

ENERGY DEPENDENCE OF COSMIC RAY COMPOSITION ABOVE  $10^5$  GEV/NUCLEUS

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## ABSTRACT

It is argued that above  $10^5$  GeV/nucleus, in the range where charge-resolved spectra have not yet been determined, the appropriate measures of equal-energy composition are  $\langle \ln A \rangle$  and  $\{ \ln A \}$ , the mean value and dispersion relative to the mean of  $\ln A$ , where  $A$  is the mass number. Experimental data which are sensitive to changes in  $\langle \ln A \rangle$  with increasing energy are examined. It is found that, taken as a whole, they show no change ( $\pm 0.5$ ) between  $10^5$  and  $10^6$  GeV, and a decrease of  $1.5 \pm 0.5$  between  $10^6$  and  $10^8$  GeV, with no further change ( $\pm 0.5$ ) above  $10^8$  GeV. Taken as a whole, the various indirect estimates of the absolute value of  $\langle \ln A \rangle$  above  $10^5$  GeV/nucleus are also consistent with this pattern. For a wide range of astrophysically plausible composition models the value of the other measure,  $\{ \ln A \}$ , is insensitive to changes in  $\langle \ln A \rangle$ . Because of this the existing data on  $\{ \ln A \}$  can likewise easily be reconciled with this pattern.

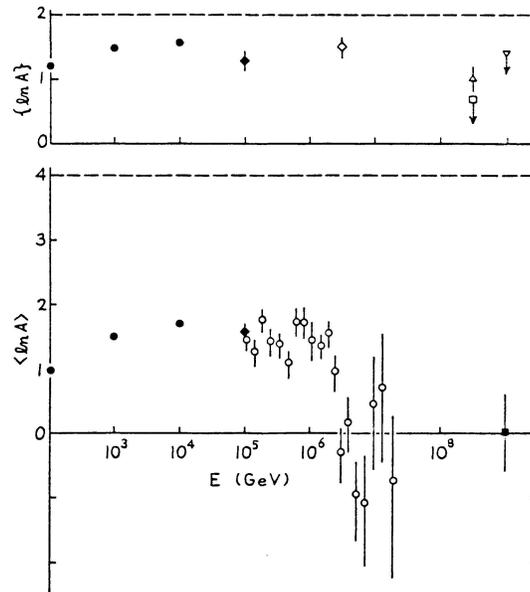
1. Introduction. The energy spectra of all the elements, insofar as they have been measured to date at the top of the atmosphere or above it, are well explained by a simple leaky box model with fragmentation in the interstellar medium and a rigidity dependent escape length. However, measurements of charge-resolved spectra are increasingly difficult at higher energies. Particles are usually selected on the basis of energy per nucleus, the practical upper limit being at present about  $10^5$  GeV/nucleus. The composition of cosmic rays with equal energy is strongly biased in favor of heavy elements compared to cosmic rays with equal magnetic rigidity. Below  $10^5$  GeV/nucleus the equal-energy mass spectrum is in fact nearly rectangular from protons to iron.

Above  $10^5$  GeV/nucleus the evidence on cosmic ray composition is indirect. There is overwhelming evidence that nearly all of these cosmic rays are bare atomic nuclei, as at lower energies, rather than electrons,  $\gamma$ -rays, neutrinos, dust grains, or exotic objects such as quark globs, magnetic monopoles, or mini-black holes. The indirect experiments are sensitive to primary mass rather than charge, but in view of the low resolution, conversions from one to the other are carried out assuming that  $Z = A/2$  for nuclei other than protons. With a few exceptions the indirect methods select primaries of a given energy per nucleus, rather than energy per nucleon. They are unable at present to resolve the mass spectrum into individual nuclei or even groups of neighboring mass. With a few exceptions they can be classified into two groups: those

which measure the average primary mass and those which measure the width of the primary mass distribution. In most cases the theoretical line separation is proportional to  $\ln A$  rather than  $A$ . For this reason, and to avoid giving undue importance to elements in the Fe group, it is preferable to use  $\ln A$  as the underlying variable, and to group the experiments into some which measure the mean value  $\langle \ln A \rangle$  and others which measure  $\{ \ln A \}$ , the dispersion of  $\ln A$  relative to the mean. The remainder of this work summarizes the available experimental evidence on the energy dependence of these two quantities, with emphasis, of course, on energies above  $10^5$  GeV/nucleus.

2. Low Energy Region. The behavior of  $\langle \ln A \rangle$  and  $\{ \ln A \}$  as a function of energy/nucleus is shown in Fig. 1. For energies  $\leq 10^5$  GeV the points are calculated from directly observed charge spectra (see Linsley 1983). In this region the value of  $\langle \ln A \rangle$  increases from 1.0 at  $10^2$  GeV to 1.7 at  $10^4$  GeV and then levels off. Although one cannot rule out a certain degree of heavy enrichment at the sources in the upper part of this range (Juliusson 1975, Goodman *et al.* 1979), it is not necessary to assume any such enrichment; the increase of  $\langle \ln A \rangle$  can be explained entirely by a diminished path length at higher energies, resulting in less fragmentation of nuclei such as Fe during propagation from the sources to the earth. There is direct evidence from the JACEE experiment that the value of  $\langle \ln A \rangle$  is not significantly greater at  $10^5$  GeV than at  $10^4$  GeV (Burnett *et al.* 1983), and there is direct evidence from an experiment by Sood (1983) that the intensity of Fe nuclei at the top of the atmosphere is no greater at  $10^5$  GeV than predicted by the standard model.

3. High Energy Region. A number of ground level experiments measure  $\langle \ln A \rangle$ . Calibration is a problem, so some results are sensitive mainly to changes in  $\langle \ln A \rangle$  vs  $E$ , while others yield estimates of the absolute value of  $\langle \ln A \rangle$ . One approach uses data on  $x_m$ , the atmospheric depth at which air showers reach maximum development; another uses data on  $N_\mu$ , the number of muons for a fixed number of electrons at ground level. For a given primary  $A$ , barring any sudden unexpected changes in the character of high energy interactions,  $\langle x_m \rangle$  and  $\langle \ln N_\mu \rangle$  are expected



*Fig. 1. Energy dependence of  $\langle \ln A \rangle$  and  $\{ \ln A \}$ . CLOSED CIRCLES, calculated from charge-resolved spectra obtained in many balloon experiments; CLOSED DIAMONDS, Burnett *et al.* 1983; CLOSED SQUARE, Linsley & Watson 1981 from  $\langle x_m \rangle$  obtained in several air shower experiments; OPEN CIRCLES, Acharva *et al.* 1983; OPEN DIAMOND, Nikolskii *et al.* 1979; TRIANGLE, Hara *et al.* 1983; INVERTED TRIANGLE, upper limit from  $\{ x_m \}$  obtained in several air shower experiments; OPEN SQUARE, upper limit from  $\{ \ln N_\mu \}$  (Volcano Ranch experiment).*

to be almost linear functions of  $\ln E$ . Then for a mixed primary composition, according to the superposition principle of Peters (1960), they are linear functions of  $\langle \ln A \rangle$ . Consequently one expects to detect significant changes in  $\langle \ln A \rangle$  by observing changes in the experimentally measured rates of increase,  $d(\langle x_m \rangle)/d(\ln E)$  and  $d(\langle \ln N_\mu \rangle)/d(\ln E)$ .

The former is called the 'elongation rate'. The first systematic investigation capable of applying the elongation rate test indicated that  $\langle \ln A \rangle$  undergoes a large decrease in going from  $\sim 10^6$  to  $10^8$  GeV (Thornton and Clay 1979). Since then the energy dependence of the elongation rate has been investigated by many groups using a wide variety of methods (Kalmykov *et al.* 1979, Antonov *et al.* 1979, Walker and Watson 1981, Chantler *et al.* 1982, Kvashnin *et al.* 1983, Alimov *et al.* 1983, Inoue *et al.* 1983, Cady *et al.* 1983). Although the later results are not all perfectly consistent, taken as a whole the  $\langle x_m \rangle$  results require a decrease in  $\langle \ln A \rangle$  of 1.5 or more, which corresponds to changing from a mixed (low energy) composition to one highly proton enriched, between  $10^6$  and  $10^8$  GeV. In the region above this change, where the elongation rate test indicates little or no further change in  $\langle \ln A \rangle$ , the absolute value of  $\langle \ln A \rangle$  was found from a detailed analysis of  $\langle x_m \rangle$  data to be  $0^{+0.6}_{-0}$  (Linsley and Watson 1981).

The other indicator,  $d(\langle \ln N_\mu \rangle)/d(\ln E)$ , is less sensitive and more difficult to calibrate. The independent variable in actual experiments is  $N_e$  rather than  $E$ , but one expects  $N_e$  to be nearly proportional to  $E$  for given primary  $A$ , so the same principles apply. A change in composition will cause the value of  $d(\langle \ln N_\mu \rangle)/d(\ln N_e)$  to be less in a region where  $\langle \ln A \rangle$  is decreasing than it is where  $\langle \ln A \rangle$  is constant, but for low energy muons ( $E_\mu < 10$  GeV) the expected change (corresponding to the variation in  $\langle \ln A \rangle$  described above) is only 8-10% (Grieder 1983). This is not much more than the uncertainty in the reference value (the value for  $\langle \ln A \rangle \sim \text{constant}$ ), and the actual sensitivity could be even less. In fact,  $d(\langle \ln N_\mu \rangle)/d(\ln N_e)$  for  $E_\mu < 10$  GeV does not show any significant variations in the region where it has been studied, from  $\sim 10^5$  to  $10^8$  GeV/nucleus. For higher energy muons the expected difference is greater, however, amounting to  $\sim 15\%$  for  $E_\mu = 220$  GeV. The only experiment on high energy muons capable of showing this kind of change has given results in good agreement with those from the  $\langle x_m \rangle$  measurements (Acharya *et al.* 1983). A notable feature of this experiment is that the primary energy range extended down to  $10^5$  GeV; that is, to the region where  $\langle \ln A \rangle$  has been measured directly using balloons (Burnett *et al.* 1983, Sood 1983). This result and the one by Linsley and Watson are shown in Fig. 1.

Constancy of  $\langle \ln A \rangle$  in the interval  $10^5$ - $10^6$  GeV is also indicated by data requiring other types of analysis: data on very high energy (TeV) muons (Elbert 1982, Battistoni *et al.* 1983, Matsuno *et al.* 1984, Allkofer *et al.* 1984), and on the energy spectrum of air shower hadrons, as analyzed by Grieder (1983, see also Dybovy and Nesterova 1983). Some other results on the hadron component have been seen as favoring a strong Fe enhancement in the interval  $10^5$ - $10^7$  GeV (Goodman *et al.* 1979, Amenomori *et al.* 1983). However, like earlier claims for an iron anomaly at lower energies, these claims are not well enough supported to withstand the overwhelming weight of contrary evidence.

It should be noted that many of the indirect experiments are sensitive primarily to  $\{\ln A\}$  rather than  $\langle \ln A \rangle$ . These experiments measure air shower fluctuations. The quantities that have been studied mainly are, again,  $x_m$  and  $N_\mu$ . Unfortunately  $\{\ln A\}$  is not very sensitive to the various assumptions that can be made about cosmic ray composition. If one assumes that the possibilities range from pure protons ( $\langle \ln A \rangle = 0$ ) to pure Fe ( $\langle \ln A \rangle = 4$ ), then the maximum value that  $\{\ln A\}$  can have is 2, not much greater than the observed value in the low energy domain. Even a small admixture of protons with otherwise pure Fe, or of Fe with otherwise pure protons, will appreciably enhance the shower fluctuations so as to give  $\{\ln A\} \sim 1$ , which is about as low a value as any of the experiments have given. Experiments which measure the fluctuations of  $x_m$  escape this criticism somewhat because  $\{x_m\}$  is sensitive to  $\langle \ln A \rangle$  as well as  $\{\ln A\}$  (Linsley 1983). The observed fluctuations above  $10^8$  GeV are consistent with pure proton primaries or with mixtures containing up to 50% of nuclei heavier than helium. They are not consistent with pure Fe primaries or with mixtures containing only a small percentage of light elements (Walker and Watson 1982, Dyakonov *et al.* 1983, Hara *et al.* 1983).

4. Conclusions. Below  $10^5$  GeV/nucleus the equal-energy composition varies with energy in the manner expected due to fragmentation in the interstellar medium with a rigidity dependent path length. The increase of  $\langle \ln A \rangle$  in this region is not a property of the sources, but is rather a propagation effect. Between  $10^5$  and  $10^6$  GeV there is little change in  $\langle \ln A \rangle$ . Between  $10^6$  and  $10^8$  GeV the average primary mass decreases to about 1 ( $\langle \ln A \rangle \sim 0$ ). It then remains constant, from  $10^8$  GeV to the highest observed energies ( $E \sim 10^{11}$  GeV/nucleus).

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