MEASUREMENT OF PARTICLE VELOCITIES AT NAL

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ABSTRACT

A survey of various possibilities for counters to determine the velocities of particles in the NAL energy range is given. Cerenkov, dE/dx, secondary emission, transition radiation, and miscellaneous other counters are considered. It is concluded that only Cerenkov counters provide proven capabilities at present, with transition radiation and secondary-emission detectors showing promise for the future.

I. CERENKOV COUNTERS

We recall that the threshold for Cerenkov radiation is at

$$\beta_{thr} = \frac{1}{n}, \tag{I. 1}$$

where n is the refractive index of the medium. The Cerenkov angle is given by

$$\cos \theta_c = \frac{1}{\beta n}. \tag{I. 2}$$

For large γ,

$$\beta = 1 - \frac{1}{2\gamma^2}. \tag{I. 3}$$

Substituting (3) into (1) we see that

$$\frac{1}{2\gamma_{th}^2} = n - 1. \tag{I. 4}$$

For E >>m, for a fixed momentum, $\gamma_1/\gamma_2 = m_2/m_1$ for particles of mass m_1 and m_2. Therefore,

$$\frac{(n-1)_{th,1}}{(n-1)_{th,2}} = \frac{m_1^2}{m_2^2}. \tag{I. 5}$$

We note the following points:

1. From Eq. (I.5) we see there is in principle no reason why threshold counters should not work up to arbitrarily high energies. In fact, with a qualification we shall discuss below, a threshold Cerenkov counter functions as a device dependent on γ^2 rather than β.

2. The number of photoelectrons produced by the Cerenkov light generated in 1 cm of medium incident on a UVP photocathode is given by[1]

$$N = 272 \sin^2 \theta_c. \tag{I.6}$$

Suppose we wish to count particle A and not particle B, where $m_B > m_A$. Then we can select $(n - 1) = 1/2\gamma_B^2$ and $\theta_C^2 = (1/\gamma_B^2 - 1/\gamma_A^2)$ for particle A. Therefore, $N_e = 272\ (1/\gamma_B^2 - 1/\gamma_A^2)\ell$, where ℓ is the length of the counter in cm.

It is therefore obvious that to discriminate between two particles and retain a definite detection efficiency, the length of the counter increases as the square of the particle momentum.

As a practical example, consider separation of π's and K's at 100 GeV. If we demand an average of 10 photoelectrons, we arrive at a length of ℓ = 15 meters. In estimating the length required for a given counter, it is useful to recall that the distribution in photoelectrons is very nearly Poisson and the length can be scaled according to the rejection efficiency required. In view of the small angles of the emitted radiation it is also reasonable to assume no losses in light transmission other than those accounted for in Eq. (I.6).

3. Dispersion. One of the most important factors in determining the ultimate resolution of a Cerenkov counter is the dispersion, $dn/d\lambda$. Since $d\beta/\beta = dn/n$, $d\beta \approx dn/n$. We note that in a gas, however, dn/n is not constant. In fact, as the pressure is varied, $d(n-1)/(n-1)$ is constant for a given gas. Therefore, $dn = K(n-1)$. Typical numbers are $n - 1 \sim 2 \times 10^{-3}$ at NTP, so $dn \sim 2 \times 10^{-5}$ at NTP, over the sensitive wavelength region of the phototube, yielding a corresponding error in β.

Dispersion can be corrected optically to first order and this can yield an improvement of approximately a factor of 10.

4. Scattering and δ rays are less of a problem at high energies than they are at lower energies.

From the above notes, it is clear that if we allow the length of Cerenkov counters to increase as the square of the energy of the particle we wish to detect, then the Cerenkov counter functions as a detector sensitive to γ^2, rather than β.

On the other hand, if we keep the length fixed as we increase the energy, threshold counters fail because too few photons are emitted. In a differential counter we can overcome this problem by increasing the pressure, but then dispersion limits the ability to discriminate between different particles.

Beam Cerenkov Counters

With the exception of hyperon beams, the proposed beams at NAL are long enough, and have sufficiently low divergences for Cerenkov counters to be used in the "γ^2 mode." Both differential and threshold counters are clearly trivial to construct. In fact, in view of the small emission angles of the light, it is sufficient to fill a vacuum pipe with gas at low pressure and place a 45° mirror and a 5 in. phototube at the end in order to make a threshold counter. Differential counters are almost as easy to make.

Hyperon beams represent a problem as the mean decay length for a hyperon at 150 GeV/$_L$ ~ 5 meters. It is possible to build a DISC type counter 2 meters long which would provide adequate discrimination,[2] but a shorter counter would clearly be desirable.

Counters for Identification of Interaction or Decay Products

The situation here is not nearly as satisfactory as it is for the beam counters. In general, greater angular acceptance is required and there are limitations on the length of counters that can be used.

Threshold counters can be constructed with adequate angular acceptance for most experiments, and the main problem is that of length.

A DISC type Cerenkov counter two meters long, capable of resolution of $d\beta/\beta \sim 10^{-6}$ has been built.[2,3] However, it has an angular acceptance of 0.1-5 mrad, and it can best be used in a complex spectrometer setup which matches the acceptance to the incident beam and is essentially designed around the counter. It would appear that if one is prepared to sacrifice the use of the counter as a trigger device, the acceptance could be increased to about 10 mrad by use of image intensifiers and video readout.

Conclusions

From the above it is clear that the major need is for a velocity sensitive detector which has <u>wider angular acceptance</u>, and/or is <u>shorter</u> than Cerenkov counters.

It is from this viewpoint that we examine other proposed schemes for velocity sensitive counters.

II. dE/dx MEASUREMENTS

The mean ionization energy loss for a charged particle passing through a material is given by:

$$\frac{dE}{dX} = \frac{2\pi Ne^4}{m_e\beta^2c^2}\left\{ \ell n \left[\frac{2m_e\beta^2c^2W_{max}\gamma^2}{I^2} \right] - 2\beta^2 - \delta \right\} \quad \text{(II.1)}$$

where
m_e = the electron mass
N = number of electrons per cm^3
I = mean excitation potential of the medium
W_{max} = max energy transfer to an electron
δ = "density effect" correction

The term δ is caused by the polarization of the medium which weakens the effective field of the incident particle.[4] Its effect is such that at large γ, it cancels the relativistic rise we would expect from the $\ell n(K\gamma^2)$ term. Its dependence on γ is shown qualitatively in Fig. 1. From the figure it is also clear that for low densities δ is suppressed and does not completely offset the relativistic rise in dE/dX until higher γ values. Low densities can be achieved either by using a gas, or by using thin foils of scintillating material.

Gases

For a gas counter one can either use a scintillating gas such as Xe, or make a proportional counter. The analysis is similar and since the density effect is less severe in high-Z noble gases we shall consider only a Xe scintillation counter here.

The energy loss in a material is a statistical process and is governed by the Landau distribution, which is shown in Fig. 2 for 100 GeV π's and K's passing through 1 meter of Xe at 1 atmosphere.

The skew nature of the curve implies that in a beam of, say, π's and K's there is a lower probability of the π losing less energy than E^K prob, than there is for the K to lose more energy than E^π prob. The condition for identification of a π should therefore be: no energy loss less than E, where E is some threshold energy, i.e., an energy loss < E implies a K. This gives better resolution than the alternative which is detection of an energy loss > E' implies a π. This basic asymmetry therefore implies that such a detector would function better in a beam of few light particles to many heavy particles than it would in a beam where the ratio was reversed. We refer to counters of this type as threshold counters.

Another important property of the Landau distribution is that one gets more information from N detectors of thickness t, than from one detector, thickness Nt.

Detailed calculations show that for a threshold xenon scintillation-counter array 15 meters long, consisting of thirty 1/2-meter detectors filled with gas at 2 atmospheres, the efficiency for detection of π's at 100 GeV is 5×10^{-4} and for K's it is 0.08.[2] This compares unfavorably with a threshold Cerenkov of the same length, which would give 10 photoelectrons for π's and 0 for K's. Further the Cerenkov can be used in coincidence or anticoincidence and there is no asymmetry of the type discussed above.

The pressure dependence of δ is given by[4] $\delta = \delta\left(qp^{1/2}\right)$ where q is momentum and p is pressure. From this it is obvious that the length of counter required for a given discrimination increases as γ^2, just as it does in a Cerenkov counter. We can therefore conclude that as threshold detectors these counters are not competitive with threshold Cerenkovs at NAL energies, or any higher energies.

It is clear that these threshold arrays do not make maximal use of the information provided by the ionization loss. If one is prepared to sacrifice the use of the counter for triggering, and log the pulse heights from each element of the array, one could obtain far better resolution for a given array. This is discussed by Prof. Jones in SS-93, and the reader can compare these results.

Solids

The density effect does not occur in solids for sufficiently thin layers of the solid.[5] Typically the thickness must be $<< 10^{-3}$ cm and a very large number of foils ($> 10^5$) is required for suitable discrimination. Further the foils must be separated by a distance $d \sim hc\gamma^2/\bar{I}$, where I is the mean ionization potential of the medium. We may safely proceed to a similar, but far more promising approach.

III. SECONDARY EMISSION DETECTORS

Secondary emission from thin foils has the same energy dependence as ionization loss,[6,7] and electrons emitted in the backward direction which emerge from the foils, originate in a very thin layer near the surface and are unaffected by the density effect.

Very few secondary electrons are emitted from metallic foils. However, early work seemed to indicate that 5-6 electrons per surface could be obtained by coating the surfaces with alkali halides.[7] Unfortunately very careful work by Garwin and Llacer[8] showed that the situation was in fact nowhere near as promising as the early work had indicated. Multiplication in the material itself leads to the high average number of electrons emitted per surface and there is a high probability (~30%) for no emission at one surface. Further p(n), the probability for the emission of n electrons follows an exponential law $p(n) \propto e^{-\alpha n}$ which leads to very unfavorable statistics in the energy determination. In addition, these early measurements were made in intense electron beams, which enhances the emission. The alkali-halide treated surfaces do not appear to be a fruitful approach.

A recent theoretical estimate of the secondary emission from cesiated gallium arsenide predicts a very high yield (~50 per surface for minimum ionizing particles).[9] Early experimental work bears out the predictions[10] and further experimental work is in progress at SLAC. Should this confirm the early results, a detector with 20 plates could give 25:1 discrimination between 50 GeV π's and K's. The diffusion times for the secondary electrons to leave the foil are of the order of picosecs. This method seems to hold a lot of promise for fast, short, wide angle counters.

IV. TRANSITION RADIATION

When a charged particle crosses the boundary from a medium of dielectric constant ϵ to vacuum, or from vacuum into the medium, electromagnetic radiation known as transition radiation is emitted.

The intensity emitted in a frequency interval $d\omega$ and into solid angle $d\Omega$ is given by[11]

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2\beta^2 \sin^2\theta \cos^2\theta}{\pi^2 c(1-\beta^2\cos^2\theta)^2} \left| \frac{(\epsilon-1)(1-\beta^2 \mp \sqrt{\epsilon-\sin^2\theta})}{\epsilon\cos\theta + \sqrt{\epsilon-\sin^2\theta}\left(1 \mp \sqrt{\epsilon-\sin^2\theta}\right)} \right|^2 \qquad \text{(IV.1)}$$

The + sign is for forward radiation for vacuum to medium transitions or backward radiation in the medium to vacuum transitions, and the - sign is for backward radiation in vacuum-medium transitions or forward radiation in medium-vacuum transitions.

Integration of Eq. (IV.1) over ω and Ω shows that in the optical and near UV

$$W \propto \ln\left(E_{inc}/M_{inc}c^2\right), \qquad \text{(IV.2)}$$

and in the x-ray region

$$W \propto \left(E_{inc}/M_{inc}c^2\right). \qquad \text{(IV.3)}$$

We shall discuss the two regions separately.

A. Optical

The logarithmic dependence on the incident energy coupled with the low probability of photon emission (~10^{-3}/surface), makes the detector very insensitive and ~10^5 plates are needed to discriminate π's from K's at NAL energies. However, if we examine the intensity dependence on incident energy in the angular interval 0 to θ we find[11]

$$\frac{dW}{d\omega} = \frac{e^2}{\pi c}\left[-\frac{1}{1+\frac{1}{(\gamma\theta)^2}} + \ln 1 + (\gamma\theta)^2\right].$$

For $(\gamma\theta) << 1$

$$\frac{dW}{d\omega} \simeq \frac{e^2}{2\pi c}(\gamma\theta)^4,$$

and for $(\gamma\theta) >> 1$

$$\frac{dW}{d\omega} \simeq \frac{e^2}{\pi c}\left[2 \ln(\gamma\theta) - 1\right].$$

Although there is a loss in intensity if one uses only the light for which $(\gamma\theta) << 1$, the strong energy dependence more than compensates for this loss. Actually for the counter design we shall discuss below, a compromise design with $\gamma\theta_{max} \sim 20$ is found to be optimum.[11]

Before discussing this counter we note:

1. From a single plate we get the sum of the radiation from both surfaces if $t_p \sim c/\omega = \lambda\!\!\!^{-}$, where t_p is the thickness of the plate, and $\lambda\!\!\!^{-}$ is the wavelength of the radiation divided by 2π.

2. For two or more plates we require a formation zone of vacuum between the plates in order to get the sum of the radiation from each plate. This thickness is given by:

$$t_v = \lambda\!\!\!^{-}\gamma^2; \qquad (\gamma\theta)^2 << 1 \qquad \text{(IV.4a)}$$

$$t_v = \lambda\!\!\!^{-}\gamma^2; \qquad (\gamma\theta)^2 \sim 1 \qquad \text{(b)}$$

$$t_v = 2\lambda\!\!\!^{-}/\theta^2; \qquad (\gamma\theta)^2 >> 1 \qquad \text{(c)}$$

From the above formulae it is clear that the thickness of the counter is almost entirely due to the formation zones, the plates themselves contributing a negligible fraction. Also we see that the length of a counter increases as p^2 to distinguish two different particles of momentum p. (This assumes we keep a fixed $\gamma\theta$ as discussed above.)

Alikhanian et al.,[11] describe a counter designed to minimize the length of counter required for a given discrimination. The counter is designed to work with

$\gamma\theta \sim 20$ for π-K separation and has 3000 plates spaced according to condition (IV.4c). Although this causes a suppression of radiation for which $\gamma\theta < 1$ and leads to a weakening of the energy dependence, the authors point out that this optimizes the length. The counter is shown schematically in Fig. 3. The mirrors 1, 2, etc., are necessary since light is attenuated at the interfaces, and a mirror every 50 plates is proposed.

The authors claim that the counter need only be one-sixth the length of a threshold Cerenkov required for the same discrimination. However, they appear to have underestimated the collection efficiency of a Cerenkov by about a factor of 8. Also they do not appear to have taken into account the mirrors, which would effectively double the length of a 10 cm $\times$ 10 cm counter designed to distinguish π's from K's at 100 GeV.

B. X-Ray Transition Counters

As mentioned earlier, the energy dependence in the x-ray region is much more favorable.

The reason for the departure from the log γ dependence expected for surface phenomena is that the upper limit of ω, ω_{max} increases with γ; ω_{max} is given by the formula

$$\omega_{max} = \frac{\gamma}{2}\sqrt{\frac{4\pi Ne^2}{M_e}} ,$$

where N is the number of free electrons per cm^3.

In addition the formation zone for x rays is far shorter than for optical photons, enabling the counters to be correspondingly shorter.

Recent work of Yuan, Wong, and Prunster[12] shows that a stack of 231 foils, 25μ thick, spaced 0.3 mm apart yields an average of 12 x-ray photons for each 2-BeV positron which traverses the stack. The photons were detected by a lithium-drifted germanium detector.

It is clear that at 150 BeV, a pion could be distinguished from a kaon with a detector less than 1 meter long. Furthermore, as the energy increases, these detectors will compete even more favorably with Cerenkovs, as their length does not increase as γ^2, since λ decreases with γ, and consequently the separation of the plates does not increase as γ^2.

The main difficulty in using these counters is the separation of the sharply forward-peaked radiation from the beam. This is especially troublesome for counters with a large cross-sectional area. One can alleviate the problem, at some expense, by using a large array of small x-ray detectors. Then it is only necessary to bend the particles enough to miss the particular counter at which the x rays are directed. Nonetheless this seems to be the major drawback in an otherwise promising method, which is capable of extension to far higher energies.

Another counter of the x-ray transition type is the resonance counter.[13] Here one needs even fewer foils but the x-ray detection problems are even more severe.

V. MISCELLANEOUS DETECTORS

A. Bremsstrahlung and Synchrotron Radiation

Both of these methods are completely useless for identification of any particles, except electrons, at NAL energies as far too few photons are emitted.

B. Doppler Shift

In principle this method could be used as follows: If a particle can be made to execute periodic oscillations with frequency f, in its own rest frame, then in the lab frame, the observed frequency is

$$f' = f\sqrt{\frac{1+\beta}{1-\beta}} ,$$

in the forward direction; $f' \approx 2\gamma f$ for $\beta \sim 1$.

An ingenious method for obtaining oscillations of sufficient magnitude is the "undulator." This consists of an undulating metallic surface which forces the image charge to oscillate and radiation is thereby emitted. This has actually been observed.[14] Unfortunately the acceptance of such a device is too small to be of any practical use.[15]

C. Interfering Cerenkov Counters

The light produced by the passage of a particle through two Cerenkov radiators is coherent. Consider the simple arrangement shown in Fig. 4; ℓ is the distance between the radiators and d is their thickness. If $\epsilon = 1 - \beta$ and Δt is the time difference between light from the first radiator and light from the corresponding place in the second radiator, then

$$\Delta t = (\ell + d) \left[(2 - n^2)^{1/2} - 1 \right] + \frac{(\ell + d)}{(2 - n^2)} \epsilon .$$

(This is only true for an axial ray.) More generally:

$$\Delta t = f_1 (\ell, d, n) + f_2 (\ell, d, n) \epsilon .$$

Cerenkov light is "white." Suppose we filter the light and accept only a band from say 2800-3200 Å and choose $f_1 = 0$ by suitable compensation; then if $f_2 \epsilon \approx \lambda/2$ we get destructive interference and no signal. Since f_2 is $\approx \ell$, for $\epsilon \approx 10^{-6}$, we require $\ell \sim 10$ cm.

For the counter to have reasonable acceptance it is necessary to make

$\partial f_1/\partial\theta_{inc}$, $\partial f_1/\partial n$, $\partial f_1/\partial x$, and $\partial f_2/\partial\theta_{inc}$ small; θ_{inc} is the angle the incident particle makes with the axis, and x is the distance from axis of the particle. In addition at NAL energies multiple scattering is still a problem, although at higher energies this problem is negligible.

Work is in progress to determine whether a short counter of this type, suitable for hyperon beams, can be constructed.

VI. CONCLUSIONS

At present Cerenkov counters provide the only proven detectors for determination of velocities close to $\beta = 1$. They are perfectly adequate for most proposed beams at NAL but leave something to be desired for the detection of interaction products and for hyperon beams. X-ray transition counters seem the next best tried method, but the detection of the x rays is still a problem. The cesiated gallium arsenide SEM detectors are perhaps the most promising, but they remain to be tested.

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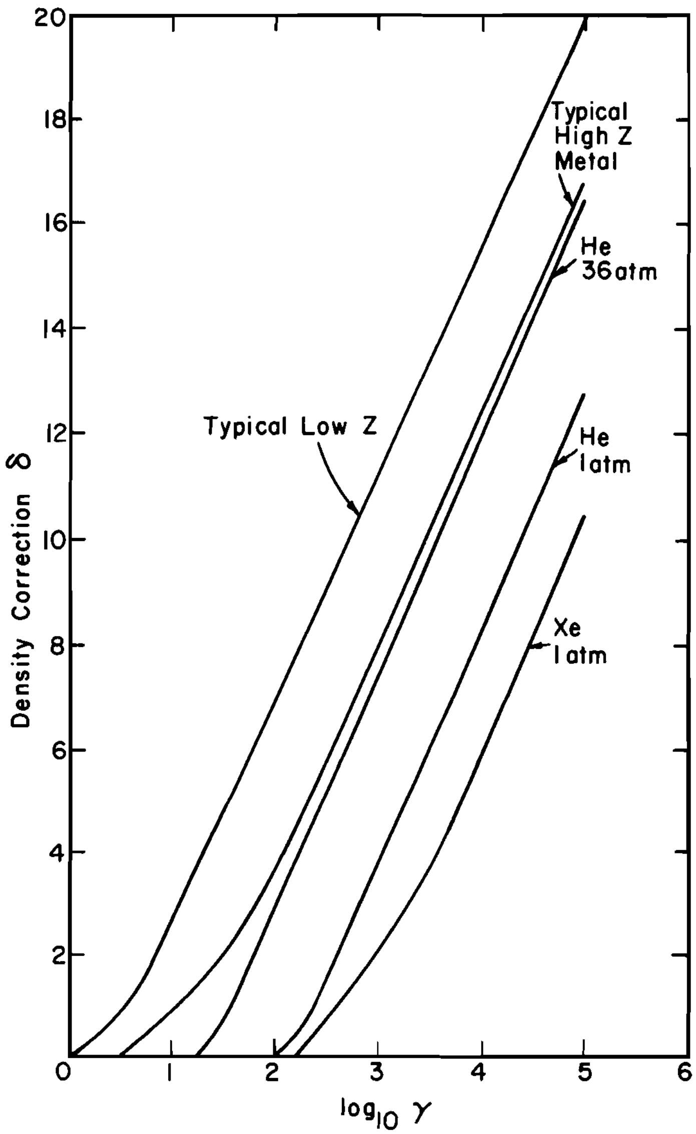

Fig. 1. Density correction for various materials as a function of γ.

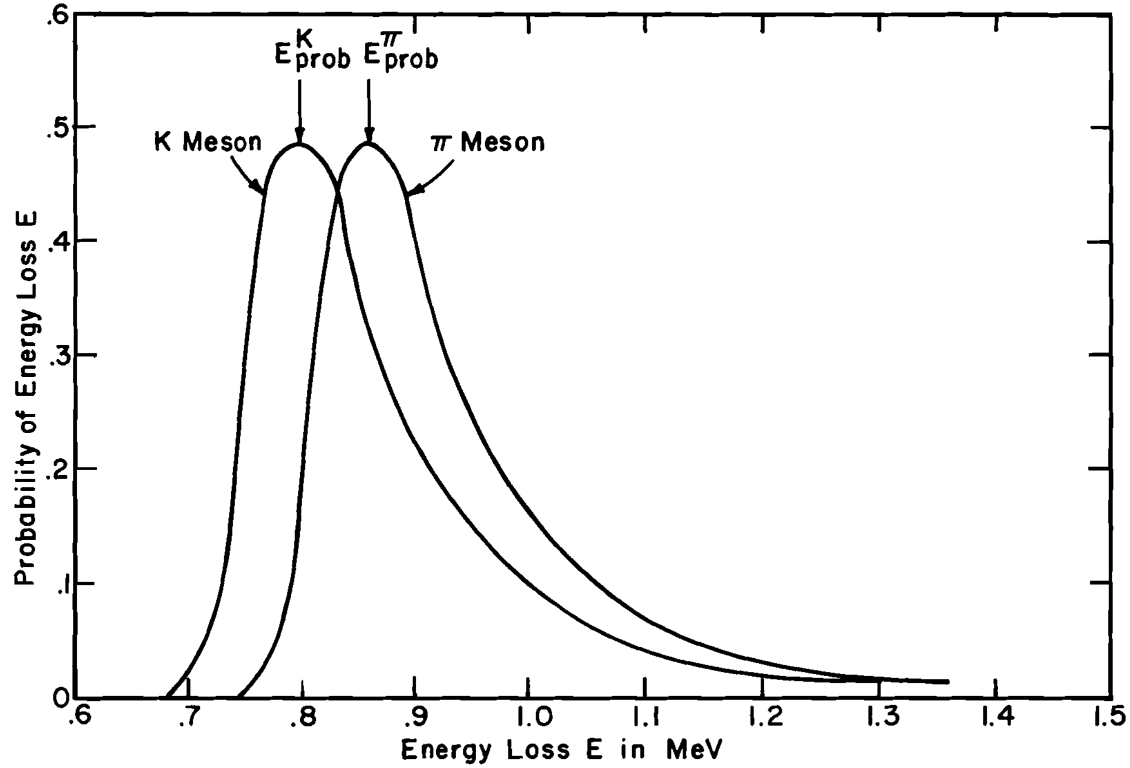

Fig. 2. Probability of energy loss E for 100-GeV π and K mesons in 1 meter of Xe at atmospheric pressure.

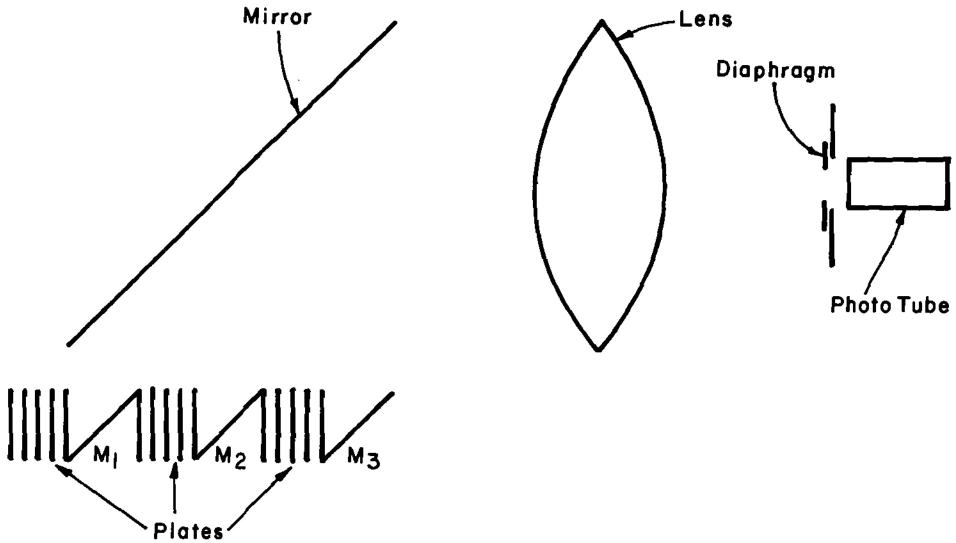

Fig. 3. Schematic drawing of optical transition radiation detector.

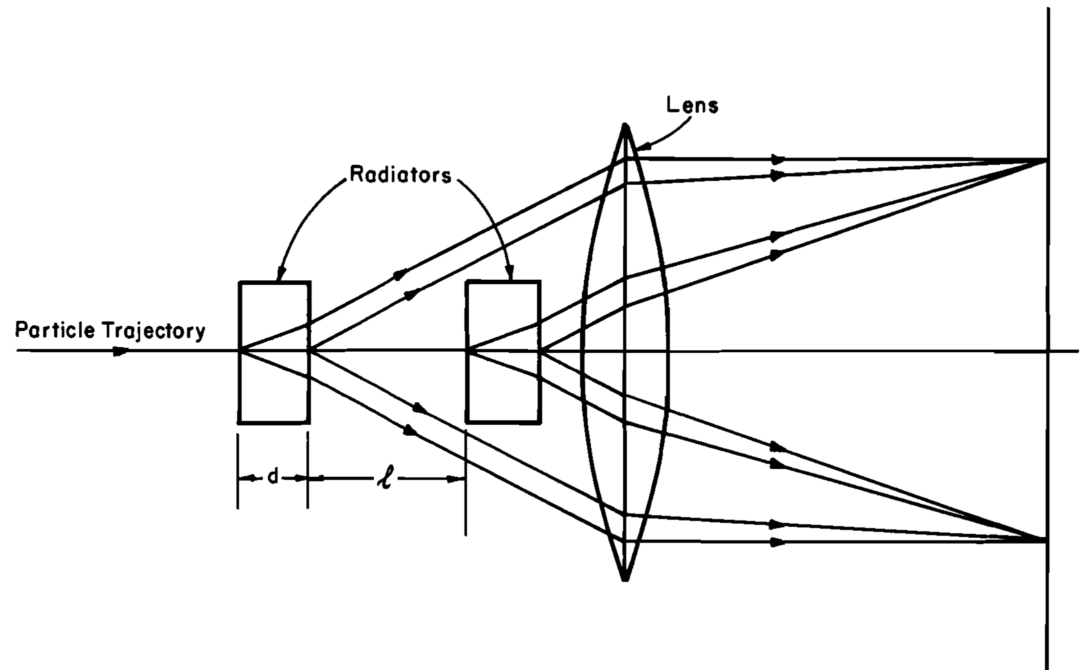

Fig. 4. Schematic drawing of interfering Cerenkov counter.