1973ICRC....1..157O

VARIATIONS OF THE CARBON+OXYGEN TO IRON AND THE PRIMARY TO SECONDARY RATIOS WITH ENERGY FROM 2 TO 50 GeV/NUCLEON

J. F. Ormes, V. K. Balasubrahmanyan and J. F. Arens

NASA/Goddard Space Flight Center

Greenbelt, Maryland (USA) 20771

New data on the differential energy distribution of heavy nuclei in the galactic radiation indicate that the cosmic ray charge composition is energy dependent. The data were obtained on a balloon flight of a 5,000 lb. ionization spectrometer and cover the energy range from the geomagnetic cutoff at 1.5 GeV/nucleon to more than 50 GeV/nucleon. Complex couplings between the energy measurement, the charge determination and the background subtraction have been understood and will be discussed. A striking difference between the spectrum of iron and carbon + oxygen of 0.56 ± 0.14 of a power has been found. This difference is much larger than the observed difference between the spectra of primary and secondary nuclei, $\Delta\gamma = 0.21 \pm 0.09$. If this difference holds to higher energy, iron nuclei will become as abundant as carbon + oxygen at a few hundred GeV/nucleon. The difference between primary spectra probably cannot be understood in terms of propagation as we understand from contemporary composition data. New experiments to differentiate between charge dependent acceleration, a separate cosmic ray source for iron nuclei, and an extreme propagation model will be discussed.

1. Introduction. We have now completed a reanalysis of our data on the charge composition using a balloon borne ionization spectrometer (Ormes et al., 1970). The final results to be presented here include a revised charge determination scheme with greatly improved background rejection, and a reanalysis of the energy measurement of the spectrometer in terms of energy/nucleon. An expanded discussion of these techniques and the complex couplings between the charge and energy measurement have been submitted for publication in the Astrophysical Journal. We present here a summary of the results and the corrections used to obtain them.

The details of the instrument and the corrections made to the raw data have been presented previously (Ormes and Balasubrahmanyan, 1970). Here we will present only information relevant to our reanalysis. The experiment was flown on Nov. 11, 1970. Useful data was obtained at 7.4 gm/cm^2 for 14.4 hours. The geometric factor for the data was 725 cm^2 ster and the live time was 21.7×10^3sec. Particles at zenith angles greater than 25° were excluded, finally yielding a total exposure factor of 1420 cm^2 ster sec.

2. Charge and Energy Determination. The balloon-borne instrument consisted of three major components: a charge measuring module, a spark chamber for determining particle trajectories, and an ionization spectrometer for measuring total energy. The charge of an incoming particle was determined using two plastic scintillators, a Lucite Cerenkov counter, and a CsI mosaic. Each detector had a sensitive area of 50 cm x 50 cm. The

trajectory from the spark chamber was used to eliminate the dispersion in pulse height due to geometric variation of response.

The charge analysis is extremely critical because of its coupling with the energy determination and because of the background problems. The response of the spectrometer depends upon energy/nucleon, and in order for this to be determined from the total observed energy deposit, the mass of the particles must be known. Unique charge identification and background rejection depend upon two factors. The charge as measured by all four detectors had to be consistent within errors, and the trajectory of the particle had to be well defined and lie within the telescope geometry.

Since the study included singly charged particles and iron nuclei, the tracks of the incident particles had to be determined over an ionization range of more than 600. With the knock-on probability increasing as Z^2, heavier nuclei were invariably accompanied by knock-on electrons which caused confusion in determining the track.

Since the probability of a spark <u>not</u> forming along the track of the heavy nucleus was negligible, the main problem was to pick the correct trajectory from a number of possible trajectories. We selected the best fit straight trajectories through all combinations of sparks in the four decks of the wire grid spark chamber. By selecting tracks for the presence of sparks in which 2 or more wires participated, most of the possible spurious tracks were eliminated. The trajectories were projected to their exit point in the iron spectrometer and were found highly correlated with sudden drops in the module signals.

By comparing zenith angle distributions to calculations, we estimate that the tracks are determined to $\sigma \leq 2°$. Our confidence in the tracks is further enhanced because we have subsequently flown an experiment in which the number of decks was increased from 4 to 8. From an analysis of this new data it is clear that the trajectories picked by the 4 deck algorithm correspond closely to the 8 deck tracks.

The selection of simple events according to the criteria listed in Table 1 served to eliminate a large fraction of the background events. These background events were most abundant at Li and fell off rapidly with increasing charge. In particular, the spark chamber removed atmospheric showers and many events caused by interactions in the spectrometer which triggered the experiment with backscattered particles. The remaining background is eliminated by the charge determination procedure.

TABLE 1

<u>Criteria for selecting simple events</u>:

1. Particle trajectory intersects coincidence scintillators
2. All 4 planes contain sparks
3. Least squares fit of data to straight line ≤ 1.5 wires
4. There is no second trajectory in the chamber satisfying 1, 2 and 3 above which has a different zenith angle (>50) and/or position (>0.5 in)

Due to the dispersions in the detectors, the observed pulse heights were distributed around the centroids characteristic of each charge in the four dimensional representation. A distance of every event from the charge centroids was determined by calculating the root mean square distance in units of the resolution for the appropriate charge. Charge was assigned from the centroid which gave the minimum distance. Particles were rejected if their average distance was more than about FWHM/2 away from the centroid. This strict criteria was used in order to insure that background was minimized. The resulting resolution is shown in Figure 1.

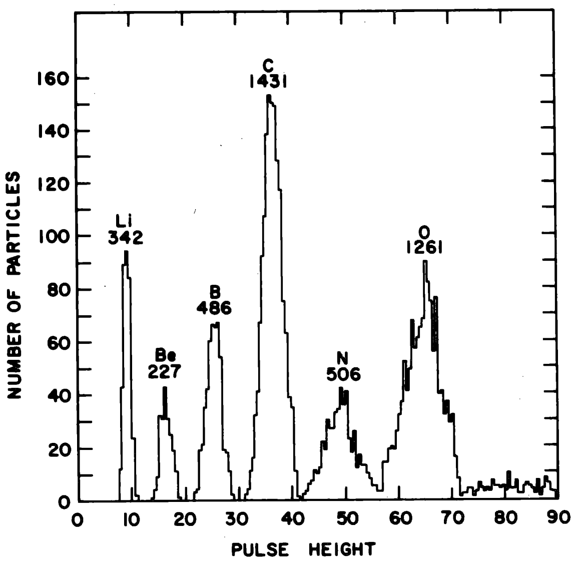

Figure 1. Charge Resolution

These strict criteria may mean that events, especially those which interact near the top of the spectrometer and produce backscatter, may be rejected. This problem affects the acceptance of nuclei in the range of the light and medium nuclei, because the energy loss of backscattered particles can be some 10 or 20 times minimum. However this probably does not affect the heavier nuclei. It is difficult to identify these events in the data. Pulse heights are either totally inconsistent or the spark chamber trajectory is complex and a track cannot be found. The use of the value FWHM/2 is chosen so that the L/M ratio and the individual charge composition agree with the generally accepted values. Under these conditions, we do not believe our spectra for B and all higher charges are affected by background contamination. Some good events are rejected by this criterion. This effect is estimated to be 25% for nuclei with charge ≤8, 15% for the 10-14 group and negligible for higher charges.

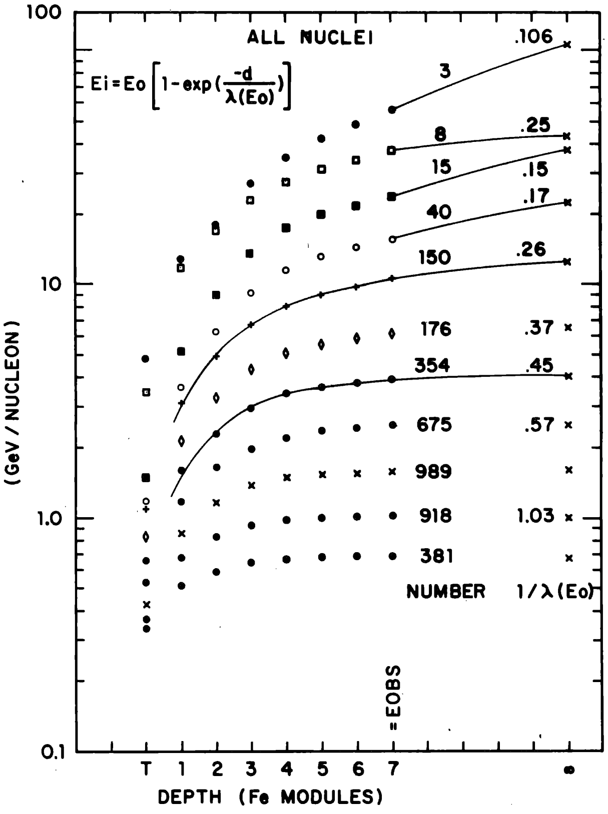

Figure 2. Integral Cascade Growth Curves

Corrections for lack of trajectories in the spark chamber are believed to be 5 to 10% and have been neglected.

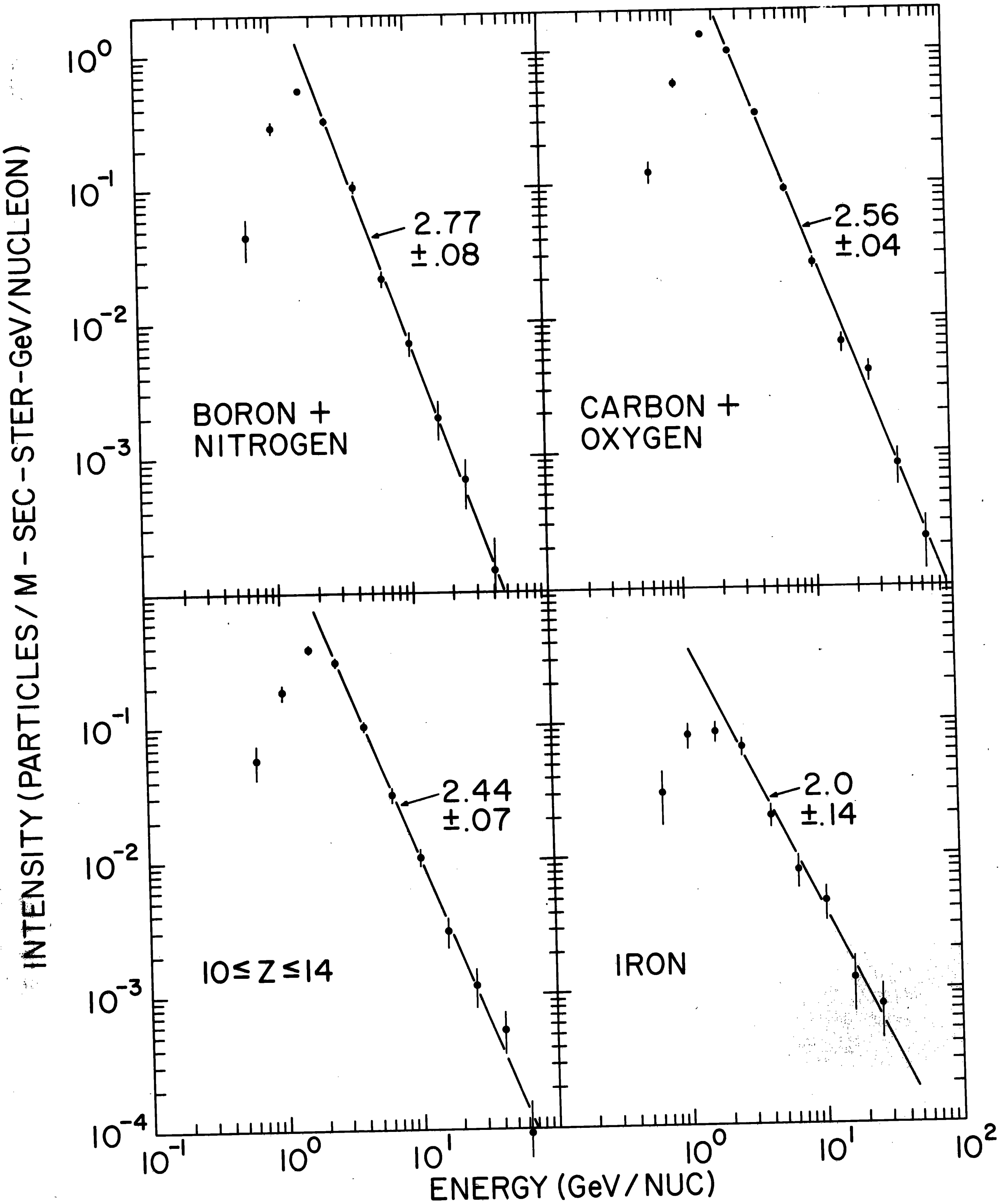

Figure 3. Energy Spectra

Table 2 gives the integral flux of the different groups of nuclei at the top of the atmosphere.

Flux from Different Experiments in Particles/m^2-sec-ster

Group of Nuclei	GSFC (> 4.5 GV)	Webber et al	Smith et al (> 5 GV)	Mewaldt et al (> 5 GV)
C+O	3.45 ± .7	4.66±.014 (>4.35 GV)	4.13±.07	
10≤Z≤14	1.08±.2		1.5±.03	
15≤Z≤23	.33±.06		.36±.03	
20≤Z≤28	.44±.09	.489±.02 for Z>17 (>4.10 GV)		.417±.03

Our carbon and oxygen fluxes are about 35% low compared to those of other workers, whereas there are no severe discrepancies for the other nuclei. This is probably due to events interacting near the top of the spectrometer which appear as background to the charge module.

Using the total energy deposited particles which pass through the entire spectrometer were used to construct average integral cascade growth curves. These were done separately for the various charges and plotted on an energy/nucleon basis. Above 2 GeV/nucleon the curves are quite similar, and so all the data were combined on an energy/nucleon basis to get the series of growth curves shown in Figure 2.

The curves could be expressed as: $E_n = E_o\ (1 - \exp(-n/\lambda))$ where E_n is the measured energy using n modules and E_o is the energy of the incident particle. $\lambda(E)$, the number of modules necessary for absorbing (1 - 1/e) of the incident energy, was energy dependent. These empirically fitted curves give the energy E_o as a function of the measured energy.

The final correction to the data was for the energy going into nuclear disintegrations which is not observed by the spectrometer. Based on Monte Carlo calculations (Jones, 1970) and accelerator calibrations (Whiteside et al., 1973), we use a correction to the observed energy which decreases logarithmically from 33% at 1 GeV/nucleon to 20% at 100 GeV/nucleon. This represents a significant change from our earlier analysis (Ormes et al., 1971) in which our corrections were based upon much less information and results in somewhat flatter spectra than those reported previously. Uncertainties in these corrections leave us with a possible systematic error in our spectral exponents of perhaps ±0.1. We believe however, that the relative spectra are accurate to within the statistical uncertainties. The fluxes have been corrected to 0gm/cm^2 using the procedure described by Webber et al., (1972). The estimated systematic uncertainty is ±20% in the fluxes quoted.

3. <u>Results</u>. The energy spectra of various nuclei are shown in Figure 3.

Below 2.0 GeV/nucleon the spectral shape is determined by the geomagnetic cutoff and was time dependent because the balloon drifted from 5.0 Gv to 3.2 Gv cutoff during the course of the flight. The data were fitted to power law spectra of the form $dN/dE = k/E^{\gamma}$.

Our result that the spectrum of B+N is steeper than the spectrum of C+O is qualitatively consistent with those of Juliusson et al., (1972), Webber et al., (1973) and Smith et al., (1973). The data all indicate the spectra of secondary nuclei are steeper than those of primaries. However we believe that the decrease in the secondary/primary ratio is gradual and represents a power law difference of about 0.2. The large spectral difference (0.57 ± 0.14) between iron and C+O is at the 3 σ level. It persists in spite of possible systematic errors which limit our knowledge of the spectral exponents themselves to 0.1 to 0.2.

We believe (Ormes and Balasubrahmanyan, 1973, Ramaty et al., 1973) that the difference between the Fe and C+O spectra is too large to be explained as a propagation effect as attempted by Webber et al., (1973). This interpretation is, in part, related to experimental differences in the data from the secondaries produced by spallation of the iron and can only be resolved by further experimentation. If the differences are related to the acceleration mechanism, it may be due to either separate sources (either location or type) or to Z dependent forces on the particles. Our spectra of the 10 to 14 group are consistent with having the same spectrum as the C+O within statistical uncertainties. By measuring the spectra of Ne, and Si more accurately we should be able to resolve this question. Future experiments are planned to extend the measurements to 200 or 400 GeV/nucleon where the flux of iron may become comparable to that of carbon. It is crucial to find whether the iron continues to become relatively more abundant or just undergoes a transition from one ratio to another. In order to determine this we are planning a flight with a larger area thin ionization spectrometer. We also plan to cross calibrate our spectrometer with a gas Cerenkov detector. This will tell us the magnitude of the nuclear disintegration correction at high energies and eliminate one important source of systematic errors.

4. References.

Jones, W. V., 1971, Proc. 12th Intl. Conf. Cosmic Rays, Hobard, 1, 190.

Juliusson et al., Phys. Rev. (Letters) 29, 445.

Mewaldt et al., Relativistic Heavy Cosmic Rays, preprint, Washington U., St. Louis, 1973.

Ormes et al., Proc. 12th Intl. Conf. Cosmic Rays, Hobart, 1, 178.

Ormes, J. F., and Balasubrahmanyan, V. K., 1973, Nature, 241, 95.

Ramaty et al., 1973, Science, 180, 731.

Smith et al., 1973, Ap. J., 180, 987.

Webber, W. R., Damle, S. V., and Kish, J., 1972, Astrophys. and Sp. Sci., 15, 245.

Webber, W. R., Lexniak, J. A., Kish, J. C., and Damle, S. V., 1973, Nature, 271, 97.

Whiteside et al., 1973, Nucl. Inst. and Methods, in press.