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A STUDY OF THE COSMIC-RAY INDUCED BACKGROUND IN TWO-PHOTON CORRELATION AND NEUTRAL PION PRODUCTION MEASUREMENTS WITH A BaF_2 MULTIDETECTOR

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Abstract

The problem of the cosmic–ray induced background in neutral pion production and high–energy $\gamma-\gamma$ correlation measurements with barium fluoride multidetectors is discussed. As a reference example, the response to cosmic rays of the MEDEA photon spectrometer is studied. The interaction of the cosmic radiation with the experimental filter has been treated by means of full Monte Carlo computer simulations with the GEANT3 code. The results of the simulations are compared with experimental data and general criteria to minimize the cosmic background are discussed.

I. INTRODUCTION

Hard photons ($E_\gamma > 30$ MeV) and neutral pions are indicated as interesting probes in the study of heavy–ion collisions at intermediate energies [1–3]. Both particles are expected to be produced from single incoherent nucleon–nucleon collisions in the early stage of the nucleus–nucleus interaction and could give useful information on the reaction mechanism, on the space–time evolution of the emitting source, and on the geometrical (location) and physical (density) properties of nuclear matter during the reaction. Because of the absence of final state interactions, photons represent ideal particles to be used in intensity interferometry experiments in order to evaluate both the spatial size and lifetime of the emitting source in an almost model–independent way [4,5]. Neutral pions, on the contrary, strongly interact with the surrounding nuclear medium and the study of their phase–space distributions (such as rapidity plots) at different impact parameters [6,7] offers a unique tool to evaluate and compare reabsorption mean free paths at different nuclear densities without the noise due to the Coulomb interactions as for charged pions.

Photon–photon correlation and neutral pion production measurements, however, requiring the simultaneous detection of two high energy γ–rays, are extremely delicate with respect to their effective experimental realization and to the real understanding of the results [4]. This is due to the small involved cross sections and, mainly, to the strong effects of the experimental filter on the physical signal (response function to photons, solid angle, intrinsic efficiency, presence of background, etc.).

In these last years, very important results in these fields of intermediate–energy heavy–ion physics have been obtained with a new generation of large solid angle photon/pion spectrometers, TAPS (Two/Three Arm Photon Spectrometer) [8] and MEDEA (Multi Element DEtector Array) [9], both based on the use of BaF_2 scintillation modules. These detectors combine, for the first time, the availability of a large solid angle coverage with fair energy and angular resolutions and make possible, owing to the peculiar properties of barium fluoride, the detection, in the same experimental setup, of photons or neutral pions in coincidence with light charged particles. In spite of their great usefulness, however, all these scintillator–based spectrometers suffer the common problem of the noise induced by the interaction of the hard component of cosmic rays with the detector. Although they are extremely useful in the energy calibration [10], as they provide a high–energy peak of minimum–ionizing particles (well above energies provided by any radioactive γ–source), cosmic rays play a negative role in photon detection as they are responsible for a high–energy background [11,12]. The problem arises from the fact that high–energy muons, mostly present in the cosmic radiation at sea level [13–15], traversing the modules of a real photon multidetector, can originate inside it electromagnetic showers quite similar to those due to high–energy photons coming from the target.

Since the possibility to observe rare events in a detector is, as a general rule, always limited by the background associated with it, the possibility to measure the production of very energetic photons or neutral mesons with these scintillator–based multidetectors is then strongly dependent on the possibility to suppress or, at least, greatly reduce the cosmic background unavoidably linked to them. Consequently, a complete understanding of the effects of this undesired contribution on the physical observables under study is, every time, mandatory before to draw any conclusion from the analysis of experimental data.

In this work we report on a study of the cosmic–radiation induced noise on two–hard–photon correlation as well as neutral pion production measurements using the MEDEA multidetector. The interaction of cosmic rays with the experimental setup has been treated by means of full Monte Carlo computer simulations with the GEANT3 code [17]. The paper is organized as follows. Section II contains the description of the event generation procedure. The experimental filter is briefly described in Sec. III together with the used event–treatment method. Section IV contains a review of the results of the simulations and the comparison with experimental data. As an example, a quantitative estimation of the cosmic background in the ^{27}Al(^{36}Ar,2γ) [5] and ^{27}Al(^{36}Ar,π^0) [7] reactions at 95 MeV/nucleon is performed. Possible methods to reduce cosmic noise in the study of this kind of processes are also presented and discussed. Summary and conclusions are given in Sec. V.

II. EVENT GENERATION

In all simulations described in this paper cosmic rays have been represented by their dominant muon component. The procedure of the event generation is graphically illustrated in Fig. 1 for a generic spherically symmetric detector. First of all, a large number (10^6) of points, standing on the outer surface of the upper part of the detector, have been randomly sampled according to an uniform angular distribution. Each of these points has been then considered as the impact point of a cosmic muon with the multidetector. In order to determine the three components of the muon momentum, a reference system having the origin at the impact point, two axes standing in a plane parallel to the equatorial plane of the multidetector and passing through the impact point, and the third axis perpendicular to this plane, has been chosen (see Fig. 1). Muons have been created with a kinetic energy of 2 GeV, which represents a realistic mean energy of the muon flux at sea level [14,16], a polar angular distribution proportional to $\cos^2 \eta$ [16], where η is the minimum angle between the muon momentum and the vertical direction (see Fig. 1), and an uniform azimuthal angular distribution ($\psi \in [0, 2\pi]$). The coordinates of the impact point and the components of the muon momentum form the so–called "simulation vertex" necessary to GEANT3 to start the tracking inside the detector. At the end of the tracking, the simulation code stores in a matrix the nominal (central) angles of each detector module and the value of the deposited energy inside it by the muon–induced electromagnetic shower.

III. THE EXPERIMENTAL FILTER

The MEDEA multidetector has been designed and realized as a facility of the INFN Laboratorio Nazionale del Sud to detect at the same time photons as well as light charged particles coming from heavy–ion collisions at intermediate energies. It consists of a ball (22 cm inner radius) formed by seven rings of barium fluoride crystals (168 elements, 20 cm thick), covering the zenithal angular range between 30° and 140°, and a forward wall formed by five rings of phoswich (NE102A + NE115) detectors (120 elements, 30 cm thick, placed at 55 cm from the target), covering the zenithal angular range between 10° and 30°. A very detailed description of this multidetector can be found in Ref. [9].

In all simulations reported in this work we have taken into account the BaF_2 ball only, shown in perspective in Fig. 2, which is the part of the MEDEA multidetector sensitive to photons. In order to compare the results of the simulations with the experimental data taken in the ^{27}Al(^{36}Ar,2γ) and ^{27}Al(^{36}Ar,π^0) reactions at 95 MeV/nucleon, an exact software replica of the detection setup used in that experiment has been considered including energy thresholds and presence and location of a few (only seven) not–working modules. In the same spirit, the detection mathematical algorithm used for the analysis of the showers originated by the simulated cosmic muons has been exactly the same of that employed in the reduction of the experimental data relative to the above–mentioned reactions. It consists of the following procedure. First of all, all modules having a value of the deposited energy different from zero are scanned in order to find the "most–touched" detector (i.e., with the highest value of the deposited energy). When this detector is found the analysis code looks at the eight detectors around this one in order to determine whether or not the electromagnetic shower spreads out in these neighbouring modules. If none with a deposited energy greater than its threshold is found, the photon energy is fixed equal to the deposited energy of the central detector and the polar and azimuthal detection angles are fixed equal to those relative to the central point of that detector. Otherwise, the energy of the photon–induced shower is obtained by summing over all elements of the cluster and the photon detection angles are evaluated as the averages of the corresponding nominal (central) angles of the detectors of the cluster, weighted over the deposited energy in each cluster element. When the energy and the detection angles of the first shower are determined and the shower multiplicity is greater than one, the first "most–touched" detector and the involved neighbouring modules are excluded from the loop and the program starts again to find a new "most–touched" detector. As it as been shown in Refs. [9,18], this kind of procedure minimize the sideward leakages of the shower (the full side dimension of each detection module is nearly twice the Molière radius of barium fluoride), ensures a good estimate of the detector response to photons, and improves the reconstruction of the photon detection angle which is of capital importance in order to obtain a good resolution in the pion invariant mass reconstruction. The performances of the BaF_2 ball of MEDEA as a photon and neutral pion detector have already been extensively studied (by GEANT3 simulations) in Refs. [9,18] and experimentally verified in Refs. [5,7,19–21]. Since in this report we are interested in the study of the cosmic background in hard $\gamma - \gamma$ correlation and neutral pion production (i.e., two–high–energy–photons events), only those simulated events producing two separate showers inside the BaF_2 ball, each having a total deposited energy larger than 30 MeV, have been considered for further analysis. The percentage of this kind of filtered events over the total number of generated ones is about 25%.

IV. RESULTS AND DISCUSSION

A. Response to cosmic rays

A global view of the interaction of the simulated cosmic muons with the BaF_2 ball of the MEDEA multidetector is reported in Fig. 3. It shows the distribution of the relative angle between the two generated showers as a function of the total deposited energy inside the detector. For the sake of clearness and completeness, the two projections of that bi–dimensional plot are also drawn in Figs. 4 and 5. Because of the geometry of the detector, the relative angle distribution presents a deep minimum around 60–80 degrees between two large bumps at small and large relative angles. At small relative angles, the deposited energy is related to those muons traversing the detector modules along their short side, while at large relative angles the deposited energy refers to those muons crossing the detector modules along its long side. This is also clearly visible in Fig. 6, where the spectrum of the deposited energy inside one module of a muon traversing two mutually opposed detectors ($\theta_{12} > 175°$) is reported. As expected (each detector is 20 cm long and the specific energy loss of cosmic muons in barium fluoride is about 6.6 MeV·cm^{-1} [10,22]), the peak is centered around 130–140 MeV of photon–equivalent energy.

Figure 7 shows the invariant mass distribution of the two showers originated by the simulated cosmic muons inside the BaF_2 ball. Apart from the steep descent of the spectrum below 60 MeV, which is simply due to the experimental limitations in the two–photon energy and relative detection angle, it is worth noting that the "cosmic" invariant mass distribution includes the region of the π^0 rest mass ($m_{\pi^0}c^2 \simeq 135$ MeV). This unequivocally demonstrates that the cosmic radiation may represent a background in neutral pion production experiments as will be discussed in the next subsection.

B. Comparison with experimental data

In order to compare the results of the simulations with the experimental data, we have taken into account only the pairs of high–energy photons detected in those events, relative to the ^{27}Al(^{36}Ar,2γ) and ^{27}Al(^{36}Ar,π^0) reactions at 95 MeV/nucleon, having a total charged particle multiplicity strictly equal to zero ($\nu = 0$), namely any charged particle neither in the whole MEDEA multidetector (BaF_2 ball + Phoswich wall) nor in a hodoscope of plastic scintillators which was added to cover the polar angles from $\theta = 2.5°$ to $\theta = 10°$. Owing (i) to the large coverage of the total solid angle (nearly 90% of 4π), and (ii) to the fact that neutral pions as well as hard photons are mainly produced in central collisions [2,19,21], the previous $\nu = 0$ condition reasonably select real cosmic–ray events producing two showers inside the detector. The reliability of this assumption is clearly demonstrated by Fig. 8, where the relative angle distribution, as a function of the total energy of the two showers, is reported for simulated events (left panel) and experimental ones satisfying the $\nu = 0$ condition (right panel). In order to keep the comparison as homogeneous as possible, a number of simulated events equal to that of experimental ones has been considered. Within the statistics, the overall agreement is rather good. This is not true, on the contrary, for

$\nu > 0$ events which are reported in the two panels of Fig. 9 (also in this case the two contour plots are relative to the same number of events). Although the small–relative–angle contribution is absent in the experimental distribution, the large–relative–angle one is well reproduced by the simulations both in shape and intensity confirming that cosmic rays are, in principle, an important source of noise which has to be carefully considered in neutral pion production and/or two–photon correlation experiments.

Neutral pions have been recorded in the BaF_2 ball of the MEDEA multidetector through the usual simultaneous detection of the pair of photons coming from their main decay mode. These pairs of photons have been identified, among all two–γ events selected by the analysis trigger, by imposing severe conditions on the experimental distributions of their relative angle, θ_{12}, and invariant mass, m_{inv}, as functions of their total energy, $E_1 + E_2$ (see Fig. 10, upper and lower panel, respectively) [7]. The graphical cuts reported in Fig. 8 select those photons coming from π^0 decay and derive from the results of full GEANT3 simulations where neutral pions, generated with a realistic phase–space distribution, have been filtered through the BaF_2 ball of the MEDEA multidetector [7]. It is worth noting that pions belong to the large–relative–angle part of the distribution shown in Fig. 9.

Fig. 11 shows the comparison between the invariant mass distribution of pions detected in $\nu = 0$ events (points) and that (histogram) of the two simulated–muon–induced showers (the two spectra are normalized each other at the neutral–pion–mass channel). In order to have a homogeneous comparison, we have reported here only those two–shower simulated events staying inside the contours reported in Fig. 10 and those pions whose decay photons have, both, an energy larger than 30 MeV. The resemblance of the two distributions is quite impressive. Furthermore, both look different from the invariant mass distribution relative to pions detected in those events having a total charged particle multiplicity greater than zero, which is reported in Fig. 12.

Starting from the energies (E_1 and E_2) and detection angles (θ_1 and θ_2) of the two decay photons, it is straightforward to calculate the kinetic energy (E_{π^0}) and the polar emission angle (θ_{π^0}) of the neutral pion ($c = 1$):

$$E_{\pi^0} = \sqrt{\frac{2m_{\pi^0}^2}{(1-\cos\theta_{12})(1-X^2)}} - m_{\pi^0} \qquad (1)$$

where

$$X = \frac{E_1 - E_2}{E_1 + E_2} \tag{2}$$

and

$$\cos\theta_{\pi^0} = \frac{E_1 \cos\theta_1 + E_2 \cos\theta_2}{\sqrt{E_1^2 + E_2^2 + 2E_1E_2\cos\theta_{12}}} \tag{3}$$

Figs. 13 and 14 show the energy and polar angular distributions, respectively, of π^0's detected in $\nu = 0$ events with $E_1 > 30$ MeV and $E_2 > 30$ MeV. In both figures, histograms are relative to simulated data where the two muon–induced showers have been treated as coming from the decay of a neutral pion. The relative normalizations have been chosen only to compare the shapes of the spectra. Also in this case, the shapes of the energy spectrum and angular distribution are very different from those of the same distributions relative to $\nu > 0$ events which are reported in Figs. 15 and 16 with (lower panels) and without (upper panels) efficiency correction. This allows to conclude that all physical–observable distributions related to those pions detected in $\nu = 0$ events can be accounted for the interaction of cosmic radiation with the multidetector.

The same evidence is also visible in high–energy $\gamma - \gamma$ events. Fig. 17 shows, as an example, the comparison between the relative angle distribution of the two photons emitted in the ^{27}Al(^{36}Ar,2γ) reaction at 95 MeV/nucleon with $\nu = 0$ (points) and that obtained with the two showers originated by the simulated cosmic muons (histogram). All pairs of photons, both experimental and simulated, stay outside the contours reported in Fig. 10 and the two spectra have been normalized each other to their maxima. The agreement of the shapes is good up to $\theta_{12} = 60°$–$80°$. For larger values of the relative angle, simulated data exhibit a stronger contribution than experimental ones due to the different effects of the geometrical limitations of the detector and of the cuts selecting neutral pions on the different primary relative–angle distribution of the two showers induced by a cosmic muon, on one side, and on that of the two correlated photons coming from the target, on the other side.

C. Methods of reduction of cosmic background

So far, the cosmic radiation induced background has been studied only from a qualitative point of view. In order to give a quantitative estimation of the importance of this spurious contribution let us consider, again, the geometry of the BaF_2 ball of MEDEA. This detector covers, between the polar angles $\theta = 30°$ and $\theta = 140°$, the complete azimuthal dynamics subtending a total solid angle of 10.25 sr over an useful surface of 0.55 m^2. Taking into account the absolute cosmic ray intensity at sea level [14,16] (without the correction due to the geomagnetic latitude of the experimental site), it is straightforward to calculate a value of the total expected cosmic rate of about 200–250 Hz. Considering that, because of the time resolution of the BaF_2 modules, all photons coming from the target are generally gathered in about 2 ns, over realistic total coincidence windows of about 80–100 ns, the expected cosmic rate under the "photon–peak" is 4–5 Hz. Taking also into account that the probability of a cosmic muon to be detected as two distinct showers, each having an energy larger than 30 MeV, is about 25% on the average, the final rate of the real cosmic background in the processes under study is about 1–2 Hz. This number is of the same order of the measured rate of 150–MeV photons from the $^{36}Ar+^{27}Al$ reaction at 95 MeV/nucleon (with a beam current of about 2 nA and a target thickness of 1.6 mg/cm^2) [7] and can also be compared with 1.8 π^0 per second [7] and about $2 \cdot 10^{-2}$ $\gamma - \gamma$ events per second ($E_{\gamma_1}, E_{\gamma_2} > 30$ MeV) [5] detected from the same reaction.

In principle, the subtraction of the cosmic–ray induced background in photon or neutral pion detection is possible in two different ways. If one is only interested in the integral representation of physical observables, such as energy spectra and/or angular distributions, it is enough to acquire data with the same trigger condition used during the run but without beam, or, better, to move the time window to encompass an equivalent region of the spectrum below the prompt "photon–peak" and analyze these data with the same conditions. Then (if, in the first case, the correct normalization factor due to the eventually different run times is known) real spectra and spurious ones can be easily subtracted channel by channel. This method has been successfully used, as an example, in Ref. [11] to extract the correct slope parameter of the inclusive photon energy distribution.

If one is, vice versa, working on global variables or on the analysis of correlation observables, the subtraction of the cosmic noise must be done on an event–by–event basis and this aim is much more complicated to attain due to the fact that, in general, the detector response to cosmic rays is very much similar from that relative to high–energy photons. Some work in this field has been recently made by the TAPS collaboration [12] who has used a combined condition on the shower multiplicity and on a specific variable called linearity (related to the deposited energy on the surface of a detector block) to select high–energy–photon events from cosmic background. Due to the fact that MEDEA covers a much larger fraction of the total solid angle and that we are mainly interested in central collisions, in this subsection we explore the possibility that the effects of the interaction of cosmic rays with the detector can be strongly reduced, without perturbing the physical information, by imposing simple conditions on the charged particle multiplicity. The conclusion of the last subsection is that the events with $\nu = 0$ are essentially due to cosmic rays. Now, let us demonstrate that cosmic contamination in those events having $\nu > 0$ is practically negligible. In fact, unlike normal plastic scintillators, barium fluoride detectors exhibit typical recovery times in the order of 1 μs. Thus, in order to avoid undesired pile–up effects, the beam currents are usually limited to have not more than 10^4 reactions per second. This means that, if one works with a typical total coincidence window of about 100 ns, only one beam pulse over 10^3 contains a physical reaction. Considering also the dead time of the data acquisition system, the expected cosmic rate in the BaF_2 ball, after imposing the $\nu > 0$ condition, decreases to about $3 \cdot 10^{-4}$ Hz. The cosmic–radiation induced background is, then, essentially related to $\nu = 0$ events. This fact, hence, gives a method to make a quantitative estimation of the cosmic noise, simply calculating the ratio $N^{ev}_{\nu=0}/N^{ev}_{\nu\geq 0}$. In the ^{27}Al(^{36}Ar,π^0) reaction at 95 MeV/nucleon, for example, the percentage of the cosmic–ray contamination was 2.3 ± 0.1 without imposing the $\nu > 0$ condition. An exact numeric evaluation of the cosmic background in photon–photon correlation measurements is much more complicated and can not be made in such a simple way. This is due to the fact that, as it has been shown in Ref. [5], the set of two–photon events standing outside the contours shown in Fig. 10 mainly contains those spurious pairs of photons coming from "badly" detected pions. The result of the comparison of the full

GEANT3 simulations reported in Ref. [4] with the experimental data of Ref. [5] allows to conclude that the percentage of cosmic ray contamination in the ^{27}Al(^{36}Ar,2γ) reaction at 95 MeV/nucleon, after imposing the $\nu > 0$ condition, was about $2 \cdot 10^{-2}$ with a statistical error of 50%.

V. SUMMARY AND CONCLUSIONS

The problem of cosmic–radiation induced background in neutral pion production and high–energy photon–photon correlation measurements with the MEDEA multidetector has been investigated. Cosmic muons have been generated in accordance with their known spatial distribution and their interaction with the experimental filter has been carried out by full GEANT3 simulations. The response of the multidetector to cosmic radiation originating two separate high–energy electromagnetic showers has been studied and the results of the simulations have been compared with experimental data coming from the ^{36}Ar+^{27}Al reaction at 95 MeV/nucleon. Almost all π^0 and $\gamma - \gamma$ events recorded in coincidence with zero charged–particle multiplicity can be successfully interpreted as due to cosmic rays. This evidence has allowed, at the same time, a quantitative evaluation of the cosmic–ray induced noise in these kinds of events and the definition of an analysis method to strongly reduce cosmic background on an event–by–event basis.

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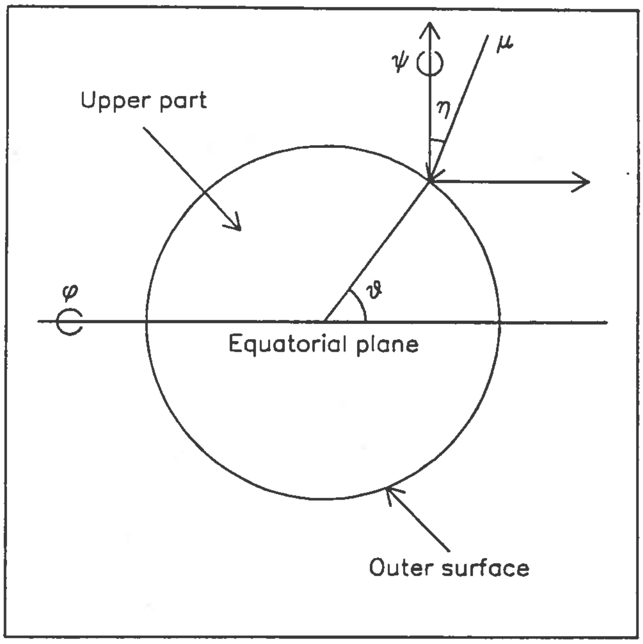

FIG. 1. Schematic view of the reference system chosen for the generation of the "simulation vertex" in GEANT3 (see text). The generic detector has been assumed to be spherically symmetric.

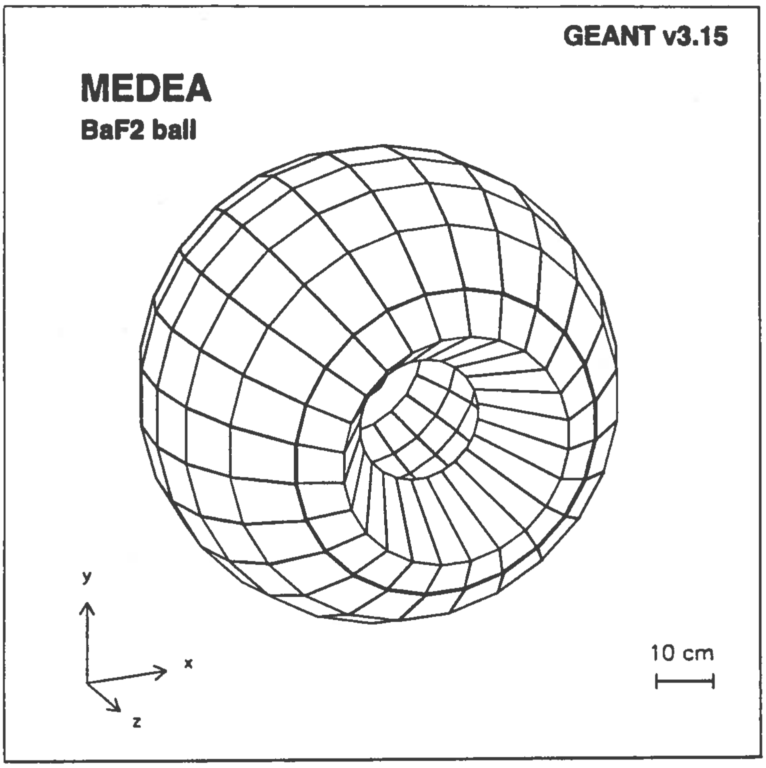

FIG. 2. Perspective view of the geometry of the BaF_2 ball of the MEDEA multidetector as defined in GEANT3.

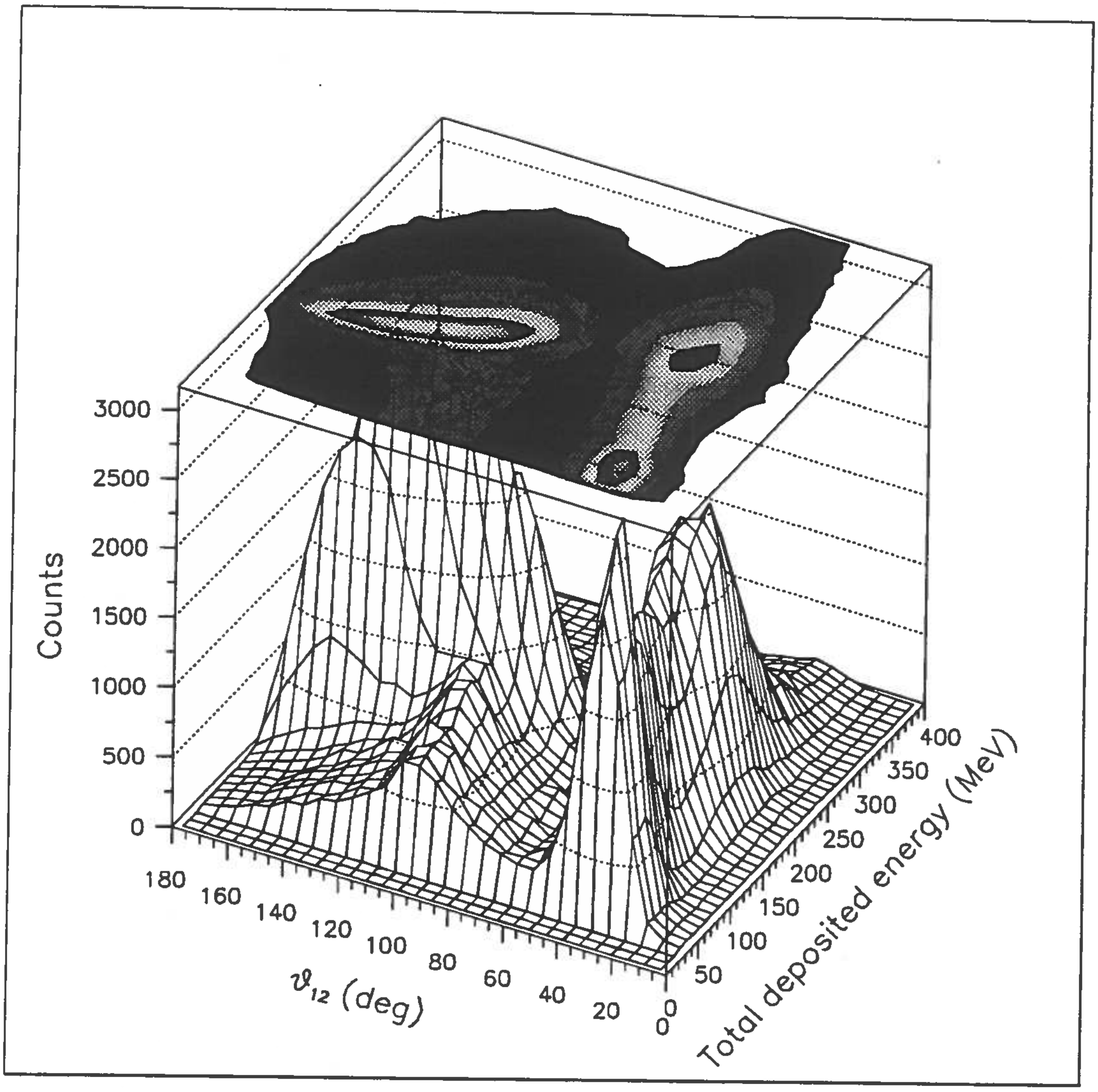

FIG. 3. Relative angle versus total deposited energy distribution of the pairs of showers generated inside the BaF_2 ball by the simulated cosmic rays.

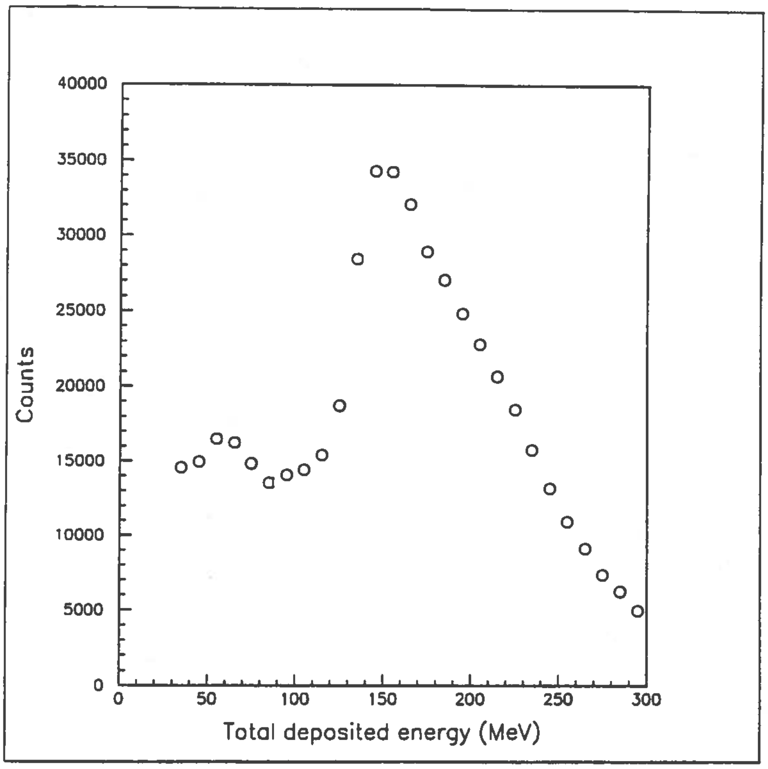

FIG. 4. Total deposited energy distribution of the pairs of showers generated inside the BaF_2 ball by the simulated cosmic rays.

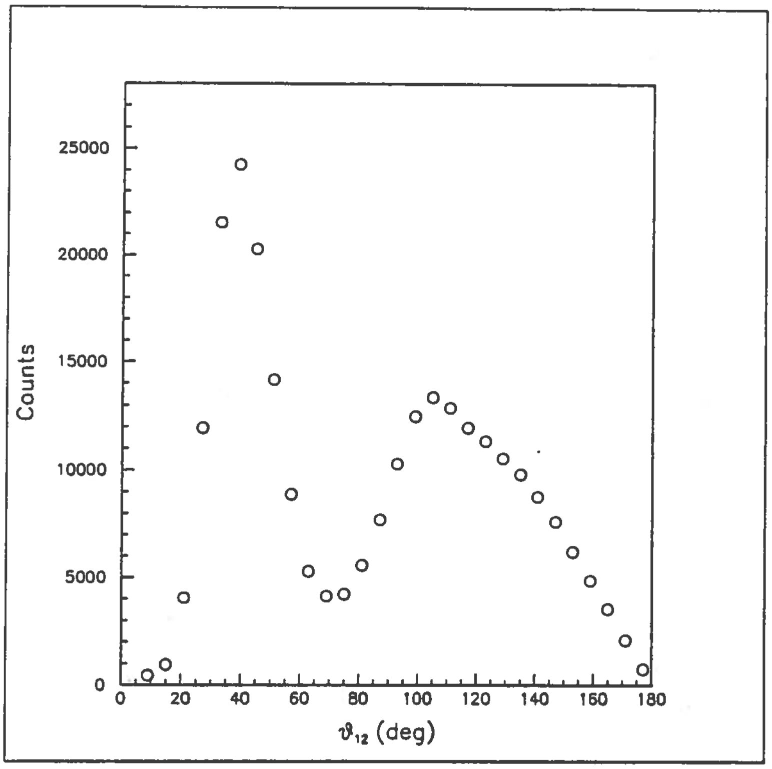

FIG. 5. Relative angle distribution of the pairs of showers generated inside the BaF_2 ball by the simulated cosmic rays.

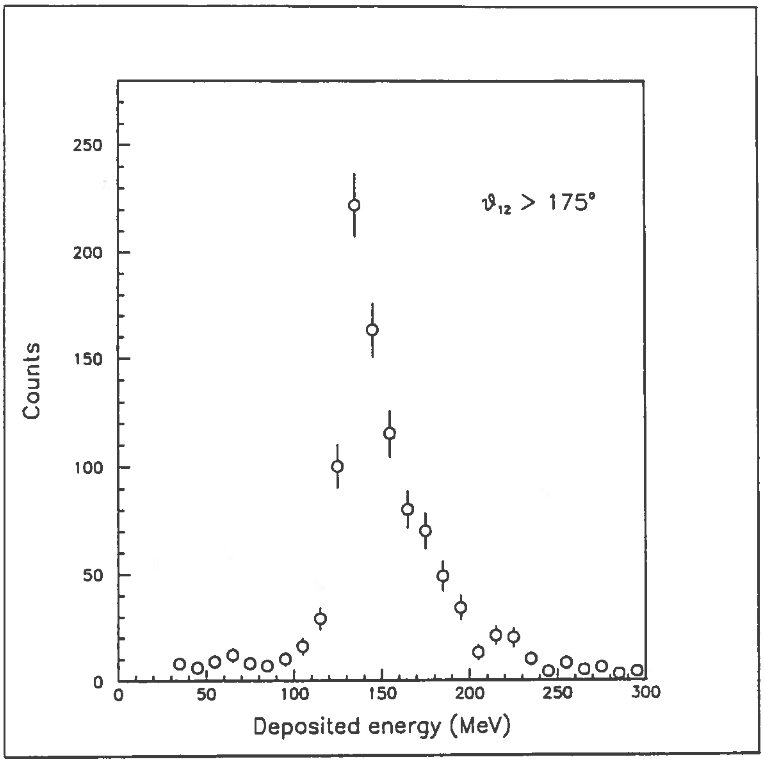

FIG. 6. Deposited energy distribution of cosmic muons traversing two detector modules mutually opposed ($\theta_{12} > 175°$).

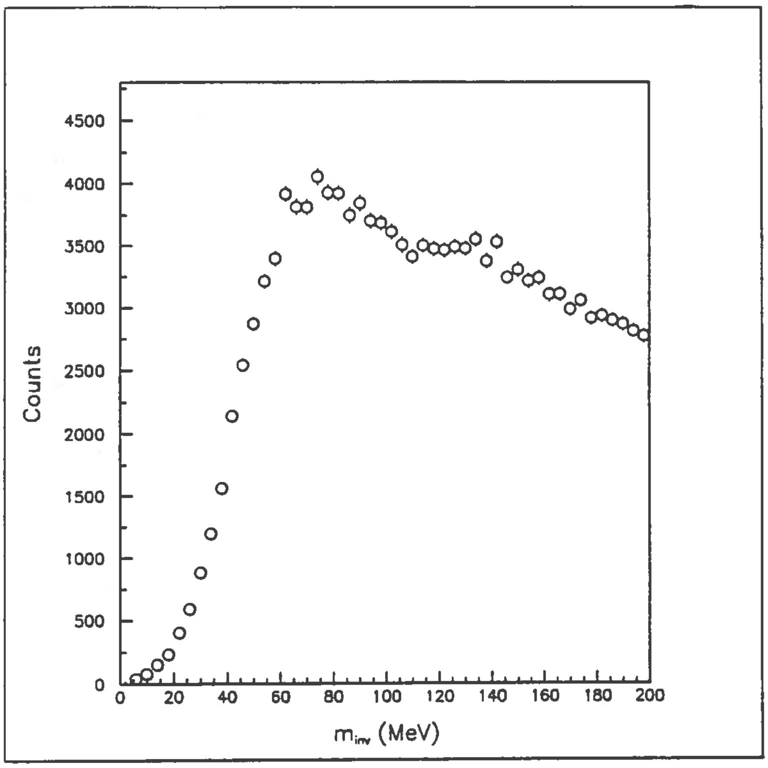

FIG. 7. Invariant mass distribution of the two showers originated by the simulated cosmic muons inside the BaF_2 ball the MEDEA multidetector.

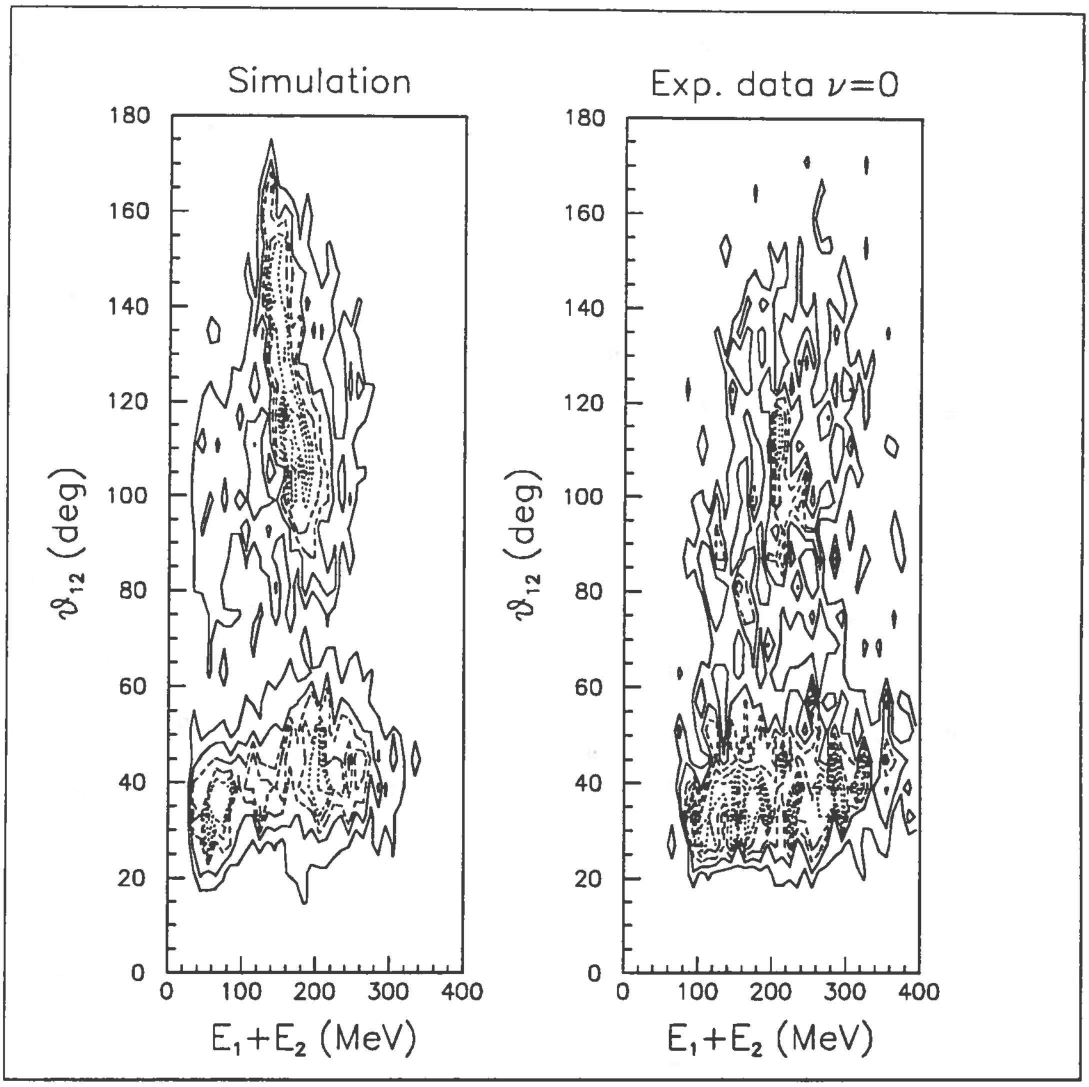

FIG. 8. Relative angle distribution as a function of the total energy of the two showers. Left panel is relative to simulated events, while the right one is relative to the pairs of photons detected in the $^{36}Ar+^{27}Al$ reaction at 95 MeV/nucleon with the $\nu = 0$ condition.

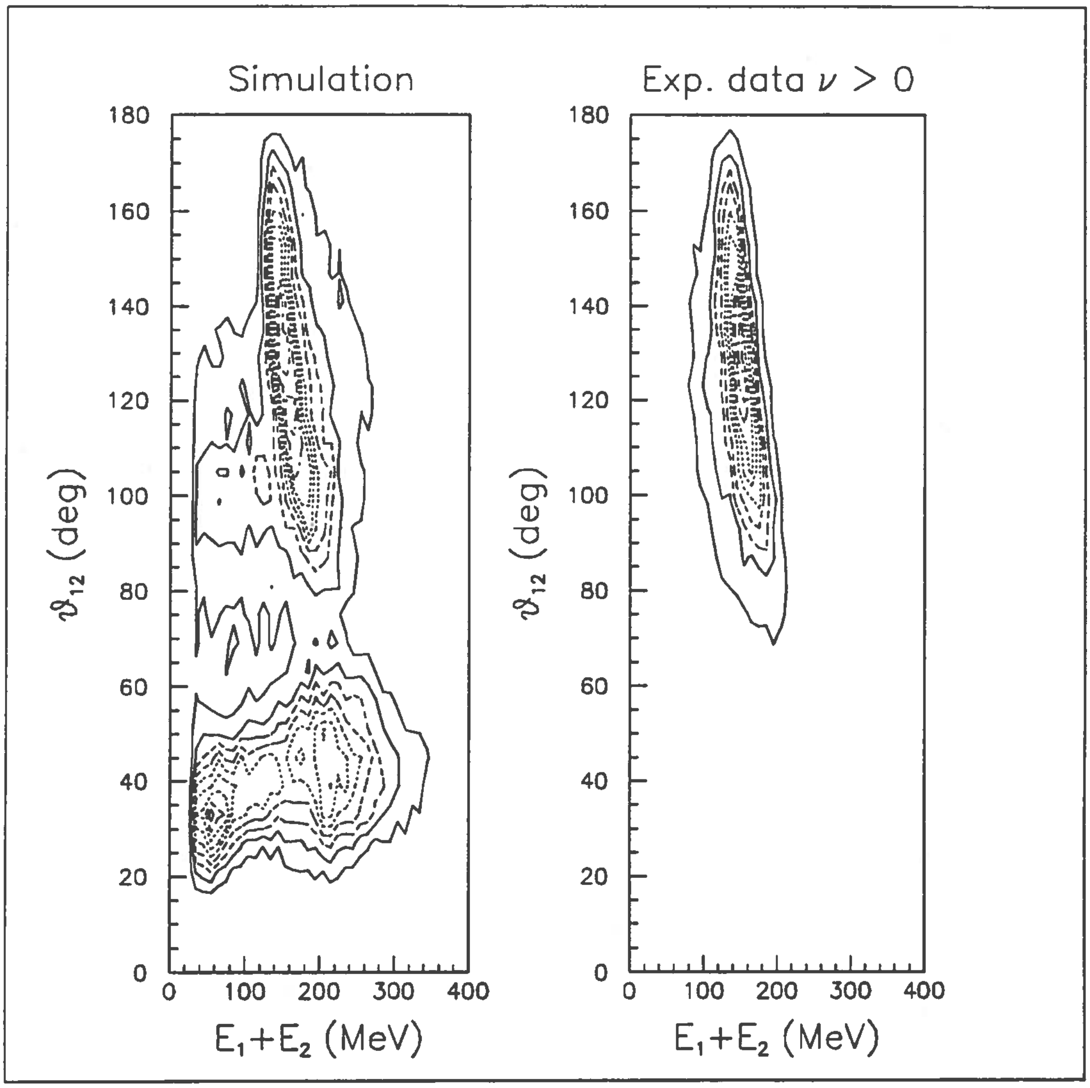

FIG. 9. Relative angle distribution as a function of the total energy of the two showers. Left panel is relative to simulated events, while the right one is relative to the pairs of photons detected in the $^{36}Ar+^{27}Al$ reaction at 95 MeV/nucleon with the $\nu > 0$ condition.

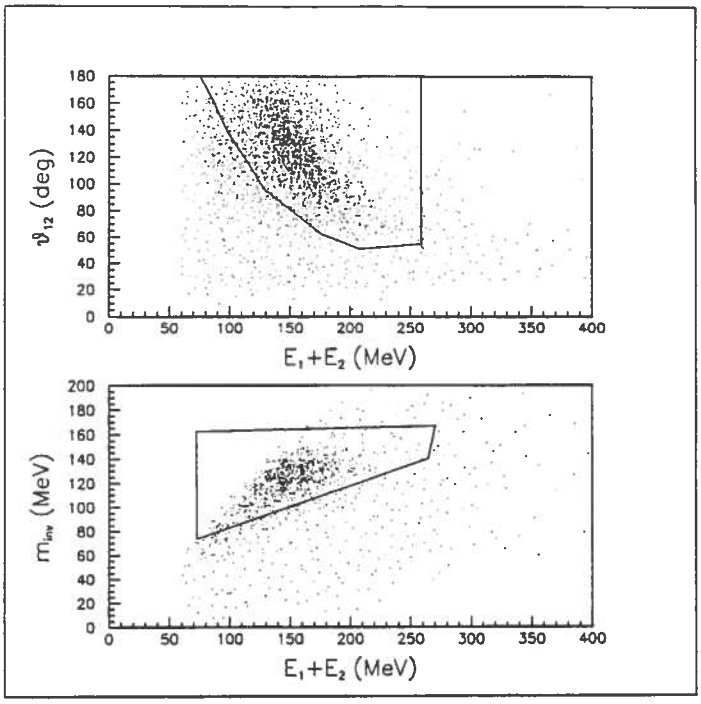

FIG. 10. Relative angle (upper panel) and invariant mass (lower panel) versus total energy distributions of the pairs of photons detected in the reaction $^{36}Ar+^{27}Al$ at 95 MeV/nucleon. In both plots, the contours define those pairs of photons coming from π^0 decay.

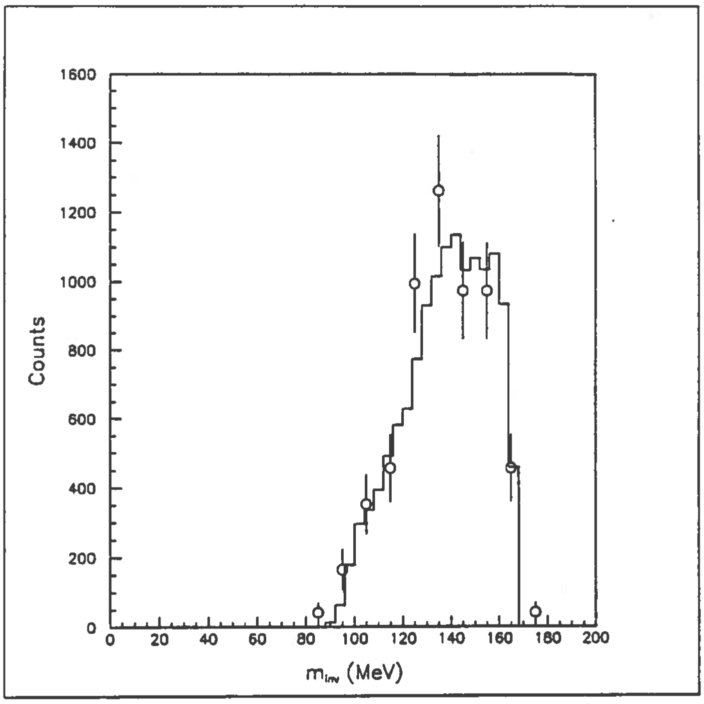

FIG. 11. Comparison between the invariant mass distribution of pions detected in $\nu = 0$ events (points) and that of the two simulated–muon–induced showers (histogram). The two spectra are normalized each other at the neutral–pion–mass channel.

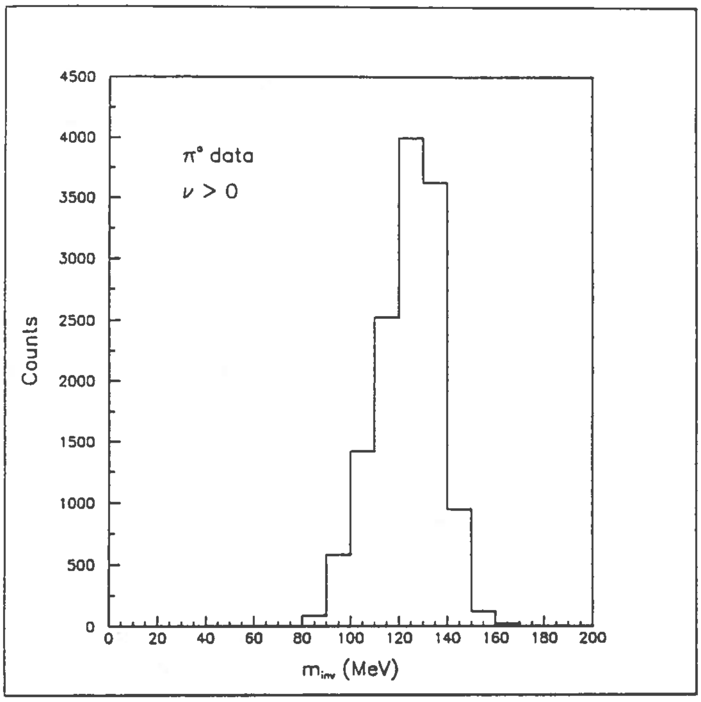

FIG. 12. Invariant mass distribution relative to pions detected in those events having a total charged particle multiplicity greater than zero.

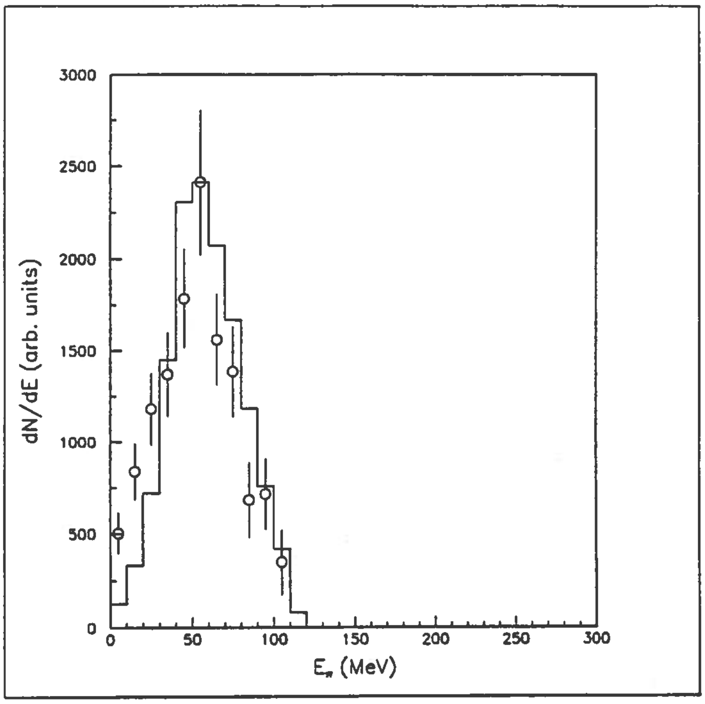

FIG. 13. Comparison between the experimental energy distribution of π^0's detected in $\nu = 0$ events (points) and that relative to simulated data (histogram) where the two muon–induced showers have been treated as coming from the decay of a neutral pion. The relative normalization has been chosen only to compare the shape of the spectra.

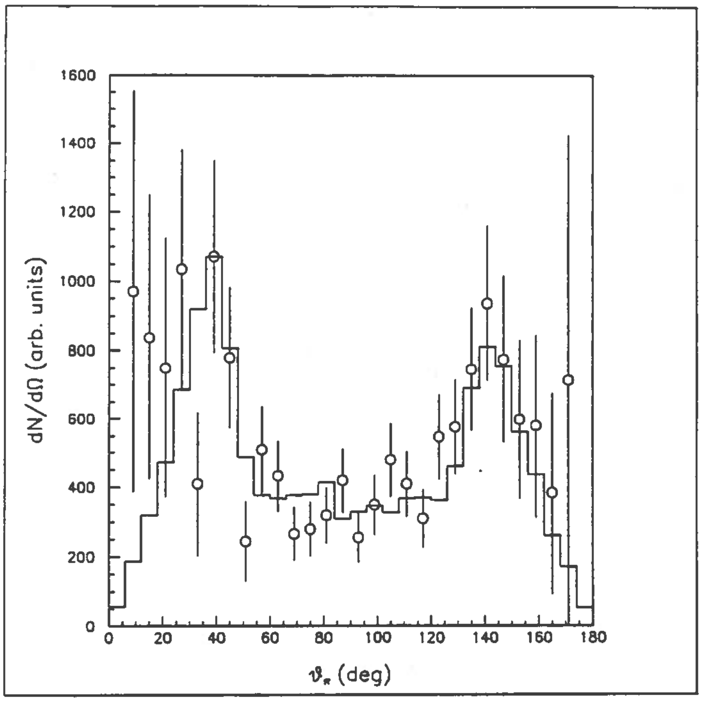

FIG. 14. Comparison between the experimental polar angle distribution of π^0's detected in $\nu = 0$ events (points) and that relative to simulated data (histogram) where the two muon–induced showers have been treated as coming from the decay of a neutral pion. The relative normalization has been chosen only to compare the shape of the spectra.

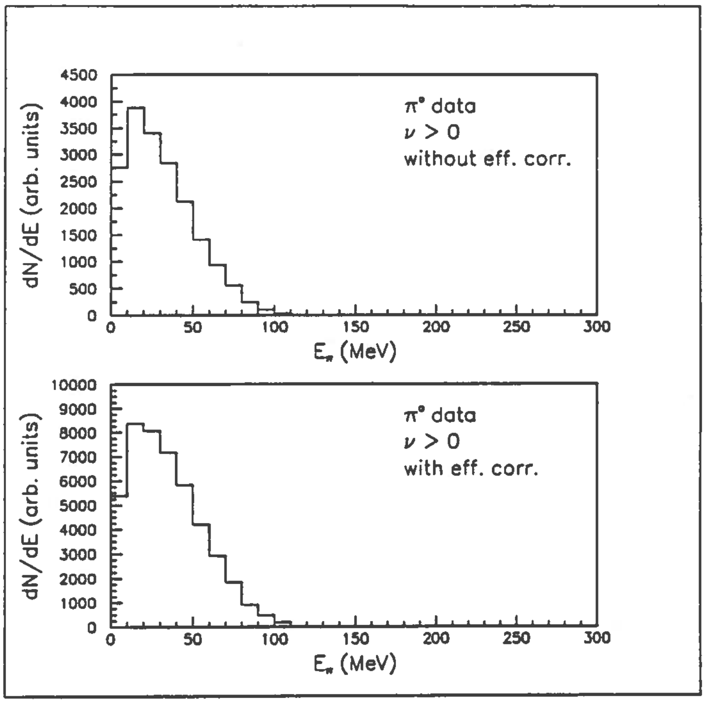

FIG. 15. Experimental energy distribution of π^0's detected in $\nu > 0$ events with (lower panel) and without (upper panel) efficiency correction.

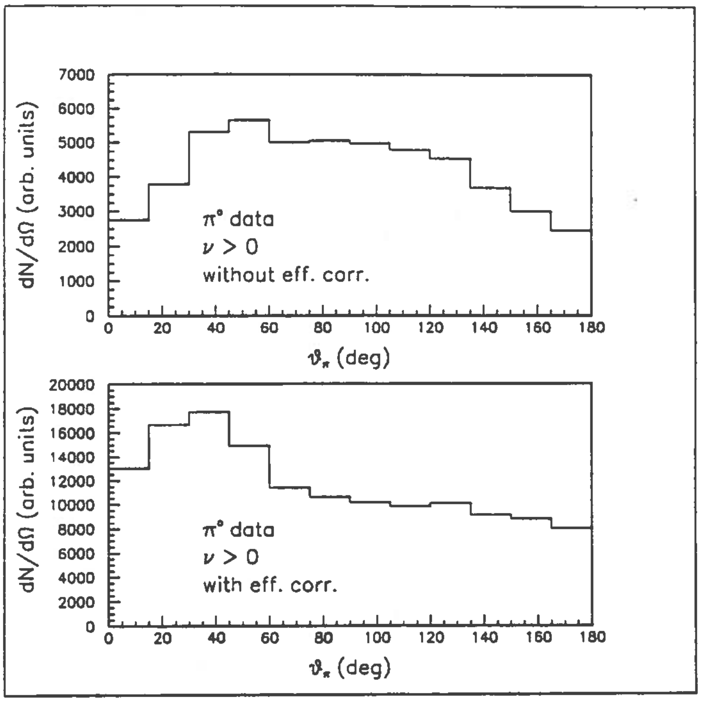

FIG. 16. Experimental angular distribution of π^0's detected in $\nu > 0$ events with (lower panel) and without (upper panel) efficiency correction.

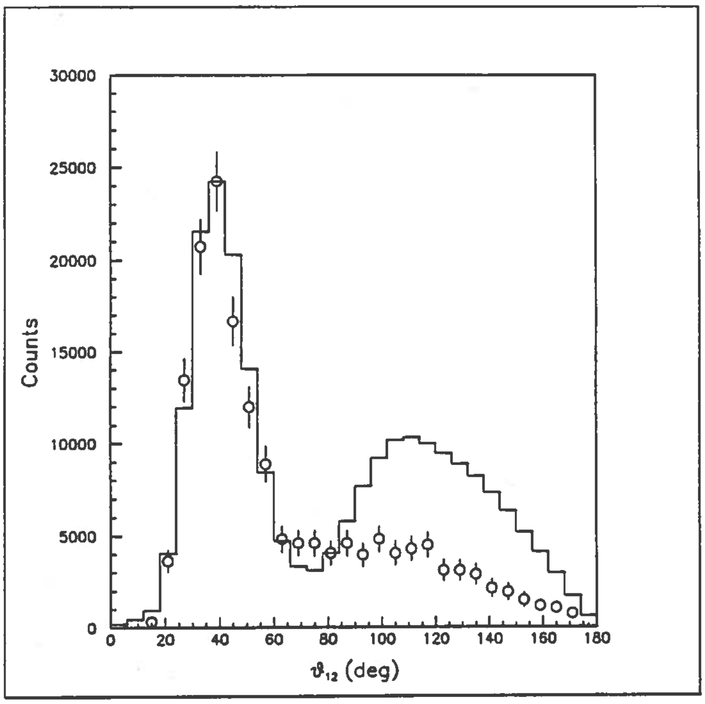

FIG. 17. Comparison between the relative angle distribution of the two photons emitted in the ^{27}Al(^{36}Ar,2γ) reaction at 95 MeV/nucleon with $\nu = 0$ (points) and that of the two showers originated by the simulated cosmic muons (histogram).