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FINAL TECHNICAL REPORT

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Spectra, Composition and Interactions of Nuclei above 10 TeV Using Magnet-Interferometric Chambers (SCIN/MAGIC)

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FINAL TECHNICAL REPORT

Purchase Order H-11204-D

1. Introduction

The "Spectra, Composition and Interactions of Nuclei Above 10 TeV Using Magnet Interferometric Chambers" (SCIN/MAGIC) experiment was selected for flight as an attached payload to utilize the Astromag Facility on Space Station Freedom. The investigation has two aspects. The first experiment involves the use of emulsion chambers to record individual nuclei in the cosmic radiation at energies above ~10 TeV (SCIN) in order to investigate the composition and the energy spectra of cosmic rays in the energy region above currently available data, extending into the air shower regime. This is an astrophysically important region of the energy spectrum which may provide clues to the origin of the highest energy particles. The second aspect involves using emulsion chambers of a different design in the field of the Astromag magnet (MAGIC). In this case, the experimental goal is to study the high energy nuclear interactions of the cosmic ray particles. For each event that interacts, the secondary particles will be deflected in the magnetic field permitting the charge and the rigidity to be measured. This permits analysis of π^+, π^- correlations and searches for heavier particles produced in the interaction. Since such interactions are the current basis for measurements of cosmic rays at the highest energies, the results will, undoubtedly, improve our understanding of this fundamental process.

The SCIN/MAGIC program in the US is a collaboration between MSFC, Louisiana State University (LSU), University of Alabama in Huntsville (UAH) and University of Washington in Seattle (UW). The team is lead by T. A. Parnell from MSFC who directs the overall project and supervises the work of the university co-investigators.

This purchase order covered the initial effort at LSU directed towards a Definition of the SCIN/MAGIC project for the space station office. The principal objectives were the development of Science Requirements, Experiment Accommodation, Instrument Requirements and Analysis Planning. The SCIN/MAGIC experiment is unique in that it involves visual detectors, nuclear emulsions, x-ray films and etched plastic track detectors, which must be recovered from SSF for subsequent processing and analysis in the laboratory. This requires that the detector materials be developed and tested to withstand the anticipated environment, both pre-launch, on the station and return to Earth, requiring detailed materials testing and packaging. Further, the science data is obtained only <u>after</u> the space exposure, return to Earth and processing in the laboratory. SCIN/MAGIC data acquisition commences some 6-12 months after the initial launch of the modules and requires 2-3 years to complete. Thus, detailed analysis planning and analysis equipment development must be an early and integral part of the SCIN/MAGIC investigation plan. Each of these areas was studied by LSU during the initial effort covered by this purchase order.

2. Science Objectives

The goals of the SCIN portion of the overall investigation have been refined during this period. One of the basic purposes of the investigation is to extend the region of directly measured particle spectra upward in energy. Figure 1 illustrates this for the Hydrogen (proton) component, the most abundant species among the cosmic rays. Plotted is a summary of previous measurements of the differential energy spectra including the recent balloon results from the JACEE experiments at the highest energy.

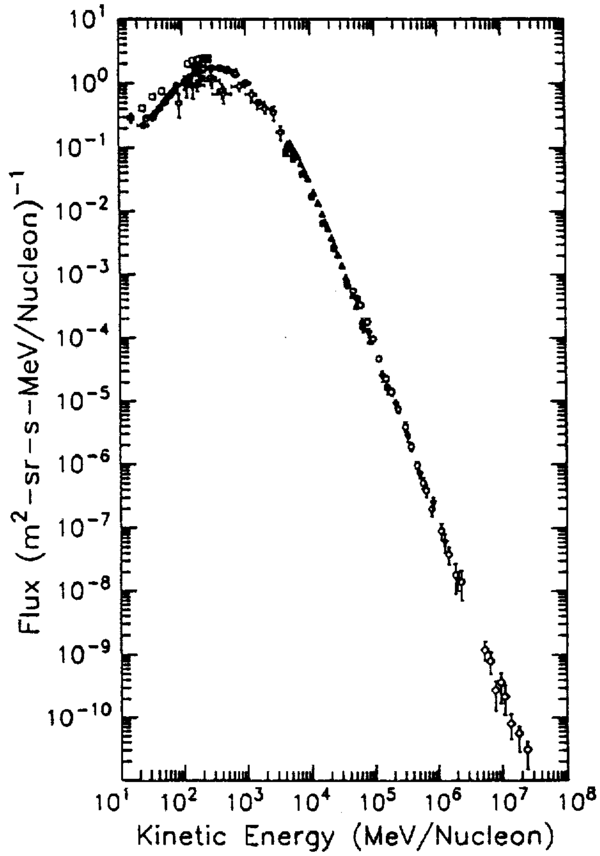

Figure 1. Compiled differential energy spectra for Hydrogen measured at Earth.

The current measurements extend to ~2.5 x 10^7 MeV (25 TeV) with reasonable statistics and join smoothly to the lower energy results. The SCIN/MAGIC program must be capable of reducing the uncertainties on the data at 5-25 TeV and extending the measurements, with good statistics, to at least 100 TeV.

Figure 2 shows the compilation of the all particle cosmic ray spectrum as deduced from direct measurements at low energies and from air shower observations at higher energies. Note that there is a feature in the spectrum at ~10^{15} eV (1000 TeV) beyond which the slope of the all-particle spectrum changes. The SCIN exposure for extended periods in space is designed to push the direct measurements as close to this feature as possible to search for the beginning of the spectral change. Thus, repeated exposure of SCIN chambers may be necessary to carry out this objective. It is recommended that such a multi-exposure plan be incorporated into the overall investigation scenario.

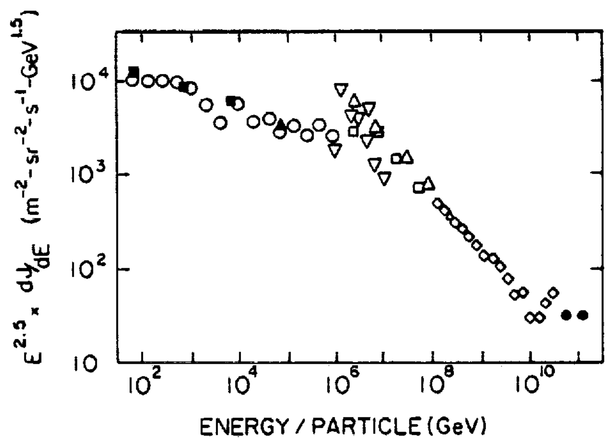

Figure 2. Compiled cosmic ray all particle spectrum from 0.1 TeV to the highest measured energies.

Turning to the multiply charged nuclei, Figure 3 shows a compilation of recent data on the proton to helium (p/α) ratio. The highest energy point was measured at several TeV/nucleon and shows an anomalously low value, compared to the lower energy data. Since the proton results (Figure 1) show no suppression, this effect is due to an increased helium flux at TeV energies, a possible indication of new physics at the high energies to be studied

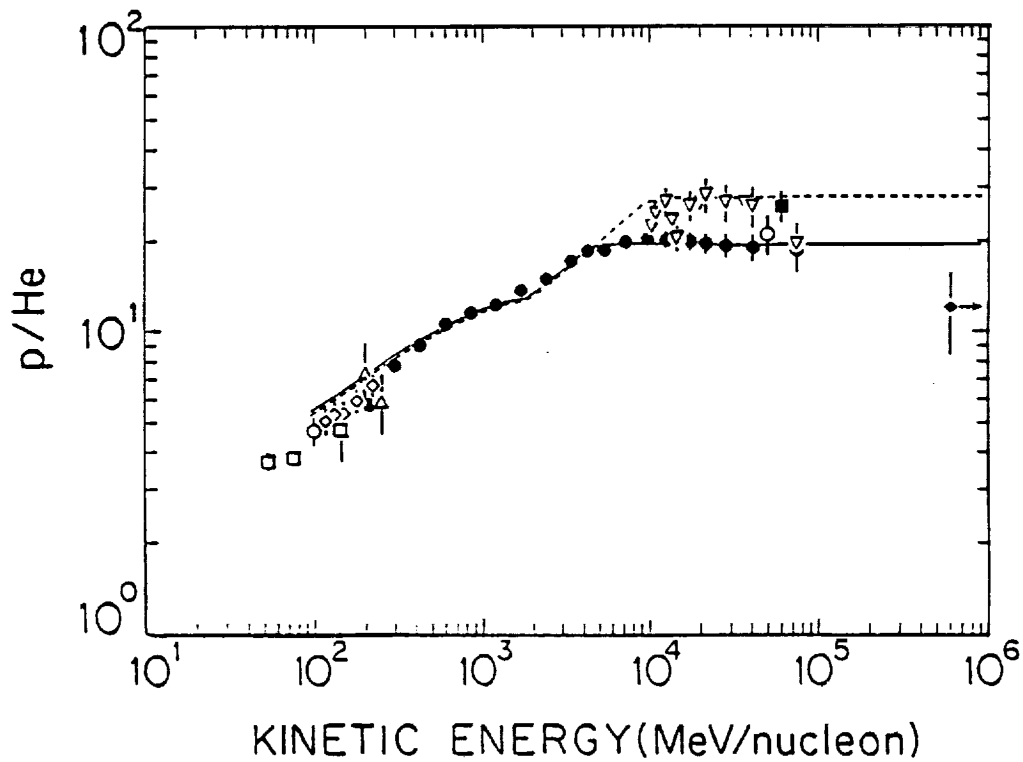

Figure 3. Compiled data for the H/He ratio as a function of energy

by SCIN/MAGIC. Such composition effects may be related to the (unknown) astrophysics that causes the "feature" in Figure 2. The reduced p/α ratio measured by the balloon experiments must be confirmed and, moreover, the measurements must be extended to cover a larger energy range to search for an energy dependence in the ratio above a few TeV. This becomes an important objective for the SCIN/MAGIC investigation.

The composition of the cosmic rays is known to be energy dependent. In particular, secondary to primary ratios decrease with increasing energy, indicating that the particles pass through less interstellar matter at high energies. One of the important outstanding questions is whether this decreasing matter traversal continues to the highest energies. Figure 4 shows a compilation of data for the B/C ratio which illustrates the energy dependence. The recent high energy measurements are shown as vertical rectangles, and the upper limit at the highest energy refers to data at ~1 TeV/nucleon. There is no evidence for a flattening of the B/C ratio with increasing energy, but such a flattening at a matter traversal of 1-2 g/cm^2 cannot be ruled out with current experimental results. If the matter traversal does reach a finite limit, then even the highest energy particles must pass through some interstellar matter which implies the necessity of correcting the composition for fragmentation in the interstellar medium. If the ratio continues to decrease, then at the highest energies it should be possible to observe the source composition directly.

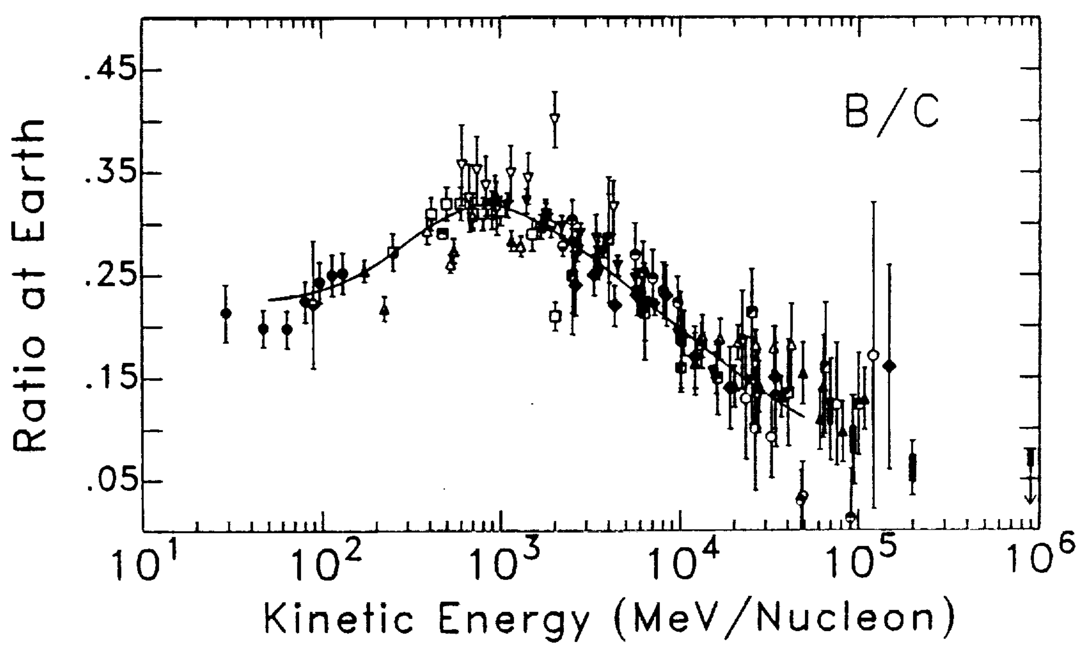

Figure 4. Compiled data for the energy dependence of the B/C ratio.

The experimental challenge for the SCIN/MAGIC investigation is two-fold. First, sufficient statistics for Carbon nuclei must be collected to allow, at least, a reliable upper limit to be placed upon the B/C ratio at energies of 5-10 TeV/nucleon. Second, the charge resolution of the SCIN/MAGIC detectors must be demonstrated to be sufficient to separate any (few) Boron events that are observed from the "tail" of the Carbon distribution.

Another important region is the iron peak. Here, measurements extend to 1-2 TeV/nucleon and show that the iron spectrum is flatter (γ~2.55) than the spectra of other primary elements (γ~2.7). At higher energies, only upper limits are available. If all of the cosmic ray heavy nuclei are accelerated by the same source or sources, then the spectra should be same, when the particles leave the acceleration region. These source spectra are then modified by the propagation of the particles in the galaxy. In this picture the iron spectrum should begin to steepen at some energy and eventually become a γ~2.7 spectrum. If this does not occur, then the whole acceleration model for cosmic rays would be called into question.

Thus, the iron spectrum is a very important measurement for the SCIN/MAGIC experiment. This is, perhaps, the most stringent experimental requirement since achieving this objective will require both a large collecting power to obtain sufficient iron events, good energy resolution for the measured events and excellent charge resolution to separate iron from the sub-iron secondaries. The latter will require detailed detector specifications, quality control during production and careful environmental control before, during and after the exposure in space.

3. Accommodation of SCIN/MAGIC

The SCIN/MAGIC payload is to be carried to orbit by the STS, deployed to SSF and then attached to the Astromag facility either by Astronauts or by the station robotic servicing system. This provides two accommodation questions: (1) Orbiter accommodation and (2) Astromag attachment.

The transport of emulsion chambers in the orbiter cargo bay involves the emulsion chamber "box" and its attachment to the structure, for example an MPESS type system. This problem is being investigated by the UAH group under contract to NASA, working with MSFC staff. Under this program a "box" and a carrier system are being developed.

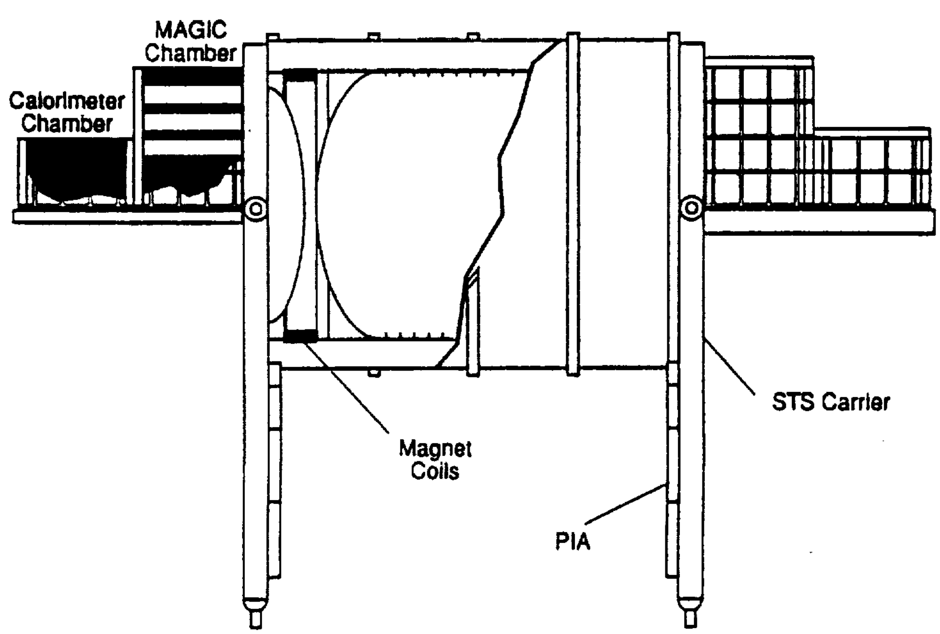

Figure 5. Proposed configuration for SCIN/MAGIC attached to Astromag.

For the Astromag accommodation, the question is the configuration of the MAGIC emulsion chamber within the field of the Astromag magnet. The initial configuration proposed for the experiment is shown in Figure 5. Note that the chambers are mounted in the upper region of the field produced by the magnet. The Astromag is a "single coil" system so that the field is strongest near the face of the coil and diverges with distance from the coil. Obtaining the maximum bending and the best rigidity resolution in the MAGIC chambers, requires a mounting as close to the magnet face as possible and in the central region of the field. It is recommended that the "box" be designed to have a minimum thickness on the side next to the magnet coil and that an Astromag accommodation be investigated that places the center of the MAGIC drift spaces near the center line of the coil.

4. Automated Microscopy

A major factor in the success of the SCIN/MAGIC program will be the degree to which the event measurement process can be automated to allow both an increase in measurement speed and the use of less well-trained personnel to perform many of the measurements. Automated microscopy, or at least a semi-automated system will be needed to meet this requirement. Automated systems are available commercially, but designed for specific applications, e.g. analysis of biological specimens, inspection of microelectronics substrates, etc. Such systems are, in general, too limited for the variety of problems encountered in emulsion analysis, which is inherently three-dimensional. Rather, one can either build a custom system or begin with a commercial product and modify it for the present task. Both approaches are being studied by the SCIN/MAGIC collaboration.

At LSU, we are developing a custom system based upon a CCD camera mounted on a microscope with a digitized stage. This is a semi-automated system developed for use in accelerator beam experiments. The system is controlled by an 80386 microcomputer, which could easily handle control of the stage motion if stepper motors were attached to the stage. The CCD image is of high quality and can be used to automate some of the measurement process.

For use with SCIN/MAGIC, however, the incident particle trajectory will vary over a large angular range (compared to an accelerator beam), and this will necessitate changes in procedures and in the event reconstruction software. A first step has been taken in the latter area by developing a reconstruction program for events in emulsion chambers. An example is shown in Figure 6 for a JACEE event from a balloon-borne emulsion chamber. Figure 6 shows a three-dimensional plot of the secondary tracks emerging from the interaction occurring at the origin of the coordinate system, with the primary particle incident from the left along the Z-axis. Dimensions are in micro-meters and illustrate the fiducial volume that must be examined microscopically to find and separate all of the secondary particles. In the case of a MAGIC chamber, many of these particles would show a curvature that would be fit to indicate the particle's rigidity.

The current software development is a beginning and shows that semi-automated microscopy is possible for a SCIN/MAGIC program. The nature of the problems is well understood, but significant effort will be necessary to turn the current level of software into a fully functioning system for SCIN/MAGIC analysis. It is recommended that this development effort be continued, with increasing resources, over the next several years.

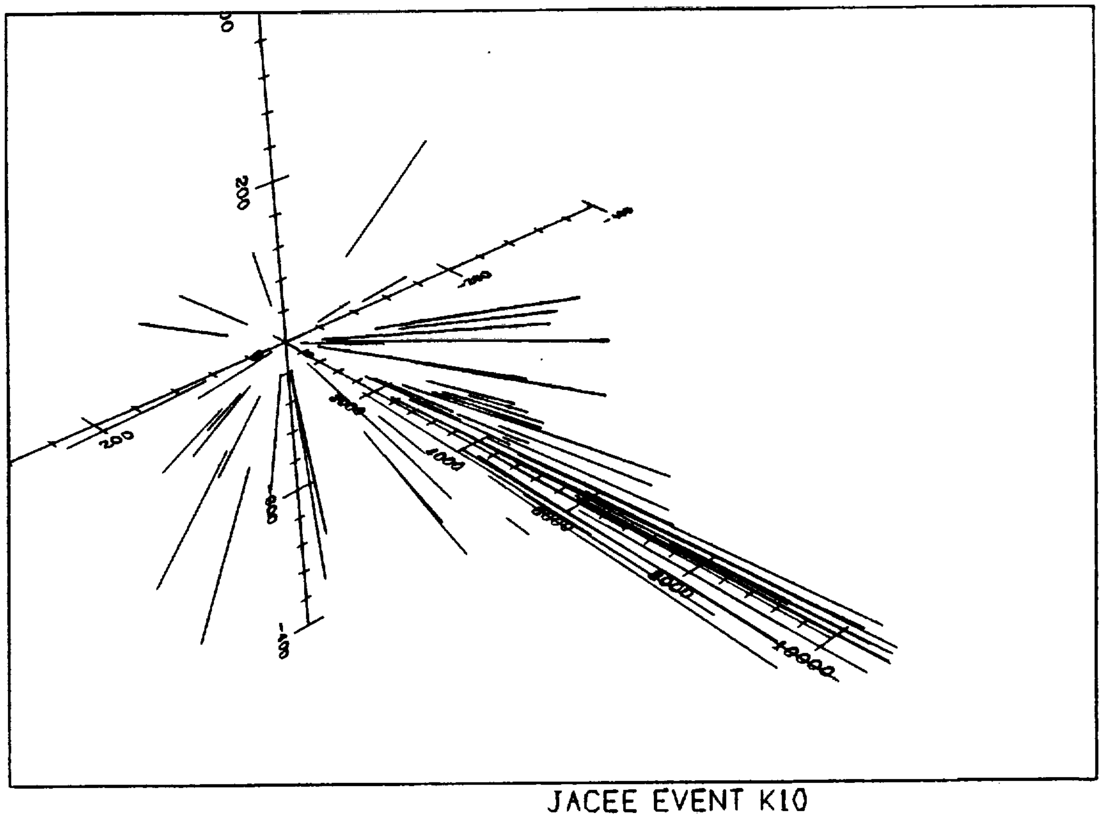

Figure 6. Software reconstruction of a JACEE emulsion chamber event.

5. Background Measurements

One of the principal differences between a space exposure and a balloon experiment is the higher level of low energy background tracks, even in the SSF orbit. These are due to the penetrating protons encountered in the South Atlantic Anomaly region of the orbit. This background may limit the exposure time for emulsion chambers in space or dictate the degree to which ultra-high energy events can be analyzed in the exposed chambers. The latter problem can be evaluated from balloon experiments flown near the magnetic poles, so that the chambers experience a large "dose" of low energy events along with the ultra-high energy particles that are the main goal of the SCIN/MAGIC program.

Under this contract we have participated in such a test by including several small emulsion chambers on a payload launched from Antarctica in December, 1990. The flight lasted ~8.5 days completing one circumnavigation of the South Pole. The package was successfully recovered and returned to the US for development and analysis. Test plates have been developed and show that the detector materials survived the exposure quite well. Processing of the full stack is in progress and the materials will be analyzed over the next several months. The results will be extremely important for the final design of the SCIN/MAGIC chambers and for the "box" that holds the photosensitive materials.

6. Reference

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15. Supplementary Notes

16. Abstract

Initial definition studies have been performed for the SCIN/MAGIC experiment selected as an Astromag investigation on Space Station Freedom. The study focused on Science Objectives and Science Requirements, Accommodation on both the STS and the Astromag facility, Data extraction techniques and Background Studies. The detectors are emulsion chambers which will be exposed for ~90 days and then recovered from orbit for subsequent processing and analysis in the laboratory. Such a technique is the only means to obtain information on the ultrahigh energy cosmic rays and their nuclear interactions. The SCIN/MAGIC investigation can supply unique data in relatively unexplored energy region and address many of the fundamental questions in particle astrophysics.

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