Advanced Thin Ionization Calorimeter (ATIC)

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Abstract

Advanced Thin Ionization Calorimeter (ATIC) balloon payload will be used to investigate the cosmic ray proton and helium spectra over the energy range 10^{10} to $>10^{13}$ eV. The proposed payload is described here and consists of a totally active BGO calorimeter coupled with a thick carbon target and multiple layers of scintillators. Current plans call for a first flight during ~1998.

1. Introduction

The energy spectra of Galactic Cosmic Rays (GCR) in the ultra-high energy regime have emerged as one of the outstanding questions in Cosmic Ray physics with implications for particle acceleration in supernova remnants or other exotic objects, transport of particles through the interstellar medium and the nature of the cosmic ray sources. This importance has been emphasized in Space Physics strategic planning, in the GOAL report, in the preliminary NRC/BPA briefing and in the Snowmass 1994 discussions (see e.g. [1,2]). Current results from the JACEE experiments [3] have created considerable excitement, and independent verification of these results is of the utmost importance.

The initial ATIC program will concentrate on measuring the cosmic ray proton and helium spectra from about 10^{10} eV to more than 10^{13} eV, with statistical accuracy better than 30% at the highest energy. This unique coverage of, at least, three orders of magnitude in energy with a single instrument will approach the energy range of both the Grigorov [4,5] and the JACEE experiments, both of which concluded that a bend exists in the proton spectrum. Most significantly, our measurements will be able to verify whether the proton and helium spectral differences that have been reported (e.g. [6]) from combining all the existing data are indeed real. In addition, the ATIC results will fill an existing gap in measurements of the proton/helium ratio between the traditional "standard" measurements below 100 GeV [7,8] to the highest emulsion chamber energies.

Follow-on flights will use the Long Duration Balloon (LDB) capability to extend the measurements to $> 10^{14}$ eV, beyond the spectral bend in the proton spectrum at 40 TeV reported by the JACEE Collaboration. Concurrently, the ATIC flights will also measure the spectra of heavy nuclei up to iron, with individual element resolution and superior energy resolution.

2. Ionization Calorimetry

The most practical method of energy determination for cosmic ray nuclei from H-Fe, over the entire energy range from 10^{11} to 10^{15} eV, is ionization calorimetry. 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 is a measure of the energy of the incident hadron. In principal, an infinitely deep absorber will provide 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 cascade.

Practical calorimeters for space and balloon 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 electromagnetic energy resulting from the interaction(s) must be measured with good resolution.

An optimal thin calorimeter would have a target as thick as possible in interaction lengths to force interactions of both the incoming primary and 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 should be thick in terms of both radiation length, to absorb the cascades, and interaction length, to force additional interactions of both secondary and primary particles. It also should have an active volume as large as possible.

An optimal calorimeter material fulfilling most of these conditions is Bismuth Germanate, BGO. It 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 scintillation crystal which does not cleave and does not show any significant amount of self absorption of its scintillation light. It also allows the calorimeter to be fully active. Thus BGO is the material selected for this calorimeter.

3. The Instrument Concept

A schematic drawing of the proposed ATIC instrument is shown in Figure 1. The instrument is composed of two major subsystems: the target module and the calorimeter. The target module consists of five layers of plastic scintillator (S1 to S5) alternating with four 10 cm thick carbon targets. The total thickness of the carbon (40 cm) is a little more than one interaction length (38.1 cm) and somewhat more than two radiation lengths (18.8 cm). Thus, more than 60% of the incident particles will interact somewhere in the target, but the photons created in the interactions, even at the very top of the target, would still be very "young" when they enter the calorimeter. The conversion length for photons is 9/7 radiation lengths, more than half of the full target thickness, so the electron showers would, on average, be less than 1 radiation length in shower age upon impinging on the calorimeter.

Each scintillator plane (S) has two layers mounted at right angles and composed of individual panels to form a particle position hodoscope.

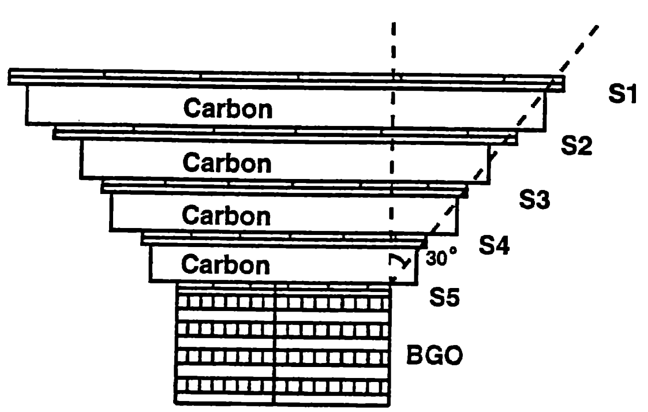

Figure 1. ATIC instrument schematic.

The width of the panels is set to provide approximately 10° accuracy in determining the incident particle trajectory and the length varies from about 110 cm for S1 to 50 cm for S5 to maintain a 30° opening half angle. The scintillators also provide a measure of the incident particle charge prior to its interaction in the carbon target. The thickness of each S layer is optimized to maximize the light output as well as to minimize Landau fluctuations and total target module thickness. Multiple independent measurements of the incident particle charge will further improve the charge resolution.

While there is no fundamental problem with charge determination, there is empirical evidence that charge resolution of primary particles becomes more difficult in the presence of a calorimeter [8]. This is due to back-splash of particles from the calorimeter into the charge measuring/target module. This effect was first encountered by the apparent failure of Grigorov's detectors to record many single-ionization pulses when the energy exceeded a few TeV (Grigorov et al, [4]). Ellsworth et al. [9] argued, on the basis of experience with ground-level calorimeters, that this was caused by particles back scattered from the calorimeter into the detectors. Possible solutions to this problem include 1) fine segmentation of the scintillator hodoscope planes to reduce the probability that the incident particle signal is overwhelmed by back-scatter events; and/or 2) including one or more Cherenkov detectors constructed to be sensitive to downward moving particles but relatively insensitive to upward moving events. In the later case it may be possible to substitute a Cherenkov radiator such as LiF for the carbon (as LiF and C have similar densities, interaction lengths and radiation lengths) and have a fully active target module.

The calorimeter module (BGO in Figure 1) is composed of about 400 BGO crystals, each of which has approximate dimensions 2.5 cm by 2.5 cm by 25 cm. The crystals are arranged in 10 layers, and each layer has an area of 50 x 50 cm^2. Alternating layers are placed at right angles to maximize area coverage. This arrangement also allows the calorimeter to provide supplementary trajectory information. The maximum dynamic range expected in a crystal is about 2.5×10^4. Each crystal, therefore, will be readout by a photodiode and either an avalanche photodiode or a mini photomultiplier tube. These photodetectors will be mounted on the outer surface of the calorimeter on each 2.5 cm x 2.5 cm crystal face. The remaining surfaces will be coated with a light reflecting material to increase the light output and each crystal will be wrapped for protection and optical isolation.

The total thickness of the calorimeter is about 25 cm, corresponding to 22 radiation lengths and ~1.1 interaction lengths. This is more than sufficient to contain the average shower maximum from photons created in 10^{14} eV proton interactions in the target. At the same total energy, helium and heavier nuclei would produce lower energy electromagnetic cascades compared to those produced by protons. All the secondaries produced in the target, as well as the surviving primary, would have a ~70% probability of interacting further in the thick BGO calorimeter. The photon cascades from these BGO interactions would quickly convert in the BGO crystals, thereby further improving the energy resolution.

This instrument is expected to have a geometrical factor of about 0.3 m^2-sr. Assuming that at least 10 particles in the highest energy bin have their first interaction in the target module, it is possible to achieve the near-term objectives of simultaneously measuring the proton and helium spectra up to 10^{13} eV in a nominal one- to two-day "turn-around" flight. The exposure needed to reproduce the JACEE results [3] will require only 3-4 LDB flights in Antarctica.

4. Conclusions

A balloon payload consisting of a fully active BGO ionization calorimeter is currently under development and will be used to measure energy spectra of cosmic ray H-Fe over the energy range 10^{10} eV to $>10^{13}$ eV. Proton and Helium spectrum up to 10^{13} eV could be measured to at least 30% accuracy in a single "turn-around" flight and statistics up to 10^{14} eV comparable with current results, could be achieved with 3 to 4 long duration balloon flights.

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