ANALYSIS OF SOME RESULTS OF QUARK SEARCHES

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The interpretation of the results of Cairns, McCusker, Peak, and Woolcott, indicating a discovery of quarks in the cores of very energetic extensive air showers, is shown to be extremely difficult to reconcile with the results of other negative experiments. Alternative explanations of their results are then suggested.

McCusker and his colleagues[1,2] at the University of Sydney have examined tracks in cloud chambers triggered by an extensive air-shower array and have found five tracks out of 55 000 with droplet densities which they measure to be about half of the droplet densities of accompanying tracks. They have concluded that these tracks result from the passage of particles with anomalously low charge, presumably quarks of charge $2e/3$. From a knowledge of the acceptance of their cloud-chamber system and the primary cosmic-ray flux at the shower energies of about 3×10^6 GeV, they estimate that the average shower of this energy must include about ten charge-$\frac{2}{3}$ quarks in order to account for the number which they observe.

Measurements which we have conducted,[3] designed to detect quarks produced by cosmic rays under a variety of possible production mechanisms, have given negative results. A variety of measurements of comparable sensitivity by other observers[4,5] have also failed to detect quarks. It is clearly important to determine if it is possible to construct a model of quark production which is consistent with all of these results.

Our experiment[3] (and other experiments[4]) have placed limits on the flux of quarks in the secondary cosmic rays of about 10^{-10}/cm^2 sec sr. The results of McCusker et al. indicate a flux of about 5.5×10^{-10}/cm^2 sec sr on the basis of the five events which they report. These results can be reconciled only if the two measurements observe production of quarks under different conditions. Our measurements are not sensitive if more than one particle passes through our detector, which has an area of about 1.4 m^2, during our resolving time of about 2.5×10^{-8} sec. As a result of this constraint we are limited in our observations to quarks which appear separated in either space or time from the cores of very energetic showers. On the other hand, the observations of the Sydney group are constrained to regions near the cores of showers initiated by particles with energies of the order of 2×10^6 GeV. We must then ask if their observations indicate that the particles which they identify as quarks are definitely associated with the core of the shower and we must ask if reasonable production mechanisms demand that the particles arrive at the same time as the shower front.

McCusker et al. are able to estimate the total energy of the showers which accompany two of their events. Event 64 915 occurs[1] with a shower of about 2×10^6 GeV and event 66 240 accompanies a shower[2] where the total energy is about 3.5×10^6 GeV. The latter event is suspected to be initiated by an alpha particle so that the nucleon energy is then about 10^6 GeV. The authors indicate that event 64 915 might also be initiated by an alpha particle. The center-of-mass energy for a nucleon-nucleon interaction initiated by a nucleon with a laboratory energy of 2×10^6 GeV is about equal to 2000 GeV and the center of mass is moving with a velocity β such that $\gamma=(1-\beta^2)^{-1/2}=1000$. A particle produced at rest in this center-of-mass system would not lag behind the shower front and could not be differentiated in time from the particles which constitute the front. If the particle were a heavy quark, it is probable that it would not be slowed appreciably by collisions with nuclei[6] in its path to the detector. However, if the rest frame of the quark did not correspond rather precisely with the center-of-mass system, the quark would have a high probability of lagging behind the shower so that it would be detected in our measurements[3] and other measurements using time-delay techniques.[5] It is well known that even at moderate energies most particles produced in nucleon-nucleon interactions have rather large momenta in the center-of-mass system in directions parallel to the beam direction. If the ratio

P/Mc is not smaller than 3.5, where P is the momentum of the quark in the beam direction measured in the center-of-mass system and M is the mass of the quark, quarks would be detected by our instrumentation. Any small degree of peripheralism in the interaction between the two nucleons would be expected to result in larger deviations from pure kinematic symmetry in individual nucleon-nucleon collisions. To reconcile the Sydney results with the results of our group and others on the absence of any substantial flux of quarks delayed behind shower fronts, we must then postulate a most unusual nucleon-nucleon interaction: The interaction must occur with a cross section near geometric such that as many as ten quarks are produced nearly at rest in the center-of-mass system.

Since the large density of particles found near the cores of showers saturate the instrumentation used in our measurements, we are sensitive to quarks produced in the interactions of primaries with energies of 2×10^6 GeV only if the quarks are more than 70 m from the core at sea level. Since a quark with a mass of 10 GeV/c^2 produced nearly at rest in the center-of-mass system at the top of the atmosphere will be deflected by only 1 or 2 m from the center of the shower by the transverse momentum of 0.5 GeV/c that we might expect as a lower limit from the uncertainty principle and the size of the collision area, it is plausible that we might not be able to see quarks which arrive at the same time as the shower front induced by such high-energy interactions. At lower energies, such as 10^5 GeV, the spread of the quarks which might be produced will be greater and the density of shower particles will be much smaller so that we can presume we will see quarks which might be produced.

Since the cosmic-ray flux varies with the energy of the primary E approximately as $dN/dE \approx E^{-3}$, the cross section for production of quarks must be a steep function of energy if quarks are observed to be produced at 2×10^6 GeV but not at 10^5 GeV. Since the flux observed by McCusker et al. requires that about ten quarks are produced in every interaction at 2×10^6 GeV, the energetic threshold for the production of a pair of quarks cannot conceivably be more than 8×10^4 GeV (for quarks with a mass of about 100 GeV/c^2!) and must reasonably be considered to lie below that. If the cross section were then linear with center-of-mass energy from 5×10^4 to 2×10^6 GeV, we should have expected to see more than 1000 quarks based on the Sydney observations where, of course, we saw none. We should still expect to see several quarks if the cross section increased as fast as the fourth power of the center-of-mass energy.

Even this implausible model, where a large number of quarks are produced nearly at rest in the center-of-mass system with a cross section which rises from a very small value at 10^5 GeV to a value near geometric at 2×10^6 GeV, seems to be contradicted by the evidence presented by the Sydney group. If the quarks are associated with the core of the shower, the quark tracks should be accurately parallel to the tracks of the particles making up the core of the shower. All of these tracks should be parallel to within a milliradian as a condition that a core exists. In no case are the tracks identified as quarks parallel to any track identified as belonging to the core. Track R of event[2] 66 240 is most closely associated with other tracks which seem to be part of the core of the shower. It is clear from even a casual inspection of the photograph and the marks imposed on the photographs by the authors that tracks 2, 3, 4, and 5 are parallel within the accuracies of measurements on the photographs while track R makes an angle of about 20 mrad with these tracks on this one projection alone. Moving at such an angle, the particle associated with track R would soon leave the core and cannot, then be considered as a particle associated with the core. None of the other four tracks[1] identified as quarks are so nearly parallel to other tracks shown in the same published photographs. These tracks do not then belong to the core of the shower and if they are quarks it is most difficult to understand why they could not have been seen in our experiment or in other experiments.

If these tracks which exhibit low droplet density are not quarks, what are they? It appears to us that these are probably tracks of relatively low-energy electrons and muons. The electrons are produced as delta rays and low-energy pairs from the fund of electromagnetic energy near the core of such showers and the muons are derived from the hadronic cascade from the shower. The tracks display low droplet densities as a result of statistical fluctuations in ionization where the expected ionization is already less than the average ionization expected of the very energetic core particles because of relativistic effects. It is also possible that statistical fluctuations in the ionization produced by these core particles might also contribute to the total of low-density tracks.

Under favorable conditions a droplet of vapor will form on every ion produced by the passage of a charged particle through a cloud chamber. Ions are produced in pairs, of course, and the average interaction of a moving particle with an atom produces more than one ion pair: That is, the atom ejected in such an event may also ionize other atoms. In argon, at a pressure of 1.4 atm, as was used in the cloud chambers of the Sydney group, a minimum-ionizing particle will produce[7] about 42 events/cm. If delta rays with energies greater than 600 V can be excluded, there will be about[8] 77 ion pairs/cm or, under ideal conditions, there will be about 154 droplets/cm of track length from 42 statistically independent events. Or there will be $\frac{1}{4}$ as many events as droplets. If the efficiency of forming droplets on ion pairs is low, the ratio of droplets to events will be nearer 1. For example, is the efficiency is as low as 25% there will be $\frac{2}{3}$ as many events as droplets. These correlations do not seem to have been considered by the Sydney group.

McCusker et al. typically measure their standard tracks to have about 230 droplets in the regions which they select as free of delta rays. Typically, the low-density tracks have about 115 droplets in countable regions: They report 200 droplets for the light track in event 62 348, 130 droplets for the light track in event 64 915, 94 in event 65 677, and 110 droplets on the light track of event 66 240. If 230 droplets are to be expected on an acceptable region of track, the statistical standard deviation will be about 13% if the efficiency for forming droplets is 1. Then the probability of finding a track with less than 115 droplets in a similar region will be about one in 15 000. This is not very different than the ratio of five low-density tracks in 55 000 reported by McCusker et al. However, we suspect that the efficiency for the development of droplets on the ions of their chambers was rather less than 1 and then the probability of finding light tracks is smaller according to the statistical methods we are using. Of course it is always dangerous to use a statistical model to differentiate between very small probabilities without a very careful investigation of the relation of the physical problem to the mathematical model.

In their discussion of the deviations of the low-density tracks, the Sydney group appears to presume implicitly that all tracks produced by charge-one particles should be associated with about the same ion density. In fact we can expect large variations in ion densities as a result of the increase in ionization at very large values of $\gamma = E/m$ – the relativistic rise. Particles which make up the core of the shower must have energies such that $\gamma \geqslant 1000$ since the angular dispersion of the electrons will be about $1/\gamma$ rad and the dispersion of muons will be even greater. These core particles, which are mainly electrons with energies near 10 GeV, will produce ion densities which are of the order of 1.5 times the density produced at minimum by muons such that $2 \leqslant \gamma \leqslant 10$.[9] Electrons with such low velocities will scatter noticeably in the chamber, but higher-energy electrons such that $20 \leqslant \gamma \leqslant 60$ will appear as straight tracks with mean ionizations about 1.2 times minimum ionization. Then we might expect that a large portion of the low-energy particles, which will generally pass through the chamber at large angles with respect to the shower direction, will have mean droplet densities between 0.67 and 0.80 of the density of the shower particles. Some of these will pass through nearly parallel to the shower particles as a matter of chance, and rather small fluctuations in the droplet density corresponding to two or three standard deviations, or probabilities of from 1 in 20 to 1 in 400, will result in these tracks simulating quarks with a charge of $2e/3$. An inspection of the pictures of McCusker et al.[1,2] shows that a large flux of particles passing through the chamber at large angles is present.

There might also be a contribution to the set of tracks of small droplet density from particles which pass through the chamber before expansion and half of the ions are removed by the clearing field. While the Sydney group shows that most such tracks will be excluded through their anomalously large width produced through diffusion, again there will be statistical fluctuations in this width representing the spread of only 100 droplets. It appears to us that the probability of such a simulation is small however.

In summary, we find that the conclusion of Cairns, McCusker, Peak, and Woolcott[1] and of McCusker and Cairns[2] that the anomalously light tracks found in their cloud chamber are probably quarks, is in contradiction with the results of our searches for quarks[3] and the results of experiments by other groups.[4,5] We suggest that their tracks with small droplet densities may be explained as statistical fluctuations in the density of shower tracks when the correlations in the production of droplets is correctly considered, and, more likely, as much smaller statistical fluctuations in the ionization of minimum ionizing muons present in the shower and fluctuations in the ionization of relatively low-energy electrons produced in the interaction of the shower with materials about the apparatus.

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DISINTEGRATION AND ENERGY DEGRADATION OF VERY HIGH-ENERGY COSMIC RAYS IN INTENSE PHOTON FIELDS*

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Very high-energy cosmic rays, on emerging from their places of origin, are subject to photodisintegration and energy degradation by blue-shifted photons. It is shown that the intense photon fields of supernova explosions, of quasistellar objects, and of one of the current pulsar models are able to cause complete disintegration of complex nuclei and significant energy losses of protons at energies consistent with observed changes in the cosmic-ray charge and energy spectrum, respectively.

Photons having modest energies in their source's frame of reference can be Doppler-shifted into gamma rays in the rest frame of very high-energy cosmic rays. As a result, these photons can cause cosmic-ray protons to lose energy by photomeson and pair production[1,2] and cosmic ray nuclei to lose nucleons by photonuclear reactions.[1-3] It is tempting to invoke the latter mechanism to explain Linsley and Scarsi's observation[4] that between total energies of 10^{17} and 10^{18} eV heavier nuclei are less abundant than at lower energies. Conceivably, at these energies only protons are present. However, various authors have shown that neither the universal microwave-background photons[1-3] nor the interstellar and intergalactic optical photons[3,5,6] are able to disintegrate cosmic-ray nuclei at energies sufficiently low to explain the Linsley-Scarsi observation. This failure has led some authors[2,3] to suggest that perhaps photodisintegra-