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# METHODS OF PARTICLE DETECTION FOR HIGH-ENERGY PHYSICS EXPERIMENTS

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## INTRODUCTION

Recent advances in our knowledge of the phenomena of high-energy physics and of the elementary particles has resulted from rapid advances in the technology of particle accelerators and the art of particle detection. The instruments for the detection of energetic particles can be divided into two classes: (1) the "track-imaging" device in which one sees or photographs tracks which coincide with the actual path taken by the particles, and (2) counting devices which give only an indication that the particles pass somewhere in the sensitive volume.

Among the visual detectors in current use in high-energy physics experiments are the nuclear emulsion, the diffusion cloud chamber, the expansion cloud chamber,[1] and the bubble chamber.[1,2] The scintillation chamber, a new type of visual detector now being developed shares some of the virtues of the visual and of the counter-type detectors. Measurements that can be made on events photographed in visual detectors include angles between tracks of different particles; ranges of stopping particles; distances of flight of decaying or colliding neutral particles; magnetic curvature, which gives a measure of the momentum of the particle; scattering due to coulomb interactions with the sensitive medium, which gives a measure of $p\beta c$; and density of visual elements along the track (developed grains in emulsion, droplets in cloud chambers, bubbles in bubble chambers), which give a measure of ionization or velocity. From a set of measurements of this kind on an event of interest, one can deduce the energy absorbed or released by a process, as well as the masses and charges of the particles involved, their lifetimes, the strength of their interactions with other particles, etc. It is these quantities that are the raw materials for the theories of high-energy physical phenomena. The spatial resolution of these detectors varies from about 0.1 $\mu$ in the case of nuclear emulsion to about 1 mm in the case of the diffusion cloud chamber and the scintillation chamber. The time resolution is practically infinity for the nuclear emulsion, 0.1 sec for cloud chambers, a few $\mu$sec for some bubble chambers, and $10^{-8}$ sec for scintillation chambers.

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Among the counter-type detectors are the Geiger-Mueller counter, the ionization chamber, the proportional counter, the scintillation counter, and the Cherenkov counter. Typically counters have dimensions of a few centimeters, although very small counters of various types have given spatial resolutions as good as 1 mm. In addition to detecting the presence of a charged particle in its sensitive volume, the counter may also give an indication of the rate of energy loss of the particle. The fastest of these counters is the scintillation counter. Some varieties of scintillation counters are capable of resolving times of the order of $10^{-9}$ sec.

## EXPANSION CLOUD CHAMBER

The oldest of the visual detectors is the expansion cloud chamber in which paths of ionizing particles can be seen as trails of fine droplets that condense on the ions created in the gas by the flying particles. Cloud chambers as large as 1.5 meters have been constructed. Some of these chambers have been fitted with magnetic fields that allow, in favorable cases, very precise measurements of the momentum of particles. By means of these momentum measurements, rather accurate measurements of the energy release in various collision and decay processes can be made. Often cloud chambers are equipped with plates of solid material in the sensitive volume so that one can observe interactions of the high-energy particles with matter and see the nature and types of the products produced. It is possible to operate a cloud chamber together with an array of counters of various types so that the chamber is operated and photographed only when the counter array detects the occurrence of an interesting event containing a required number of particles having certain definite properties. Expansion cloud chambers have been operated with a large number of gases at pressures ranging from below atmospheric to 300 atmospheres. These very-high-pressure chambers were developed in an attempt to increase the probability of observing an interesting collision of a fast particle within the photographable sensitive volume of the chamber. High-pressure chambers are large and expensive and can be cycled only once every 15 to 30 minutes depending on their size. Ordinary expansion cloud chambers may be cycled as often as once a minute.

## DIFFUSION CLOUD CHAMBERS

Because high-energy particle accelerators produce beams of particles much more often than once per minute, the diffusion cloud chamber was developed in order to have a continuously sensitive cloud chamber. It can, in principal, be exposed to every pulse of the machine that operates every few seconds. Unfortunately, the sensitive depth in the vertical direction of a diffusion chamber is limited to about 10 cm, and it can stand only moderate loads of ionization, without depletion of the supply of diffusing vapor into the sensitive volume. Diffusion cloud chambers of various types have been built. The most useful have been high-pressure hydrogen-filled diffusion chambers that operate at pressures up to 35 atmospheres. The measurement characteristics of diffusion cloud chambers are similar to those of the expansion cloud chambers except that distortions of the tracks because of the motion of the gas is generally somewhat more severe. Diffusion chambers cannot be operated successfully at pressures higher than about 30 or 40 atmospheres, because the high density of the gas reduces the rate of diffusion of vapor into the sensitive volume and thus limits the sensitive depth excessively.

## BUBBLE CHAMBERS

In a bubble chamber the path of a charged particle is seen as a chain of small bubbles in the volume of the liquid that constitutes the sensitive medium. One of the advantages of the bubble chamber over the cloud chamber is that very high densities can be achieved at only moderate pressures, so that the probability of seeing an interesting collision is increased by several orders of magnitude over the probability for cloud chambers. Further, many existing types of bubble chambers may be expanded as often as once a second; more rapid cycling rates can probably be achieved. In bubble chambers, a great variety of liquids including liquid hydrogen, liquid helium, liquid xenon and a great variety of hydrocarbons, fluorocarbons, and mixtures of these, can be used. In the liquid hydrogen chamber, one can present to the particle beam a pure proton target in which it is possible to make rather accurate measurements of magnetic curvature. The hydrocarbon chambers have higher density and therefore larger probability by an order of magnitude for seeing interesting events. They have also larger stopping power, so that particles are more often stopped so that their decays are more accessible for study in a hydrocarbon chamber. Chambers utilizing freon, xenon, or various hydrocarbon mixtures, are examples of the heavy-liquid type of chamber. The main advantages of the heavy-liquid bubble chambers are their high stopping power and short radiation length. The former means that interesting interactions as well as the stopping and decay of particles can be seen frequently in the chamber. The latter means that high-energy gamma rays will be very likely to make electron pairs that show the direction and energy of the gamma ray so that processes involving the emission of neutral $\pi$ mesons and gamma rays and other particles that decay into gamma rays can be studied in some detail. For a quantitative comparison of the characteristics of these visual detectors see Table I.

## NUCLEAR EMULSIONS

This type of image-forming detector is generally the most convenient to use with high-energy accelerators; it is also very easy to send to other laboratories for study. The spatial resolution of approximately 1 $\mu$ is far superior to any other detector, and hence, emulsions are valuable for studying very short half-lives. Associated events 1 cm apart are, on the other hand, almost impossible to detect. There is no time discrimination between events on successive pulses of the accelerator. Emulsions are usually not the best tool for studying inelastic interactions of high-energy particles in the detector, since it is rarely possible to say in which nucleus the interaction took place. Range measurement, laborious grain counting, and multiple-coulomb-scattering measurements often serve to establish mass, momentum, and magnitude of charge of particles in emulsions; but until pulsed strong magnetic fields are used, the sign of the charge will frequently be uncertain.

These detectors have, nevertheless, continued to occupy an important place in high-energy physics. Recent developments in the United States of America have been in the measurement of events rather than in the production of emulsions to compete with the Ilford L-series or the ultra-fine-grain Perfilov plates.

There is a trend toward automation in measuring tracks: Ilford G- and K-series emulsions are most commonly used for stack exposures. Several

Table I. Comparison of track-forming detectors.
Frequency of rare events in a 50-cm chamber.

| | Type | Density $\rho$ (gm/cm$^2$) | Radiation length ($\lambda$ cm) | Scattering sagittal $\delta$ S for 2-Bev proton track 5 cm long (microns) | Magnetic field required for 10% momentum error in 5-cm relativistic track (gauss) | Stopping power of a 50 cm chamber (gm/cm$^2$) | Events/day for $\sigma$/nucleon (= 1 microbarn) | Events/pulse for $\sigma$/nucleon (= 1 millibarn) |
|---|---|---|---|---|---|---|---|---|
| 1 | One-atmosphere argon expansion cloud chamber | 0.0017 | 11600 | 0.79 | 2400 | 0.085 | 0.015 | 0.0003 |
| 2 | Twenty-atmosphere hydrogen diffusion cloud chamber | 0.0019 | 36300 | 0.45 | 1300 | 0.095 | 0.016 | 0.0003 |
| 3 | Hydrogen bubble chamber | 0.05 | 1380 | 2.3 | 6900 | 2.5 | 0.43 | 0.008 |
| 4 | Helium bubble chamber | $\sim$0.10 | 963 | 2.75 | 8200 | 5.0 | 0.86 | 0.015 |
| 5 | Propane ($C_3H_8$) bubble chamber | 0.44 | 108.3 | 8.2 | 25000 | 22 | 3.7 | 0.07 |
| 6 | $SnCl_4$ bubble chamber | 1.5 | 7.35 | 31.5 | 94000 | 75 | 13 | 0.23 |
| 7 | Xenon bubble chamber | 2.3 | 3.1 | 48.5 | 140000 | 115 | 20 | 0.34 |
| 8 | Nuclear emulsion (AgBr) | 4.0 | 2.8 | 51.1 | 150000 | 200 | 34 | 0.59 |

laboratories make use of photoelectric gap-counting and grain-counting apparatus. Microscopes have been equipped with shaft encoders to allow automatic recording of stage coordinates onto paper tape or punched cards. G. Goldhaber (private communication) at Berkeley has connected a scattering microscope directly to a Friden paper punch to record first and second differences automatically.

## COUNTERS: GENERAL

The Geiger-Mueller counters and proportional counters used in low-energy physics have reduced utility for high-energy physics experiments, in which all singly charged particles have approximately the same rate of energy loss, and the slow Geiger response and "dead time" are objectionable. Scintillation counters and Cherenkov counters have replaced the above-mentioned detectors almost completely in high-energy accelerator experiments.

Counters are capable of producing data at a rate $10^2$ or $10^3$ times as high as the image-forming detectors discussed above, but they have very poor spatial resolution. Complicated arrays of counters are usually required to explore interactions of particles with high enough energy to have inelastic collisions that produce pi mesons or strange particles.

## SCINTILLATION COUNTERS

When a high-energy proton or other singly charged particle passes through matter, it loses energy at the rate of approximately 1.5 Mev per gram of material traversed. Certain inorganic materials such as thallium-activated sodium iodide, and organic materials such as terphenyl with tetraphenyl-butadiene can radiate several percent of this energy as visible light. The light from the sodium iodide decays with a 1/e time of approximately $3 \times 10^{-7}$ sec, while the corresponding decay time of terphenyl is $5 \times 10^{-9}$ sec. The light pulse can be detected by a photomultiplier attached directly to the scintillator, or connected to it by a Lucite "light-pipe", and the electrical signal from the multiplier can therefore be used to indicate the passage of a charged particle through the detector.

Because of the requirement of time resolution faster than $10^{-8}$ sec., most scintillators in high-energy physics have been made of organic material.[3] Polystyrene-loaded terphenyl is available in pieces as large as 40 kg. The trend has been to large scintillators, and large counter arrays. Figure 1 shows an array of 16 ring counters used by Kerth to study the scattering of $K^+$ particles by hydrogen.[4]

Photomultipliers followed by fast amplifiers and then fast coincidence circuits and high-speed oscilloscope displays are often used.

The passage of a particle through a scintillator or Cherenkov counter, in a high-energy physics experiment, often produces less than ten electrons from the photocathode of the photomultiplier tube (in contrast with the situation in low-energy physics or chemistry). Variation in transit time of electrons from different parts of the photocathode therefore can severely limit the resolution time of the multiplier. The fastest tube in general use is the RCA experimental model C-7251, with a gain of approximately $10^8$ sec and a rise time of

2 to $3 \times 10^{-9}$ sec. This tube is a curved-cathode version of the RCA 6810A, which has a rise time of about $5 \times 10^{-9}$ sec. Large-area photocathode tubes (RCA 7046) are available with approximately $10^7$ gain and approximately $4 \times 10^{-9}$-sec rise time.

Fast coincidence circuits of modified Garwin or Rossi type permit resolution times of 2 to $3 \times 10^{-9}$ sec. The limitation is imposed by the characteristics of the photomultipliers viewing the scintillators.

Transistors (solid-state diodes and triodes) are extensively used for the coincidence circuits. The excellent G7A germanium diodes can no longer be obtained; some laboratories are successfully using Hoffman-Zener diodes and Hewlett-Packard silicon diodes instead.[5]

## CHERENKOV COUNTERS[6]

Charged particles with velocity v traveling through a transparent material, will radiate light if v is greater than the velocity, $c/\mu$, of light in the material. Here $\mu$ is the index of refraction of the material, and c is the velocity of light in vacuum. This radiation is emitted in a cone with half angle $\theta$, measured from the particle trajectory, which is given by

$$\cos \theta = c/v\mu \; .$$

An energetic electron with $v \doteq c$ will produce about 250 photons of visible Cherenkov light in traversing 1 cm of Lucite.[7] This light intensity is much less than the light produced by scintillators, and hence Cherenkov counters must be made from nonscintillating materials.[8]

Most of the high-energy physics experiments done with counters involve Cherenkov-radiation detectors. They have been used to discriminate against particles below a predetermined velocity, to discriminate against particles traveling faster than a predetermined velocity, or to determine the velocity of a particle by observing the angle of emission of Cherenkov light. All three types must be designed to have high counting efficiencies and to accept particles entering through apertures several centimeters in diameter, with finite angular spread. The remaining sections of this paper describe some Cherenkov counters recently built at the University of California Radiation Laboratory at Berkeley, U. S. A.

A broad-band velocity-selecting counter is shown in Fig. 2.[9] This counter, based on a design suggested by V. L. Fitch, will detect particles with velocities from the Cherenkov-emission threshold up to a maximum determined by the design of the radiator. Light emitted beyond a critical angle, i. e. from particles beyond some critical velocity, will be totally internally reflected from the end of the radiator. Fig. 3 shows the efficiency of this counter for detecting protons, as a function of the proton velocity. The Cherenkov radiator in this case was a 5-cm-thick cell of liquid styrene, with 2% of methyl bromide added to reduce scintillation.

A narrow-band velocity-selecting counter, developed by Chamberlain and Wiegand, is shown in Fig. 4.[10] Only one of three plane mirrors placed symmetrically around the beam axis is shown. Approximately eight photoelectrons are emitted from each of the three photocathodes, when a charged particle of appropriate velocity traverses the Cherenkov radiator. Background is kept low by requiring coincidence between any two of the three multipliers, to register a count. The response of the counter to protons of different velocities is shown in Fig. 5.

Limits of velocity response in design of Cherenkov counters are set by the index of refraction of available radiator materials. Dense glass, with an index of refraction $\eta$ as high as 1.7, is commonly used. Indices as low as 1.276 are achieved by the use of Fluorochemical liquid FC-75, obtainable from Minnesota Mining and Manufacturing Co., St. Paul, Minn., U.S.A. Still lower indices are being obtained by Hill, Caldwell, Ritson, and others at MIT[11] by the use of FC-75 at temperatures and pressures near the critical point.

## SUMMARY

Table II summarizes some characteristics of the detectors which have been described above. This short table does not completely characterize the various detectors. The data apply to a representative model of each type, and do not indicate the ultimate capabilities of the detectors.

Table II

Comparative characteristics of detectors

| Type of detector | Characteristics (all quantities approximate) | | | | | | Representative applications |
|---|---|---|---|---|---|---|---|
| | Time resolution[e] (sec) | Space resolution (mm) | Density (g/cc) | Velocity or momentum resolution | Nucleus unique ? | Particles per machine pulse | |
| High-Pressure Cloud Chamber | | | | | | | |
| $H_2$ | (1 pulse)[a] | 0.5 | 0.03 | 2% | almost | 30 | Interactions; particle production in chamber |
| Diffusion Cloud Chamber | | | | | | | |
| $H_2$ | (1 pulse) | 0.5[b] | 0.002 | 2% | almost | 30 | " " |
| Bubble Chamber | | | | | | | |
| $H_2$ | $10^{-3}$ | 0.1 | 0.05 | 2% | yes | 30 | " " |
| hydrocarbon | $10^{-4}$ | 0.05 | 0.45 | 5% | no | | |
| xenon | $10^{-4}$ | 0.05 | 2.2 | poor | almost | 30 | as above; also interactions involving γ rays |
| dissolved gas | $10^{-3}$ | 0.1 | 0.5 | 5% | no | 30 | |
| Scintillation Chamber | | | | | | | |
| | $10^{-8}$ | 1 | 1 | | no | 100 | Detection of fast particles; interactions in detector |
| Nuclear Emulsion | | | | | | | |
| | (very slow) | 0.001 | 4 | fair | no | no limit | " " |
| Scintillators | | | | | | | |
| inorganic | $10^{-6}$[f] | 10 | 4 | | no | $10^4$ | beam studies |
| organic | $10^{-9}$ | 10 | 1 | | no | $10^4$ | detection of fast particles |
| Cherenkov Counters | | | | | | | |
| liquid or solid | $10^{-9}$ | 30 | 1 | good | no | $10^5$ | detection of particles above critical velocity |
| gas | $10^{-9}$[c] | 30[d] | 0.03 | good | no | $10^5$ | " " |

[a] Can operate at only about 1 pulse per 10 minutes.

[b] Sensitive depth normally about 7 cm.

[c] Time resolution is limited by available photomultipliers.

[d] Figures apply to space resolution of "poor geometry" counter. Space and momentum resolution of "good geometry" counters is ~1%.

[e] This figure refers to the possibility of distinguishing between two particles passing through the detector. Chambers can be used to resolve particle decay times of $\sim 10^{-11}$ sec, and nuclear emulsions can be used to resolve [illegible] times of $\sim 10^{-13}$ sec.

[f] If scintillator is cooled, it may have resolution comparable to organic scintillator.

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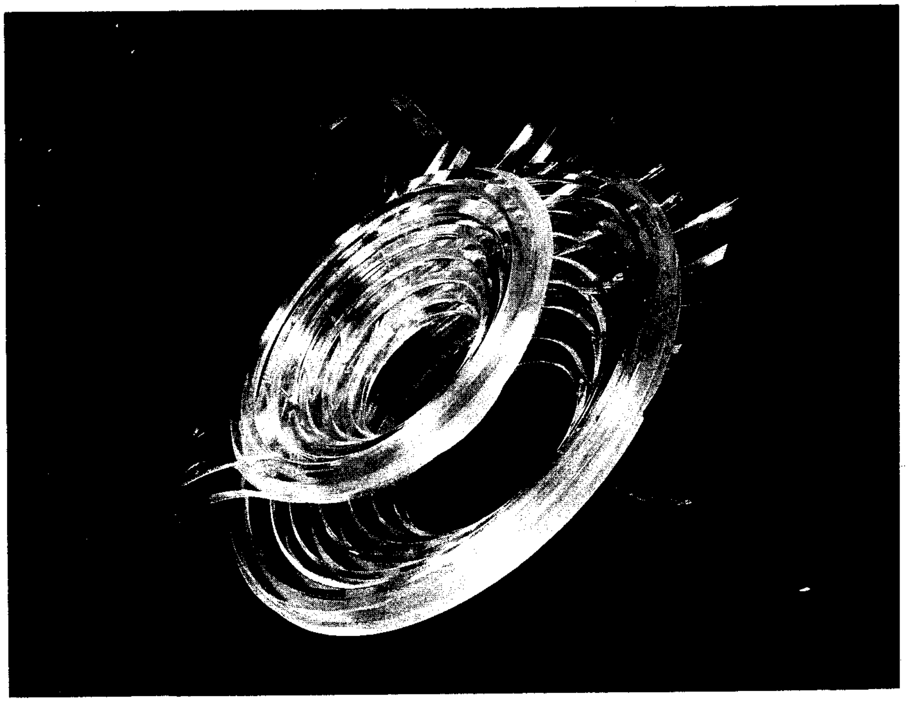

Fig. 1. Array of 16 scintillation counters for high-energy particle-scattering experiments.

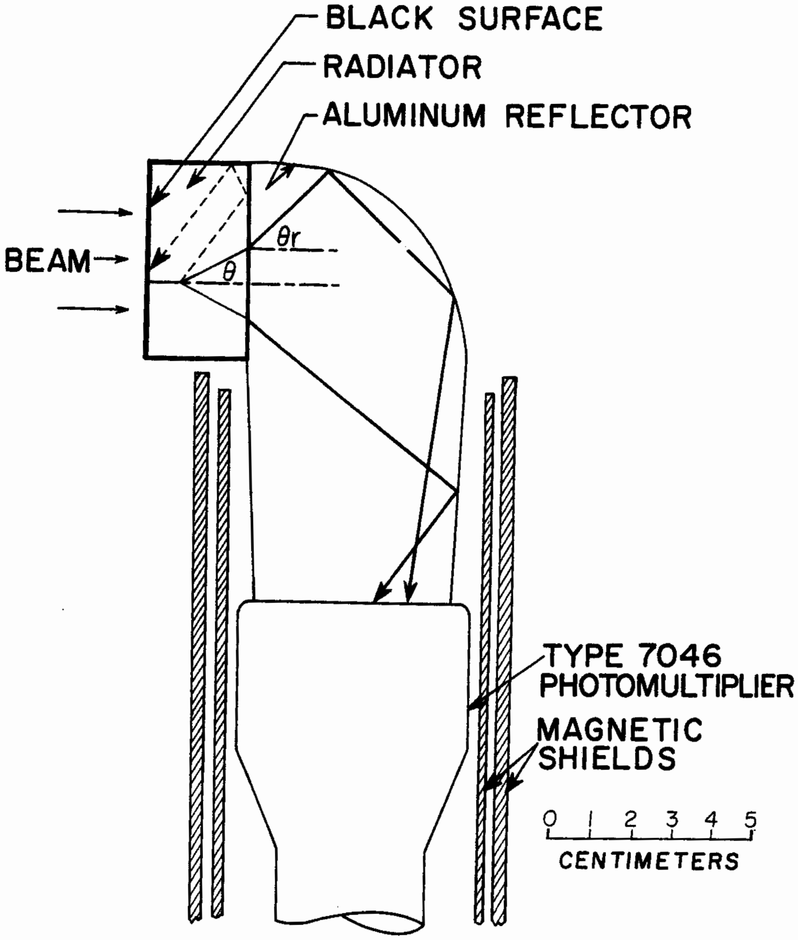

**Fig. 2. Schematic diagram of Fitch-type broad-band velocity-selecting counter.**

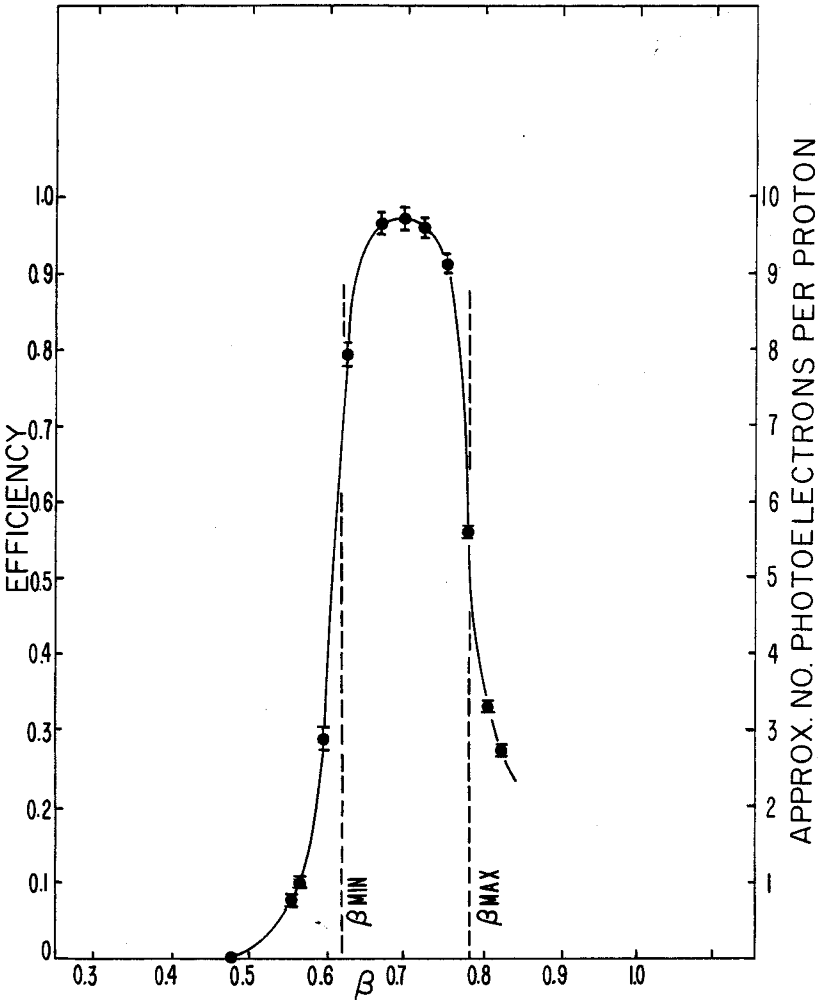

**Fig. 3. Efficiency versus β for the Fitch-type counter illustrated in Fig. 2. The efficiencies were determined by placing the radiator between two scintillators of a counter telescope.**

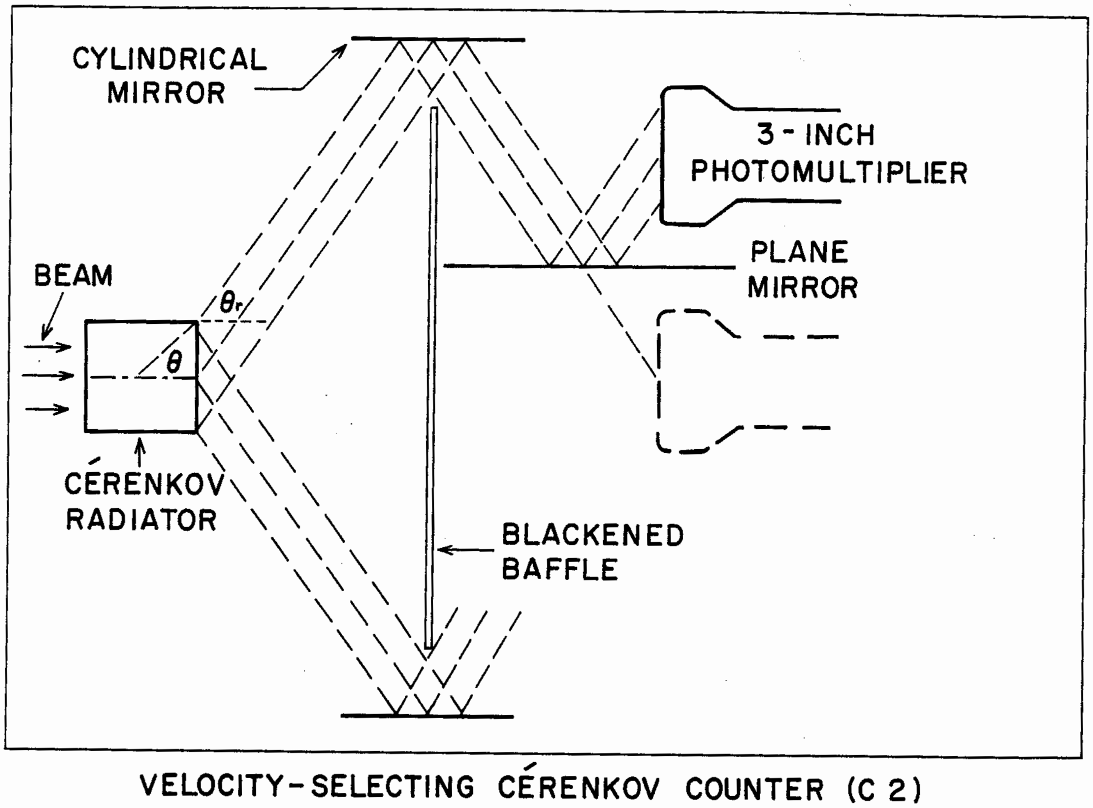

**Fig. 4. Schematic diagram of the narrow-band velocity-selecting Cherenkov counter.**

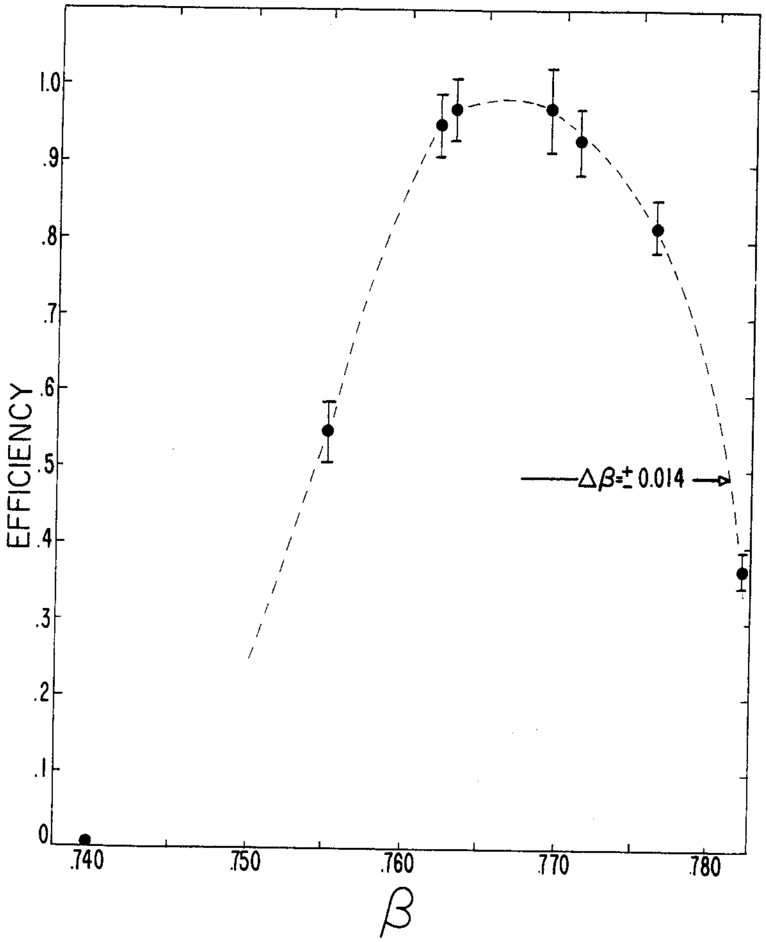

Fig. 5. Efficiency versus β for the narrow-band counter illustrated in Fig. 4. The efficiencies were determined by placing the velocity-selecting counter between scintillation counters of a counter telescope array.