Could particles with energies above 4×10^{17} eV be neutral?

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The individual arrival directions of extensive air showers with energies above 4×10^{17} eV in data from the Yakutsk installation are analyzed in equatorial coordinates. There is a significant number of groups of showers in narrow solid angles which form chains and which partly coincide with extragalactic radio sources.

Information about the primary cosmic rays is important for reaching an understanding of processes which occur in the local galaxy and in the universe as a whole. The cosmic rays of ultrahigh energies (above 10^{15} eV) are believed to consist primarily of charged particles: protons and nuclei of various other chemical elements. That interpretation is not indisputable, since no direct measurements of the composition of the primaries have been carried out in this energy range, while the conclusions drawn from data on extensive air showers are ambiguous and contradictory.

I suggested in Ref. 1, on the basis of a complex analysis of many experiments on extensive air showers, that a significant fraction of the primary cosmic rays might be neutral particles. The present letter presents some new facts in favor of that point of view.

Figure 1 shows the arrival directions of 8776 individual showers with energies in the range 4×10^{17}-4×10^{19} eV, measured at the Yakutsk installation, in equatorial coordinates. In order to find the direction of the axis of the shower within a small error (1–2°), we made use of only those showers for which there were indications of time channels at four or more stations of the installation which formed "master" triangles with spacings of 0.5 and 1 km. In order to ensure that the time channels were operating correctly, their relative readings were monitored with the help of the χ^2 test. The densities of particles at the stations were detected by two scintillation detectors, each with an area of 2 m^2 (the total area was 4 m^2). The total number of particles detected at a station had to be at least eight in order to weaken the effect of the "porous" structure of the disk of the extensive air shower on the accuracy of the determination of the arrival direction. Showers with zenith angles greater than 60° were included in the analysis.

The large points (which we will call "nodes") in Fig. 1 show the arrival directions of two or more (up to six) showers for which the differences in the coordinates are less than 0.5°. A statistical analysis showed that a relatively large number of such points, with a low overall density of all events, would be unlikely in the case of a random distribution. This circumstance can be seen in the example of data from the catalog of giant showers (with energies above 8×10^{18} eV) from the Sydney extensive-air-shower installation,[2] in which eight pairs of the 392 events, distributed nearly

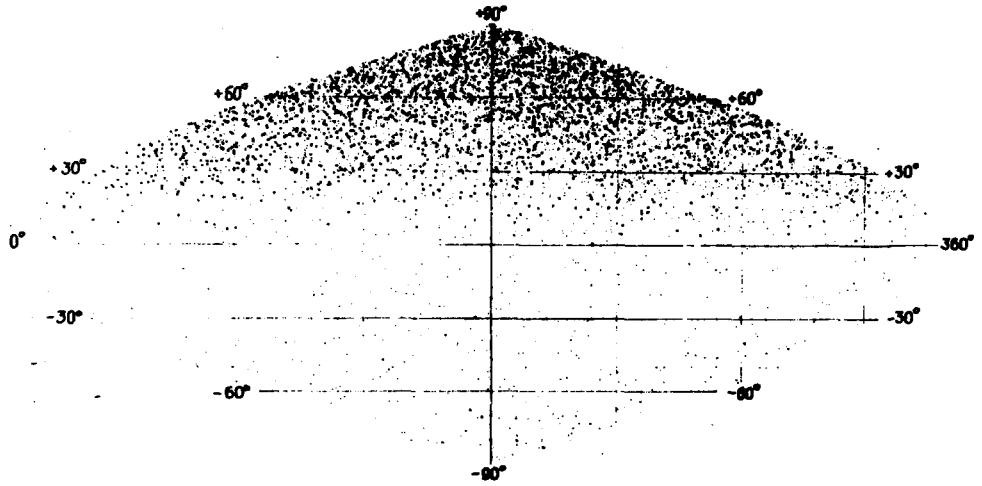

FIG. 1. Arrival directions of showers with energies in the range 4×10^{17}–4×10^{19} eV in equatorial coordinates. ●—Two or more events; ·—individual events.

uniformly over the southern hemisphere, have differences in coordinates less than 0.5°, and 50 pairs have differences less than 1.5°. The random numbers of such pairs should be 3.7×10^{-3} and 3.8×10^{-2}, respectively.

Another curious point is that of the 130 showers from the catalog of Ref. 2 which were observed in the northern hemisphere in the declination band 0–35° there are 35 showers which coincide within 0.7° with the Yakutsk data. Analysis of the showers from the Volcano Ranch[3] and Havera Park[4] catalogs with energies above 10^{19} eV reveals coincidences within the same angular limits with the Yakutsk data[5] in respectively 36% and 49% of the events.

The relatively dense distribution of nodes near the north is a consequence of the geographic position of the Yakutsk installation (60°N).

These results are difficult to explain on the basis of the usual picture of the propagation of charged particles in the galactic magnetic field. The difficulty is aggravated by the circumstance that the events in nodes have different primary energies. Specifically, if there is a charge z, the particles must have moved along nonidentical paths with different radii of curvature, depending on the energy E:

$$R = E/300Hz.$$

Even protons with 10^{19} eV would have had, in the magnetic field of the local galaxy ($H\sim3\times10^{-6}$ G), a radius of curvature $\sim10^{22}$ cm, comparable to the radius of the galactic disk, $\sim4.5\times10^{22}$ cm. Under these conditions, the cosmic rays would have "forgotten" where they were formed, and they should have had a random distribution of arrival directions—at odds with the observations. Furthermore, it can be seen from this figure that the nodes and the other points generally form chains. We do not rule

out the possibility that the primary particles are neutral and preserve their arrival-direction association with point sources.

Extragalactic radio sources apparently play a definite role in the generation of such particles. I have analyzed the coordinates of the arrival directions of 330 showers with energies above 10^{19} eV in the declination interval 17°–90° from the catalogs in Refs. 3–5. These coordinates were compared with the positions of 169 radio galaxies and quasars in this region of the sky.[6] Thirty radio sources coincided within 1° with the arrival directions of showers; this figure is smaller by a factor $\sim 10^{-5}$ than the 12 events which would be expected in the case of a random positive result.

A preliminary analysis has shown that cosmic rays may also be formed in other extragalactic sources: Seyfert galaxies, galactic clusters, etc. Again in these cases we observe a correlation between the arrival directions of showers and the coordinates of these objects which goes beyond the random correlation. In order to reach firmer conclusions, we will need a larger statistical base of showers (we would like to combine the data from the various extensive-air-shower installations around the world) and to look at a longer list of various astronomical objects.

If the primary particles are indeed neutral, then the bulk of them could hardly form in the local galaxy. This conclusion is indicated by the absence of a relationship between the positions of the nodes in Fig. 1 and the galactic plane. We do not rule out the possibility that the boundary between the regions of galactic and extragalactic cosmic rays is significantly closer to an energy of 4×10^{17} eV. An analysis of the individual arrival directions of showers in this energy region would be very useful.

In summary, the pattern of arrival directions of individual extensive air showers with energies above 4×10^{17} eV in equatorial coordinates has a fine-scale structure which cannot be explained in terms of random statistical processes in the distribution of the initial data. In my opinion, this pattern may be associated with the positions of point sources which generate neutral particles. Further work is presently being carried out at the Yakutsk installation to explain these points. The results will be published.

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