[Journal of the Arkansas Academy of Science](http://scholarworks.uark.edu/jaas)

Volume 49 Article 27

1995

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Abstract

A scintillating optical fiber calorimeter (SOFCAL) is being developed by NASA/Marshall Space Flight Center for use in balloon-borne experiments to study the spectrum of high-energy cosmic rays and gamma rays. SOFCAL will not saturate for long exposures and the calorimeter will be useful in emulsion chambers to study primary cosmic-ray nuclei with energies from 100 GeV to 1,000 TeV. The event generator FRITIOF was used to model the collision of a cosmic-ray projectile with a target nucleus in an emulsion chamber. The measurements of charged particles from the interaction in the emulsions are related to the energy of the primary cosmic ray nucleus-nucleus interaction, computer simulations of electromagnetic cascades allow computation of the energy ΣE_γ deposited in different regions of the calorimeter. The Monte Carlo program GEANT was used to model SOFCAL response to incident gamma rays and to compute the measure of energy deposition ΣE_γ in different layers of the calorimeter within the emulsion chamber. The partial coefficient of inelasticity k_γ, defined by $\Sigma E_\gamma = k_\gamma E_0$, was computed for different energies E_0 of primary cosmic rays. The k_γ-distributions were computed and compared with existing calorimeter data. Funding was provided by the NASA/University Joint Venture (JOVE) Program.

Introduction

Cosmic rays are now known to span the energy range from 10^9 to beyond 10^{20} eV (Asakimori et al., 1993a; Asakimori et al., 1993b; Swordy, 1994; Teshima, 1994). They are, predominantly, the nuclei of atoms from hydrogen to iron. Above 10^{14} eV the particles are so rare that their detection relies mainly on observations of the giant cascades or extensive air showers created in the atmosphere which may be observed with arrays of particle and optical detectors at ground level. The flux of particles decreases inversely as the square of the energy rises, up to 10^{19} eV, and continues to decrease above 10^{19} eV as only about one particle per km_2 per year is collected (Watson, 1994). The origin of these particles is unknown and how they are accelerated to such high energies is a major astrophysical puzzle (Bird et al., 1993).

Even though the flux of the primary cosmic rays is so low that small detectors in spacecraft or balloons can intercept only a small number for study, emulsion chambers are an important tool for the direct measurement of the composition and spectra of primary cosmic rays above 10^{12} eV/nucleus (Parnell et al., 1989). The emulsion chamber method (Burnett et al., 1986) is especially useful for ultrahigh energy cosmic ray observations because (1) the efficiency for detecting interactions approaches 100% above about 10 TeV and (2) the energy resolution is approximately constant with energy for a given incident species. Most other energy measuring techniques are impractical for balloon observations of primary cosmic rays at such high energies.

Balloon-borne emulsion chambers employing calorimeters (Fig. 1) have been used for direct measurements of cosmic-ray composition (protons through Fe) between 10^{12} and 10^{15} eV (Kaplon et al., 1952; Minakawa et al., 1958; Niu et al., 1971; Burnett et al., 1986; Takahashi et al., 1986; Burnett et al., 1987; Parnell et al., 1989; Burnett et al., 1990; Asakimori et al., 1933a; Asakimori et al., 1993b). The typical emulsion chamber (Burnett et al., 1986) is composed of four parts: (1) a charge-determination module, (2) a target module with ≈0.2 vertical interaction mean free paths for protons, (3) a spacer module, and (4) an emulsion calorimeter module with about fourteen vertical radiation lengths.

The "target section"includes many layers of nuclear emulsion plates to measure the charge of the incident particle and the emission angles of the produced charged particles with high accuracy (0.01 mrad). The "calorimeter section" includes layers of nuclear emulsion and X-ray film among lead plates to measure the electron distributions from the electromagnetic cascades initiated by gamma rays from π^0 decay. The calorimeter is used to measure the spectrum of energy deposition $\sum E_\gamma$ from which the primary energy E_0 spectrum is derived (Burnett el al., 1986). The SOFCAL simulations (Yang et al., 1994) described here are for a scintillation optical fiber counterpart to the calorimeter section in the emulsion chamber.

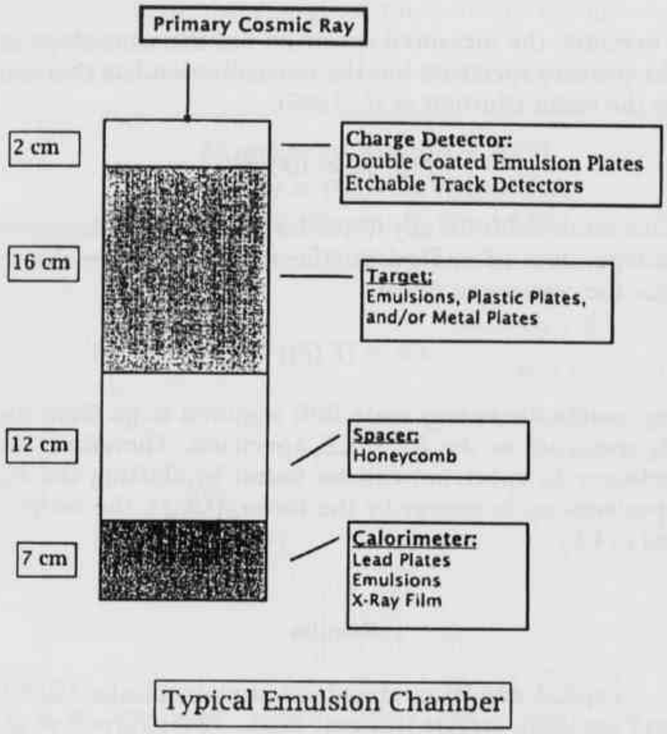

Fig. 1. Block diagram of an emulsion chamber (Parnell et al., 1989).

Methods

That part of the primary energy going into gamm-rays $\sum E_\gamma$ is the parameter most easily related to the primary cosmic ray spectrum in emulsion chamber experiments. The photons originating from a primary interaction will develop individual electromagnetic cascades in the calorimeter. The ability to measure the energies of these electron-photon cascades is one of the most important functions of the calorimeter. In the initial simulations, a calorimeter module with ten vertical radiation lengths of Pb was used. In one geometrical configuration each subsection of the calorimeter consisted of a 4-mm lead block, 100 fibers (0.5-mm thick) in the x-direction and 100 fibers (0.5-mm thick) in the y-direction. This lead and optical fiber combination was repeated fourteen times.

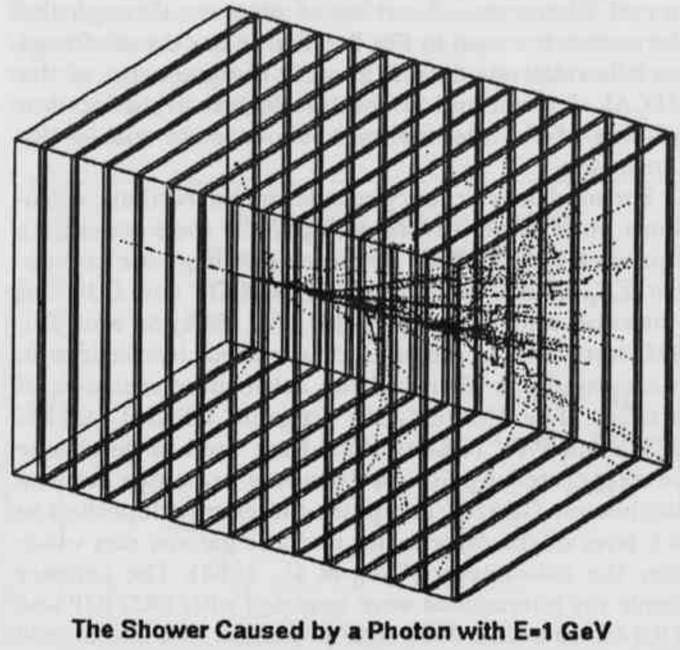

Fig. 2. The trajectories of a photon event with 1 GeV energy in the calorimeter SOFCAL. The cascade was modeled with GEANT and PAW for the graphic simulation.

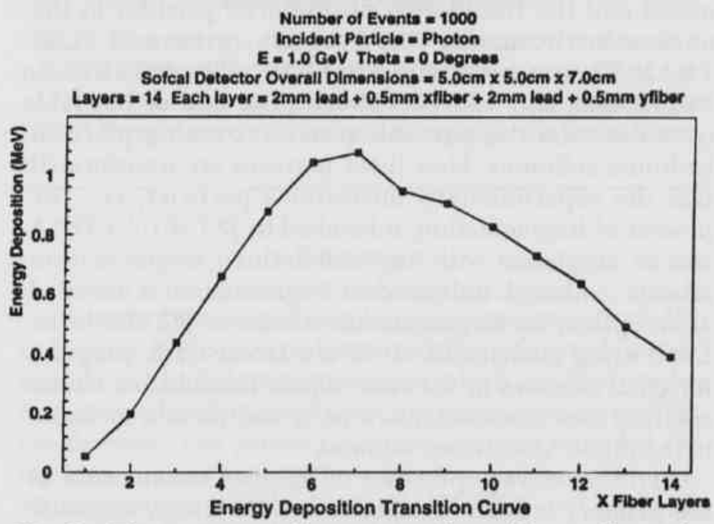

Fig. 3. The corresponding energy deposition and transition curve for 1 GeV photons incident on the calorimeter SOFCAL.

The trajectories or cascade of electrons and photons produced by a gamma ray with an incident energy of 1 GeV is illustrated in Fig. 2. For these simulations with

GEANT, the incident gamma ray lies along the z-axis which is normal to the plane of each lead plate and layer of fibers. The corresponding energy deposited in each x-layer of fibers, as a function of distance through the calorimeter, is shown in Fig. 3. GEANT has the advantage that it is relatively easy to modify the geometry of the SOFCAL detector and to observe changes in the location and size of the electromagnetic cascade within the calorimeter.

For modeling primary cosmic ray interactions, calculations must be performed with particle event generators to predict distributions in the electromagnetic component ΣE_γ. The event generator FRITIOF and LUCIAE (Sjöstrand and Begtsson, 1987; Pi, 1992; Sa and Tai, 1994) were used to model nucleus-nucleus interactions in an emulsion chamber and the subsequent emission of particles. The Monte Carlo program GEANT (CERN 1992a) and PAW (CERN 1992b) are used to determine the associated optimum "window" settings for the calorimeter. GEANT computes the energy deposited in each layer of the calorimeter by those gamma rays which enter the calorimeter (Yang et al., 1994). The primary cosmic ray interactions were modeled with FRITIOF and LUCIAE on a DEC 3000 AXP processor. The photon and electron events in the Scintillating Optical Fiber Calorimeter (SOFCAL) were modeled with GEANT version 3.21 on DEC 5000 workstations.

The event generator program included LUCIAE 2.0 for simulating gluon emission in the FIRECRACKER model and the rescattering of produced particles in the nuclear environment. The program, written in FORTRAN 77, was used with FRITIOF7.02R, JETSET7.3, PYTHIA5.5, and ARIADNE4.02R. The task of PYTHIA is to describe the partonic processes taking place in hadronic collisions. How these partrons are transformed into the experimentally measurable particles, i.e., the process of fragmentation, is handled by JETSET. PYTHIA can be combined with any well-defined fragmentation scheme. Although independent fragmentation is included as an option, the fragmentation scheme of JETSET is the Lund string model. ARIADNE is a Monte Carlo program for QCD cascades in the color dipole formulation. Gluon splitting into quark-antiquark paris and photon emission in the dipole cascade are allowed.

The measured spectrum of ΣE_γ is a convolution of the primary cosmic ray spectrum with energy response function of the detector. The latter depends on the distribution of partial inelasticity k_γ. There is a unique relation or simple scale shift between the ΣE_γ spectrum and the corresponding primary spectrum (Parnell et al., 1989), as long as the spectral index and the characteristics of the interactions do not change substantially over the observed energy range. When the differential primary (E_0) spectrum of a cosmic ray species is given by the simple power law relation

$$g(E_0)\mathrm{d}E_0 = I_0 E_{0\text{-}\beta\text{-}1}\ \mathrm{d}E_0,$$

the differential spectrum (E_m) measured by an emulsion chamber is given by

$$G(E_m)\mathrm{d}E_m = F(\beta)\, I_0 E_{m\text{-}\beta\text{-}1}\ \mathrm{d}E_m.$$

Therefore, the measured spectrum has the same slope as the primary spectrum but the normalization has changed by the factor (Burnett et al., 1986)

$$F(\beta) = \int_0^1 k^\beta\, f(k)\mathrm{d}k$$

This result holds for any f(k) as long as that distribution is independent of energy. Furthermore, it can be shown that the conversion factor

$$\mathrm{C}k_\gamma = \{\mathrm{F}(\beta)\}^{1/\beta}$$

represents the energy scale shift required to go from the E_0 spectrum to the $E_m = \Sigma E_\gamma$ spectrum. Therefore, the primary E_0 spectrum can be found by shifting the E_m spectrum up in energy by the factor, $[\mathrm{C}k_\gamma]^{-1}$, the reciprocal of $\mathrm{C}k_\gamma$

Results

Typical emulsion chambers contain plastic (CHO) and emulsion targets (Burnett et al., 1987; Parnell et al., 1989). The composition of CHO was 33% C, 53% H, 14% O. The composition of emulsion was 17.5% C, 40.7% H, 4.0% N, 12.0% O, 0.17% S, 12.7% Br, 12.8% Ag, and 0.07% I. The main absorber material in a typical calorimeter is lead, which is used to improve energy resolution. Therefore, a light target nucleus (C) and a heavier target nucleus (Ag) were used in modeling the interaction of cosmic ray particles within the emulsion chamber. For a proton, nitrogen, and iron nucleus incident on a fixed target carbon nucleus, the distribution of gamma rays produced by an incoming projectile with an incident energy of 1000 GeV/nucleon is shown in Fig. 4. For these primary cosmic rays incident on a fixed target silver nucleus, the distribution of gamma rays produced by an incoming projectile with an incident energy of 1000 GeV/nucleon is shown in Fig. 5. Each distribution was based on 2000 events.

In a calorimeter the maximum electron number in an electromagnetic cascade can be related to the total energy of the electromagnetic component ΣE_γ. This quantity is directly proportional to the energy E_0 of the original cosmic ray: $\Sigma E_\gamma = k_\gamma E_0$. The factor k_γ is the partial coefficient of inelasticity, which represents that fraction of the energy of the primary cosmic ray used to create the γ-rays. It is a function of the mass number of both the primary nucleus and the target nucleus (Burnett et al., 1986). Once the target nucleus and the primary cosmic ray have been identified in an emulsion layer of the apparatus, the distribution of k_γ becomes a known quantity. This distribution and the energy of the electromagnetic cascade are used to estimate the energy of the primary cosmic ray (Parnell et al., 1989).

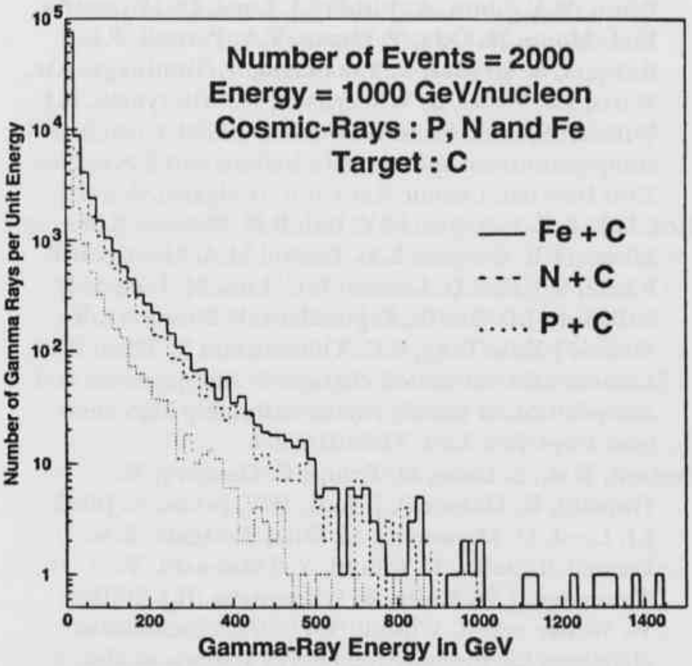

Fig. 4. The energy distribution of gamma rays due to a proton, nitrogen or iron nucleus incident on a fixed target carbon nucleus. Only gamma rays within a polar angle of 30° from the axis of the incident projectile were counted.

Using 2000 events, representative distributions for $f(k_\gamma)$ are shown in Fig. 6 for a cosmic ray proton, nitrogen, or an iron nucleus colliding with a fixed target lead nucleus (A = 207) in an emulsion chamber. Each projectile has an energy of 200 GeV/nucleon. By using FRITIOF and LUCIAE to generate gamma rays from the primary interaction, partial inelasticity distributions were calculated from those gamma rays within a polar angle of 30° from the z-axis. The energy conversion factors Ck_γ for obtaining the primary E_0 spectrum energy from $\sum E_\gamma$ were 0.256 and 0.108 for proton and iron, respectively, where $\beta = 1.7$ is the assumed primary particle spectral index. An energy of 200 GeV/nucleon was used for the primary energy of the proton and iron nucleus that interacts with a fixed target lead nucleus. These Ck_γ should be compared with those calculated with the Multi-Chain Model (Asakimori et al., 1993b), where all successive collisions are included. For events that interact within the calorimeter section of the chamber, they found that the energy conversion factors Ck_γ are typically 0.273 and 0.108 for proton and iron, respectively, (Parnell et al., 1989).

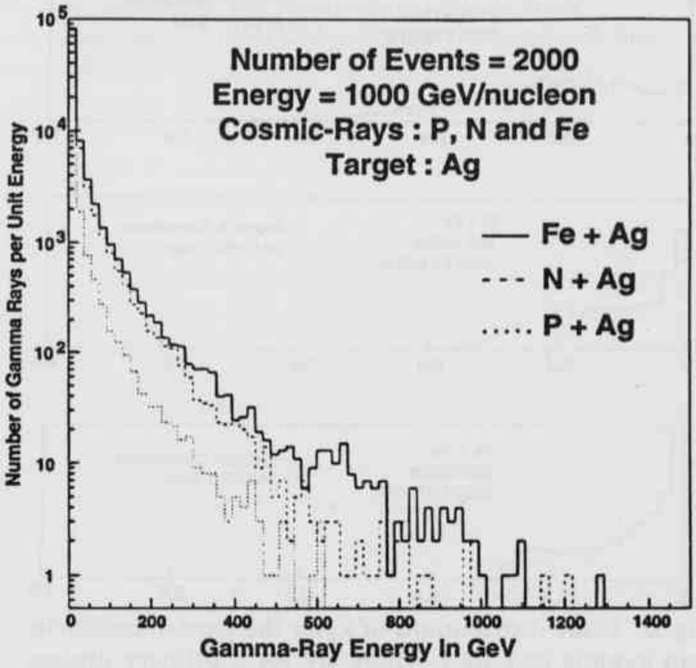

Fig. 5. The energy distribution of gamma rays due to a proton, nitrogen or iron nucleus incident on a fixed target silver nucleus. Only gamma rays within a polar angle of 30° from the axis of the incident projectile were counted.

Discussion

Cosmic rays span a very large energy range from 10^9 to beyond 10^{20} eV. A realistic modeling of particle detectors should include those energies which are likely to be encountered and measured by the cosmic ray or gamma ray detector. The primary cosmic rays were modeled for nucleus-nucleus interactions in an emulsion chamber. These simulations were done with FRITIOF and LUCIAE up to 1000 GeV/nucleon and appear to agree well with existing data. For detailed modeling of electron-photon cascades in the calorimeter, GEANT and PAW were used to determine energy deposition and transition curves for the electromagnetic energy incident on the calorimeter. By using the actual dimensions of the SOFCAL detector, which will be tested in a balloon flight this year, the modeling of SOFCAL will be useful for analyzing cosmic ray events. At the same time, modeling the primary cosmic ray interaction in the emulsion chamber should be done at energies higher than 1000 GeV/nucleon with FRITIOF and LUCIAE to determine primary energy and composition of the incident cosmic rays.

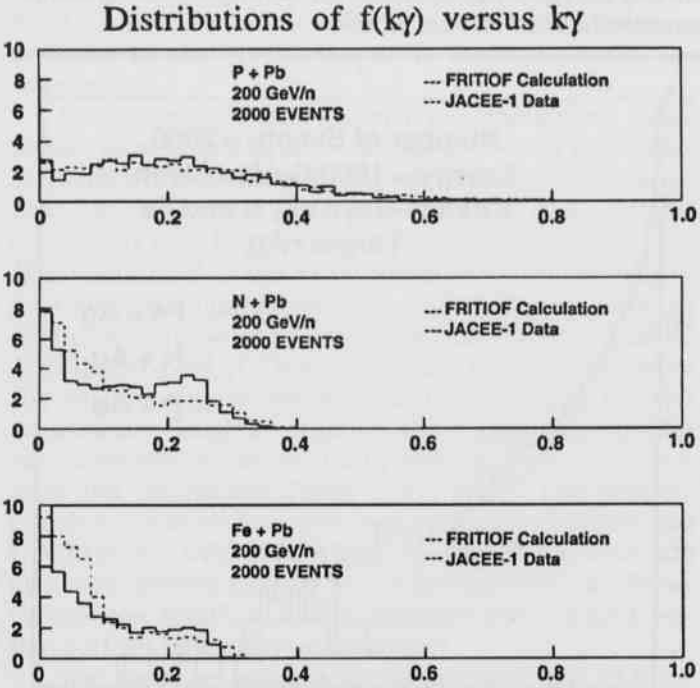

Fig. 6. Some distributions of k_γ for the partial inelasticity into gamma rays $f(k_\gamma)$. These are for a primary proton, nitrogen, and iron nucleus which interact with a fixed target nucleus of lead. The assumed primary particle spectral index was $\beta = 1.7$. The electromagnetic component was calculated with FRITIOF and LUCIAE.

ACKNOWLEDGMENTS.—The authors acknowledge the help of colleagues at the NASA George C. Marshall Space Flight Center, Huntsville, Alabama and the University of Arkansas at Little Rock. Dr. Thomas A Parnell, Dr. Geoffrey N. Pendleton, and Ms. F. Ellen Roberts generously gave the authors valuable support. Mr. Lon Jones III has served as systems manager for the DEC 3000 AXP and the DEC 5000 workstations. This work was supported in part by NASA and funding for the project was provided by the NASA/University Joint Venture (JOVE) Program.

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