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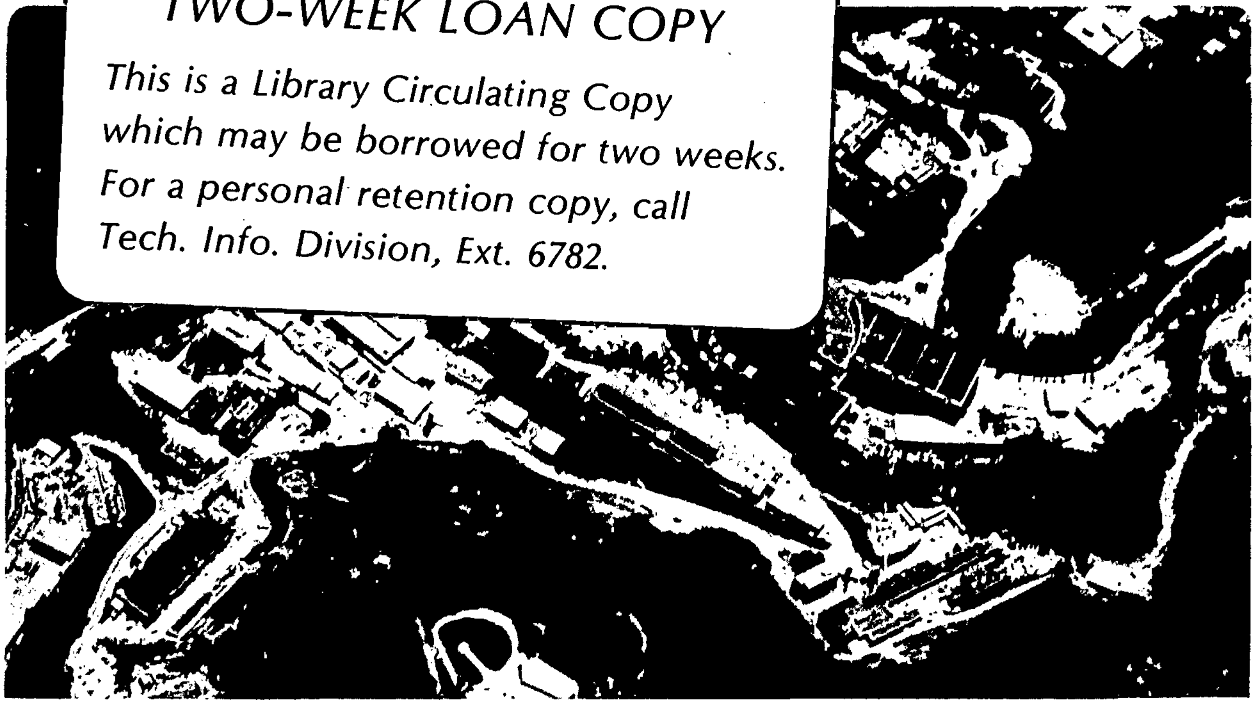

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DISCLAIMER

A WATER CERENKOV NEUTRINO DETECTOR*

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ABSTRACT

We describe the construction and performance of a water Cerenkov counter designed to detect neutrino reactions in 6000 liters of H_2O or D_2O. The detector has a yield of 5.3 photoelectrons/MeV and a resolution $\sigma = 12\%$ at energies around 40 MeV.

1. Introduction

In a neutrino experiment[1] performed at the Los Alamos Meson Physics Facility, LAMPF, we needed a detector capable of observing electrons and positrons of about 40 MeV produced in inverse beta decay reactions of neutrinos on free protons and on deuterons,

$$\bar{\nu}_e p \rightarrow n e^+ \quad , \qquad (1)$$

$$\nu_e d \rightarrow p p e^- \quad . \qquad (2)$$

The detector was required to have a large mass of hydrogen or deuterium and to measure the total energy, but not the direction or charge, of the $e^{\pm}$ in reactions (1) and (2). We therefore needed a large volume detector of uniform response, reasonably good energy resolution, but no tracking capabilities.

To satisfy these criteria, we built a 6000 liter water (H_2O or D_2O) Cerenkov counter. By choosing water and heavy water as the working medium we avoided the cryogenic and safety problems associated with handling large volumes of liquid hydrogen and liquid deuterium.

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The counter is a low energy total absorption calorimeter for the electrons, since their range of about 15 cm is short compared to the detector size. The total amount of Cerenkov light produced measures the energy of the $e^{\pm}$. The energy measurement would have been easier in a scintillator. However, our choice avoided a serious background problem in the experiment; recoil protons from fast neutrons traversing the counter would scintillate but are below the Cerenkov threshold of our detector.

2. Construction

The Cerenkov counter, illustrated in Fig. 1, is a cube 1.8 m on a side, with cast epoxy walls. Nonmetal construction is chosen to minimize electron-neutrino interactions in the walls, since electron-neutrino cross sections are known to be small on carbon and oxygen. The cubical shape, while it is not ideal hydrostatically, maximizes the active water volume inside a box of flat scintillators used as an active cosmic-ray shield.

The Cerenkov counter was fabricated by the Formcrete Company.[2] The walls are made from EPON 828 resin,[3] with curing agent Z and 10% woodflour filler, and are 1.3 cm thick. Each wall is cast independently, then cured at 65° C for 14 hours. Five sides of the counter are then assembled inside an aluminum L-bar frame, illustrated in Fig. 2, with 3 cm diagonal epoxy filling (EPON 872, curing agent Z) completing the cube. The top of the counter is a removable lid bolted down over a rubber gasket; it is otherwise identical to the other sides.

The epoxy walls themselves do not have sufficient strength to withstand the hydrostatic pressure of the counter. A system of struts, illustrated in Fig. 3, perpendicular to the walls of the counter, is used to provide mechanical integrity. The struts are cut from 1.3 cm thick Benelex,[4] a cellulose laminate, chosen because of its exceptional stiffness (its modulus of elasticity is 9 x 10^{10} dyne/cm^2). The struts are slotted at their intersections, bonded to the epoxy walls, and bolted together at the corners. They hold the deflection of the counter walls to less than 3 cm.

The portholes for the 96 phototubes are distributed in a square matrix, 16 on each of the 6 sides, in the spaces formed by the Benelex ribs. We do not use transmission windows, in order to minimize light losses; the water seal is formed directly by the 12.5 cm tube faces. The phototube assembly is shown in Fig. 4. Pre-cast epoxy porthole rings are cast into the epoxy walls. Each porthole ring contains an O-ring groove and threaded inserts for attaching a matching epoxy follower ring. The phototubes are bonded into the follower rings with RTV 602 silicone rubber.[5] A fiber-optics light guide, its tip bonded to the tube face, is incorporated into the assembly to allow individual testing of the tubes.

The top and bottom sides of the cube have 2 cm diameter water fittings cast into their corners. Each of the 16 porthole rings on the top has a 0.3 cm inside diameter Tygon tube[6] attached to prevent the formation of air bubbles under the phototubes. Tygon tubes also connect all the counter fittings to plastic manifolds with PVC valves, located outside the scintillator shield. These manifolds allow water handling while the counter is inaccessible behind the cosmic ray anticoincidence shield. The bottom one, with connections to filling and emptying lines, as well as to the bottom of the counter, is our control manifold; the top manifold, open to the air and connected to the top of the counter, acts as an overflow bottle. Its water level is kept above the top of the counter to assure that the counter is always completely filled.

3. Mechanical Performance: Critique

The counter was kept filled with water, with occasional drainings, over a period of four and a half years, and with heavy water for five months. It has remained intact, with no major water loss, during this period.

However, the counter did have a long history of repairs. Under the hydrostatic load of 200 cm of water (0.2 atmospheres), cracks developed in the short fiber laminate of the Benelex rib system, compromising the mechanical support of the epoxy walls. The problem persisted until we splinted all of the ribs with aluminum bands and brackets, adding about 100 kg of metal to the counter. For comparison, the counter walls and ribs contained about 1000 kg of epoxy and Benelex and the counter holds 6000 kg of H_2O and 6600 kg of D_2O.

Partly as a result of strut failure and partly from casting stresses around the porthole rings, some cracks appeared in the epoxy walls themselves. These cracks, none serious enough to cause a major water leak, were repaired from the outside of the counter, using fiberglass tape and epoxy patches. Some small leaks in the phototube assemblies (Fig.4) were repaired as they developed.

An external water recovery and alarm system was installed in order to minimize the loss of heavy water[7] in case of either a leak or a catastrophic failure of the counter. The counter was put down on a heavy duty waterproof tarpaulin, which was folded up to cover the sides and attached to the top of the counter. A 12.5 cm diameter pipe connected the bottom of this bag to a large stainless steel holding tank installed on a grade below the bottom of the counter. A 5 cm diameter valve and pipe connected the bottom manifold to the same tank to allow us to empty the counter in about 1/2 hour. Water sensing alarms at the bottom and water loss sensors at the top were also installed. In the event, the D_2O running was entirely trouble free.

4. Light Collection

Because of the relatively long path lengths involved in light transmission through the counter, we require a high degree of transparency in the water. For filling the counter with H_2O, tap water is run through two ion exchange resin columns[8] and a particulate filter. After this treatment the resistivity of the water is over 10^7 ohm-cm. Similarly the D_2O is pumped into the counter from polyethelene-lined barrels through a commercial (undeuterated) resin ion exchange system.[9]

In order to increase the light yield of the counter and improve its uniformity of response, we convert some of the ultraviolet Cerenkov radiation with a wavelength shifter, 4-methyl-umbelliferone,[10] dissolved in the water. The absorption peak of umbelliferone is at 360 nm, its emission peak at 450 nm. This chemical will not fluoresce unless it is in a solution whose pH is at least 8.0. To achieve this, we use 87.5 mg/liter of ammonium phosphate $[(NH_4)_2HPO_4]$ and 16.7 μliter/liter of 58% ammonia solution $(NH_3 + H_2O)$. This amount of additive has no effect on the transparency of the water. Fig. 5 is a curve showing the gain of the counter, in arbitrary units, vs. the umbelliferone concentration. We use 0.5 mg/liter as our standard concentration.[11]

After the addition of the wavelength shifter and buffer the water needs to be circulated for several hours to achieve uniform mixing. Neglecting this step results in layering, with widely varying gain in the counter, which persists unchanged for periods of several weeks or more. Convection and diffusion appear to be very inefficient for mixing.

We find that there is no problem with biological activity or with dirt dissolving from the counter walls. Once the counter is filled we do not re-purify the water in the course of a run of several months. The stability of the water sitting in the counter is excellent; the light yield of the counter typically decreases to about 80% of its initial value in the course of a 4 month run. This corresponds to a "mean life" of about 2 years for the clarity of the water in the counter.

The 96 phototubes cover 5% of the area of the counter. We line the remaining surface with a diffuse white reflector in order to improve the light collection. To select the reflector we have tested a series of materials for diffuse reflectivity using the apparatus of Fig. 6 . The emission spectrum of umbelliferone, dissolved in water, is excited by an ultraviolet lamp. The light reflected from the sample is viewed by a phototube. Table I shows the relative reflectivity we obtained for a series of samples.

TABLE I. DIFFUSE REFLECTIVITY OF VARIOUS SAMPLES

Material	Reflectivity
Boric acid	100
Magnesium oxide	92
Teflon[12]	84
Kydex[13]	82
ABS[14]	75
Crumpled aluminum foil	77
Black sample	<3

Our choice for lining the counter is the industrial plastic Kydex, which has good mechanical properties, excellent stability under water, and is much less expensive than teflon. We cut 14 cm diameter holes for the phototubes into large sheets of 0.15 cm thick Kydex attached to the counter walls.

5. Electronics

The phototubes we use on the Cerenkov counter are 12.5 cm EMI 9618R[15] photomultipliers with "super S-11" photocathodes and 12 stages. The high gain of these phototubes allows us to use bases without pre-amplifiers, an advantage, since the bases are inaccessible behind the anti-counter shield. For voltages of about 1500 V, one photoelectron corresponds to 4 mV pulse height (60 ns full width at half height) into 50 Ω. With their faces in contact with water, the phototubes do not work properly unless the photocathodes are grounded. Therefore, we run the tubes with positive high voltage and AC couple the anode signal output.

Fig.7 shows the elements of our Cerenkov counter front end electronics. The outputs of 4 adjacent phototubes are passively mixed at the counter to give a "supertube" signal which is sent to our electronics trailer. The 24 supertube signals drive discriminator coincidence registers which show the hit pattern of each event. They are also added, four at a time, in active linear mixers which give the total signal from each side of the counter. A voter coincidence requirement of 2 sides/6 is used to eliminate phototube noise events. Each side signal goes to an ADC. Finally, the analog signals from the 6 sides are added to provide the total energy signal, which in turn is analysed by an ADC. The rest of the logic, not shown, utilizes signals from the cosmic ray scintillators in addition to the Cerenkov counter to define interesting events.

6. Calibration and Performance

Before mounting the tubes on the Cerenkov counter we calibrate their gain and relative quantum efficiency using an α-source, ^{241}Am, mounted on a scintillator and a light emitting diode. Each tube is mounted in a fixed position with respect to the light sources; the high voltage is adjusted to give a fixed pulse height for the alpha source. The LED light output is then adjusted to give the same pulse height. Under the assumption that photostatistics dominate the resolution of the LED signal, we translate the observed width to the number of photoelectrons for this pulse height, $N_e = 1/\sigma^2$.

The spectrum of vertical relativistic muons, traversing the full length of the counter near its center, is shown in Fig. 8. Using the average pulse height of these cosmic rays together with the phototube calibrations above, we obtain the gain of the counter in photoelectrons/MeV. Table II gives the gain as well as the top to bottom signal ratio, which measures the anisotropy of the light with respect to the direction of radiating particle, for several conditions.

TABLE II. TOTAL GAIN AND ANISOTROPY VS. REFLECTOR AND WAVELENGTH SHIFTER CONDITIONS

Reflector	Wavelength Shifter	Gain (p.e./MeV)	Ratio (Top/Bottom)
No	No	1.1	< 0.15
Yes	No	1.8	0.43
Yes	Yes	5.3	0.73

Adding the reflectors nearly doubles our light yield and the dissolved wavelength shifter increases it another factor or 3. The final gain of 5.3 photoelectrons/MeV gives about 200 photoelectrons at our typical neutrino event energy of 40 MeV and a satisfactory resolution.

We make a daily check of the operation and gain of each phototube with a multiplexed system of 32 light emitting diodes whose light is transmitted to the 96 tubes through fiber optic light guides. We see no short term fluctuations in tube gain; the temperature stabilization of the tubes from our large heat reservoir of 6 tons of water is excellent. We realign the gain of the tubes every few months.

The counter is surrounded by a cosmic ray anti-coincidence shield made up of scintillators, lead shielding and drift chambers described in detail elsewhere.[16] The system rejects charged particles with an inefficiency < 10^{-4} and also attenuates neutral backgrounds by an order of magnitude. The segmented scintillator box allows us to define through-going cosmic muons in four vertical slices of the counter. Table III gives the ratio of the signal collected by the near and far sides of the Cerenkov counter, as well as the total Cerenkov signal vs. the centroid position of each slice.

TABLE III. COUNTER RESPONSE VS. POSITION

Distance from Center	$\frac{\text{Side at +90 cm}}{\text{Side at -90 cm}}$	Sum of six sides (arbitrary scale)
- 75 cm	0.50	364
- 25 cm	0.73	376
+ 25 cm	1.18	372
+ 75 cm	1.72	348

From the near/far ratio we obtain an effective attenuation length $\lambda = 250$ cm of the water-umbelliferone mixture for its own light. The summed signal shows that the counter response is uniform to better than 5%.

The electron spectra from neutrino reactions (1) and (2) extend from 0 to 50 MeV and are very similar to the spectrum of electrons from muon decay at rest. Three per cent of all incident cosmic muons stop in the counter providing us with an ample source of these calibration events. We use them to set the energy scale and to check the counter response to electrons originating in its interior. We define a muon decay trigger as a neutral Cerenkov event in a 2 μs long gate starting 10 μs (5 muon lifetimes) after each incident muon, selected by the cosmic scintillators alone. By not including a Cerenkov counter signal in the stopping muon signature we assure a uniform distribution of muon stops in the counter. We require the long delay in the gate in order to avoid perturbing the electron signal by the overshoot tail, due to AC coupling, of a Cerenkov signal from the stopping muon.

Fig. 9 shows the observed muon decay electron spectrum from a particular run, together with the predicted distribution. The latter is generated by a small Monte Carlo program which folds edge effects, radiation losses and resolution into the theoretical spectrum. We assume that the resolution $\sigma \propto \sqrt{E}$ but do not fix the proportionality constraint a priori. The best fit to the spectrum gives a resolution $\sigma/E = 12\%$ at 40 MeV, compared to $\sigma/E = 7\%$ contributed by photoelectron statistics alone.

7. Conclusions

Large volume water Cerenkov detectors are of interest both for neutrino counting and for recently proposed experiments to search for proton decays. With reasonable care in construction, cleanliness and water preparation, it is possible to build such counters with good photoelectron yield, reasonable resolution, good uniformity and excellent long term stability.

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9. Catalog No. COMB-012-04, Millipore Corp., Bedford, MA 07130

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11. We note that the optimum concentration depends on the detector size. Increasing the concentration (up to 20 mg/liter) beyond the plateau edge does not help; the conversion efficiency stays constant while the self-absorption increases.

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Figure Captions

1. Photograph of Cerenkov counter.
2. Assembly of counter sides.
3. Benelex strut system.
4. Phototube assembly.
5. Gain of counter vs. wavelength shifter concentration.
6. Apparatus for reflectivity measurements.
7. Schematic diagram of Cerenkov counter electronics.
8. Energy spectrum of traversing muons.
9. Energy spectrum of electrons from stopped muon decays in counter.

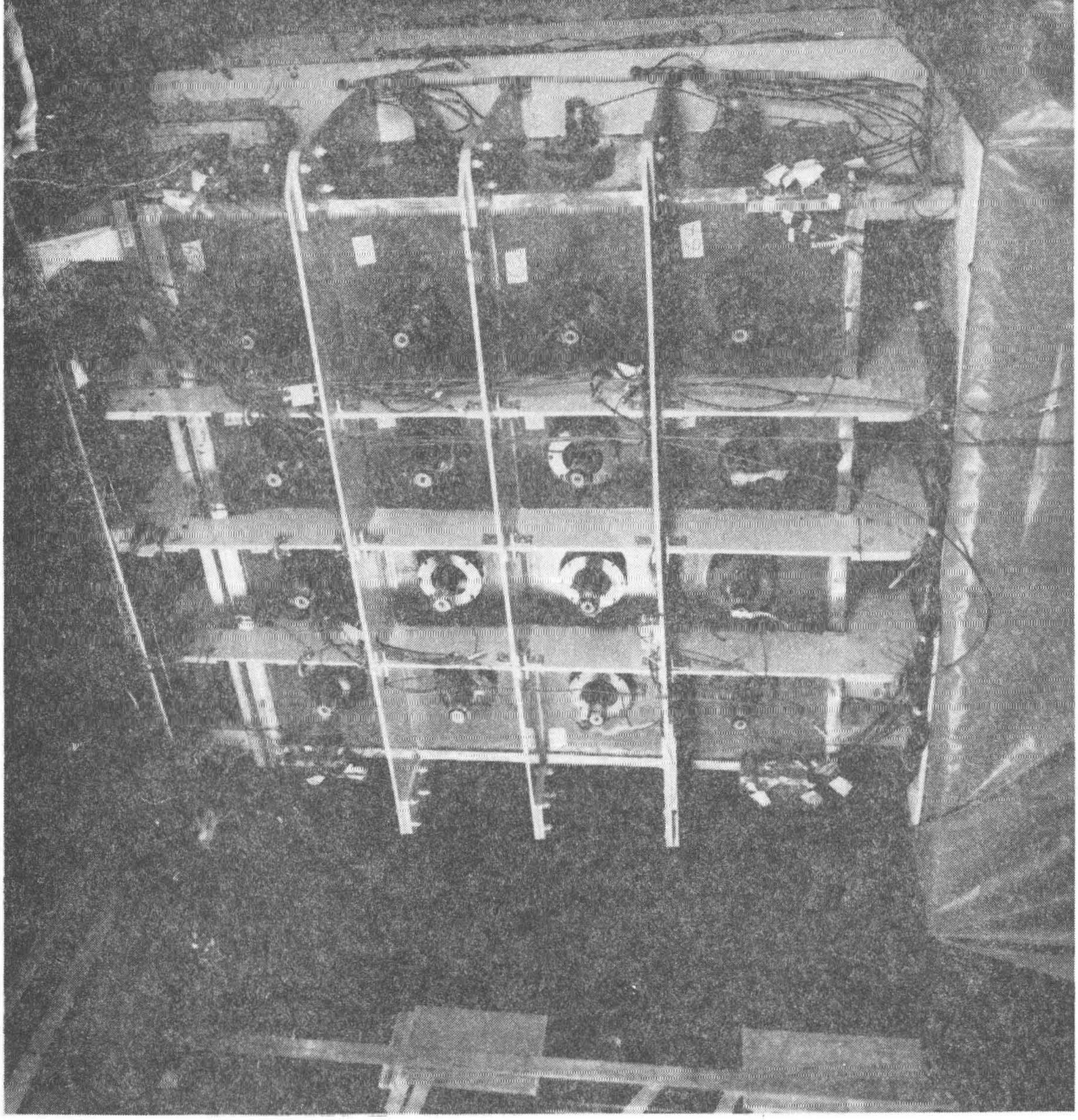

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Figure 1

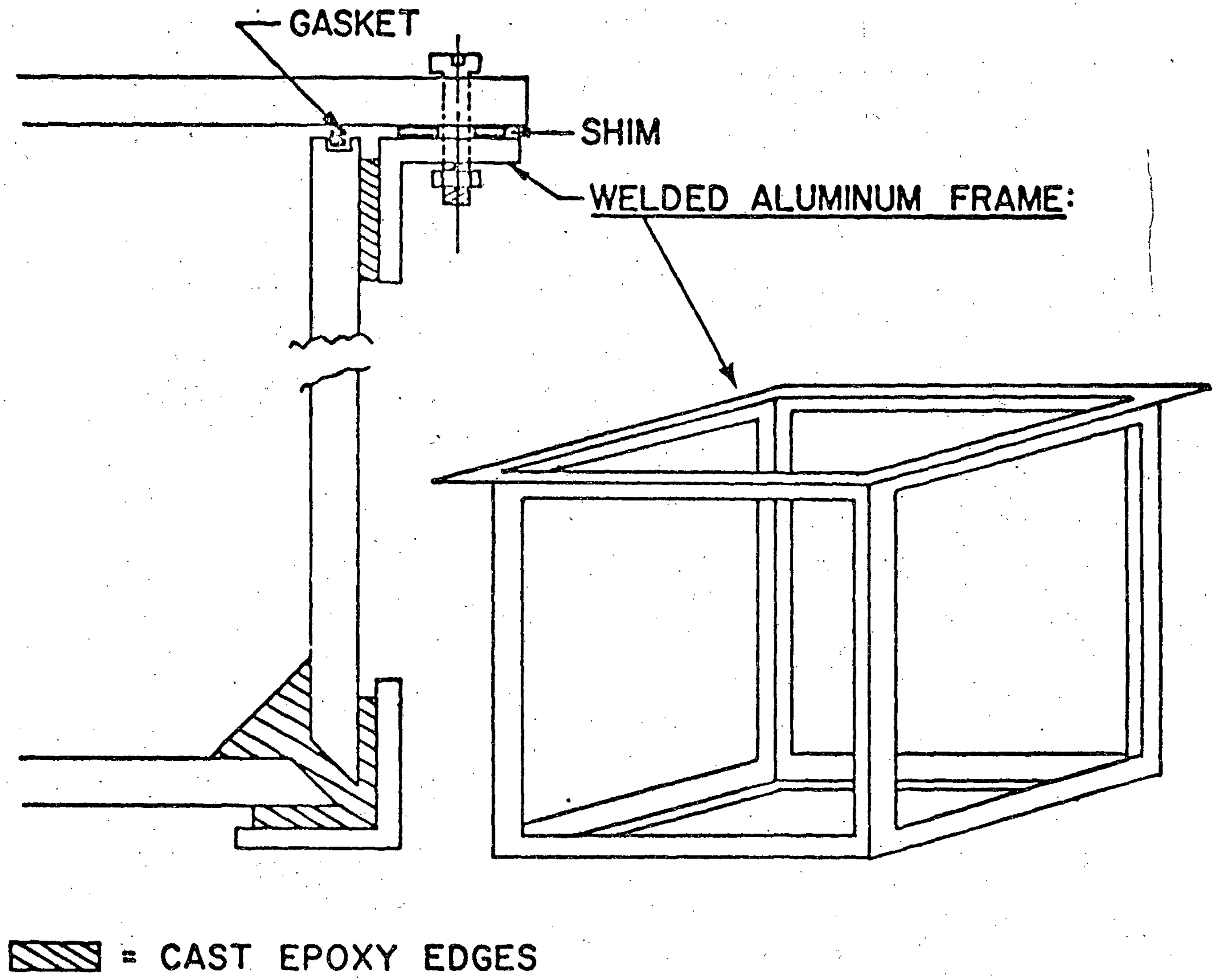

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Fig. 2

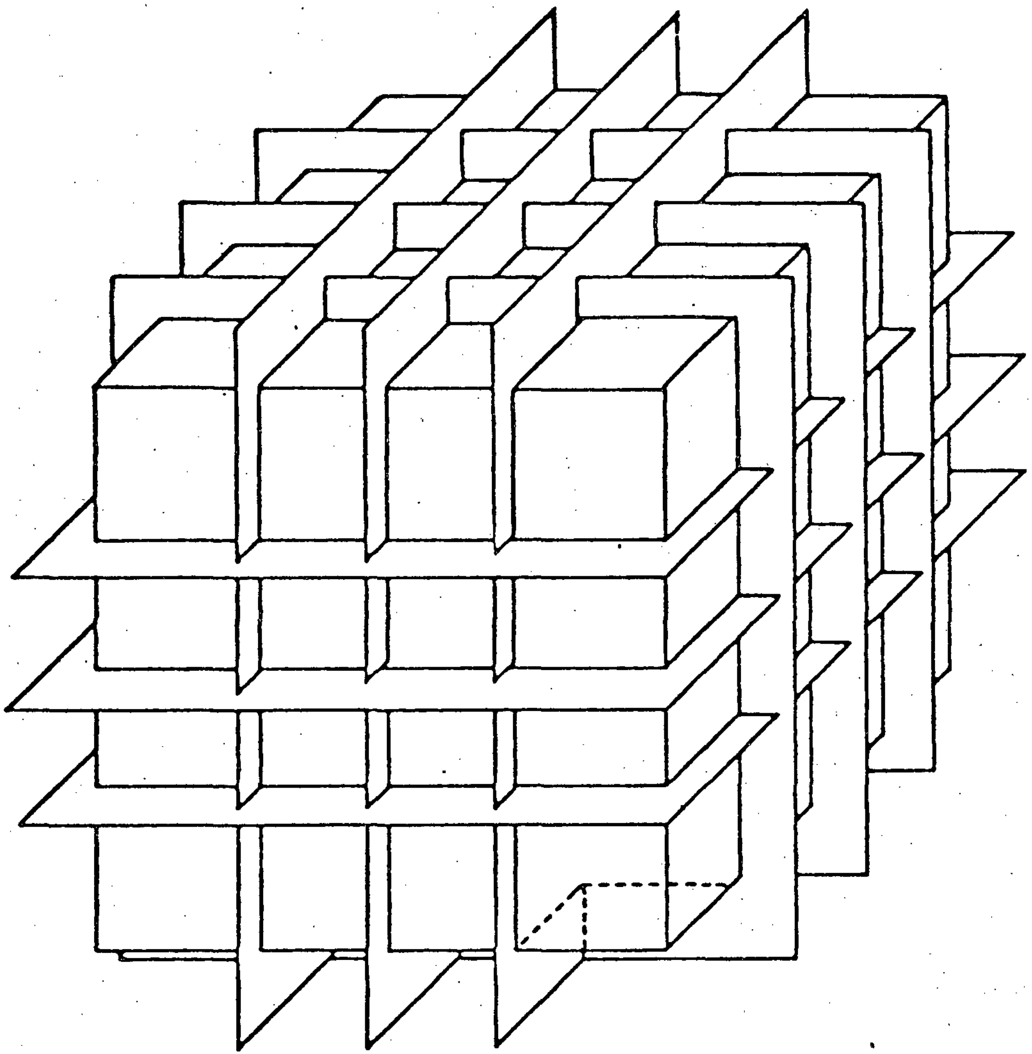

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Fig. 3

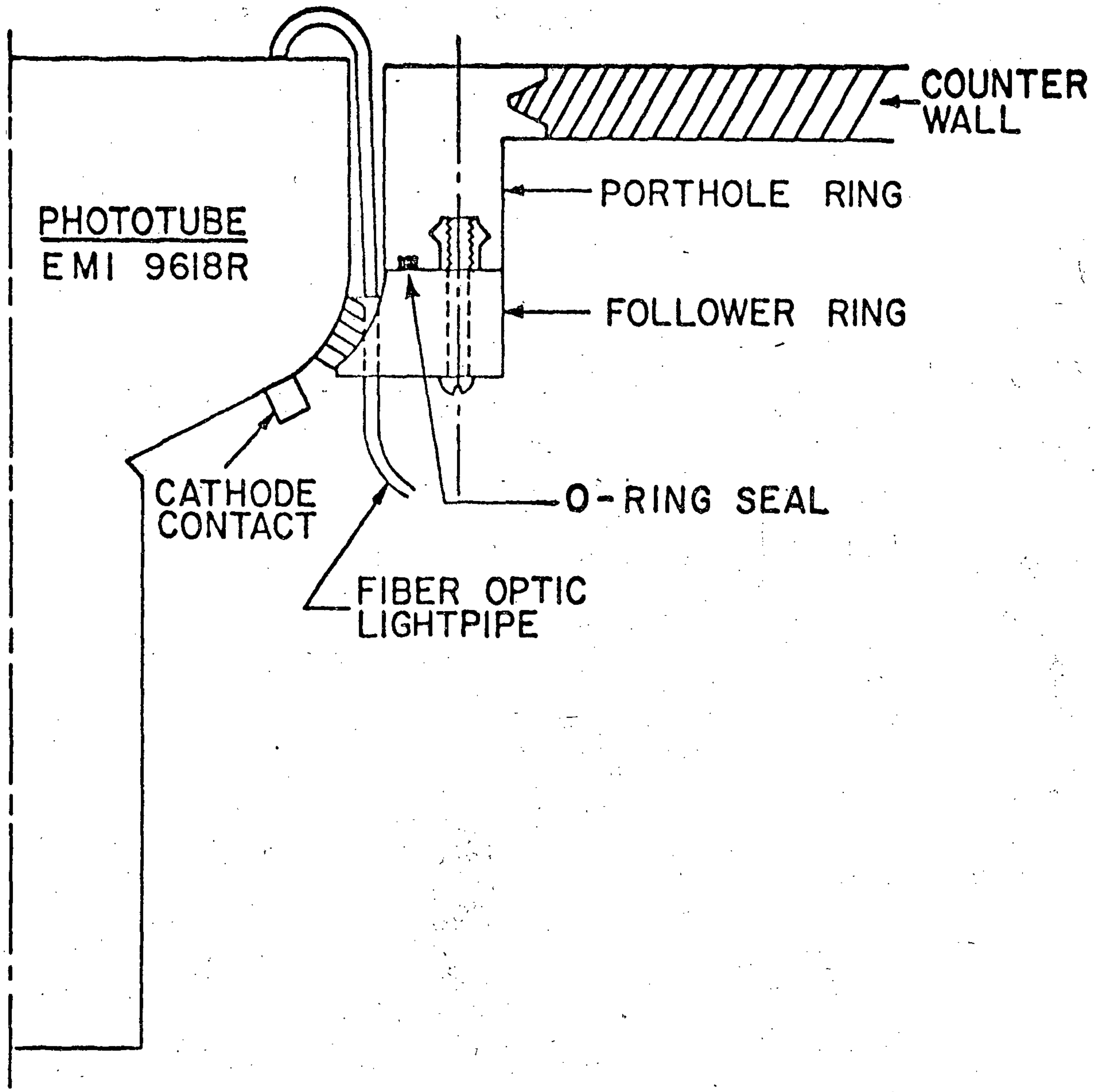

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Fig. 4

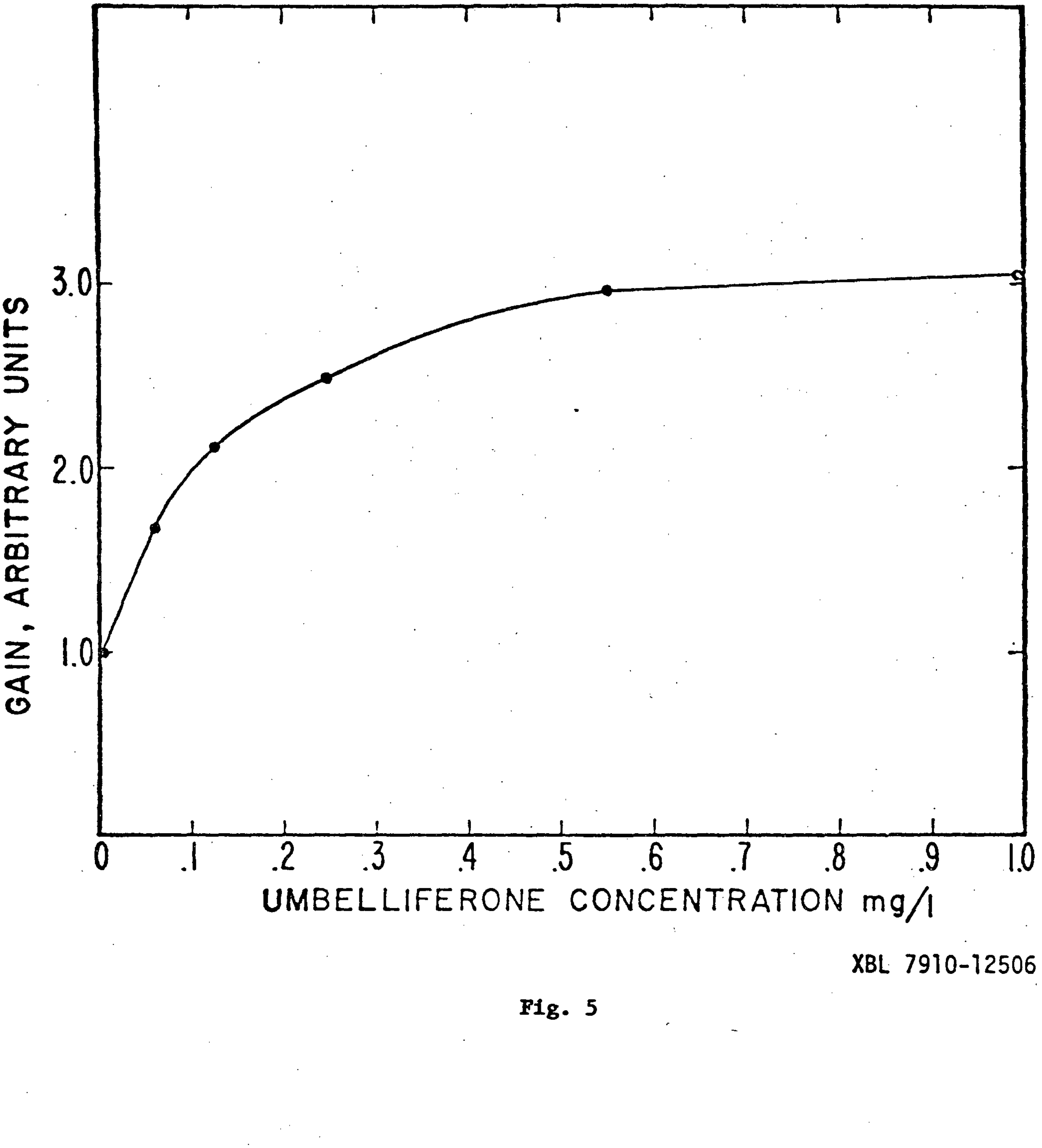

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Fig. 5

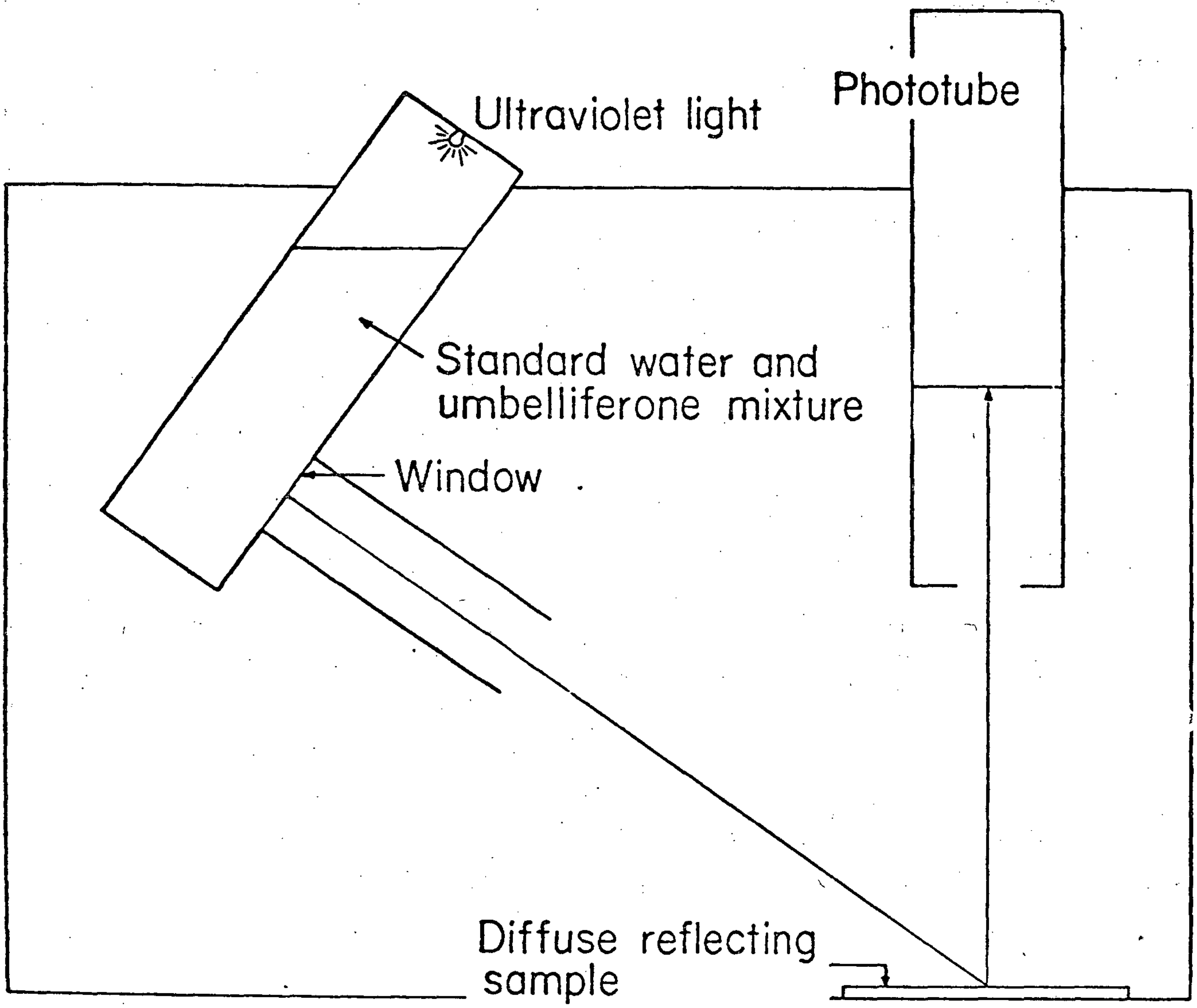

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Fig. 6

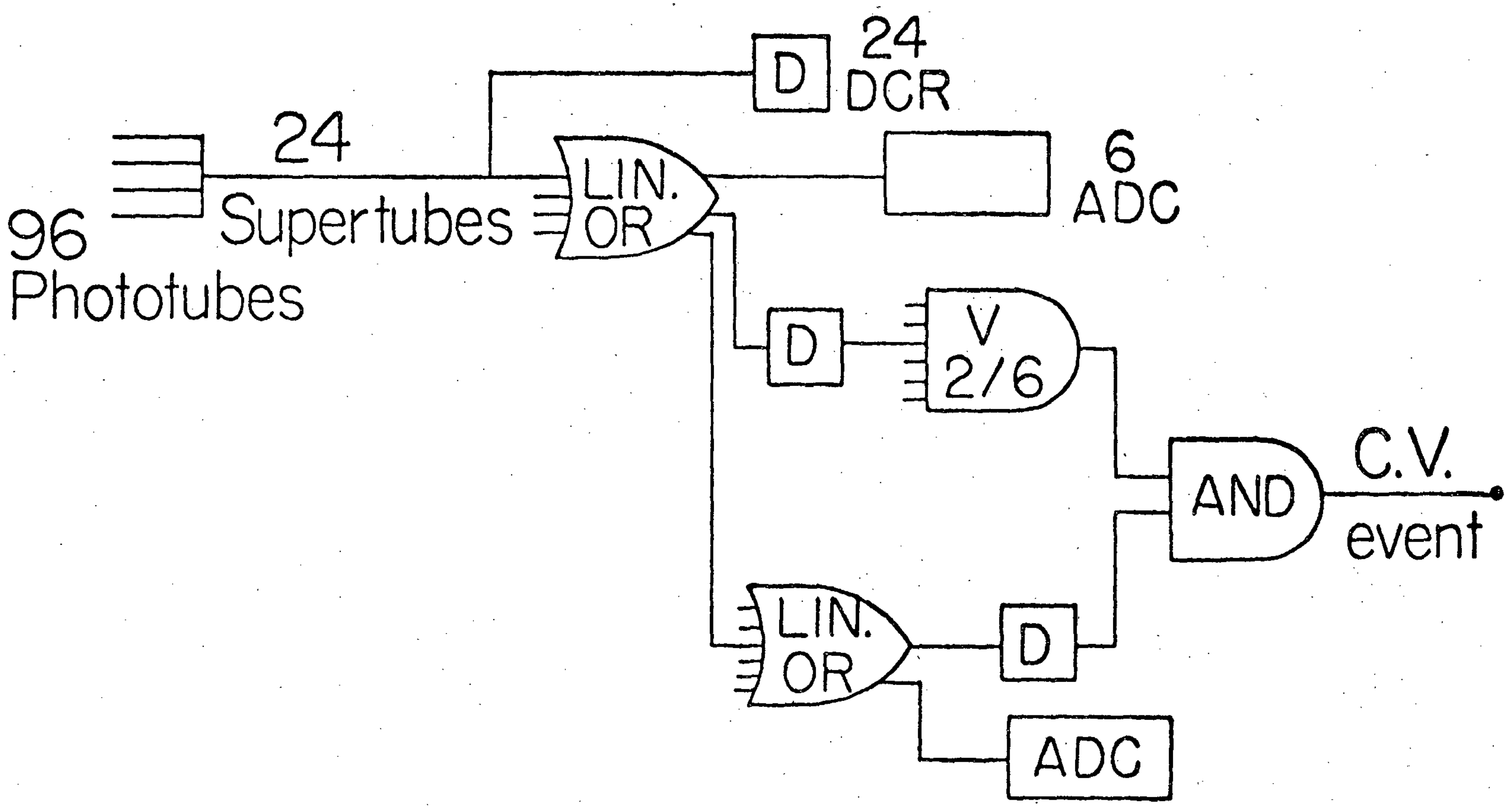

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Fig. 7

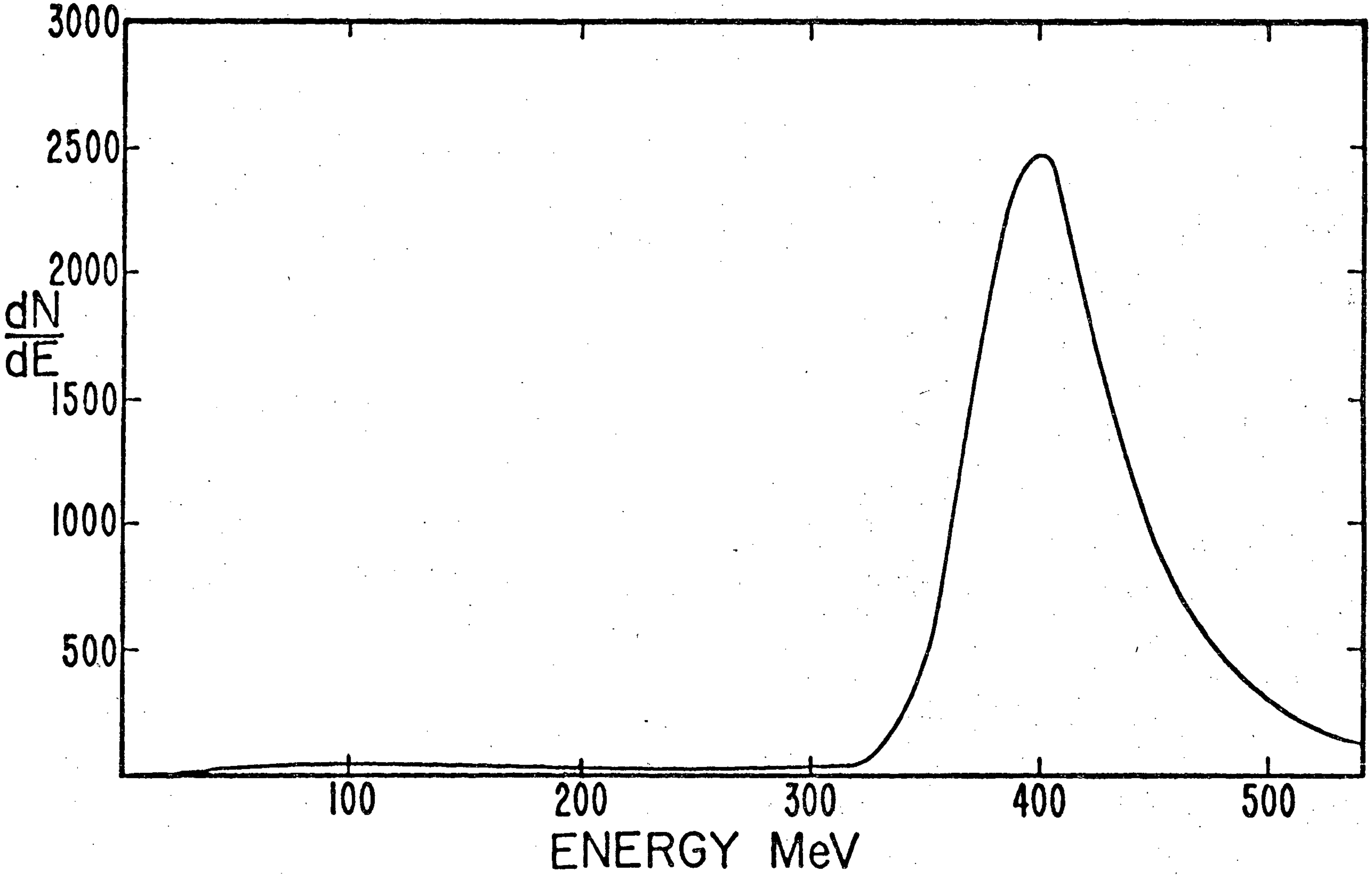

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Fig. 8

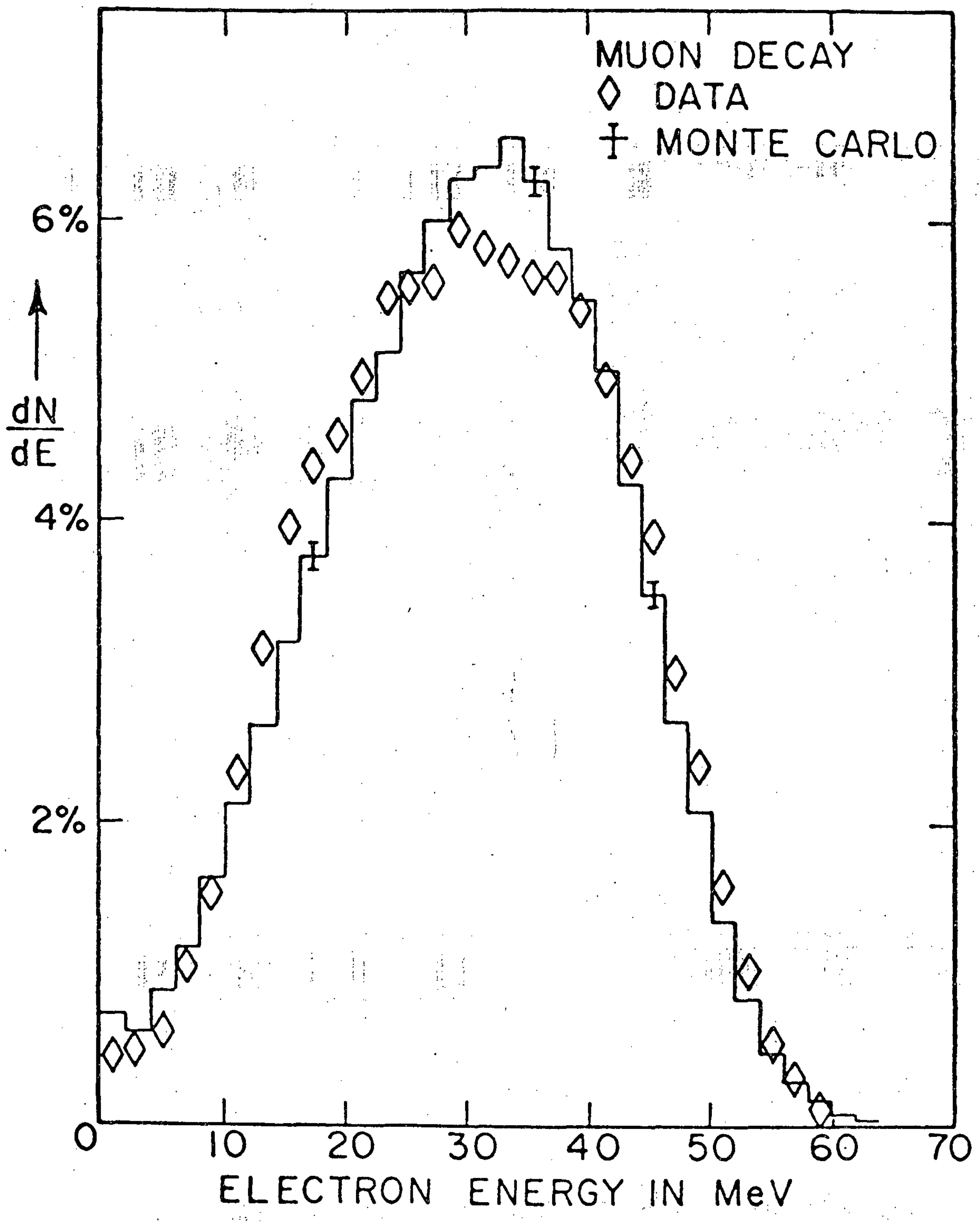

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Fig. 9

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