for several interesting conversations.

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Composition of Cosmic-Ray Nuclei at High Energies*

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We have measured the charge composition of cosmic-ray nuclei from Li to Fe with energies up to about 100 GeV/nucleon. A balloon-borne counter telescope with gas Cherenkov counters for energy determination was used for this experiment. Our first results show that, in contrast to low-energy observations, the relative abundances change as a function of energy. We find that the ratio of the galactic secondary nuclei to primary-source nuclei decreases at energies above about 30 GeV/nucleon.

The past years have provided an increasing body of evidence regarding the nuclear composition of the primary cosmic radiation over a wide range of energies through the use of new and sophisticated detector systems flown on satellites and high-altitude balloons.[1-6] This work has led to the remarkable result that the energy spectra of the various nuclear species are closely alike in shape, yielding energy-independent relative abundances. Important consequences regarding particle sources as well as particle propagation in the interstellar medium can be drawn from these observations. In particular, energy-independent lifetimes against leakage from the galaxy, diffusion coefficients, etc. have been assumed in the models describing particle propagation.[7] It is presently not known up to what energy this situation will continue to hold.

In view of the importance of this question we wish to report some preliminary results concerning the cosmic-ray composition at high energy which we have obtained with a balloon-borne detector. Our instrument has measured this composition from Li to Fe at energies up to about 100 GeV/nucleon. The results gained from data gathered in one balloon flight provide the first indication of an energy dependence of the charge composition at energies exceeding about 30 GeV/nucleon.

Figure 1 shows a schematic cross section of the instrument. It is a counter telescope consisting of two plastic Cherenkov counters C_1, C_4 (Pilot 425), and a plastic scintillation counter C_3 (Pilot Y) for charge analysis, two gas Cherenkov counters C_{2A}, C_{2B} for energy analysis, a guard counter G for background rejection, and a small scintillation counter C_0 which may be used to limit the opening angle of the telescope. The geometric factor is 820 cm^2 sr. All counters, except the lower gas counter (which has focusing mirrors) and the guard counter, are in light-diffusion chambers, using expanded polystyrene as reflective wall covering. The top Cherenkov counter is segmented in order to minimize the

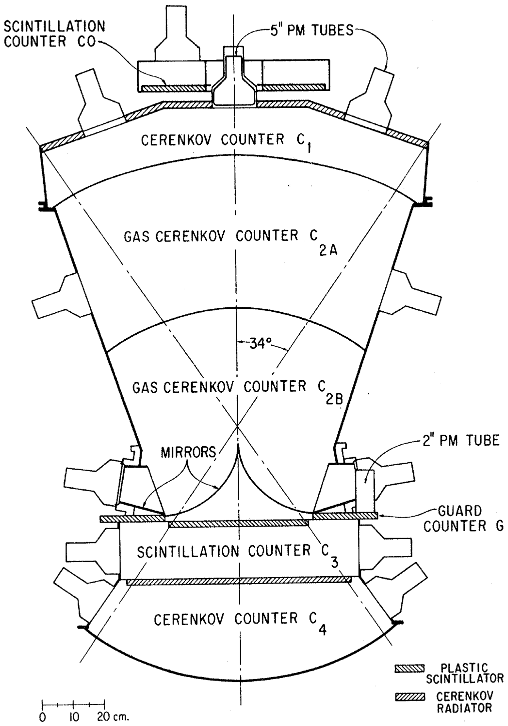

FIG. 1. Schematic cross section of the detector system.

pathlength distribution. The selection of the gas in counters C_{2A} and C_{2B} determines the range over which accurate energy measurements can be made.

This detector has been flown once from Palestine, Texas in September 1971. During 29.5 h at an altitude ~4.8 g/cm^2 of residual atmosphere,

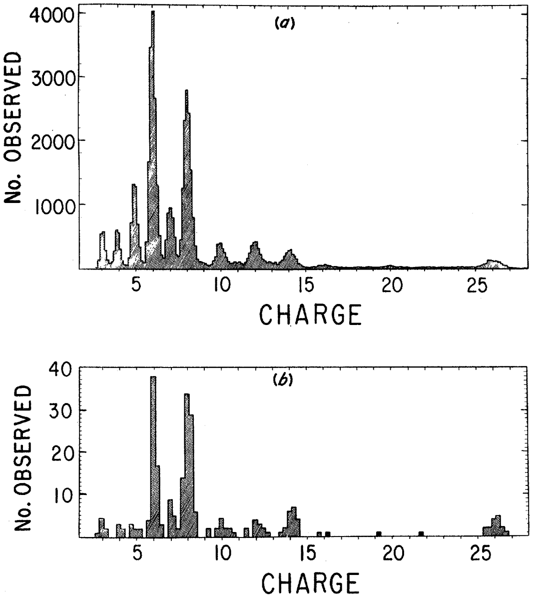

FIG. 2. Charge distribution of cosmic-ray nuclei measured under 4.8 g/cm^2 of atmosphere: (a) above the geomagnetic cutoff at Palestine, Texas ($E \gtrsim 1.6$ GeV/nucleon); (b) at energies above 50 GeV/nucleon.

97 000 events were collected from which we selected 50 000 noninteracting nuclei between Li and Ni by requiring the guard counter signal to be low or absent, and the outputs from the three plastic counters to be mutually consistent. Figure 2(a) shows, in the form of a histogram, the measured charge distribution for energies exceeding the geomagnetic cutoff at Palestine, corresponding to approximately 1.6 GeV/nucleon.

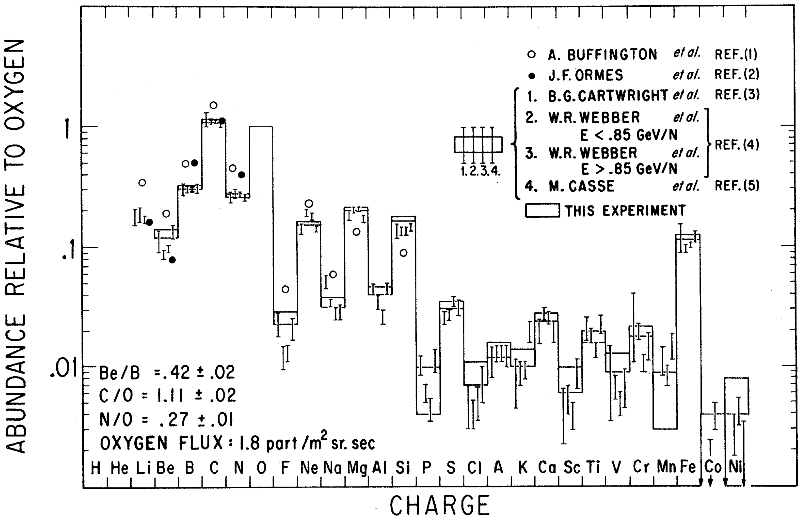

FIG. 3. Relative charge composition (normalized to oxygen) for $E \gtrsim 1.6$ GeV/nucleon corrected for interactions in the detector and extrapolated to the top of the atmosphere. For comparison, the results of other authors are included.

It exhibits the capability to resolve individual charges. In Fig. 3 our charge distribution for $E > 1.6$ GeV/nucleon, corrected for interactions in the detector and extrapolated to the top of the atmosphere, is compared with results of other investigators, some obtained at lower energies. The agreement is generally good.

Through the use of the two gas Cherenkov counters, of which the upper one (C_{2A}) was filled with Freon-12 and the lower one (C_{2B}) with air, both at atmospheric pressure, we can examine the chemical composition at energies between about 25 and 80 GeV/nucleon. Figure 2(b) shows a histogram of the measured charge distribution above 50 GeV/nucleon. While the charge resolution is better than at the lower energies, the number of observed particles is small at this high energy. We now wish to raise the question whether the charge composition above 50 GeV/nucleon is different from that at lower energy. Lack of statistical accuracy prevents definite claims for changes in the abundance ratio of most individual elements. However, if one investigates the ratio of the abundance of all those nuclei which originate predominantly, or to a significant fraction, from fragmentation in interstellar space, to all of those which are believed to originate mostly in the sources, a definite change of this ratio as a function of energy is becoming apparent. This is shown in Fig. 4 where the ratio is plotted as a function of energy per nucleon. Li and Be are not included because of difficulties in obtaining a high-energy sample of these low-Z nuclei entirely free of contamination from low-energy particles. The ratio at 1.6 GeV/nucleon agrees well with that measured by other observers. However, it now appears that it is energy dependent, decreasing with increasing energy beyond about 30 GeV/nucleon. This would indicate steeper energy spectra of galactic secondary nuclei, as compared to the source nuclei. The fact that both groups of elements involved in this ratio are distributed over the entire range of charges strengthens our confidence that this effect is not instrumental in origin.

The astrophysical implications of this result are interesting. It is not likely that the energy dependence of the ratio can be explained on the basis of energy-dependent fragmentation cross sections. Neither theoretical models nor experimental evidence[6,8] point toward a strong energy dependence of the fragmentation parameters at the energies with which we are dealing here. Rather, we believe that the cause has to be sought in terms of particle propagation in the galaxy, for instance, an energy dependence of the leakage lifetime.

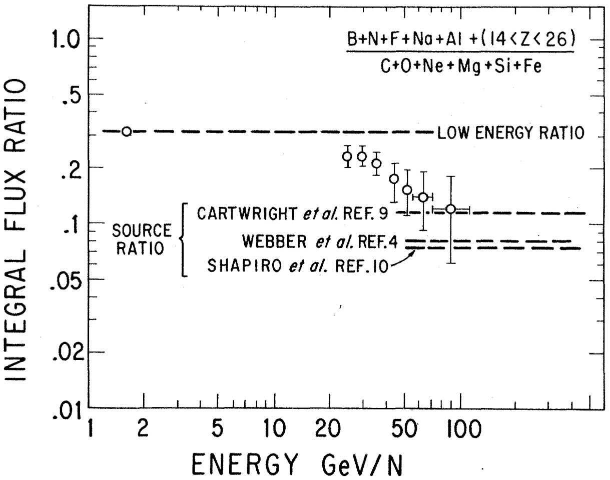

FIG. 4. Ratio of predominantly galactic secondary nuclei to predominantly source nuclei as a function of energy. The measured ratio at low energy (1.6 GeV) is indicated by a dashed line. For comparison the ratio at the sources, as extrapolated by several authors for energies near 1 GeV/nucleon, is also shown by dashed lines.

This experiment is being continued with a slightly modified instrument in order to substantiate and further clarify the effects that we have presented here. We are indebted to H. Boersma, W. Hollis, D. Hunsinger, W. Johnson, G. Kelderhouse, and A. Kittler for their contributions to the construction of the instrument and the performance of the balloon flight. Our thanks go to Ms. L. Glennie and L. Littleton for programming and data handling. John Caldwell contributed significantly to all phases of this experiment. The excellent cooperation by the staff of the National Center for Atmospheric Research balloon facility is gratefully acknowledged.

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Approach to Factorization and Scaling in Inclusive Reactions[*,†]

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We present a compilation of existing data on inclusive reactions which provide evidence for the factorization hypothesis in the "central" region of pion production but only at infinite beam momentum. The approach to limiting behavior in the central region is consistent with that expected on the basis of the Mueller-Regge formalism.

Several groups have recently examined the question of the validity of the hypothesis of limiting fragmentation, scaling behavior, and the factorization hypothesis in inclusive pion-production reactions.[1] In general, the conclusion which has been reached is that these principles appear to hold to good accuracy in the fragmentation region of momentum space; these principles, however, do not appear to be valid for small values of emitted-pion momentum in the center-of-mass system (i.e., small $x = p_l^*/p_{l,\text{incident}}^*$). In fact, several groups have pointed out that, particularly for reactions such as

$$p + p \to \pi^- + \text{anything}, \qquad (1)$$

$$\pi^+ + p \to \pi^- + \text{anything} \qquad (2)$$

scaling near $x=0$ is badly violated.

We wish to make here several comments and observations concerning inclusive pion-production reactions at accelerator energies, and point out that a great simplification results when the invariant cross section for these reactions is extrapolated to infinite momentum. The results of this extrapolation strongly suggest that, to better than 10% accuracy, factorization of inclusive reactions obtains at $x=0$, and consequently at all values of x.

Figure 1 presents a plot of the normalized invariant single-particle production cross sections (integrated over p_t) at $x=0$ as a function of $p^{-1/4}$ (p is the bombarding momentum in the laboratory system). We define the ordinate in the graph, the parameter c, as follows:

$$c = \frac{1}{\sigma_T} \int_{\text{all } p_t} E^* \frac{d^2\sigma}{dp_l^* \, dp_t} dp_t \bigg|_{p_l^*=0}.$$

The starred variables are c.m. quantities, p_t^* is

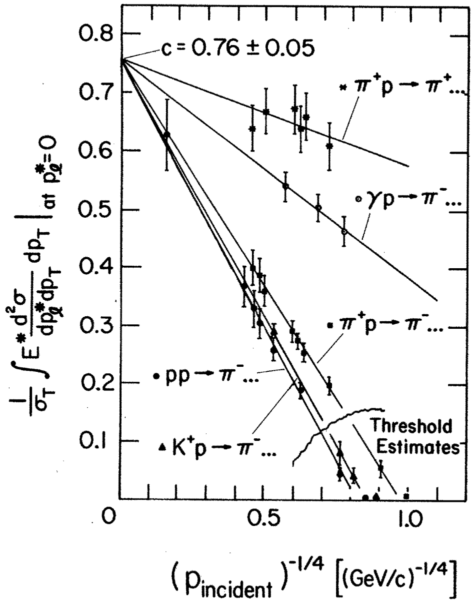

FIG. 1. Normalized invariant single-particle inclusive cross section at $x=0$ as a function of beam momentum. In the normalization we use the following asymptotic values of σ_T: for pp, 39.8 mb; π^+p, 23.4 mb; K^+p, 17.4 mb; and γp, 99 μb.