
Freon 114	$C\ ClF_2\ C\ ClF_2$	2.0×10^{-2}		115 (M)		Du Pont
Freon C 318	C_4F_8 cycl	5.3×10^{-2}		132 (M)		Du Pont
Vinylidene fluoride	$CH_2\ CF_2$	3.2×10^{-3}		69 (M)		Du Pont
Sulphur hexafluoride	SF_6	4.1×10^{-2}		71.9		Fluka
Ethene	$CH_2\ CH_2$	$< 5 \times 10^{-5}$		68.6		
Vinylchloride (chloroethene)	$CH_2\ CHCl$	9×10^{-4}		106 (M)	puriss	Fluka
Propane	$CH_3CH_2CH_3$	5.4×10^{-4}		104.9 (at 411 nm)		
Propene	$CH_3CH\ CH_2$	$< 5 \times 10^{-5}$		102.4	purum	Fluka
Butane	$CH_3CH_2CH_2CH_3$	1.6×10^{-3}		131.6	purum	Fluka
Isobutane (trimethyl methane)	$(CH_3)_3CH$	6.4×10^{-4}	< 3	131.5, 139 (M)	puriss	Fluka
1 Butene (α-butylene)	$CH_3CH_2CH\ CH_2$	1.0×10^{-4}		130.4, 140 (M)	purum	Fluka
cis, trans-2-butene (β-butylene)	$CH_3CH\ CHCH_3$	$< 5 \times 10^{-5}$		131.2, 140 (M)	purum	Fluka
Isobutene (2-methyl propene)	$(CH_3)_2C\ CH_2$	1.0×10^{-4}		131.4, 110 (M)	purum	Fluka
Butadiene stab	$CH_2\ C\ CHCH_3$ $+ CH_2\ CHCH\ CH_2$	5×10^{-5}		140 (M)	purum	Fluka
Neopentane (2,2-dimethyl propane)	$C(CH_3)_4$	3.0×10^{-3}		171 (M)	purum	Fluka
Gas mixtures (Vol %)						
30% He + 70% Ne		5.6×10^{-1}	15	5.4 (C)		
75% He + 25% H_2		3.0×10^{-3}	< 3	5.8 (C)		
50% He + 50% H_2		1.2×10^{-3}	< 3	8.3 (C)		
25% He + 75% H_2		9×10^{-4}	< 3	10.2 (C)		
75% Ne + 25% H_2		3.8×10^{-2}	4	8.1 (C)		
50% Ne + 50% H_2		1.4×10^{-2}	< 3	9.8 (C)		
25% Ne + 75% H_2		3.4×10^{-3}	< 3	11.6 (C)		

the scintillation yield per centimeter varies linearly with the energy loss by ionization The apparatus was calibrated with Cherenkov light The results are summarized in table 1

Although it scintillates slightly, isobutane was used as Cherenkov radiator in the experiments of refs 1–4 because of its favourable refractive index and chemical properties The breakthrough of unwanted particles due to gas scintillation was a few times 10^{-6} in the experiments on hyperon β-decay[1,2] In the counter described here, it was further reduced by requiring coincidences between several phototubes

Scintillations and unwanted Cherenkov light could also be produced in the windows and in the mirror-backing material of Cherenkov counters The use of black foils and black perspex is therefore recommended

2.4 RANDOM SIGNALS

If the production of light by unwanted particles is suppressed, the limitation of the rejection is given by random signals of the phototubes in the Cherenkov counter

In the experiments described in refs 1–4, it was found that phototube noise was unimportant in this connection, provided the photocathodes were kept at ground potential The general machine background, however, produced a high rate of random signals, probably by interactions in the glass of the phototubes

A fraction of random signals can be rejected by pulse height discrimination and by sharp timing cuts, making use of the fact that in a focussing counter all photons reach the photocathode at approximately the same time A more efficient rejection of random signals is obtained, if an array of phototubes is placed into the focal plane of the Cherenkov counter, such that the image of the Cherenkov cone falls on several phototubes The requirement of coincident signals from two phototubes greatly improves the rejection of random background

3. Design of the counter

The counter described in this section was used to distinguish electrons and muons from $K^+ \rightarrow e^+ \nu$ and $K^+ \rightarrow \mu^+ \nu$ decays resp The branching ratio $K_{e2}/K_{\mu 2}$ is $\sim 10^{-5}$ K^+ mesons were stopped in a target and charged decay particles coming out of the target were analyzed in a magnetic spectrometer The Cherenkov counter was placed between the target and the spectrometer Details of the experimental apparatus are given in refs 3 and 4

The counter was designed according to the following requirements

1) Identification of electrons with $p = 247$ MeV/c, rejection of the order of 10^{-5} for muons with $p = 236$ MeV/c in the presence of a very high machine background*

2) Minimum multiple scattering and minimum production of bremsstrahlung in the counter

3) Angular acceptance 60° (hor) × 30° (vert) for particles from a source of 25 × 6 × 8 cm³

4) The width of the counter in the direction vertical to the beam should not exceed 50 cm (fig 1)

The construction of the counter is shown in fig 1 The Cherenkov light from electrons coming out of the target was focussed on an array of 22 phototubes 56 DVP 03 by means of a curved, nearly spherical mirror CM and of plane mirrors M The geometry of the mirrors and of the phototube array was optimized by Monte Carlo calculations The whole structure was contained in a box of aluminium plates, with entrance and exit windows made of black foils Additional thin windows were provided for the passage of beam particles not stopped in the target The counter was filled with isobutane at atmospheric pressure δ-rays from muons up to 330 MeV/c were below the Cherenkov threshold The average amount of counter material traversed by particles from the target corresponded to

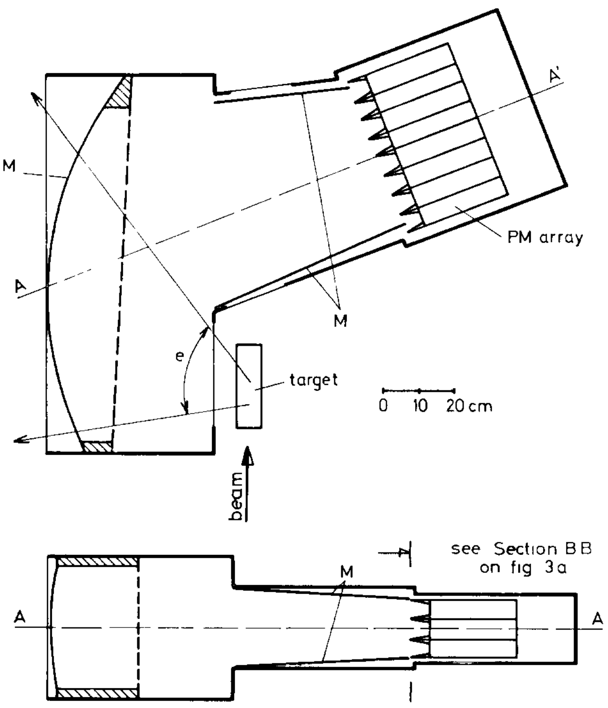

Fig 1 Construction of the Cherenkov counter CM curved mirror, M plane mirrors, e angular acceptance for electrons in horizontal direction

* The experiment was situated at a distance of 9 m from the target struck by the external proton beam The dose rate measured near to the Cherenkov counter (mostly due to neutrons) was 30 mrem/h The kaon beam was accompanied by 2×10^6 pions per burst, which crossed the Cherenkov counter as indicated in fig 1

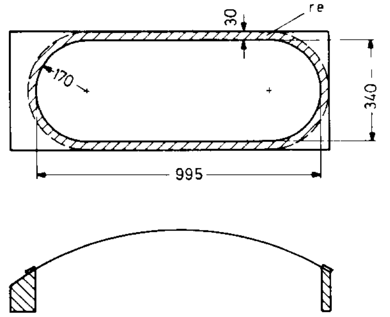

Fig 2 Frame for clamping the curved mirror, r e reinforced edge of mirror foil

$4\ 3\times10^{-3}$ radiation lengths, 3×10^{-3} radiation lengths being due to the gas

The mirror was made of an aluminized mylar foil 25 μm thick The foil was clamped into a frame curved in horizontal direction The clamped edge of the mirror was reinforced by two frames of 125 μm mylar welded to both sides of the foil (fig 2) The horizontal radius of curvature of the mirror was essentially given by the curvature of the frame ($r=93$ cm) A suitable vertical curvature of ~ 85 cm was achieved by a constant overpressure of 20 torr inside the counter Under these conditions, the displacement of the central point of the mirror was 21 mm Relaxation of the mirror was avoided by applying an overpressure of 50 torr for a few hours before the first operation of the mirror During a period of two months, the central point of the mirror moved by less than 1 mm Tests with a pencil light beam showed, that a shift of 1 mm did not affect the focussing properties of the counter

The phototubes were arranged in the pattern shown in fig 3 Light funnels, conical inside and hexagonal outside, served to cover the gaps between the phototubes They were machined from brass, polished and vacuumcoated with aluminium The Cherenkov light was focussed by the mirror to a ring of 10 cm diameter at the photocathode plane On the average this ring covered six phototubes

The phototubes were shielded individually against hf-coupling by a grounded copper foil around the tubes and by a grounded brass wire mesh around the bases, the latter to allow for cooling The tubes were also shielded against the fringe field of the spectrometer magnet by μ-metal cylinders around the individual tubes and a box of thick iron plates surrounding the whole phototube arrangement For details of the construction see ref 5

4. Operation of the counter

The phototubes were operated at high voltages between $+2\ 5$ kV and $+2\ 6$ kV The average anode pulse height for one photoelectron was 120 mV The anode signals were fed into individual discriminators with 40 mV threshold The discriminator outputs (width 10 ns) were added linearly and the resulting signal was fed into two discriminators with thresholds adjusted for signals from 1 or 2 phototubes resp The clipped outputs of these two discriminators, the "1-PM-signal" and the "2-PM-signal", were fed into a fast coincidence circuit with 3 ns resolving time The purpose of this coincidence was to suppress pile-up of uncorrelated 1 PM signals Its output, the "1 2 signal", was fed into the master coincidence. The acceptance of the master coincidence was 30 ns, such that also events with out-of-timing Cherenkov signals were recorded The exact timing of the Cherenkov signal within this 30 ns interval was measured using a TDC started by a suitable scintillator signal and stopped by the 2-PM-signal

Signals of the individual phototube discriminators were also fed into a pattern unit In this way, for every event the multiplicity and the locations of the phototubes involved in that event were recorded Furthermore, the dynode pulses of all phototubes were linearly mixed after suitable attenuation and fed into an ADC In this way, for each event the total pulse height of the phototube array was recorded

Fig 4 shows the timing, pulse height and multiplicity distributions for both electrons and random background, which were recorded in the experiment described in ref 4

The efficiency of the counter was measured with electrons from K_{e3} decays, which could be identified without making use of the Cherenkov counter[3 4]) Using the 1-PM-signal, an efficiency $\varepsilon=0\ 9993\pm0\ 0003$ was measured This efficiency yields for the mean

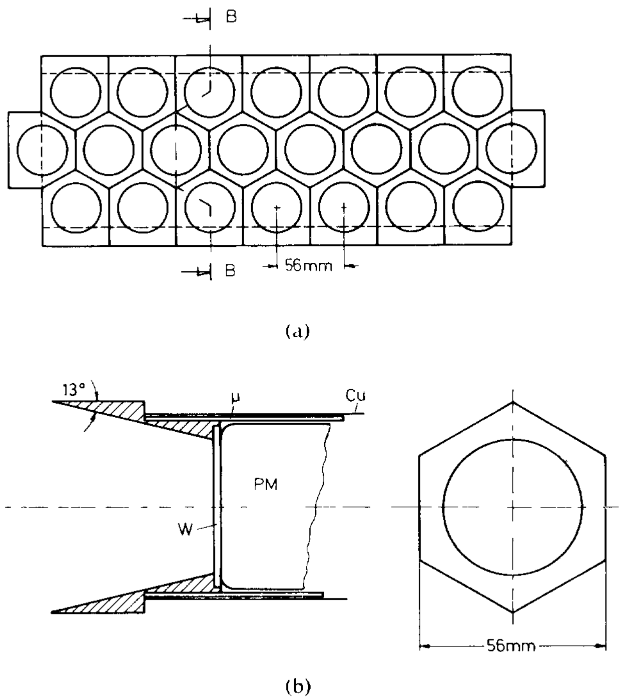

Fig 3 Arrangement of phototubes and light funnels (a) light funnel array seen from inside the gas volume The mirror edges are indicated by dashed lines (b) detailed view of one light funnel and its phototube (PM) W plexiglass window, μ μ-metal shielding, Cu copper foil for hf-shielding

number of photoelectrons $\bar{n} = -\log(1-\varepsilon) = 7.3 \pm 0\ 5$, in agreement with the calculated value $\bar{n} = 7\ 5$ Also the measured multiplicity and pulseheight distributions are in agreement with this number Note that the mean number of phototubes is expected to be smaller than the mean number of photoelectrons The agreement of fig 4c with $\bar{n} = 7\ 5$ was checked carefully by computation

In the practical application, the efficiency of the counter is reduced by use of the 1 2 signal and by various cuts which were applied in the off-line event selection in order to improve the rejection of muons from $K_{\mu 2}$ decay These cuts were different in refs. 3 and 4 Numerical values for the rejection and efficiency are compiled in table 2 The timing cut corresponded to the 3.2 ns window indicated in fig 4a The pulse height

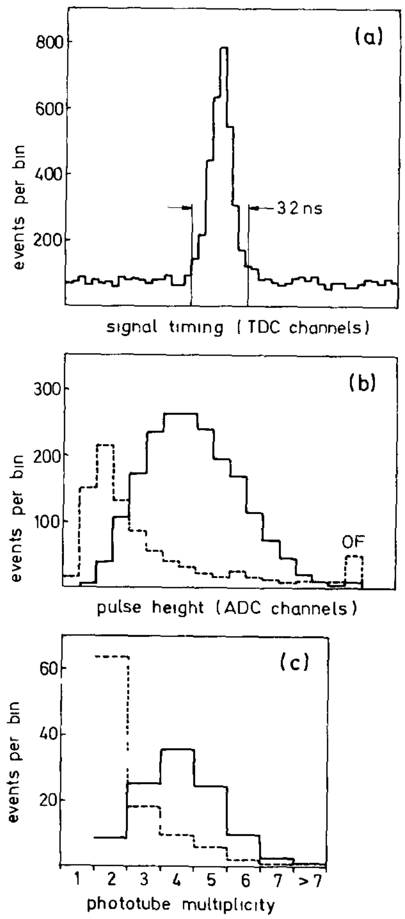

Fig 4 (a) Timing distribution of Cherenkov counter signals from both electrons and random background (b) Pulse height distribution of Cherenkov counter signals Full line electrons, dashed line random background (c) Multiplicity of phototubes for Cherenkov counter signals from electrons (full line) and from random background (dashed line)

TABLE 2

Rejection and efficiency of the gas Cherenkov counter under various conditions ε efficiency, r rejection, i e efficiency for slow particles

Signal used	Ref 3		Ref 4	
	ε	r	ε	r
(a) 1 2 signal	0 95	3×10^{-4}	0 955	$1\ 3 \times 10^{-4}$
(b) Timing cut applied to (a)	0 94	5×10^{-5}	0 945	$2\ 6 \times 10^{-5}$
(c) Pulse height cut applied to (b)	0 86	$1\ 6 \times 10^{-5}$	0.89	$1\ 1 \times 10^{-5}$
(d) Location cut applied to (c)	—	—	0 89	6×10^{-6}
(e) Random contribution subtracted from (d)	—	$< 2 \times 10^{-6}$	—	$< 1\ 5 \times 10^{-6}$ (90% CL)

cut was applied at a fixed threshold in ref. 3, while in ref 4 a variable threshold depending on the phototube multiplicity was applied. The location cut removed events in which the location of the signal carrying phototubes in the array (fig 3a) was incompatible with the observed track direction This cut was applied only in ref 4

The resulting performance of the counter is demonstrated in fig. 5, which shows the momentum distribution of particles associated with Cherenkov counter signals after application of all cuts At the momentum of $K_{\mu 2}$ muons, $p = 236$ MeV/c, a bump corresponding

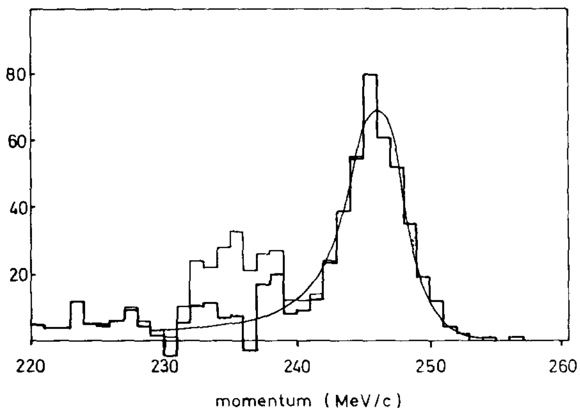

Fig 5 Momentum spectrum of particles with Cherenkov counter signals, taken from the experiment described in ref 4 Thin line data with all cuts (table 2) applied Thick line data after subtraction of events with random Cherenkov counter signals Smooth curve K_{e2} line at 247 MeV/c with calculated radiative tail.

to a rejection of 6×10^{-6} is visible If the momentum distribution of events with random timing (fig 4a) is subtracted, the $K_{\mu 2}$ bump disappears Taking the radiation tail of the K_{e2} line into account, an upper limit of $1\ 5 \times 10^{-6}$ (90% CL) for the breakthrough of muons is obtained The efficiency for electrons under these conditions is $0\ 89 \pm 0\ 01$

It should be noted, that the rejection of $K_{\mu 2}$ muons would have been limited to about 10^{-2} if just the signal of any one of the phototubes had been used The total rate of 1-PM-signals was $\sim 10^{6}$ cps in this experiment

5. Conclusions

The results presented in this paper demonstrate that in a large aperture Cherenkov counter the breakthrough of unwanted slow particles can be kept at a level $< 1\ 5 \times 10^{-6}$ The most essential design feature of the counter described here is the phototube array used for the detection of the Cherenkov light A coincidence requirement within this array is a powerful remedy not only against random background, but also against breakthrough due to gas scintillations This is of great importance, since only very few gases do not scintillate and since, on the other hand, a satisfactory operation of the counter requires a careful selection of the refractive index of the gas Another interesting feature of the counter is the aluminized mylar mirror The curvatures of such a mirror can be adjusted conveniently and without noticeable relaxation

By suitable combination of these elements and by a careful choice of the gas it should be possible to construct large aperture Cherenkov counters with good rejection for a variety of applications

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