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COSMIC RAY NUCLEAR COMPOSITION ABOVE 20 GeV/NUCLEON

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In three balloon flights during 1971 and 1972 we have exposed for a net total of 7.6 m^2 sr hours a scintillator-Cerenkov counter telescope to measure the charge composition of cosmic ray nuclei. The telescope includes two gas Cerenkov counters for energy measurements above 20 GeV/nucleon. In this energy range about 3400 nuclei between Li and Fe have been detected and analyzed. We present the resulting charge composition and energy spectra. The nuclear composition has been found to change with energy. The flux of galactic daughter nuclei decreases faster with increasing energy than the flux of source nuclei. The carbon/oxygen abundance ratio is significantly reduced as compared to low energy measurements, and iron seems to exhibit a flatter energy spectrum than other nuclei.

I. Instrumentation. The instrument used in this experiment is shown schematically in Fig. 1 as flown in the fall of 1971 from Palestine, Texas. It is a counter telescope consisting of two Cerenkov counters C1 and C4 (Pilot 425) and a scintillation counter C3 (Pilot Y) to measure the charge and energy of nuclei passing through the instrument. In two later flights in fall of 1972 from Cape Girardeau, Missouri, scintillation counters were used in C1 and C4 and a Cerenkov counter in C3. These counters are housed in light integration boxes lined with high reflectance white walls and looked into by a number of photomultiplier tubes (RCA 4525). As reflective wall covering, molded expanded polystyrene and filter paper (HAWP, Millipore) have been used both having about 97% effective reflectance which makes possible photon collection efficiencies of around and above 50%. This configuration also insures uniform collection of the light from different parts of the counters. This uniformity is better than 1% for C3.

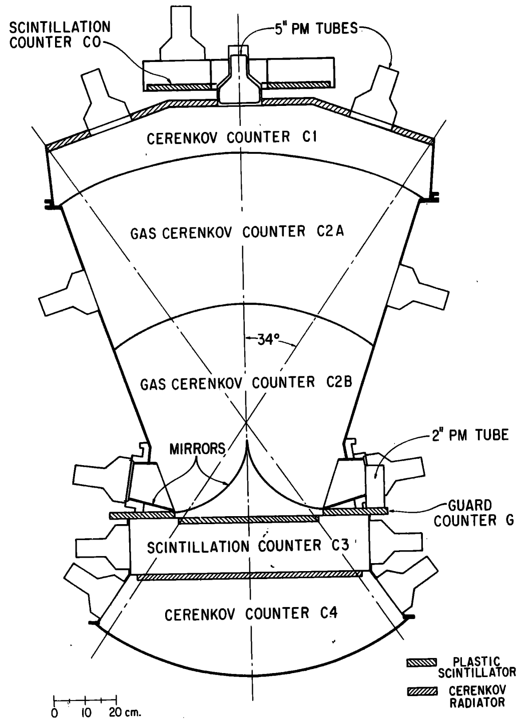

Figure 1

The instrument contains two gas Cerenkov counters for energy measurements above 20 GeV/nucleon. The upper

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counter C2A utilizes the light integration method while the lower one C2B uses mirrors to focus the Cerenkov light into the phototubes.

The two gas counters can provide two distinct Cerenkov thresholds and ranges for velocity measurements. The main advantage of utilizing two gas counters lies, however, in the redundancy they provide in the overlapping energy range, minimizing danger of error due to non-nuclear background, delta-rays, noise or scintillation of the gas. The two types of gas counters complement each other since C2B, the focussing counter, is rather insensitive to noise and scintillations, while C2A, the white counter, has good resolution, limited only by the photon statistics.

The gases that we have flown include for all three flights freon 12 which was flown in C2A in the first flight, and in C2B for the later two flights. To provide a lower index of refraction we have used air, CO_2 and SF_6+ methane mixture. These four gases correspond to thresholds of 19, 40, 31 and 24 GeV/n respectively.

The maximum energy resolvable by C2A is dependent on the gas and on the charge of the cosmic ray nucleus and limited by photon statistics to $E_c \times N_{p.e.}^{.25}$ where E_c is the threshold energy and $N_{p.e.}$ the number of photo electrons produced by an ultrarelativistic nucleus. With CO_2 as the Cerenkov gas a relativistic oxygen nucleus gives approximately 50 photoelectrons in the C2A photomultipliers.

The instrument also contains a guard counter G that helps to eliminate non-nuclear background, and a small counter C0 that can be used to limit the opening angle of the telescope. The geometric factors of the instrument as determined by the $C1 \cdot C4 \cdot \bar{G}$ coincidence is 950 cm^2 sr, while for some low energy measurements the telescope defined by the $C1 \cdot C4$ coincidence can be used (1750 cm^2 sr).

All counters except C0 are pulseheight analyzed, using three 1024 channel linear analyzers for C1,C3, C4 and 256 channel 3-ramp analyzers for the gas counters. Information is written on onboard magnetic tape and simultaneously transmitted to ground.

2. Data Analysis. To determine whether a particular event should be accepted as a nucleus of charge Z in an energy interval ΔE we have established certain selection criteria. We will not here discuss the selection criteria for charge and energy, but all high energy events ($E > 20$ GeV/n) have to satisfy the following conditions. (1) The pulseheight in the top counter C1 has to agree with the pulseheight in the bottom counter C4 to within 20%. (2) Similarly the pulseheight from the center counter C3 must agree with C4 to within $\pm$ 20%, and finally, (3) The signal in the guard counter must be less than 10% of the signal expected had the particle itself traversed the guard counter.

The resulting data are shown in Table 1. These numbers have to be corrected for a) The loss of legitimate particles by the selection criteria, a correction that can be easily and accurately calculated, and which is shown in the next to last column of Table 1; b) improper events which were not excluded by the selection criteria

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Table I. Number of Events Satisfying Selection Criteria

Diff. energy/n	22 GeV	27 GeV	34 GeV	48	75	120	Correction	
Int. energy/n 20	24	30	40	60	80		Sel.	Int.
3. Lithium	31 (11)	46 (16)	24 (14)	13	6	2	2.30	.95
4. Beryllium	30 (15)	35 (17)	23 (16)	11	10	1	1.09	.96
5. Boron	67 (44)	66 (43)	47 (38)	23	24	7	1.04	.97
6. Carbon	285 (214)	308 (230)	258 (219)	171	102	26	1.02	.98
7. Nitrogen	63 (50)	76 (61)	51 (46)	32	27	4	1.01	.99
8. Oxygen	238 (202)	289 (245)	252 (239)	196	142	37	1.00	1.00
9. Fluorine	9	5	5	3	2	1	1.00	1.01
10. Neon	31	34	35	38	15	2	1.00	1.02
11. Sodium	2	7	9	6	6	0	1.00	1.03
12. Magnesium	26	68	37	28	26	6	1.00	1.04
13. Aluminium	6	8	9	2	3	2	1.00	1.05
14. Silicon	14	35	38	33	28	6	1.00	1.06
15. Phosphorus	0	1	1	2	2	0	1.00	1.07
16. Sulphur	4	8	6	9	3	0	1.00	1.08
17. Chlorine	2	1	3	0	0	0	1.00	1.09
18. Argon	2	0	3	8	2	0	1.00	1.11
19. Potassium	1	5	1	1	0	0	1.00	1.12
20. Calcium	2	2	9	5	0	0	1.00	1.13
21. Scandium	0	2	0	0	2	1	1.00	1.14
22. Titanium	2	2	3	1	2	0	1.00	1.15
23. Vanadium	0	3	1	2	5	0	1.00	1.16
24. Chromium	0	1	2	5	3	0	1.00	1.17
26. Iron and Mn.	15	25	33	20	22	6	1.00	1.19
28. Nickel	2	1	2	2	2	0	1.00	1.21

Table II. Relative Abundances for Cosmic Ray Nuclei at 6.0 g/cm^2 in Atmosphere

Energy/nucl.	22 GeV	27 GeV	34 GeV	48 GeV	75 GeV	120 GeV	1 GeV	Atm. Corr.
Lithium	12 ± 8	15 ± 10	13 ± 5	15 ± 5	9 ± 4	12 ± 9	27	-6
Beryllium	8 ± 4	7 ± 3	7 ± 2	6 ± 2	7 ± 2	3 ± 3	16	-4
Boron	22 ± 5	18 ± 4	16 ± 3	12 ± 3	17 ± 4	19 ± 7	39	-8
Carbon	106 ± 12	94 ± 11	92 ± 8	87 ± 7	72 ± 7	70 ± 14	116	-5
Nitrogen	25 ± 4	25 ± 4	19 ± 3	16 ± 3	19 ± 4	11 ± 5	33	-5
Oxygen	100 ± 9	100 ± 8	100 ± 7	100 ± 7	100 ± 8	100 ± 16	100	0
Neon	16 ± 3	14 ± 3	15 ± 3	20 ± 3	11 ± 3	6 ± 4	17	-
Magnesium	13 ± 3	29 ± 4	16 ± 3	15 ± 3	19 ± 4	17 ± 7	20	-
Silicon	7 ± 2	15 ± 3	17 ± 3	18 ± 3	21 ± 4	17 ± 7	15	-
F+Na+Al	9 ± 2	8 ± 2	10 ± 2	6 ± 2	8 ± 3	8 ± 5	11	-
14< Z < 25	7 ± 2	11 ± 3	13 ± 3	19 ± 4	15 ± 4	3 ± 3	15	-
Fe+Mn+Ni	10 ± 2	13 ± 3	17 ± 3	13 ± 3	20 ± 5	19 ± 8	10	+3

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and have to be corrected for. This correction is a minor one at low energies and in the energy range where both gas counters are used for energy measurements, but becomes large for the lighter elements in that region where just one gas counter is used for the energy measurement. When this correction is applied to the numbers shown in the table one obtains the numbers given in parentheses. Finally, in the last column of Table 1, a correction factor is shown which takes care of the interactions of nuclei inside the instrument. The energy given in the first line shows the median energy for each sample and in the second line we show the energies corresponding to the effective bin edges.

Table II shows the resulting relative abundances of the cosmic ray nuclei at different energies and normalized to oxygen. Errors given in the table are the statistical errors plus an estimated uncertainty in the correction (b) amounting to 25%. Our measured composition at low energy and atmospheric corrections (Casse et al. 1971) are shown in the last two columns of Table II.

3. Results. A characteristic feature of the data that we have reported earlier (Juliusson et al. 1972) is the progressively decreasing abundance of galactic secondary nuclei as energy increases. Data from all three flights are shown in Fig. 2 where we have plotted the ratio of all those nuclei that are mostly secondary to those that are presumably mostly primary. Agreement with our earlier results which were based on just one flight is good, although the ratio has decreased somewhat in the energy range 20 - 40 GeV/nucleon. This energy range was covered using only C2A and the contamination by low energy nuclei, especially boron, was seemingly larger than we accounted for. This change brings the data in better agreement with those of other observers (Smith et al. 1973, Ormes and Balasubrahmanyan 1973, Webber et al. 1973) who have measured this effect at energies as low as 3 GeV/n. Our data combined with those of Smith et al. (1973) show a difference in spectral index between the parent nuclei and daughter nuclei of about 0.3 from 3 GeV/n up.

Fig. 3 shows our published data for the C/O ratio (Juliusson and Meyer 1973). This ratio changes significantly at high energies, and somewhat more than can readily be explained by the reduction in secondary carbon. Unless the source ratio is substantially overestimated, the result indicates a new feature in the high energy data.

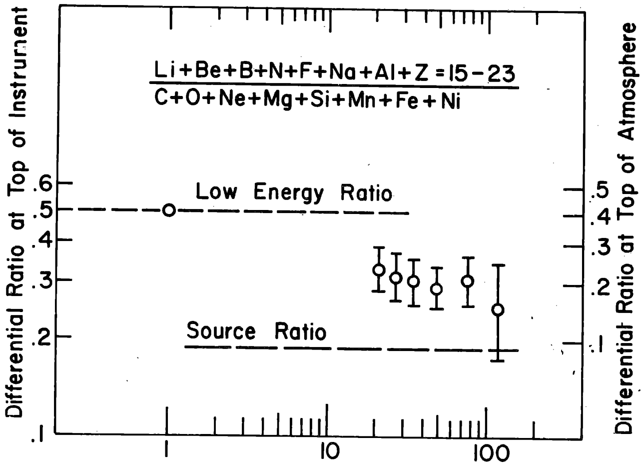

Figure 2

Fig. 4 shows our data for the Fe+Mn+Ni/ (C + O) ratio. This ratio rises with energy and again somewhat more than one would expect from a reduced spallation at high energy. The data do not yet warrant a claim that the ratio is significantly above the source

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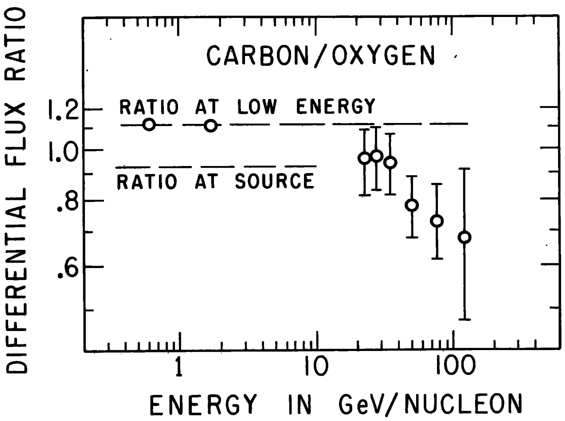

Figure 3 C/O ratio at top of atmosphere

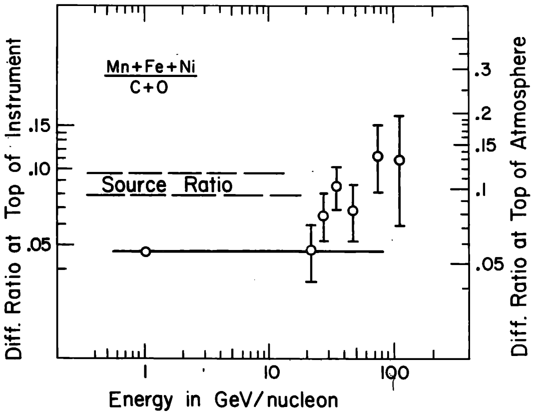

Figure 4

ratio but it would be interesting to measure this ratio at still higher energies.

The energy spectrum of C + O that we obtain in this measurement is shown in Fig. 5. It can be well approximated by a single power law in total energy for all energies down to the region of the geomagnetic cut off ~ 0.5 GeV/n with an exponent - 2.65 ± .05 for the differential spectrum. These data are preliminary but they indicate no obvious steepening of the spectrum with energy. The errors are almost exclusively due to errors in the energy determination. They depend on the accuracy with which we can relate the pulseheight in the gas counters to energy. While these errors limit the accuracy with which we can measure the spectral index, they become insignificant for relative abundance measurements such as shown in Figs. 2 to 4, since the differences in spectral indices for the different elements are an order of magnitude smaller than the indices themselves.

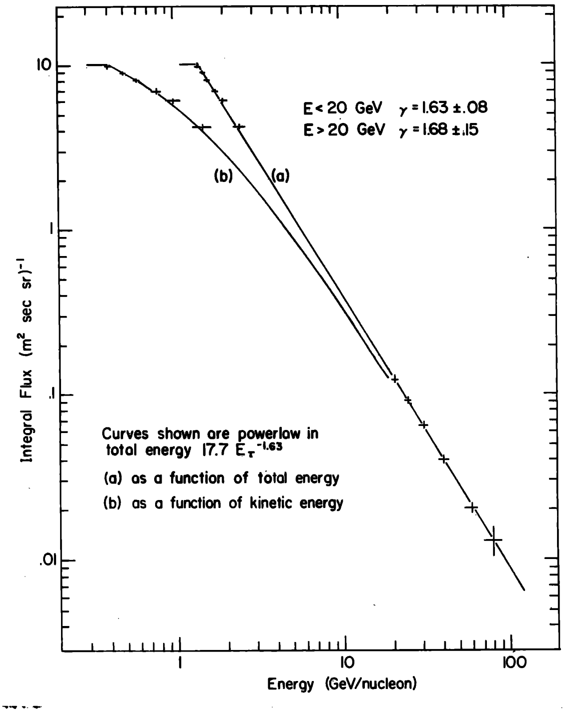

Figure 5 C + O integral spectrum

4. Discussion. Figure 2 shows that the high energy nuclei have spalled less than low energy nuclei. Since we can measure the spallation in the instrument and determine that it is energy independent this must be an astrophysical effect. The high energy nuclei have traversed less matter than the low energy nuclei, which is most easily explained by a reduced lifetime of the high energy nuclei in the galaxy.

The result that the spectra of the source nuclei do not seem to steepen with energy is best reconciled with a lifetime τ

that is a smooth function of energy

$$\tau \propto E^{-0.3} \qquad (1)$$

Since the daughter to parent ratio seems quite constant at low energies (1) would seemingly only be valid down to around 3 GeV/n. Whether or not this energy dependence of the lifetime persists at energies below a few GeV/n would be difficult to determine experimentally due to the increasing roles of modulation, and adiabatic deceleration in interplanetary space,changing production cross sections, and ionization losses in the interstellar medium. Finally, if one interprets E in (1) as total energy the lifetime at very low energy would only be 60% longer than at 3 GeV/n.

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