THE ASTROPHYSICAL JOURNAL, 327:L31–L34, 1988 April 1

ENERGY SPECTRA OF COSMIC-RAY NUCLEI FROM 50 TO 2000 GeV PER AMU[1]

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Received 1987 November 6; accepted 1987 December 30

ABSTRACT

A direct measurement of the elemental composition of cosmic rays up to energies of several TeV amu^{-1} was performed during the Spacelab 2 flight of the Space Shuttle. In this *Letter* we present results on the spectral shape for the elements C, O, Ne, Mg, Si, and Fe, obtained from this experiment. It was found that the C and O energy spectra retain a power-law spectrum in energy with an exponent Γ of about 2.65. The Fe spectrum is flatter ($\Gamma \approx 2.55$) up to a particle energy of $\sim 10^{14}$ eV, indicating a steady increase in the relative abundance of iron in cosmic rays up to this energy. The energy spectra of Ne, Mg, and Si are steeper than anticipated. This behavior is unexpected within current models of cosmic-ray acceleration.

Subject heading: cosmic rays: abundances

Observations of extensive air showers and of muons deep underground have revealed that the energy spectrum of the cosmic radiation extends up to energies of 10^{20} eV. The elemental composition of particles at these energies contains important information as to their origin. However, at energies beyond about 10^{12} eV, very little is known about this composition. In this *Letter* we shall describe the first results from a space-borne experiment that provides direct energy measurements of individual nuclear species well beyond 10^{12} eV. These results indicate differences between the relative energy spectra of primary species, an important finding for understanding acceleration mechanisms and the nature of the cosmic-ray sources.

Previous direct observations of cosmic-ray nuclei have been made at lower energies with instruments carried on balloons and satellites. These measurements revealed that the relative abundances of galactic secondary nuclei, those that are predominantly produced by spallation of primaries in the interstellar medium, decrease with increasing energy (Juliusson, Meyer, and Müller 1972; Smith *et al.* 1973; Juliusson 1974; Caldwell 1977; Simon *et al.* 1980; Engelmann *et al.* 1983). Thus, the amount of interstellar matter traversed by the primary cosmic rays appears to decrease with energy, perhaps due to a higher probability for escape from the Galaxy. This effect must be taken into account when one extrapolates the energy spectra of the primary nuclei to their sources. Over the energy range of previous measurements, no significant energy or rigidity dependence of the source composition has been observed.

The previous observations have utilized a variety of experimental techniques including calorimeters, magnet spectrometers, and Cerenkov counters. In the present work, we used, for the first time, transition radiation detectors for energy measurements from 500 GeV amu^{-1} to several TeV amu^{-1}. Our instrument was flown on the Spacelab 2 mission of the Space Shuttle Challenger from 1985 July 29 to August 6. The upper limit to the energy range that could be covered in this flight was determined by counting statistics rather than by limitations in the dynamic range of the instrument.

Shown in Figure 1 is a schematic cross section of the instrument. It consisted of three main detector assemblies.

1. Two plastic scintillation counters T1, T2 (NE-110 in light integration boxes) served as the main trigger by requiring that each nucleus pass through both counters. The scintillation signal provided an accurate measure of the charge of each traversing particle. The charge resolution at energies above 50 GeV amu^{-1} was approximately 0.2 charge units at oxygen. In addition, the direction of traversal of each particle was determined by a time of flight measurement (1 σ resolution ≈ 1 ns) between these two counters.

2. Two identical gas Cerenkov counters C1, C2 located above and below the scintillation counters were filled with a N_2-CO_2 gas mixture at atmospheric pressure to achieve a Lorentz factor threshold of $\gamma_0 = 40$, allowing energy measurements in the range 40–150 GeV amu^{-1}.

3. A six-layer transition radiation detector (TRD) was placed between the scintillation counters. Each layer consisted of a polyolefin fiber radiator, and a multiwire proportional chamber (MWPC), filled with a Xe/He/CH_4 gas mixture. The relativistic rise in the ionization loss measured in the MWPCs provided an estimate of the particle energy up to about 500 GeV amu^{-1}, thus overlapping with the energy range of the Cerenkov counters. Above 500 GeV amu^{-1} the detection of transition radiation X-rays, superposed upon the ionization energy loss signal, was used as a measure of the particle energy. The transition radiation signal reaches saturation well above the energy region for which we obtained statistically meaningful data. The MWPCs also served as a hodoscope to determine the particle trajectory through the instrument. The overall energy resolution of the detector combination varied both with charge and with energy. For instance, the resolution (1 σ) for oxygen was 8% just above the Cerenkov threshold of 40 GeV amu^{-1}, but 35% at 100 GeV amu^{-1}, and 11% at 1000 GeV amu^{-1}. The respective resolution figures for iron were 2%, 13%, and 8%. Details of the instrument and its performance will be published in a separate paper (L'Heureux *et al.* 1988).

The effective exposure time during the 7 day flight was 94 hr, yielding approximately 4×10^7 events. The aperture used for the results presented here has a geometric factor of ≈ 2 m^2 sr.

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[1] Work supported in part under NASA contract NAS 8-32828 and NASA grants NGL-14-001-005 and NGL 14-001-258.

[2] Submitted to the Department of Physics, University of Chicago, in partial fulfillment of the requirements for the Ph.D. degree.

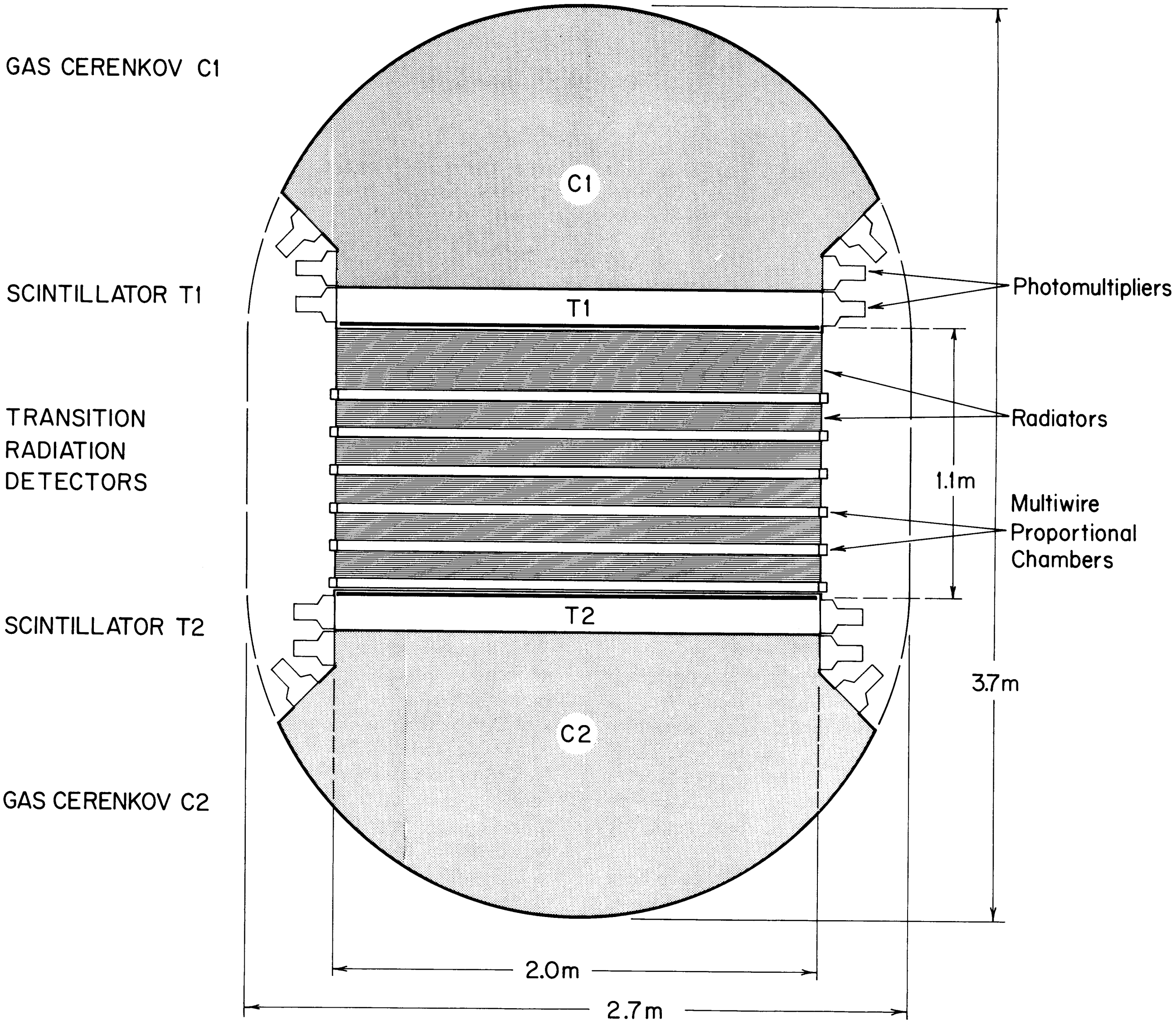

FIG. 1.—Schematic cross section of the instrument

In the data analysis, all events exhibiting clean trajectories through the instrument and not showing evidence for nuclear interactions in the detector, were selected. All signals were corrected for systematic effects due to spatial nonuniformities in the response of the counters, and due to path length variations in the detectors. Individual charges were well resolved in the scintillation counters.

To make full use of the information contained in the signals from all counters, an analysis technique was developed which compares the measured signals with those expected for a given charge and energy, for all detectors simultaneously. The analysis explicitly incorporated the energy dependence of signals in the various counters, as well as fluctuations in these signals. These details of the response of the counters were known from preflight calibrations, including calibrations on accelerator beams, and from consistency checks on the flight data themselves, utilizing the fact that different counters overlap in response to charge and energy, and that each individual measurement (scintillation light, Cerenkov signal, or TRD signal) was performed with at least two identical but independent counters. For instance, the relativistic increase in the ionization signal in the MWPCs was first measured on accelerator beams, but then verified in a cross-calibration against the Cerenkov response with flight data. The energy-loss distributions due to heavy nuclei in the MWPCs were extensively studied with the Bevalac heavy ion accelerator (Lamport *et al.* 1979), and the transition radiation yield was calibrated using relativistic particle beams at the Bonn Synchrotron and at Fermilab (Swordy *et al.* 1982). Integrating gas Cerenkov counters have the undesirable property that background light is emitted upon passage of the particle through the white reflective paint coating of the counter walls. In our case, this background amounted to about 20% of the saturated Cerenkov yield, necessitating a careful correction of the measured Cerenkov response. Again, the magnitude of this correction, its charge dependence ($\sim Z^2$) and its fluctuations have been determined from the data obtained during flight.

The analysis of the data provided the charge and energy of each nucleus as well as an estimate of the error in each determination. The requirement of consistency between the two scin-

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tillation counters and the two Cerenkov counters allowed great leverage in suppression of background events. In order to account for the finite energy resolution of the detectors, deconvolution corrections, based on Monte Carlo modeling of the instrument, were applied to the data. These corrections amounted to approximately 10% of the flux values obtained in a given energy interval. This model also verified that a correction due to charge misassignment was not necessary. The differential energy spectrum was fit by a power law in energy ($dN/dE \propto E^{-\Gamma}$) and the spectral index Γ was determined from this fit.

At this stage of the work, we present spectra of the most abundant primary nuclei C, O, Ne, Mg, Si, and the Fe group (Mn + Fe + Co) as observed at the instrument. They are shown in Figure 2 and compared with results by other authors. The error limits indicated on our data are due to statistics only. For instance, the highest energy iron group point is based on nine particles. We have not yet determined absolute fluxes, and the figure is based on a reasonable but somewhat arbitrary normalization of our measured spectra to the published data of other authors, at 50 GeV amu^{-1}. Table 1 shows the spectral indices observed with our data alone.

The most significant results are the following: the energy spectrum of Fe remains fairly hard up to a particle energy of

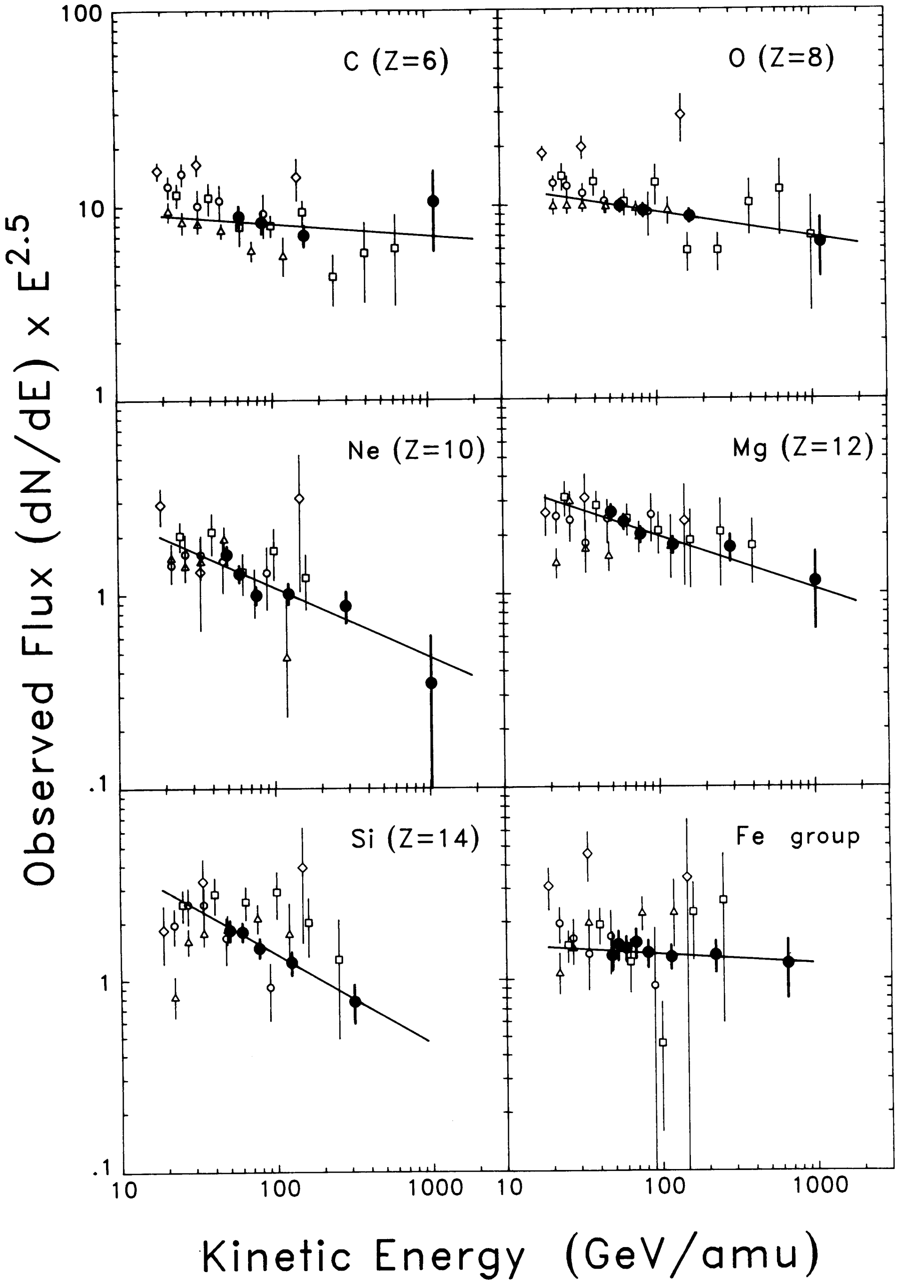

FIG. 2.—The differential energy spectra of C, O, Ne, Mg, Si, and Fe group (Z = 25, 26, 27) nuclei. Our results are shown as filled circles, and power-law fits to our data are given as solid lines. The spectra are multiplied by $E^{2.5}$ to emphasize spectral differences. Our spectra are compared, with an arbitrary normalization at 50 GeV amu^{-1}, with the results of previous measurements (*open circles*, Caldwell 1977; *triangles*, Juliusson 1974; *squares*, Simon *et al.* 1980; *diamonds*, Orth *et al.* 1978).

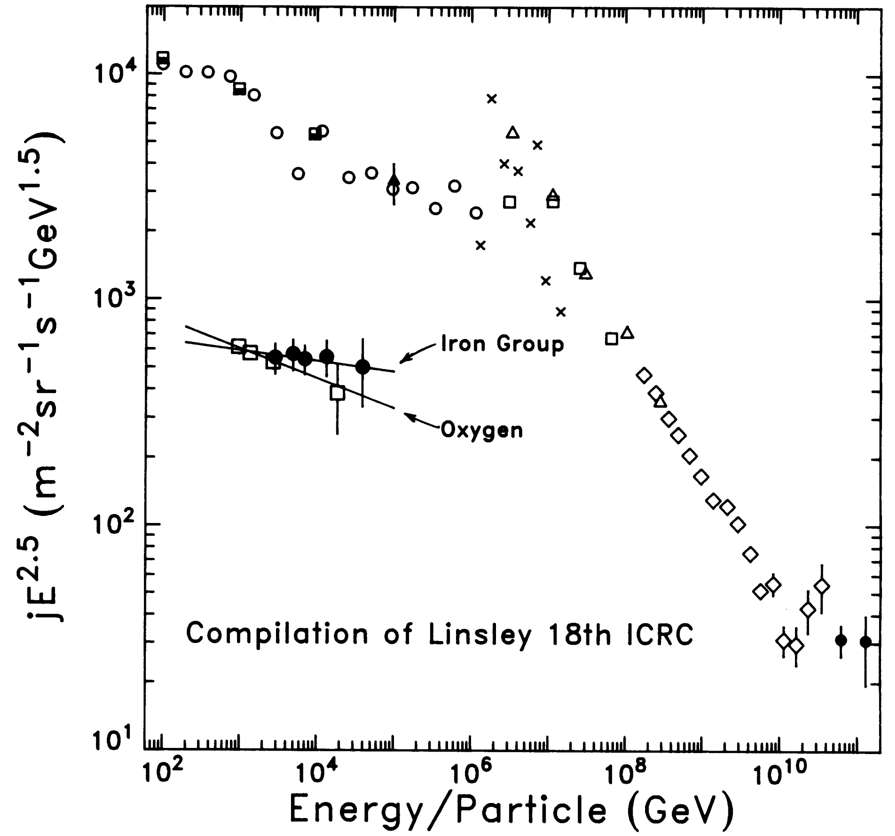

FIG. 3.—The all-particle energy spectrum as compiled by Linsley (1983) and the spectra of O and the Fe-group ($Z = 25, 26, 27$) as measured in this experiment. The lines represent the power-law fits to the O and the Fe group data obtained in this experiment. Note that in the absence of absolute fluxes, the normalization of our data is somewhat arbitrary.

TABLE 1

SPECTRAL INDICES FOR $E > 50$ GeV amu^{-1}

Element	Value[a]
Carbon	2.60 ± 0.17
Oxygen	2.65 ± 0.08
Neon	2.86 ± 0.10
Magnesium	2.77 ± 0.08
Silicon	2.97 ± 0.12
Iron group ($25 \leq Z \leq 27$)	2.55 ± 0.09

[a] Statistical errors only.

almost 10^{14} eV, indicating an increase in the relative iron abundance at least up to this energy. A similar conclusion was derived from the interpretation of some ground based experiments (Goodman *et al.* 1982). The spectra of C and O exhibit a power law close to that found at lower energy. The three elements Ne, Mg, and Si show surprisingly soft spectra at high energy. These differences in the power-law spectra of the primary cosmic rays observed near Earth are difficult to understand in the context of current models of interstellar propagation and of shock acceleration. To illustrate the range of our results we show in Figure 3 the all-particle energy spectrum compiled by Linsley (1983) together with our spectra for O and Fe. Note again that the normalization is somewhat arbitrary.

Our sincere thanks go to the engineers, programmers, technicians, and students in the Laboratory for Astrophysics and Space Research who participated in the design, construction, and integration of the instrument. We are particularly indebted to Don Bonasera, Linda Glennie, Wayne Johnson, and Roger Ray for their contributions. The support and help from the Spacelab 2 team at the NASA/Marshall Space Flight Center led by Roy Lester was crucial for the success of this experiment. John M. Grunsfeld acknowledges support by the NASA Graduate Student Research Program under grant NGT 14-020-804.

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