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EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
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Analysis of a cosmic-ray air shower recorded at the MIT Volcano Ranch station in February 1962 indicates that the total number of particles in the shower (Serial No. 2-4834) was 5×10^{10}. The total energy of the primary particle which produced the shower was 1.0×10^{20} eV. The shower was about twice the size of the largest we had reported previously (No. 1-15832, recorded in March 1961).[1]

The existence of cosmic-ray particles having such a great energy is of importance to astrophysics because such particles (believed to be atomic nuclei) have very great magnetic rigidity. It is believed that the region in which such a particle originates must be large enough and possess a strong enough magnetic field so that $RH \gg (1/300) \times(E/Z)$, where R is the radius of the region (cm) and H is the intensity of the magnetic field (gauss). E is the total energy of the particle (eV) and Z is its charge. Recent evidence favors the choice $Z=1$ (proton primaries) for the region of highest cosmic-ray energies.[2] For the present event one obtains the condition $RH \gg 3\times10^{17}$. This condition is not satisfied by our galaxy (for which $RH \approx 5 \times10^{17}$, halo included) or known objects within it, such as supernovae.

The technique we use has been described elsewhere.[1] An array of scintillation detectors is used to find the direction (from pulse times) and size (from pulse amplitudes) of shower events which satisfy a triggering requirement. In the present case, the direction of the shower was nearly vertical (zenith angle $10\pm5°$). The values of shower density registered at the various points of the array are shown in Fig. 1. It can be verified by close inspection of the figure that the core of the shower must have struck near the point marked "A," assuming only (1) that shower particles are distributed symmetrically about an axis (the "core"), and (2) that the density of particles decreases monotonically with increasing distance from the axis. The observed densities

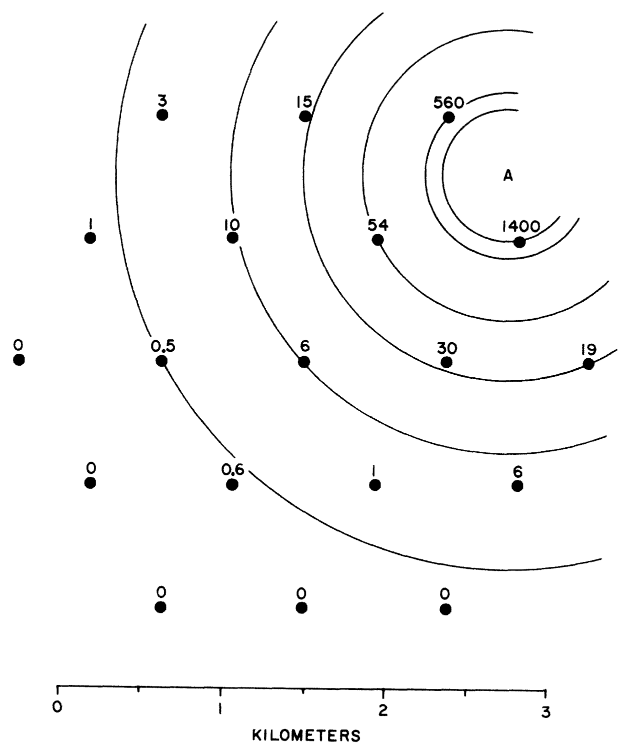

FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m² scintillation detectors. The numbers near the circles are the shower densities (particles/m²) registered in this event, No. 2-4834. Point "A" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

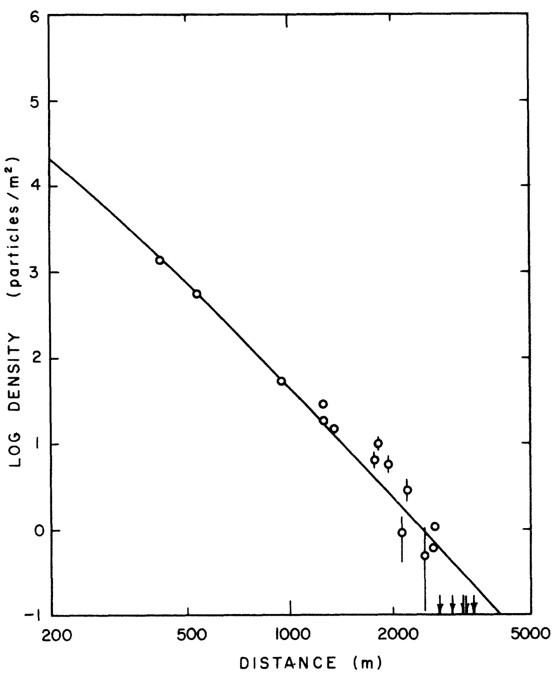

FIG. 2. Observed shower densities as a function of distance from the shower axis. The curve is the Greisen approximation of the Nishimura-Kamata lateral distribution for $s=1.0$, $N=5\times10^{10}$.

are shown as a function of distance from point "A" in Fig. 2. The curve represents a function, borrowed from cascade theory, which we have used as a tool in estimating the size of this shower.

The principal uncertainty in our final result, the energy of the primary particle, arises in estimating the total number of particles in the shower at the level of observation, and has to do with the lack of any shower density measurement nearer than 420 m from the axis. In general, the unnormalized lateral distribution function, $F(r)$, has by definition the property

$$\int_0^\infty 2\pi r F(r) dr = N,$$

where N is the shower size. Experiments on small showers ($N \lesssim 10^7$) show that about half of the particles in a shower are within 40 m of the axis, and only a few percent are further from the axis than 400 m. Because of experimental difficulties, it is only for small showers that one can measure F for all distances that contribute significantly to the above integral. Going to larger showers, one can assume that the unmeasured portion of F has the same shape that it had for smaller showers, or else one can try to estimate how much change may have taken place in the unmeasured portion of F from the amount that has been seen to take place in the measured portion. Fortunately, the amount of change that is seen to take place in the shape of F is small, even for order-of-magnitude changes in shower size. This is what one would expect, because of the mixing of generations within the shower.

In the present case, there are data for $420 < r < 1000$ m. One can calculate the logarithmic slope $d(\ln n)/d(\ln r)$, where n is the density, for that interval, and can make some comparisons. One finds that the slope is the same as for showers of comparable size (five other events with $N > 10^{10}$), that it is 10% greater than for showers with $N = 10^9$, and that it is 25% greater than for showers with $N = 10^8$. Turning to the region $r < 420$ m, we looked at the consequences of three different assumptions concerning F. They are assumptions as to a ratio of logarithmic slopes: the slope of the lateral distribution for the present event to the slope for showers with $N = 10^8$. The lateral distribution for $N = 10^8$ was chosen as the basis for comparison because it has been measured at Volcano Ranch from $r = 60$ m (near enough to the axis so that extrapolation is not much of a problem) to $r = 1000$ m (far enough from the axis so that there is some overlap with measurements for the present event).[1] As we stated above (in slightly different language), for $r > 420$ m the ratio in question is 1.25.

Assumption (1)—The ratio remains 1.25 for $r < 420$ m. One obtains a value 1.2×10^{11} for the shower size. We consider this to be an upper limit.

Assumption (2)—The ratio drops suddenly to 1.00 at $r = 420$ m and remains unity for $r < 420$ m (i.e., the unmeasured portion of F has the same shape as for $N = 10^8$). One obtains a value 2×10^{10} for the shower size. We consider this to be a lower limit.

Assumption (3)—The ratio decreases smoothly from 1.25 at $r = 420$ m to 1.00 near the shower axis. We chose a particular function whose logarithmic derivative behaves in this way, and obtained the value 5×10^{10} for N. We believe that the actual value is almost certainly within a factor of two of that estimate.

One can evaluate how much energy a primary particle has to have in order to produce a given shower by considering the total amount of ionization that is produced. This is Greisen's method of the "track length integral." Finding the size of the shower is equivalent to determining the lateral distribution of ionization. Longitudinally, the ionization extends from the initial interaction to some point where the last muon comes to rest, far underground. A large body of observation can be brought to bear in estimating the longitudinal distribution. Greisen has found for small showers ($N \approx 10^6$ at maximum development) that the primary particle must provide 1.65 GeV per electron at maximum development. This quantity should increase slowly with primary energy, so the proper value for showers like the one we are reporting must be about 2 GeV per electron at maximum development, which is the value we have used. If this shower was not at maximum development, the energy of the primary particle was even greater than our estimate.

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[4]This is the value one would obtain for a fictitious shower in which each particle seen at maximum development travels with minimum ionization through about 1000 g/cm^2 of material, or equivalently, through the atmosphere. The slow increase in that value with primary energy results from an increase in the depth at which the shower reaches maximum development.

ERRATUM

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The author of reference 7 is incorrectly identified. Instead of "J. L. Yntema, ···," footnote 7 should read "G. B. Yntema, ····."