VERY HIGH ENERGY COSMIC RAYS

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Results from ground level and underground experiments on cosmic rays with energy 10^{12} to 10^{20}eV are reviewed. They show that the energy spectrum has two significant features, a 'knee' and an 'ankle'. The arrival directions of these cosmic rays at the solar system are anisotropic, features of the anisotropy appearing to be correlated with features of the spectrum. Detailed interpretation of this information awaits conclusive evidence regarding the composition of these cosmic rays. New results and prospective new results on the composition are described and discussed.

1. INTRODUCTION

Very high energy cosmic rays, those with energy per particle greater than 10^{12}eV, carry information that promises to be indispensable for deciding between theories of the origin of Galactic cosmic rays. Such cosmic rays may provide especially direct evidence on the magnetic field structure of the Galaxy, out to distances of some kiloparsecs from the solar system. Some of these cosmic rays, having energies greater than 10^{19}eV, appear to be extragalactic. There are difficulties in imagining an astrophysical setting in which acceleration to such great energies can occur at all. Moreover, the amount of energy required to fill the local supercluster with these particles at the observed level of intensity is quite considerable.

Up until now, the clearest result obtained from observations of these cosmic rays is the energy spectrum, meaning the distribution in energy per particle. Instead of being the featureless inverse power law that was at first anticipated, this spectrum (Figure 1) exhibits two structures, a 'knee' at $\sim 10^{15}$eV and an 'ankle' at $\sim 10^{19}$eV. Studies of the arrival directions of these cosmic rays show a definite pattern of energy dependent anisotropy, with evidence of correlation between this pattern and features of the spectrum.

These results already provide some guidance for our speculations

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about cosmic ray origin, so I will begin by presenting them, noting some of the experimental problems. At the same time I will go over conclusions that have already been reached. General reviews have been given by Sreekantan (1972) and Hillas (1975). The subject of anisotropy has been reviewed by Wolfendale (1977) and more recently by Kiraly et al. (1979b). A useful summary on the highest energy particles has been given by Watson (1980a).

In a sense, however, the existing results, although they have taken decades to obtain, have only brought us to where we can make informed plans for a new generation of experiments. We know now what kind of 'signals' are present, and about how strong they are, so we can tell how much it will cost in dollars and effort to make these signals stand out above the background. The principal requirement, for experiments belonging to the new generation, is a capability of determining spectra and anisotropies of resolved primary components, rather than a 'spectrum' and an 'anisotropy' for primaries that are unspecified except for having about the same total energy per particle.

The composition of cosmic rays selected to have equal energy is strongly biased in favor of heavy elements compared to cosmic rays having equal magnetic rigidity. The equal-energy mass spectrum is in fact approximately rectangular in the low energy region, as is shown by Table 1. Thus it is not implausible to imagine a change taking place, at higher energies, leading either to nearly pure H or to nearly pure Fe.

Table 1. Equal-energy mass spectrum from low energy data.

Mass number	1	4	12-16	20-40	52-58
Percentage*	43.1	20.6	13.1	10.6	12.6

*Assuming power-law spectra with differential exponent 2.6 and source-region charge composition (from Rasmussen 1974).

The resolving power I have in mind, for new-generation experiments, is the power to distinguish between the groups listed in Table 1, or between showers initiated by protons and those initiated by γ-rays. In the final section of this report I will discuss methods of investigating the composition of very high energy cosmic rays and describe some of the results that have been obtained.

2. ENERGY SPECTRUM

Figure 1 shows the dependence on energy E of the intensity of all particles with kinetic energy greater than E, multiplied for convenience

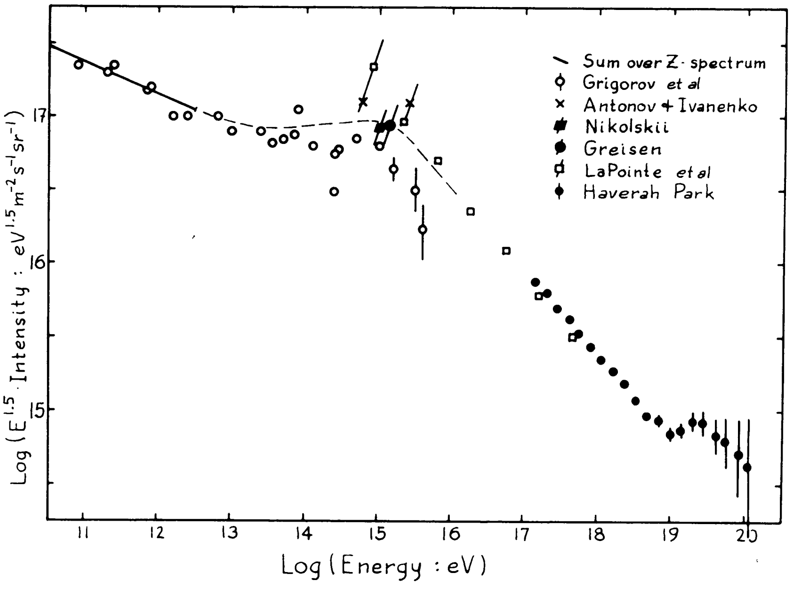

Fig. 1 Integral energy spectrum of cosmic rays.

by $E^{1.5}$. The solid line, 'sum over Z-spectrum', was derived from measurements in which the primary particles (nuclei) could be sorted according to charge (from Hillas 1979, Fig. 2). The open circles were obtained using an ionization calorimeter carried on a satellite (Grigorov et al. 1971). The remaining points were derived from measurements of extensive air showers. The large filled circle and the trapezoid are calorimetric results by Greisen (1956) and Nikolskii (1962), respectively. The energy was determined by adding the energy deposited in the atmosphere and the earth by the three major components: electrons (and photons), muons, and hadrons, using data obtained at sea level and mountain altitudes by a variety of techniques, with small allowances for neutrinos and excitation of nuclei. The crosses (Antonov and Ivanenko 1975) and squares (La Pointe et al. 1968) were derived similarly. The energy deposited in the atmosphere was determined empirically by measuring showers at various atmospheric depths, starting at 540 g cm^{-2} in case of the earlier experiment and 200 g cm^{-2} in case of the later one. The relatively small fraction of energy ($\simeq$10%) not accounted for by their track length integrals was evaluated by means of a hadronic cascade model. The filled circles are results obtained at Haverah Park (Cunningham et al. 1980, converted to integral form by Watson). In this case, also, the determination of energy was essentially calorimetric. The cascade model used to derive energy from the 'ground parameter' ρ_{600} was constrained to agree with such a number of independent measurements that it functioned essentially as an interpolation device.

The error bars for the Haverah Park points indicate Poisson-statistical standard deviations. The small scatter of the lower energy points shows the high relative accuracy that is typical of long-term air shower

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experiments. It is greater, of course, than the accuracy of the energy calibration in absolute units such as eV. Results from the only two comparable northern hemisphere experiments, those carried out at Volcano Ranch and Yakutsk, confirm the existence of an ankle. The Volcano Ranch and Yakutsk calibrations are also essentially calorimetric, but the methods differ from each other and from the Haverah Park method in important details. The Yakutsk method gives energies about 10% higher than the Haverah Park method, while the Volcano Ranch method has given energies about 20% lower. (In Figure 1 the error bars on the point due to Greisen correspond to ±20%.)

The detailed shape of the energy spectrum in the neighborhood of the knee has been investigated by several groups. Corresponding changes of slope are found in the number spectra of electrons, muons and atmospheric Cerenkov photons (Hillas 1975 and references therein). A typical result is the electron number spectrum measured at Chacaltaya by Bradt et al. (1965), shown in Figure 2.

Such changes in slope cannot be explained by assuming that above 10^{15}eV there is a change in the character of high energy interactions as they occur in air showers. A downward break at about the right energy is expected for open-galaxy models due to rigidity dependence of the diffusion coefficient (Ginzburg and Syrovatskii 1964). It is difficult, however, to account for the sharpness of the observed break on such a model (Bell et al. 1974). It has also been proposed that the knee corresponds to the limiting rigidity of a dominant source (Peters and Westergaard 1976). In either case, the effect on primaries with the low energy composition of Table 1 would be to produce secondary breaks at higher energies than the proton-cutoff break. The resulting spectra would disagree qualitatively with the observed one (Bell et al. 1974, Hillas 1979). Thus, if the knee results from magnetic processes a change in composition must already have taken place at somewhat lower energies. Alternatively, the knee, assuming that it is produced in the source region, may correspond either to a threshold for breakup of preferentially accelerated heavy nuclei, or to the threshold for energy loss by collisions with photons (Zatsepin et al. 1963, Hillas 1979). It has also been suggested that the knee is formed of cosmic rays from a different source or class of sources than those which produce the bulk of cosmic rays (Karakula et al. 1974).

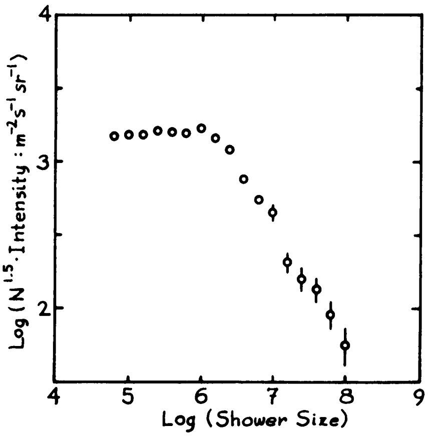

Fig. 2 Size spectrum of nearly vertical showers at Chacaltaya (depth 540 g cm^{-2}). The ordinate is integral intensity multiplied for convenience by (size)$^{1.5}$.

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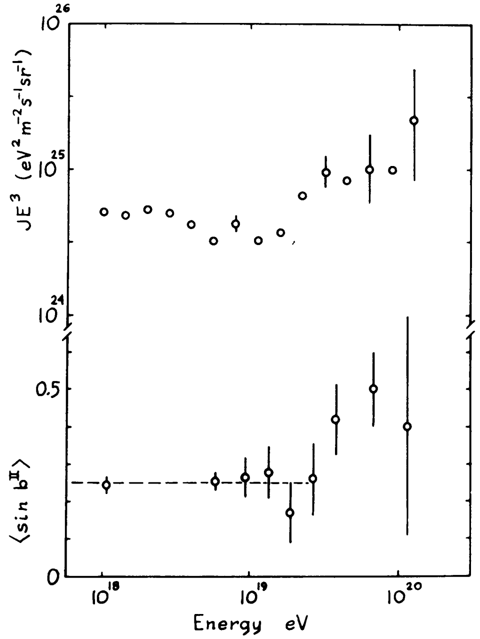

Fig. 3 Correlation between mean galactic latitude and energy. The dashed line indicates the expected mean for a random arrival direction distribution.

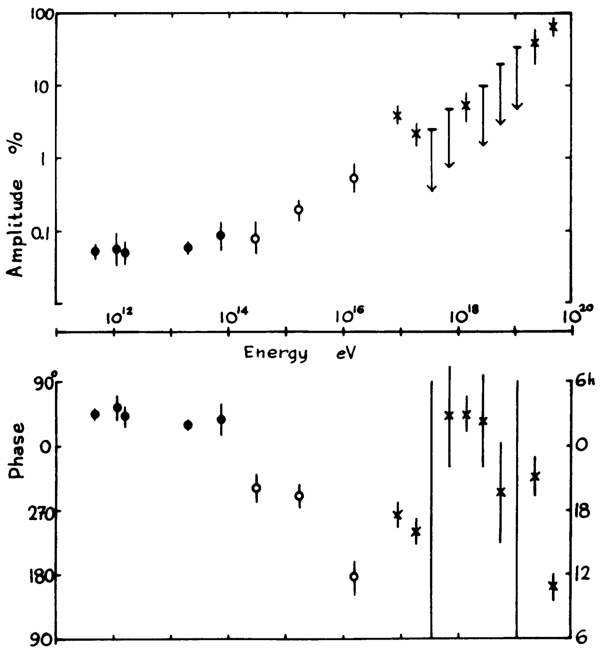

Fig. 4 Cosmic ray anisotropy

The other feature of the spectrum, the ankle just below 10^{19}eV, has frequently been associated with a crossover from Galactic to extragalactic cosmic rays. Data from Haverah Park (see Figure 3, from Lloyd-Evans et al. 1979) indicate that the additional flux arrives from high galactic latitudes, suggesting an association with active galaxies belonging to the Virgo cluster (Stecker 1968, Krasilnikov 1979).

3. ARRIVAL DIRECTIONS

Figure 4 shows results of Fourier-analyzing the variation of cosmic ray intensity with right ascension. Above is the amplitude, below is the phase, of the first harmonic. The 3 lowest-energy points, from left to right, are given by underground muon telescopes at Holborn (Davies et al. 1979), Poatina (Fenton and Fenton 1976), and Heber Mine (Bergeson et al. 1979). For these points, 'energy' means energy per nucleon, so the response is due mainly to primary protons. The next two points are given by air shower measurements at Mt. Norikura (Sakakibara et al. 1979) and Musala Peak (Benko et al. 1979). The following 3 (open circles) are from a survey of air shower data from many sources, by Linsley and Watson (1977), while the remaining 10 (crosses) are given by air showers recorded at Haverah Park (Lapikens et al. 1979a, Watson 1980b).

These results are shown as evidence that sidereal anisotropy is present, at levels that exceed noise, over most of the range from 10^{11} to 10^{20}

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eV. The work of interpreting results of this kind is proceeding apace. At the lower energies the effects observed are nearly energy independent. Even at 10^{14}eV the Larmor radius of a proton approaching the solar system is a small fraction of a parsec, so one does not expect to be able to localize sources. Instead, the present goal is to determine the magnetic field configuration outside, but not far outside, the heliosphere (Wolfendale 1977, Kiraly et al. 1979a). It is hard to imagine how this could be done in any other way.

At an energy about equal to (somewhat less than) that corresponding to the knee in the spectrum, the magnitude of the anisotropy, as measured by the first harmonic amplitude in right ascension, begins to increase about as $\sqrt{E}$, while the direction of maximum intensity shifts to earlier times. These changes occur in an energy region where, according to most models, Galactic sources are still dominant. They can be used, therefore, as a basis for choosing between models of the source distribution and propagation mode for the bulk of Galactic cosmic rays.

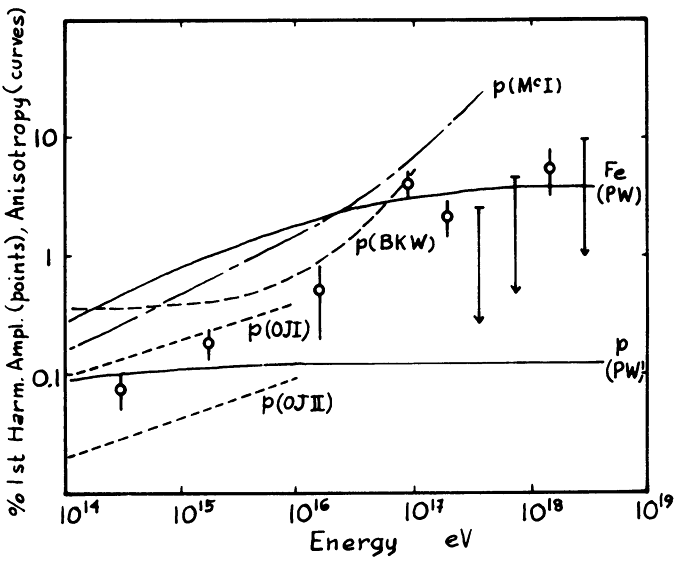

Fig. 5 Predictions of cosmic ray anisotropy. The points, taken from Figure 4, give the amplitude of the first harmonic of counting rate in right ascension. The curves give the anisotropy, $\partial = (I_{max}-I_{min})/(I_{max}+I_{min})$, according to Peters and Westergaard (PW) 1976, McIvor (McI) 1977, Bell et al. (BKW) 1974, and Owens & Jokipii (OJI,II) 1977. All of the predictions are for proton primaries except one of those by Peters and Westergaard.

Figure 5, taken from Lloyd-Evans et al., shows part of the data given in Figure 4, together with several predictions identified in the caption. It should be noted that the anisotropy equals the quantity measured times $(\cos\lambda \cos\delta)$, where λ is the latitude of the observation and δ is the declination of the upstream direction. Since δ is unknown, the measurements give lower limits. The two lowest curves clearly disagree with the evidence; the others are consistent with it.

Returning to Figure 4, the data above 10^{17}eV offer no easy interpretation. Looked at in detail, the evidence from Haverah Park is that above 10^{17}eV the simple trends shown

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by lower energy data break up into complex patterns (Lapikens et al. 1979a and references therein). The complexity has several aspects: 1) distributions in right ascension may contain significant harmonics higher than the first, 2) there may be significant changes in amplitude and phase from one 10° declination band to the next, and 3) there may be considerable differences in amplitude and phase between the first harmonics (summed over declination) for adjacent factor-of-2 energy bins. Such features are also shown, at lower significance levels, by earlier data from the Volcano Ranch experiment (Linsley 1975).

The most extreme example I can point out is shown in Figure 6. The data are from Haverah Park. The top curve shows a rather broad region of enhanced intensity near 18h for declinations 40-50°. At the same energy, neighboring declination bands are enhanced similarly but to a lesser degree. The middle curve is for an energy twice as great and a declination band displaced 20° toward the equator. The enhancement is highly significant in the band shown but is absent in neighboring bands. Assuming that the differences in right ascension and declination are due to magnetic deflections, one might expect by a naive extrapolation to find a very sharp enhancement at ~16h in the bottom curve (energy greater by another factor 2, declination 10° less), but one finds nothing of the sort. So this feature is not evidence for a localized power-spectrum source. It appears to be a modulation effect.

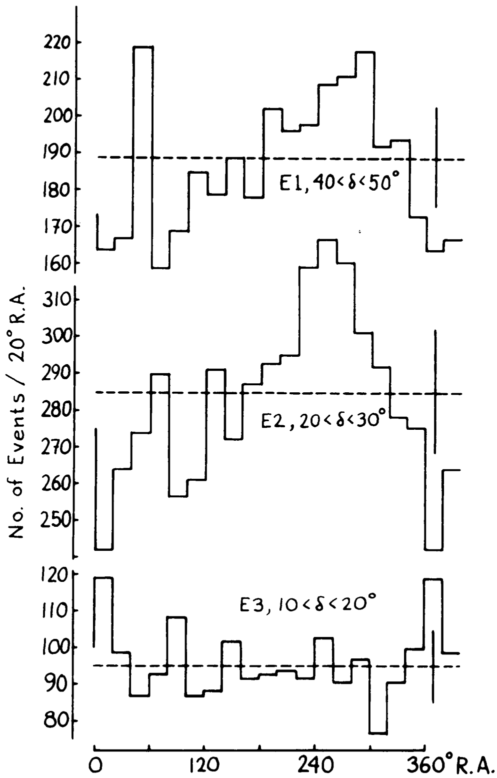

Fig. 6 Distributions in right ascension of shower directions for adjacent energy bins (Lapikens et al. 1979a, Pollock 1978). The mean energies of bins E1, E2, E3 are 0.9, 1.8, and $3.5 \cdot 10^{17}$eV, respectively. Each distribution is for a different 10° declination band, as explained in the text.

Complexity of this general nature would be expected above 10^{17}eV even for a simple, regular Galactic field, as has been shown by the calculations of Karakula et al. (1972). It is expected all the more in light of evidence for numerous large-scale irregularities within a few kpc of the solar system (Kirshner 1980, Cassé and Paul 1980 and references therein). If one estimates that cosmic ray arrival directions

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will be disturbed by field irregularities over a range of 3R to 30R, where R is the Larmor radius, then the observations suggest that a substantial fraction of the primaries are protons. (Assuming a field of $3\mu G$, R is equal to $(.37E/10^{15}Z)$ parsec, where E is energy in eV and Z is charge number. For $Z \sim 26$ one expects that the streaming regime would persist up to $\sim 10^{18}$eV, contrary to observation.)

A tendency of primaries with energy $>10^{19}$eV to arrive from higher Galactic latitudes has already been mentioned. Figure 7 shows the arrival directions of the most energetic particles that have been detected by the 4 giant air shower arrays. In the southern hemisphere 2 well-known clusters are evident. In the northern hemisphere one can discern a much larger, rather diffuse group centered between the Galactic north pole and the anticenter. The zone $-30^\circ < b^{II} < 30^\circ$ is nearly vacant except near the spiral-out direction and near the anticenter.

It seems nearly impossible to sustain, against the evidence shown in Figure 7, a theory that cosmic rays are confined to galaxies, including their haloes. Such a theory would require that essentially no particles of this energy be protons or alpha particles, contrary to my previous argument and to strong evidence from shower profile fluctuations (Lapikens et al. 1979b and references therein). Even if one assumes for the purpose of discussion that all of the Figure 7 primaries are Fe-nuclei, the arrival directions do not support Galactic origin. 1) The tendency of the 3 clusters of points to be associated with the principal axes of Galactic symmetry is no greater than would be expected by chance. 2) The possible association between one cluster and the spiral-out direction is denied by the absence of any cluster near spiral-in. 3) Where symmetry would be expected, the cluster in the northern Galactic hemisphere is much larger than its southern counterpart.

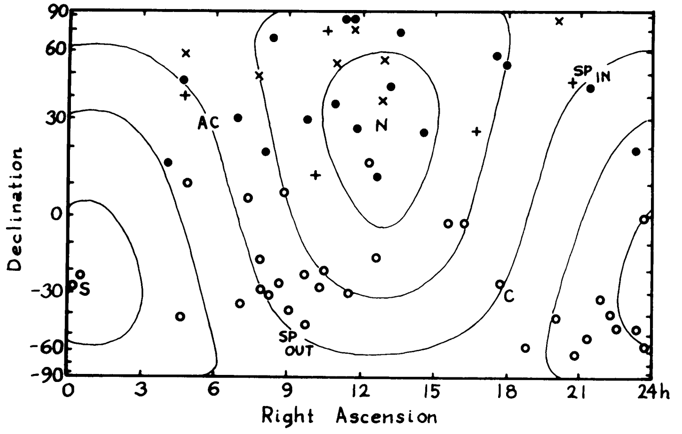

Fig. 7 Arrival directions of cosmic rays with energy $>5\cdot10^{19}$eV, from Krasilnikov (1979) with minor additions and amendments. The filled circles represent events recorded at Haverah Park; the open circles, those recorded at Sydney; the +'s and ×'s, those recorded at Volcano Ranch and Yakutsk, respectively. The contour lines show the Galactic latitude (b^{II}) at 30° intervals. The letters indicate the Galactic poles, the center and anticenter, and the directions 'spiral-in' and 'spiral-out'. The nonlinear declination scale compensates for differences in exposure.

4. COMPOSITION

Methods of determining the composition of air shower primaries depend on measuring secondary characteristics in addition to those used to give the energy of the showers. One such secondary characteristic is X_{max}, the depth of maximum development, another is the proportion of low energy muons at ground level. X_{max} is given directly by the time distribution of atmospheric Cerenkov photons at moderate core distances (Fomin and Khristiansen 1971, Orford and Turver 1976, Thornton and Clay 1979) and by the atmospheric scintillation technique (Bergeson et al. 1977). It is given less directly by time distributions of particles (Lapikens et al. 1979b), and indirectly by the shape of the radial distribution of particle flux at ground level (Linsley 1977, England et al. 1979). The median depth of production of low energy muons is expected to be another useful parameter. It can be derived rather directly from arrival time profiles (Blake et al. 1979, Aguirre et al. 1979) and indirectly from the shape of the muon radial distribution at ground level. For primary energies $<10^{15}$eV, measurements of air shower hadrons (Goodman et al. 1979) and of the high energy muons in air showers (Acharya et al. 1979) afford valuable information.

Possible constituents of the primary radiation at these energies range from γ-rays and neutrinos, through atomic nuclei of all reasonably abundant species, to dust grains containing 10^{10} nucleons or more. (Very high energy electrons are excluded because of synchrotron losses.)

Arguments for the presence, with detectable intensity, of very high energy γ-rays and neutrinos have been reviewed by Stecker (1973). Showers initiated by γ-rays are expected to be strongly deficient in muons. At energies of 10^{15}-10^{16}eV, where systematic searches have been carried out, the equal-energy abundance of γ-rays is so small ($\lesssim 2\cdot10^{-4}$) that they cannot be resolved with certainty from fluctuated nucleus-initiated showers (Firkowski et al. 1962, Toyoda et al. 1965). The average muon content of higher energy showers is consistent with the assumption that nearly all of them are nucleus-initiated, but an admixture of γ-ray showers up to ∿1% of the total cannot be ruled out at present.

The neutrino hypothesis (Berezinsky and Zatsepin 1969), that some or all of the largest air showers are produced by neutrinos, depends on the possibility that through continued increase with energy the cross section for inelastic neutrino-hadron collisions might become equal to the hadron-hadron cross section at cosmic ray energies $\sim3\cdot10^{21}$eV. Evidence against this hypothesis is afforded by the zenith angle distribution of large showers, which does not show an increasing proportion of very inclined showers ($\theta>60^\circ$) above 10^{18}eV. (Particles with a mean free path for shower initiation that is > the vertical depth of the atmosphere will be detected preferentially at large zenith angles for reasons of geometry.) This evidence can be strengthened by applying available measures of shower age (pulse risetime, lateral distribution) to neutrino candidates. (Neutrino showers will be observed preferentially as young showers, near maximum development, regardless of inclination.) However,

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these tests are statistical; it is impossible to say that any one of the observed large showers was not produced by a neutrino. Hence the 'resolving power' for separating primary neutrinos from nuclei becomes poor at the highest energies where the total number of events is small.

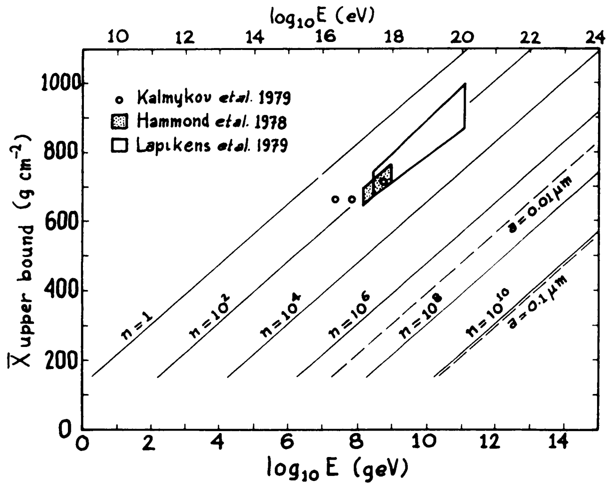

Fig. 8 Evidence that the primary particles above $\sim 10^{16}$eV are atomic nuclei, not dust grains (Linsley 1980).

The dust grain hypothesis (Alfvén 1954, Hayakawa 1972), that the largest air showers are produced by relativistic dust grains, is disproven by evidence (Figure 8) that these showers require almost the entire thickness of the atmosphere for growth to maximum size. By the superposition principle, the depth of maximum development is determined by the energy per nucleon. For dust grains having the energy of these showers, the energy/nucleon would be $< 10^{13}$eV. Showers produced by such grains would reach maximum size high in the atmosphere and at sea level would consist almost entirely of muons.

The positive identification, at very high energies, of any of the 'exotic' constituents, γ-rays, neutrinos or dust grains, would be a discovery with important astrophysical consequences. Unaffected by magnetic fields, γ-rays or neutrinos might reveal the location and strength of powerful extragalactic cosmic ray sources. A discovery of neutrinos would automatically involve determining a fundamentally important interaction cross section. Dust grains, having a much larger ratio of mass to charge than nuclei, can reach the solar system from much greater distances, possibly from distant galaxies (Elenskiy and Suvorov 1977). Thus they might provide the most favorable means of detecting primordial antimatter, if it should exist. It is possible, using present data, to find an upper limit of the intensity of each of the exotic constituents as a function of energy, although this has not yet been done.

The mass spectrum of very high energy nuclei has a direct bearing on theories of cosmic ray acceleration, and in addition has great importance for interpreting features of the energy spectrum and the anisotropy. Methods of determining the mass of air shower primaries depend on one or another of the following three principles: 1) heavier nuclei have greater volumes, hence greater geometric cross sections, 2) heavier nuclei consist of a greater number of nucleons, hence the showers they produce are more regular in structure because of averaging, 3) the Lorentz factor of the primary particles, which for a given total energy is inversely proportional to the number of nucleons, determines the number of generations in the showers. This in turn determines the depth of maximum longitudinal development (optimum depth) and the proportion at ground level of low energy muons to electrons. The methods all make use of the superposition principle, which states that an average shower produced by a nucleus with energy E and mass number A is indistinguishable, except in early stages of development, from a superposition of A average proton-initiated showers each with energy E/A.

The result just shown in Figure 8 was obtained by the third method. The relation between optimum depth and primary mass is based on superposition and the so-called 'elongation rate (ER) theorem' (Linsley 1977). Another recent result having the same theoretical basis is one published by Thornton and Clay (1979). They claim that their measurements of optimum depth, derived from the pulse width of atmospheric Cerenkov signals, imply a change in primary composition between 10^{15} and $3 \cdot 10^{16}$eV. Their data have been challenged on technical grounds by Orford and Turver (1979). However, it is pointed out by Linsley and Watson (1980) (see Figure 9) that the same conclusion reached by Thornton and Clay can be drawn from independent results by Antonov et al. (1979) using a technique to which the objections of Orford and Turver do not apply. The conclusion is that in this energy interval (located just past the 'knee' in the spectrum) the equal-energy primary composition changes from predominantly heavy to predominantly light. A more gradual change, from mixed composition (Table 1) to predominantly heavy (mostly Fe) in the energy interval 10^{12} to 10^{15}eV is implied by results of Grigorov et al. (1971) and Goodman et al. (1979).

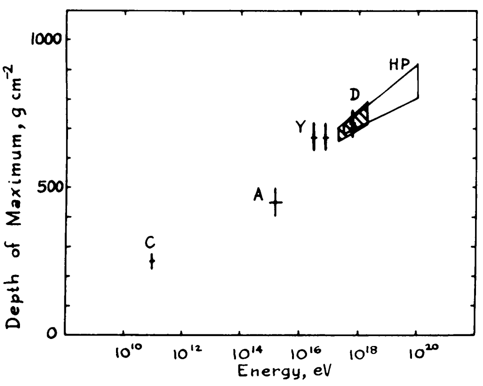

Fig. 9 Depth of maximum development of air showers, as a function of energy/particle. Sources are (Y) Kalmykov et al. (1979) and (D) Protheroe and Turver (1977). The point labeled (C) is calculated, using the known low energy composition and known properties of hadronic interactions. Point (A) is derived from results by Antonov and collaborators, reported in several publications since 1975. Point (HP) is derived from time profile measurements at Haverah Park. The derivation of points (A),(C) and (HP) will be described elsewhere (Linsley and Watson 1980).

The method illustrated by Figures 8 and 9 has the advantage that the relation between the optimum thickness and the average primary mass is model-dependent to only a small degree, and that the model-dependence is manageable by use

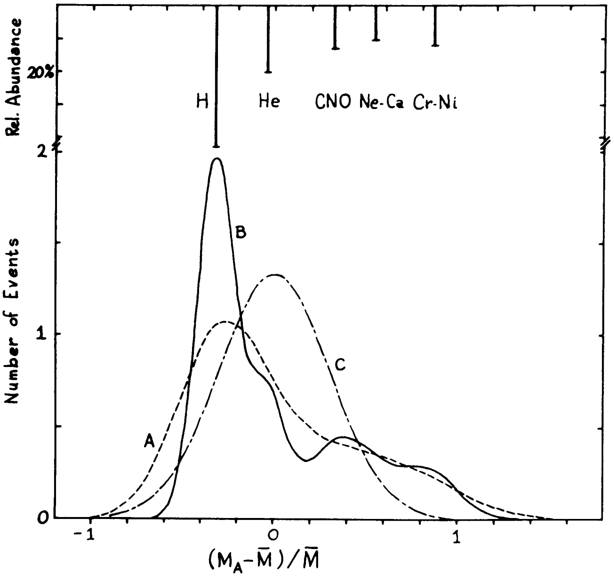

Fig. 10 Primary mass resolution attainable by measuring the muon content of large air showers ($N\sim10^8$) at a moderately high elevation ($X\sim850$ g cm^{-2}). M_A is the ratio of low energy muon flux to total flux at core distance 200m. $\bar{M}$ equals av(M_A). The line spacing (upper bar diagram) is derived from measurements of $\bar{M}$ vs shower size. The primary composition of Table 1 is assumed. Curve B includes 2 effects: bias in favour of lower-mass primaries, assuming that showers are selected using unshielded detectors, and line broadening due to fluctuations in shower development, estimated from simulations based on a range of hadronic cascade models. Curve A assumes an additional 30% reception fluctuations typical of early attempts to exploit this method (Linsley and Scarsi 1962, Toyoda et al. 1965). Curve C, representing the results of those attempts, is calculated assuming pure primary composition and 30% reception fluctuations.

of the ER theorem. However the resolving power is poor. The power to resolve, say, proton showers from those produced by alpha particles can be described in the same general terms used to describe methods for resolving neighboring isotopes at much lower energies; in terms, namely, of line width in relation to line separation. Figure 10 shows the theoretical resolving power afforded by one of the most promising methods. In order to achieve even this degree of resolution one will have to use shielded detectors with a very large combined area ($\sim10^3$ m^2) distributed over an area of several km^2 at an altitude well above sea level.

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