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ABSTRACT

Cherenkov counters as particle detectors in high-energy physics experiments are discussed, with emphasis on the practical design of velocity-sensitive devices. The performance and problems associated with three types of detectors are considered: simple velocity-threshold counters, wide-band and narrow-band velocity selectors. The limitation in resolution of practical velocity-sensitive counters in high-energy experiments arises mainly from the characteristics of the beams that must pass through their radiators. These limitations include divergences in the direction of the beam particles, multiple coulomb scattering and changes in velocity of particles as they pass through the Cherenkov radiator. Methods of coupling radiators to multiplier phototubes include direct optical contact, specular reflection, and diffuse reflection. Magnesium oxide is an excellent diffuse reflector, and methods of its application are given. Statistical fluctuations in the small numbers of photoelectrons produced from Cherenkov radiators limit the accuracy of determining the times of passage of individual particles.

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INTRODUCTION

It is probably safe to say that most of the experiments in high-energy physics done with counters involve Cherenkov radiation detectors. Several good papers have been written on Cherenkov counters. These include an article by J. Marshall, Annual Review of Nuclear Science 4 (1954), and papers by J. Marshall, J. V. Jelley, and O. Chamberlain and C. Wiegand in the CERN Symposium of 1956, Vol. 2. In their papers can be found the general rules relating to Cherenkov radiation, such as the intensity and the direction of emission and the spectral distribution. The material in this paper comes mainly from the experience of the high-energy physics group at the Radiation Laboratory of the University of California.

Cherenkov counters are used in high-energy nuclear physics experiments as detectors that give information on the velocities of particles: in many instances to discriminate against particles below a certain velocity, sometimes to reject those traveling faster than a given velocity, and in some experiments to actually measure the velocity. It is quite remarkable that the velocity of an individual charged particle moving at nearly the speed of light can be determined within a few percent, even though the measurement takes place along a space interval of only about 10 cm. The measurement of speed is accomplished by determining the angle of emission of the Cherenkov light, which follows the rule

$$\cos\theta = 1/n\beta, \tag{1}$$

where θ is the angle between the light rays and the direction of the particle, n is the index of refraction of the medium, and β is the velocity of the particle divided by the velocity of light.

Practical detectors for use in connection with high-energy accelerators must have high counting efficiencies and be able to accept beams of particles several centimeters in diameter and with a finite angular aperture. Present-day Cherenkov counters consist of two basic parts: a radiator transparent to Cherenkov light and one or more multiplier phototubes to receive the light and convert it to electrical impulses.

A VELOCITY-THRESHOLD DETECTOR

Let us consider the design of a counter to detect particles that exceed a given velocity β_0. We choose a radiator with index of refraction n such that $n\beta_0$ is 1. Particles of lower velocity than β_0 do not produce Cherenkov radiation, whereas those of greater velocity produce light of intensity proportional to $1 - 1/n^2\beta^2$. The cutoff characteristics depend upon the sensitivity of the photomultiplier and associated apparatus.

In practice we usually desire to keep the amount of material in the beam of particles with which we are working to a minimum because such material scatters our particles and introduces extraneous nuclear reactions. This means that we must not put the phototube in the beam, especially if the index of refraction of the radiator is smaller than that of the glass face of the tube. The problem of getting the light from the radiator to the photocathode is difficult because the light is emitted in a cone whose axis is that of the beam. No good system of specular reflectors has been devised that will direct the light onto an ordinary photocathode. The best solution we have found is to use a diffuse reflector of magnesium oxide. Magnesium oxide was selected because of its excellent reflectivity, which extends into the ultraviolet region of the spectrum. Magnesium oxide powder can be made into a slurry by mixing with just enough clear acrylic lacquer to hold the oxide in place. This mixture can be applied to lucite and adheres satisfactorily to aluminum. Some paints and binders are poor ultraviolet reflectors, but we have found that acrylic lacquer as a binder does not appreciably reduce the reflectivity of magnesium oxide in the spectral region of 3600 A. Cherenkov radiation is rich in short-wave-length light, and photocathodes are most sensitive in the vicinity of 4000 A. A typical counter designed on these principles is illustrated in Fig. 1.

The intensity of Cherenkov light is feeble compared with that of scintillators. This means that care must be taken to choose radiators that do not scintillate. The relative scintillation efficiencies of a number of materials are given by Madey and Leipuner.[1]

The approximate number of photons emitted as Cherenkov light in the visible region can be calculated by the formula given by Marshall (CERN Symposium 1956 Volume 2),

$$I = 450\,(1 - 1/n^2\beta^2), \tag{2}$$

where I is the number of photons emitted in the visible spectrum by a singly charged particle traversing 1 cm of radiator with index of refraction n. The counter of Fig. 1 has a radiator of water 5 cm thick. For particles of $\beta = 1$ there should be about 950 visible photons generated. If we assume that one-half the light reaches the photocathode, whose efficiency is 0.05, we expect 24 photoelectrons per particle.

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[1] Nucleonics 14, No. 4, 51 (Apr. 1956)

A BROAD-BAND VELOCITY-SELECTING COUNTER

A rather simple velocity band-pass counter is that suggested by V. L. Fitch. This counter uses as its lower limit of response the threshold of Cherenkov emission. The upper limit of velocity is determined by the design of the radiator, which is a right circular cylinder with the beam parallel to its axis but not necessarily on the axis. If we choose a suitable index of refraction and examine the path of light emitted from a particle's trajectory we see that as the velocity increases and the angle of the light with respect to the axis of the radiator increases a point is reached at which the light is totally internally reflected from the end of the radiator. The light is then trapped within the radiator. We can blacken the end of the radiator to form an effective sink for the light. Evidently there can be an interval of particle velocity in which light can escape from the radiator and be directed to a phototube. For particles parallel to the axis of the radiator, the minimum and maximum velocities are determined by the relations

$$\beta_{min} = 1/n, \quad \beta_{max} = 1/(n^2 - 1)^{1/2}. \tag{3}$$

The second of the above equations does not hold if the counter is tilted with respect to the beam direction, and is further altered as the angular aperture of the beam increases.

The main problem of design of this type of counter is to couple the light output from the radiator to a photocathode. Obviously we cannot couple the photocathode directly to the radiator because the total internal reflection would be destroyed. Light pipes cannot be used because they would produce Cherenkov radiation. We have used an aluminum reflector in an arrangement illustrated by Fig. 2. For light emitted in the plane of the paper the cylindrical aluminum surface reflects the rays to the photocathode directly, but light emitted out of the plane of the paper must make many reflections on the parallel sides of the light chamber in order to arrive at the photocathode. Perhaps there are better designs than the one here illustrated. However, this is a practical and simple design and the counter is effective. The performance of the counter represented in Fig. 2 is indicated in Fig. 3, in which the efficiency for counting protons is presented as a function of proton velocity. We have used many counters of this type to help sort antiprotons of $\beta = 0.75$ from other particles of about $\beta = 1$. Counters of this type are not completely insensitive to particles outside the band pass, because of nuclear collisions within the radiator. Such collisions send charged particles at skew angles with respect to the radiator axis and give rise to light that can leave the radiator. For example, the counter designed to detect antiprotons responded to about 5% of the mesons that passed through it.

It is very important for the radiator of the Fitch-type counter not to scintillate, as light from scintillators is emitted uniformly in all directions and, of course, some of it would escape from the radiator. The counter used to detect antiprotons of $\beta = 0.75$ employed 5 cm of liquid styrene, $n = 1.543$ plus 2% methyl bromide to reduce scintillation. The number of photons generated by an antiproton amounted to about 600. Probably not more than one-third of the light was collected; the number of photoelectrons was about 10. The pulses resulting from 10 photoelectrons are sufficient for detection in a multiple-coincidence array, but the time of passage of the particle cannot be so accurately determined as would be possible if larger pulses were available.

A NARROW-BAND VELOCITY-SELECTING COUNTER

A counter that accepts particles of only a narrow range of velocities was developed by Owen Chamberlain and the writer, and was used in the antiproton experiments. It is described in the CERN Symposium Volume 2 of 1956. The device consists of the basic elements of Cherenkov counters: a radiator and photomultiplier tubes. The counter is illustrated in cross section in Fig. 4. The radiator has the same shape as the one previously described for the wider-band counter--a right circular cylinder with its axis on the beam. The charged particles traverse the radiator parallel to its axis but not necessarily on the axis.

Let us consider a beam of particles all of the same velocity and a radiator of refractive index such that the angle of emission of the Cherenkov light is about 45°. As the light leaves the end of the radiator it is refracted to a wider angle but still has a well-defined direction with respect to the axis of the system. The rays lie on the surfaces of cones whose apexes are on the end surface of the radiator and whose axes are parallel to the beam. Next the light is reflected by the cylindrical mirror, and would fall on the face of a photomultiplier (shown dotted in the diagram) if it were not intercepted by the plane mirrors. Three plane mirrors, one of which is indicated in Fig. 4, are placed in the form of an equilateral triangle around the axis of the system. Their purpose is to allow us to place the phototubes out of the beam (for the same reasons as mentioned in connection with the Fitch-type counter). Actually the three plane mirrors divide the light from the radiator into three equal parts which fall on three phototubes placed in relation to the mirrors as indicated on the diagram. If the velocity of the particles is that for which the instrument is set, all the light generated in the radiator falls upon photocathodes except that lost by absorption and imperfect reflection.

The number of photoelectrons ejected from each photocathode in a typical application can be estimated as follows: assume $\beta = 0.75$, $n = 1.5$, length of radiator 10 cm. Equation (2) predicts 940 photons will be generated in the radiator. Assuming that half the light reaches the photosensitive surfaces whose quantum efficiency is 0.05, we expect 8 photoelectrons per particle to be emitted by each photocathode. Signals from each tube are, in practice, fed to a coincidence circuit which responds to any two out of three input pulses. This procedure results in a high counting efficiency and only a tolerable number of random coincidences if the instrument is used in an array with other counters.

If the particle velocity is different from that for which the counter is adjusted the light is intercepted by the blackened baffle. The geometry of the counter is such that if the light deviates more than ± 5 degrees it does not fall on the photocathodes. The change in angle of emergence θ_r is related to the change in β by

$$\Delta\beta = n\beta^3 (1 - 1/n^2\beta^2)^{1/2} (1 - n^2 + 1/\beta^2)^{1/2} \Delta\theta_r. \qquad (4)$$

If we assume $\beta = 0.75$, $n = 1.5$, and $\Delta\theta_r = \pm 5^\circ$, Eq. (4) predicts $\Delta\beta = \pm 0.017$. We have tested the counter, using a Lucite radiator and a beam of protons. The results are shown in Fig. 5. The performance of the instrument checks quite well with the calculations. The efficiency at the peak of the curve is 97%, and the background is 3%. The background is presumably due mainly to nuclear collisions within the radiator.

In his paper in the CERN Symposium of 1956, Marshall presents an excellent discussion on the resolution of Cherenkov counters. The main factors that limit the velocity resolution are multiple Coulomb scattering in the radiator, optical dispersion of the light in the radiator, and slowing down of the particles as they traverse the radiator.

The velocity-selecting devices thus far mentioned cover an interval of β extending from about 0.6 to 0.95. The limits are established by the availability of radiator materials with proper refractive indices. Readily obtainable materials range from $n = 1.276$ (Fluorochemical liquid FC-75*) to $n = 1.7$ (dense glass).

The lower limit of index of refraction can be extended for velocity-threshold-type counters by employing gases and liquids at abnormal pressures and temperatures. Lindenbaum and Yuan at Brookhaven have constructed counters using high-pressure CO_2 to obtain refractive indices from 1.0 to 1.1. A group at Massachusetts Institute of Technology has used the fluorochemical at elevated temperature and pressure to achieve indices of refraction lower than 1.276. At Berkeley, Atkinson, Hess, and Perez-Mendez have constructed a counter using Freon 12 at pressures up to 5 atmospheres to obtain refractive indices in the interval from 1.0 to 1.0036. Their counter consists of a cylinder 6 feet long and 10 inches in diameter. Cherenkov light from the high-pressure gas is reflected out of the cylinder at right angles and is viewed by a type 7046 photomultiplier.

Users of Cherenkov counters welcome a continued search for suitable radiator materials of unusual refractive index.

TIME RESOLUTION OF CHERENKOV COUNTERS

Cherenkov light is emitted instantaneously from a charged particle as it traverses a radiator. The duration of the light pulse on a photocathode depends upon the difference in lengths of the optical paths of the light from its origin on the particle trajectory to the photocathode, and on the time of traversal of the particle through the radiator. For counters of a few inches in diameter and length these differences can amount to about 10^{-9} sec. Presently available multiplier tubes have rise times longer than 10^{-9} sec, which means that the timing of the output pulses would appear to depend upon the characteristics of the multiplier. However, the situation may not be as good as it seems, because in many applications the number of photons incident on the photocathode is so small that only a few photoelectrons are emitted. The

* Obtainable from Minnesota Mining and Manufacturing Co., St. Paul, Minn.

statistical fluctuation in this small number invariably leads to a broadening of the time spread in output pulses.

We have compared, by photographing the pulses, the time spread of the outputs of two models of counters. Each radiator was similar to that described in Fig. 1, but one was coupled to a 6810 and the other to a 7046-type tube. The counter using the larger-area photocathode showed a spread in time of the output pulses that was about half the width of the spread of the smaller 6810 type tube. This was probably due to the increased light collecting efficiency and consequently greater number of photoelectrons from the larger photocathode. It may be important to know of these limitations when Cherenkov counters are used in millimicrosecond coincidence and anticoincidence circuits. Improvement of photocathode efficiencies will greatly improve the time resolution of many Cherenkov counters.

The writer wishes to acknowledge the assistance of Mr. Tom Elioff in constructing the counters and gathering the data.

This work was performed under the auspices of the U. S. Atomic Energy Commission.

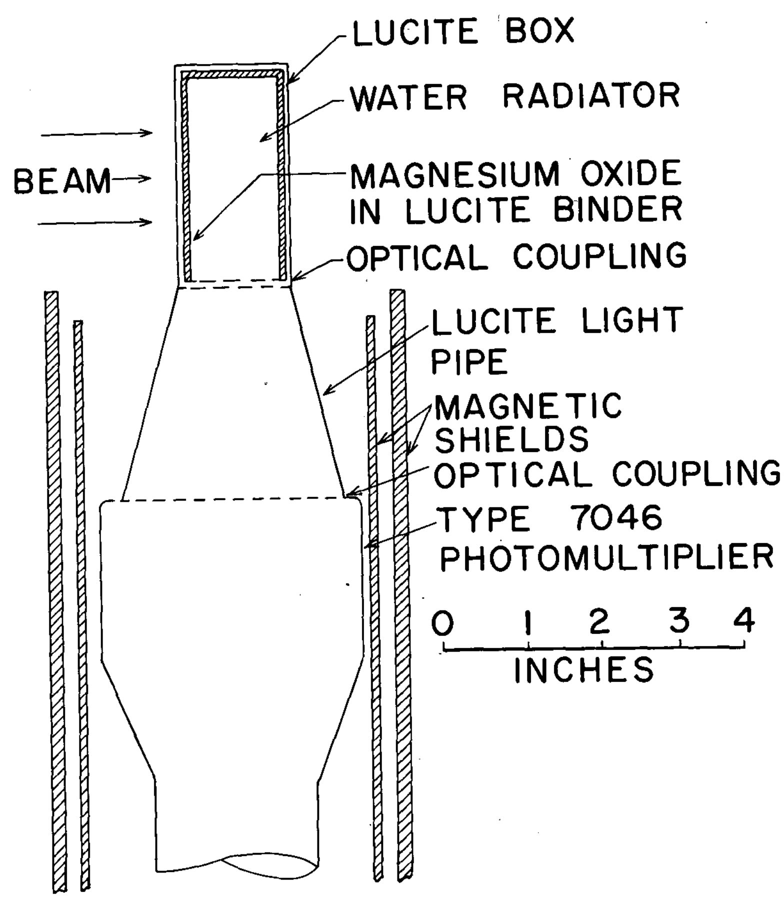

Fig. 1. Schematic diagram of velocity-threshold counter.

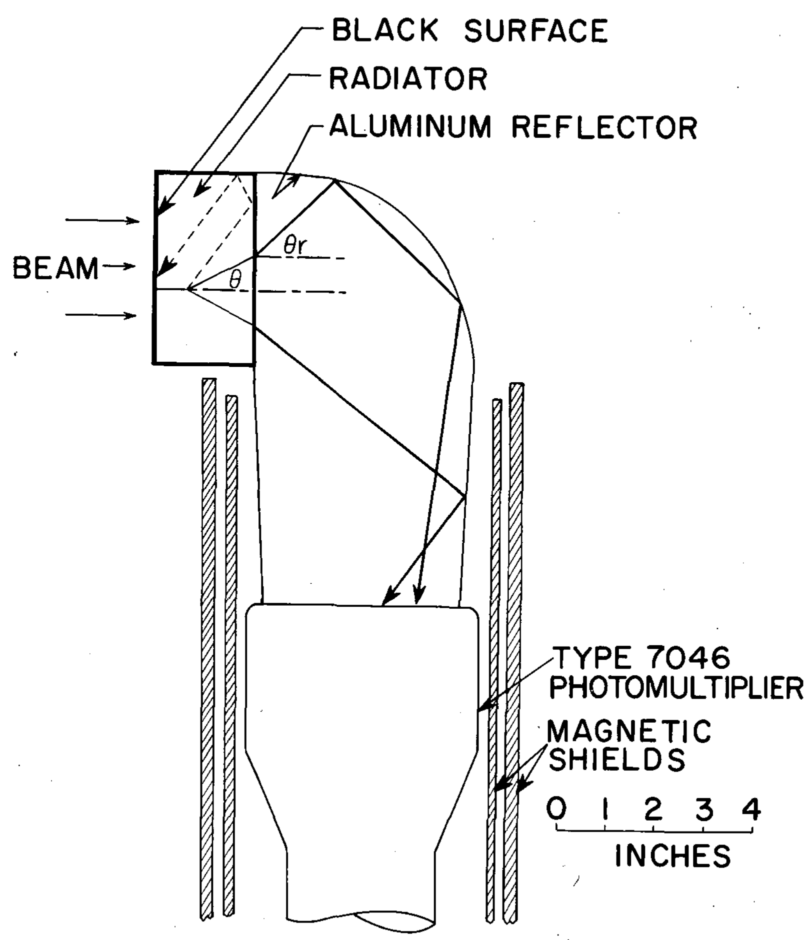

Fig. 2. Schematic diagram of Fitch-type broad-band velocity-selecting counter.

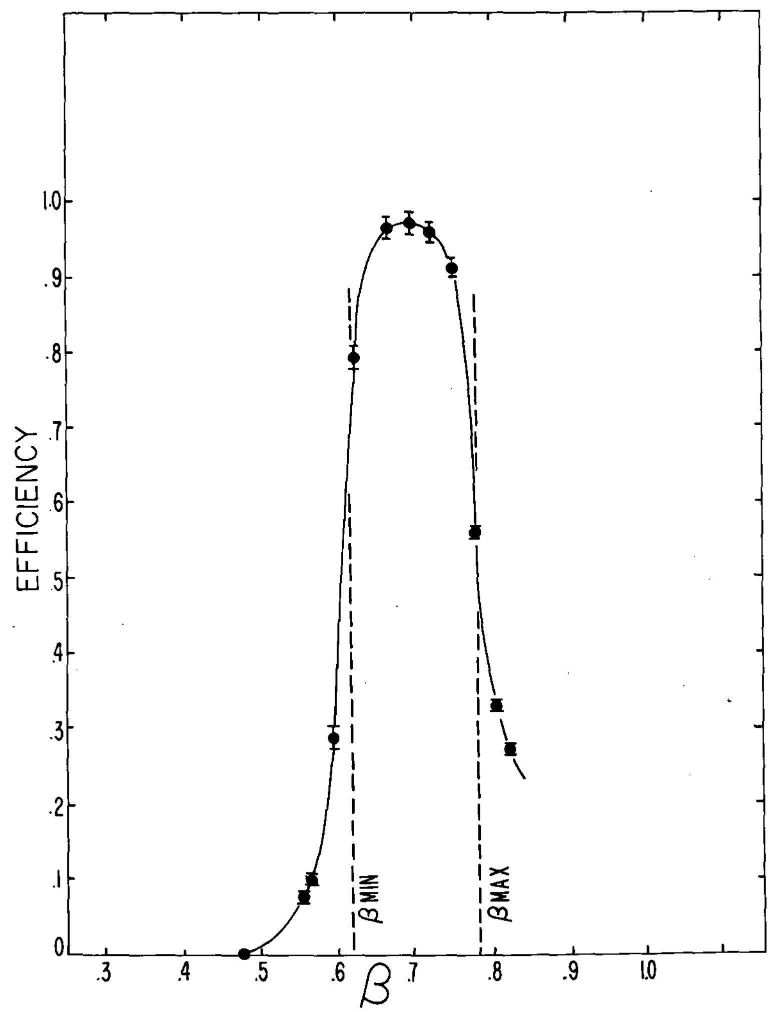

Fig. 3. Efficiency versus β for the Fitch-type counter illustrated in Fig. 2. The efficiencies were determined by placing the radiator between two scintillators of a counter telescope.

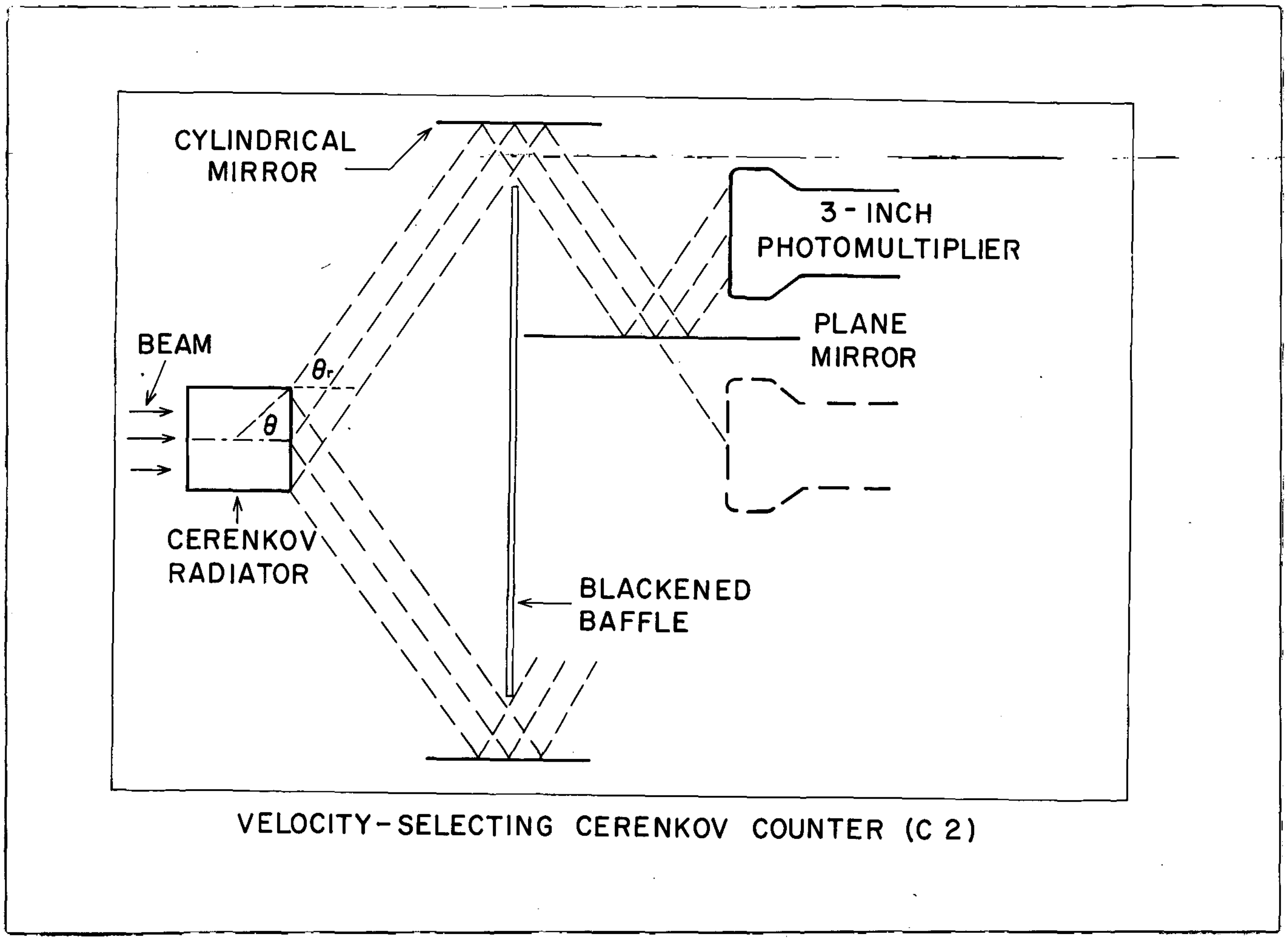

Fig. 4. Schematic diagram of the narrow-band velocity-selecting Cherenkov counter.

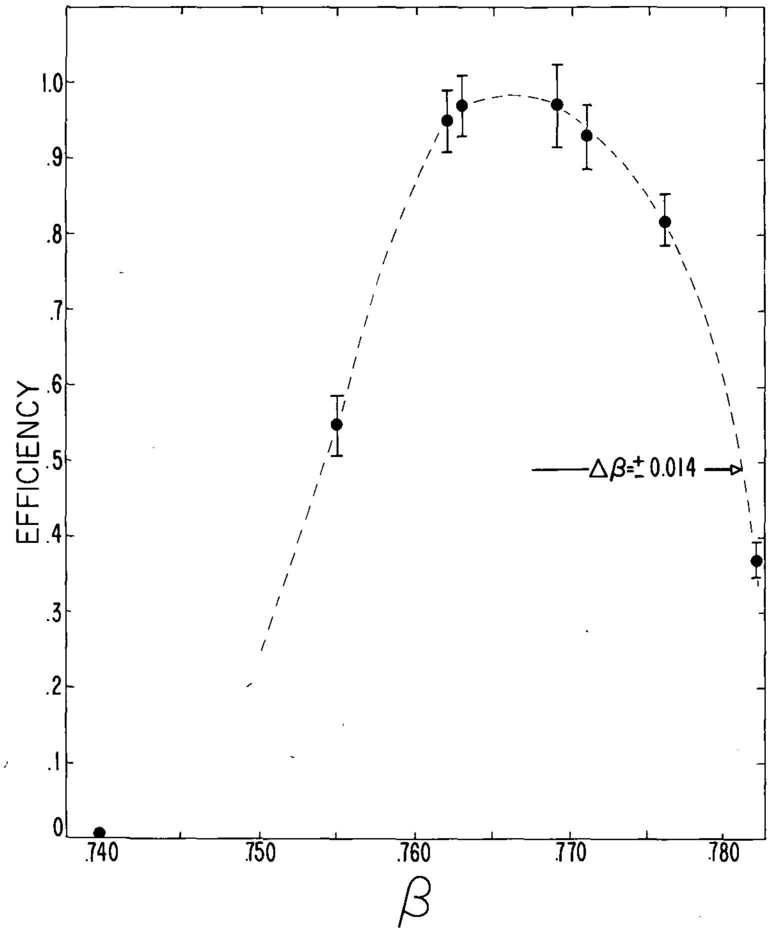

Fig. 5. Efficiency versus β for the narrow-band counter illustrated in Fig. 4. The efficiencies were determined by placing the velocity-selecting counter between scintillation counters of a counter telescope array.

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