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ISOTOPIC COMPOSITION OF PRIMARY COSMIC RAYS H-FE FOR ISEE-C

FINAL REPORT

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INTRODUCTION

This report describes the high energy Cosmic Ray Instrument built for the International Sun-Earth Explorer project by the University of California at Berkeley and the Lawrence Berkeley Laboratory. It also gives a critical review of a number of aspects of that system so that the experience gained in the design, construction and operation of this experiment can serve as a guide in designing future cosmic ray particle identification systems.

Basic descriptions of the instrument and its major subsystems are contained in the following documents, which are included as appendices to this report:

1) Greiner, D.E., Bieser, F.S., and Heckman, H.H. "ISEE-C HKH High Energy Cosmic Rays", ISEE Transactions on Geoscience Electronics, GE-16, 163 (1978)

2) Ball Brothers Research Corporation, Time Zero Laboratories "UCB Cosmic Ray Experiment (ISEE-C, HKH) Final Report" (excerpts).

3) Walton, J.T., Sommer, H.A., Greiner, D.E., and Bieser, F.S., "Thin Window Si (Li) Detectors for the ISEE-C Telescope", ISEE Transactions on Nuclear Science, NS-25, 391 (1978).

4) Bieser, F.S., Greiner, D.E., Beleal, E., and Aalami, D.D., "A Proportional Drift Chamber Array for Cosmic Ray Instruments,"

Proceedings of the 15th International Cosmic Ray Conference (Plovdiv) 9, 91 (1977).

5) Greiner, D.E., Bieser, F.S., Crawford, H., Heckman, H.H., and Lindstrom, P. J., "Mass Resolution of a Particle Identifier to be Flown on ISEE-C," Proceedings of the 15th International Cosmic Ray Conference (Plovdiv) 9, 97 (1977).

The following sections of this report discuss the in-flight performance of the cosmic ray isotopic composition experiment described in the documents listed above. Also included is a bibliography of the scientific publications which had resulted from this experiment as of 31 September 1983.

I. ENERGY LOSS DETECTORS

The detectors used to measure the total energy and the energy loss rate of cosmic ray nuclei as they slow down and stop in the instrument were developed by the solid state instrumentation group of the Lawrence Berkeley Laboratory's Nuclear Science Division to meet the special requirements of this experiment. The most important of these are the following: large area; a high degree of thickness uniformity; dead layers of minimal thickness; and low noise and leakage current. The lithium drifted silicon detectors which were developed met or exceeded all of the design goals and contributed greatly to the success of the experiment. Some of the important features of the Si(Li) detector performance are discussed below.

A. THICKNESS UNIFORMITY

The thickness typically varied by less than 10 μm (out of a nominal thickness of 4700 μm) over the 15 cm^2 active area of the detectors. Since mass identification requires that a particle's pathlength through the detector material be known with an rms uncertainty no greater than about 0.2%, this high degree of thickness uniformity made it possible to treat the Si(Li) detectors as if they had a completely uniform thickness profile and thereby avoid the complications involved in making and using detailed thickness profile maps to obtain the amount of detector material traversed by each cosmic ray nucleus. This is particularly important for such thick detectors since there can be a considerable spatial separation between the point at which a cosmic ray enters and exists a detector and a knowledge of the topography of each of the detector surfaces could, in principle, be required to make adequate corrections in a non-uniform device.

B. DEAD LAYERS

The presence of "dead layers", detector material in which the ionization electrons produced by the deposition of energy cannot be collected, can significantly degrade the performance of charge particle telescopes. The mass identification error introduced by the failure to detect the energy deposited in dead material can significantly degrade mass resolution[1] if the thickness of such layers is even 1% of the detector thickness. In conventional Si(Li) detectors, a thick dead layer is present on one face of the detector due to the requirement that Li (which constitutes the dead material) must be deposited on the detector surface to carry out detector compensation by the lithium drifting process. The LBL group developed a technique for removing the residual Li dead layers after drifting and replacing it with a very thin (< 15 μm) layer of Li re-evaporated onto the detector.

Subsequent to the launch of ISEE-3 it has been reported[2] that these lithium contacts tend to grow with time when the detectors are stored at room temperature. Initial growth rates of 9 μm/yr have been observed. No effects of dead layer growth were evident in the cosmic ray isotope data which we collected with the ISEE-3 instrument, but further consideration should be given to the possibility of such effects when detectors of this design are to be applied in future long duration experiments.

C. DISTORTION OF ENERGY LOSS SIGNAL AT 0° INCIDENCE ANGLE

In the pre-flight accelerator calibration of our ISEE instrument it was observed that the pulse height signal obtained from a Si(Li) detector penetrated by a heavy nucleus with a trajectory nearly perpendicular to the detector surface ($\lesssim 2°$ from normal incidence) could differ significantly ($\sim$1%) from the expected pulse height. It has been noted that, due to the usual biasing arrangement used with such detectors, these trajectories are also nearly parallel to the direction of the electric field in the detector. This effect has also been observed by other groups using Si(Li) detectors produced both by LBL and by commercial manufacturers. The effect has been found not to occur, however, in Si detectors of the surface barrier type.

The presence of this "0°-effect" does not pose significant problems for cosmic ray observations since only a very small fraction of the solid angle viewed by a typical instrument lies within the angular region where this problem occurs. Furthermore, the use of trajectory sensing in high resolution particle identifiers makes it possible to identify and remove these events, if necessary. However, it is important that the 0° effect be taken into account in performing accelerator calibrations of such systems, since it is particularly convenient to collect calibration data at a 0° incidence angle where the back detectors in a telescope will not be shadowed by the inactive mountings of the front detectors. A good calibration can be obtained by orienting the detector telescope at a small angle (say 5°) to the beam direction.

D. IMPORTANCE OF REDUNDANT ENERGY LOSS MEASUREMENTS

The charge and mass of a cosmic ray nucleus can be determined from a measurement of its energy loss in penetrating a single detector together with a measurement of its total energy (assuming that its trajectory is known). A number of effects can alter one or both of these signals to produce an erroneous particle identification. Such effects include fragmentation of the nucleus in the energy loss detector and entry or exit of the particle through the side of a detector. With a simple two detector measurement there is no way to identify such events, so data based on 2-detector particle identification can contain a significant background contribution. We find that the use of three or more detectors to provide redundant particle identification provides a very powerful means for eliminating these backgrounds. This is essential when studying rare species which can be contaminated by backgrounds produced by nearby species with much greater abundances (e.g., beryllium isotopes being contaminated by interactions of carbon).

In order to achieve redundant particle identification we restricted most of our analysis to particles which stopped in detectors 3 through 9. For such events at least two energy loss measurements, together with a total energy measurement, are available and at least two nearly independent estimates of the particle's charge and mass can be derived. The requirement that the particles penetrate at least as far as D3 significantly increases the minimum energy for mass identification (to the energy at which a given nuclide can penetrate approximately 1 cm of silicon). One could reduce this lower limit in future instruments. For example, if the first 5 mm thick detector in our instrument were replaced with three 1 mm thick detectors followed by one 2 mm thick detector, the minimum energy for three parameter analysis of ^{16}O would be reduced from 95 MeV/amu to 40 MeV/amu. Even thinner front detectors could provide additional improvements. In instruments such as this where a large geometrical factor is sought it is important that the front detectors not have active areas much smaller than the later detectors. It is, at present, difficult to produce good very large area detectors much thinner than 1 mm, thus trade offs between geometrical factor and energy range may be required.

II. TRAJECTORY MEASUREMENT SYSTEM

The innovation which made isotopic resolution possible for a wide range of elements in this experiment was the inclusion of a trajectory measurement system which could determine the angle at which each cosmic ray nucleus entered the instrument and which made possible a determination of the amount of matter traversed in each of the detectors. Such systems have now become a standard part of cosmic ray particle identifiers. The trajectory measurement was accomplished in this instrument by means of an array of six gas proportional drift chambers, which yielded three measurements of each of two orthogonal coordinates (X1, X2, X3 and Y1, Y2, Y3) at successive positions along the track of the particle. The spacing between these measurements (5 cm between first and last measurements of X and also between first and last measurements of Y) established the position resolution required to resolve adjacent isotopes for the heaviest elements being measured (iron and nickel). This required position resolution was approximately 0.3 mm (rms). The resolution actually achieved was only ∿ 1.0-1.3 mm (rms), due to a number of technical difficulties discussed below. This resolution was sufficient for making a number of major advances in cosmic ray composition investigations, but further improvement in position sensing capability is of prime importance for obtaining the maximum scientific yield from future cosmic ray isotope investigations using this sort of instrumentation.

A. RESOLUTION IN THE DETERMINATION OF PARTICLE TRAJECTORIES

The uncertainties in our trajectory measurement result from jitter in the start and stop signals used to determine the electron drift time in the chambers. The start signal is derived from the logical AND of the outputs of low-level leading edge discriminators in the D1 and D2 Si(Li) detector electronics. The walk in the timing of these discriminator outputs due to variations in the pulse height and shape can cause a significant uncertainty in the measured position. For example, for nuclei stopping in D3 through D9 we see a change in the quantity X2 - 1/2 (X1+X3) (which should be constant) of 9.0 mm between Li (Z = 3) and Ni (Z = 28). Even larger changes were observed for nuclei stopping in D2 since both the size and the shape of the signal in D2 varies significantly depending on the depth in the detector to which the particle penetrated. For high resolution mass measurements, only nuclei stopping in D3 through D9 were analyzed.

Since all drift chamber coordinates are measured using the same start time, approximate cancellation of the start time walk can be achieved by using only coordinate measurements involving drift in the same direction for calculating the particle's incidence angle. Thus, we based our calculation of incidence angle on X1, X2, Y1 and Y3 alone. The mass resolution obtained using incidence angles calculated in this way implied a residual position uncertainty of approximately 1.0 to 1.3 mm (rms), consistent with pre-flight accelerator tests.

The electron drift in the X2 and Y2 drift chambers was in a direction 180° from that of the electron drift in the other X and Y drift chambers, respectively. The X2 and Y2 coordinates were used to check that the measured trajectory was consistent with a straight line. That is, the quantities $\Delta X \equiv X2 - 1/2\ (X1+X3)$ and $\Delta Y \equiv Y2 - 1/2\ (Y1+Y3)$ were formed and a Z-dependent correction was added to compensate for the start time walk effect. The quantities ΔX and ΔY, which would be zero if the coordinate measurements were not subject to fluctuations, were found to have distributions with rms widths of approximately 2.3 mm (independent of the particle's charge). Data having $|\Delta X|<5$ mm and $|\Delta Y|<5$ mm were selected to eliminate most events with erroneous trajectories (and therefore possibly erroneous mass assignments) without eliminating a significant fraction of good events. This selection was found to be essential to eliminating background from charge and mass histograms since an event with an erroneous assignment of incidence angle can mimic a good event with an incorrect charge and/or mass well enough so that consistency tests among the multiple ΔE detectors will not identify the event as background.

The effective resolution of $\sim$ 1.0-1.3 mm ultimately achieved in measuring the particles' trajectories was limited by the performance of the analog circuitry used to produce the stop pulses from the drift chambers. Because of the presence of ionization caused by knock-on electrons spreading out from the tracks of cosmic ray nuclei, the drift chamber discriminators employed a sliding threshold to minimize sensitivity to ionization outside the dense core of the cosmic rays' tracks. The implementation of this sliding threshold required a delay of the analog drift chamber pulse to obtain sufficient time to establish the threshold level. It was found that unless delay lines of sufficiently large bandwidth were employed for producing this delay the attenuation of high frequencies by the delay lines could significantly distort the stop time determination. Delay lines were selected to have the highest bandwidth achievable within the weight constraints on the experiment. A further increase in this bandwidth would have resulted in improved position resolution and, therefore, improved charge and mass resolution.

B. SELECTION OF HIGH RESOLUTION SUBSETS OF THE DATA

Since the drift chamber resolution was not sufficient for unambiguously determining the charge and mass of all of the cosmic ray nuclei observed, it was necessary to select subsets of the data in which such identification was possible. The overall mass resolution was dominated by uncertainties in the trajectory determination and this contribution to the mass resolution scales as sin 2θ (for fixed position resolution) where θ is the angle of a particle's trajectory from the normal to the detector surfaces. Therefore, by considering only those events having θ less than some selected θ_{max}, a data set with improved mass resolution could be obtained. This improvement in resolution was achieved at the cost of poorer statistical accuracy. Thus, for each element we chose a value of

θ_{max} to give an optimum combination of resolution and statistics for the abundance distribution of the isotopes of that element. For the lightest elements, Li, Be, B, we were able to use essentially all of the data which we collected, whereas for iron we needed to restrict the analysis to < 3% of all data collected to achieve sufficient resolution for separating individual isotopes.

C. PRESSURE VESSEL FAILURE

A pressure vessel was used to maintain the drift chambers in a gas mixture of 10% CH_2 + 90% Ar at a pressure of approximately 1 atm. This vessel successfully maintained the required atmosphere for 32 months of flight. In April 1981 a leak in the gas system developed and the drift chamber gas was lost over a period of one half hour. The time elapsed between launch and the occurrence of this failure is consistent with the flux of micrometeoroids of sufficient size and velocity to puncture the 0.13 mm beryllium-cooper pressure vessel window, as calculated prior to launch. There is insufficient information on the nature of the pressure vessel failure, however, to definitely establish that puncture by a micrometeoroid was the cause.

The possibility of such failures of thin windowed gas filled detectors has important implications for the design of future detector systems. When a large area detector is to be exposed for extended periods in space with no opportunity for repair, several possibilities should be considered:

1) use detectors which do not require a gas filling, rather than gas filled detectors (for example, position sensitive solid state detectors rather than drift chambers);

2) increase the shielding of the gas volume against direct micrometeoroid impacts as much as possible and make the vessel as resistant to such impacts as possible (for example, in a high energy cosmic ray detector the pressure vessel window could be reasonably thick and baffles could be used to block out particles with trajectories outside the range analyzed by the instrument); and

3) the gas detectors could be housed in separate pressure vessels so that loss of gas from a single vessel would only reduce redundancy rather than entirely disable the gas detector system.

The loss of trajectory measurement capability from our instrument did not completely preclude particle identification. With no trajectory sensing we are still capable of resolving individual elements through $Z \simeq 8$, even charge elements through $Z \simeq 16$, and the dominant heavy element iron ($Z = 26$). Isotopic resolution is still possible for separating ^3He from ^4He and ^7Be from ^9Be.

III. LOGIC CIRCUITRY

The logic circuitry for this experiment was entirely hard wired. Future experiments of this type will certainly employ microprocessors for the bulk of the logic functions needed, thereby replacing much of the digital circuit design effort with software development effort. For this reason we will not discuss details of the logic implementation in this experiment, but will confine our comments to a few aspects of the logic functions which could be altered to particular benefit.

A. PILE-UP REJECTION

Circuitry to determine when an analyzed event was preceeded or followed within preselected time intervals by another event was implemented so that such instances of pulse pile-up could be identified. The elimination of pile-up events is important for minimizing the experiment's background level. The implementation in this experiment employed rather long pre- and post-pileup intervals to allow for worst-case conditions. This resulted in a large fraction of the recorded events being tagged as "pile-up". Mass analysis of these pile-up events showed that most of them were perfectly acceptable for analysis. Thus the pile-up flags were useless for rejecting background unless one was willing to discard a significant fraction of good events.

It should be possible in future experiments to adjust the duration of the pile-up gates in accordance with the height of the pulse responsible for triggering the pile-up condition. Thus a long pile-up interval would be required only for the relatively rare heavy nuclei (such as iron and nickel) while much shorter intervals could be used for the much more frequent hydrogen and helium events, which produce much smaller pulses.

B. EVENT RATE ACCUMULATION

The experiment employed two types of rate accumulation - analog rate meters for recording singles rates from each of the detectors, and digital scalers for counting how many nuclei satisfying each of the five event type definitions were discarded (due to telemetry limitations) between successive readouts of events of that particular type. This latter approach to reading out coincidence rates proved rather inconvenient since the read out intervals for the various event types could vary enormously and when a particular event type was disabled no readout of that particular rate would be available at all. Furthermore, to obtain an average value of any of these rates over an extended time interval (days, months, etc.) one must process the entire data base during that interval to sum all the individual event counts which were read out.

The continuous accumulation of event counts in the experiment logic, together with periodic readouts, could greatly simplify the use of the rate information.

C. LIVE-TIME ACCUMULATION

A determination of the fraction of time that the experiment is "live" (that is, prepared to accept a new incoming event rather than busy processing a previous event) is needed for the determination of absolute fluxes. The experiment measures dead time by means of a scaler which counts clock pulses that occur every 31.25 msec, gated by a signal which indicates that the pulse height analyzer is not busy. This scaler is 13 bits long, and the most significant 7 bits are readout with each analyzed event. Thus the scaler will overflow every 128 seconds when the dead time is negligible.

This scheme, while providing sufficient information for dead time correction, is inconvenient in much the same way as the coincidence event scalers discussed above. The dead time information is statistical in nature, so averages over extended time intervals are desired, but since the counter overflows about every 2 minutes, it is necessary to follow the data stream rather closely to avoid miscounting the number of overflows. An implementation with a much longer counter and a less frequent readout would provide a more convenient measure of dead time.

D. REDUNDANT LOGIC

Two identical copies of the digital logic circuitry were included in the instrument and a command from the spacecraft can be used to select which of the two is to be used. This system was used to provide the redundancy needed to maintain normal operation if a failure in the logic were to occur. In the first five years of flight no such failure occurred and this feature has not been needed. We note, however, that just such a failure occurred in the Caltech ISEE-3 instrument 3 1/2 months after launch, and had a significant impact on the performance of that experiment. Redundant logic could have been of considerable value in that circumstance.

The trade-offs between the costs and the benefits of redundant logic systems are dependent on the specifics of the experiment and the mission and need to be evaluated on a case-by-case basis.

IV. COMPARISON OF ACTUAL PERFORMANCE WITH PROPOSED OBJECTIVES

The essential performance characteristic of an instrument intended for the study of isotopic composition is the mass resolution, σ_M. In order to resolve adjacent isotopes having relative abundances up to $\sim 100:1$, one requres $\sigma_M \lesssim 0.25$. The mass resolution projected in the proposal for this experiment ranged from < 0.1 amu for $Z \lesssim 8$ to ~ 0.16 for $Z = 26$. At the time that proposal was made the contribution of trajectory uncertainties to the mass resolution was thought to be negligible, and a trajectory measurement system was included only to aid in removing discrete ambiguities in the isotope identifications. The predicted mass resolution therefore corresponded to that which should be achievable for particles whose trajectories (i.e., angles of incidence) are known exactly. Calibrations with accelerator beams (where angles of incidence are precisely known) do, in fact, approach this predicted mass resolution.

During the course of instrument development it was determined that precise trajectory measurements would be essential for achieving the mass resolution required for the isotopic composition studies proposed, and that angular resolution better than the proposed ± 2° would be needed. The design of the trajectory sensing system was modified to improve upon this figure. The angular resolution actually achieved in flight was better than the proposed figure by a factor $\sim$ 1.3-1.8. This was sufficient for isotope separation for $Z \lesssim 5$. In order to separate adjacent isotopes up to $Z = 26$, a further improvement by a factor $\sim$ 4 would be necessary. In order to achieve the necessary mass resolution, data selection based on particles' angles of incidence was used (see Section II.B of this report). Thus the necessary resolution was attained throughout the range of elements covered in the proposal, but in some cases only for a restricted subset of the data. This trade-off of statistics for resolution caused difficulties only for heavy, low-abundances elements such as scandium ($Z = 21$) through manganese ($Z = 25$) for which too few events were available to permit the necessary data selection. It has been possible to meet essentially all of the scientific objectives set out in the proposal, as well as to investigate a number of important questions which were not even anticipated at the time the proposal was made.

FOOTNOTES

1. Greiner, D.E., Nucl. Instr. and Methods, 103, 291 (1972).
2. A.J. Tuzzolino, University of Chicago, private communication.

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