Cosmic rays with energies above 3×10^{20} eV

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Calculations in the model of quark–gluon strings incorporating the Landau–Pomeranchuk–Migdal effect and interactions of neutral pions in the atmosphere confirm the estimates ($E_0 \geqslant 3\times 10^{20}$ eV) of the energy of the primary particles which generated some huge showers observed in Russia, the U.S., and Japan. The calculated relative number of muons in both oblique and approximately vertical showers agrees with the experimental results under the assumption that the primary particles are of a proton nature. Since the arrival directions of these showers do not point to any known active sources on the celestial sphere at distances out to 30–50 Mpc, it is necessary to search for possible sources of such particles. © *1995 American Institute of Physics.*

I. INTRODUCTION

Interactions with photons of the microwave background cause the protons (or nuclei) of the cosmic rays to suffer large energy losses. These losses should lead to a "cutoff" of the energy spectrum at energies of $(3-6)\times 10^{19}$ eV, if the distribution of the sources of particles with such energies is assumed to be uniform throughout the universe.[1,2] For this reason, the distances to the sources of particles with energies $E > 10^{20}$ eV must be limited to those on the order of 30–50 Mpc in the framework of an extragalactic model.[3] For example, Fanarof–Rayleigh radio galaxies of class II (Ref. 4) and radio galaxies in the Local Supercluster of Virgo[5] have been suggested as possible sources of cosmic rays with such energies. Possible acceleration mechanisms (e.g., acceleration at a shock front[6] or as a result of unipolar induction) and sources are reviewed in Ref. 7.

Three huge air showers, with energies estimated to be about $(2-3)\times 10^{20}$ eV, have recently been observed.[8–10] Significantly, these showers were observed at different installations (at Yakutsk in Russia, at Fly's Eye in the U.S., and at AGASA in Japan) and by different detection methods (the detection of charged particles or scintillation radiation). The oblique Yakutsk shower consists primarily of muons, while the approximately vertical shower detected at the AGASA installation consists primarily of electrons. The arrival directions of these showers do not point to the Local Virgo Supercluster or other active objects as possible sources.

In the present study we confirm, by means of detailed calculations, the high esti-

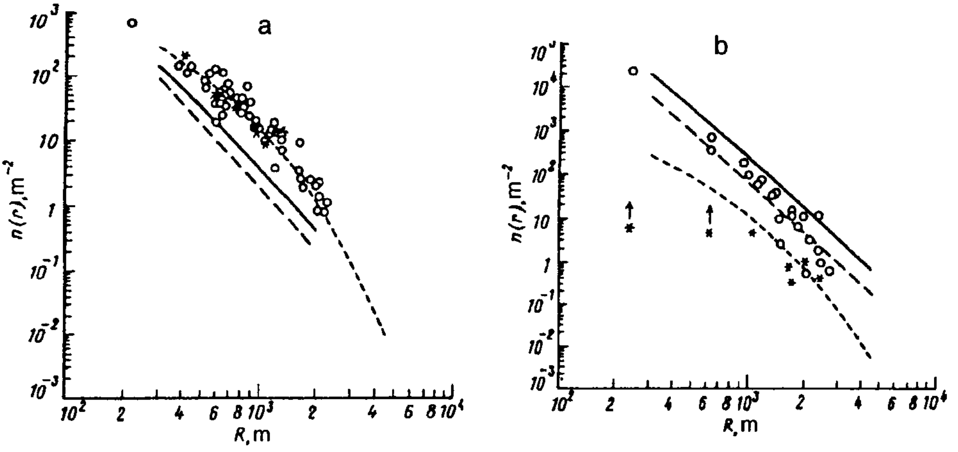

FIG. 1. Spatial distributions of electrons and muons in extensive air showers. Experimental data: O—Charged particles; *—muons. a) Ref. 8 (proton energy $E_0 = 5.5\times 10^{20}$ eV, $E_{\rm th} = 1\times\csc\theta$ GeV, $\theta = 58°$); b) Ref. 10 ($E_0 = 2.7\times 10^{20}$, $E_{\rm th} = 0.5\times\csc\theta$, $\theta = 23°$) (the muon detectors with $R < 1000$ m are in a state of saturation. Calculations for primary proton: Solid curves—Electrons, NKG; dashed curves—electrons, $\rm NKG_{mod}$; dot-dashed curves—muons with a threshold energy $E_{\rm th}$

mated energies of these huge showers.[8-10] We offer some arguments for the proposition that the primary particles are of a proton nature.

II. RESULTS OF CALCULATIONS AND DISCUSSION

The spatial distributions of electrons and muons have been calculated for the two huge showers detected at Yakutsk[8] and Akeno[10] in the model of quark–gluon strings.[11] Incorporating the Landau–Pomeranchuk effect, and using Migdal's cross sections[12] (the LPM effect), we find a ~20% increase in the electron density in oblique showers. At such high energies, the interactions of neutral pions in the atmosphere were taken into account. The electron spatial distribution was calculated both in the Nishimura–Kamata–Greisen (NKG) approximation and in the modification of this approximation ($\rm NKG_{mod}$) in which the parameter R_m is replaced by kR_m, where[13] $k = 0.5$. At distances greater than ~1 km from the shower axis, a further modification of the NKG approximation becomes necessary, to deal with the increase in the length of the cascade of electrons and photons. For the shower of Ref. 8, we used the parameter value $R_m = 80$ m, while the threshold muon energy was $E_{\rm th} = 1\times\csc\theta$ GeV, where the zenith angle is $\theta = 58°$. For the shower of Ref. 10 the inclination angle was $\theta = 23°$, and we had $R_m = 91.6$ m and $E_{\rm th} = 0.5\times\csc\theta$ GeV.

Figure 1 shows experimental data of Ref. 8 (these are the readings of the charged-particle detectors and the muon detectors), along with results of calculations of the spatial distributions of electrons and muons from the NKG model for a primary-proton energy $E_0 = 5.5\times 10^{20}$ eV. This energy was adopted since it leads to the best fit of the experimental data. It can be seen from Fig. 1a that the muons are predominant in this oblique shower, according to the readings of the muon detectors; the electrons constitute only a small fraction of the charged particles (we also need to allow for the electrons which arise from muon decay and the δ-electrons, which together make up about 25% of the muon density). Our estimate of the energy is about five times the value from Ref. 8, indicating the importance of a systematic modeling of all processes in an extensive air shower.

For the approximately vertical shower detected at Akeno[10] the ratio of muons and electrons is directly opposite that in the case just discussed. The muon detectors within 1000 m of the shower axis were in a state of saturation. Again in this case, our calculations for a primary proton lead to a good fit of the experimental data on both the electron component and the muon component, as illustrated by Fig. 1b. This figure shows the results calculated for an energy $E_0 = 2.7 \times 10^{20}$ eV (the upper estimate from Ref. 10). However, if we use the version of the calculation with $\mathrm{NKG}_{\mathrm{mod}}$, which leads to a better explanation of certain experimental data,[13] for the fit, then we should increase the estimate of the energy by a factor ~ 1.5 (to $\sim 4 \times 10^{20}$ eV). In the case of a primary iron nucleus, the muon density would increase by a factor ~ 2.5, while the number of electrons would change only insignificantly (because the shower maximum is close to the observation level). The effect would be to substantially change the relative number of muons and thereby contradict the readings of the muon detectors (Fig. 1b). Accordingly, if we do not require a substantial change in the model of hadron interactions at ultrahigh energies (in the direction of a slower dissipation of energy) from the KGS model,[11] then primary protons, rather than iron nuclei, should be the primary particles with energies $\geqslant 3 \times 10^{20}$ eV. This conclusion poses a problem for models which assume acceleration in shock waves.[6]

In summary, calculations carried out on the basis of the model of quark–gluon strings[11] incorporating the LPM effect[12] and the interactions of neutral pions in the atmosphere lead to an estimate $[(4-5) \times 10^{20}$ eV$]$ of the energy of the two huge air showers which is slightly higher than the value reported in the experimental papers.[8,10] A comparison of the relative numbers of muons in oblique and approximately vertical showers on the basis of these calculations provides evidence in favor of a proton nature of the primary particles. Since there are no known active sources at distances of 30–50 Mpc near the arrival directions of these three showers on the celestial sphere,[8–10] it is necessary to undertake a search for sources of primary particles with energies $\geqslant 3 \times 10^{20}$ eV. We should also point out that four showers with energies $> 10^{20}$ eV were detected at the Havera Park installation a long time ago, with arrival directions which again failed to point to any source.[14] As an alternative, one might seek some magnetic fields extending over large volumes.[7]

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