THE UNIVERSITY OF MICHIGAN
COLLEGE OF LITERATURE, SCIENCE, AND THE ARTS
Department of Physics

Technical Report No. 31

A DESIGN STUDY OF A LARGE APERTURE GAS THRESHOLD CHERENKOV COUNTER USING A WAVELENGTH-SHIFTER TECHNIQUE FOR LIGHT COLLECTION

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1. Introduction

The Cherenkov effect is a commonly used means of detecting and identifying elementary particles. The basis for this use, provided by the theory of Frank and Tamm,[1] is summarized in the following paragraph.

The Cherenkov radiation created by a particle traversing a dielectric with $\beta n > 1$ is confined to a cone about its direction of motion with an opening angle given by

$$\cos(\varphi) = 1/\beta n, \tag{1}$$

and the number of photons created in a length d (cm.) of dielectric in the frequency interval $(\nu, \nu + d\nu)$ is given by

$$N(\nu) = \frac{2\pi}{c}\left(\frac{e^2}{hc}\right)\left(1 - \frac{1}{n^2\beta^2}\right) . \tag{2}$$

Detection and velocity selection of charged particles may thus be sccomplished by using the threshold property $\beta > 1/n$ or by detecting the Cherenkov photons over some range in φ.

This report considers the feasibility of utilizing the Cherenkov effect to distinguish incident cosmic ray π^+ particles from protons for energies greater than 100 GeV.

Physicists from California, Wisconsin, Colorado, and Michigan are currently developing a cosmic ray facility on Mt. Evans in Colorado, where the techniques and tools used in accelerator experiments are being applied to cosmic ray studies.[2]

With the use of a hydrogen target and the momentum and energy analysis of spark chambers, large magnets, and an ionization calorimeter, quantitative studies of high energy interactions in the energy range of 50 to 1000 GeV can be made.

At the Mt. Evans facility (14,000 ft.), the cosmic ray flux of π^+ and π^- particles is 50% of the p flux. An identification of the π^- can be made from its deflection by an analyzing magnet. Two approaches have been made to the problem of distinguishing the π^+ from the p. The first studies the use of the dE/dx property of proportional counters.[3] The second considers the use of a He threshold Cherenkov counter and is the subject of this report. He was chosen as the Cherenkov radiator because it has the highest Cherenkov threshold energy of all the gases.

The following requirements are imposed by the Mt. Evans facility:

a) The Cherenkov counter must have a large phase space acceptance of incoming particles, e.g., it should have uniform efficiency for particles incident over an area greater than 20 ft.^{2} with an angular variation from the vertical up to 20°.

b) Its height can be no greater than 10 meters.

II. He Threshold Counter

Integrating Eq. (2) from ν = 3500A° to ν = 5600A° (the S11 spectral response of the 6810 photomultiplier tube), the number of Cherenkov photons created in the path length d (cm.) becomes

$$N = 500d \left(1 - \frac{1}{n^2\beta^2}\right) . \tag{3}$$

In the limit of n → 1, Eq. (3) becomes

$$N = 500d \left((\frac{1}{\gamma_{th}})^2 - (\frac{1}{\gamma})^2 \right),$$

where γ is the Lorentz factor for the radiating particle and γ_{th} is the Lorentz factor corresponding to the Cherenkov threshold. For the case of p and π^+ particles

$$N = 500d \left(\left(\frac{M_p}{E_{pth}}\right)^2 - \left(\frac{M}{E}\right)^2 \right), \tag{4}$$

where E and M are the energy and mass of the Cherenkov radiating particle and where M_p and E_{pth} are the mass and Cherenkov threshold energy for a proton. A plot of N vs. E for the π^+ and p is shown in Figure (1). A He threshold counter at S.T.P. is seen to be uniformly efficient over the energy range $30\text{ GeV} < E < 110\text{ GeV}$.

For $d = 3$ m, $N_{max} = 11$ photons for n(He) = 1.000036 at S.T.P., $N_{max} = 87$ photons for n(air) = 1.00029 at S.T.P.

Since the energy distribution of the Cherenkov photons is peaked toward the ultraviolet, in a frequency range above the spectral response of the S11 photocathode and glass window of the 6810, much of the Cherenkov radiation is undetectable by the 6810 photocathode.

Because $\varphi_{max} = 8 \times 10^{-2} r$ from Eq. (1), the Cherenkov photons may all be reagrded as following the path of the radiating particle to good approximation. From Liouville's theorem on the conservation of volume in phase space we can hope at best to focus these photons only to within a certain area on a detecting surface.

This requirement of a large detecting surface, the small number of Cherenkov photons detectable by S11 photocathode, and the large number of ultraviolet photons has led us to consider the use of a wavelength-shifter and light trapping in plexiglass as a means of gaining an efficient large area detector. We are indebted to J. Keuffel for suggesting this approach and sharing with us results of unpublished tests made in his laboratory.

The wavelength-shifter detector which we considered consists of a 1'x2'x1/8" sheet of ultraviolet absorbing plexiglass (Type UVA) coated with a plexiglass paint containing the wavelength-shifter POPOP and two 6810 phototubes viewing the 1'x1/8" edges of the POPOP sheet through adiabatic bent strip plexiglass light pipes. Some fraction of the ultraviolet photons incident on the POPOP surface will be absorbed by the POPOP, and the excited POPOP will isotropically radiate photons within the S11 Spectral response in a time on the order of 10^{-9} sec. Approximately 15% of these photons will be transmitted to each phototube by total internal reflection in the sheet and bent strip light pipes ignoring absorption.

III. Properties of the POPOP Coated Plexiglass Detector

The POPOP paint consists of plexiglass chips (15g./l.) and POPOP dissolved in dichloroethane. The efficiency of a POPOP-coated plexiglass sheet, relative to the 6810 photocathode, for different POPOP concentrations in paint of type UVA plexiglass is shown in Figure (2). The plateau suggests that a POPOP concentration of (2.5g./l.) is near maximum efficiency. Some improvement in efficiency can be expected for a paint of ultraviolet transparent plexiglass (Type UVT). For various POPOP concentrations the absorption length for the photons radiated from the POPOP and trapped by total internal reflection in the plexiglass is large with a minimum absorption length of 4 ft. corresponding to (2.5g./l.) of POPOP. The most efficient method for applying the POPOP paint is to submerge the plexiglass sheet in the paint and withdraw it vertically at a rate of 2 in. per minute. A clear craze-free surface is produced by this method, but the thickness of the paint layer cannot be increased by successive painting without badly crazing the plexiglass sheet. All results are for sheets prepared by the "dip" method unless otherwise stated. A commercially made plexiglass sheet impregnated with POPOP (0.17g. POPOP/g. UVT plexiglass) was found to be slightly less efficient.

	POPOP coated sheet (2.5g. POPOP/l. UVA plexiglass paint)	POPOP impregnated sheet (0.17g. POPOP/g. UVT plexiglass)
Efficiency relative to the 6810 photocathode	65%	45%
Absorption length	4 ft.	1 ft.

The apparatus used to make these tests is a Cherenkov light source consisting of a Sr 90 β source, a $\frac{1}{2}$" thick cylinder of fused quartz, and a 1/8" thick plastic scintillator viewed by two phototubes as shown in Figure (3) together with a block diagram of the associated logic. The quartz cylinder is taped over with black tape except for a 1"x$\frac{1}{2}$" window for the Cherenkov light. The following properties of the Cherenkov light source make it ideal for our purpose and, aside from complexity, basically an excellent standard light source for the measurement of phototube characteristics.

a) The defining properties of a standard Cherenkov light source depend only on the geometry of the radiator and the Cherenkov light window and the thickness of the monitor scintillator.

b) The monitor signal allows the rejection of photomultiplier tube noise by the counting electronics.

c) There is no problem of shielding the photomultiplier tube from the radiation from a high voltage pulser.

d) Measurements do not have to be made relative to a standard tube.

All tests were made using 1'x2"x1/8" strips of plexiglass with all edges polished for maximum internal light reflection. One end of the strip was held in optical contact with the face of a 6810, and a face of the strip was placed in close contact but not optical contact with the quartz window at 4" or 7" from the tube face. Measurements were made by counting coincidences of counters

1 + 2 and counters 1 + 2 + 3 for different D3 discriminator threshold settings. A comparison of the plots of $\frac{1+2+3}{1+2}$ vs. D3 threshold voltage for different concentrations of POPOP in the plexiglass paint and for the two measurement positions on the test strips yields the results of Figure (2) and the absorption length result stated previously. A typical plot of $\frac{1+2+3}{1+2}$ vs. D3 threshold voltage is shown in Figure (4).

IV. Efficiency of the POPOP He Threshold Cherenkov Counter

To test and determine the absolute efficiency of a He threshold Cherenkov counter using the POPOP-coated plexiglass sheet, a cosmic ray experiment was run using air contained in an 8'x4'x3' light-tight box as a Cherenkov radiator. The apparatus and a block diagram for the logic are shown in Figure (5). Counters 1, 2, 3, and 4 are plastic scintillation counters, and 1C and 2C correspond to the two 6810 photomultiplier tubes viewing the 1'x2'x1/8" edges of the POPOP sheet. Relativistic charged particles (mostly muons) traversing counters 1 or 2 and 3 with no coincident particle traversing 4 are counted and are represented by the logical configuration (1v2) + 3 + $\bar{4}$ + M. For an M particle above the Cherenkov threshold its Cherenkov photons are reflected from the aluminum front-surfaced mirror onto the POPOP sheet. Counts of the coincidences M,M+2C = A and M+1C+2C = B are made as well as background counts of M, A, and B taken with the mirror covered with a black cloth and indicated by the subscript b. The thresholds of D1C and D2C are set equal and less than the mean pulseheight for single photoelectrons for the 1C and 2C photomultiplier tubes.

From the energy distribution of cosmic ray muons at sea level,[4] approximately 30% of the muons are above the Cherenkov threshold for air, and the distribution of muons with the mean number of Cherenkov photons created in the air in the box has the form shown in Figure (6). Thus a good indication of the probability P1 for 1C detecting a $\beta \approx 1$ muon is provided by the expressions

$$P1 \geqslant P1' = \left(\frac{B}{M} - \frac{Bb}{Mb}\right) \Big/ \left(\frac{A}{M} - \frac{Ab}{Mb}\right)$$

and

$$P1 \approx P1'' = 3.3\left(\frac{A}{M} - \frac{Ab}{Mb}\right) .$$

The probability of detecting a $\beta \approx 1$ muon by 1C or 2C is

$$P2 \approx P1\ (2 - P1) .$$

For the 1'x2'x1/8" sheet of plexiglass impregnated with POPOP,

$P1' = 4\%$ with 6% error and
$P1'' = 2.4\%$ with 3% error.

For a 1'x2'x1/8" sheet of UVA plexiglass painted by the "dip" method with a paint of (15g./l.) of Type UVT plexiglass and (2.5g./l.) of POPOP idssolved in dichloroethane,

$P1' = 17\% \mp 10\%$

$P1'' = 7\% \mp 1\%$

$P2' = 14\% \mp 2\%$.

All the above errors are purely statistical errors.

An optimistic calculation of the mean number of photoelectrons created by a $\beta \simeq 1$ muon traversing the 7 ft. of air at S.T.P. in the box yields

mean number of photoelectrons = 3.

A plot of $\left(\frac{A}{M} - \frac{A_b}{M_b}\right)$ vs. the 2C discriminator threshold is shown in Figure (7). Because the mean number of photoelectrons is small the absence of the high threshold voltage cutoff as indicated in Figure (6) and the small detection efficiency can be explained by the large dispersion in the anode pulse height distribution for single photoelectrons.[5]

The expected mean 2C pulse height for cosmic ray muons was optimistically calculated to be

$$\bar{V} = .035 \text{ v} . \qquad (6)$$

In obtaining this result the 2C phototube was calibrated with the Cherenkov light created by cosmic ray muons traversing a plexiglass cylinder in optical contact with the phototube. Figure (6) and the measured efficiency of the POPOP-coated plexiglass relative to the 6810 phototube were then used to calculate (6). The experimental mean 2C pulse height from Figure (7) is

$$\bar{V} = .036 \pm .007 ,$$

in agreement with the expected value.

The low detection efficiency can possibly be considerably improved by using selected phototubes and optimizing the focusing electrode and dynode voltages. We have not used selected phototubes and have not attempted to optimize the tube voltages in any of the work described above.

The detection efficiency of the 2C phototube for $\beta \simeq 1$ charged particles for air and He at sea level and at 14,000 ft. is shown in the following table. These values are obtained from the experimentally measured efficiency of 7% ± 1% for 7 ft. of air at S.T.P. through the use of the Lorentz - Lorentz law relating the index of refraction of a gas with its molar refractivity, molecular weight, and density.

Altitude	Useful Energy Range for Distinguishing π^+ from p	Efficiency for d Meters of Radiator d = 3M	Efficiency for d Meters of Radiator d = 10m
0 feet			
air	6 - 39 GeV	10% ∓ 1.4%	29% ∓ 4 %
Helium	17 - 110 GeV	1.3% ∓ .2%	4% ∓ .6%
14,000 feet			
air	8 - 50 GeV	6% ∓ 1%	19% ∓ 3 %
Helium	21 - 140 GeV	.8% ∓ .2%	2.5% ∓ .4%

V. Conclusion

Using as a detection surface a POPOP-coated plexiglass sheet viewed by two 6810 phototubes, a He Cherenkov counter with 10 m. of He radiator and operating at atmospheric pressure at 14,000 feet can distinguish π^+ from p in the energy range 30 - 140 GeV with an efficiency of at least 5% ± 1%. The efficiency can possibly be considerably improved by the selection of photomultiplier tubes with optimum single photoelectron pulse height distributions and by optimizing tube voltages. Although a sample of π^+ cosmic ray events can be labelled in spite of the small detection efficiency, unless the efficiency can be improved the event rate becomes almost prohibitively small.

For Cherenkov counters used in accelerator experiments, the use of POPOP-coated plexiglass sheets for a detection surface has the following merits:

a) A uniform efficiency for photons incident over a large area of arbitrary shape, e.g., an absorption length of 4 ft.

and

b) A fast rise time provided through the use of photomultiplier tubes of small photocathode area, thus enabling the use of the Cherenkov counter in fast timing.

VI. Acknowledgements

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2. "A Cosmic Ray Program for the Study of Strong Interaction Physics in the Range of 100 - 1000 GeV," L. W. Jones, University of Michigan Technical Report No. 30; (paper presented at the X International Conference on Cosmic Ray Physics, Calgary, Alberta, Canada, June 1967 [to be published]).
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5. J. R. Prescott, Nucl. Instr. Methods 39, 173 (1966).

Figure Captions

Figure (1) A plot in the limit n → 1 of the mean number of photons (in the frequency interval corresponding to the S11 spectral response) created in 3m. of cherenkov radiator vs. π^+ and p energy. The number of photons for a particular radiator are counted from a baseline passing through $E_p = E_{pth}$ which corresponds to the cherenkov threshold for the radiator.

Figure (2) The efficiency of UVA plexiglass sheets coated with UVA plexiglass paint vs. the POPOP concentration in the plexiglass paint.

Figure (3) A block diagram of the logic and apparatus of the cherenkov light source.

D → discriminator

C → coincidence circuit.

Figure (4) Typical plots of the ratio of the coincidence counts $\frac{1+2+3}{1+2}$ vs. the discriminator threshold voltage for POPOP tests using the cherenkov light source.

Curve 1 6810 photocathode

Curve 2 plexiglass strip (2.5g. POPOP/l.)

Curve 3 plexiglass strip (0.0g. POPOP/l.).

Figure (5) A block diagram of the logic and apparatus used to measure the absolute detection efficiency of the POPOP sheets for detecting the cherenkov light of $\beta \approx 1$ charge particles traversing a He cherenkov counter.

D → discriminator

C → coincidence circuit

Fi → fanin

Fo → fanout

x → anticoincidence input.

Figure (6) The distribution of cosmic ray muons with the mean number of cherenkov photons created in traversing 10 feet of air.

Figure (7) A plot of $\left(\frac{A}{M} - \frac{A_b}{M_b}\right)$ vs. the 2C discriminator threshold voltage.

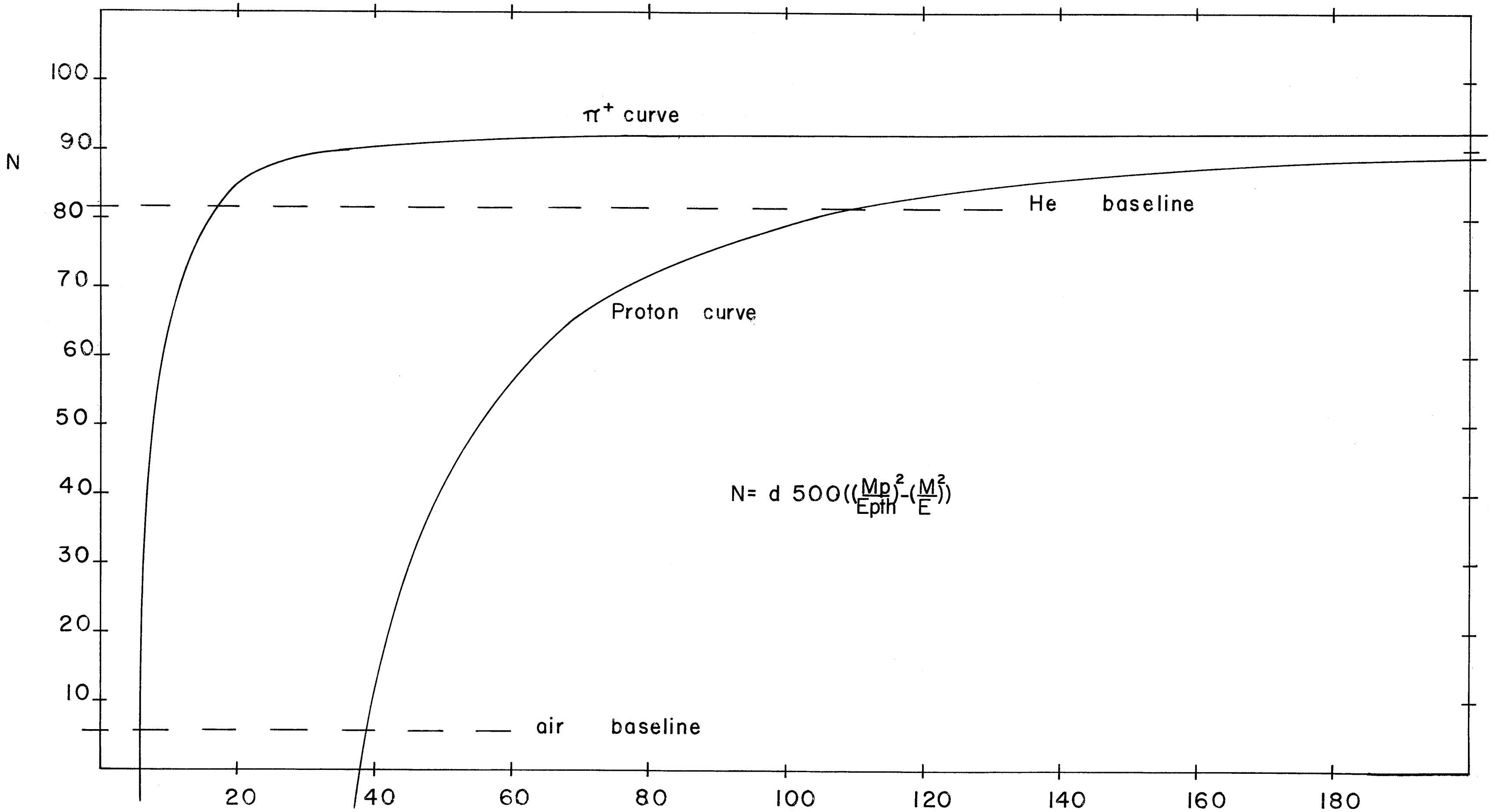

π^+ curve
Proton curve
He baseline
air baseline
N= d 500$((\frac{Mp}{Epth})^2-(\frac{M^2}{E}))$
N
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
E (Gev)

Figure (1)

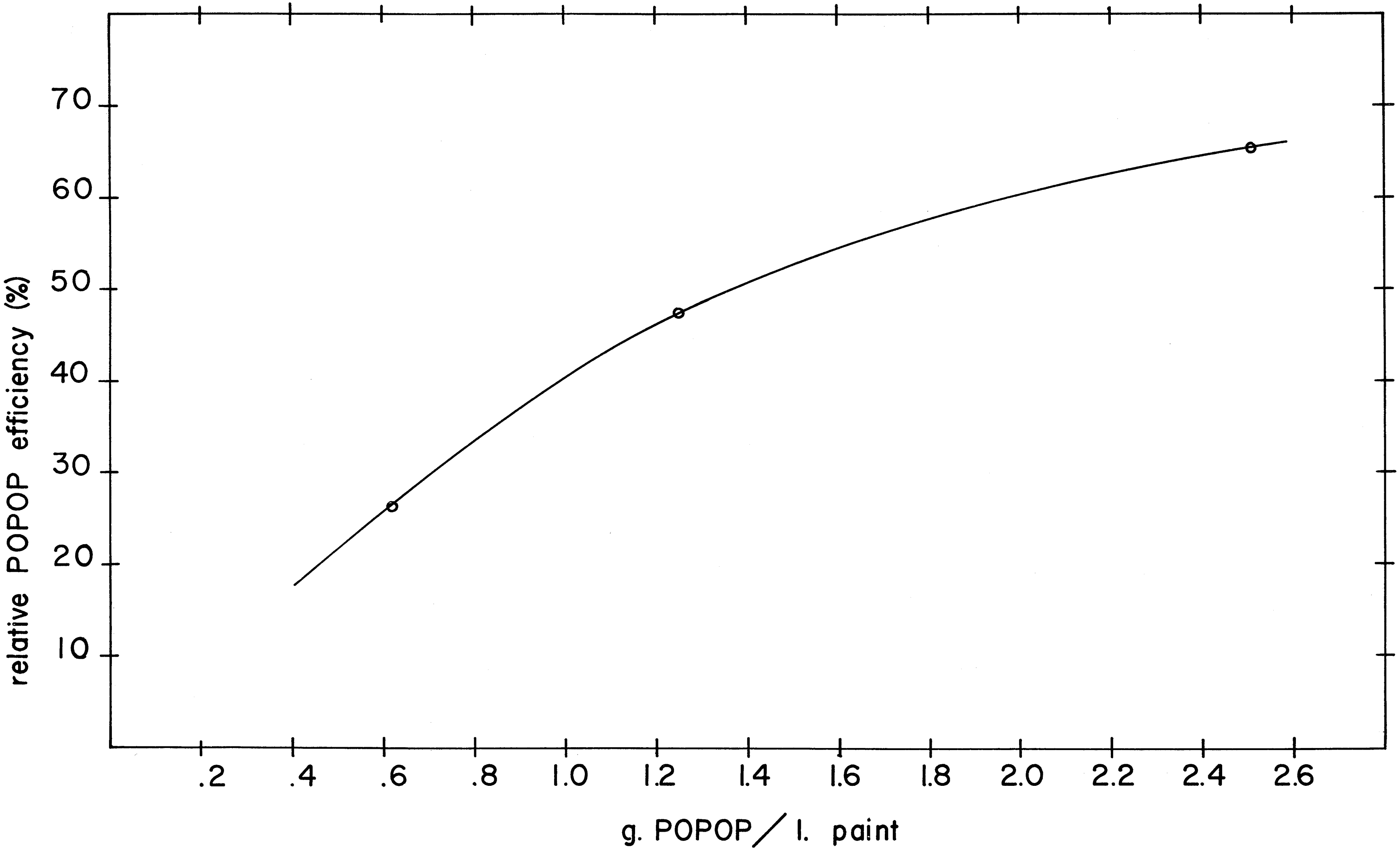
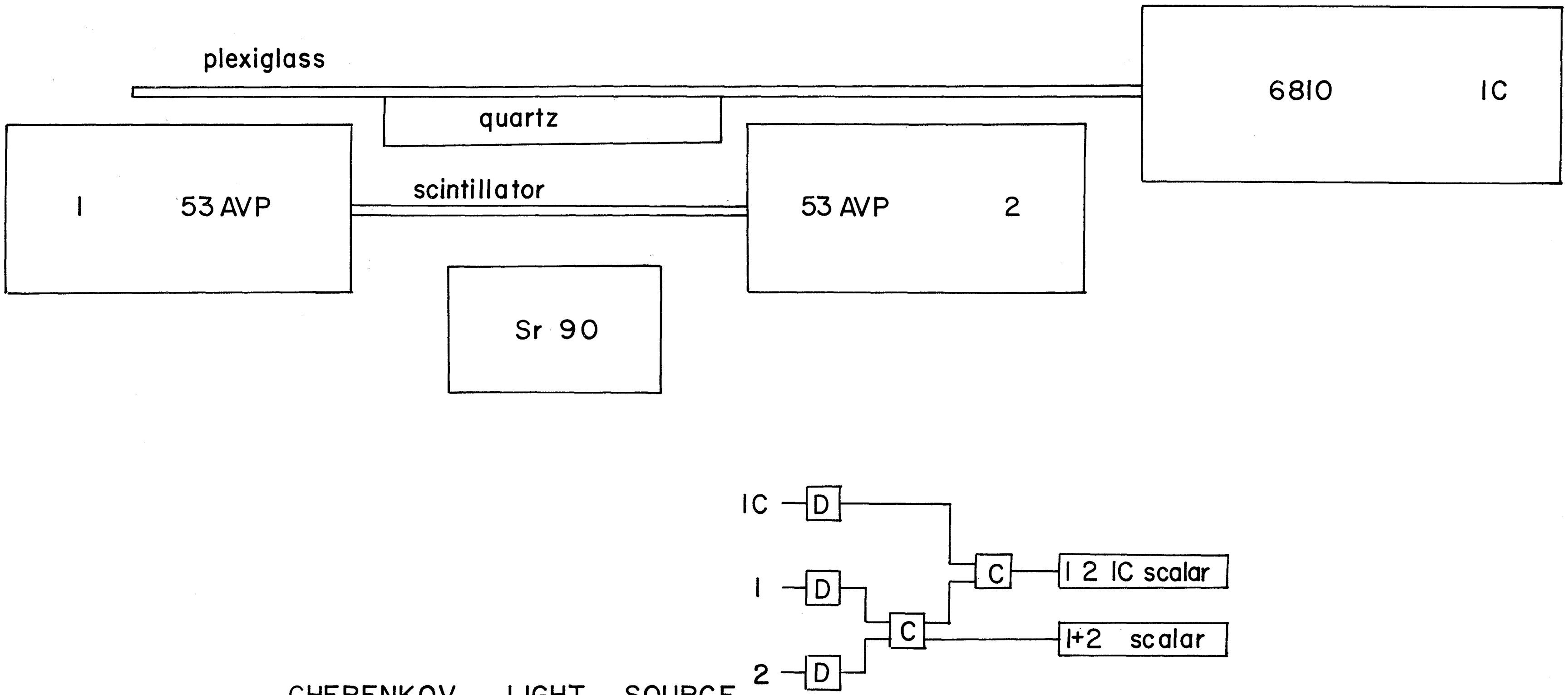

relative POPOP efficiency (%)
70
60
50
40
30
20
10
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
g. POPOP / l. paint

Figure (2)



CHERENKOV LIGHT SOURCE

Figure (3)

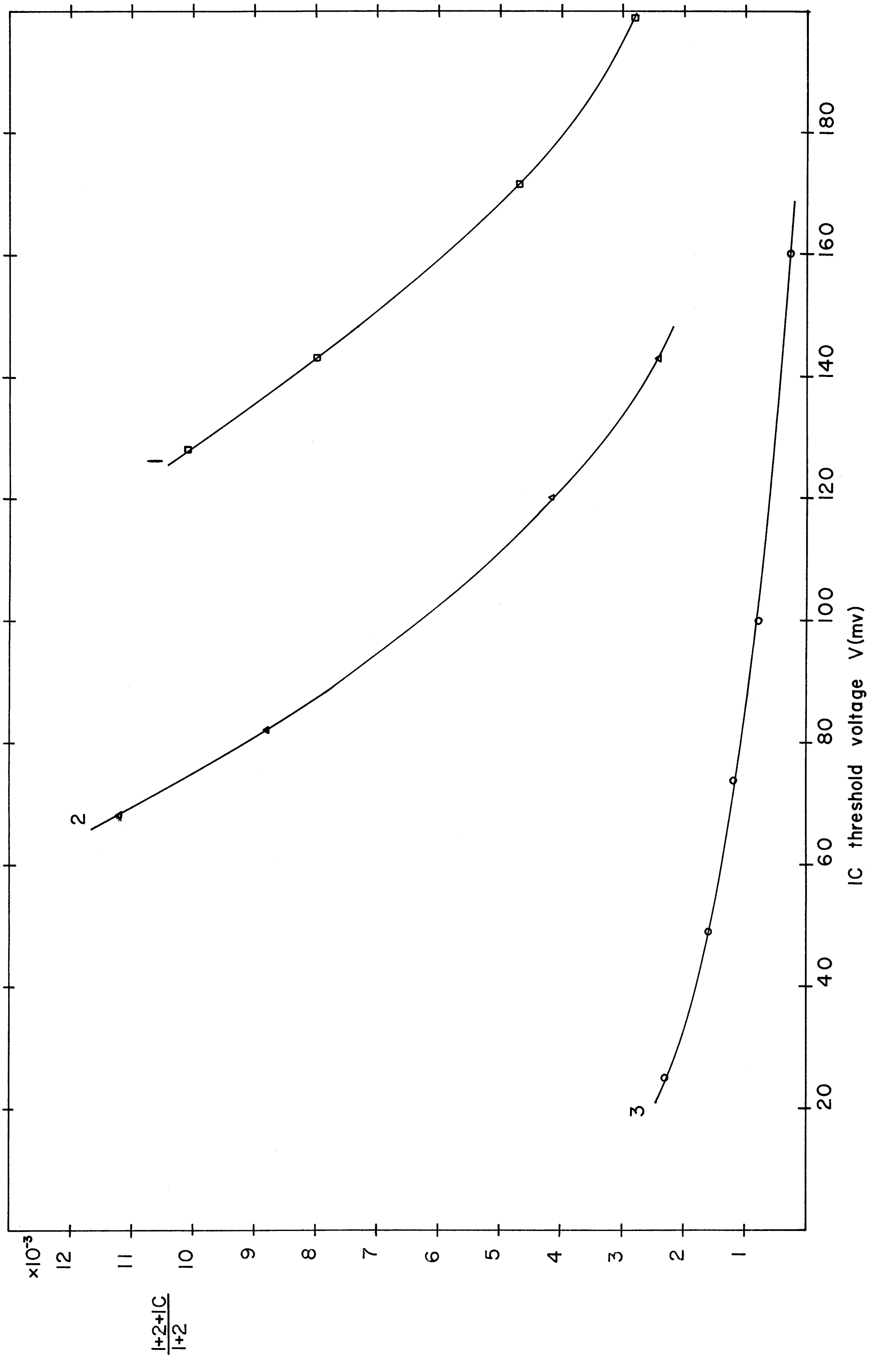

×10⁻³
1+2+IC / 1+2
12
11
10
9
8
7
6
5
4
3
2
1
20
40
60
80
100
120
140
160
180
IC threshold voltage V(mv)
1
2
3

Figure (4)

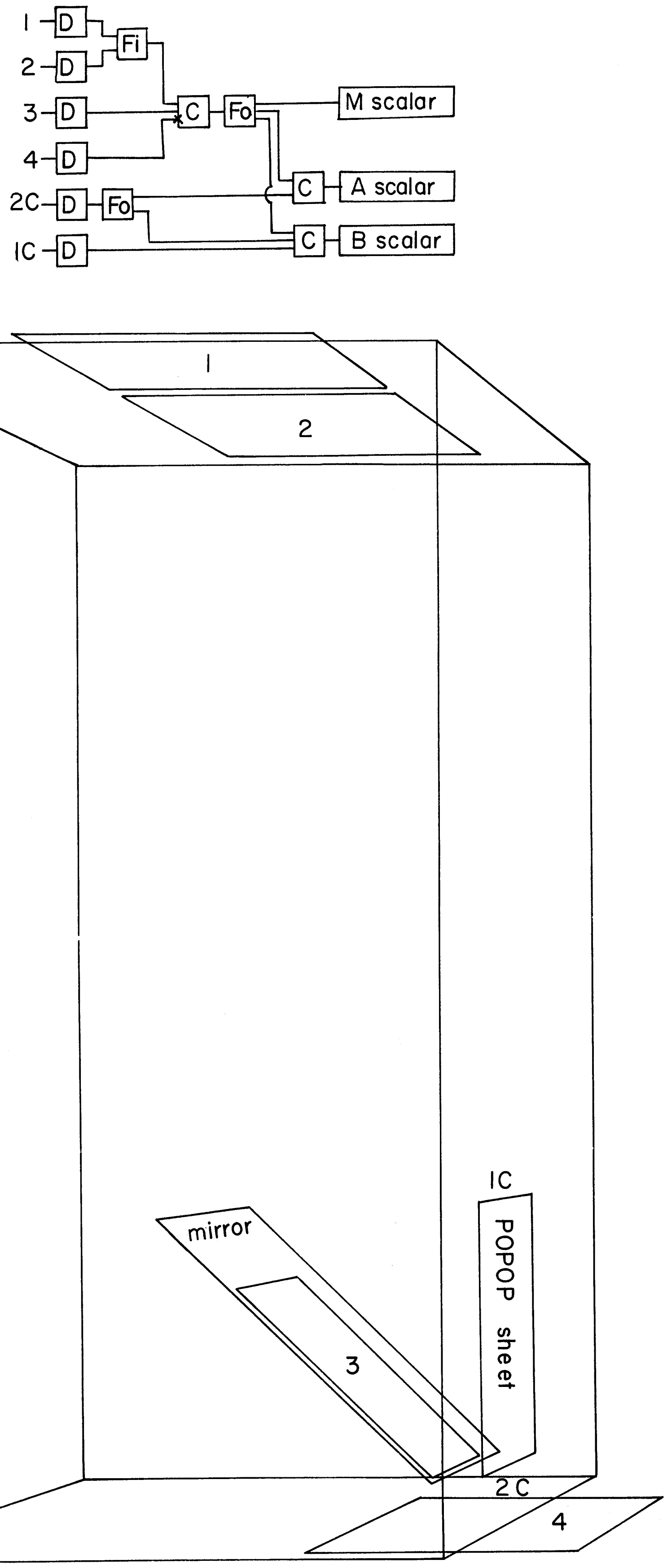

1
2
3
4
2C
1C
D
Fi
C
Fo
M scalar
A scalar
B scalar
1
2
mirror
3
1C
POPOP sheet
2C
4

Figure (5)

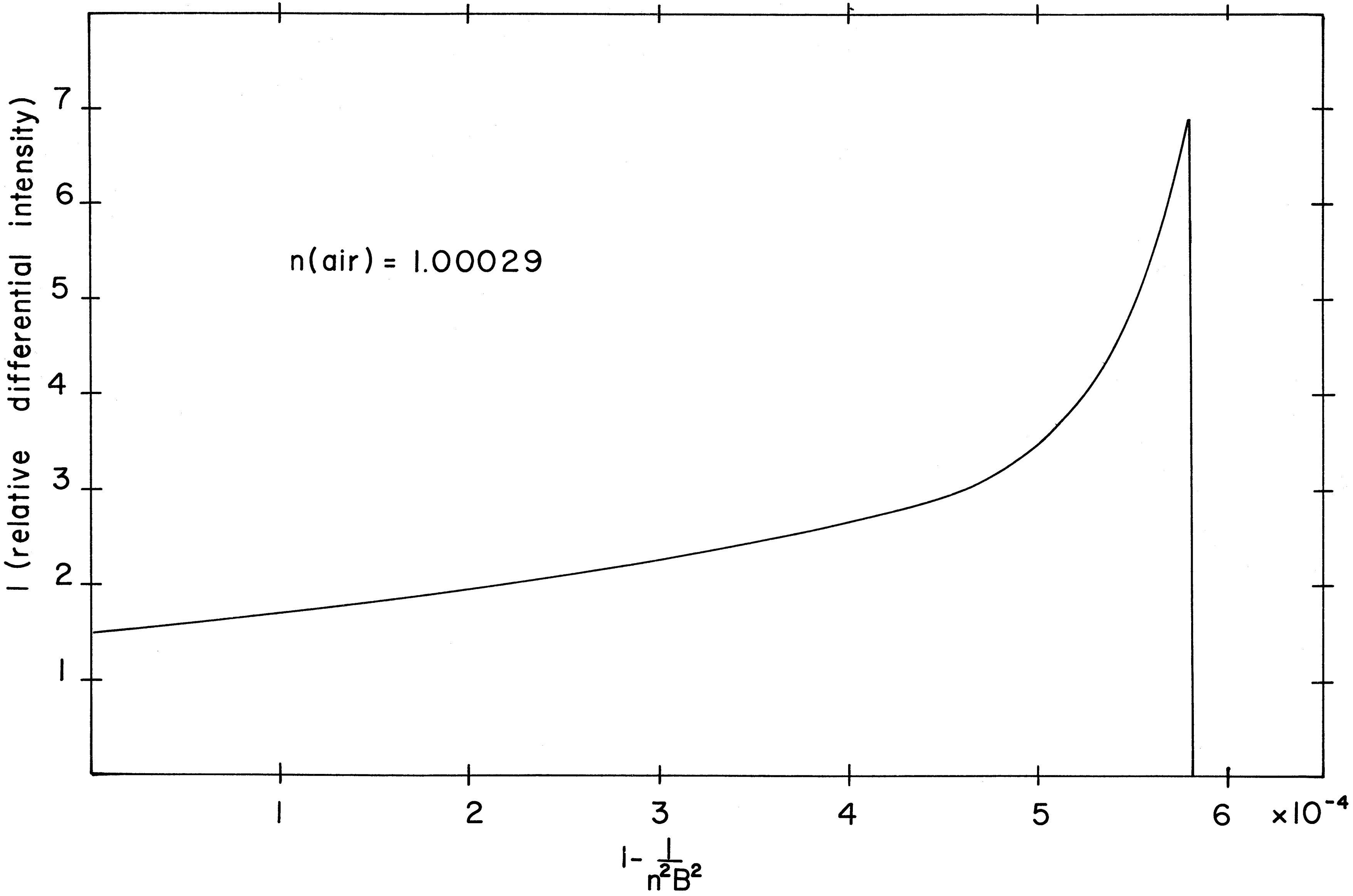

I (relative differential intensity)
7
6
5
4
3
2
1
n(air) = 1.00029
1
2
3
4
5
6
×10⁻⁴
1 - 1/n²B²

Figure (6)

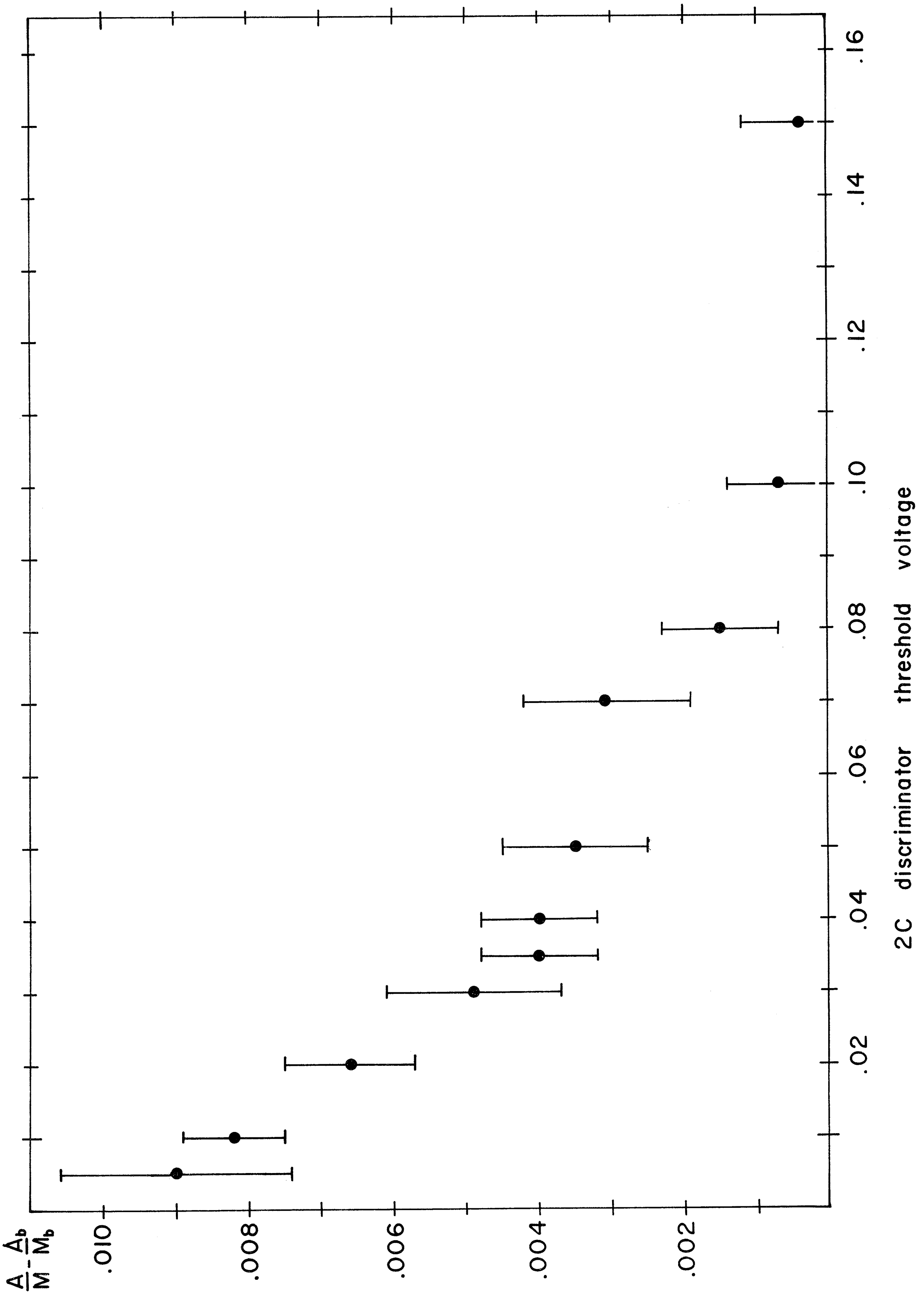

$\frac{A}{M}-\frac{A_b}{M_b}$
.010
.008
.006
.004
.002
.02
.04
.06
.08
.10
.12
.14
.16
2C discriminator threshold voltage

Figure (7)

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