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ELEMENTAL ABUNDANCES IN THE LOCAL COSMIC RAYS AT HIGH ENERGIES

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ABSTRACT

We discuss recent measurements of cosmic-ray fluxes at high energy. The energy spectra of heavy nuclei determined on the Space Shuttle and on *HEAO 3* are considered in the context of a simple leaky box model. A fit to this model requires a source energy spectrum of the form $E^{-2.2}$ for all nuclear species, which is slightly steeper than our previous estimate. We represent these data in terms of total energy per particle to make a direct comparison with the observed all-particle spectrum of cosmic rays. We find that the sum of the fluxes of heavy nuclei from these satellite measurements and of protons and α-particles as measured on balloons agree well with the all-particle flux in the energy region 10^{13}–10^{14} eV obtained in space by the *Proton* satellite. This shows that the all-particle spectrum contains about 25% (by number) heavy nuclei ($Z \geq 6$) in this energy region. However, an extrapolation of our model to higher energies would predict particle fluxes that are significantly below the reported all-particle flux between 10^{14} and 10^{15} eV. This may either suggest a drastic change in the behavior of galactic cosmic rays in this energy range, or the appearance of an additional component. We note that this departure from the leaky box prediction occurs at energies well below the steepening in the all-particle spectrum that has been observed in air shower measurements.

Subject headings: cosmic rays — ISM: abundances

1. INTRODUCTION

The elemental composition and the energy spectra of high-energy cosmic-ray particles arriving at Earth provide the primary data set from which the origin of these particles and their history in the Galaxy must be determined. For instance, the relative abundance of nuclei produced by fragmentation is used to evaluate the path length of the material encountered in the interstellar medium. From the observed abundances of primary nuclei, the composition of the cosmic-ray source can be derived after choosing a model for the particle propagation in the Galaxy.

At present direct measurements of the nuclear composition of cosmic rays are limited to the region below 10^{14} eV per particle. A break or "knee" in the *all-particle* spectrum of cosmic rays around an energy of several 10^{15} eV has been reported on the basis of air shower data (for a compilation of data see Hara et al. 1983). The energy region of the knee appears to be close to the maximum energy that a particle can attain by first-order Fermi acceleration near interstellar shock fronts (for a review see Völk 1987). To confirm this expectation and to find experimental clues for the origin of the cosmic rays with still higher energies, a determination of the elemental abundances in this energy region has been a prime goal of particle astrophysics for a long time. However, direct measurements require large exposure factors above the atmosphere to collect sufficient numbers of particles, while indirect air shower measurements have little sensitivity to the nature of the primary nucleus. The intent of this paper is to discuss recent direct measurements up to $\approx 10^{14}$ eV, to study the implications of the data with a simple propagation model, and to investigate how the cosmic-ray composition may evolve at still higher energy.

2. ENERGY SPECTRA OF INDIVIDUAL ELEMENTS

Detailed measurements of the elemental composition of cosmic rays have been performed with balloons and with the *HEAO 3* spacecraft at energies below 100 GeV per amu. The Cosmic Ray Nuclei experiment (CRN) on Spacelab 2 (1985) has extended the measurements for heavy nuclei to almost 2 TeV per amu which corresponds to about 10^{14} eV for an iron nucleus (Müller et al. 1991). The JACEE[2] balloon program provided data on proton and helium fluxes beyond 10^{14} eV (Asakimori et al. 1991), together with some data for groups of heavy nuclei.

The CRN instrument, through the use of gas Cherenkov counters and transition radiation detectors, has measured the spectra of the individual elements boron to iron above 50 GeV per amu. The upper energy limit, about 2 TeV per amu for the more abundant primary species, is determined entirely by counting statistics achievable in a few days of Space Shuttle flight. The design and operation of this detector has been discussed elsewhere (L'Heureux et al. 1990; Swordy et al. 1990a). We note that this measurement has yielded absolute fluxes of arriving nuclei by accounting for the instrument aperture, data selection efficiencies, and dead time corrections, etc. (Müller et al. 1991). For instance, the total net exposure factor for carbon at high energies is 2.26 m^2 sr days and that for iron is 1.93 m^2 sr days. The numbers are different because the apertures and efficiencies depend on the nuclear charge, Z. The remaining normalization uncertainty is estimated to be ±10%. In Figure 1, we show the spectra of the major primary nuclei resulting from this investigation. The most recent data at energies just below our measurement come from the French-Danish experiment on *HEAO 3* (Engelmann et al. 1990). Again, this data set represents absolute fluxes, without aribitrary normalizations. We have included the data above 10 GeV per amu from this

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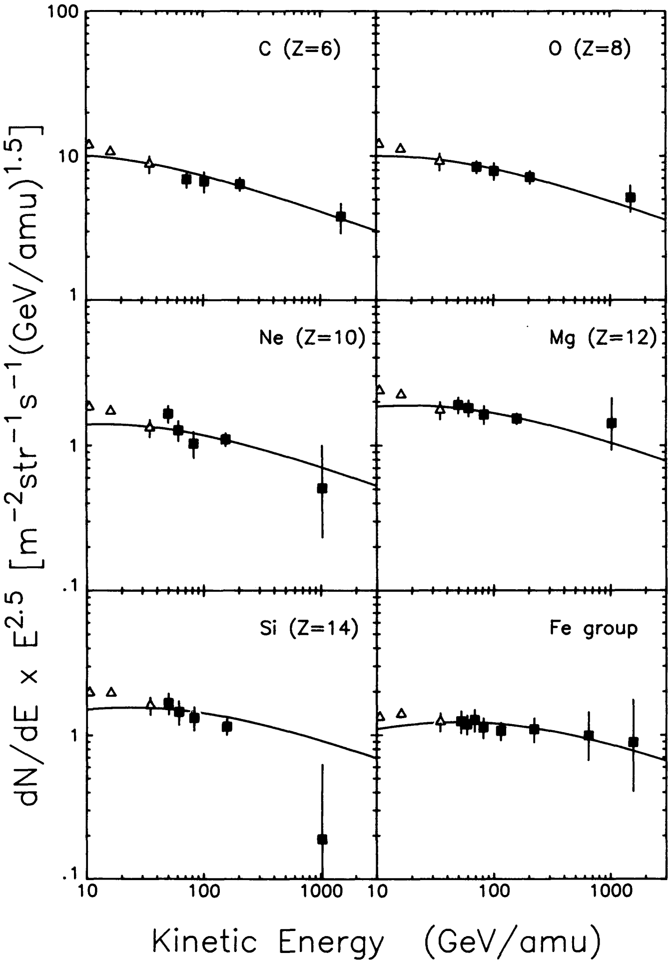

FIG. 1.—Differential energy spectra of heavy nuclei. *Solid squares:* data from CRN. *Open triangles:* data from *HEAO 3* C-2. *Curves:* leaky box model described in the text.

measurement in Figure 1. The agreement around 40 GeV per amu between the two sets of data from different spacecraft, both with good statistical accuracy, seems excellent. We therefore assume that the combination of these data accurately reflects the flux of heavy cosmic rays over a wide energy range.

We also indicate in Figure 1 a fit of the data to a simple "leaky box" model of cosmic ray confinement in the Galaxy. This assumes that the magnetic fields of the Galaxy act as a containment "box" for the cosmic rays, with a constant probability per unit time of a particle to escape. Simultaneously, particles can also be lost (or generated) by spallation reactions on nuclei of the interstellar gas. The containment path length, and therefore the containment time τ, has been found to decrease with increasing energy in a characteristic power-law fashion. Assuming dynamic equilibrium between particle production and loss, and ignoring particle energy losses during propagation (a valid assumption for nuclei at high energies), the "leaky box" model has the following form:

$$Q_i(E) = \frac{N_i(E)}{\tau(E)} + N_i \sigma_i nc - \sum_{j>i} N_j \sigma_{ji} nc \ ,$$

where $N_i(E)$ represents the Galactic cosmic-ray density and $Q_i(E)$ the source production rate of species i at energy E, n is the number density of interstellar gas, σ_i the cross section for spallation, and c the speed of the particles, essentially the speed of light. Particles of type i can also be gained by the breakup of heavier nuclei during interstellar collisions (σ_{ji} is the cross section for production of species i from j). For a constant density of interstellar material, the containment time scale is proportional to the path length of propagation λ (where $\lambda = \rho c \tau$, with ρ the mass density of the interstellar gas). We have previously determined the dependence of λ on the particle rigidity R from measurements of the relative abundances of secondary and primary cosmic rays (Swordy et al. 1990b), to be given by

$$\lambda(E) = 6.9\left(\frac{R}{20\ \mathrm{GV}}\right)^{-0.6} \mathrm{g\ cm^{-2}} \quad \text{for } R > 20\ \mathrm{GV}\ .$$

At energies high enough such that λ becomes small relative to the interaction length of a nucleus in the interstellar medium, escape from the Galaxy becomes the dominant loss process. For instance, for iron the interaction length is 2.6 g cm^{-2} and equals $\lambda(R)$ at $R = 102$ GV. The power-law dependence of λ on R will then lead to an observed spectrum $N_i(E)$ that decreases more steeply with increasing energy than the source spectrum $Q_i(E)$.

We use this model to calculate the *expected* fluxes of observed cosmic rays as a function of energy. To do so we need to specify the relative source strengths $Q_i(E)$ of the individual components. From the mechanism of shock acceleration we expect all source spectra to be power laws of the form $Q_i(E) = q_i E^{-\alpha}$, where q_i reflects the composition of the source and α is the source spectral index.[3] The spectra at high energy would be expected to become asymptotic to the form $E^{-(\alpha+0.6)}$ because of the energy dependence of the propagation path length discussed above. To specify the source abundances q_i, we assume that the values obtained at much lower energies (Hinshaw & Wiedenbeck 1983) remain the same in the high-energy region, except for the cases of iron and neon where we choose values that are larger by 15% and 20%, respectively. The results of this model are shown as solid lines in Figure 1. The model fluxes are normalized to a single oxygen data point at 206 GeV per amu. The source energy spectral index used is $\alpha = 2.2$ which provides a better fit to the combined data set (*HEAO 3* and CRN) than the value $\alpha = 2.1 \pm 0.1$ that was used previously for the CRN data alone (Müller et al. 1991). There is general agreement between the model and the measured data, although the low-energy points from the *HEAO 3* instrument seem systematically above the prediction. Since the normalization between the two data sets is uncertain at the level of this discrepancy (10%), we cannot exclude this effect being due to a normalization error. The parameters of the fit imply that at high energy all spectra should become asymptotic to a form $E^{-2.8}$, a value that is very close to those given at high energy for protons ($\alpha = 2.83 \pm 0.07$) and He nuclei ($\alpha = 2.72 \pm 0.09$) by the balloon-borne calorimeter measurements of the JACEE collaboration (Asakimori et al. 1991).

3. THE ALL-PARTICLE SPECTRUM

Indirect measurements of cosmic rays determine the total energy per particle, rather than the energy per amu as used in the data of Figure 1. To make a comparison of these data with other indirect measurements, the fluxes and energy scale must

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[3] More exactly, one would expect power laws in rigidity R. However, in the high-energy region of interest here, R and E are strictly proportional to each other.

be converted using the atomic mass, A, of the nucleus. Since the isotopic composition of cosmic rays at these energies is unknown, we use the following values, based on the isotopic composition measured at lower energies (for a review see Simpson 1983): carbon $A = 12$, oxygen $A = 16$, neon $A = 21$, magnesium $A = 24$, iron group $A = 56$. The uncertainty in the mean mass of the nuclei will affect the calculated fluxes only at a level below the overall normalization uncertainty of 10%. The resulting spectra are given in Table 1, including both the CRN and *HEAO 3* data shown in Figure 1.

The combined differential energy spectrum of arriving cosmic rays (the "all-particle spectrum") from 10^{11} to 10^{20} eV per particle is shown in Figure 2. Here, the flux of particles has been multiplied by $E^{2.5}$ to aid in the interpretation of the steeply falling spectrum. The small open symbols in this figure are measurements of the "all-particle" flux derived from air showers and from the *Proton* satellite measurements below 10^{15} eV (Grigorov et al. 1971). The "knee" feature is clearly visible above 10^{15} eV. Also shown in Figure 2 are some of the data from Table 1. We note that the measured iron spectrum extends to about 10^{14} eV. It can be readily seen from Figure 2 that oxygen or the iron group each contribute about 10% to the all-particle spectrum up to this energy. A summation over the measured intensities of the heavy primary elements ($Z \geq 6$) given in Table 1 yields the "heavy spectrum" shown in Figure 2. We note the good statistical accuracy with which the "heavy spectrum" is known from direct measurements. The balance between the all-particle flux and the "heavy spectrum" must be essentially given by the combined flux of protons and He nuclei. The fluxes of these particles in the 10^{13}–10^{14} eV per particle region have been measured by the JACEE program (Asakimori et al. 1991). Adding these results to our "heavy spectrum" in this region leads to an all-particle flux which agrees well with the "all-particle spectrum" based on earlier data from the *Proton* satellites. This is indicated in Figure 2. However, the energy spectra implied by our fit to the heavy spectrum are expected to become asymptotic to $E^{-2.8}$, significantly steeper than the all-particle spectrum observed in this region.

To estimate the percent fraction of heavy particles in the total cosmic-ray flux as a function of energy we use the "leaky box" model fit shown in Figure 1. We compare the model fluxes with the all-particle spectrum, taking into account uncertainties in the latter by defining two limiting power laws with indices 2.66 and 2.69, respectively that enclose the measured data points. In Figure 3 we show the fraction of heavy particles ($Z \geq 6$), and the fraction of iron group nuclei according to the "leaky-box" fit. The shading indicates the region where measured data exist. The figure indicates that the heavy fraction may become as large as 30% and that the iron fraction increases to about 10% in the 10^{13}–10^{14} eV per particle region.

The agreement between the direct composition measurements over the region where data with fair statistical accuracy exist (10^{13}–10^{14} eV) and the all-particle spectrum as shown in Figure 2 is quite reassuring. Equally significant is the fact that a simple leaky box model of propagation seems to describe the composition data reasonably well and that the composition of the cosmic-ray source does not seem to change with energy. In fact, the element abundances in the source at energies above 10^{13} eV exhibit the same correlation with the first ionization potential of the elements (Müller et al. 1991) that has been known for particles at much lower energy for a long time (Meyer 1985a, b). It is therefore tempting to investigate how the cosmic-ray composition would evolve if we extrapolate our model to still higher energies. This is illustrated in Figure 4. In this figure we compare again the intensities of the individual species according to our model with the all-particle flux. The flux are given cumulatively such that a given curve corresponds to the sum of the spectra of all species below that curve. It is obvious that, with increasing energy, the model and the all-particle spectrum will no longer be compatible with each other. While only new measurements will clarify the situation,

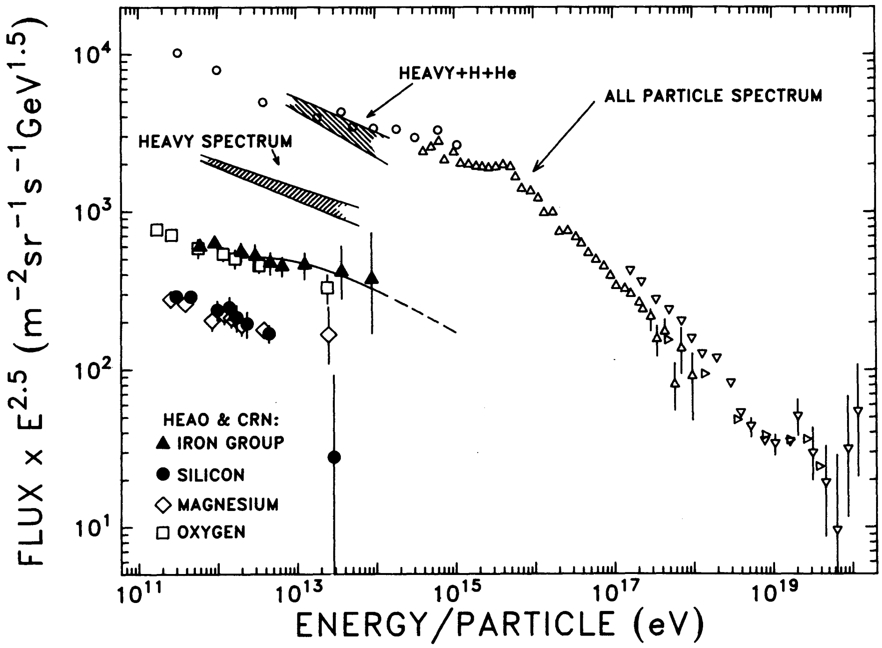

FIG. 2.—The all particle spectrum and spectra of several individual elements. *Solid curve:* leaky box model for iron (*dashed:* extrapolation to 10^{15} eV). Data for the all-particle spectrum: ○ Grigorov et al. 1971; △ Hara et al. 1983; ▷ Diminstein et al. 1982; ▽ Bower et al. 1981.

TABLE 1

Differential Flux per Total Particle Kinetic Energy

Element	Data Source[a]	Energy × 10^{-11} (eV)	Flux × 10^8 $(m^2\ sr\ sGeV)^{-1}$
C	h	1.27	$2.71 \times 10^5 \pm 5.2 \times 10^3$
($Z = 6$)	h	1.94	$8.42 \times 10^4 \pm 3.5 \times 10^3$
	h	4.20	$1.01 \times 10^4 \pm 1.4 \times 10^3$
	c	8.71	1280 ± 164
	c	12.3	522 ± 86
	c	24.8	86.6 ± 9.0
	c	180	0.363 ± 0.085
O	h	1.69	$2.06 \times 10^5 \pm 3.8 \times 10^3$
($Z = 8$)	h	2.59	$6.60 \times 10^4 \pm 2.7 \times 10^3$
	h	5.60	$7.91 \times 10^3 \pm 1.1 \times 10^3$
	c	11.6	1180 ± 113
	c	16.4	461 ± 63
	c	33.1	72.6 ± 7.5
	c	240	0.368 ± 0.076
Ne	h	2.23	$2.39 \times 10^4 \pm 5.0 \times 10^2$
($Z = 10$)	h	3.40	7740 ± 326
	h	7.35	869 ± 119
	c	10.5	443 ± 60
	c	12.9	206 ± 33
	c	17.4	78.8 ± 16
	c	32.6	17.5 ± 1.8
	c	216	$0.0715^{+0.068}_{-0.039}$
Mg	h	2.54	$2.71 \times 10^4 \pm 5.5 \times 10^2$
($Z = 12$)	h	3.89	8780 ± 367
	h	8.40	1000 ± 119
	c	12.0	447 ± 57
	c	14.7	256 ± 33
	c	19.9	109 ± 15
	c	37.9	20.3 ± 1.7
	c	247	$0.175^{+0.084}_{-0.058}$
Si	h	2.96	$1.92 \times 10^4 \pm 4.0 \times 10^2$
($Z = 14$)	h	4.54	6610 ± 278
	h	9.80	794 ± 109
	c	14.0	338 ± 55
	c	17.2	176 ± 33
	c	23.2	76.0 ± 14
	c	44.0	13.3 ± 1.7
	c	288	$0.0199^{+0.048}_{-0.016}$
Fe	h	5.94	7000 ± 170
($Z = 26$)	h	9.07	2540 ± 109
	h	19.6	328 ± 45
	c	29.5	111 ± 20
	c	33.2	79.1 ± 12
	c	38.4	58.7 ± 10
	c	45.7	33.6 ± 5.4
	c	64.6	13.4 ± 1.9
	c	124.0	2.67 ± 0.5
	c	363	$0.165^{+0.07}_{-0.05}$
	c	875	$0.0165^{+0.016}_{-0.009}$

[a] h = *HEAO 3* (Engelmann et al. 1990); c = CRN (Müller et al. 1991).

several possibilities to explain this behavior have been discussed in the literature. One may consider a hitherto unidentified source of particles, for instance extragalactic protons above 10^{14} eV, generated by active galactic nuclei as suggested by Protheroe and Szabo (1992). Alternatively, one may invoke a propagation model referred to as the "nested leaky box" (Cowsik & Wilson 1975; Cowsik & Gaisser 1981; Cesarsky & Montmerle 1981). This model implies that the $E^{-0.6}$ dependence of the propagation path length Λ does not continue to the highest energies, but that $\Lambda(R)$ levels out to reach a finite asymptotic value Λ_∞ that reflects a fixed amount of matter traversed by cosmic rays in interstellar space. A finite value $\Lambda_\infty \approx 0.5$ to $1.0\ g\ cm^{-2}$ at TeV energies cannot be excluded by existing data. This model would account for a flattening of the

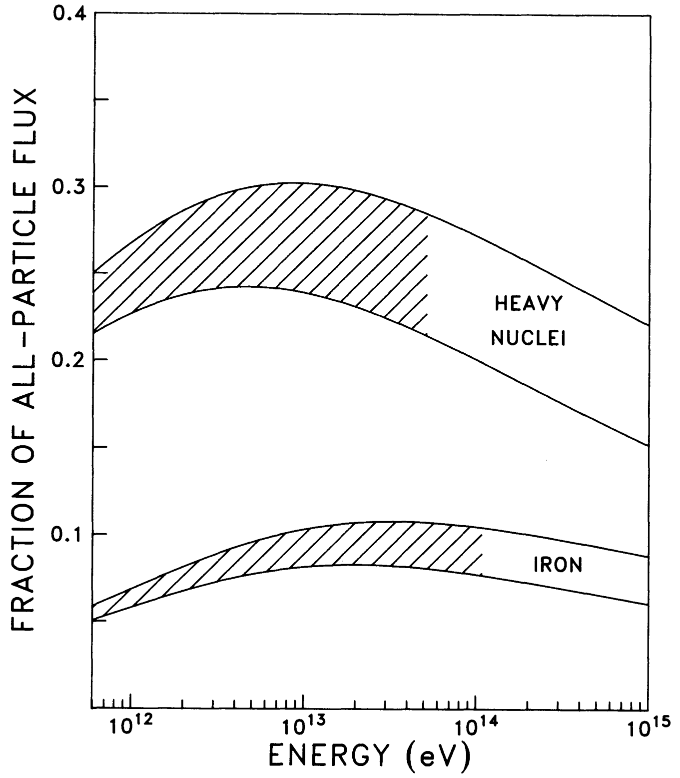

Fig. 3.—Model fraction of heavy components in the all-particle cosmic-ray flux. The shaded areas indicate the energy regions where measurements exist. The widths of the two bands reflect the uncertainty in the normalization to the all particle flux (see text).

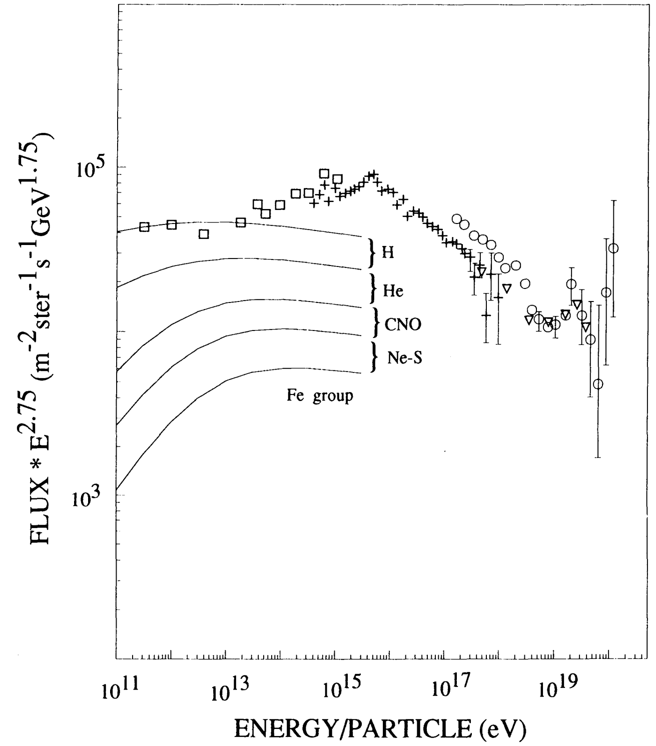

Fig. 4.—Cumulative intensities of nuclear spectra compared with the all particle spectrum. Solid lines are representative of the leaky box model described in the text. Note that the flux is multiplied by $E^{2.75}$. (Data: □ Grigorov et al. 1971; + Hara et al. 1983; ▽ Diminstein et al. 1982; ○ Bower et al. 1981).

energy spectrum before the region of the "knee" is reached. In this respect, it is interesting to note that results from JACEE suggest a relative enhancement of the fluxes of heavier nuclei above 2×10^{14} eV (Burnett et al. 1990).

4. CONCLUSIONS

We have shown that recent measurements from the CRN and *HEAO 3* space experiments produce consistent results for the flux of galactic cosmic rays and describe the energy spectra of the arriving individual elements very well over three orders of magnitude in energy. A simple "leaky box" model for the particle propagation in the Galaxy provides a good fit to these data under the assumption that the source spectral index has a value $\alpha = 2.2$ for all species, and that the escape length from the galaxy varies as $R^{-0.6}$. This leads to an asymptotic spectrum of the form $E^{-2.8}$ for heavy nuclei which is in good agreement with the spectral slopes of high-energy protons and He nuclei measured by the JACEE collaboration. When compared with the all-particle spectrum as measured by air showers and the *Proton* satellites, the sum of the fluxes of the heavy nuclei, and of protons and He nuclei agree well with the total intensity given by the all-particle spectrum. The fraction of heavy nuclei in the all-particle spectrum is 20% to 30% of the arriving particles at 10^{13}–10^{14} eV. However, when we extend the "leaky box" model to higher energies, the overall fraction of heavy nuclei is predicted to decrease since the asymptotic spectral slope given by the model is steeper than the all-particle spectrum. If further measurements confirmed this discrepancy between the heavy spectrum and the all-particle flux, one would have to conclude that additional sources, that are not part of our model, contribute to the cosmic-ray flux in this energy regime.

Thus, only additional, accurate measurements of the elemental composition up to 10^{15} eV per particle will provide a decisive answer. It is important that these measurements include both protons and helium, and the individual heavy nuclei. Such measurements would ideally require the exposure of a detector system in a year-long space flight, although recent developments of long-duration balloon flight capabilities may provide a less costly alternative. A particularly important aspect of such new measurements would be the fact that they can yield over a decade of overlap with the energy range of air shower detectors. So, one may hope that the new generation of air shower arrays, after cross-calibration with direct measurements, will reliably provide information on the cosmic-ray composition as it evolves at energies well beyond the knee.

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