COMPOSITION OF COSMIC RAYS AT 10^{10} TO 10^{13} eV/NUCLEUS

E. Juliusson

Centre d'Etudes Nucléaires de Saclay, France

We have calculated the nuclear composition of the cosmic rays around 10^{10} - 10^{13} eV total energy per nucleus, from recent counter measurements. The abundance of iron in the highest energy range is comparable to the abundance of protons and alpha particles, and increasing with energy. If this trend continues, the highest energy airshower events recorded are caused mostly by iron nuclei, and we cannot be sure of their extragalactic origin.

1. Introduction. Measurements of the cosmic ray nuclei now extend up to about 10^{20} eV. These measurements have provided valuable information about the sources of the cosmic rays and about their propagation in the galaxy. The high energy end of the spectrum is of great importance to the questions of the origin of the cosmic rays, of their confinement in the galaxy, and of a possible extragalactic origin.

In order to answer the question of galactic or extragalactic origin of these particles we must know their composition. This knowledge is also of vital importance for interpreting any irregularities in the spectra in terms of propagation in the galaxy. Unfortunately measurements of the composition of the highest energy nuclei are very difficult to perform, and the question of the composition above 10^{13} eV is still not settled. This question can of course only be answered by direct measurements of the composition in this energy region, and any extrapolation of the lower energy composition into this energy region gives at best only a standard with which to compare actual measurements. However it is important to have such a standard, and we shall calculate here the composition as a function of energy per nucleus from low energies, up to as high energies as direct measurements exist.

2. Composition as a function of energy per nucleus. The composition of the elements up to Nickel, around a few GeV per nucleon is now rather well known, and in fig. 1 we show some recent measurements of four groups of nuclei, Hydrogen, Helium, Carbon plus Oxygen, and the Iron group nuclei. Since the cosmic ray spectra are very steep, direct comparison of different measurements is difficult. The spectra in fig. 1 have therefore been flattened by multiplying the reported differential fluxes n(E) by the square of the total energy per nucleon E_T^2. Some experimenters report integral fluxes which we want to compare with the differential fluxes, and these points are plotted also on the same figure. However the composition above energy E correspond to the composition at a higher energy $e^{1/(\gamma-1)} \cdot E$ where γ is the differential spectral index. We have used an average value of 1.8 for this

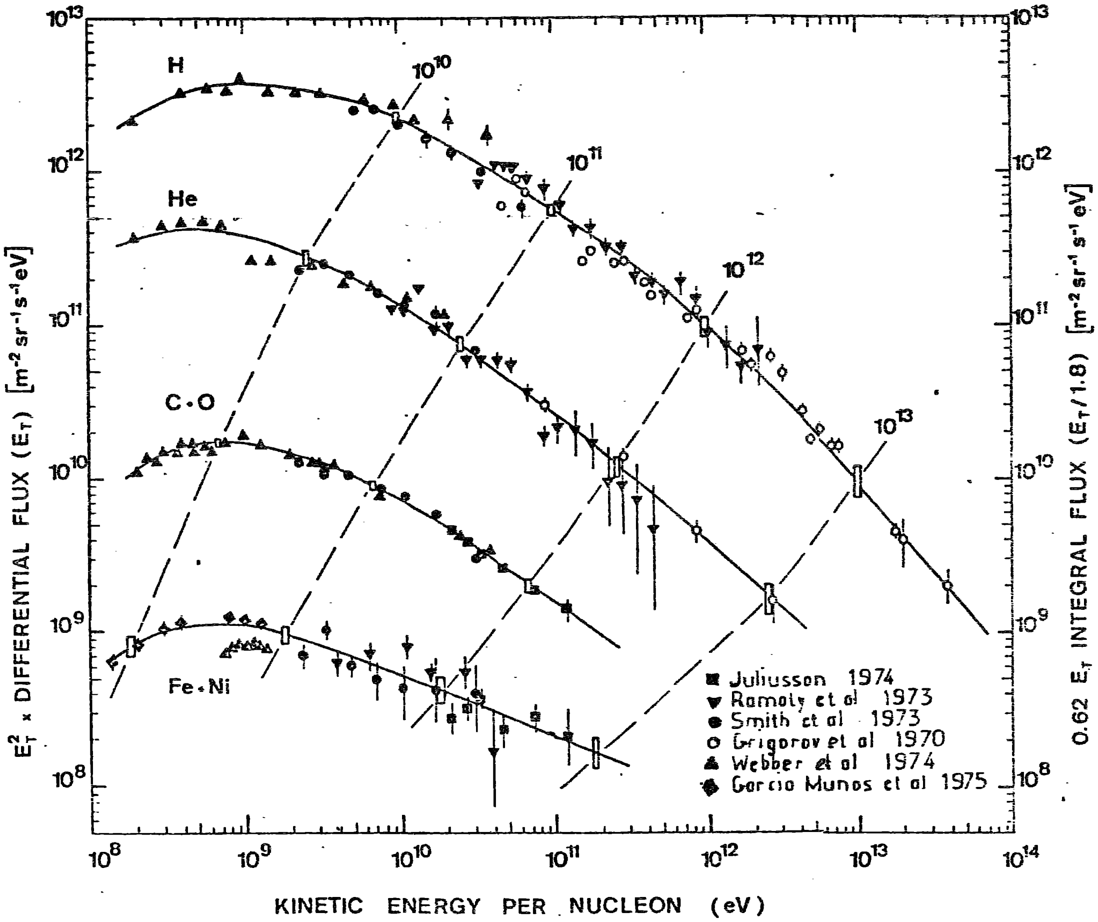

Fig. 1. Cosmic ray velocity spectra

γ-dependent factor, and the integral fluxes are plotted at an energy a factor 1.8 above the reported energy. In order to make the integral points comparable to the differential points we multiply the integral flux N by 0.62 x E_T. There is of course in general case no one to one correspondence between differential and integral points, but the implied connection, i.e.

$$E \times n(E) \approx 0.62 \times N(E/1.8) \qquad (1)$$

is in fact accurate to better than 1% for all powerlaws in E of a differential spectral index between 2.4 and 3.0.

There are some differences between the individual measurements, larger than the reported errors, but overall the agreement is very good. The estimated flux values at 10^{10}, 10^{11}, 10^{12} and 10^{13} eV are marked by an open rectangle. In fig. 2 we show similarly the relative composition of the groups Light, Heavy and Very Heavy nuclei, compared to the groups already shown in fig. 1. From the results in fig. 1 and fig. 2 we have computed the relative composition of the different charge groups at 10^{10} to 10^{13} eV. This composition is shown in table I, normalized as a percentage of the total.

The division between the charge groups is made here at a measured charge of 1.5, 2.5, 5.5, 9.0, 15.0, 25.0 and 29.0 and the abundance of fluorine, phosphorus and manganese are divided between two groups. When these rare elements are not well resolved, this division will minimize the error due to charge overlap between the groups.

The basic departure of table I from the table of Ginzburg and Syrovatskii (1964) is that the abundances clearly depend on energy. We must emphasize that if the composition of the cosmic rays were independent of velocity (energy per nucleon), the composition would still depend on energy, unless the spectra were straight powerlaws in kinetic energy. The rise in the abundances of iron with energy, is due not only to a change in the relative abundance of iron with velocity, but even more due to the suppression of iron at low energies by energy losses and spallation in the interstellar medium, energy losses caused by the solar modulation and, most likely, due to source spectra that do not rise with decreasing velocity as fast as a powerlaw in kinetic energy.

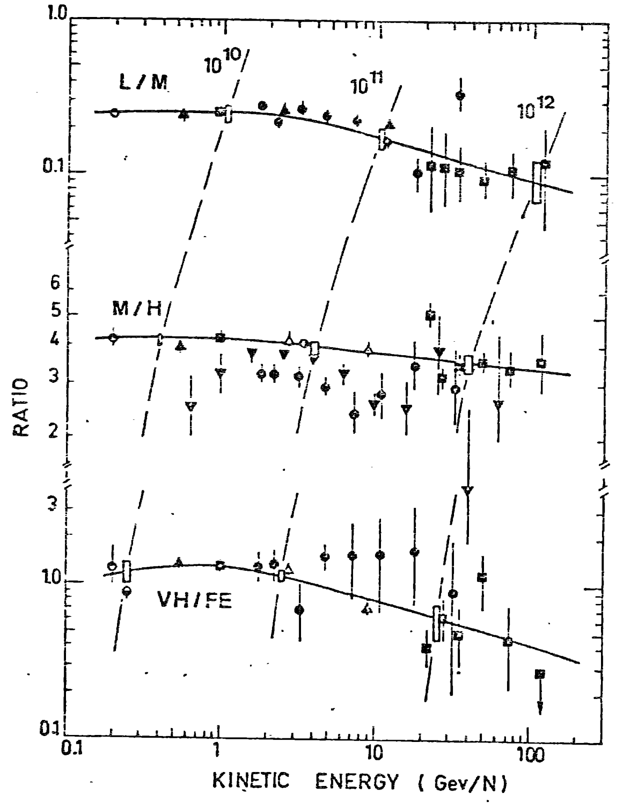

Fig. 2. Relative abundances in cosmic rays

TABLE I - COMPOSITION OF COSMIC RAYS AT HIGH ENERGIES

		KINETIC ENERGY PER NUCLEUS (eV)			
Z	ELEMENTS	10^{10}	10^{11}	10^{12}	10^{13}
1	Hydrogen	58 ± 5	47±4	42±6	24±6
2	Helium	28 ± 3	25±3	20±3	15±5
3 - 5	Light-nuclei	1.2± 0.1	1.1±0.1	0.6±0.2	
6 - 8	Medium-nuclei	7.1± 0.4	12.2±0.8	14±2	
10-14	Heavy-nuclei	2.8± 0.2	6.7± 0.5	10±1	
16-24	Very heavy-nuclei	1.2± 0.2	3.6± 0.4	4±1	
26-28	Iron group nuclei	1.2± 0.2	4.5± 0.5	10±2	24±7
≥ 30	Very very heavy-nuclei		.007 ±.004		

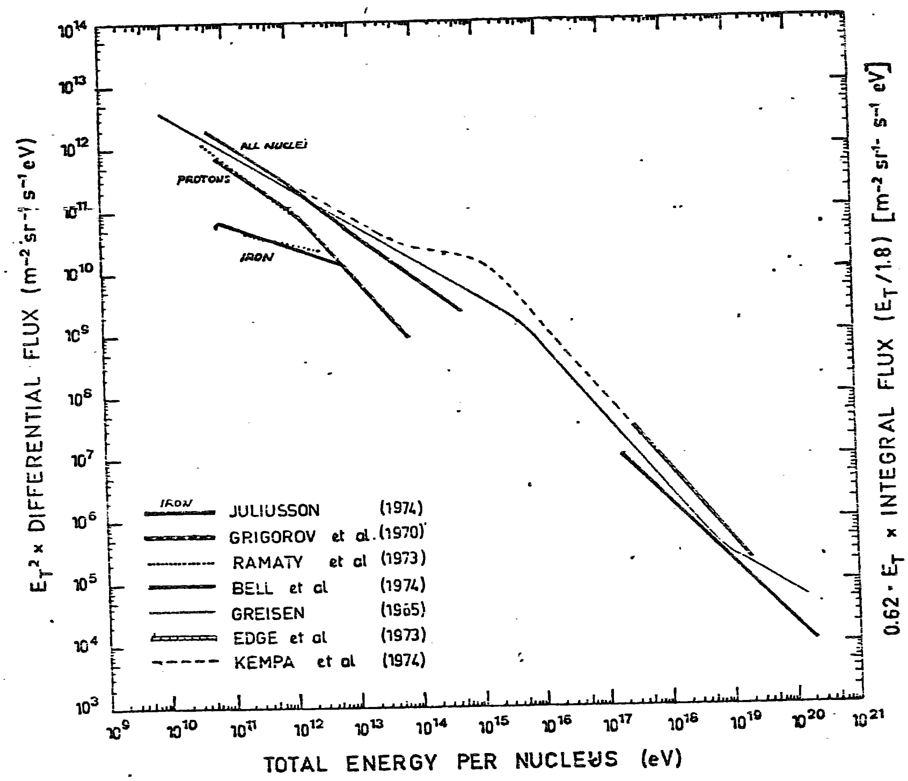

Fig. 3. Energy per nucleus spectra of cosmic rays

At the highest energy, iron is measured to be as abundant as hydrogen in the cosmic rays. This is in agreement with measurements by Grindley and Helmken (1973). In view of the smooth nature of the spectra below 10^{13} eV, and as the spectra are still steepening above this energy, iron is probably the most abundant component in the cosmic rays for all energies above 10^{13} eV.

3. Cosmic ray spectra at high energies. The spectra of cosmic ray Hydrogen and Iron shown in fig. 1 are displayed again in fig. 3 as a function of energy per nucleus. This figure also includes spectra obtained at higher energies by airshower measurements. The measurements above 10^{13} eV do not all agree completely. Kempa et al. (1974) show significantly higher flux values between 10^{13} and 10^{16} eV than most others. At the highest energies above 10^{16} eV the spectra reported by Bell et al. (1974) and Edge et al. (1973) differ in spectral index by about 6 standard deviations and in intensity by about 10 standard deviations. These differences seem to be mostly due to the models used to interpret the shower size data. Bell et al. (1974) have used what we might call here a "low" model to calculate the energy of the primary particles while Edge et al. (1973) have used a "high" model. These two models do not at all seem to represent any extremes. Bell et al. (1974) report that if some other models were used, the intensities might be 65 sigma below, or 125 sigma above the reported value. Clearly no final answer can be given about the high energy spectra to a higher accuracy than the differences between the two reported spectra.

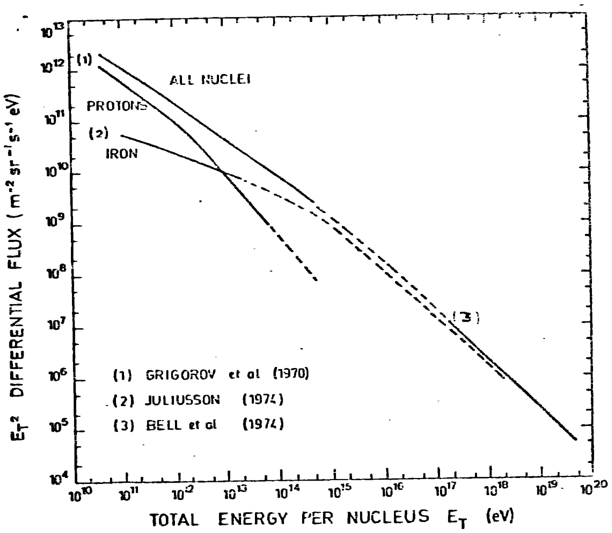

Fig. 4. A possible interpretation of cosmic rays spectra

We shall try to look for a consistent picture of the cosmic ray spectra. We shall assume that at lower energies the measurements of Grigorov et al. (1970) and our own (Juliusson, 1974) are correct, noting that these agree well with the measurements of Ramaty et al. (1973) which however do not extend up to as high an energy. These are redrawn in fig. 4. At high energies we have some preference for a low model, and we have therefore shown the measurements of Bell et al. (1974). At intermediate energies we do not know whether the measurements have been interpreted with a "high" or a "low" model and we simply extrapolate our measured iron spectrum until it meets the extrapolated spectrum of Bell et al. (1974). We must emphasize the importance of using one single model to interpret all the airshower data, as Kempa et al. (1974) seem to have done and we expect that the spectrum we have drawn in the intermediate region approximates the measured spectra if a "low" model comparable to the Sidney model were consistently used to interpret the measurements.

We emphasize that fig. 4 is of course just one possible way of interpreting the data, and may not represent the true situation at all. We only wanted to find the simplest possible picture that agreed with as many of the measurements as possible. Since the steepening of the iron spectrum seems to occur at about 5 times higher energy per nucleon, or about 10 times higher rigidity than the steepening of the proton spectrum, the picture in fig. 4 is not even a very simple one. We want however to emphasize that the picture of the cosmic ray spectra is simpler if the high energy spectra are connected to the iron spectra at low energy rather than the proton spectra. This remains so even if we believe in the higher model and spectra of Kempa et al. (1974) or if we do not believe the starting results of Grigorov et al. (1970). The measurements of Grigorov et al. seem to be still controversial and it is usually stated (Ashley et al. 1973) that measurements of the muon charge ratio are inconsistent with a break in the proton spectrum. However since the muon measurements refer only to the composition as a function of velocity, we do not see these measurements as a sufficiently strong evidence to exclude the results of Grigorov et al. If the proton spectrum does not steepen around 10^{12} eV we would expect protons to be the most abundant component in the cosmic rays up to 10^{14} eV. Above 10^{14} eV the simplest extrapolation of the lower energy data would still be to assume that iron becomes the most abundant component.

4. Cosmic ray escape from the galaxy, and extragalactic cosmic rays.

The spectrum in fig. 5 has a break between 10^{14} and 10^{15} eV. Such a break has usually been explained in terms of cosmic ray diffusion in the galaxy. The energy of 10^{15} eV/nucleus corresponds to roughly a gyroradius of 1 parsec or about 10^{-3} of the expected dimension of the confinement region for the cosmic rays. If the size of the scattering irregularities in the magnetic field are generally of this order, then we expect below this energy a constant cosmic ray lifetime, about 10^{3} times longer than it takes for the cosmic rays to travel in a straight line out of the galaxy. Above this energy we expect a rapid decrease in the confinement time, and therefore a steepening of the spectra. However in fig.4 it is the iron spectrum and not the proton spectrum that is steepening below 10^{15} eV, and this interpretation is then not as attractive. Secondly the breaks in the different spectra in fig. 4 are not at the same rigidity, and thus seem unlikely to be explained by propagation alone.

Anisotropy has in the past not been found in the arrival directions of the cosmic rays, and the highest energy nuclei are therefore generally assumed to be extragalactic in origin. However if these events are caused by galactic iron nuclei, anisotropy would probably not appear until well above 10^{19} eV. At 10^{19} eV the radius of curvature for an iron nucleus in 2 μG magnetic field is about 200 parsec, which is probably much less than the dimensions of the confinement region. Even at 10^{20} eV the 2kpc radius of curvature could be expected to distort heavily any picture of the far away galactic plane. The question of possible anisotropy above 10^{19} eV is furthermore not completely closed. Hillas and Ouldridge (1975) suggest that "the arrival directions of the most energetic cosmic rays are almost certainly highly anisotropic". As the data look isotropic to the eye, perhaps a better summary of the present situation is the statement of Bell et al. (1973) that "the highest energy cosmic rays are not obviously isotropic".

In view of the uncertainty in the composition and in the energy measurements at the highest energies, in the strength and extent of the confining magnetic fields, and in the isotropy measurements, we feel that the evidence for any extragalactic contribution to the cosmic ray nuclei at high energy is not very convincing. We also consider the straightness of the spectra measured by Bell et al. (1974) and Edge et al. (1973) an evidence against extragalactic component joining the galactic spectra.

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