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Improvements to light collection in scintillation detectors intended for fast cosmic ray timing

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A common design for scintillation detectors intended for fast cosmic ray timing involves collecting the light produced from one of the large faces of a cuboid block. A large fraction of the light produced has an initial direction such that it cannot reach the photocathode within the integration time of the photomultiplier and so cannot contribute to the timing signal. A simple modification is shown which allows this light to be used. The result is that thinner and consequently cheaper scintillator may be used with equal effectiveness.

1. Introduction

A common design for a cosmic ray detector intended for fast timing is a flat cuboid block of scintillator, viewed at some distance by a single photomultiplier. To ensure uniform timing response across the block, it is read out by collecting the light emitted by one of the large faces, using a fast photomultiplier set at some distance from the block, as shown in fig.1a. Many thousands of detectors of this type have been used on different experiments,

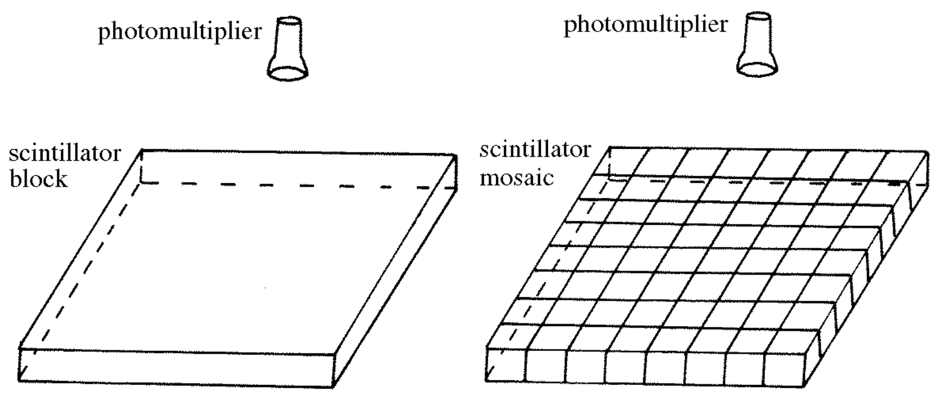

Figure 1. (a) Fast timing scintillation detector (b) Mosaic scintillation detector

in particular for fast timing of air-showers. Similar detectors have found use in accelerator experiments.

In order to give reasonable signals for minimum ionizing muons, the thickness of the scintillator should be at least 50mm, while the area of the block is typically one square metre. Such a block of plastic scintillator costs typically thousands of euros, and while liquid scintillator is much cheaper, containment is always problematic.

2. Theory

When a photon strikes the internal surface of a scintillator, of refractive index $n > 1$, refraction occurs and it escapes provided the angle of incidence is less than the critical angle. At greater angles, total internal reflection occurs and it is reflected back into the scintillator. In cuboid scintillators, a significant proportion of the photons produced cannot escape the volume as a result of this total internal reflection and symmetry considerations [3, 2, 4].

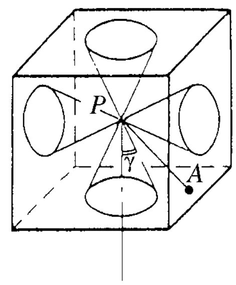

Figure 2. Light escape cones from a cuboid. For simplicity, only four of the six cones are depicted.

Consider a cuboid of scintillator with a point, P, at which photons are emitted isotropically, as shown in fig.2. The paths of photons which do not undergo total internal reflection lie within six "escape cones" with their apexes at P, and having axes perpendicular to the faces of the cuboid. The half angles of these cones are $\gamma = \sin^{-1}\frac{1}{n}$ where n is the refractive index of the material. For scintillators with $n > \sqrt{2} = 1.41$, the escape cones do not overlap and light trapping becomes possible. Photons striking the faces of the cuboid and lying outside one of the cones (for example, path PA, incident with the base of the cuboid), will still be outside all the cones even after reflection, so they will not escape from the scintillator and remain trapped.

The fraction of the total light produced in each of the escape cones is:

$$f_{cone} = \frac{1}{2}(1 - \cos\gamma). \tag{1}$$

Consequently, the proportion of trapped light is

$$f_{trap} = 1 - 6f_{cone} = 3\cos\gamma - 2. \tag{2}$$

For scintillator with a refractive index $n = 1.58$ (polyvinyltoluene, NE102A, etc.), $f_{cone} = 0.112$ and $f_{trap} = 0.323$. From fig.2 it can be seen that the amount of light trapped in a cuboid does not depend on the point of scintillation or on the ratio of the sides. A cuboid is the only solid which possesses this characteristic.

Referring back to fig.1a, it can be understood that a proportion, determined by solid angle, of the photons in the upward going escape cone can be directly viewed by the photomultiplier. By placing a mirror below the scintillator, the downward going escape cone can be redirected upward and a proportion of these photons can also be used. These photons are often referred to as the "direct light". The photons which are in the four sideways going escape cones and the trapped light cannot contribute to the photomultiplier signal.

By containing the scintillator and photomultiplier in a larger cuboid, a pyramid or other shape, lined on the inside with diffusely reflective material, the side going photons can be utilized. Further, some photons which have left the scintillator in a direction in which they will not directly strike the photomultiplier can be reflected so that they do. The result is effectively an integrating cavity. Note, however, that the side going photons have to travel by larger paths than the direct photons, depending on the interaction position in the sheet. They, therefore, cannot contribute to the leading edge of the photomultiplier signal which determines its merit as a timing detector.

3. Mosaic scintillators

An alternative approach was devised which would allow both the side going escape cones and the trapped light to be used in a way that would contribute to the leading edge of the photomultiplier pulse. The method used was to subdivide the cuboid block into a large number of perfect cubes, as shown in fig.1b thus forming a mosaic. Each cube had all surfaces treated to break the symmetry described above. The side faces and lower face were diffuse reflectors while the upper surface was a diffuse window.

The effect of this on the upward going escape cone is negligible and the downward going cone is similarly reflected back upwards, as before. Photons in the side going escape cones and in the trapped light have only to traverse the dimension of the cube before encountering a surface which scatters them into a different direction. As each photon reflects from one of the walls there is another chance of it being on a trajectory which can escape through the top face. Some of these photons will escape, having traversed the cube a very small number of times and can therefore contribute to the leading edge of the photomultiplier signal and hence to the overall performance as a timing detector.

4. Experimental

The ideas presented above were investigated experimentally. A test chamber was constructed which was a $750 \times 750 \times 1100$mm cabinet which could be completely blacked-out. This was painted matt black inside to avoid spurious reflections. The scintillator being tested was placed on the floor of the cabinet and was viewed from a distance of 650mm with a single 75mm diameter photomultiplier, type Electron Tubes 9821B.

Below the scintillator sheet was a muon telescope, consisting of two scintillator paddles of sensitive area 160×120mm each edge-viewed by its own 50mm diameter photomultiplier. Between the paddles was a 20mm thick slab of lead to ensure that only muons were selected. About 10cm to one side of the muon telescope was an additional outrigger scintillator paddle 300×90mm which was operated in anticoincidence with the main telescope with the intention that events produced by showers, in which multiple muons would be present, would not be recorded. The signal from the main photomultiplier was split, one half going to a discriminator while the other went to the recording oscilloscope. Only events in which a signal was recorded in the main photomultiplier, in both muon telescope paddles and not in the outrigger were considered.

The oscilloscope was a LeCroy LT342 500MHz/500MSPS instrument, capable of building histograms of parameters measured from individual traces. For each event, the total charge and 20–80% risetime of the signal were calculated and histograms of these quantities over many events built. The charge per event was a direct measure of the number of photons seen per event, while the risetime measurement provided a check that late-arriving light was not affecting the measurement. The charge histogram had a clear single peak corresponding to single muons crossing the scintillator under test. The mean of this peak gave the average number of photons per muon.

5. Results

A slab of NE102A, polyvinyltoluene scintillator (Nuclear Enterprises, circa 1970) was first cut into two identical squares measuring $250 \times 250 \times 50$mm so that comparisons on identical material could be made. One square was further divided into 50mm cubes to form a mosaic.

Initially these cubes were lightly grit blasted to roughen the surface and painted on five sides with white paint. Domestic white emulsion paint was used, specifically “Dulux Rich Matt Pure Brilliant White”, applied with a brush in three coats. This first mosaic gave 1.15 times the light of the larger square block. This showed that mosaics were in no way worse than large blocks but the result was far short of the theoretical improvement.

Visual examination of the cubes showed that very little light scattered from the side walls at angles where it was likely to escape. It was clear that a more radical disruption of the optical symmetry was required. Fields and Jankowski [1] show an elegant technique for extracting the light from a flat sheet of scintillator by machining a 90° cone into the surface of the material. Inspired by this, as a second attempt to break the symmetry, each cube had a pattern of shallow conical pits drilled on every face. No attempt was made to develop a rigorous theory. A 10mm drill with a standard 118° cut was used to provide 23 pits per face on a 15mm triangular grid. This meant that about 0.72 of each face was actually at 31°. After the machining, five of the sides were again painted with white paint. This treatment gave 1.92 times the light of the large block and clearly demonstrated that this type of treatment seriously disrupts the optical symmetry of the cubes, releasing light that would otherwise be unavailable. Further work is required to determine the optimum configuration and size of these scattering pits.

6. Conclusions and Implications

By subdividing cuboid blocks of scintillator into a mosaic with pitted faces, the optical symmetry of the system has been broken, allowing light that would otherwise be lost to be collected. This can be extended to a block of scintillator any shape, such as hexagonal or cylindrical, which is read out through the large face. The subdivision can be made into any shape which tessellates, i. e. cubes, hexagonal prisms and triangular prisms.

By increasing the light yield, an actual cost saving may be achieved, in that thinner and consequently cheaper scintillator may be used with equal effectiveness. A further saving can be envisaged. The production of large size optically perfect blocks of plastic scintillator by casting or in-situ polymerization is a difficult and expensive operation. The small cubes required by the mosaic technique need not be optically perfect and a technique such as injection moulding is capable of producing large numbers of cubes at costs dominated by the initial tooling charges.

In the case of liquids, the division could be made by placing scattering optical dividers in the liquid. A more interesting concept is to contain the liquid in individual plastic bottles similar to the blow-moulded transparent PET bottles used for cooking oil and solvents. Suitable bottles would be square or hexagonal in cross section to form a mosaic. They should be dimpled to simulate the machined pits of the plastic scintillator and diffusely reflective on all faces with the exception of one which would form a window. This may provide a solution to the liquid scintillator tank problem. Since the photons make relatively few crossings of the scintillator before escaping, attenuation length in the liquid is not a problem. The low cost liquid scintillators proposed by Vasilchenko [5] may prove useable.

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