Development of a high resolution scintillating fiber gamma ray telescope

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Abstract

We report on further development and testing of a Compton Telescope composed of scintillating fibers and position sensitive photomultipliers. Initial tests of the telescope result in a better than 1 mm (rms) position resolution, and in a 17.5 mrad (rms) angular resolution for 1.2 MeV photons from a collimated ^{60}Co gamma source. This type of device can be used for constructing large area telescopes for gamma ray astronomy. We are encouraged by the results and working on the development of a larger Compton telescope.

1. INTRODUCTION

The success of gamma ray astronomy and gamma ray cosmology requires a new generation of high resolution telescopes. In order to detect point sources, very good angular resolution is required and good energy resolution is needed to study possible structures in the diffuse γ-ray spectrum, such as the possible bump at the few MeV region. It is likely that the new generation of telescopes will also require large viewing areas and be deployed in space.

It was reported earlier that this collaboration is developing high resolution gamma ray telescopes using cryogenic liquids (argon, xenon, and krypton) and scintillating fibers as detection media [1-3]. Here we are presenting construction, operation principles, and test results of a prototype double Compton γ-ray telescope using plastic scintillating fibers and position sensitive photomultiplier tubes. The main characteristics of this system are its excellent time resolution (better than 2 ns), self-triggering capability, providing better than 1 mm position accuracy, relatively good energy resolution, compact and very safe usage (no flammable gas, no cryogenics), and ease of construction [2].

2. OPERATION PRINCIPLE OF THE TELESCOPE

The basic operation of the double Compton telescope is illustrated in Fig. 1. An incident γ-ray of energy $E_{\gamma 0}$ is Compton scattered in the scintillating fiber converter block S_1, producing a scattered gamma, γ_1, and a scattered electron of energy E_{e1} at a position of (x_1, y_1, z_1). The γ_1 undergoes a scattering in the second block S_2 at a position of (x_2, y_2, z_2) and produces a second Compton electron with an energy of E_{e2}. Thus the energy of the γ-ray incident on S_1 is

$$E_{\gamma 0} \geq E_{e1} + E_{e2} \qquad (1)$$

and the cosine of the scattering angle is

$$\cos\theta \leq 1 + m_e c^2 \left(\frac{1}{E_{e1} + E_{e2}} - \frac{1}{E_{e2}} \right), \qquad (2)$$

The direction of the scattered photon is determined from the x, y, and z coordinates of the interaction vertex in S_1 and S_2, and using E_{e1} and $E_{\gamma 0}$ one can calculate the scattering angle θ. In this test experiment the incident gamma energy is 1.2 MeV.

If γ_1 loses all of its energy in S_2 by multiple Compton scattering, pair production or photoelectric absorption, then the equation given above can be written as

$$\cos\theta = 1 + m_e c^2 \left(\frac{1}{E_{\gamma 0}} - \frac{1}{E_{\gamma 0} - E_{e1}} \right). \qquad (3)$$

and by measuring E_{e2} in S_2 one can determine the scattering angle of incident γ's of unknown energy. The whole picture of this sequence of events can be observed with our system in the scintillating plastic fiber stacks and the position sensitive photomultiplier tubes. We can detect if multiple Compton scattering or pair production occurs in the same stack and, together with the energy information, we can observe partial or total absorption of energy in either of the scintillating stacks.

For each detected photon, we have an "event cone" about the scattered γ direction with a half angle given by Eq. (2). By analyzing the "event cones" of at least three of the incident γ-rays, one can determine whether they are originated from the same point source.

Events in the test process were accepted by the software if one and only one Compton conversion occurs in S_1 and S_2; this is required to identify single Compton scattering events in each block without ambiguities. There are two major factors to degrade the angular resolution of the telescope. One is the error in measuring the Compton scattering angle due to the finite energy resolution of the telescope. The other is the error in measuring the scattered photon direction due to finite position resolution. Our telescope is characterized by its event-by-event processing capability. Enhanced angular resolution is obtained if events are selected such that the incident gamma transfers

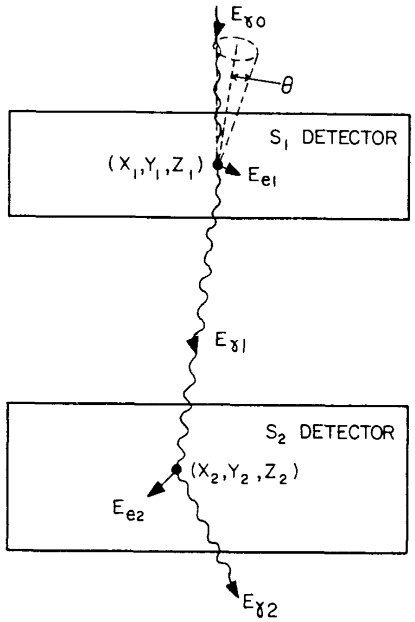

Fig. 1. Principles of measurement of the double Compton telescope. In the first collision in detector S_1, the incident γ-ray Compton-scatters and transfers E_{e1} energy to an electron. The scattered photon Compton-scatters in detector S_2 and transfers E_{e2} energy.

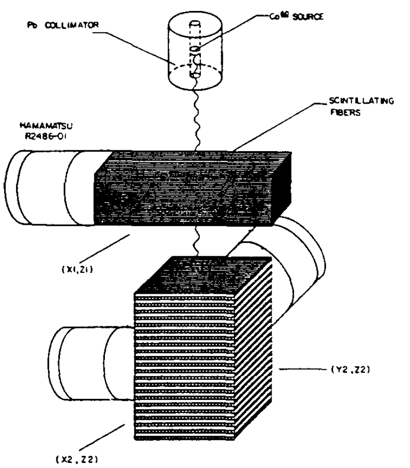

Fig. 2. Schematic of a prototype fiber double Compton telescope. Each fiber stack is composed of layers of plastic scintillating fibers viewed by position sensitive PMT's.

only a small fraction of its energy to the first Compton electron in S_1 (very forward scattering case). In this case the γ will deviate from its original direction by a small angle. For these events the angular resolution will be mainly determined by the finite position resolution:

$$\Delta\theta_{rms} = \frac{(\Delta r_1^2 + \Delta r_2^2)^{1/2}}{L_0} \qquad (4)$$

where L_0 is the distance between the two interactions in S_1 and S_2, respectively.

3. DESIGN OF THE PROTOTYPE INSTRUMENT

A small prototype telescope has been designed for testing the operation of the scintillating fiber detectors, photomultipliers, and the whole telescope concept. Both the scintillating fiber converter (S_1) and calorimeter (S_2) are composed of a bundle of scintillating fibers viewed by Hamamatsu R2486 position sensitive photomultiplier tubes [4] (Fig. 2). The anode signals are amplified by independent monolithic Fujitsu transconductance amplifiers [5] which are directly attached to the base of the PMT. The scintillator stack S_1 is 0.15 radiation length deep and made from 1 mm diameter fibers of polystyrene scintillator doped with Butyl-PBD and DPOPOP, with an acrylic cladding of 25 μm thickness. These fibers are arranged into coherent bundles of 6.35 x 5 cm^2 cross section and 21 cm length. The lower

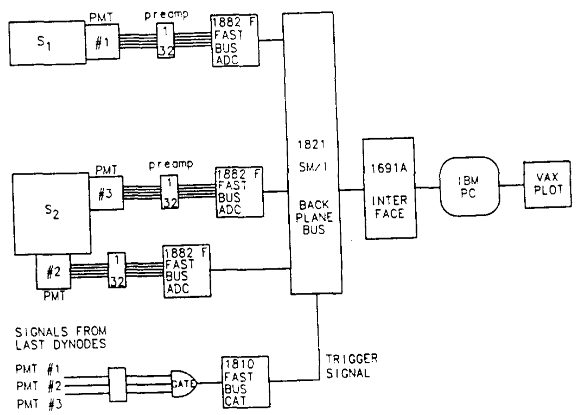

Fig. 3. Block diagram of the electronics and data acquisition system. PMT 1 records the interaction point and energy deposition in S1 while PMT 2 and 3 record the same type of information in S_2.

scintillator (S_2) consists of alternating layers of cross section 10 x 10 cm^2 stacked to a 5 cm depth (0.12 radiation length). The fibers making up each layer are 0.5 x 0.5 mm^2 square fibers of the same type of scintillating fibers as used in S_1, painted with TiO_3 to prevent crosstalk between adjacent fibers. Both S_1 and S_2 are read out from one end of the fiber only and the other end is sealed with teflon tape to partly compensate for the attenuation of light in the fiber ($\lambda \sim 1.5$ m). S_1 is viewed by one photomultiplier giving 2-d information while S_2 is viewed by two photomultipliers giving 3-d information.

The charge obtained from each wire is sorted in a 96 channel 1882F LeCroy FASTBUS ADC within about 50 ns gate width. The data is transferred from the 1821 FASTBUS segment manager to an IBM PC via the 16914 FASTBUS interface. During data taking any major hardware errors in the readout are detected by monitoring the integrity of data. Fig. 3 shows the block diagram of the readout and data acquisition system.

4. ENERGY CALIBRATION WITH COSMIC RAYS

The method used to study the energy resolution was to observe energetic cosmic ray particles traversing the scintillation fiber stack, S_1. The triggering was accomplished by requiring a threefold coincidence between the last dynode signals of the Hamamatsu PMTs and the pulses from two 2.54 x 2.54 cm^2 square plastic scintillators placed above and below the detector. These plastic scintillators were carefully aligned to select only vertical cosmic rays passing directly through the detector. Fig. 4 shows the X- and the Z- channel pulse heights for a cosmic ray event in S_1. With this geometry the cosmic rays produce a sharp peak in the X-channels while in turn producing a relatively constant pulse height in the Z channels as expected. Because of the finite size of the plastic scintillator plates used to produce the cosmic ray trigger, events were accepted traveling within a given angle with respect to the vertical. The energy resolution was estimated by adjusting for these inclined tracks, for the detector packing materials (glue, cladding material), and the light loss at the edge of the fiber block. The energy calibration of the detector turned out to be about 20% (FWHM) at 6 MeV [6].

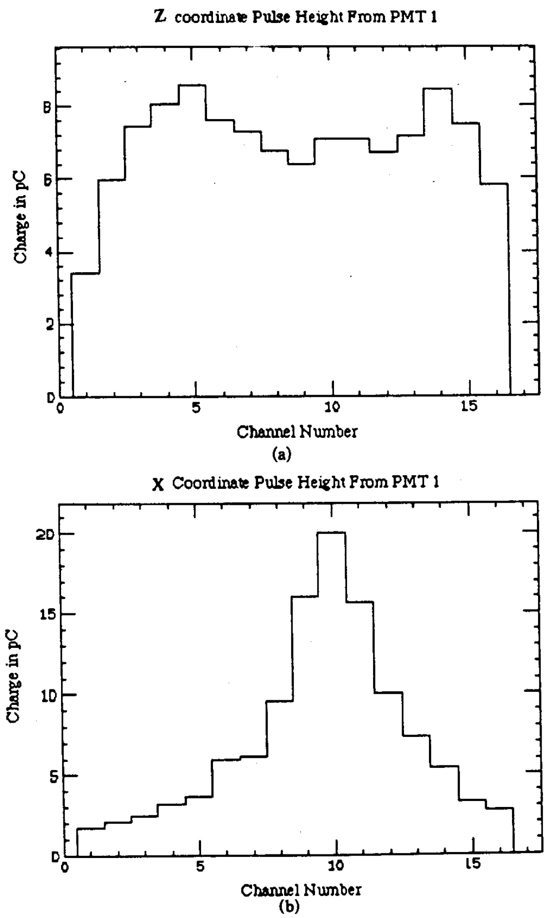

Fig. 4. Cosmic ray particle induced charge distribution from X and Z wires. The sharp X distribution indicates a nearly vertical cosmic ray.

5. TEST WITH A ^{60}CO SOURCE

The experimental arrangement to measure the angular resolution of the telescope using 1.2 MeV γ-rays from a ^{60}Co source is shown in Fig. 2. The collimated beam was produced by using a 20 cm thick lead block collimator with a 6 mm diameter hole drilled through its center. Events were chosen by requiring a threefold coincidence between the last dynode signals of the three position sensitive PMTs. The majority of γ-rays passed through S_1 without any interaction. The γ-rays producing Compton electrons in S_1 were usually scattered only once due to the fact that the scintillator stack is less that ⅙ of a radiation length thick. An unambiguous measurement of the direction of the scattered γ's is achieved if one requires that the γ-rays scattered only once in S_1 and that the scattered gammas in turn scatter only once in S_2. In this case, however, the energy deposits are underestimated, and the calculated cos θ will be smaller than the real one as indicated in Eq. 2. All coordinate pulse height distributions from all three PMTs were required to be sharply peaked in order to distinguish these events from the cosmic ray induced background.

6. SPATIAL RESOLUTION

Fig. 5 shows the X, Y and Z coordinate pulse height distributions produced by a single 1.2 MeV gamma ray undergoing Compton scattering in S_1 and S_2. The data, fitted to a Gaussian distribution, indicates that the measurement of the position of the conversion points can be determined with an accuracy better than ¼ of the PMT anode wire spacing (3 mm). This is predicted from the observed charge sharing by at least three anode wires. Calculating the charge centroid provides us with position accuracies better than 1 mm.

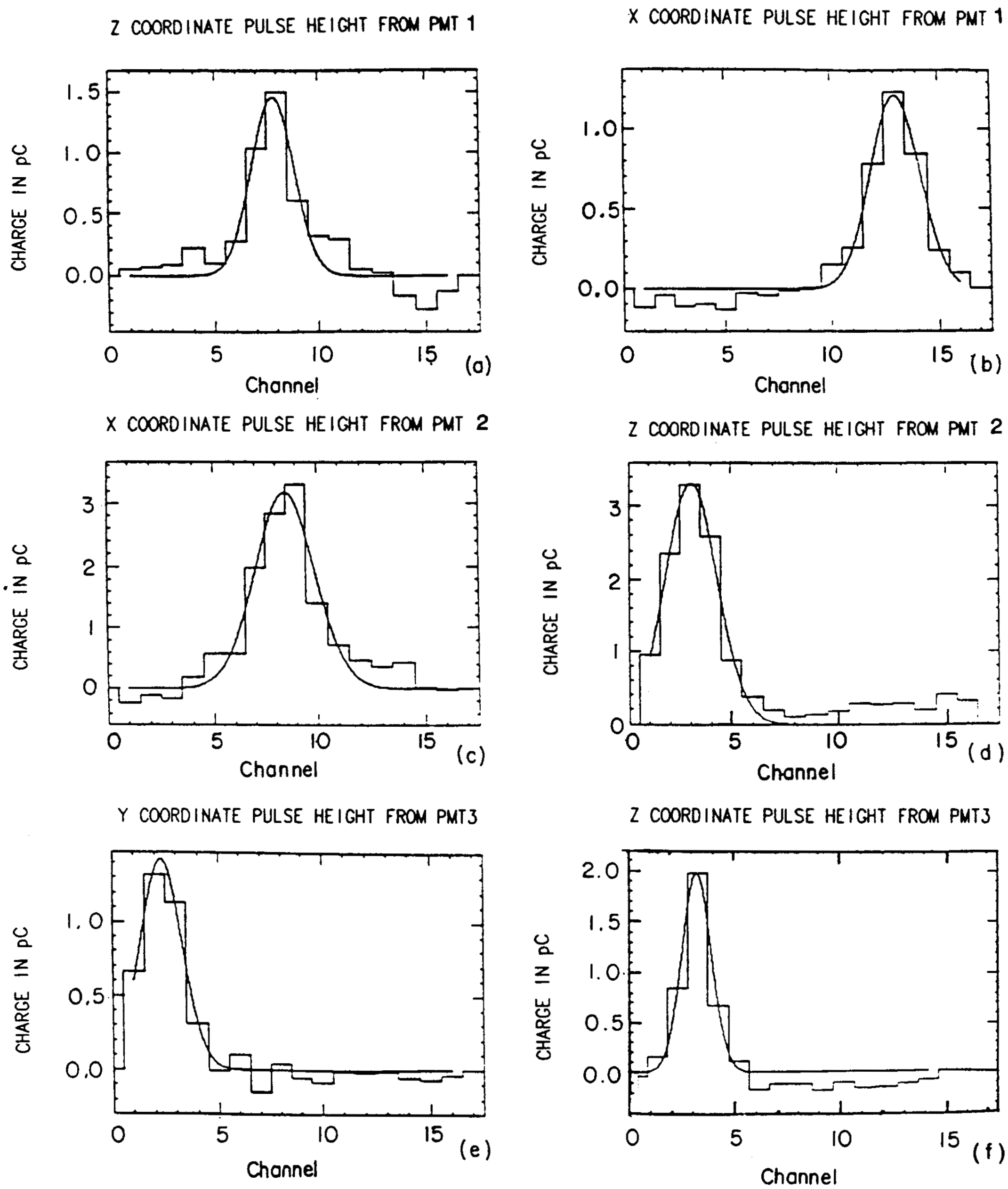

Fig 5. A double Compton scattering event in S_1 and S_2. a and b show the interaction point and energy deposited in S_1, while c, d, e, and f show the same information for S_2. The Gaussian curves have been fitted to the above distributions.

7. ANGULAR RESOLUTION

The angular resolution of the Compton telescope was determined from the positional information of the scattered γ's using double Compton scattered events of the 1.2 MeV gammas in S_1 and S_2. Because the collimated gamma rays have an angle of about 0°, the scatter angle is about equal to the angle of the scattered gammas.

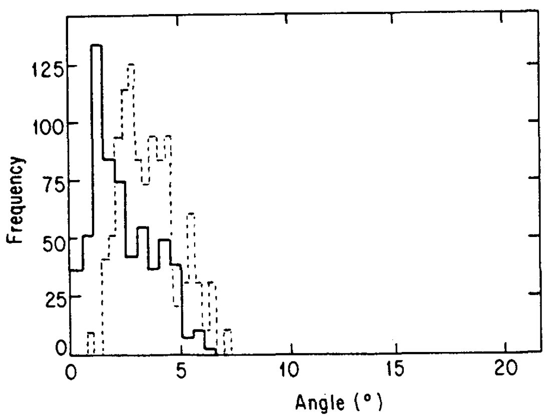

Fig. 6. Histogram of the number of events vs. scatter angle.

Fig. 6 shows the histogram of the angular distribution of the events observed vs. the scatter angle (solid curve) [6]. This angular distribution is in a relatively good agreement with the Monte Carlo simulated angular distribution (dotted curve) for the above experimental setup [6,7], and the comparison of the observed and simulated angular distributions indicate that an angular resolution of about 1° is achievable with the telescope.

The angular resolution may be improved substantially by reducing systematic errors (i.e. gain fluctuations of the PMTs, etc.). Experimental efforts are

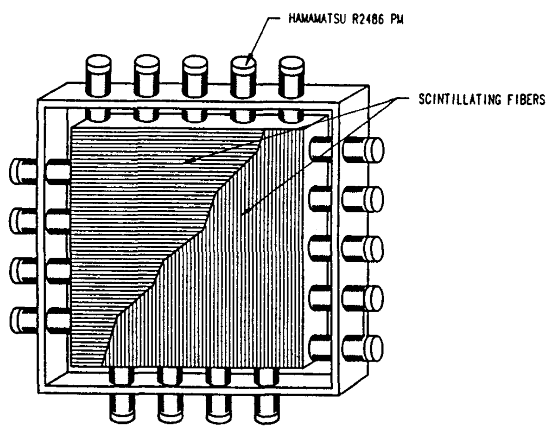

Fig. 7. Schematic of a 1 x 1 m^2 surface area and 5 cm deep scintillating fiber detector module.

Experimental efforts are currently under way to improve the angular and energy resolution of the prototype Compton telescope.

A larger Compton telescope is under development at present. Its converter has a surface area of 1 x 1 m^2 and a depth of 10 cm ~ ¼ radiation length consisting of 5 cm deep units, one shown in Fig. 7.

The calorimeter of this telescope will have also an 1 x 1 m^2 area and a depth of ~ 10 radiation lengths: 80 cm depth of plastic scintillation fiber planes (~ 2 radiation lengths), and 10 cm depth of alternating plastic scintillation fiber planes and lead absorber plates (~ 8 radiation lengths). Both the fiber layers and the lead plates will be 2 mm thick. This large telescope will provide the possibility of time-of-flight measurements which could not be carried out with the small-sized present telescope.

For this new Compton telescope we are planning to use lower refractive index cladding scintillating fibers to improve the fraction of scintillating photons collected at the end of the fiber, and thus significantly improve the photon statistics and the energy resolution of the detector. The refractive index of the present cladding material is 1.48, and the refractive index of the scintillation fiber is 1.60.

Cladding materials having refractive index of 1.3 - 1.4 are commercially available for scintillating fibers, and we intend to test this telescope at higher gamma ray energies, too.

8. SUMMARY

In summary, we have shown that the gamma ray telescope using scintillating fibers and position sensitive photomultipliers worked successfully. We believe that this type of telescope will help advance γ-ray astronomy. This principle can be used for medical imaging as well. We are in the process of constructing such devices.

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