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**A GAMMA RING-IMAGING TELESCOPE
FOR HIGH-ENERGY PHOTON DETECTION**

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ABSTRACT

We describe experimental results obtained using a new type of detector for high-energy gamma astrophysics. The detector will measure gamma rays in the GeV range, with an angular resolution of few milliradians and a field of view of 50°.

The telescope is based on the imaging of the Cherenkov light produced in a dense medium (liquid or solid) limited by a parabolic or spherical reflecting surface. The high-energy electrons produced at the start of the electromagnetic shower retain enough information about their initial direction to generate a ring-shaped photon image. This may produce hundreds or thousands of photoelectrons on an appropriate photon-imaging detector placed at the focal plane of the system, which is at the entrance surface of the converter. A prototype consisting of a liquid radiator (C_6F_{14}), a multistep parallel-plate avalanche chamber, and an optical readout system was tested in a 9 GeV/c charged-particle beam. Preliminary results show that an angular resolution of a few milliradians can be obtained. Furthermore, the capability of such a detector to identify e/π in the GeV range seems promising.

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1. INTRODUCTION

The determination of the direction of high-energy gammas is a challenge both to particle physics and to astrophysics. In most accelerator physics experiments, the direction of a gamma is determined by the conversion point inside a calorimeter and by the interaction point lying a few metres away, and the main goal is to improve the spatial and the energy resolution. However, this is possible for short-lived particles only, as for example in the case of $\pi^0 \rightarrow 2\gamma$ disintegration or in the case of direct gamma production. It is not possible for long-lived particles such as K_L^0 , K_S^0 , etc. [1], nor in experiments where the interaction point is not well known, as for example in neutrino experiments. In high-energy gamma-ray astronomy, where the photon intensity is very low [2] (for instance, on the ground, the Crab pulsar intensity is of the order of 5×10^{-6} gammas per square centimetre and second at 1 GeV/c, i.e. many orders of magnitude lower than the charged-particle flux), the development of detectors with better energy resolution—and, in particular, higher angular resolution—is needed in order to improve the signal-to-noise ratio.

The ring-imaging technique [3] for high-energy γ -direction measurements relies on the fact that the direction of electrons produced during electromagnetic shower development is strongly correlated to the momentum vector of the gamma ray initiating the shower [4]. Although the direction of each individual electron in the shower is affected by multiple scattering, the Cherenkov photons are emitted around the well-known cone. However, because of their relatively high number, and if they are registered with good efficiency and spatial accuracy, they retain much of the information on the initial direction.

In our prototype, the Cherenkov light produced in a transparent medium (C_6F_{14}) by shower electrons, and lying in the ultraviolet (UV) region, is reflected by a spherical mirror and detected by a multistep avalanche chamber [5] filled with a mixture of He (97%) + C_2H_6 (3%), doped with a photosensitive compound (TMAE at 35–45°C, which corresponds to its partial vapour pressure of 1.29–2.46 mbar) [6]. The active area of the prototype is 20×20 cm², and the overall thickness, including the radiator, the mirror, and the multistep chamber, is less than 15 cm (Fig. 1). The Cherenkov ring image is read out by a charge-coupled device (CCD) camera equipped with an image intensifier. Here we exploit the phenomenon of light emission during the charge-multiplication process in the parallel-plate gaseous chamber filled with a TMAE mixture. A more detailed description of the apparatus is given in Ref. [7].

The proposed telescope, now under development at CERN, has an angular resolution of the order of a few milliradians in the GeV range. In addition, the separation capability of photons from protons (the latter being the main source of background in an experiment in the space environment), and in particular the large aperture of this apparatus, permits a simultaneous scanning of a large number of celestial high-energy gamma-ray sources.

2. TEST RESULTS

The reconstruction of the Cherenkov rings proceeds in different and successive steps: information from the optical readout system (i.e. the image-intensified CCD camera) is fed to a frame-grabber*) connected to an IBM PC port and stored on a magnetic device [7]. With the present video digitizing system, we could record 2–3 events per second. This limitation is due to the speed of our data transfer and storage system. Showers were initiated on a lead-glass plate of 1 radiation length thickness, placed in front of the gaseous detector.

*) DT-2851, Data Translation, Inc., Marlborough, Mass., U.S.A.

We studied the performance of the detector, using a charged-particle beam containing electrons tagged by a gas Cherenkov counter, at 9 and 10 GeV/c. The average size of an electromagnetic shower event was about 15 Kbytes—significantly larger than that of the single- π events, collected under the same conditions, which did not exceed 5 Kbytes per event. Factors contributing to the event size are: variation of the CCD thermal noise, accidental hits, and background hits due to direct ionization in the gaseous detector. In the case of an electromagnetic shower event, we could observe—apart from the ring pattern—a bright spot at the point of beam incidence on the detector, along with 5–6 hits around the core of the shower; these hits came from ionization in the multistep avalanche chamber (Figs. 2a,b). In the case of pions, the picture is about the same, but there is only one single bright spot at the point of beam incidence without any other dispersed hits on the image. This background hit is easily distinguishable from the ring pattern as it is 3–4 times brighter than single-photoelectron hits (as expected from the gas mixture we used), and in addition as it lies at a fixed geometrical position for a given angle of beam incidence.

If four or more points are found in an event, a ring fit is done. The ring radius r is initially fixed to the calculated value of $r_0 = 4$ cm. In the iterative ring fit, only points with a distance $\langle r - r_0 \rangle \leq 1.5\sigma_r$ are considered to belong to the ring, where σ_r is the r.m.s. distance of the points from the ring. We collected a total of 680 events for which ring fits with ≥ 4 points are possible according to these criteria, and with $\sigma_r \leq 2.4$ mm. This allows background hits from the fit to be discarded. Setting these conditions, we were able to analyse 75.5% of the total data sample, collected with an electron trigger. The average number of hits on the ring pattern is $\langle n \rangle = 25$. The rest of the events were mainly empty owing to the acquisition problems, or they contained very few hits because of varying gain in the chamber. The centroids of the fitted events are overlaid in Fig. 3. Apart from the ring pattern, an intense spot at the centre of the image can be observed, which is due to primary ionization in the chamber, and in addition there is a second, fainter ring, which is probably due to multiple reflections on the mirror. Further away, a part of the ring of Cherenkov light on the CaF_2 window is visible. The angular resolution for the determination of the direction of the incident electron can be given by measuring the spread of the fitted ring centres; the analysis gives $\sigma_\theta = 7.3$ mrad, which is determined mainly by the beam dispersion and multiple scattering in the shower converter. Figures 4 and 5 show the position distribution of the fitted ring centres. The asymmetry observed on the x-plot of the position of the ring centre is caused by the asymmetric distribution of background hits lying at radii that are smaller or bigger than the ring radius (Fig. 6). These hits are mainly due to reflections on the mirror, to accidental hits (sparking etc.), and to Cherenkov light produced on the CaF_2 entrance window. The distribution of hit radii with respect to the fit centre is shown in Fig. 7. The Gaussian-like peak has an average of $\langle r \rangle = 4$ cm and a FWHM = 2.2 mm. According to a Monte Carlo simulation, for a geometry such as that in Fig. 1 and the same type of radiator, the contribution of multiple scattering is expected to be 3.5 mrad at 9 GeV/c, for normal incidence of the initial electron at the centre of the lead-glass converter. The beam divergence was 3.1 mrad and 5.6 mrad along the horizontal and vertical planes, respectively. We expect that the use of another type of radiator, made of dense material such as CaF_2 or NaF , would improve the angular resolution of the apparatus, as the incident gamma or electron will initiate the shower inside the radiator. The Monte Carlo simulation for a 5.2 cm thick BaF_2 crystal gives an angular resolution of 1.5 mrad for normal incidence of a 10 GeV/c electron at the centre of the crystal. However, the use of BaF_2 is not recommended for this application because of a heavy direct-scintillation component to which TMAE vapours are sensitive [8]. Another improving factor, in this case, will be the absence of background hits observed in the ring pattern caused by ionization in the chamber, and the resulting ambiguity will be minimized. Other factors that contribute to this uncertainty are electron diffusion in the conversion gap of the avalanche chamber and the error coming from the reconstruction method used by us.

According to Monte Carlo simulations [9], a spread σ_r of the individual hits results in a resolution $\sigma_0 = 1.6\sigma_r/\sqrt{n}$ for the ring centre in one dimension and for n hits on the ring. In this case, we therefore expect $\sigma_0 \approx 700 \mu\text{m}$ for the $\langle n \rangle = 25$ hits found per ring and $\sigma_r/r = 5.4\%$, which results in an angular resolution of $\sigma_\theta = 7.6 \text{ mrad}$, comparable with the result obtained by taking the ring-centre distributions. Single events with more than 50 points on the ring pattern were also detected. The inconsistency between the average number of photoelectrons of the sample and single events containing more than twice as many hits was due to the non-fully optimized test conditions and to the statistics of the shower development. Another limitation came from the geometrical properties of the gaseous detector we used, and from the TMAE temperature T : namely, the conversion stage of the multistep avalanche chamber was 7 mm and the TMAE temperature was always below 45°C . The absorption mean free path ℓ of TMAE for $\lambda = 200 \text{ nm}$ is given by [10]:

$$\ell \text{ (mm)} = 19.4 \exp \left[-5614 \left(\frac{1}{300} - \frac{1}{T} \right) \right] .$$

In our case, the photon conversion depth was always $\geq 6.2 \text{ mm}$, resulting in a loss of $\approx 33\%$ of the UV photons. For these reasons, we cannot quote a final number for N_0 . An optimization of the gaseous detector will lead to an improvement in the light yield. To achieve this, we are thinking of introducing a gating electrode before the last amplifying stage, and operating the chamber at pressures higher than 1 atm. Thus we expect that the light yield will increase and the diffusion be smaller, resulting in a better angular resolution.

A sample of hadron events at 9 and 10 GeV/c was collected. The trigger was provided by a set of scintillators in anticoincidence with a threshold Cherenkov counter. We detected similar ring patterns, but in this case the pattern contained less hits on the ring and the ionization spot was better localized (Fig. 8). The event size for hadrons did not exceed 6 Kbytes. Another interesting characteristic of these events is that by applying the same analysis method as that used for the shower events, we obtained $\sigma_r/r = 3.1\%$ (Fig. 9). We are currently investigating the possibility of distinguishing between single shower and hadron events by taking into account the integrated intensity of the pattern and the spread of individual hits. For this, a more sophisticated pattern-recognition code is being developed.

3. CONCLUSIONS

We have proved that electromagnetic shower ring-imaging is feasible. An angular resolution of $\approx 7 \text{ mrad}$ at 9 GeV/c was obtained, which is close to the limits imposed by beam dispersion and multiple scattering of the lead-glass converter. The overall performance of the proposed scheme could be bettered by developing the chamber. This could be done by controlling the pressure and gating the last amplifying stage, and by improving the transparency of the radiator (or replacing it with a dense, transparent medium of low refraction index, which would serve both for shower initiation and as the Cherenkov radiator). Such improvements should result in minimizing the background hits observed and maximizing the number of hits on the ring pattern. Extrapolating from the results obtained for an optimized detector, we expect an angular resolution of $\approx 1 \text{ mrad}$ for an incident photon of 10 GeV energy.

Electron-pion separation in the 1–10 GeV/c range is another interesting feature of the proposed telescope. In a subsequent paper, we will present the e/π discrimination obtained with this device, along with Monte Carlo expectations.

The possibility of using the apparatus for π/K separation up to 4 GeV/c is under investigation. For this reason, another prototype has been constructed and tested, and data are being analysed [11]. The first results seem to be encouraging.

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Figure captions

- Fig. 1 Schematics of the apparatus.
- Fig. 2 Cherenkov rings from a shower initiated by an electron at 9 GeV/c (single event).
- Fig. 3 Overlap of the centroids of 680 events having four or more points on the ring.
- Fig. 4 Ring-centre distribution x-axis. An angular resolution $\sigma_\theta \approx 4$ mrad is observed.
- Fig. 5 Ring-centre distribution y-axis. The angular resolution is $\sigma_\theta \approx 6$ mrad.
- Fig. 6 Radial light distribution for a) the right half and b) the left half of the ring. Comparing the background around the peak, asymmetry can be seen.
- Fig. 7 Fitted radius distribution for electromagnetic shower events. As expected from Monte Carlo calculations, $\sigma_r \approx 2.2$ mm, which is higher than in the case of a single-pion event.
- Fig. 8 Cherenkov ring from a single pion at 9 GeV/c. The pattern contains less points than in the case of showers, and the ionization hit is better localized.
- Fig. 9 Radial light distribution of a pion at 9 GeV/c. In this case, $\sigma_r \approx 1.2$ mm.

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Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9