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ADVANCED THIN IONIZATION CALORIMETER TO MEASURE ULTRAHIGH ENERGY COSMIC RAYS

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ABSTRACT

An Advanced Thin Ionization Calorimeter (ATIC) will be used to investigate the charge composition and energy spectra of primary cosmic rays over the energy range from about 10^{10} to $>10^{14}$ eV in a series of long-duration balloon flights. The totally active BGO calorimeter, 22 radiation length thick, will measure the electromagnetic energy ensuing from nuclear interactions in a one interaction length thick carbon target. Trajectory information will be obtained from the location of the cascade axis in the BGO calorimeter and in the segmented scintillator layers of the upstream carbon target. The highly segmented charge module comprised of scintillator strips, a silicon matrix, and a Cherenkov array will minimize the effect of backscattered particles on primary charge measurements. While obtaining new high priority scientific results, the ATIC balloon payload can also serve as a proof of concept, or engineering model, for a BGO calorimeter-based instrument on the International Space Station. We examine the added advantage of locating such an experiment for long durations on a platform such as the Space Station.

INTRODUCTION

The high energy ($> 10^{10}$ eV) cosmic rays are characterized by a power law energy spectrum, which supports the belief that they are accelerated at shock waves associated with supernova remnants (SNR). According to shock acceleration theory, at least in the test-particle formalism, there is a maximum energy for the accelerated particles. In the case of SNR shock acceleration, the maximum total energy of a charge Z particle is thought to be about 10^{14} Z eV in the quasiparallel geometry (e.g. Lagage and Cesarsky 1982). This implies that the composition would begin to change beyond about 10^{14} eV, the limiting energy for protons: the limiting energy for Fe would be 26 times higher. The maximum energy attained depends on the rate at which the particles diffuse back and forth across the shock (i.e., on the magnetic field) and on how long the acceleration mechanism acts. Other assumptions about the magnetic field topology, such as quasiperpendicular shock geometry, suggest that the limiting energy may be higher (see e.g. Ellison *et al.* 1994). In any case, this theory provides definite predictions about the composition changes due to the acceleration limit that can be tested by direct measurements at these energies.

All-particle measurements, principally from ground-based experiments, which provide the spectrum to the highest energies, ~ 10^{20} eV, indicate that the cosmic ray energy spectrum is somewhat steeper above 10^{16} eV than it is below 10^{14} eV. However, the interpretation of data from these indirect measurements depends upon assumptions about the primary particles that initiated the showers, and the energy estimates are in turn affected by the assumed composition of the cosmic rays. Direct measurements of cosmic ray particles have been limited to energies < 10^{14} eV by the low fluxes and the limited exposure in space or on balloons. It is important to push the upper limit of the direct measurement to address this major question in cosmic rays, whether and how this structure, the spectrum knee, is related to the mechanisms of acceleration, propagation, and confinement.

The Advanced Thin Ionization Calorimeter (ATIC) investigation will study the charge composition and energy spectra of ultrahigh energy primary cosmic rays in a series of long-duration balloon flights. A few such flights would provide elemental differential energy spectra from the low energy region around 10^{10} eV through the highest practical energies, about 10^{14} eV, with statistical accuracy better than 30% at the highest energy. In order to extend the highest energy direct measurements by another order of magnitude, a major leap forward beyond currently available long duration balloon flights is required. The International Space Station (ISS) provides a suitable platform for achieving this goal, and the ATIC collaboration has proposed the Advanced Calorimeter for Composition of Elements on the Space Station (ACCESS) as an ISS accommodation study.

THE ATIC DESIGN

The ATIC experiment is based on the principle of ionization calorimetry, the high energy particle physics analog to the traditional measurement of heat energy with a calorimeter. This seems to be the only practical method of energy determination for cosmic ray nuclei over the entire energy range from 10^{10} 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 Ei of an incident hadron is dissipated via ionization and excitation of the absorbing material. The area under the curve of ionization energy versus depth in the absorber provides a measure of Ei. From Monte Carlo simulations and detailed investigations using accelerator exposures to monoenergetic particles there is a good understanding of how the energy resolution depends on calorimeter depths, absorber materials, particle species, and primary energies (Refs. 10-23 in Jones *et al*, 1977).

Practical calorimeters for space applications must necessarily be limited in absorber thickness, in order to meet the weight restriction and still have a reasonable geometrical factor for collecting the particles. The spectra of galactic cosmic rays can be measured with a thin calorimeter as long as the primary nucleus undergoes at least one inelastic interaction, and the electromagnetic energy resulting from that interaction(s) can be measured with good resolution. The calorimeter should be as thick as possible in radiation lengths to absorb the cascades, and it also helps to be thick in interaction lengths, to force more interactions of the surviving primary and secondary hadrons. In order to maximize the geometrical factor, the total thickness should be thin in physical dimensions, and the cross-sectional area should be as large as possible.

Figure 1 shows the strawman design of the ATIC payload, which was chosen to be consistent with the weight limit for long-duration balloon payloads, while maximizing the area and thickness of the calorimeter. The instrument has three major sections. The top section is the charge module, composed of a silicon matrix detector (Si), scintillators (S1), and a Cherenkov detector (Ck). This is followed by the target section, containing the carbon target layers (T1 - T4) and interleaved scintillators (S2, S3). The bottom section is the Bismuth Germanate calorimeter (BGO). The instrument, described in detail in Guzik *et al.* (1996), is constructed with a maximum use of modularity in order to be easily taken apart in the field for recovery.

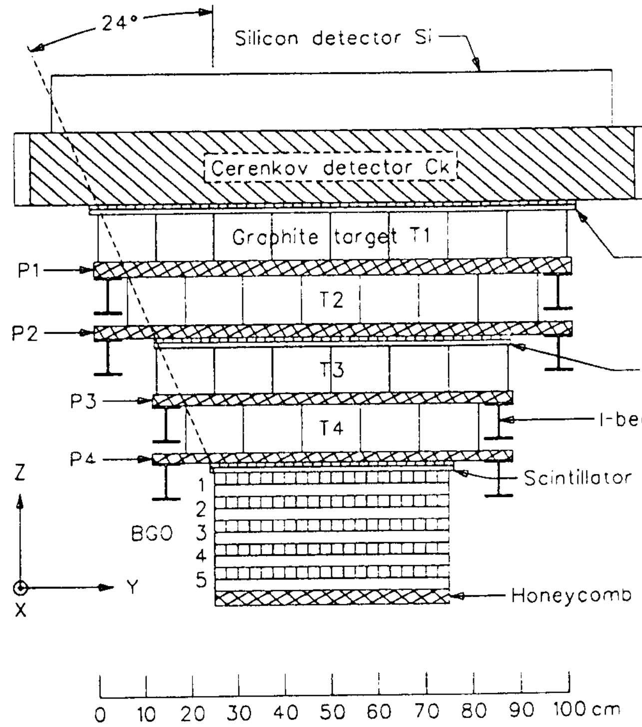

Fig. 1 The ATIC "strawman" design.

BGO Calorimeter

The calorimeter is composed of an array of BGO crystals, each 2.5 cm x 2.5 cm x 25 cm, layered horizontally with 40 crystals forming a 50 cm x 50 cm layer. Each layer is rotated 90 deg to the preceding one. Each pair of layers, an x-y unit, is contained in a tray fitted with handles for easy removal. Each unit weighs under 100 kg. The total calorimeter shown in Figure 1 contains 5 units for a vertical thickness of 25 cm (22.3 rad. len.), which is more than sufficient to contain the average shower maximum from photons created in 10^{14} eV proton interactions in the target. Based on the Monte Carlo simulations, the total energy deposit in the BGO calorimeter is about 30 - 40% of the incident energy with a resolution (ratio of the standard deviation to the mean of the energy deposit distribution) of 30 - 60% for protons over the energy range 10^{10} to 10^{14} eV. Figures 2a and 2 b, respectively, show the mean energy deposit and the energy resolution for P, He and Fe as a function of energy. Refer to Seo *et al.* (1996) for the detector simulation details.

Much of the recent high energy cosmic ray data (direct measurements) have come from emulsion chambers, such as JACEE, which also use a thin calorimeter technique. The ATIC configuration differs from the emulsion experiments in its innovative choice of absorber materials and thicknesses, and the calorimeter is 'advanced' in that it uses a totally active, >20 rad. len. thick, BGO electromagnetic calorimeter downstream of a segmented 1 int. len. thick carbon target. (For example, the ATIC baseline thickness is 2 int. len. and >20 rad. len., while a typical JACEE chamber thickness is ~0.5 int. len. and 6-8 rad. len.) The target depth is only a few rad. len., so the electromagnetic shower development will occur almost totally in the BGO calorimeter, which will measure all the deposited electromagnetic energy. The ATIC instrument will provide measurements that overlap at the low energy end (< 100 GeV) with previous space and balloon data and extend upward in energy to the region now explored only by balloon-borne emulsion chambers (> 2 TeV). While the basic technique is similar to the emulsion chambers, the ATIC approach is sufficiently different so as to be able to verify and extend the previous measurements.

Carbon target

The target section contains 40 cm of graphite arranged in four layers, each 10 cm thick. In total, this

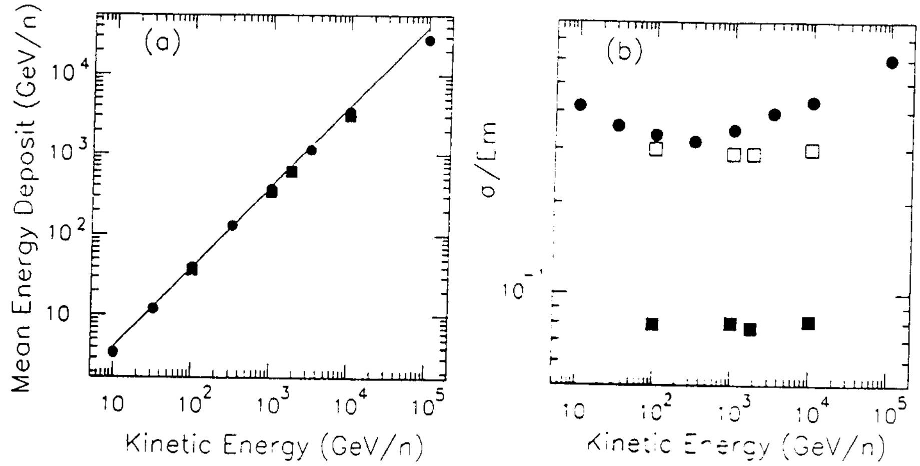

Fig. 2 Energy dependence of (a) the mean energy deposit and (b) the energy resolution for protons (filled circles), He (open squares), and Fe (filled squares).

gives an interaction probability for protons of 0.64. The top graphite layer weighs about 230 kg and is supported by an aluminum honeycomb structure. The graphite is inserted into this tray in four pieces. This allows for rapid disassembly in the field. The other three layers have the same construction but are of decreasing area, just filling the 24 deg half-angle open cone. There is an x-y plane of crossed scintillators (S2) located in the middle of the carbon target and another plane of scintillators (S3) at the bottom, just preceding the calorimeter. These scintillators provide additional information to help reconstruct the trajectory of the incident particle, and this improves the position resolution in S1 by about 20%.

Charge Module

Located at the top of the detector, the charge module is a three-fold redundant set of independent detectors designed to minimize the effect of backscattered particles on the primary charge measurement. The scintillator layer (S1) is used in the event trigger as well as the charge measurement. It consists of two perpendicular layers of 2 cm wide by 1 cm thick by >100 cm long strips of BC-408 scintillator read at both ends by small Hammamatsu R5611 photomultiplier tubes. Laboratory tests show that these strips are >98% efficient for minimum ionizing particles.

The Cherenkov detector (Ck) is a matrix consisting of 45 detector elements, each of which is a separate Cherenkov radiator and photomultiplier tube (PMT). The elements are designed to be sensitive to downward-moving particles, while their response to upward moving particles is strongly suppressed. Each Cherenkov radiator is a hexagonal plate of 5 cm thick UV-transmitting methyl methacrylate (refractive index of 1.48 - 1.5), with a minimum diameter of 16 cm. A PMT is attached to the bottom of each plate. The top surface of the radiator is blackened, to absorb Cherenkov light from upward moving particles, and the sides are aluminized. The Cherenkov detector matrix is similar to the one used in the SOKOL satellite experiment (Grigorov 1990). Flight experience with such detectors shows that the ratio of downward/upward moving particle signals is about 10:1. The use of hexagonal radiators allows us to pack the radiators together in a matrix that essentially fills ATIC's aperture.

The Silicon Matrix Array is a mosaic of silicon diode detectors which fully cover the aperture of the ATIC instrument. Because the Si matrix is the top detector module in the ATIC aperture, it is the largest detector with an area in excess of 1 m^2. The basic building blocks of the matrix are Si diode detectors with areas of 1.37 cm by 1.66 cm. Each detector is an N-type silicon diode, 380 μm thick, with a resistivity of 6000 Ω-cm. It is operated with a reverse-bias and is fully depleted. The detectors are cut from wafers in strips of 4 detectors which are then mounted in ladder assemblies. The strips of each plane are bonded to its honeycomb panel. The facing sides of the matrix panels will have a separator cushion between them to prevent damage due to parachute and landing shock. Aluminum channel is built into the sides of the honeycomb to permit mounting to the gondola structure.

Charge and trajectory measurements

Backsplash from the calorimeter is a rather widely accepted explanation (Ellsworth *et al.* 1977) for the apparent bend in the proton spectrum reported by Grigorov *et al.* (1971). In this explanation, the signal from the backscattered particles adds to the primary signal, thereby causing protons to be misidentified as heavier nuclei, mainly helium, and erroneously leading to a "loss" in protons. The number of backscattered particles in a unit area increases as the incident energy increases, so the probability to misidentify protons as helium nuclei increases with energy. This leads to an apparent bend in the proton spectrum. While the steepening of the proton spectrum due to the effect of backscattered particles is intrinsic, the charge module can be finely segmented to greatly reduce the effect.

Monte Carlo simulations show that most (88%) of the 1 TeV protons would be misidentified, due to the albedo contamination, as heavier nuclei if the charge were measured with a single plane of scintillators without segmentation. The fraction of misidentified protons reduces to 4% with the 2 cm crossed strips. A preliminary study of a highly-segmented Si matrix (~ 3.0 x 3.3 cm^2) shows that 1% of 1 TeV protons would be misidentified as heavy nuclei. With the ATIC design, backscatter effects are not expected to steepen the proton spetrum by changing the spectral index by more than 0.01. We note that the albedo effect is reduced if the charge measuring layer is farther away from the calorimeter. Additional charge detectors, e.g, ATIC directional Cherenkov counter, definitely increase the albedo rejection efficiency.

Another important consideration for the charge measurement is how well the incident position can be known. Typically, the trajectory of the primary particles can be obtained by backward projection of the cascade axis measured in the calorimeter to the entrance detector. The energy deposit pattern in the totally active BGO crystals provides information on the cascade axis location at each layer. The 10 layers of cross-stacked BGO crystals can give 5 measurements of each cascade axis coordinate, x and y. By extrapolating the linear fit of the 5 cascade coordinates to the top scintillator S1, the entrance particle position can be estimated. The deviation between the actual incident position and this "measured" position in S1 for vertically incident protons at an energy of 1 TeV gives the position resolution of 0.54 cm.

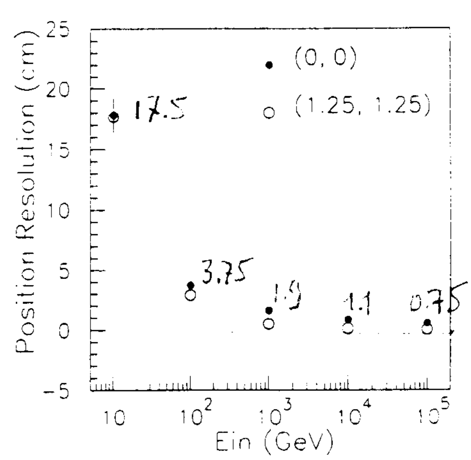

Fig. 3 Energy dependence of the trajectory resolution.

Figure 3 shows the position resolution obtained from our totally active BGO calorimeter as a function of incident energy. The resolution gets worse as energy decreases. At the lowest energies, it is too large to take any advantage of the charge detector segmentation. Fortunately, the backscatter effect is not significant at low energies. At high energies, where the backscatter effect is larger, finer segmentation can greatly reduce the effect of backscattered particles on the charge resolution.

Balloon Payload

We would expect to have an average event rate in the ATIC experiment of about 10 per second, assuming a trigger threshold at ~ 30 GeV. The corresponding data rate will be about 14 kilobits/second (kbps). The ATIC data stream will also contain housekeeping data, composed of position, universal time, pressure, temperature and voltage information, about once every 5 minutes; a complete readout of all singles and coincidence rates about once every 30 minutes; and a two point ADC calibration about once an hour. These extra information frames add about 1% to the average data rate, bringing the total data collected per day to 80 Megabytes (MB). Thus, in a 10 day long duration balloon flight ATIC should accumulate about 1 GB of high energy cosmic ray information.

The pressure vessel gondola follows a design pioneered by CalTech and manufactured by Irvin Industries, Inc. that consists of two Kevlar fabric hemispherical domes bolted to a 6" tall by 90" diameter aluminum ring using o-ring fitted flanges. An inner bladder composed of polyurethane coated nylon provides the gas-tight seal for the gondola. The advantages of this design are that it is light weight (125 lbs total), tough and puncture resistant, is very thin (~0.06 g/cm^2) and is about a factor of 5 to 6 less expensive than equivalent spun aluminium shells. The pressure vessel is, in essence, free floating and is not a structural element of the payload.

To maintain flexibility in the weight of the instrument, in order to meet possibly changing launch and/or recovery requirements, and to avoid building an instrument with less than optimal science capability, we have designed the ATIC charge detectors, carbon target, calorimeter and electronics as modules which can be easily removed or inserted on the support structure. For example, a light-weight configuration might consist of modifying the strawman (Figure 1) by removing the top carbon target (T1) with its associated support structure, moving the Si array, Cherenkov and S1 detector to the top of the T2 target layers, removing the S2 detector, and replacing the bottom calorimeter module (2 layers of crystals) with honeycomb support structure. This would result in a thinner calorimeter (10% poorer energy resolution) and somewhat less target material, but with a somewhat larger geometry factor, 0.23 m^2-sr. With this modification, about 20 hrs would be needed to achieve 30% statistical accuracy > 10^{13} eV, and about 40 days would be required for the same statistics > 10^{14} eV.

THE ACCESS NEW MISSION CONCEPT

Transitioning the ATIC balloon concept into a space mission involves a redesign to increase the acceptance. In space, without a residual atmosphere, we can accept events at larger incident angles. To maintain reasonable compactness, it is possible to 'wrap' the target and charge detectors around the calorimeter and to replace much of the carbon target with BGO material. In addition, a calorimeter of increased thickness is required to measure the higher energy events. This leads naturally to the Advanced Calorimeter for Composition of Elements on the Space Station (ACCESS) design shown in Figure 4. Particles entering from the sides of the instrument, as well as the top, give an overall geometry factor of about 0.5 m^2-sr or an exposure factor of about 550 m^2-sr-days for a 3 year mission on the International Space Station (ISS).

The measurement technique used by ACCESS is identical to the ionization calorimetry technique discussed above for ATIC. The major difference is that ACCESS employs a much deeper calorimeter: 26 layers of 2.5 cm x 2.5 cm x 25 cm long BGO crystals or about 58 radiation lengths vertically. This provides the advantage that higher energy showers from particles incident on the detector up to about 65 deg from the vertical can be contained. Further, the extra layers provide additional x-y coordinates along the shower core, thereby increasing the accuracy of the incident particle trajectory measurement.

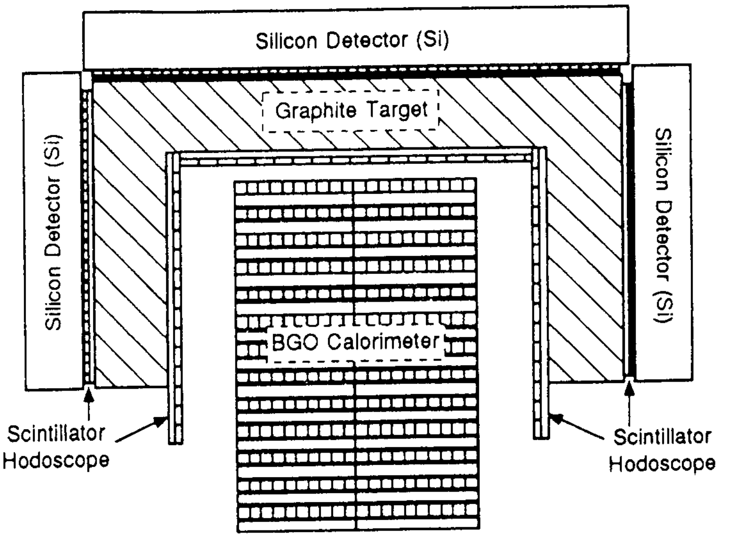

Fig. 4 The ACCESS instrument concept.

As with ATIC, scintillator hodoscopes provide the event trigger and supplements the trajectory information for ACCESS. The top scintillator also provides a redundant measure of the particle charge. The primary charge measuring devices, however, are the Silicon-matrix detectors mounted on all five outer surfaces. These detectors would be constructed of individual elements in a fashion similar to that being developed for ATIC. Thus the combination of the outer, finely segmented scintillator horoscope and the silicon-matrix provides a two-fold redundancy for rejecting backscattered particles. Whether a three-fold redundancy, as is planned for ATIC by including the direction sensitive Cherenkov detector, is necessary will be one of the issues studied under the accommodation study (if approved): this can be tested during the ATIC balloon flights. The main trigger will involve simultaneous 'hits' in both scintillator hodoscopes on a side (or the top) and in the calorimeter.

CONCLUSION

The ATIC balloon project will offer the best opportunity to measure the proton and He spectra over four decades in energy, 10^{10} - 10^{14} eV, with a single instrument. Concurrently, it will also measure the spectra of heavy nuclei up to iron with superior energy resolution. A one day flight of ATIC would provide the most accurate H/He data below 100 GeV and the first measurement of this ratio over the range 100 GeV to 1 TeV. It will fill the existing gap in measurements of the H/He ratio between the traditional 'standard' measurements below ~ 100 GeV (e.g. Ryan *et al.* 1972) and the highest emulsion chamber energies (> 2 TeV). It will also be able to verify whether the proton and helium spectral differences that have been reported (e.g. Ellison *et al.* 1994) from combining all the existing data sets are indeed real. Depending on the final design of the instrument to meet the weight requirement for long-duration balloon payloads and depending on the number of flights, i.e., exposure time, the actual statistics can vary. A few long duration balloon flight will extend the measurements to > 10^{14} eV, beyond the reported spectral bend in the proton spectrum at 40 TeV (Asakimori *et al.* 1993)

A major advance in exposure would be needed to push the spectral measurements to > 10^{15} eV. The new mission concept ACCESS on the International Space Station would be adequate to accomplish this purpose: ACCESS is basically a larger version of ATIC. The ACCESS measurements of the galactic cosmic ray elemental energy spectra will (1) test the supernova blast wave model for the cosmic ray acceleration (2) search for spectral changes or composition effect ~ 10^{14} eV, (3) provide space-instrument confirmation to the preliminary balloon measurements of elemental spectra < 10^{14} eV, and (4) calibrate the ground-based air shower measurements by providing a decade in energy of overlap with a new generation of extensive air shower experiments.

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