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VERY LARGE AREA SCINTILLATION COUNTERS FOR HADRON CALORIMETRY*

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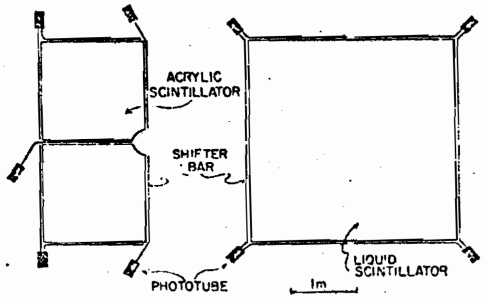
SUMMARY

Very large area scintillation counters have been developed for use in a neutrino experiment at Fermilab. These counters are used to measure the energy and position of hadronic cascades. In order to do this economically, we have developed a technique utilizing "wave-shifter" bars for gathering scintillation light from each of these counters into a small number of photomultiplier tubes. A low cost acrylic plastic scintillator (5' x 5' x 1.5") and larger (10' x 10' x 1") acrylic tanks filled with liquid scintillator are being viewed with wavelength-shifting bars.

INTRODUCTION

We have developed very large scintillation counters for a neutrino experiment at the Fermi National Accelerator Laboratory. These counters are designed to measure the energy and position of hadronic cascades produced by neutrino interactions. The energy is proportional to the total light output of the scintillator counters as utilized in most calorimeters.[1] In addition, the position of the cascade in a particular counter is found by comparing the relative amounts of light emitted from different edges of the counter. Position resolution is ± 5cm at the peak of a 75 GeV hadron shower.

Basic to our approach is the "wave-shifter bar" technique for gathering scintillation light. The idea was first proposed by Shurcliff[2] and Garwin[3] and later extensively studied by Keil[4]. A related technique was first used in an experiment by Keuffel[5]. Ordinary methods for collecting light from scintillation counters require many photomultiplier tubes or complicated light guides when applied to large counters. The wave-shifter bar technique while substantially less than 100% efficient, is considerably more economical and simple for such applications.



(a) FIG. 1 (b)

Neutrino Calorimeter Scintillation Counters

The two types of scintillation counter with shifter bars used in the neutrino experiment are drawn in Fig. 1. In typical scintillator, ionizing radiation excites a primary fluor which emits ultraviolet light. Since U.V. light is quickly absorbed by most materials, the scintillator is doped with a second fluor which absorbs U.V. light and re-emits isotropic blue light. Light emitted at angles greater than the critical angle is trapped between the polished faces of the counter and travels to the edge by total internal reflection. A wave-shifter bar is an acrylic bar doped with a third fluor (e.g., BBQ[6]) which absorbs blue light and re-emits isotropic green light. When this bar is placed against the edge of the scintillation counter, the blue scintillation light is absorbed and re-emitted as isotropic green light which propogates by total internal reflection to the end of the bar where it is collected by a single photomultiplier tube. A sketch of this process is shown in Fig. 1c. It is not to scale,the U.V. light is shifted immediately.

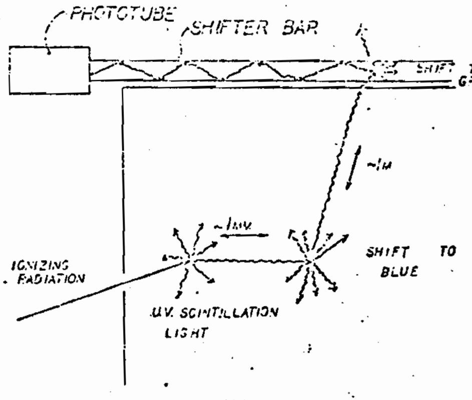


FIG 1c

Light Collection with the Wave-Shifter Technique

I. Scintillator and Wave-shifter Spectra

The first problem to be faced when designing a shifter-bar system is matching the shifter bar response to the emission spectrum of the scintillator and the spectral response of the photomultiplier tube. There are three constraints on the design. The attenuation length for light in the scintillator and shifter bar must be large to maximize the light output over the entire counter surface. This requirement forces one to choose wave shifters with well separated emission and absorption spectra so that the shifted light is not quickly re-absorbed by the wave shifter. Second, the shifter bar should absorb as much of the scintillation light as possible so that the transmission of light from one stage to the next is efficient. The third constraint is that the light reaching the phototube be in a range where the photocathode has good quantum efficiency. This conflicts with the first requirement since typical photocathodes are most efficient at fairly short wave lengths.

A typical scintillator with blue wave shifter has an emission spectrum that peaks between 400 and 420 nanometers. (The emission spectrum for NE235H[6] is shown as an example in Fig. 2.) The shifter bar should be designed to absorb these wavelengths efficiently and then re-emit light at a wavelength at which the phototube has good quantum efficiency. The absorption spectra for two different wave shifters

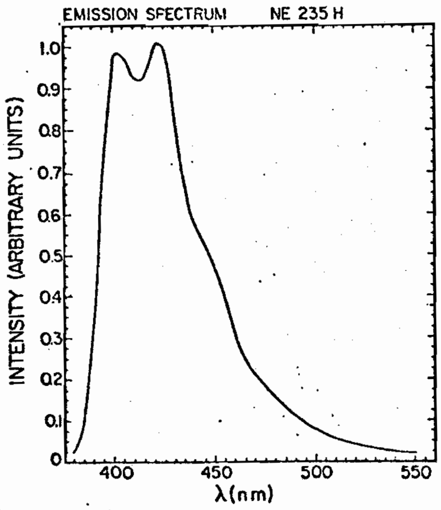


FIG. 2

are shown in Fig. 4. Both are very efficient at wavelengths below 430 nm.

The spectral response of an S-11 and a bi-alkali photocathode is shown in Fig. 3.^{7} Phototubes with these photocathodes are commonly used in high energy physics applications, where low noise rates are desirable. In both cases the response is an almost exponentially falling function beyond 500 nm. A phototube with either response detects the BBQ emission spectrum (Fig. 4a) which peaks at 495 nm more efficiently than the green 740^8 (Fig. 4b) whose maximum emission is at 525 nm.

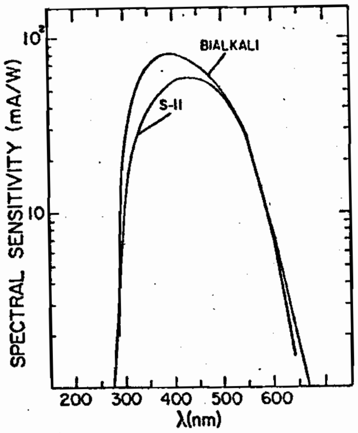


FIG. 3

Photocathode Spectral Response

We have chosen to use an acrylic shifter bar doped with BBQ and an RCA 6342A photomultiplier tube which has an S-11 photocathode. This combination was found to provide the best overall response to the primary scintillation light.

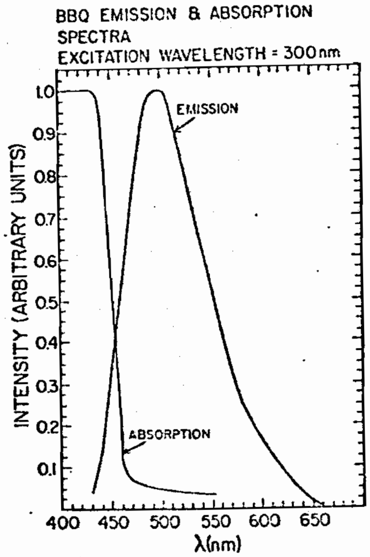


FIG. 4a

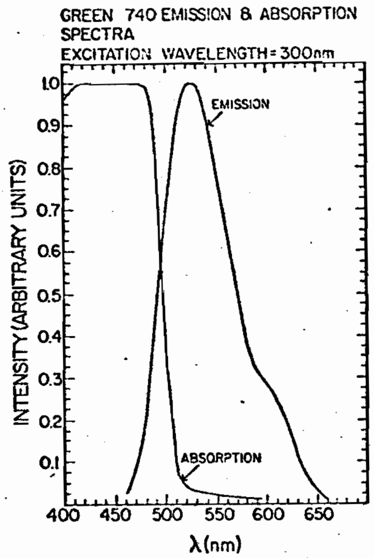


FIG. 4b

II. BBQ Concentration

The cross section of our shifter bars (20mm x 40mm) is predetermined by the area of 2" diameter photocathode; the length of the bars (about 1.5 meters) is fixed by the size of the scintillation counters. With these limitations in mind, the concentration of wave shifter, BBQ, was adjusted to convert as much of the scintillation light as possible without creating an attentuation length for the shifted light of less than two meters. The optimum concentration was 90 mg of BBQ per liter of acrylic plastic. At this concentration one attenuation length for the blue scintillation light is 13.4 mm and for the shifted light is 3 meters. Several disappointing attempts were made to make shifter bars from BBQ and PVT plastic. These bars were unusable because they severely attenuated the shifted light.

The shifter bar is wrapped with reflecting foil on three sides so that any blue scintillation light that has escaped will pass through the bar a second time. More than 95% of the light is shifted. The shifter bar response is made more uniform by placing a Kodak #4 Wratten filter between the bar and the phototube. This eliminates the portion of the BBQ emission spectrum that is self-absorbed (Fig. 4a) and produces an attenuation curve in the bar that is exponential. The effective attenuation length of the green light is increased to greater than 5m by placing a mirror at the end of the shifter bar opposite the phototube.

III. Coupling Shifter Bar to Scintillator

The shifter bar is not directly coupled to the scintillator. A small air gap between the bar and the scintillator allows the shifted light to travel down the bar by total internal reflection. If the bar were optically coupled to the scintillator the shifted light would pass directly back into the counter and be lost. The phototube is optically coupled to the end of the shifter bar (see Fig. 1).

IV. Light Collection Efficiency

As mentioned in the introduction the shifter bar technique is less than 100% efficient. In fact, it has been calculated that the method is only 12% as efficient as a system of perfect adiabatic light pipes and phototubes. The calculation assumes that light is collected from the entire edge of a scintillation counter. The factors that contribute to this calculation for the shifter bar system are listed in Table I, and the factors for the adiabatic light pipe method are listed in Table II.

TABLE I

Light Collection in a Shifter Bar System

Factor	Value
1. Fraction of light emitted into an air gap	0.13
2. Transmission of light across the air gap	0.75
3. Absorbtion of blue light by BBQ	0.70
4. Shifting efficiency of shifter bar	0.95
5. Fraction of light emitted into a phototube optically coupled to a shifter bar	0.48
6. Phototube output: overlap of S-11 response with BBQ emission spectrum	0.74
Net Output = product of 1 through 6	2.3×10^{-2}

TABLE II

Light Collection in an Adiabatic Light System

Factor	Value
1. Fraction of light emitted into an optically coupled phototube	0.18
2. Phototube output: overlap of S-11 response with NE235H emission spectrum	1.00
Net Output = product of 1 and 2	1.8×10^{-1}

The numbers in these tables assume an isotropic source of light in the primary scintillator. The first factor in Table I is the fraction of light emitted from the edge of a counter into air. It is less than one-sixth because some of the initial light is trapped by total internal reflection (Ref. 4c, equation 4). Factor five differs from factor one because optically coupling the phototube to the shifter bar collects the trapped light and because the shifter bar has a mirror at the end opposite the phototube (Ref. 4c, equation 9). The sixth factor in the table is the numerically calculated overlap integral of the S-11 photocathode response folded with the BBQ emission spectrum. The BBQ spectrum was normalized to have the same area as the NE235H emission spectrum. Factor one of Table II differs from factor five of Table I because it is assumed that there is no reflector on the scintillator edge opposite the adiabatic light pipes. Measurements of light collection efficiency are consistent with this calculation.

This result is not as discouraging as it first appears. It is trivial to cover all four edges of a scintillation counter with shifter bars and collect four times as much light. The light output can also be increased without increasing the number of phototubes by increasing the thickness of the counter and the width of the shifter bars. The only way light output can be improved with adiabatic light collection is to increase the number of phototubes. The large 10' x 10' x 1" scintillation counters in use at FNAL each use four phototubes and shifter bars (Fig. 1b). 20 phototubes would be required to achieve the same light collection efficiency if adiabatic light pipes were used.

V. Counters

Two types of scintillation counters were constructed for the experiment - acrylic plastic scintillation counters (Fig. 1a) that are used to instrument the 12' diameter toroidal iron magnets and hollow acrylic plastic tanks (Fib. 1b) filled with liquid scintillator that are used to instrument the neutrino target.

The acrylic counters are made of 5' x 5' x 1.5" quadrants of plastic scintillator. The composition of the scintillator, manufactured by Polytech[8], is listed in Table III. The light output of the plastic is approximately one-third that of NE110.[6]

The total light output of a minimum ionizing particle which passes through the center of a quadrant is eight photo electrons. There is no more than a 30% variation of response over the entire surface of the counter. A minimum ionizing particle which passes through the center of a tank counter produces a total light output of 13 photo electrons. The total response does not vary by more than 70% over the face of the counter.

TABLE III

Acrylic Scintillator Composition

Material	Percent by Weight	Function
PPO	1%	Primary Fluor
POPOP	0.01%	Secondary Fluor
Napthalene	3%	Solvent
Acrylic	96%	Base

VI. Position Detection

An important use of the scintillation counters is measurement of the vertex position of hadronic showers in neutrino interactions. This use is particularly important for neutral current interactions for which wire chambers produce incomplete or ambiguous measurements of the shower vertex. In addition, the total pulse height of the shower provides information about the energy of the interaction (Ref. 1, p.229).

In order to extract the position and energy information of a shower it is necessary to understand how each counter attenuates light. The shower energy and location can then be determined by making a likelihood calculation which minimized the difference between the measured pulse heights and the counter maps. We map each counter and measure the number of photoelectrons per minimum ionizing particle seen by each photomultiplier tube. This gives a map, $f_i(x,y)$, for each phototube which has units of photoelectrons per minimum ionizing particle. If there are N particles in a shower and they pass through a scintillation counter at position x,y the pulse height in the i^{th} phototube of that counter is

$$P_i = N\, f_i(x,y)$$

in the ideal case. However, photoelectrons are distributed according to Poisson statistics resulting in a measured phototube pulse height, m_i, which is not necessarily equal to P_i. The probability that a shower would produce a set of pulse heights, m_i, is then

$$\mathcal{L} = \prod_i \frac{P_i^{\,m_i}}{m_i\,!} \exp(-P_i)$$

where the product is taken over all the phototubes of the counter. The best estimate of the shower position and the number of particles in the shower is found by minimizing $\ln \mathcal{L}$ with respect to the three parameters x, y, and N. The solution to the three equations

$$\frac{\partial}{\partial x} \ln \mathcal{L} = 0$$

$$\frac{\partial}{\partial y} \ln \mathcal{L} = 0$$

$$\frac{\partial}{\partial N} \ln \mathcal{L} = 0$$

gives the best values for the parameters. This is usually a difficult system of equations to solve since the maps, $f_i(x,y)$, are generally complicated functions. The acrylic counters are viewed by three phototubes. This is the minimum number needed to measure all three parameters but does not provide any constraints on the result. Four phototubes collect light from the tank counters. In this case it is possible to calculate the three parameters and have one constraint left which is used to check the answer.

The error on each of the parameters may be calculated from the likelihood function by standard methods.[10] These calculations were applied to a simplified model of our scintillation counters. It was found that an attenuation length of one-half the counter size was the best compromise between good position resolution and uniform light collection. These calculations also showed that position resolution varies as $1/\sqrt{N}$. This is a consequence of assuming that the photoelectrons follow a Poisson distribution. As the number of particles passing through the counter increases the fractional error on a phototube pulse height decreases as $1/\sqrt{P_i}$ which is proportional to $1/\sqrt{N}$.

The actual maps of the scintillation counters are made in two different ways. The tank counters are mapped with a muon beam after they have been installed in the neutrino target. The acrylic scintillation counters are mapped with a Co^{60} source before installation. The source is placed at the center of a quadrant and the phototube gains are adjusted so that the three tubes viewing the quadrant give equal pulse heights per shutter bar (the D.C. current output of each tube is actually measured). The output of each tube is then recorded as the source is moved over a 7 x 7 grid on the quadrant.

In practice maps are used which are combinations of the directly measured maps. The likelihood calculation is unaffected since the functions $f_i(x,y)$ can always be rewritten in terms of the new maps. These new maps are more physical as illustrated in Figures 5a and 5b. The deviations of the contours from linearity are in part due to the shadow caused by the notch.

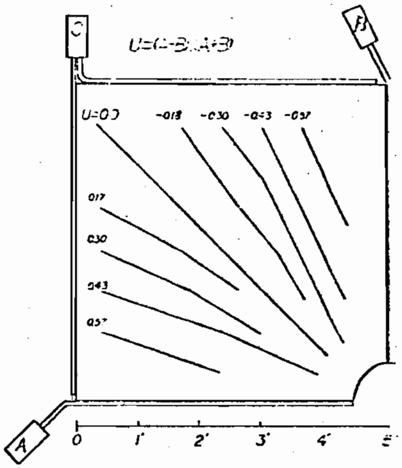


Fig. 5a

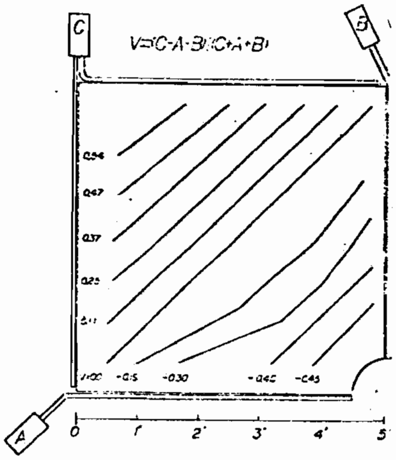


Fig. 5b

The position resolution of an acrylic counter was measured in a hadron beam and found to be ± 50 cm/$\sqrt{N}$ where N is the number of minimum ionizing particles passing through the counter. The measured resolution functions for the counter are drawn in Fig. 6. This data was collected with the beam passing through the center of the counter. The number of particles in the hadron shower varied from 75 to 125.

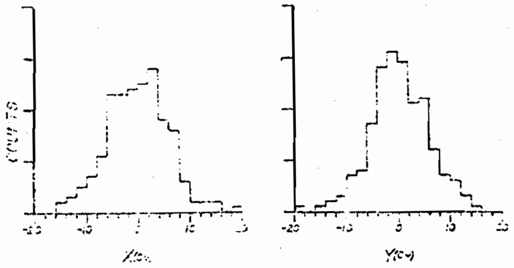


FIG. 6

Acrylic Counter Resolution Function

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7. Although these curves are quoted in most photomultiplier catalogs, in practice only phototubes manufactured by RCA have been measured to have a bi-alkali spectral sensitivity that equals that of S-11 above 500 nm. In general, the measured bi-alkali response is two to three times less than the S-11 response in this region.

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