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Abstract

A liquid hydrogen differential Cerenkov counter was developed to detect 0.3-GeV/c ($\beta = 0.92$) pions for comparing π^+ and π^- lifetimes in a check of CPT invariance. This type of counter, previously reported, has now been improved considerably so that it gives no counts when empty, remains clean with no window fogging, and has a very stable index of refraction. Two similar counters were constructed with 4-in.- and 7-in.-diameter apertures, and both could be used with either liquid hydrogen or liquid deuterium as the radiating medium. Each counter cleanly separated pions and muons of the same momentum, with a rejection of better than 10^4.

1. Introduction

Cerenkov counters occasionally need radiators with an index of refraction $n \approx 1.1$, a difficult requirement to meet. A gas above its critical point may be used[1]), but very stable operation is not easy to achieve. Transparent solids are unavailable in this index range. On the other hand, liquid hydrogen and liquid deuterium do have the required index and possess the important advantage of minimal multiple scattering of the radiating particles.

In an experimental check of CPT invariance, made by comparing π^+ and π^- lifetimes, an index $n \approx 1.1$ was required. In a first version of this experiment[2]), a single 4-in.-diameter liquid hydrogen Cerenkov counter (fig. 1) was used to define pions and to count the number surviving as a function of distance in a well-defined pion beam. A description of the construction and operation of this counter was given[3]) at the 1966 instrumentation conference at SLAC. A second experiment[4, 5]), just completed and with much higher precision, utilized two Cerenkov counters of somewhat different design and employed both liquid hydrogen and liquid deuterium. These counters, which were of 4-in. and 7-in. diameters, were designed to avoid problems inherent in the first counter, namely: (a) some counts when empty, (b) window fogging, and (c) fluctuations of the index of refraction. In the second experiment we had ample opportunity to explore counter characteristics, and our findings are presented here.

2. Optical Design

The basic optical design has been described[1, 3]), and hence is discussed only briefly. Cerenkov light generated in the liquid hydrogen or deuterium strikes a 45-deg mirror either directly or after an angle-preserving reflection from the cylindrical mirror that forms the radial limit to the Cerenkov medium. The Cerenkov light that has been reflected from the 45-deg mirror is then focused by a quartz lens doublet[1]) to a ring image, the radius of which depends upon the angle of emission of the Cerenkov light. It should be noted that the dispersion of the refractive optics partially cancels the dispersion of the Cerenkov medium, resulting in cleaner imaging than is possible with reflective optics. All particles passing within the confines of the cylindrical mirror and traveling with the correct velocity parallel to the axis of the cylinder produce light which passes through an annular aperture at the ring focus. A conical light funnel beyond the ring diaphragm brings the light to a photomultiplier.

The optical differences between the older (fig. 1) and newer (figs. 2 and 3) counter designs are considerable. The older counter used a sapphire window at the end of the cylindrical radiator to provide a length of Cerenkov medium which did not vary with position across the counter. It had the disadvantage that the sapphire window, in full view of the photomultiplier, was traversed by the particles and gave rise to counts when the counter was empty. The observed empty rate was 0.6% of the rate with the counter full. The high index of refraction of sapphire should have prevented Cerenkov light produced in the window from emerging anywhere except at the window edges. The spurious counts resulted either from surface imperfections, which allowed Cerenkov light to escape, or possibly from weak scintillation.

In the newer design, Cerenkov light does not traverse a window to reach the 45-deg mirror[6]. This mirror is immersed in the Cerenkov medium and the light leaves through a side window[7] which is then out of the beam. Because of the 45-deg mirror, the lengths of the light-producing particle paths depend on the position across the counter (in one dimension), and this could produce a position-dependent efficiency. Such an effect would have had serious consequences in our experiment and hence was investigated thoroughly; to better than 0.1% accuracy no such effect was found. The empty-counter efficiency was found to be less than 0.01% of the full-counter efficiency.

In both the older and newer counters, light was also collected from an annular region outside the correct ring focus. This light from off-axis or off-velocity particles was carried by Lucite light pipes to two anticoincidence photomultipliers (figs. 1 and 3). In the larger counter, replacement of these solid plastic light pipes by hollow reflective ones resulted in an increase in pulse height. In addition to vetoing spurious particles, the anticoincidence ring vetoed about 0.2% of the pions registered by the central photomultiplier, which itself was 99.9% efficient. Hence the overall efficiency for pions which traversed the counter was 99.7%.

The counter shown in fig. 2 is the smaller one, which was used as part of the intensity monitor in our experiment. The larger counter shown in fig. 3 was similar, except that its optical window was on the bottom rather than on the side. The large counter is discussed in refs.[4,5]), along with a description of the special problems associated with the way in which it was operated.

3. Cryogenic Features

The problems posed by using liquid hydrogen or deuterium include keeping the index of refraction constant, avoiding bubbles and turbulence in the optical path, and keeping mirrors and optical windows clear. Some of the techniques developed to achieve these conditions are now discussed.

A deuterium-type condenser was used when either liquid hydrogen or liquid deuterium was employed as the Cerenkov medium. Liquid hydrogen was used to condense the Cerenkov medium from gaseous hydrogen or deuterium, as shown in fig. 4. This arrangement, together with filters[8]), not only insured the purity of the Cerenkov medium, but also made it possible to control the index of refraction. The latter aim was accomplished by regulating the vapor pressure of the condensed Cerenkov medium at approximately 3 psig, with a precision of ±0.01 psig. To maintain constant pressure, the regulator[9]) would either take more gas from the bottle or exhaust excess gas. About 100 ft^3 per day was used in this process.

The index of refraction was monitored by measuring the temperature with platinum resistance thermometers[10]) immersed in the top and bottom of the stainless-steel-and-Mylar flask containing the Cerenkov medium. Similar thermometers monitored the temperature of the reservoirs. By means of the pressure regulation, the temperature was held constant to within ±0.02°K, which corresponds to

± 0.00006 in the index of refraction. The resulting change in Cerenkov angle of ± 0.02 deg is to be compared with our ring aperture of ± 3 deg.

It was very important that there be little boiling in the optical path of the Cerenkov light. This problem was made more serious because the large transparent flask window allowed heat from the room-temperature photomultiplier assembly to enter the Cerenkov medium. Boiling was kept to a minimum by surrounding the flask (except for the optical window) with 20 layers of 0.00025-in. aluminized Mylar. It was enclosed in an aluminum heat shield held at liquid-nitrogen temperature, which was supported by insulating rods attached to the outer vacuum jacket. The insulating vacuum was 5×10^{-8} torr. Bubbling in the optical region was partially eliminated by immersing the cylindrical mirror in the Cerenkov medium, so that boiling took place outside, rather than inside, the mirror. A bubble shield was also provided at the cylindrical mirror exit in the large counter, to conduct bubbles from the edge of the window around the outside of the mirror. The separate liquid hydrogen shield connected to the condensing system (figs. 2, 3, and 4) considerably reduced the heat flow into the flask through the optical window, and boiling was observed to be much slower with the lenses in place than it had been during tests without the lenses.

The hydrogen shield outside the flask served also to prevent condensation on the flask window and lenses. A liquid-nitrogen trap was used during the initial diffusion pumping, and then the vacuum was maintained with only an ion pump. In spite of these precautions, internal surfaces were still contaminated by some material which could migrate to the cold flask window. Accumulation on the flask window was prevented by the surrounding liquid-hydrogen shield which was always cooled before the flask was filled. With the older counter, which did not have such a shield, window fogging caused enough scattering of Cerenkov light into the anticoincidence ring to decrease the counter efficiency by 1% per day. The effect was not observed in the newer counters when the shields were used properly.

4. Counter Performance

For the purposes of the pion-lifetime experiment[2]) it was necessary that the counters' response be broader than the beam's limits in momentum ($\Delta p/p = \pm 0.5\%$) and in angle (± 0.6 deg), and also be capable of separating cleanly pions and muons of the same momentum. A ring aperture of ± 3 deg (for 12-deg Cerenkov light) satisfied these requirements, and a momentum-response curve for this aperture is shown in fig. 5. This curve was obtained by measuring the counter efficiency as a function of beam momentum. In the fig. 5 the percentage of muons and percentage of pions do not add to 100% although the beam consisted solely of these two particles, electrons having been eliminated by another counter. Also one sees that the flat tops of the muon and pion peaks have slight slopes. Both these effects are due to the variation of the π/μ ratio with momentum in the beam itself, and they both give the same value for this variation. The flat tops and steeply sloping sides (30% change in efficiency with 1% momentum change) indicate that the counter had both high efficiency and excellent rejection. An indication of the latter is the 10^4:1 ratio of the pion peak to the valley on either side. The very deep dip on the high-momentum side of the pion peak occurs because Cerenkov light from pions of that momentum goes directly into the anticoincidence ring. By extrapolating the number of muons and their counting efficiency to the central pion momentum, a rejection of better than 10^4 is obtained.

The excellent rejection of the counter is also apparent in the pulse-height distribution obtained from the central photomultiplier when the counter is responding only to pions which are required to go completely through the Cerenkov medium. The pulse-height spectrum labeled "3-in. diam." in fig. 6(a) was obtained from particles that completely traversed the larger Cerenkov counter and produced a count in a 3-in.-diameter scintillation counter behind the flask. A measure of the counter performance is the peak-to-valley ratio, which was 500:1 in this case.

5. The Effect of Pion Interactions

The problem of pion interactions in the Cerenkov medium is particularly acute because the momentum is near the peak of the T = 3/2, J = 3/2 first pion-nucleon resonance. The effect of the interactions is shown in fig. 6(a), in which the shape of the pulse-height distribution depends on the size of a downstream coincidence counter. The upper two curves were obtained with no coincidence requirement, and by requiring a count in a 12-in.-diameter downstream coincidence counter. The continuous spectrum of small pulses which "fill up" the valleys of these two curves is due to pions which enter the counter and penetrate only a short distance into the liquid hydrogen radiator before undergoing a nuclear interaction. Such particles produce a pulse whose height is proportional to the distance traveled before the interaction.

At our momentum the $\pi^- p$ cross section is only 1/3 that of $\pi^+ p$, and hence in fig. 6(b) the curve labeled "$LH_2(\pi^-)$" has a much deeper valley than the "$LH_2(\pi^+)$" spectrum. It was for this reason that we used liquid deuterium rather than liquid hydrogen in our experiment. Although the extra neutron produces more interactions and hence an even worse pulse-height distribution, that distribution--labeled $LD_2(\pi^{\pm})$ in fig. 6(b)--is identical for π^+ and π^- because of charge independence. For most purposes, however, liquid hydrogen makes a more satisfactory radiating medium. Peak-to-valley ratios obtained under various conditions are listed in table 1, along with a summary of other counter characteristics.

Some slight differences between the two Cerenkov counters were due to the lower beam velocity at the larger counter. However, the biggest difference stemmed from the fact that the small counter (fig. 2) was constructed to be used with a downstream coincidence counter, while the large one could not be operated in this way. The latter situation arose because of our requirement that the Cerenkov-counter aperture be larger than the pion beam, making the detection efficiency independent of small changes in the beam position. A downstream coincidence counter improves the pulse-height distribution because it does not intercept most of the "halo" of pions scattered by the Cerenkov medium, but this very fact makes the efficiency sensitive to beam position within the counter. Even if such effects could be made small, the construction of the large counter (fig. 3), which had its beam exit window parallel to the 45-deg mirror, poses another problem. The amount of deuterium Cerenkov radiator (an absorber) encountered by a pion trajectory depends on its vertical position in the flask, and the efficiency was very sensitive to this position when a downstream coincidence counter required that the particle traverse the entire deuterium radiator. For this reason, if uniform efficiency is important, a counter of this type should be constructed to provide uniform absorption for all particles.

Even though the larger Cerenkov counter was operated without a downstream coincidence counter, we found a significant nonuniformity of response of the counter across its entrance aperture. The effect was eventually traced to the 4.5-in.-diameter RCA-4522 central photomultiplier. Despite some mixing of light-ray directions by the lenses and the reflecting cone, there was a strong correlation between the position of the pion entrance into the Cerenkov medium and the position of the light on the photomultiplier face. The photocathode efficiencies were found to be highly nonuniform, resulting in counter efficiency changes as large as 3% per inch of lateral displacement of the pion trajectories. The problem was solved by selecting a photomultiplier with more uniform efficiency, and by rebuilding the conical mirror to use only the central 3.5-in.-diameter portion of the photocathode. Typical efficiency profiles, with variations of less than 0.2% per inch over the central 5.5 in. of the counter aperture, are shown in fig. 7. At our urging, RCA has also begun producing photomultipliers with somewhat more uniform photocathode efficiencies.

A number of difficulties having been solved, these liquid hydrogen or deuterium counters are now at a state of perfection in which limitations on stability and uniformity of response seem to depend primarily on photomultiplier characteristics. They have been used successfully in one high-precision experiment to measure the π^+/π^- lifetime ratio, and will soon be utilized in another to compare the K^+ and K^- lifetimes.

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We wish to thank Prof. A. Carl Helmholz and Prof. Burton J. Moyer, who provided support and encouragement throughout the experiment. We are grateful to all those who assisted in the construction and operation of these complex counters. We are particularly indebted to Albert H. Kleid for the flask assembly and alignment, and to Rene Bollaert, Russell F. Ellis, and Allan R. Susoeff of the hydrogen target group, who gave invaluable aid with the installation and maintenance of both counters. We thank Dr. James G. Baker for the design of the lens system.

FOOTNOTES AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

†On leave from the Physics Department, Tufts University, Medford, Mass.

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5) David S. Ayres, Comparison of π^+ and π^- Lifetimes as a Test of CPT Invariance (Ph.D. thesis), Lawrence Radiation Laboratory Report UCRL-18369, Oct. 1968 (unpublished).

6) The mirror was made from 0.0005-in.-thick aluminized Mylar, specifically made for high reflectivity by G. T. Schjeldahl Co., Northfield, Minn. The Mylar was stretched in a frame and attached to an elliptically shaped stainless steel holder with Epoxy 828 and Versamid 140. The mirror for the larger counter,

the holder for which was 9-7/16 in. by 13 in., had to be made especially tight to prevent rippling at liquid hydrogen temperatures. This was done by heating and tightening the Mylar in its stretcher frame just before bonding.

7) After tests of many materials, it was found that the quartz could be bonded to the Kovar so as to survive many temperature cyclings by using a mixture of Adiprene L-100 (100 parts) and Moca (12.5 parts). These are both DuPont products.

8) All gas used in the deuterium system was passed through filters containing 5-Å molecular sieves (in 1/16-in. pellets) which were at liquid nitrogen temperature. The filters removed water, air, oil, and other contaminants which might otherwise have condensed on the cold optical surfaces inside the flask.

9) Bell-O-Fram self-relieving pressure regulator, type 10A, 2 to 25 psi, obtained from Bell-O-Fram Corp., Burlington, Mass.

10) Temperature sensor model No. 146AF-1, obtained from Rosemont Engineering Company, Minneapolis, Minn. These sensors had a resistance of about 6 ohms at 20°K, with a sensitivity of about 0.8 ohm/°K.

Table 1

Operating characteristics of Cerenkov counters for pions.

Parameter		LH_2	LD_2
Number of photoelectrons per particle		80	80
Index of refraction		1.11	1.13
Cerenkov angle[a] (deg)	back counter	10.1	10.1
	front counter	12.3	12.3
Cerenkov angles accepted (deg)		± 3	± 3
Cerenkov angle fluctuation due to temperature changes (deg)		± 0.02	± 0.02
Velocity (β)[a]	back counter	0.913	0.898
	front counter	0.920	0.915
Velocity acceptance (HWHM)		± 0.009	± 0.009
Usable aperture[b] (in.)	back counter	5.5	5.5
	front counter	4.0	4.0
Particle angles accepted (HWHM) (deg)		± 6	± 6
Pion efficiency (β = 0.92) (%)		99.7	99.7
Electron efficiency (β = 1.0) (%)		0.5	1.0
Muon efficiency (β = 0.95) (%)		0.02	0.04
Empty-counter efficiency (%)		<0.01	<0.01
Pions scattered out of beam by Cerenkov medium of front counter (%)		43	51
Pulse-height spectra peak-to-valley ratios			
No backup counter	π^+	6	4.5
	π^-	18	4.5
With backup counter larger than flask		25	12
With backup counter smaller than flask		500	250

a. The smaller Cerenkov counter preceded the larger one, and caused an energy loss of about 14 MeV. The ring diaphragm dimensions were adjusted to account for this fact.

b. The front counter was used with a 2-in.-diameter downstream coincidence counter, and hence had uniform efficiency (± 0.1%) over its entire 4-in. aperture. The back Cerenkov counter was operated without a downstream scintillator, and hence only the central 5.5 in. had uniform efficiency (± 0.5%).

FIGURE CAPTIONS

Fig. 1. Schematic drawing of the original liquid hydrogen differential Cerenkov counter. Note that the diameter of the ring focus depends on the angle of emission of the Cerenkov light (and hence the velocity of the particle), whereas the lateral position of the ring focus with respect to the ring aperture depends on the direction of the particle. The optically coaxial cylindrical mirror provides full efficiency across the 4-in. diameter of the radiator. LH_2: 4×8-in.-long liquid hydrogen radiator. S: 1/4-in. sapphire window. M: 45-deg mirror. L_1, L_2: quartz lenses. Q: quartz vacuum window. A: ring aperture. LP: anticoincidence-ring light pipes. C: coincidence photomultiplier. A_R, A_L: anticoincidence photomultipliers. MC: cylindrical mirror.

Fig. 2. Plan view of the smaller liquid deuterium Cerenkov counter. The optical system is similar to that of fig. 1, except that the liquid deuterium flask has its optical window on the side, out of the particle beam. Note the liquid hydrogen shield surrounding the quartz lenses. Impurities were cryopumped onto the shield, which then kept the flask quartz window free of condensation.

Fig. 3. Side view of the larger liquid deuterium Cerenkov counter. The optical system is similar to that of fig. 2 except that the cylindrical mirror has a 7-in. diameter and the flask optical window is on the bottom. In order to prevent the possible accumulation of material in the optical path, the window and the entire optical system that followed it are at an angle of 5 deg to the horizontal.

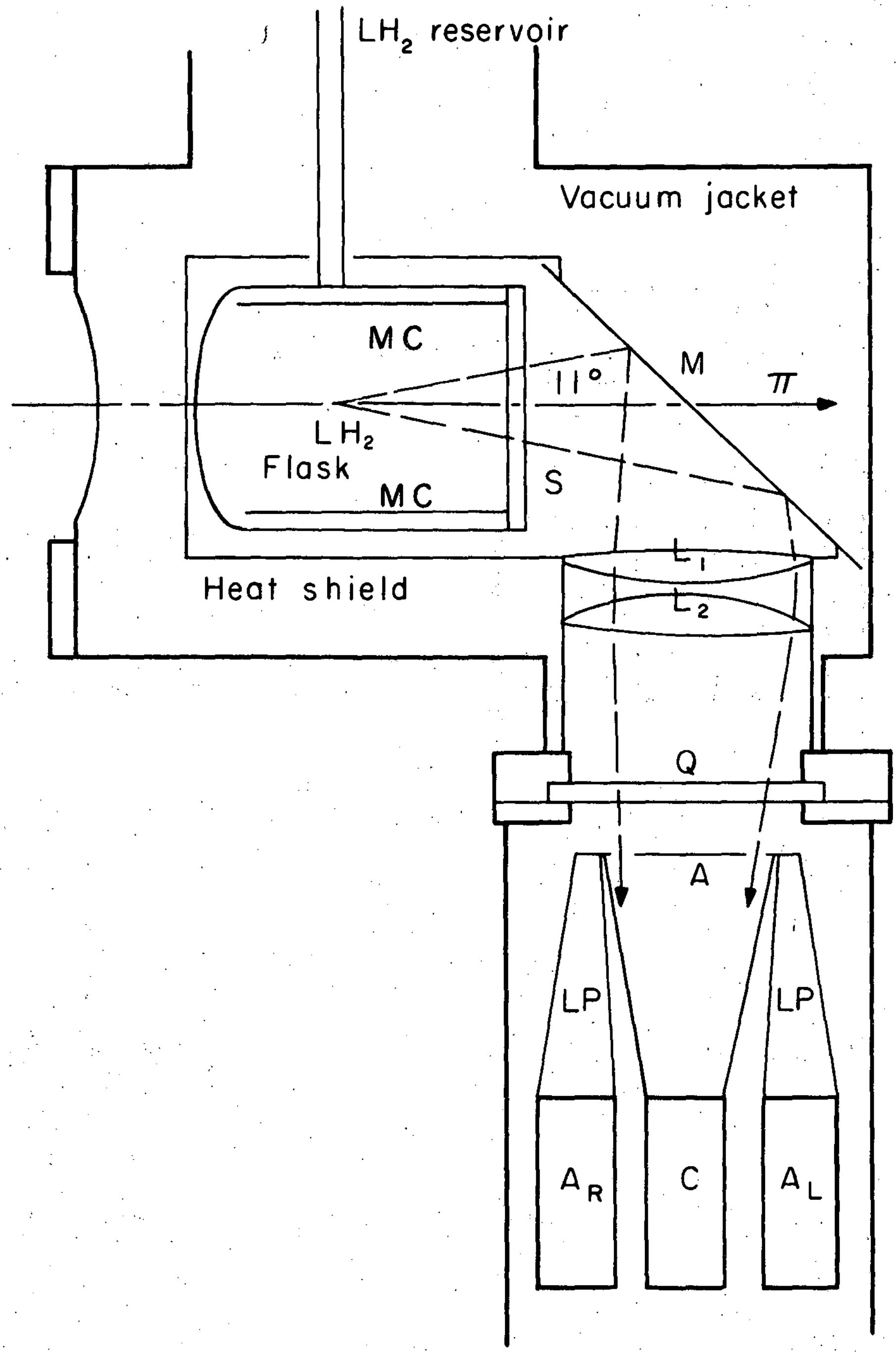
Fig. 4. Simplified diagram of the liquid deuterium condensing and pressure-regulating system used to operate both Cerenkov counters. When liquid hydrogen was used as the Cerenkov medium, it was condensed in the same way as deuterium.

Fig. 5. Efficiency of the Cerenkov counter as a function of incident-beam momentum. Note the pion and muon peaks and the deep valley between them.

Fig. 6. (a) Typical pulse-height distributions from the central photomultiplier of the large Cerenkov counter. All were obtained by using a liquid hydrogen radiator and π^+ particles, but with different downstream coincidence counters, of dimensions indicated.

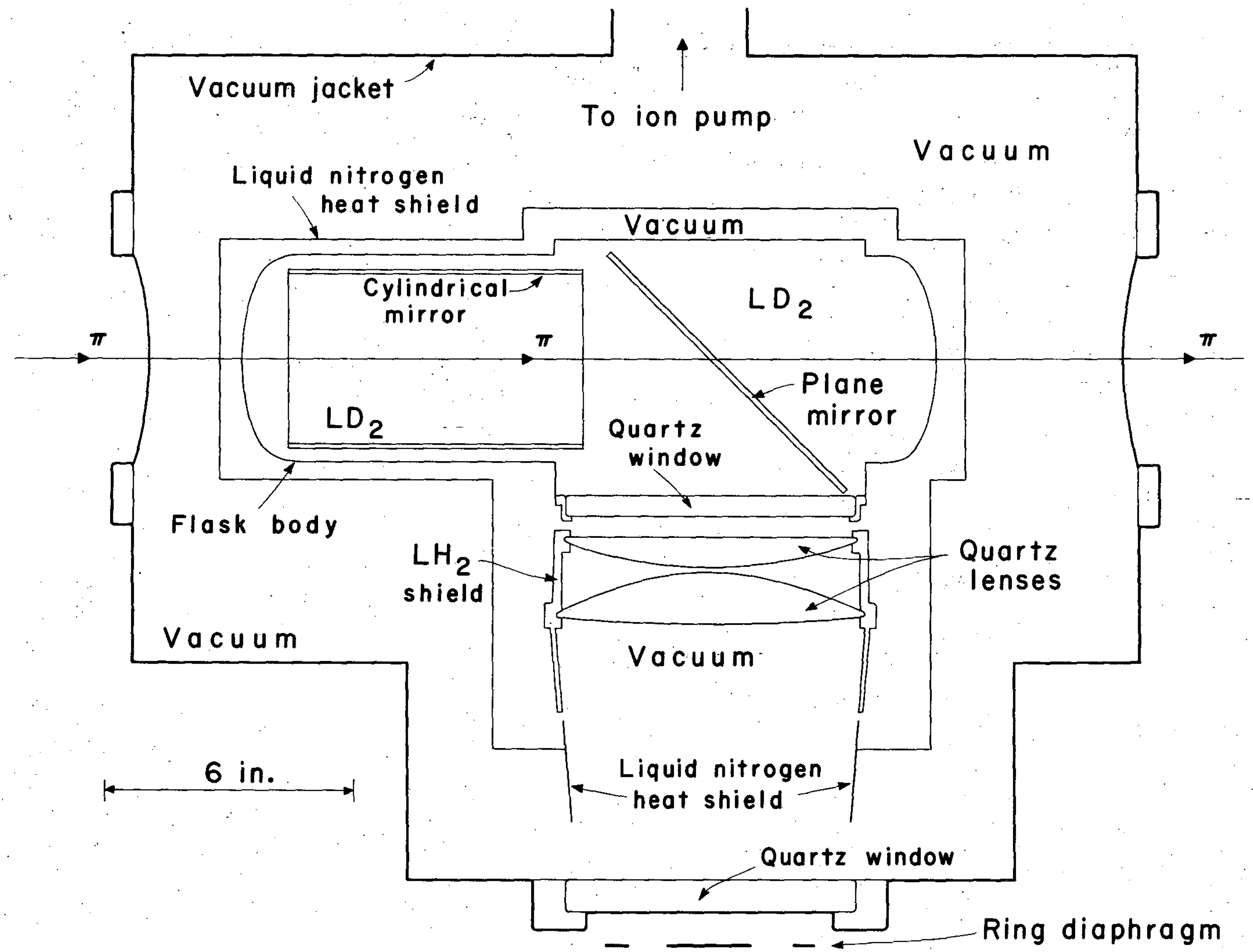
(b) Pulse-height spectra obtained from the large counter with different radiating media. All were taken without a downstream coincidence counter. Note that liquid deuterium (LD_2) produces the lowest peak-to-valley ratio, but that the spectra are the same for π^+ and π^-. When liquid hydrogen (LH_2) is used, the peak-to-valley ratios are larger than for liquid deuterium, but quite different for π^+ and π^-.

Fig. 7. Lateral and vertical efficiency profiles for the large Cerenkov counter. These were obtained by moving the counter laterally and vertically across the pion beam at a point where the beam was 2.5 in. wide by 3 in. high. D/M is the fraction of monitor coincidences which corresponds to counts in the Cerenkov counter, and hence is proportional to the counter efficiency. The D/M value of 0.4 represents the fraction of pions that had not yet decayed at this position along the decay path.



MUB-13668-A

Fig. 1



XBL687-3451

Fig. 2

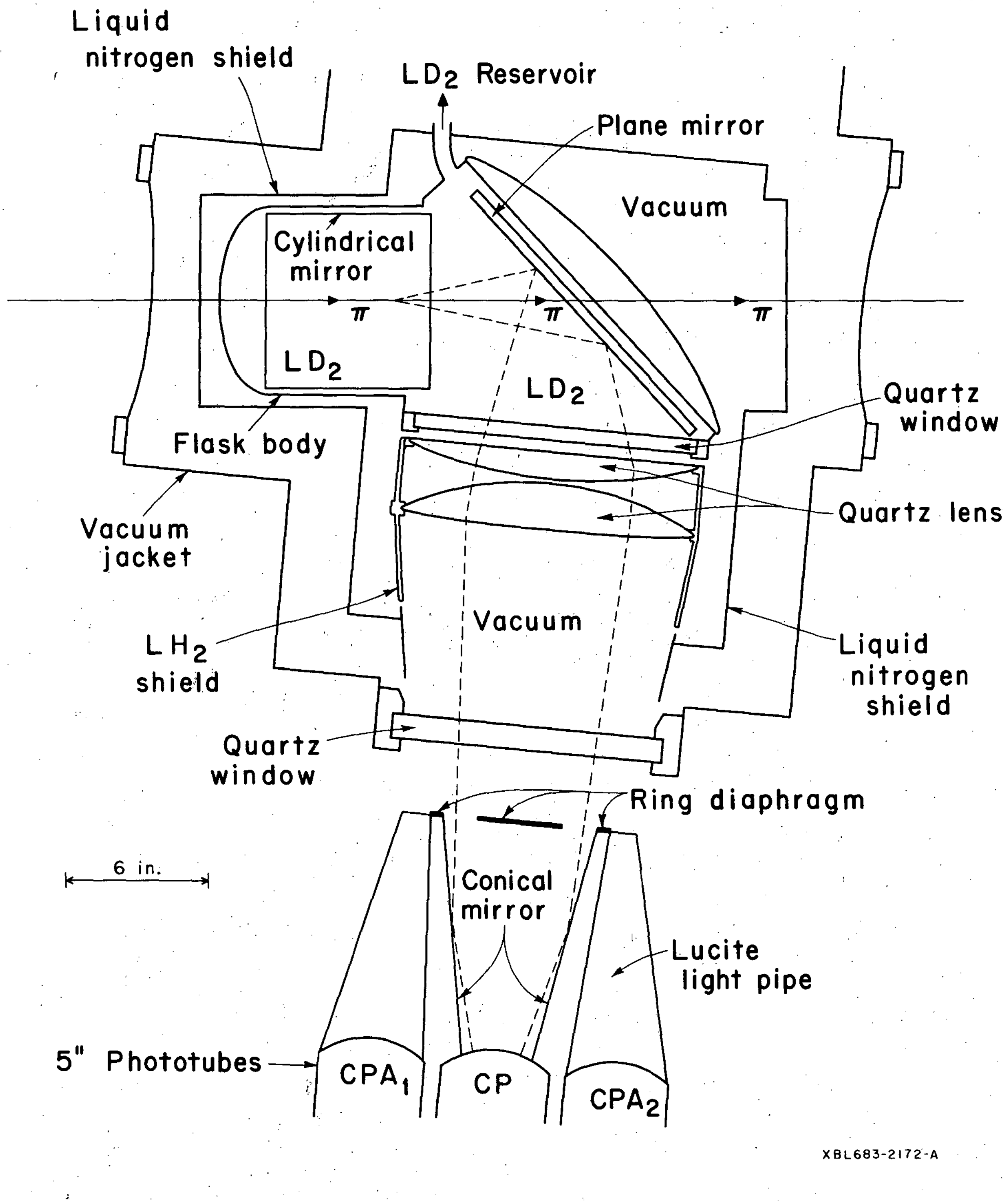

Liquid nitrogen shield
LD2 Reservoir
Plane mirror
Vacuum
Cylindrical mirror
π
π
π
LD2
LD2
Quartz window
Flask body
Quartz lens
Vacuum jacket
Vacuum
LH2 shield
Liquid nitrogen shield
Quartz window
Ring diaphragm
6 in.
Conical mirror
Lucite light pipe
5" Phototubes
CPA1
CP
CPA2
XBL683-2172-A

Fig. 3

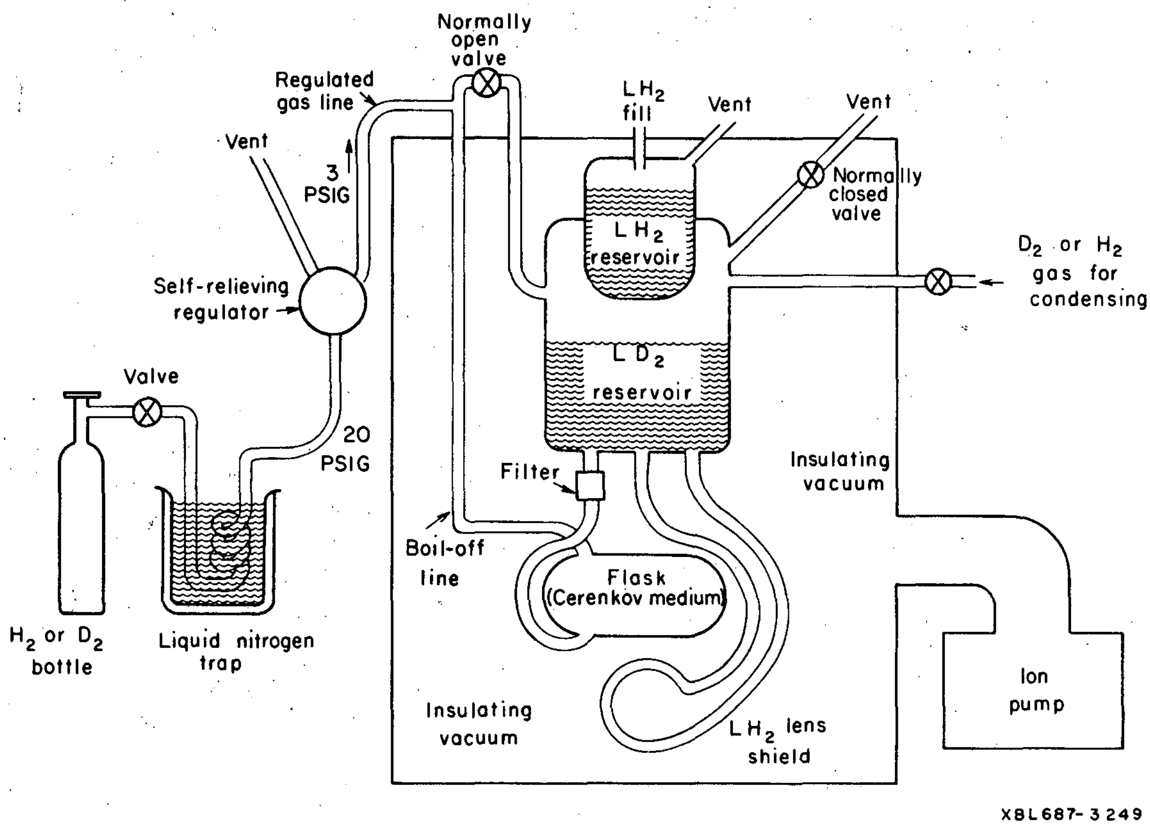

Normally open valve
Regulated gas line
Vent
3 PSIG
LH2 fill
Vent
Vent
Normally closed valve
LH2 reservoir
D2 or H2 gas for condensing
Self-relieving regulator
LD2 reservoir
Valve
20 PSIG
Filter
Insulating vacuum
Boil-off line
Flask (Cerenkov medium)
H2 or D2 bottle
Liquid nitrogen trap
Ion pump
Insulating vacuum
LH2 lens shield
XBL687-3249

Fig. 4

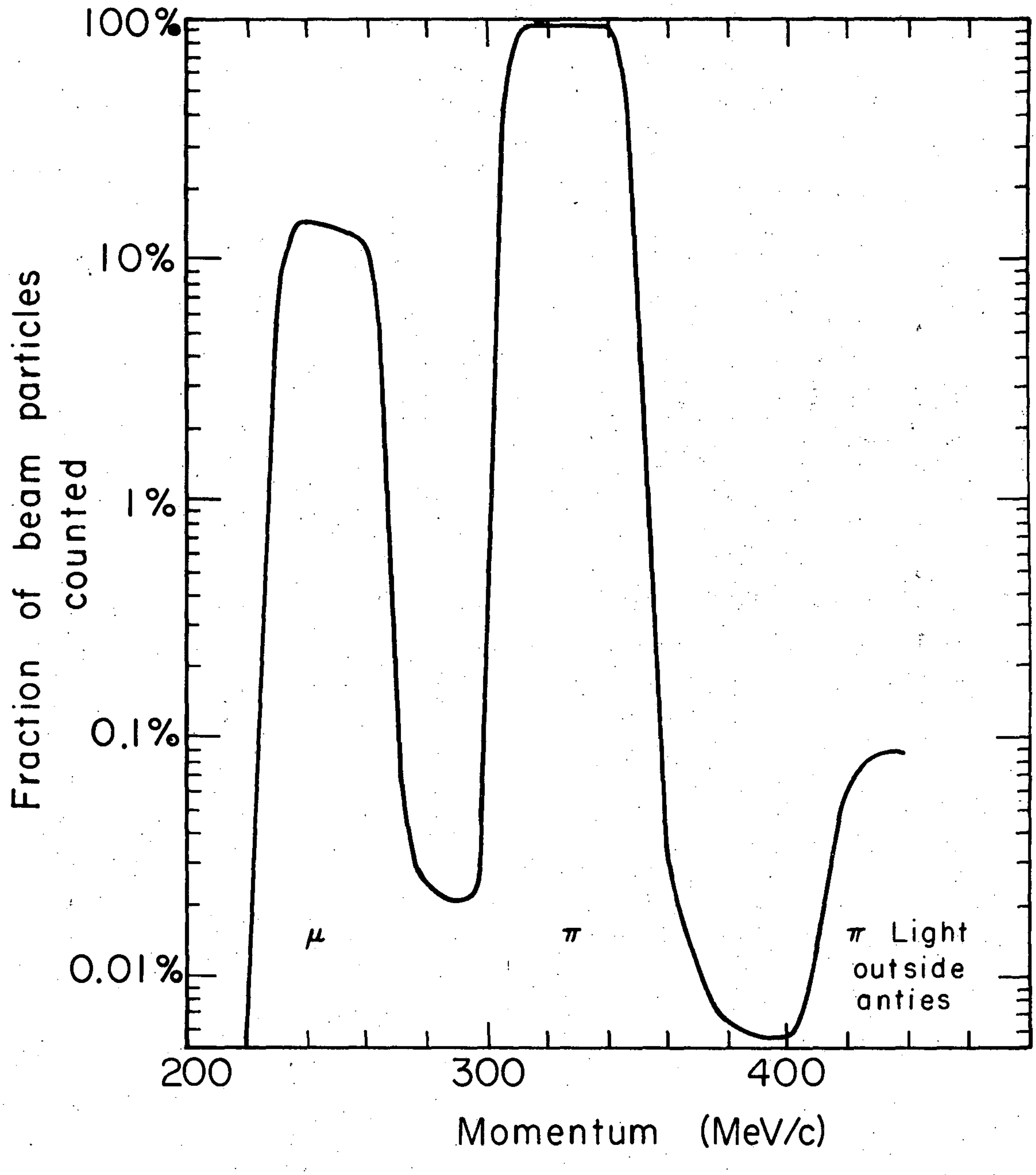

100%
10%
1%
0.1%
0.01%
Fraction of beam particles counted
μ
π
π Light outside anties
200
300
400
Momentum (MeV/c)
XBL687-3161

Fig. 5

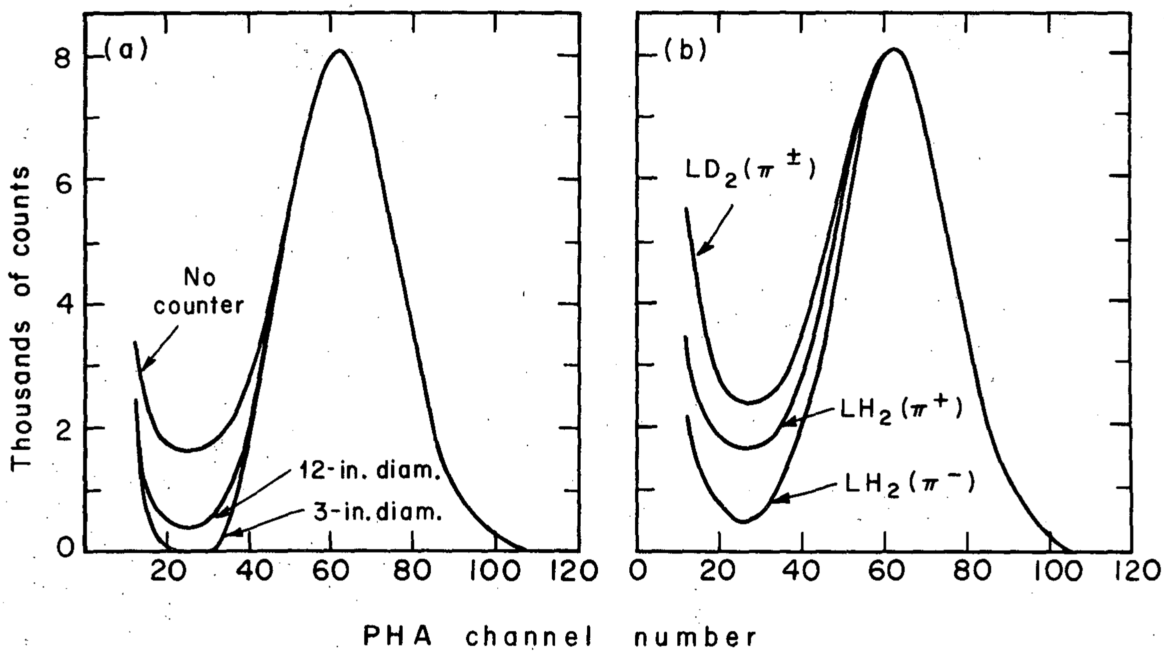
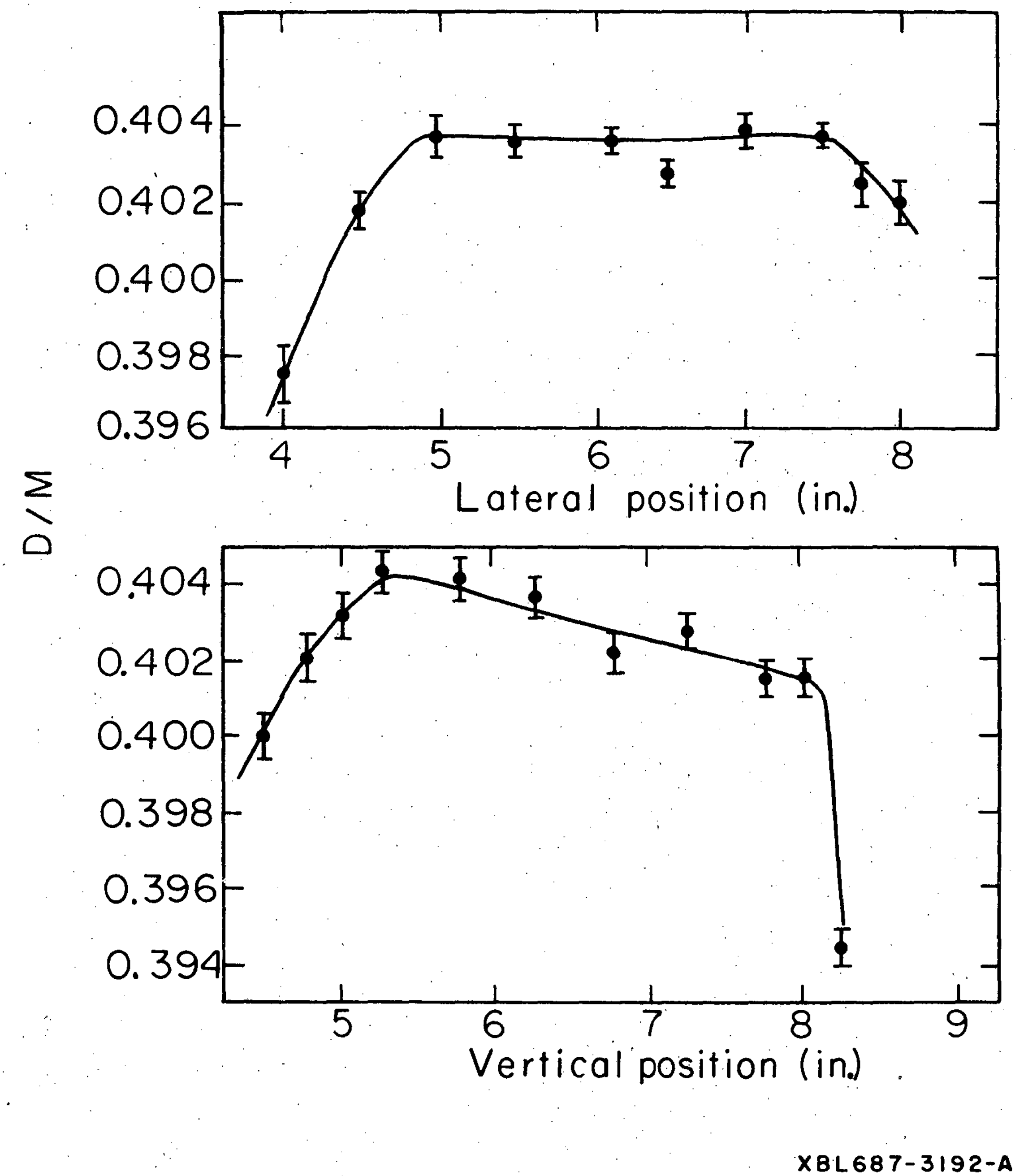

(a)
(b)
Thousands of counts
No counter
12-in. diam.
3-in. diam.
LD₂(π±)
LH₂(π+)
LH₂(π−)
PHA channel number
XBL689-6830

Fig. 6


0.404
0.402
0.400
0.398
0.396
4
5
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7
8
Lateral position (in.)
D/M
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0.402
0.400
0.398
0.396
0.394
5
6
7
8
9
Vertical position (in.)
XBL687-3192-A

Fig. 7