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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 <lnA> and {lnA}, the mean value and dispersion relative to the mean of lnA, where A is the mass number. Experimental data which are sensitive to changes in <lnA> with increasing energy are examined. It is found that, taken as a whole, they show no change (±0.5) between 10^5 and 10^6 GeV, and a *decrease* of 1.5±0.5 between 10^6 and 10^8 GeV, with no further change (±0.5) above 10^8 GeV. Taken as a whole, the various indirect estimates of the absolute value of <lnA> 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, {lnA}, is insensitive to changes in <lnA>. Because of this the existing data on {lnA} 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, γ-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 lnA rather than A. For this reason, and to avoid giving undue importance to elements in the Fe group, it is preferable to use lnA as the underlying variable, and to group the experiments into some which measure the mean value <lnA> and others which measure {lnA}, the dispersion of lnA 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 <lnA> and {lnA} as a function of energy/nucleus is shown in Fig. 1. For energies $\leqq 10^5$ GeV the points are calculated from directly observed charge spectra (see Linsley 1983). In this region the value of <lnA> 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 <lnA> 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 <lnA> 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.

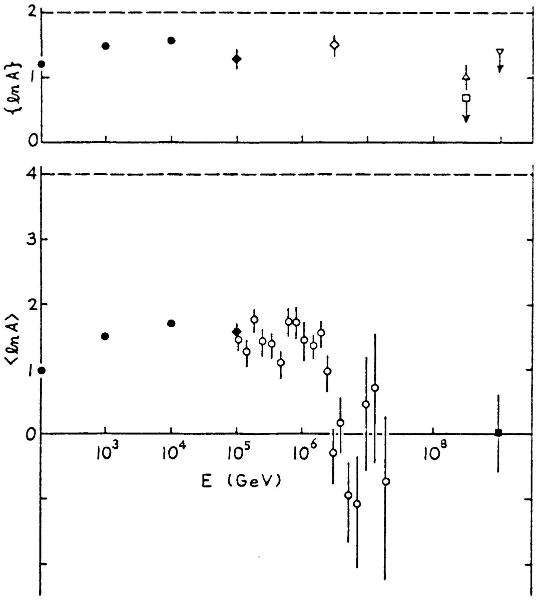

Fig. 1. Energy dependence of <lnA> and {lnA}. CLOSED CIRCLES, calculated from charge-resolved spectra obtained in many balloon experiments; CLOSED DIAMONDS, Burnett et al. 1983; CLOSED SQUARE, Linsley & Watson 1981 from <x_m> obtained in several air shower experiments; OPEN CIRCLES, Acharya et al. 1983; 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 {lnN_μ} (Volcano Ranch experiment).

3. High Energy Region. A number of ground level experiments measure <lnA>. Calibration is a problem, so some results are sensitive mainly to *changes in* <lnA> vs E, while others yield estimates of the absolute value of <lnA>. One approach uses data on x_m, the atmospheric depth at which air showers reach maximum development; another uses data on N_μ, 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, <x_m> and <lnN_μ> are expected

to be almost linear functions of lnE. Then for a mixed primary composition, according to the superposition principle of Peters (1960), they are linear functions of <lnA>. Consequently one expects to detect significant changes in <lnA> 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 <lnA> undergoes a large decrease in going from ∿ 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 <lnA> 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 <lnA>, the absolute value of <lnA> 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 <lnA> is decreasing than it is where <lnA> is constant, but for low energy muons (E_μ<10 GeV) the expected change (corresponding to the variation in <lnA> described above) is only 8-10% (Grieder 1983). This is not much more than the uncertainty in the reference value (the value for <lnA> ∿ constant), and the actual sensitivity could be even less. In fact, $d(\langle \ln N_\mu \rangle)/d(\ln N_e)$ for E_μ<10 GeV does not show any significant variations in the region where it has been studied, from ∿ 10^5 to 10^8 GeV/nucleus. For higher energy muons the expected difference is greater, however, amounting to ∿ 15% for E_μ = 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 <lnA> 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 <lnA> 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 {lnA} rather than <lnA>. These experiments measure air shower fluctuations. The quantities that have been studied mainly are, again, x_m and N_μ. Unfortunately {lnA} 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 (<lnA> = 0) to pure Fe (<lnA> = 4), then the maximum value that {lnA} 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 {lnA} $\sim$ 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 <lnA> as well as {lnA} (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 <lnA> 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 <lnA>. Between 10^6 and 10^8 GeV the average primary mass decreases to about 1 (<lnA> $\sim$ 0). It then remains constant, from 10^8 GeV to the highest observed energies (E $\sim$ 10^{11} GeV/nucleus).

References. ACHARYA *et al.* 1983, Proc. 18th ICRC 9, 191 (also ACHARYA, B. Thesis, Univ. of Bombay, 1983); ALIMOV *et al.* 1983, Proc. 18th ICRC 11, 387; ALLKOFER *et al.* 1984, Lett. Nuovo Cimento 41, 373; AMENOMORI *et al.* 1983, Proc. 18th ICRC 11, 114; ANTONOV *et al.* 1979, Proc. 16th ICRC 9, 263; BATTISTONI *et al.* 1983, Proc. 18th ICRC 11, 466; BURNETT *et al.* 1983, Proc. 18th ICRC 2, 105; CADY *et al.* 1983, Proc. 18th ICRC 11, 412; CHANTLER *et al.* 1982, J. Phys. G 8, L51; DYAKONOV *et al.* 1983, Proc. 18th ICRC 6, 111; DYBOVY and NESTEROVA 1983, Proc. 18th ICRC 6, 82; ELBERT 1982, Proc. Workshop on Very High Energy Cosmic Ray Interactions (Univ. of Pennsylvania) p. 312; GOODMAN *et al.* 1979, Phys. Rev. Lett. 42, 854; GRIEDER 1983, Proc. 18th ICRC 11, 323 (also 1984 preprint); HARA *et al.* Proc. 18th ICRC 11, 272; INOUE *et al.* 1983, Proc. 18th ICRC 11, 402; JULIUSSON 1975, Proc. 14th ICRC 8, 2689; KALMYKOV *et al.* 1979, Proc. 16th ICRC 9, 73; KVASHNIN *et al.* 1983, Proc. 18th ICRC 11, 394; LINSLEY 1983, Proc. 18th ICRC 12, 135; LINSLEY and WATSON 1981, Phys. Rev. Lett. 46, 459; MATSUNO *et al.* 1984, Phys. Rev. D 29, 1; NIKOLSKII *et al.* 1979, Proc. 16th ICRC 8, 335; PETERS 1960, Proc. 6th ICRC III, 157; SOOD 1983, Nature 301, 44 (also Proc. 18th ICRC 2, 109; THORNTON and CLAY 1979, Phys. Rev. Lett. 43, 1622 and Erratum, 45, 1463; WALKER and WATSON 1981, J. Phys. G 7, 1297; WALKER and WATSON 1982, J. Phys. G 8, 1131.