Nuclear Instruments and Methods in Physics Research A306 (1991) 563–571
North-Holland

A method to measure the γ-ray content in VHE cosmic ray showers

M. Cresti, L. Peruzzo, A. Pesci, A. Saggion and G. Sartori
INFN-Padova and University of Padova, Padova, Italy

F. Angelini, F. Bedeschi, R. Bellazzini, E. Bertolucci, G. Chiarelli [1], M. Mariotti, M.M. Massai, A. Menzione, D.A. Smith, A. Stefanini and F. Zetti
INFN-Pisa and University of Pisa, Pisa, Italy

A. Scribano
INFN-Pisa and University of Siena, Siena, Italy

B. Bartoli
INFN-Napoli and University of Napoli, Napoli, Italy

M. Budinich, F. Liello and E. Milotti
INFN-Trieste and University of Trieste, Trieste, Italy

A.R.P. Biral, J.A. Chinellato and A. Turtelli
CNRq and University of Campinas, SP Brazil

M. Luksys
CNRq and University of Paraiba, PB Brazil

Received 19 October 1990 and in revised form 25 February 1991

An experimental technique is presented to determine the effectiveness of methods to tag photon initiated air showers and reject hadron initiated ones. The technique is based on the rate reduction in the Moon direction. With a photon energy threshold below or equal to 1 TeV, with an angular resolution of a few mrad and being insensitive to visible light, the proposed CLUE detector allows a wide and original physics program. In particular the direct measurement of the fraction of primary photons in the continuum of the cosmic ray flux is feasible with adequate statistics in a few months of data taking.

1. Introduction

A detector of novel design to study cosmic ray showers through the UV component of their emitted Cherenkov light was proposed in 1988 [1]. After a period of tests [2], the collaboration is now preparing a detailed experimental proposal [3]. We show that sizeable progress can be achieved over existing detectors in the search and study of localized sources and variable emitting bodies.

We have studied in detail the performance of this detector in tagging primary cosmic photons. In fact a precise measurement in the VHE range of the photon content of the primary cosmic radiation would be of great physical interest. This measurement is attempted by a number of experiments, but it is not easy to determine experimentally how effective a technique used to tag photon initiated showers is. The ability of different experiments to distinguish electromagnetic showers from hadron initiated showers is, in fact, a widely discussed problem in cosmic-ray physics.

The measurement of primary cosmic photons is relevant in the study of localized sources since in principle

[1] Now at IFN-LNF.

only photons (and neutrinos) retain the information of their origin. Charged particles are bent enough by the galactic magnetic field to loose any information about their original direction and most neutrons decay before reaching the Earth.

The existence of photons in the primary cosmic radiation is well established at low energy (satellites, balloons etc.) where the existence of signals from localized sources is indisputable. At higher energies (TeV–PeV) where the signal from localized sources becomes less significant, the very existence of primary photons is not well proven. In very general terms, one may consider three possibilities: a) the number of photons is negligible at these energies from any point of the sky, b) there is a sizeable photon content only in the direction of localized sources, c) a signal from localized sources may exist but is on top of a strong uniform background of photons. The few available experimental results as well as extrapolations from lower energy data make this last hypothesis seem the most reasonable to us.

In the following we will assume a ratio gamma/protons = 0.1%. The arguments do not change qualitatively if this figure has a different value. The actual value of this ratio, at these energies, is unknown, but ranges from a few 10^{-5} [4] (lower limit) to some percent [5] in the galactic plane. Scaling from lower energy measurements, similar values are expected for the ratio of electrons (positrons) and hadrons [6]. In general one takes this as an irreducible source of background since the showers initiated by electrons are almost identical to showers initiated by photons. Indeed when used for gamma ray astronomy electrons will be a background for CLUE as well but, as discussed in section 4, when evaluating the photon content this background can be significantly reduced with our proposed technique.

Several techniques, briefly recalled below, are usually applied to enrich the fraction of photon initiated showers in a data sample. In the past the only reliable way to test the effectiveness of a particular technique was the appearance of a signal (localized source or variable star) otherwise not visible. Unfortunately sometimes it happened that a candidate signal in the whole sample disappeared after the application of cuts that were supposed to sharpen it.

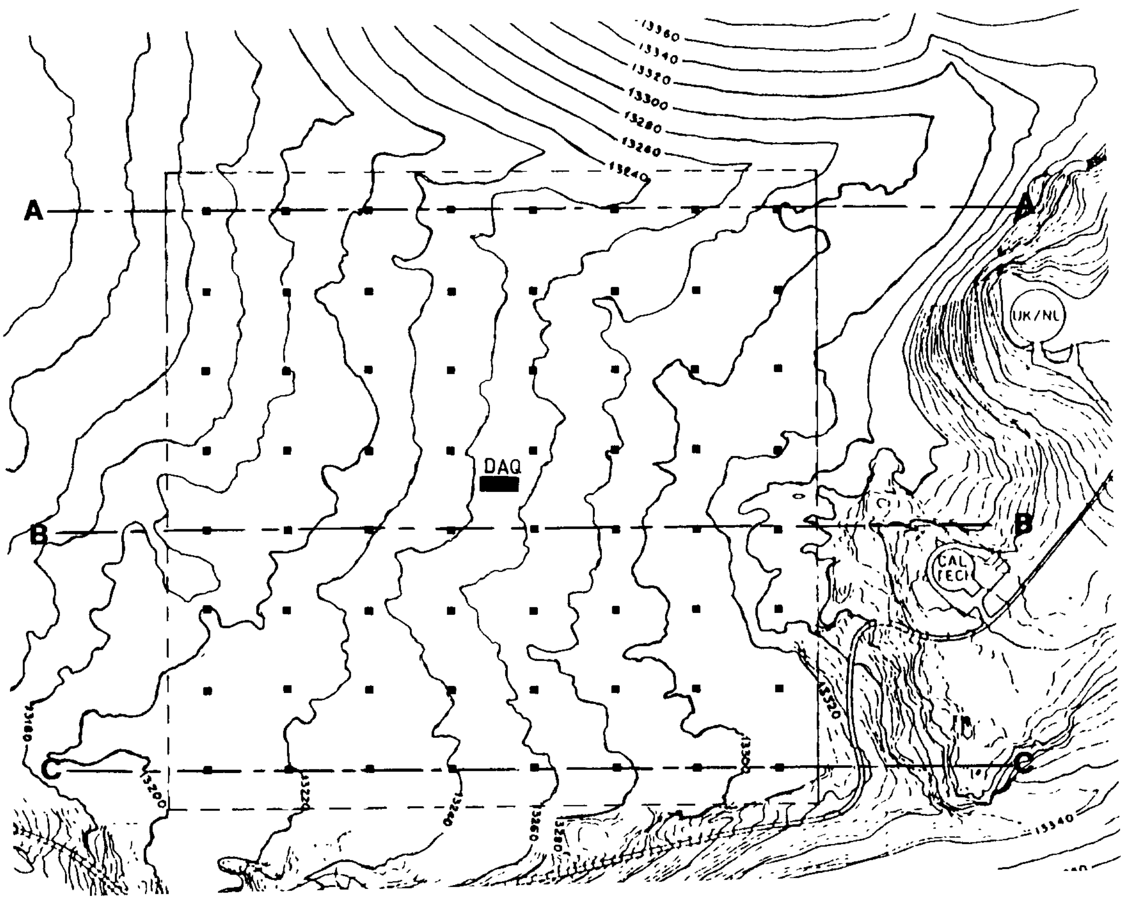

Fig. 1. Top view of the proposed setup. The pictured site is the top of Mauna Kea, Hawaii, USA, 19.5 N at an altitude of 4200 m.

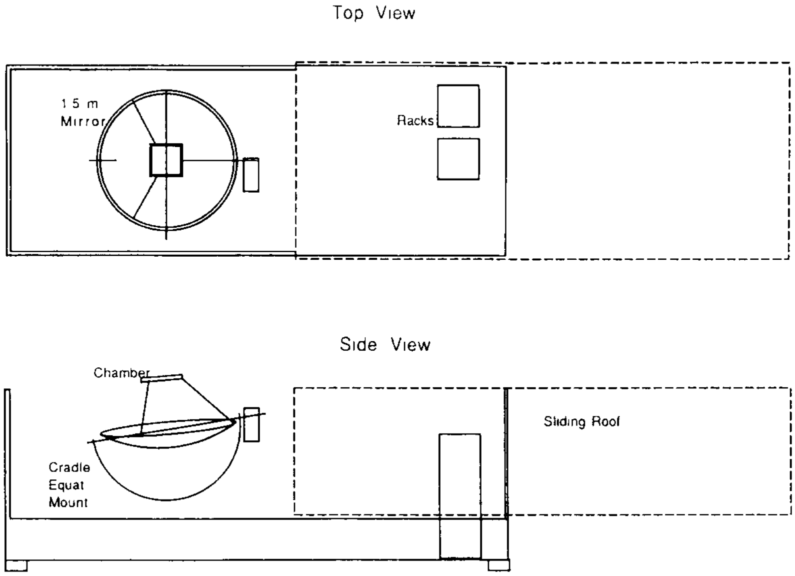

Fig. 2. Detail of one of the 64 units of the array.

CLUE can tackle this thirty year old problem in an efficient experimental way as described in sections 4 and 5.

2. The CLUE detector

CLUE will be an array of 64 mirrors, 1.5 m in diameter arranged in a matrix of 50 m pitch. It will be located in a tropical region at an altitude of 3500–4500 m above sea level. In the focal plane of each mirror a gas proportional chamber is positioned, with TMAE vapor as the photosensitive element. Each chamber is equipped with a readout of 256 (16 × 16 matrix) cathode pads giving the image of a section of the sky of $\pm 6°$. Details of the chamber construction and performance are given in ref. [7].

The chambers are sensitive to ultraviolet light only (205–235 nm). The background from the sky and from other celestial bodies is then negligible because of the screening of the ozone layer in the upper atmosphere. Only the Cherenkov light produced below the ozone layer will reach the detector. The limitation of the

Table 1
Main parameters of the CLUE experiment

Altitude	[m]	3500–4500
Latitude	[deg]	20N–20S
Number of units		64
Distance between units	[m]	45–55
Total target area	[m^2]	-2×10^5
Diameter of mirror	[m]	1.5
Focal number		1
Area of chamber	[m^2]	0.08
Number of pixels/chamber		256
Total number of channels		16384
Sensitivity range	[nm]	205–235
Quantum efficiency	[%]	25–30
Attenuation length	[m]	1500–2000
Angular opening	[deg]	± 6
Angular accuracy	[mrad]	2–3
Energy threshold	[TeV]	0.5–1
Energy resolution	[$\%/\sqrt{E[\mathrm{TeV}]}$]	20–40
Duty cycle	[%]	50–60
Trigger capability	[kHz]	10
DAQ capability	[Hz]	100

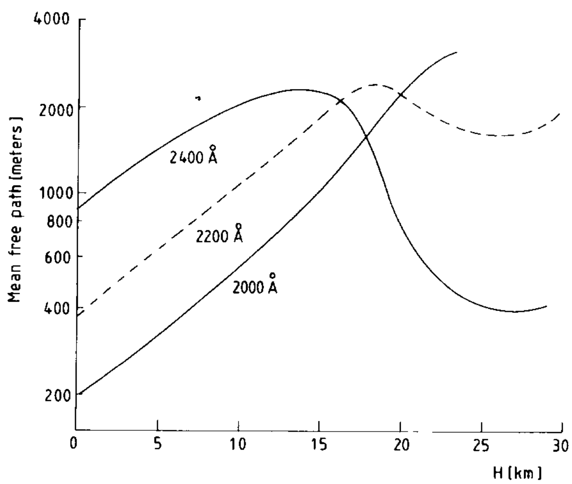

Fig. 3. Mean free path in (transparency of) the atmosphere for ultraviolet light as a function of the height above sea level.

technique is the reduced transparency of the lower atmosphere for UV light. Because of this it is important that the experiment be located in a tropical region and at high altitude. Fig. 1 is a top view of the proposed setup, fig. 2 is the detail of a single unit. Table 1 summarizes the main parameters of the experiment.

In fig. 3 the transparency of the atmosphere is given as function of its height for the values of wavelength in which the chambers are sensitive.

3. Methods of tagging photon showers

Based on the analysis of accelerator data and with the help of computer simulations, three techniques have been developed that are frequently used to discriminate, on an event-by-event basis, γ-rays from other cosmic particles: the imaging method, the timing method and the muon content method.

1) *The imaging method*: electromagnetic showers are more dense and more uniform than hadron showers of the same energy. The variable which discriminates on the basis of these quantities, AZWIDTH [8,9], allows a fair discrimination between the two types of showers. Detailed study of the shower lateral distribution helps guessing the nature of the primary since hadron showers tend to branch into more than one relative maximum.

2) *The timing method*: this method is based on the fact that e.m. showers contain mainly γ, e^+ and e^-. Since electrons travel nearly at the speed of the light, most of them will reach the detector at about the same time, within a few nanoseconds. On the other hand, hadron showers contain higher mass secondaries giving an arrival time spread of 20–30 ns. If the detector can measure the detailed shower timing, then selecting events in which most of the radiation arrives in a very narrow time window would enhance the signal due to primary photons.

3) *The muon content method*: this technique uses the fact that only hadron showers develop into secondaries which can produce a sizeable number of muons (pion decay etc.). The photo- and electroproduction cross sections of particles that can decay into muons is very small [10]. A suitable array of muon detectors could tag events with a large muon content, and thereby reduce the hadron shower background.

Here we want to show that both the measurement of photon content in the primary cosmic radiation and the experimental test of the effectiveness of the photon tagging can be done with an apparatus like CLUE. CLUE is in fact in a unique position, being the only apparatus among the existing apparatuses which will combine all the necessary features: a low enough threshold (below 1 TeV), sufficient angular resolution (few mrad) and insensitivity to visible light, so that it is possible to point directly at the Moon. It should be mentioned that the proposed apparatus ARTEMIS [11] could tackle this problem as well, if the RbTe photomultipliers which are being developed will show the expected blindness to visible light.

The measurement cannot be performed by experiments using visible Cherenkov light because of the huge background from the moonlight. It is also very difficult for EAS experiments because of the typically higher threshold in energy and/or the limited angular resolution, which severely limits the statistical accuracy.

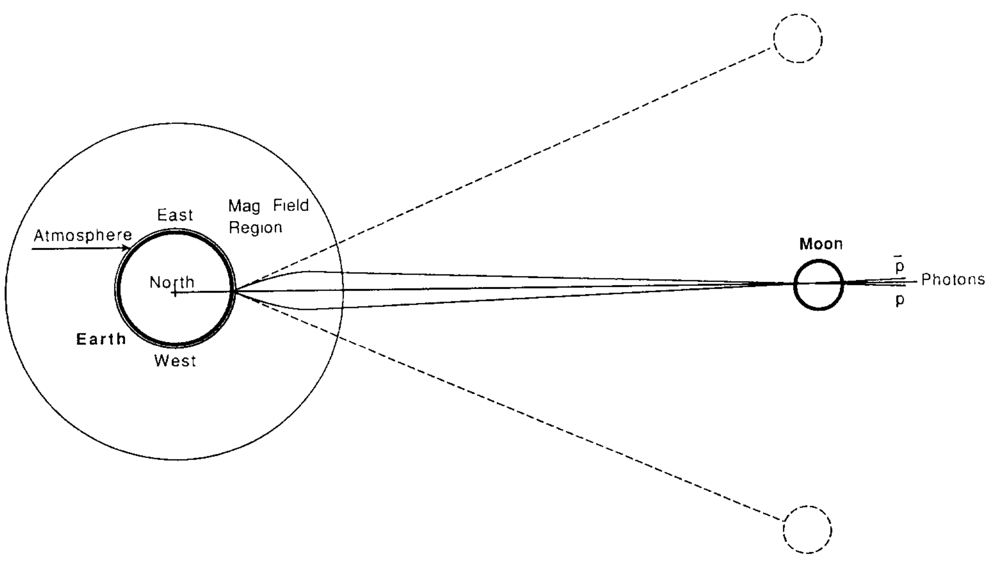

Fig. 4. Schematic illustration of the method of observing the rate decrease due to the shadowing by the Moon of different types of particles. The figure is not to scale.

4. Checking that primary photons are seen with CLUE

In order to check the abundance of primary photons in the selected sample CLUE plans to use a scheme similar to the one originally proposed by Urban et al. [12] to measure the proton–antiproton ratio. This scheme has also been independently proposed by Heinze et al. [13] (for charged particle detection). A similar concept had been previously suggested by Lloyd-Evans [14].

This measurement, and a number of other composition characteristics of the primary radiation, can be studied by looking at how rates vary with angle in a plane perpendicular to the magnetic field of the Earth in the direction of the Moon. The path of the Moon in the sky lies approximately in this plane. The Moon would act as an absorber and the Earth's magnetic field as a charge and energy analyzer. The rate should have a dip in the direction of the Moon for primary photons, while a similar dip should be present westward for protons and eastward for antiprotons. The angular distance between these dips is a function of energy. As an example, at one TeV (an achievable threshold for CLUE) the bending angle for protons due to the Earth's magnetic field is 30 mrad, 3.5 times the Moon diameter, and 10 times our expected angular resolution.

It should be observed that an experiment installed in a tropical location, as CLUE will be, is favoured in this measurement because of the smaller zenith angle (larger altitude in the sky) of the Moon, and the better weather conditions, both giving a higher duty-cycle. An important parameter is the energy resolution that an experiment can reach in the TeV energy range. At present we can only estimate the resolution of CLUE on the basis of simulations and comparisons with the results of

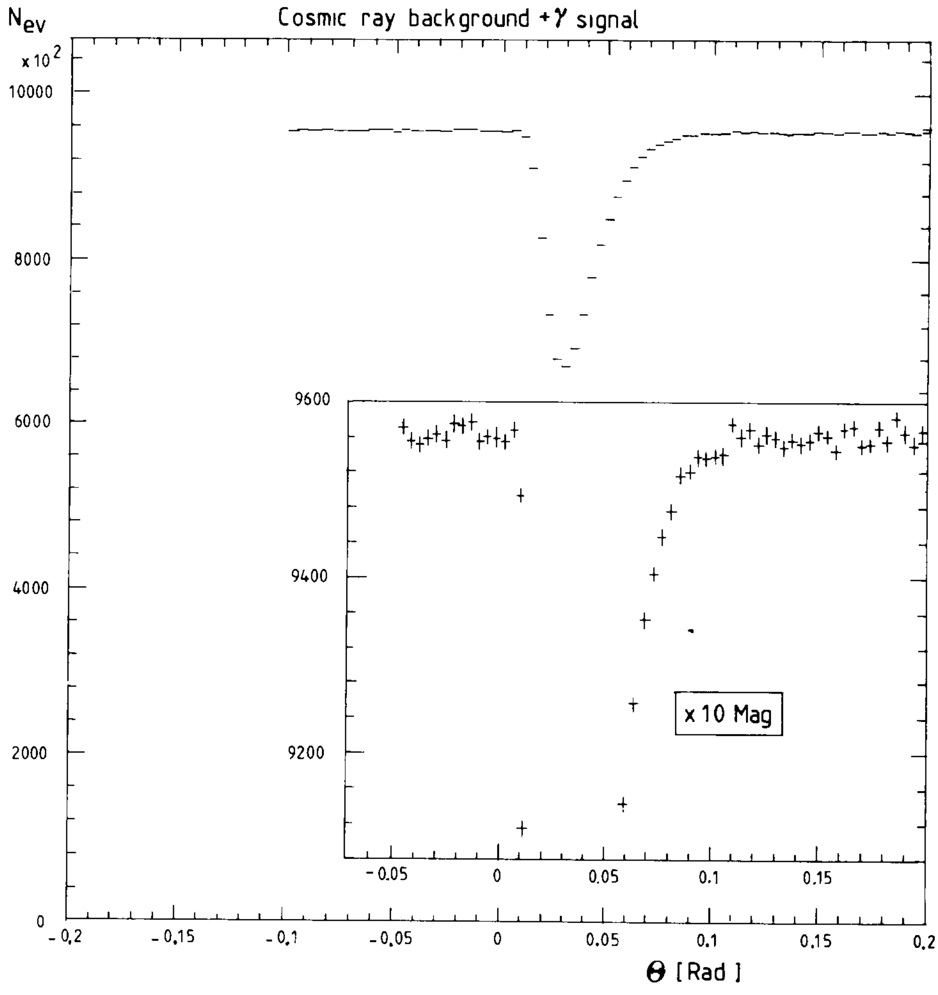

Fig. 5. (a) Expected number of events as a function of the angle θ with respect of the Moon for a four month observation of the Moon with the CLUE experiment in the hypothesis of 3 mrad angular resolution and $40\%/\sqrt{E[\text{TeV}]}$ energy resolution. The energy window is between 0.8 and 1.2 TeV. (b) Same in a more expanded scale (note the suppression of the vertical scale).

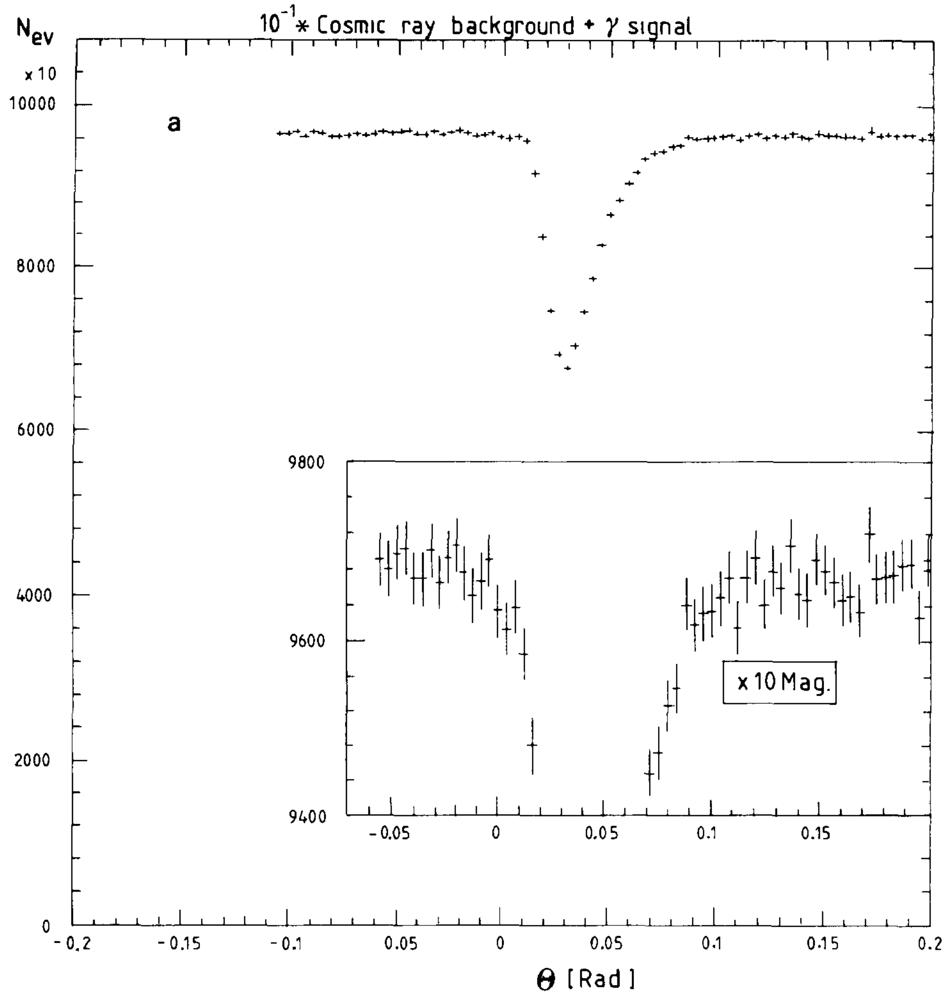

Fig. 6. Same as fig. 5, assuming hadron rejection factors of 10 (a), 100 (b), 1000 (c) (note the suppression of the vertical scale).

similar experiments. On these grounds we estimate a resolution in the range between 20 and $40\%/\sqrt{E[\text{TeV}]}$. To be conservative we will use this latter value. For the angular resolution we use the figure of 3 mrad.

It appears that, if a sizeable amount of electrons (positrons) is present in the primary radiation, it can be distinguished from the contribution of photons by using the charge-momentum analyzing capability of the Earth's magnetic field.

Fig. 4 pictures the scheme of the measurement (clearly not to scale). Photons pointing to the Earth straight through the Moon are shielded. Protons and antiprotons are bent by the Earth's magnetic field and appear to be shielded by an off-angle image of the Moon. The output of the simulation is shown in fig. 5 for 1 TeV (0.8–1 TeV) incoming radiation containing 99.9% protons and 0.1% photons for four calendar months of Moon observations. We assume that the Moon will only be observed six hours a day and 18 days out of 28. Next to the proton dip, the photon signal is very weak and would barely be noticed. For relative photon fluxes in excess of 0.1% the effect becomes of course more visible. This composition is presumably far from reality, other nuclei content may decrease the figure of proton content and the amount of photons is unknown. We use these values in our simulation to show the capability of the apparatus to distinguish the two cases.

5. Expected results

It is not the aim of this article to discuss which hadron rejection method will be most suitable for us. It will presumably be a combination of one or more of the methods described above. In particular, the imaging method is directly applicable without any change of the system. We claim that regardless of the method used to

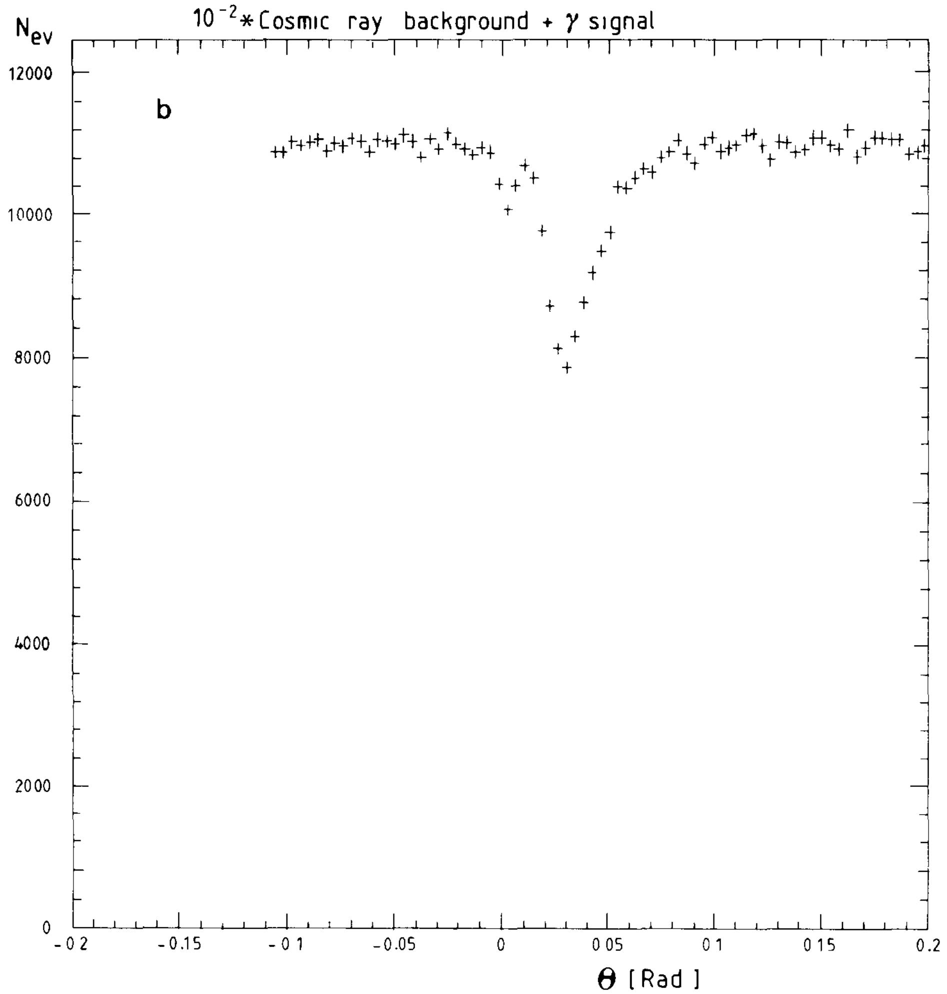

Fig. 6 (continued).

tag photons, we will be able to evaluate its effectiveness. To do this we have to analyze the data set filling the histogram shown in fig. 5 and then apply the appropriate algorithm. If the algorithm, and hence the method, is efficient we expect both the total rate and the proton signal to decrease by the same factor, while the photon signal remains practically unchanged.

Figs. 6a, 6b and 6c give the results of a simulation assuming hadron rejection factors of 10, 100 and 1000 and negligible photon rejection.

If the photon signal can be unambiguously seen one can quote the photon content within the statistical significance of the dip in the (unrealistic) hypothesis that the algorithm does not cut the photon signal. In order to evaluate the last effect one method would be to overcut and undercut on the relevant variables and interpolate the values. We cannot predict how successful this procedure would be but we are confident that it will give at least an estimate of the systematic error of the measurement.

In order to estimate, in a practical case, the loss of photon events by cuts applied to reject hadron showers one needs a simulation package that simulates both hadron and photon showers in a consistent way. Furthermore, the simulation to evaluate exact path length, speed, multiple scattering, and decay products should be very detailed, and hence very time consuming. We are not aware of the existence of such a sophisticated package.

The Whipple collaboration achieved, with the imaging method [5], a hadron rejection of 93–98% with an estimated loss of photon signal < 10%, by cutting on the variable AZWIDTH (combination of the length and the width dispersions). This, scaled to our rates, would give results somewhere between fig. 6a and 6b. We believe that in our case it will be possible to work out a

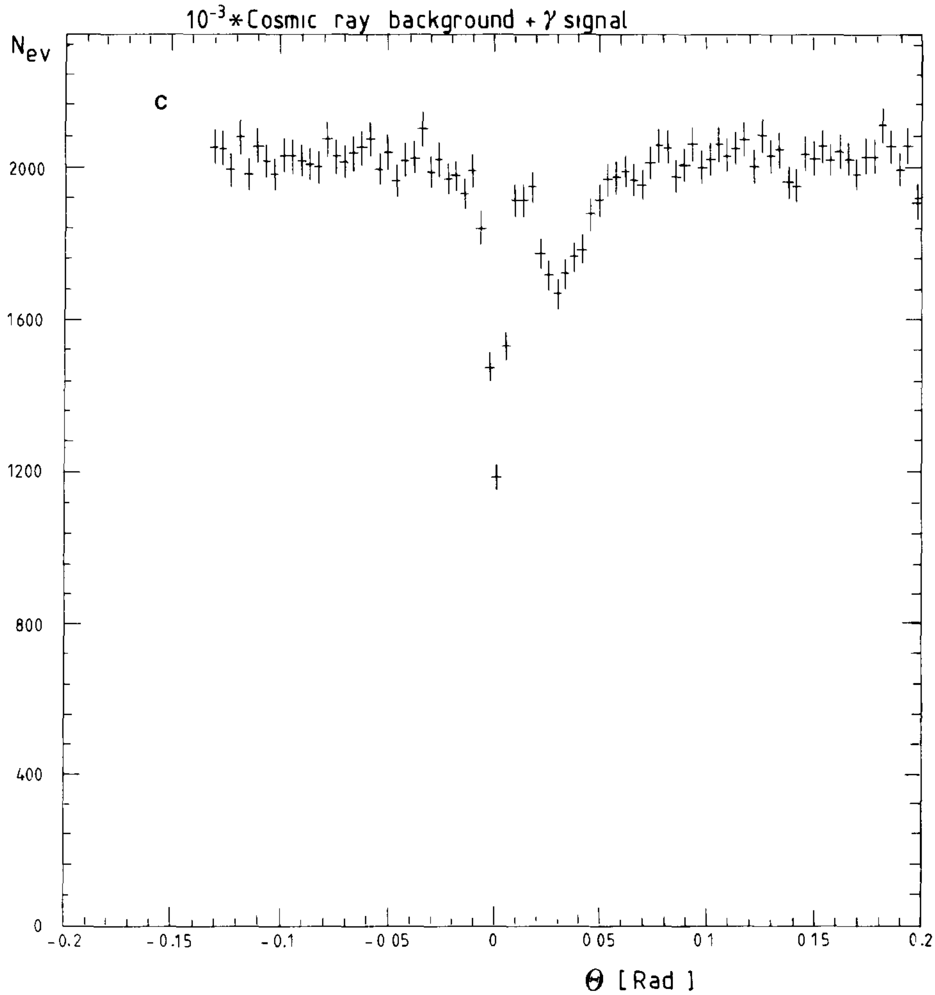

Fig. 6 (contınued).

more sophisticated and, we hope, effective algorithm taking advantage of the knowledge of the impact parameter and the multiple image of the same shower given by the multimirror array. We are aware that the quality of the image is degraded by the smaller attenuation length of UV light but preliminary simulations lead us to believe that a rejection factor of 98% is achievable.

6. Conclusions

When commissioned, the CLUE experiment stands a good chance to be able to experimentally test the performance of its method of tagging photon initiated showers. In consequence one can measure the photon content in the cosmic rays. This measurement will solve an important controversy with implications in physics and astrophysics.

Acknowledgement

We would like to thank Marcel Urban and Patrick Fleury for many helpful discussions.

References

[1] G. Apollinarı et al., Nucl. Instr. and Meth. A263 (1988) 255.
[2] B. Bartolı et al., Nucl. Instr. and Meth. A302 (1991) 515.
[3] CLUE Collaboration Proposals, VHE cosmic-ray spectroscopy by detection of ultraviolet Cherenkov light, INFN internal doc. (1990) (A. Menzione INFN, via Lıvornese S. Piero a Grado 56100 Pisa, Italy).
[4] M.T. Russell et al., FERMILAB Pub-89/214-A;
F. Halzen et al. Phys. Rev. D 41 (1990) 342.

[5] J. Wdowczyk et al., Nature 305 (1983) 609.
[6] A.M. Hillas, Cosmic Rays (Pergamon, Oxford, 1972).
[7] F. Bedeschi et al., Nucl. Instr. and Meth. A294 (1990) 622.
[8] T.C. Weekes et al., Astrophys. J. 342 (1989) 379, and bibliography therein.
[9] A.M. Hillas, proc. 19th ICRC, La Jolla (1985) vol. 2, p. 173.
[10] T.K. Gaisser et al., University of Wisconsin preprint, MAD/PH/557, BA-90-16 (1990).
[11] ARTEMIS Collaboration, Antimatter Research Through The Earth Moon Ion Spectrometer, P. Fleury, Rencontres de Moriond on New and Exotic Phenomena, 1990, Proc.; Tran Tan Van, Ed. Frontieres.
[12] M. Urban et al., Nucl. Phys. 14B (1990) 233.
[13] J. Heintze et al. (CRT Collaboration), Nucl. Instr. and Meth. A277 (1989) 29;
Exp. Astr. 1 (1989) 21.
[14] J. Lloyd-Evans, Proc. 19th ICRC, La Jolla (1985) vol. 2, p. 173.