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THE HADRON CALORIMETER FOR THE ACCESS MISSION

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ABSTRACT

ACCESS is a cosmic ray experiment presently under study for a possible accommodation as a Space Station attached payload. It is aimed at new measurements in several key areas of particle astrophysics that require the use of relatively large and heavy detectors in space. The scientific objectives include studies of nucleosynthesis and acceleration processes at the cosmic ray sources, determination of galactic propagation at high energies, and a search for characteristic changes of the cosmic ray spectra up to the "knee" region. The instrumentation will include a detector for ultraheavy cosmic rays (ZIM), a transition radiation detector (TRD) for measurements of energy spectra of primary and secondary cosmic ray nuclei ($Z \geq 3$) up to about 10^{15} eV, and a hadron calorimeter for observations of protons, helium and light nuclei up to 50 TeV/nucleon. The hadron calorimeter section of the ACCESS instrument is composed of a silicon matrix detector, a scintillator hodoscope, a graphite target section of about 1 proton interaction length and a totally active ionization calorimeter section composed of BGO crystals of approximately 27 radiation lengths depth. The ACCESS calorimeter detectors are read out with photomultipliers in the hodoscope section and with photodiodes in the BGO crystals. The readout of the detectors is accomplished by utilizing ASICs and custom designed, space qualified electronics.

1 INTRODUCTION

ACCESS is a cosmic ray experiment presently under study for a possible accommodation as a Space Station attached payload (Wefel and Wilson, 1999). It is aimed at new measurements in several key areas of particle astrophysics that require the use of relatively large and heavy detectors in space. The instrumentation will include a detector for ultraheavy cosmic rays featuring individual element resolution, a transition radiation detector for measurements of the particle velocity of primary and secondary cosmic ray nuclei ($Z \geq 3$), and a hadron calorimeter for observations of protons, helium and light nuclei up to 10^{15} eV. The scientific objectives of the mission include studies of nucleosynthesis and acceleration processes at the cosmic ray sources, determination of galactic propagation at high energies, and a search for characteristic changes of the cosmic ray spectra up to the "knee" region.

2 THE INSTRUMENT CONCEPT

A schematic drawing of the ACCESS baseline calorimeter is shown in Figure 1. The instrument includes a Silicon Matrix array at the top for charge identification, a scintillator hodoscope for tracking as well as charge identification, graphite targets to force interactions, and a BGO calorimeter section to determine the energy of the incoming particle.

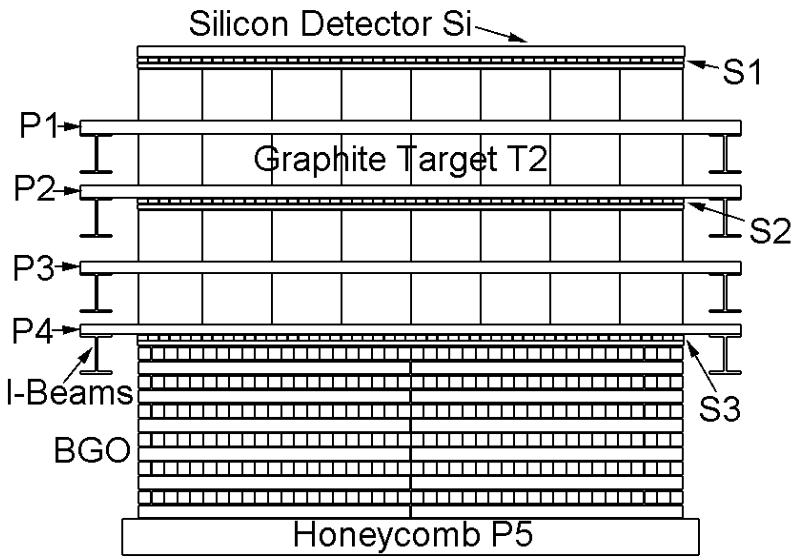

Figure 1: Configuration of the ACCESS baseline calorimeter

Three planes of plastic scintillators, S1 at the top, S3 at the bottom and S2 in the middle of the carbon target form a scintillator hodoscope. Each scintillator plane consists of two layers mounted at right angles and composed of individual strips which provide approximately 10° accuracy in determining the incident particle trajectory. They also provide a measure of the incident particle charge prior to its interaction in the carbon target. The thickness of each scintillator layer is optimized to maximize light output and minimize Landau fluctuations.

A potential problem with just using the scintillator planes for charge determination, is empirical evidence that charge resolution of primary particles at high energies becomes more difficult in the presence of a calorimeter (Simon et al. 1980). This effect was first encountered by the apparent failure of an early high energy cosmic ray experiment to record many singly charged particle ionization pulses when the energy exceeded a few TeV (Grigorov et al. 1971, 1994). Ellsworth et al. 1977 argued, on the basis of experience with ground-level calorimeters, that this was caused by particles “back scattered” from the calorimeter into the detectors. Our simulations of high energy protons (Seo et al. 1996), for the ACCESS instrument, indicate that, indeed, as the proton energy increases the number of "back-splash" particles per unit area increases, potentially adding to the charge signal of the incident cosmic ray and degrading their ability to distinguish between protons and Helium.

To address this problem, a Silicon matrix detector is located above the S1 scintillator to provide charge determination. It is composed of discrete "pixels" to reduce the sensitive area of any single sensor and, therefore, decrease the probability that a pixel hit by the incident cosmic ray will also be hit by back-scattered particles. The individual detectors are arranged in overlapping ladders to provide a matrix with minimum dead space.

The total thickness of the carbon target is a little more than one interaction length (40 cm); thus more than 60% of the incident particles will interact somewhere in the target. Due to the low Z target material (C) with its long radiation length, the showers generated by photons from these interactions, even from the very top of the target, are still very “young” when they enter the calorimeter.

The hadron calorimeter of the ACCESS instrument is composed of 12 layers of BGO crystals for a total of about 27 radiation lengths. Every other layer in rotated 90° to form 6X and 6Y planes. Each crystal is read out with photodiodes, which in turn are connected to a Front End Module (FEM) containing the readout Application Specific Integrated Circuit (ASIC) and their support electronics.

3 IONIZATION CALORIMETRY

The ACCESS calorimeter utilizes a technique called ionization calorimetry to determine the energy of cosmic ray nuclei from H-Fe. It is the most practical method over the energy range from 10^{11} to 10^{15} eV. In an ionization calorimeter, a particle's energy is deposited inside an absorber via a cascade of nuclear and electromagnetic interactions. At each step of the cascade, the energy of the primary particle is sub-divided among many secondary particles. Ultimately, the primary energy is dissipated via ionization and excitation of the absorbing material. The integral of the deposited energy versus depth in the absorber provides a measure of the energy of the incident hadron. In principal, an infinitely deep calorimeter will provide an energy resolution limited only by the statistical nature of the cascade process and the measuring technique. However, the resolution of a finite calorimeter depends on the fluctuations in the energy transferred to neutral pions which decay to the gammas that initiate the electromagnetic (EM) cascade.

4 CALORIMETERS FOR SPACE

Space based experiments face severe limitations. Space station attached payloads, such as ACCESS, are limited by the lift capacity and/or allocation of the launch vehicle, the space shuttle, as well as by the carrying capacity of the space station attach site. For the calorimeter, weight and power pose the most severe limitations.

In order to measure cosmic ray spectra, large exposure factors are needed to acquire sufficient statistics. This translates into large area detectors (A), with as large an active aperture as possible (Ω), being deployed for long time periods (t). Since calorimeters are by necessity composed of high Z, high density materials, the weight limitations determine directly, and most severely, the size of the instrument and thus the science capabilities. This means that instruments for space station payloads need to be thoroughly optimized for the task at hand to achieve the best measurements possible.

Practical calorimeters for space applications are necessarily limited in absorber thickness in order to have a reasonable mass and geometrical factor for collecting the particles. A thin calorimeter to measure the spectra of galactic cosmic rays must meet two basic requirements: (1) the primary nucleus must undergo at least one inelastic interaction; and (2) the energy resulting from the interaction(s) must be measured with good resolution. Thus, an optimal thin calorimeter would have a target section as thick as possible in interaction lengths to force interactions of both the incoming primary and the produced secondary hadrons, while remaining thin in terms of radiation lengths, so the cascade development occurs not in the target but in the calorimeter. The calorimeter section should be thick in terms of both radiation length, to absorb the cascades, and interaction length, to force additional interactions of both primary and secondary particles.

5 OPTIMIZATION OF THE CALORIMETER

The goal for the ACCESS instrument is to measure the spectra of protons, helium and light nuclei at the highest energies - limited only by statistics and thus instrument size. The first consequence of the weight limit is a limitation in calorimeter depth in order to gain area. Hadron calorimeters used in accelerator experiments are built to contain the entire shower, since they do not face a weight limitation and can be built as deep as needed for a particular energy. Thus, calorimeters for space do not contain the full hadronic shower. Unlike electrons and high energy photons, hadrons do not directly generate EM showers which can be measured in calorimeters of limited depth. They need to interact first, produce neutral pions, which, after their decay into gammas, generate an EM shower in a calorimeter. This renders the top portion of a calorimeter useless for the determination of the particle energy. Since the top portion is used primarily to generate interactions with the incoming hadrons it can be made from a lighter, lower Z material. A calorimeter utilizing a target section made of low Z material is about 30% lighter for the same area than its high Z target counterpart and can thus be built larger for a given weight limit, giving better statistics.

One of the performance issues is the energy calibration of the detector, i.e. how does the measured signal translate back into the energy of the incident particle. For calorimeters deployed at accelerators this is not a problem. The accelerator beam, which also defines the maximum energy to be measured, is utilized to calibrate the detector. Since the calorimeter itself is usually not directly in the beam, a prototype or an actual module of the calorimeter is placed into the beam and calibrated. To insure reliability and constancy of the measurement during science runs, the calorimeter is monitored utilizing LED flashers, laser pulsers and/or built in radioactive sources. Thus, the measured signal can be directly translated into the energy of the incident hadron. Even a non-linear and non-uniform response can be calibrated in this way.

For cosmic ray particle detectors the situation is different. The maximum measurable energy far exceeds all available accelerator beams. This implies that any calibration is performed only at the very low end of the spectrum. The measured signal has to be extrapolated to determine the energy of cosmic rays above the highest achievable accelerator energies.

This calibration problem is particularly important for sampling calorimeters. The shower development is not continued in the lower Z active medium, starting over at the beginning of every slab of the absorber and dying out at the end of the slab. Only a small fraction of the energy deposited in the calorimeter is actually observed in the active medium. The majority of the energy is deposited in the absorber where most of the shower develops. The signal in the active medium is produced by superposition of the energy deposited by higher energy, mostly minimum ionizing particles that pass through it, and low energy electrons produced in the absorber very near the absorber surface. Sampling calorimeters encounter additional difficulties. The small sampling fraction (e.g. 5%) makes it difficult to use the cosmic rays themselves for in-flight calibration and monitoring.

The situation is eased for fully active calorimeters where the absorber is the measuring medium. Inactive materials, e.g. for structure and optical isolation, make up only a small fraction of the mass. This allows the calorimeter to be calibrated with cosmic ray muons on the ground and with relativistic protons and He nuclei in flight, which also provide monitoring during science data taking as well.

A material such as BGO has ideal characteristics for use in the fully active calorimeter of the ACCESS baseline. BGO has both a short radiation length as well as a short interaction length due to its high Z components and its high density. BGO is a relatively hard, rugged, non-hydroscopic inorganic scintillating crystal which does not cleave and does not show any significant amount of self-absorption of its scintillation light. These properties also make it easy to handle.

6 CONCLUSIONS

Calorimeters deployed in space such as attached payloads to the space station require thorough optimization for their measurement task due to the severe limitations imposed by the infrastructure and the space environment itself.

REFERENCES

Ellsworth, R. W. et al., 1977, Astrophys. & Space Sci., 52, 415.
Grigorov, N.L., et al., 1971, 12th Int. Cosmic Ray Conf. (Tasmania), 5, 1746.
Grigorov, N.L., 1994, private communication.
Seo, E. S., et al., 1996, Proceedings SPIE, 2806, 134
Simon, M., et al., 1980, Ap. J. 239, 712.
Wefel, J.P.and Wilson T.L, 1999, 26th Int. Cosmic Ray Conf. (Salt Lake City), OG.4.2.01