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

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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 difficults 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_A^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 $e^{1/(\gamma-1)}.E$ where γ is the
differential spectral index. We have used an average value of 1.8 for this
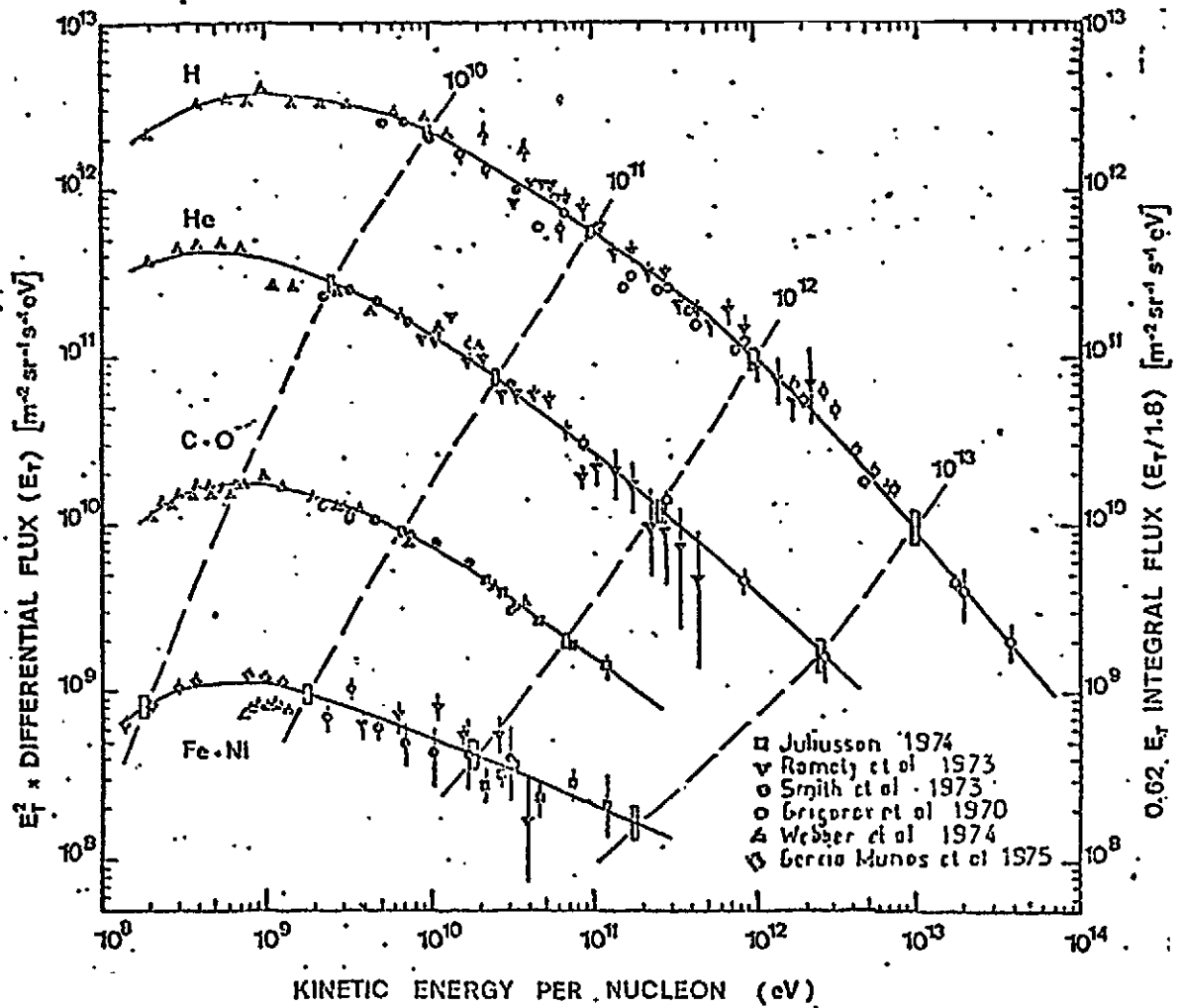
Fig. 1. Cosmic ray velocity spectra

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.

$$E \times n(E) \approx 0.62, N(E/1.8) \tag{1}$$

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 independ-
ent of velocity (energy
per nucleon), the composit-
ion would still depend on
energy, unless the spectra
were straight powerlaws in

Fig. 2. Relative abundances in cosmic rays

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
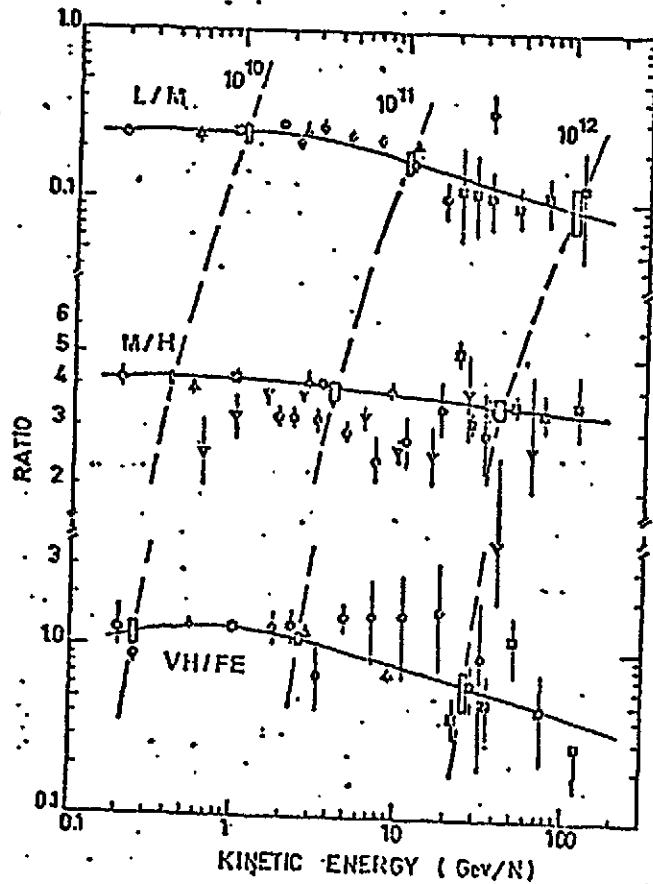do not rise with decreasing velocity as fast as a powerlaw in kinetic
energy.

TABLE I - COMPOSITION OF COSMIC RAYS AT HIGH ENERGIES

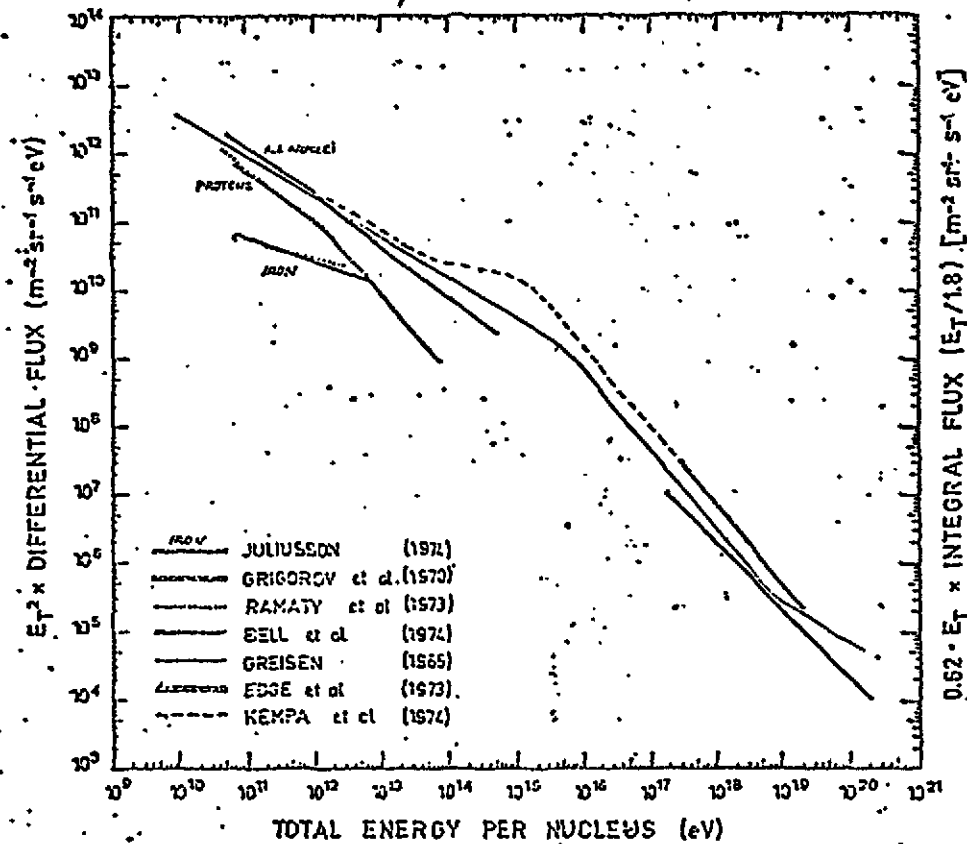| Z	ELEMENTS	KINETIC ENERGY PER NUCLEUS (eV)			
		10^{10}	10^{11}	10^{12}	10^{13}
1	Hydrogen	58 ±5	47±4	42±6	24±6
2	Helium	28 ±3	25±3	20±3	15±5
3 - 5	Light-nuclei	1.2±0.1	1.1±0.1	0.6±0.2	
6 - 8	Medium-nuclei	7.1±0.4	12.2±0.8	14±2	
10-14	Heavy-nuclei	2.8±0.2	6.7±0.5	10±1	
16-24	Very heavy-nuclei	1.2±0.2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

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 measure-
ments 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

Fig.4. A possible interpretation
of cosmic rays spectra

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
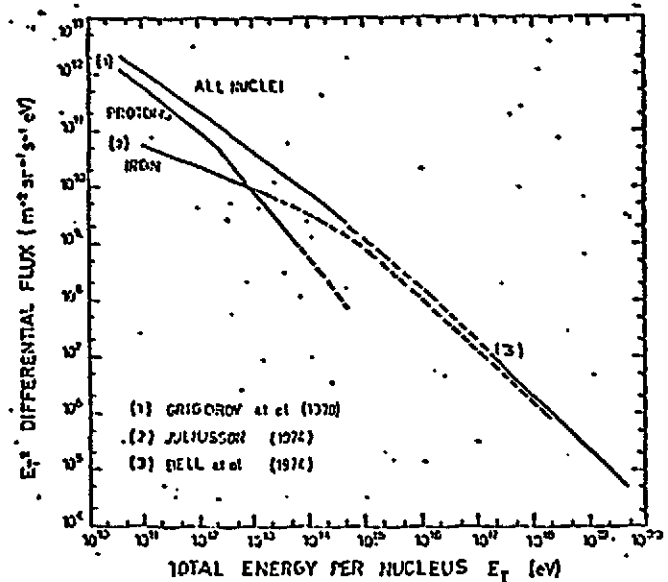abundant component.

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 if 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 interpret-
ation 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
$2\,\mu G$ 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 straight-
ness 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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