GAS CHERENKOV COUNTERS

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The recent rapid spread of the use of Cherenkov counters (C-counters) has reached the point where practically every experiment involving counter arrays to identify high-energy events incorporates one or more C-counters along with more conventional scintillation detectors. The review article by J. Marshall[1], together with his review paper at the 1956 CERN Symposium[2] and the subsequent discussion give a good survey of general design features and the recent book by Jelley[3] presents additional material.

The C-light is emitted at the angle $\theta = \cos^{-1} 1/\beta n$ with respect to the path of the radiating particle. n is the refractive index of the converter. The number of photons with frequency in the interval Δv, emitted at this angle per cm of path is

$$n_\phi = 2\pi\alpha\frac{\Delta v}{c}\sin^2\theta .$$

These classical expressions suffice for all design considerations. It is customary to define an effective number of photons $N_\phi = K l \sin^2\theta$, where l is the path length in the counter and

$$K = \frac{2\pi\alpha}{\bar{\varepsilon}}\int \varepsilon(v)\frac{dv}{c} .$$

$\bar{\varepsilon}$ is the photoelectric efficiency of the photo-multiplier (P M) cathode. A typical value is $K \simeq 500$. The number of photoelectrons produced is $N = \eta\, Kl \sin^2\theta$ where η is the product of the light collection efficiency and the average photoelectric efficiency. Typical values are $0.02 < \eta < 0.15$.

A very useful feature of the C-counter is its very fast response. All of the designs of interest here yield a signal with delay and duration which are small compared with the resolution capabilities of present PM tubes and circuits.

The applications of C-counters almost always make use of their ability to distinguish between highly relativistic particles on the basis of their velocities, in particular the unique ability to respond to particles with high velocity while rejecting others with lower velocity. We shall see that it is almost always desirable for good velocity resolution to operate a counter with a refractive index close to the threshold value $n = 1/\beta$. It is difficult to find suitable solid or liquid materials with $n < 1.3$ and it is almost impossible to vary the index of such materials over an appreciable range in a convenient manner. For these reasons gas C-counters are coming into wider use, especially as higher energy accelerators approach operation.

C-counters are used either as threshold detectors, rejecting particles with velocity β_0 but counting those with $\beta = \beta_0 + \Delta\beta$; or as differential counters detecting only particles in the range $\beta \pm \Delta\beta$. The discrimination is either between particles of the same mass but different total energy W, in which case we have $\frac{\Delta W}{W} = \frac{P^2}{\beta}\Delta\beta$; or between particles with the same momentum p (in units of Mc) but different mass, in which case $\frac{\Delta M}{M} = \frac{p^2}{\beta^3}\Delta\beta$. These expressions hold for small values of ΔW and ΔM. They show that with increasing energy we require progressively better velocity resolution $\Delta\beta$ in order to achieve acceptable discrimination in mass or energy. The value of $\Delta\beta$ which can be achieved with any particular design depends, of course, on the required values of the efficiency and of the rejection ratio, i.e. the ratio of the efficiencies for particles of the accepted and rejected velocities.

In principle, threshold detectors depend on the fact that particles with $\beta < 1/n$ produce no C-light while those with $\beta > 1/n$ do. In practice a certain minimum number of photons is required to produce a detectable pulse above some discrimination level so that the distinction is between particles producing pulses exceeding this level and those falling below it. We note that the fractional change in photoelectron yield for a velocity change $\Delta\beta$ is

$$\frac{\Delta N}{N} = 2 \cot\text{an}^2\theta \frac{\Delta\beta}{\beta}.$$

On the other hand the smallest change which can be resolved from statistical fluctuations is of the order of

$$\frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{1}{\sqrt{\eta K l} \sin\theta}.$$

Thus

$$\frac{\Delta\beta}{\beta} \simeq \frac{1}{2\sqrt{\eta K l}} \frac{\tan\theta}{\cos\theta}.$$

It is thus desirable to operate with the smallest practical C-angle, i.e. with the lowest value of refractive index n which will yield the number of photoelectrons N_0 required for the desired efficiency. For this case we find $\frac{\Delta\beta}{\beta} = \frac{N_0}{2K\eta l}$. The photomultiplier should be operated with a discrimination level which permits detection of single photoelectrons if the noise level is tolerable. Obviously the highest photocathode efficiency is desirable. The recent introduction of tubes with S20 response such as type RCA 7265 has provided significant improvement in this respect. One may also increase the yield by extending the effective wavelength range into the ultraviolet. The use of quartz optics and phototube nearly doubles the number of photoelectrons produced. There is a limit to this procedure imposed by the dispersion of the refractive index. Finally, the length of the counter must be increased to improve the resolution or to operate at higher energies. The resolution attainable by this procedure is limited by the ionization energy loss of the particles in traversing the counter. It should be noted, however, that the gas density decreases very nearly in inverse proportion to the required length so that this limitation is less severe at high energies. The limiting resolution is approximately

$$\frac{\Delta W}{W} \simeq \frac{\Delta M}{M} \simeq \sqrt{\frac{2N_0\varepsilon}{3K\eta WD}},$$

where D is the constant of the Lorentz-Lorenz law $\frac{n^2+1}{n^2+2} = D\rho$ and ε is the energy loss per gm/cm^2 in the same units as W.(*) The most severe limitation on the discrimination ratio arises from knock-on electrons which can have a greater β than the primary particles. The only effective way to eliminate this background would seem to be to use two C-counters in coincidence, separated by a magnetic field to prevent electrons from traversing both counters.

We note that small-angle scattering or beam spread should not interfere with the operation of a threshold counter, provided the particles traverse the full counter length.

Differential C-detection depend on the selection of the C-angle $\theta = \cos^{-1}\frac{1}{\beta n}$. We note that $\frac{d\theta}{d\beta} = \frac{1}{\beta\tan\theta}$ so that for a given angular resolution of the optical system the best resolution in β is obtained for operation near threshold. On the other hand the number of photoelectrons emitted is

$$N = K\frac{l\eta}{\beta^4 n}\left(\frac{\Delta\theta}{\Delta\beta}\right)^2$$

so that for a fixed counter length the C-angle must be chosen large enough to assure the desired efficiency. As in the case of the threshold detector, increasing energy, requiring smaller $\Delta\beta$, involves the use of longer counters. In the case of the differential counter the limitations imposed by the ionization loss may, in principle, be overcome by the design of an optical system which accepts different angles from different parts of the path. The optical dispersion can, in principle, also be compensated by the use of compensating lenses. The production of knock-on electrons is less serious than in the case of the threshold detector since the light from these particles is not likely to be emitted in the acceptance angle.

For the same reason scintillation of the gas, which can be a very serious problem in threshold counters is of negligible effect in differential counters.

On the other hand particle scattering in the counter or, for that matter angular spread of the particle beam present a more serious problem, as does light scattering either in the gas or from flaws in the reflecting counter walls.

(*) From the point of view of minimum ε/D, the most favorable of the common gases seems to be hydrogen, but its low density limits its use to very high energies.

C-counters with good resolution of necessity tend to produce marginal light intensity. This means that the photomultipliers must be operated at or near the threshold of detection for single photoelectrons. This produces a high back-ground counting rate which always necessitates operation of these counters in coincidence with other fast detectors. Certain precautions may be needed to reduce the background to the point where accidental coincidences are negligible. It is important to keep the photomultiplier out of the particle beam. Similarly no scintillating material should face the photocathode. The discriminator which determines the acceptance level for the counter pulses should have a very short resolving time to suppress " pile-up " of noise pulses. If necessary, two photomultipliers in coincidence may be used on the same C-radiator if sufficient light is available.

A fairly wide variety of gases is used for C-counters. At very high energy CO_2 or even air has been used. For lower velocities ($0.98 > \beta$) denser gases, such as SF_6 or CCl_2F_2 are more convenient since they permit the use of more moderate pressures. At even lower energies ($0.8 > \beta$) it is necessary to use a gas near its critical point to attain sufficient density. For this reason the fluoro carbon FC 75 (Perfluor–3–butyl–tetrahydro–furan, $C_8F_{16}O$) with $T_e = 227°$ C $p_c = 232$ p.s.i. is used. Other, similar compounds may be even more suitable. Many gases must be rejected either because of optical absorption or because of undesirable chemical properties.

We shall now describe two counters which have been successfully used. The first of these is a threshold counter developed at UCRL, Berkeley[4] and used for threshold values $0.980 < \beta < 0.99$. The main construction features (Fig. 1) are similar to some earlier

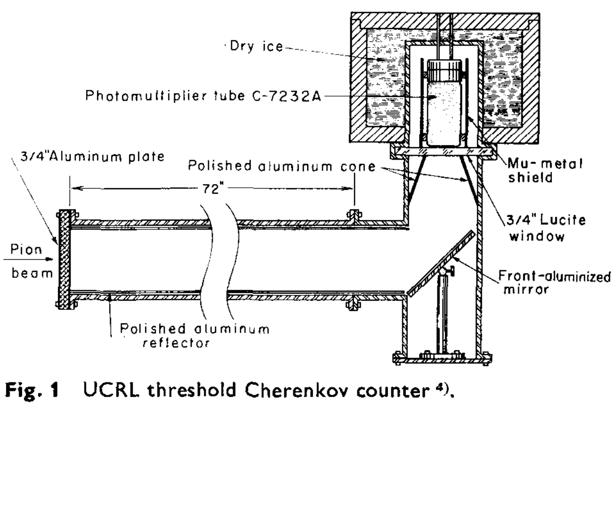

Fig. 1 UCRL threshold Cherenkov counter [4].

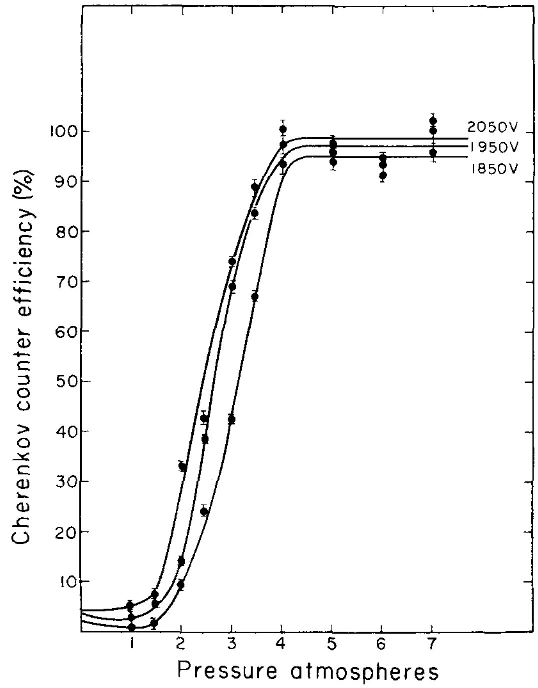

Fig. 2 Response curves of the threshold Cherenkov counter of Fig. 1.

designs [5-6]. The counter is 2 meters long and 10 cm in diameter. It has been used both with SF_6 and CCl_2F_2 filling. Figure 2 shows typical response curves, at different bias levels, for 3 GeV pions. From these and similar curves one finds the threshold value $n\Delta\beta$ for a rejection ratio of 10

$$5 \times 10^{-4} < n\Delta\beta < 2.5 < 10^{-3},$$

depending on the bias level used. With the lowest bias level this corresponds to an energy resolution, for pions, of about 4% at 1 GeV and about 30% at 2.2 Gev. It should permit the separation of protons from mesons up to about 20 GeV, of K from π mesons up to 12 GeV and of π from μ mesons up to 2.2 GeV. If we compare this performance with our preceding general discussion we find that the observed resolution is in agreement with the expression $\Delta\beta = N_0/2K\eta l$ if we assume $N_0 = 5$, $\eta = 0.05$ which seems very plausible. The fact that it was found necessary to cool the PM tube certainly suggests that the detection level of single photoelectrons was reached.

The second device is a differential focusing counter constructed at MIT[7-8] to be used in the range $0.78 < \beta < 0.999$ for separating K particles from

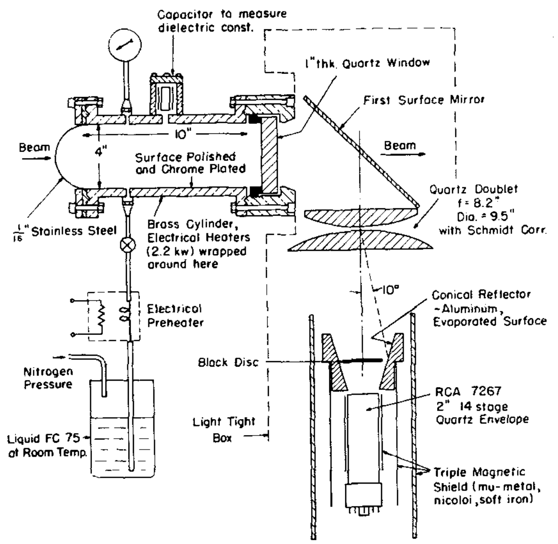

Fig. 3 MIT differential Cherenkov counter [7, 8]. Ring aperture is formed by black disc and its image in conical reflector. Thermostat and oven insulation around counter are not shown.

pions and protons. A schematic design is shown in Figure 3. The counter is 25 cm long, 10 cm in diameter and filled with FC75. The optical system is illustrated schematically in Figure 4. Ideally, all rays originating in the counter at an angle $\theta = 12°$ from the counter axis intersect the focal plane of the lens in a ring of radius $r = f \tan \theta$. A small range $\Delta\theta$ is selected by placing an annular opening of mean radius r in the focal plane. This annulus is formed by a central disc and its reflected image in the " light funnel " above the PM tube in Figure 4. The two-

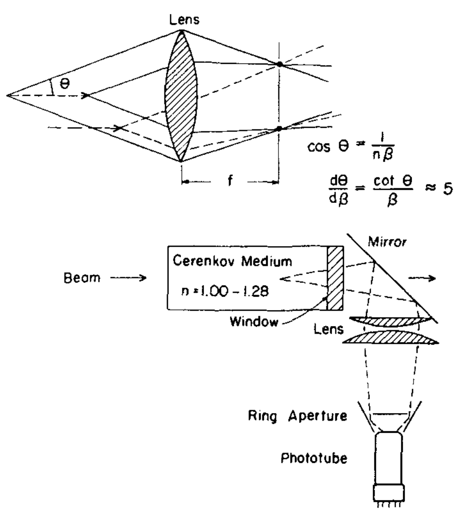

Fig. 4 Optical system of the MIT counter.

element condenser lens is basically a Schmidt-type refractive system, combined with a microscopic-type aplanatic surface that at the same time is automatically anastigmatic. The system is essentially free of coma and astigmatism but has curvature of field (unimportant at the ring focus) and some spherical aberration. The plane mirror is front-aluminised and coated with SiO. Quartz optics was used in order to utilize a wider wavelength band but it was found that in the experiments carried out with this counter a glass PM tube yielded a sufficient pulse, although a quartz tube presented some improvement.

The relevant properties of FC75 are shown in Figure 5. In order to cover the range of n required the material had to be in the neighborhood of the critical point which results in a somewhat cumbersome design. Especially the great thickness of the quartz window results in energy loss and scattering of particles passing through the counter. If this is not acceptable, it may be preferable to design a counter with part of the optical system inside the pressure vessel. Some preliminary experiments with fluorocarbon F14 have been encouraging and there is reason to believe that C318 (octofluorocyclobutane) may be a useful substitute for FC75. The density of the counter gas must be controlled within limits of the order of one per cent. This is done by measuring the dielectric constant. A 50 pF parallel-plate condenser is immersed in the side-tube indicated in Figure 3

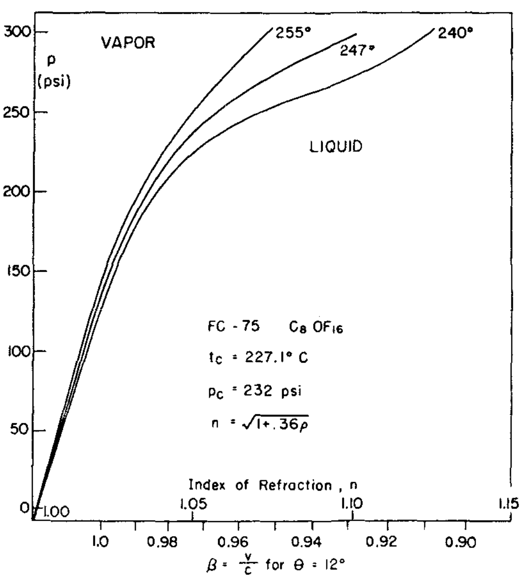

Fig. 5 Index of refraction of C_8OF_{16} vapor.

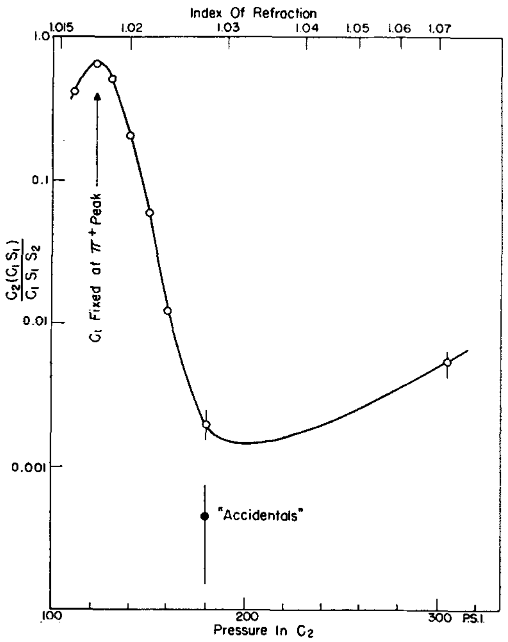

Fig. 6 Efficiency vs. pressure in "selected" 2.6 GeV/c π^+ beam.

and the capacity measured by a bridge circuit. A signal from this bridge can be used to control the heater current automatically.

The performance of this counter in the actual experiments was limited by the properties of the particle beam rather than by optical consideration. The angular spread of the beam was about $\pm 1°$ and the annular aperture was adjusted to accept this spread. The beam filled the entire aperture of the counter. As a result the light collection efficiency for some of the rays was very poor. The expected number of photoelectrons is about $N = 500\,\eta$ and the majority of the pulses showed ample intensity. A direct coincidence experiment could only establish a lower limit of about 70% for the average efficiency for particles of the accepted β.

Figure 6 shows an experimental resolution curve, obtained with pions selected by magnetic deflection and passage through another, similar C-counter. The observed value of $\Delta\beta \simeq 4 \times 10^{-3}$ for a rejection ratio of 10 is in good agreement with the accepted angular spread of 1°. Figure 7 shows the actual performance of this counter in discriminating between particles of different mass but the same momentum.

At lower energies the angular acceptance range $\Delta\Theta$ must be increased to match the spread introduced by energy loss and small-angle scattering, as illustrated in Fig. 8.

Counters of similar design are now being developed in several laboratories, e.g. at CERN and at the Collège de France. Such a counter, being put into operation at CERN, is illustrated in Fig. 9. This counter is designed for higher energies and operates with a smaller C angle, about 5°, permitting better resolution at the cost of more stringent collimation of the beam and of greater counter length. The smaller angle reduces the problems of optical aberra-

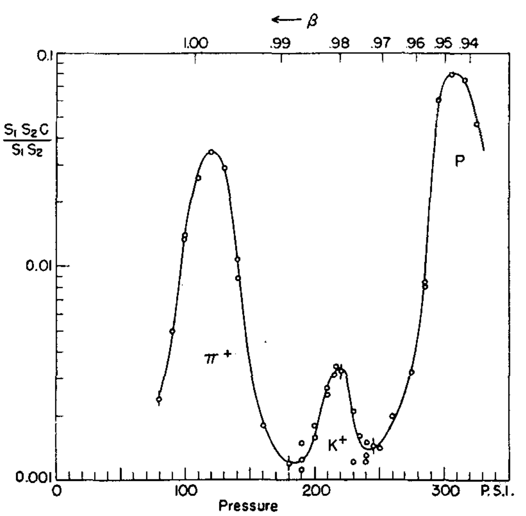

Fig. 7 Counter response vs. pressure in 2.6 GeV/c beam.

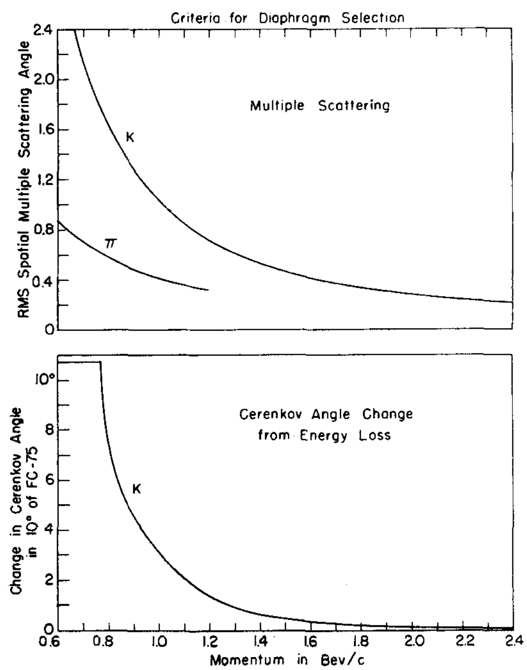

Fig. 8 Criteria for diaphgram selection.

tions so that mirror rather than lens optics becomes possible. This is a considerable advantage since C_2H_4 is used as filling gas, requiring pressures up to 70 atmospheres, although at lower temperatures than the halogen compounds. In order to improve the light collection efficiency, the simple conical light " funnel " of Fig. 3 is replaced by an approximately ellipsoidal focusing funnel. A total-reflexion refractometer is provided to calibrate the condenser device which is similar to that used at MIT. Figure 10 shows the limiting factors governing the resolution of this counter. Because of the more stringent angular definition, multiple scattering is of greater relative importance that at MIT.

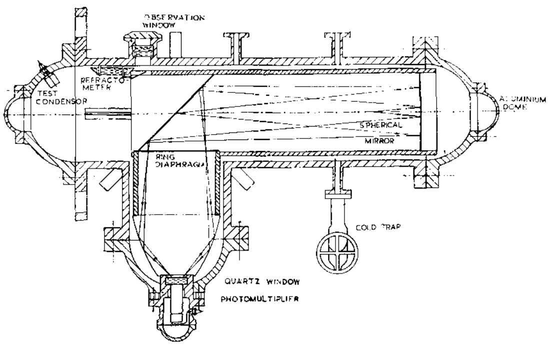

Fig. 9 CERN differential Cherenkov counter.

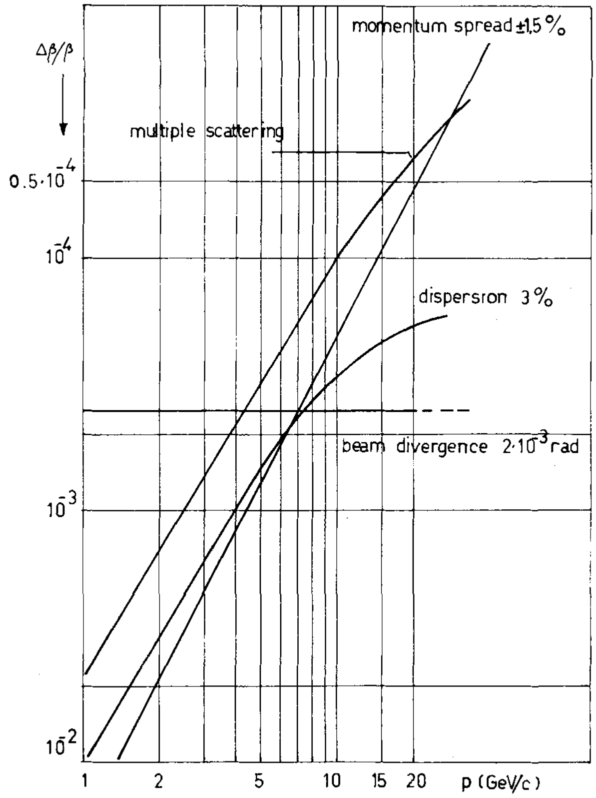

Fig. 10 Limiting factors in counter of Fig. 9 (max. acceptable $\Delta\beta/\beta = \pm 2\times10^{-3}$).

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(*) See note on reports, p. 696.

DISCUSSION

GALBRAITH: Can you say something about the operational experience of the differential Cherenkov counter using FC 75? For example, do you have difficulty in keeping the optical properties constant with time?

DEUTSCH: In fact, I did not have time to point to the way in which this has been monitored. In fact the counter ran for I think of the order of two weeks without any appreciable change in the optical properties. We did not monitor the optical properties as such. What was monitored was the dielectric constant and it was hoped that the optics would stay constant. This was found to be true over periods of even a couple of weeks. The dielectric constant was monitored by immersing a condenser into the counter gas and then monitoring its capacity. In principle, this could be fed back to the heating coil on the liquid but we found this not necessary. It was constant enough.

KOECHLIN: Is the particle beam very focused in this gas Cherenkov counter?

DEUTSCH: The particle beam had an angular spread of 1° which was the thing that limited the resolution. The beam filled almost the entire aperture of the counter radially and as a result there were marginal particles. If particles pass near the wall of the counter it is quite probable that the efficiency for detecting them was significantly less. All we know is that the efficiency over this entire area under the conditions shown was better than about 70%. We do not know how much better because of the particular conditions of the determination.

HOW MUCH DO WAVELENGTH SHIFTERS USED FOR CHERENKOV COUNTERS SCINTILLATE?

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(presented by L. Mezzetti)

The remarks I am going to present to you very briefly are somewhat marginal with respect to the main subject of this session, the detection of very high energy particles. They refer rather to the routine work of an experimentalist using Cherenkov counters, and it may be useful to someone, preventing him from wasting time in unsuccessful trials to improve the performance of his counters.

In the past few years several authors have used, or suggested using, wave shifters dissolved in typical liquid Cherenkov radiators to increase the light output and thereby the resolution of liquid Cherenkov counters of the non-focusing type. In particular, it has been reported that dissolution of small quantities of betha-methyl-umbelliferone in water and of POPOP in carbon tetrachloride increases the light output by a factor of two; increases by even greater factors have been found by using amino-G-acid. This technique would appear to be very appropriate because the wave shifting action would take place near the point where the ultraviolet light is produced, before it has had a chance to get lost by absorption in the medium or at the walls of the counter.

Scintillation of the solution would, of course, destroy the dependence of the light output from the energy, which is characteristic of a Cherenkov counter, in particular the useful threshold property. To show that this is not the case, the light output obtained with particles well below the Cherenkov threshold was measured. This, however, seemed to us not to be a direct and clear cut test for two reasons:

1. The optical efficiency is not the same as in the case of particles above Cherenkov threshold, because the geometry of the light source is different.