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# SEARCH FOR $\frac{1}{3}e$ QUARKS IN COSMIC RAYS WITH THE LEEDS CLOUD CHAMBER*

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The central regions of cosmic-ray air showers near sea level have been studied with the Leeds cloud chamber for the possible occurrence of low-ionizing tracks. The average energy of the primary particles was a few times $10^6$ GeV. Our current results give an upper limit to the "flux" of $\frac{1}{3}e$ quarks of $1.2 \times 10^{-11}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$ at a 90% confidence level. A simple model is used to obtain an upper limit to the production cross section *versus* quark mass.

## 1. Introduction

The search for quarks of charge $\frac{2}{3}e$ as a nearly time-coincident component of cosmic-ray air showers was originated by McCusker et al. and continued by others. Improved techniques have permitted the extension of the search to quarks of charge $\frac{1}{3}e$ [1]. We here report an extension of the search for $\frac{1}{3}e$ quarks by using the Leeds cloud chamber [2] and an appraisal of the results in terms of an upper limit to the production cross section. The large useful area of this chamber has enabled us to collect data at several times the rate of previous experiments and, thus, to establish a significantly lower upper limit to the flux of $\frac{1}{3}e$ quarks than heretofore possible. As in the previous experiments, it is assumed that quarks have a mean free path against either nuclear interaction or decay that is a sizable fraction of an atmosphere. Otherwise, there would be little likelihood of observing them at sea level unless they are produced with an unexpectedly large cross section.

## 2. Apparatus and experimental method

The expansions of the cloud chamber are triggered by air showers detected with

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an array of six to eleven scintillators [3]. The size of each shower and its axis location can be determined from the scintillator data to within about 30% and 0.7 m, respectively.

The chamber faces upwards, that is, the "front" window is horizontal. A 45° mirror above the chamber turns the optical path so that the cameras, in effect, look down on the chamber from above. Because they are viewed from above, the shower tracks appear foreshortened by a factor that averages three. The foreshortening increases the detectability of tracks of lightly ionizing particles; it also reduces the space occupied by each track* and thereby permits productive scanning of regions with particle density up to 500 $m^{-2}$. Another advantage of observing the chamber from above is that each track passes through the regions of good illumination and best focus.

Above the chamber there are a plastic and wood laboratory roof and a wood dark-room roof with total average thickness of 2 $gm/cm^2$. In addition, there is the 45° mirror of 10 mm glass and the 66 mm front-window glass. For Run II, an absorber consisting of (starting from the top) 10 cm Pb, 25 cm concrete, 5 cm Pb, and 1.4 cm Fe was placed 3.1 m above the illuminated region. The cloud chamber is filled with argon saturated with vapor from a 1 : 5 water-propanol mixture to an absolute pressure of 90 cm Hg in the compressed state.

Immediately upon receipt of the trigger signal, the expansion of the chamber is initiated. The exhaust orifice has been throttled down so that it takes about 200 ms to complete the expansion. The consequent diffusion by the ions before they are immobilized by accretion of liquid results in tracks of 3 mm diameter. The clearing field is established in the vertical direction by means of horizontal layers of wires. The layers are about 15 cm apart, with a spacing of 3.8 cm within the layers that border the principal illuminated layer. The sense of the field reverses at each layer.

Since the clearing field is shorted immediately by the trigger, the positive and negative ions of shower tracks are unseparated. However, pre-shower tracks (old tracks) consist of positive and negative columns whose corresponding points have been vertically separated by 0 to 15 cm, depending on the age of the track. The 15 cm upper limit is due to collection of the ions by the clearing-field wires. The lengths of the old track columns decrease with age as the ends are collected by the wires.

It is well known [5] that the probability of drop-formation on ions depends on the supersaturation, its time dependence, and the sign of the ion. In our experiment, an upper limit to the supersaturation that we can tolerate is dictated by the requirement of a negligible number of uncharged, background drops. A lower limit is dictated by the requirement that, say, 80% of the positive ions form drops. With the Leeds cloud chamber operated within the above limits, negative ions have a

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*Clark [4] pointed out to us some of the advantages of the horizontal orientation and also the usefulness of simulated quark tracks.

probability between 10 and 20% for forming drops, which means that the number of drops in the negative column is smaller than in the positive column by a factor of 5 to 10.

The useful illuminated region consists of two contiguous horizontal layers of area 2.5 $m^2$ and height 15 cm. Each layer is illuminated by two flash tubes, on opposite sides of the chamber. The two contiguous 15 cm layers are illuminated sequentially in synchronism with shutters on some of the cameras. Since one layer of clearing-field wires lies at the interface between the illuminated layers, the field is upward in one illuminated layer and downward in the other.

Four sets of stereoscopic photographs are taken, from directions up to 15° on either side of the normal to the front window, with stereo-angles of about three degrees for each set. The 3° angle permits visual stereo scanning of the photographs. The large angle between sets permits us (a) to view the tracks stereoscopically from different directions and (b) to make precise analytical or reprojection reconstructions in real space, by using one photo from each of two widely separated sets to obtain a wide-angle stereo pair of up to 30°. The outermost stereo cameras take 63 mm photographs at a demagnification of 28 and are shuttered to photograph only the upper 15 cm illuminated layer. Another, similar camera is near the axis and photographs the full 30 cm depth. The centered stereo pair consists of 180 mm photographs of the full 30 cm depth at a demagnification of 10.

Our photographic technique gives images of individual drops. We deliberately "overexpose" with some of the cameras, thereby producing very dense drop images that will enhance the visibility of tracks with low drop population. The diameter of the images is 10 to 30 $\mu$m, depending on the angle of scattering and the distance of a drop from the flash tubes. Three of the stereo pairs are taken with 68 mm and the fourth with 200 mm Kodalith Royal Ortho film or Kodak Phototypesetting film.

The scanning is done by stereoscopic viewing, usually of the 63 mm photographs from the left-most camera. These photographs see a depth of 15 cm, resulting in less clutter than with 30 cm depth. We view the film at 10 times magnification. Since the photographic demagnification is about 28 for this film, it is as if the tracks were being viewed directly from a distance of 70 cm in real space. A more informative description of the method is that we easily make drop counts in three dimensions with the above technique. For a more detailed study of tracks with low drop density, we view the 180 mm photographs stereoscopically at a magnification that corresponds to viewing the tracks from 25 cm in real space.

The usual shower particle produces a minimum of about 450 ion pairs in each 15 cm layer. Therefore, an $\frac{1}{3}e$ quark would produce a minimum of about 50 ion pairs and would be unambiguous, since 50 is only on the threshold of the rise in a frequency distribution whose mean is 450. However, the combined effect of ion separation by the clearing field and the formation of only 10–20% negative drops is that the negative column of a preshower track can have about the same appearance as a shower-age track of a $\frac{1}{3}e$ quark. The difference in track widths because of difference in age is difficult to detect. However, these two types of low-density tracks are unambiguously distinguishable by the following methods, which we use.

For immediately pre-shower tracks, identification of a negative column is made by the proximity of the partner positive column. For earlier pre-shower tracks, where the positive column is not close at hand and therefore may not be obvious at first glance, the first clue is that the low-density track is not full length (a portion is missing at the end nearer a negative wire layer). For confirmation of the above evidence, we require that our scanners be able to find the positive column segment that goes with the low density track. In some cases, for example where there is clutter from the other tracks, the scanner also looks stereoscopically at the photographs from the other cameras. The final, most powerful tool for questionable cases is the study of the 180 mm photos, where the resolution is highest and where the photographed depth of 30 cm straddles the plane where the clearing field reverses. A shower-age, true quark track would be unmistakable since it would extend through the field-reversed central plane with neither off-set nor break.

Another possible source of a quark-like track is a chance alignment of a few background drops with a drop cluster due to ionozation by a photon of soft X-ray energy. Since the minimum length is 30 cm of observed track, the likelihood of such a chance alignment in three dimensions is vanishingly small.

We now turn to the question of our efficiency of detection of tracks with density as low as those of $\frac{1}{3}e$ quarks. To measure this efficiency, we followed Clark [4] in adding artificial, quark-like tracks to regular shower photographs, always three-dimensionally in our case. The artificial quark was constructed by placing an aluminum foil screen with a needle-pricked pattern of holes over a fluorescent light tube. The longitudinal distribution was taken from photographs of low-density negative columns of cosmic-ray tracks. The pricking technique that was developed gave bright, star-like sources whose individual intensities all had nearly the same angular dependence. Thus, the appearance did not change drastically with the viewing angle. A polaroid camera photograph was used to find the direction of the shower. Then by imaging the artificial quark (arquark) in a mirror we could place it in the same orientation and region of the chamber as the tracks of the shower. A method of determining exposures was developed that led to a high yield of arquark tracks that were judged to be as (or more) difficult to find than an equally sparse real track. Each of our seven scanners acquired the ability to find arquarks with an efficiency of 75% to nearly 100%. The overall average was 85%.

## 3. Results

Run I had about 20 gm/cm$^2$ above the illuminated layer. There were two principal trigger modes, a "centered" shower trigger and a "large" shower trigger. Shower sizes and axis positions were determined by computer fitting for typical portions of the run. Frequency distributions show that the average shower size was $1.5 \times 10^5$

particles for centered showers and $5 \times 10^5$ for large showers. The above indicates that, in Run I, we have looked for quarks produced by cosmic rays of average energy a few times $10^{15}$ eV (using the usual factor of $1.5 \times 10^{10}$ eV/particle) [16], and within a few meters of the shower axis. The effective limit to proximity to the shower axis is determined by the track density effect on scanning efficiency. The efficoency drops to about half at 500 particles per square meter. This limited our search to axis distances $R \gtrsim 4\ (N/10^6) m$, where $N$ is the size of the shower [6]. From Run I, we have scanned ~5000 shower photographs, which represent 4700 hrs of sensitive time. The events are about equally devided between the two triggers.

Since we have found no tracks in Run I attributable to particles of charge $\frac{1}{3}e$, we calculate $\leqslant 2 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$ for the "flux" of quarks of charge $\frac{1}{3}e$ to a 90% confidence level. This calculation includes factors of 0.64 for average useful area, 0.85 for average scanning efficiency, and 0.5 sr for air showers. The useful area factor includes an edge effect, which is a function of angle of shower arrival, and an obscuration effect due to the presence of tracks of ordinary particles.

Our definition of "flux" is contained in the statements of this and the preceding paragraph. It is the same definition as in previous reports. It is simply a convenient way of directly summarizing the overall experimental results, but it has no particularly useful physical interpretation. Previous scintillator instrumented searches prohibited all but very low-density shower accompaniment (see Cox et al. [7] for a good discussion). The proportional-counter apparatus of Böhm et al. [7] permitted low-density accompaniment, and cloud-chamber experiments permit medium-density accompaniment as quantified earlier in this section.

Instead of stating a "flux" limit, it would be possible to give the results in a form that is closer to the data themselves, such as acceptance $A\Omega t(\mathrm{m}^2\mathrm{sr\ sec})$ *versus* particle density, or *versus* shower size, axis distance, and zenith angle. This type of cataloguing is underway. In this report, we have chosen to give a physical interpretation by estimating cross-section limits (sect. 4).

In Run II, the absorber of 250 gm/cm$^2$, which is detailed earlier in the paper, has been in place. The particular layering of the absorber was designed for another experiment, which was run concurrently. For present purposes, it simply shielded the cloud chamber from the soft component in the air showers. We triggered on an incident local particle concentration in air of $\gtrsim 15$ within 0.2 m$^2$ at any of seven scintillators that were located within an area about the same as the cloud chamber and centered above the chamber. This trigger condition is not greatly different from those of Run I and, consequently, the shower sample is about the same. We have scanned 2250 shower photographs with this arrangement, representing 3000 hrs of sensitive time, with no $\frac{1}{3}e$ quarks found. By making calculations similar to those above, we find a flux $\leqslant 3.1 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$ to a 90% confidence level for $\frac{1}{3}e$ quarks capable of penetrating 250 gm/cm$^2$ of material. In this run, there was no limitation due to particle density, as such, of the shower in air. Therefore, this search extended inward to the shower axes, in general. If the results of Runs I and II are combined, the flux limit is $\leqslant 1.2 \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$ at 90% confidence level.

## 4. Cross sections

In this section, we estimate the cross-section limits that can be deduced from the present observations.

If we assume that the inelastic interaction path length of quarks is of the order of an atmosphere or more (interaction cross section less than a few mb), nearly all quarks produced in the atmosphere would reach our detector at sea level. The upper limits for production of quarks determined by our experiment can then be deduced from a model determination of the number of hadrons $\lambda$ in the cascade produced by an average primary particle. For determining $\lambda$, a simple model using average values for inelasticity (0.5 for protons, 1.0 for pions), average interaction distances, and average multiplicities has been used. The extrapolation of multiplicity from the values measured at accelerators was done first with logarithmic dependence and again with fourth root dependence on the laboratory energy of the incident particle. The interaction length for hadrons enters only superficially, since the emission energy of most of the hadrons drops below 300 GeV by sea level for the primary energy $\simeq 10^6$ GeV that makes the principal contribution to our data.

The beam flux is determined by the intensity of primaries of $E_0 \geqslant 10^6$ GeV (shower size $N \gtrsim 7 \times 10^4$ at sea level [6]), the hadron multiplication in the atmosphere, and the acceptance of the cloud chamber, if we make the reasonable assumption that production and scattering angles are small enough so that deflections into and out of the beam compensate. Since we have used our scintillator data to analyze

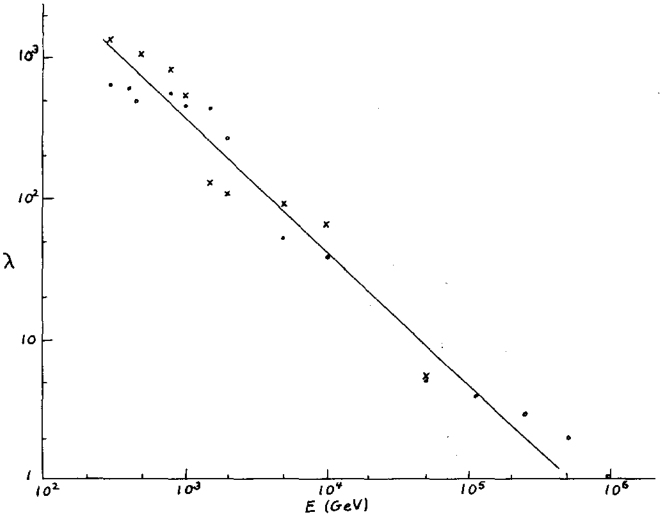

Fig. 1. The number of hadron collisions $\lambda$ with air nuclei per incident cosmic-ray primary of energy $10^6$ GeV as a function of hadron energy $E$. The crosses are from a model with $E^{\frac{1}{4}}$ multiplicity and the circles with ln $E$ multiplicity. The scatter is due to the simple wide-step model that was used.

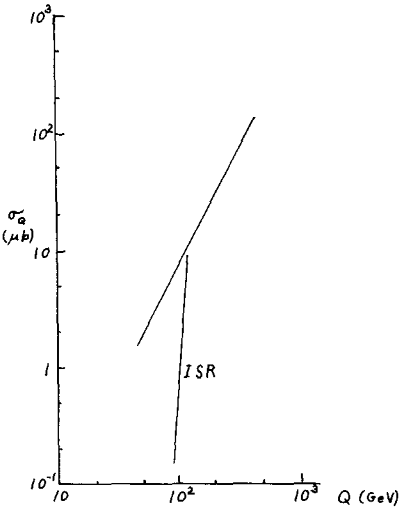

Fig. 2. An upper limit to the production cross section $\sigma_Q$ for $\frac{1}{3}e$ quarks as a function of total available energy $Q$. For a pair-production model, the maximum quark mass is $\frac{1}{2}Q$. The upper line is our result, which has an uncertainty of perhaps a factor two. The line labeled ISR is an extrapolation from fig. 3 of Bott-Bodenhausen et al. [7]; it extends down to $2.5 \times 10^{-4}$ $\mu$b at $Q \simeq 45$. A more complete analysis of the IRS data has led to approximately a factor five reduction in their limit (private communication)*.

only a sample of our showers, we can get a better figure for the primary intensity from explicit shower studies. From Greisen's survey [6], we find $I_0 \simeq 2 \times 10^{-10}$ $\mathrm{cm}^{-1}\ \mathrm{sr}^{-1}$ for $N \gtrsim 7 \times 10^4$. Our preliminary survey for the number of shower cores in the cloud chamber is consistent with this. The cross section for quark production is $\sigma_Q = \sigma_T\, n/(\lambda\, I_0 A \Omega t)$*, where $\sigma_T$ is the total inelastic cross section, $n$ is the number of quarks detected, and $\lambda$ is the number of hadrons in each cascade of energy $\geqslant E$. Since we observed no quarks, we obtain an upper limit to the cross section at 90% confidence level of

$$\sigma_Q \simeq (0.02/\lambda)\sigma_T\ . \tag{1}$$

The cascade multiplicity factor $\lambda$ is a function of energy $E$ of the cascade hadrons. Fig. 1 shows the results for $\lambda$ obtained with the simple models described earlier. The energies of interest are $E \gtrsim 10^3$ GeV, since this is the limit of current accelerator energies. It is seen from fig. 1, that $\lambda$ is not significantly dependent on the multiplicity model at $E > 10^3$ GeV.

The maximum energy $Q$ available for particle production is dependent on $E$. Since $\lambda$ falls off quite rapidly with $E$, we can associate an effective $Q$ with $\lambda$. Then eq. (1) enables us to deduce an approximate cross-section limit *versus* $Q$, or quark mass ($Mc^2 = \frac{1}{2}Q$) for a model of production in pairs. The results, using 30 mb for $\sigma_T$, are given in fig. 2.

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*The factors 0.64 and 0.85 for useful area fraction and scanning efficiency should be included. The result gives a factor of 1.8 increase in our $\sigma_Q$.

The results of Clark et al. [1] can be used similarly for estimating cross-section limits for $\frac{2}{3}e$ quark production. Their local shower density trigger responded to about the same shower size as our trigger. Their flux limit is about twice our limit. Therefore, we can say that the cross-section limits for $\frac{2}{3}e$ quarks are about double the values shown in fig. 2 for $\frac{1}{3}e$ quarks.

## 5. Conclusions

Our upper limit to the flux of $\frac{1}{3}e$ quarks of $1.2 \times 10^{-11}$ cm$^{-2}$ sr$^{-1}$ sec$^{-1}$ corroborates the results of a similar experiment by Clark et al. [1], and extends the lower limit downward by nearly an order of magnitude. Their limit for $\frac{2}{3}e$ quarks is $2 \times 10^{-11}$ cm$^{-2}$ sr$^{-1}$ sec$^{-1}$. In both experiments the average energy of the primaries that produced the triggers was about $10^6$ GeV. The combined results of the two experiments indicate that neither the $\frac{1}{3}e$ nor the $\frac{2}{3}e$ quark is produced abundantly in showers with primaries of these energies. Counter results, which are for thin regions of air showers, give flux limits about an order of magnitude greater (see Jones [1] for a summary).

Our result for an upper limit to the production cross section of $\frac{1}{3}e$ quarks as a function of quark mass is not very restrictive compared with accelerator results for quark mass $\lesssim 20$ GeV/$c^2$, but above this mass ours are the only results available. For $\frac{2}{3}e$ quarks, we have deduced from the data of Clark et al. production cross-section limits about double those for $\frac{1}{3}e$ quarks.

It should be pointed out that we have not as yet established significant limits to the possibility of quarks occurring at small lab angles. In Run I, we were limited by obscuration by tracks of shower particles. In Run II, the data cover only a few months operation.

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