COMPOSITION OF COSMIC RAYS NEAR THE BEND

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Abstract:

Air shower experiments having a bearing on the composition of primary cosmic rays near the "bend" are examined. If it is assumed that proton interactions at 10^5 to 10^7 GeV do not mimic iron collisions then there is evidence that most experiments rule out models which require 80 percent or more of primary cosmic rays to be protons at 10^6 GeV. The experimental data is consistent with models which have rigidity dependent steepening around a few times 10^5 GeV/amu.

I. Introduction:

A direct measurement of the primary composition above a total energy per nucleus of 10^5 GeV is difficult because of the smallness of the intensity of cosmic rays. This region, however, is of considerable importance for testing different models of the origin, propagation and acceleration of cosmic rays. The currently popular models of shock acceleration of cosmic ray particles in the ambient HISM predict a universal spectral slope and a rigidity dependent steepening above 10^5 GeV per amu (Lagage and Cesarsky, 83). One expects therefore a change in the mix of primary elemental species above such energies. The average mass of cosmic rays is expected to increase in the decade or two of energy above 10^5 GeV/amu.

One must turn to air shower and high energy muon experiments to study the composition at these energies. The mass resolution of these experiments, however, is quite limited and hence only general trends can be extracted from an analysis of these experiments.

Furthermore, the interpretation of these experiments requires detailed Monte-Carlo calculations of the nuclear-electromagnetic cascades in the atmosphere due to primary nuclei and therefore depends on the model of high energy interactions used in the caluclations. In the limited energy range of $\sim 10^5$ to 10^6 GeV/amu, however, only minimal extrapolation beyond the SPS-$\bar{P}$P collider energies (560 GeV in the center of mass) is required and model sensitivity is minimized. In the following discussion the model used includes scaling violation effects in the total cross section, in rapidity distributions and effects of large transverse momenta (Goodman et al 82, Ellsworth et al 81 and Yodh et al 84). In general, a superposition model is used for nuclei other than protons.

II. Experiments and their Sensitivity:

The types of studies that must be considered are:

(1) Studies of γ-families with large area emulsion chambers at mountain altitudes (Amenomori et al 82, Mt. Chacaltaya and Pamir collaboration);

(2) Multiple muon studies for high energy muons, mainly in underground detectors (Homestake, Baksan, KGF, Soudan, Mt. Blanc and Old Utah);

(3) Energy variation of depth of maximum of air showers (Buckland, Haverah Park, Samarkand, Dugway, Akeno, Fly's Eye);

(4) Time-delays and structure of hadrons near cores of air showers (TIFR and University of Maryland);

(5) Muons in air showers (KGF, MSU, Tien shan, FNAL).

These experiments have sensitivity to the average atomic mass of the primary cosmic rays. The reasons for this sensitivity are different for each of these experiments and I discuss each of the five methods and their results briefly below.

The energy dependence of the number of ultra-high energy γ-families requires a transition from a light to a heavy composition around 10^5 - 10^7 GeV/nucleus provided one does not invoke a radical change in high energy interactions which would make proton interactions look like those of a heavy or medium heavy nucleus. In particular, the data would rule out a flattening (change of slope from -2.7 to -2.5) of the proton spectrum at 10^5 GeV (Amenomori et al 1982).

In underground muon detectors one measures the frequency distribution of multiple muons of relatively high energy ($\underset{\sim}{\sim}$ TeV). The high multiplicity events are due to larger A than low multiplicity events and also come from higher energy (total energy per nucleus) primaries. In order to explain the high multiplicity tail of the multiplicity distributions it is necessary that MH and H nuclei above 10^6 GeV/nucleus have a flux consistent with a rigidity cutoff around 4 x 10^5 GeV/amu. A "light" composition is not favoured.

The energy variation of depth of maximum, X_m, is sensitive to primary composition because the height of maximum depends on the height of the first interaction. For a fixed total energy per nucleus, protons penetrate deeper in the atmosphere before interacting than say a silicon nucleus. The rate of increase in the depth of maximum (the so-called elongation rate, see Linsley and Watson 1981) per decade of energy for the type of models mentioned earlier is about 70 gm/cm^2 for a constant composition. The data on X_m(E) before the 1983 ICRC (Thornton and Clay 1980, Linsley and Watson 1981) clearly showed that between 10^6 and 5 x 10^7 GeV the elongation rate was much larger ∿ 110 gm/cm^2 and that the value of X_m at 10^6 GeV was only 450 gm/cm^2. These observations were consistent with a H dominant composition at 10^6 GeV becoming "lighter" as one approached 10^7 GeV. Given the observed fact that below 10^5 GeV the composition is L dominated the observations seemed to strongly support a changing composition going from "L" at low energies to "H" around 10^6 GeV and finally becoming L above 10^7 GeV! At Bangalore ICRC, however, the situation becomes very confusing. New and supposedly more bias-free data on X_m from Samarkand and Akeno contradicted the old data. Their values for X_m were ∿ 100 gm/cm^2 deeper in the atmosphere than the old values at 10^6 GeV and were equal to the older values at 10^8 GeV. The elongation rate with the new data above became 70 gm/cm^2, consistent with an unchanging composition. The higher value of X_m, made the composition "light". The situation around 10^6 GeV is a "mess" now and needs to be resolved with better experiments and more data. The current status of the data points is shown in figure 1.

The study of time and energy structure of hadrons (TIFR 1983; U. of Maryland, Goodman et al 1982, Mincer et al 1983) near cores of air showers is sensitive to the atomic mass because of the following circumstance: These experiments trigger on a combination high shower density and substantial hadronic energy (≳ 30 GeV)

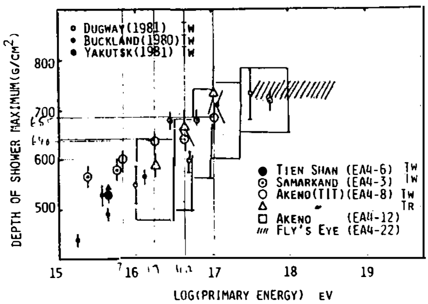

Figure 1

which places the detector within 20m of the shower core. The average distance from the core for proton initiated showers is less than that for MH and H nuclei. The hadrons that are delayed by few tens of nano seconds and have relatively low energies tend to travel away from the core. Therefore H and MH initiated showers will have more events with a delayed-hadron signal than protons. Detailed analysis of mountain level and sea level data show that the data rules out a "light" composition around 10^6 GeV and the data is consistent with a composition that is generated by having a rigidity steepening at about 2-4 x 10^5 GeV/c. The data would also rule out a 'flattening' of the proton spectrum (from -2.7 to -2.5) at 10^5 GeV.

The number of muons in an air shower, N_μ, initiated by a primary of fixed energy increases with the atomic weight of the primary while the shower size, N_e, at observation depth decreases with atomic weight because the sub-showers are from lower energy nucleons. Therefore, if one could fix the energy of a shower (say by measuring the total Cerenkov light) and measure N_μ and N_e (for fixed zenith angle), one can be sensitive to A. The sensitivity increased with the energy of the detected muons, while the statistics on the detected number of muons decrease. Experiments done so far to study the muon and electron content of shower do not have an energy estimator other than the shower size or the muon size. If data are grouped according to shower size then the sensitivity to high A primaries is decreased because to obtain the same shower size from iron primary as that from a proton primary the energy of the iron nucleus has to have about three times the energy per nucleon as that for the proton. The effective contributing flux of iron is reduced substantially because of the steepness of the energy spectrum. This effect is illustrated in figure 2 (a) and (b) where the results from the Tien-shan experiment are compared with calculations (Yodh et al 1984). Observe that grouping according to shower size reduces the sensitivity to primary mass considerably.

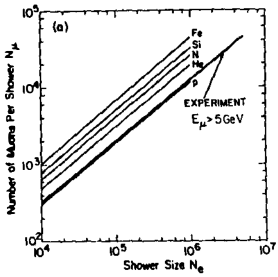

Figure 2a

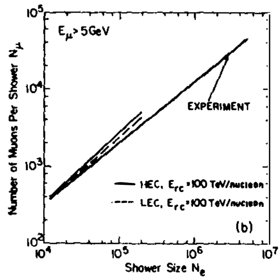

Figure 2b

Alternatively, the Tien-Shan group (Krov et al 1981) have studied the fluctuations in the number of detected muons, $\Delta\mu$, at a fixed distance from the core by looking at the frequency distribution of the quantity $\Delta\mu/\langle\Delta\mu\rangle$ for a fixed shower size group. In comparing observations with predictions one must include all fluctuations in the shower by Monte Carlo simulations. This must include not only fluctuations in the number of muons from shower to shower at a given distance but also fluctuations in a given shower as a function of azimuth. Such a comparison is made in figure 3(a) and (b) where results of a Monte-Carlo study with two different compositions (LEC and HEC) are compared with experiment (Yodh et al 1984). The point to be made here is that even though the fraction of H and MH at 10^6 GeV is increased by 20% in going from LEC to HEC the calculated distributions are indistinguishable showing the insensitivity of data grouped by shower size to atomic mass of the primary.

Finally, I give some preliminary results from an experiment done at Fermi National Laboratory, using the 80 m^2, 4m high, 6 interaction lengths deep neutrino detector of the E594 group to study the muon content (E_μ > 2 GeV) near shower cores (FNAL 1983). The E594 detector was triggered by requiring that in each of four counters placed above the detector and separated by about 16m in total, should register a shower particle density greater than 5 per/m^2. This places the detector within a 10-30 m from the shower core. The flash-chamber pictures (a typical case is shown in figure 4) are than analyzed for the number of muons in the detector. The trigger picks out protons of $\sim 5 \times 10^5$ GeV for a -2.7 spectrum and MH and H nuclei of $\sim 5 \times 10^6$ GeV energy according to Monte-Carlo simulations. The analysis procedure is to match the fraction of events with more than 30 muons and the absolute rate with different assumptions about the primary spectra. The fraction of events with more than 30 muons is a quantity that is sensitive to atomic mass. Light nuclei give about 1 to 3 percent

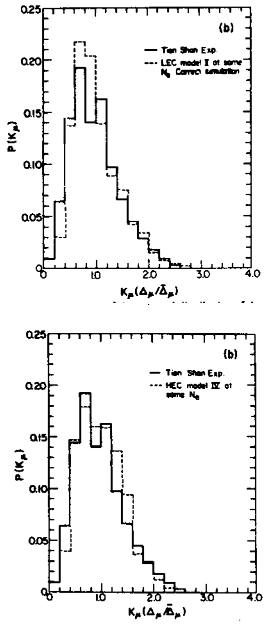

Figure 3a and b

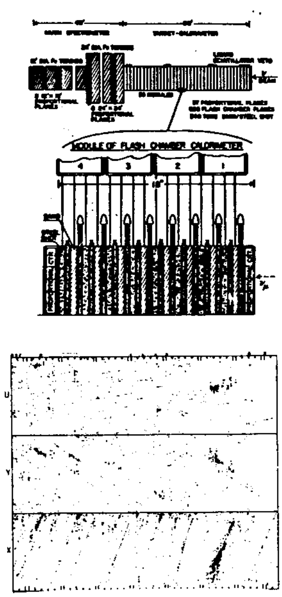

Figure 4 a and b

for this fraction while the MH and H species give about 30 percent while the data gives 16 ± 1 percent. The data require that a substantial fraction of events must be due to MH and H nuclei and that fraction is what would be obtained if the spectra for MH and H species have a spectral index of ∿ 2.5 to 2.6 and have a rigidity dependent cut-off at ∿ 2-4 x 10^5 GeV/amu. The experimental trigger rate of ∿ 4.5/hour also agrees with predictions from this model. The data are inconsistent with a flattening of the proton spectrum and a 'light' composition.

III. Discussion:

I summarize the discussion in the last section in the form of a table which represents my judgement as to which type of composition in the region of the bend best explains the data and which type of model is ruled out. No sudden radical change in the interaction model has been considered in deriving these conclusions. The models for primary spectra are described by giving the normalization energy, ε_n^i, the cut-off frequency ε_c and the spectral slope γ_i and the change in spectral index beyond the cut-off, δ. The species P, α, CNO, MH and H are normalized to directly measured data at 100, 100, 250, 250 and 63 GeV/amu respectively.

Model I: $\gamma_p = \gamma_\alpha = 2.77$, $\gamma_{CNO} = 2.66$, $\gamma_{Si} = \gamma_{Fe} = 2.5$;

$\varepsilon_i = 2 \times 10^5$ GeV/amu for P, $\delta = 0.5$ This is Maryland II.

Model II: $\gamma_p = 2.7$ up to 10^5 GeV/amu, then flattening to 2.5 up to 10^7 GeV/amu and finally steepening to 3.0. The other species all have $\gamma = 2.7$ up to $5 \times 10^5 Z_i$ GeV and then steepening by $\delta = 0.5$ (A spectrum proposed by J. Linsley in his rapportuer talk at Bangalore)

The percentage of MH + H nuclei at 10^6 GeV for Model I would be about 40 percent while for model II it would be less than 10 percent.

Table I

	Model I		Model II
	MH and H enriched at Bend		Light at Bend
Experiment			
γ-families	✓		x
Multiple muons	favoured		not favoured
X_{max}			
old	✓		
new		confused	✓
Delayed hadrons Maryland, Ooty	✓		x
N_μ versus N_e KGF, Tien-Shan msu		not sensitive between 10^5-10^6 GeV	
Δ_μ versus Δ_e and $N_\mu > 30$ MD - FNAL	✓		x

An examination of this table suggests strongly that the composition does appear to become enriched in MH and H near the bend, however for the only experiments which can measure the composition of all species at a given E, the X_m experiments, the situation remains unsettled.

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