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# SEARCH FOR QUARKS PRODUCED IN THE INTERACTIONS OF 300 GEV PROTONS

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We have searched for quarks with charge (1/3)e and (2/3)e among the secondaries produced in the interaction of 300 GeV protons from the NAL synchrotron. Fractionally charged particles were identifiable through their ionization losses in an eight-counter scintillator telescope. No quark signal was found, and we infer that the resulting limit on the quark production cross section is $1 \times 10^{-35}$ cm$^2$ at 90% significance level.

1. Introduction. We have conducted a search for quarks with charge 1/3 and 2/3 of the electron charge among the interactions products of 300 GeV protons from the synchrotron at National Accelerator Laboratory in Batavia, Illinois.

2. Experimental Method. We sought to identify fractionally charged quarks by their energy loss in scintillator. We used an eight-counter telescope consisting of 1-inch cubes of scintillator, viewed through air light pipes by RCA 8575 phototubes. The counters were slightly staggered to minimize edge effects. The combination of a thick scintillator and a high-efficiency photomultiplier assured good pulse-height resolution. A slide in the light pipe of each counter could be set so as to let all of the light from the scintillator reach the photocathode, or to reduce it by a mask, consisting of a number of holes drilled in opaque material, to 1/9 or 4/9 of the full output. We could thus simulate particles with charge (1/3)e and (2/3)e for calibration purposes.

300 GeV protons from the NAL synchrotron were steered on a beryllium target in the Meson Experimental Area. The quark telescope was located 1350 feet downstream from the target, at $0^\circ$ in the horizontal, and on a line sloping down at an angle of 6.5 mr in the vertical

(beam line M4). The secondary beam was defined by collimators at 648 feet and 1015 feet downstream from the target, and propagated largely in an evacuated pipe one foot in diameter.

During the run, the circulating beam in the synchrotron was typically a few times $10^{11}$ protons, and was slowly (0.2sec) ejected with close to 100% efficiency. Since the beam pulses have a very complex time structure, some instantaneous rates were much higher than one would get assuming a perfectly uniform beam spill. It was found, however, that the telescope would count properly when the spill quality was adequate and the intensity per pulse was below $10^5$ particles, where it was kept during the run by adjusting the collimators, if necessary.

The phototube pulses were split three ways and fed to two ranks of discriminators and to a pulse-height digitizing device (LeCroy's eightfold analog-to-digital converter Mod. 2248).

The thresholds of one rank of discriminators ($C_i$) were set at 1/30 of the average energy loss $I_o$ of a minimum-ionizing singly charged particle. The other rank ($A_i$) thresholds were set at 0.75 $I_o$. A trigger indicating a quark candidate was formed whenever there was a coincidence of all $C_i$ ($i = 1...8$) and none of the $A_i$ was tripped, i.e. when the pulses from all eight counters were between 0.03 $I_o$ and 0.75 $I_o$. The digitizer was then gated on and the pulses from the eight phototubes digitized and punched on paper tape. The frequency of such events was low, one per million or more particles passing through the telescope. The latter number was monitored continuously by scaling the number of eightfold coincidences of all $C_i$.

3. Calibration. Tapes were also taken with masks in front of the phototubes, removing the anticoincidence requirement from the trigger. We obtained thus simulated distributions of quark-line pulses. These tapes were used to obtain the resolution of the individual counters, simulate quark signals, and check periodically the stability of the system.

To find the energy loss of a particle per counter, we averaged for an event the pulse heights of the eight counters and used as a measure of correlation of the pulses in individual counters the function $f^2(\bar{H}) = \frac{1}{8}\sum_i^8 \frac{(H_i-\bar{H})^2}{\sigma_i^2}$, where $H_i$ are the pulse heights in the individual

counters, $\bar{H}$ is their average, and $\sigma_i^2$ is a measure of counter resolution taken also as a function of $\bar{H}$.

The distribution of the average pulse heights and the corresponding $f^2$ distribution for the simulated (1/3)e and (2/3)e quarks are shown in Figs. 1 and 2 respectively. These distributions were used to establish the calibration of the energy-loss scale and the correlation function cut-off. (The function $f^2$ is related to the chi-square distribution, and is used in an analogous manner.)

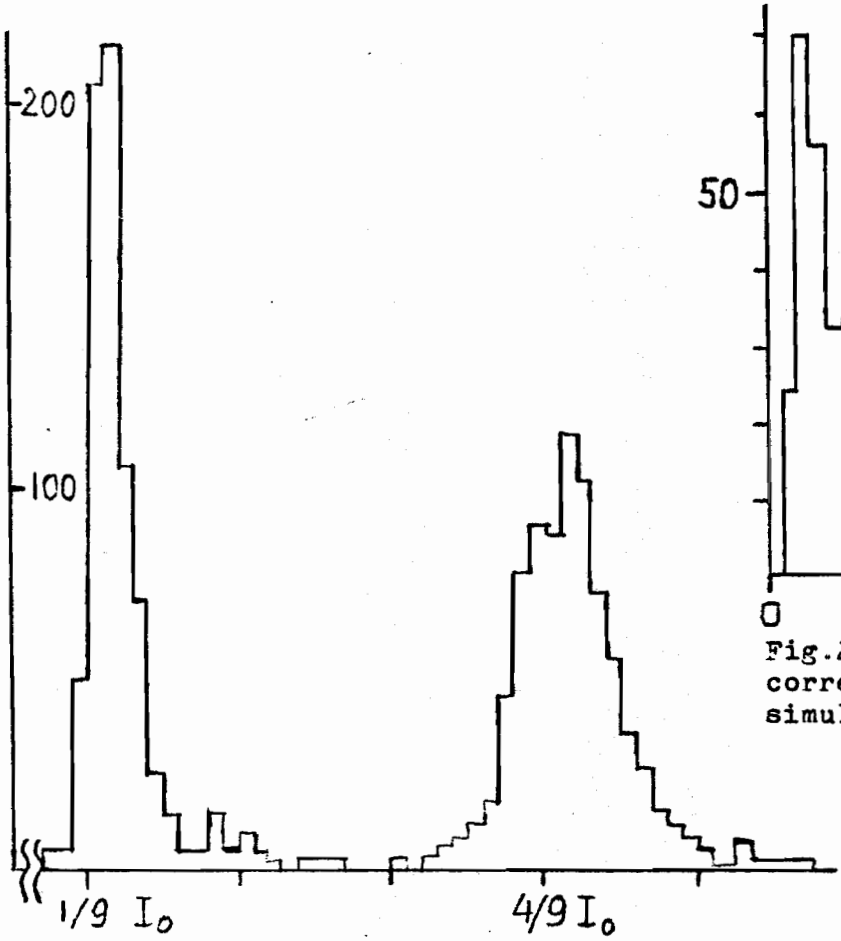



Fig. 1. Calibration runs with masks simulating (1/3)e and (2/3)e quarks. $I_o$ is the ionization produced by singly-charged minimum ionizing particles. The distribution represents the weighted average of the eight counters.

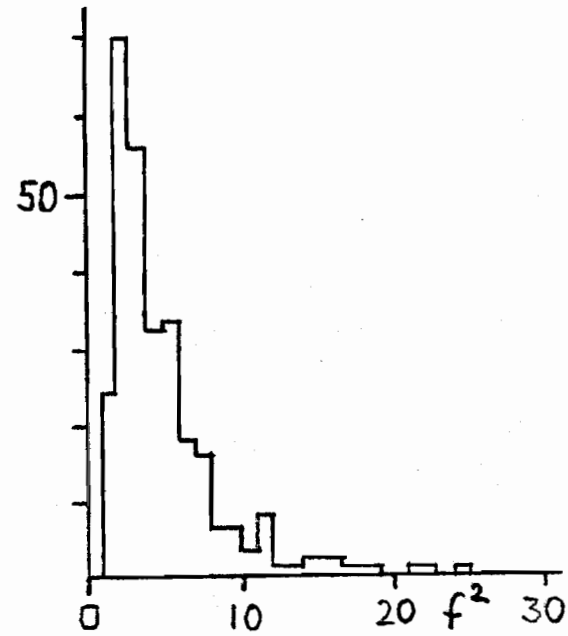
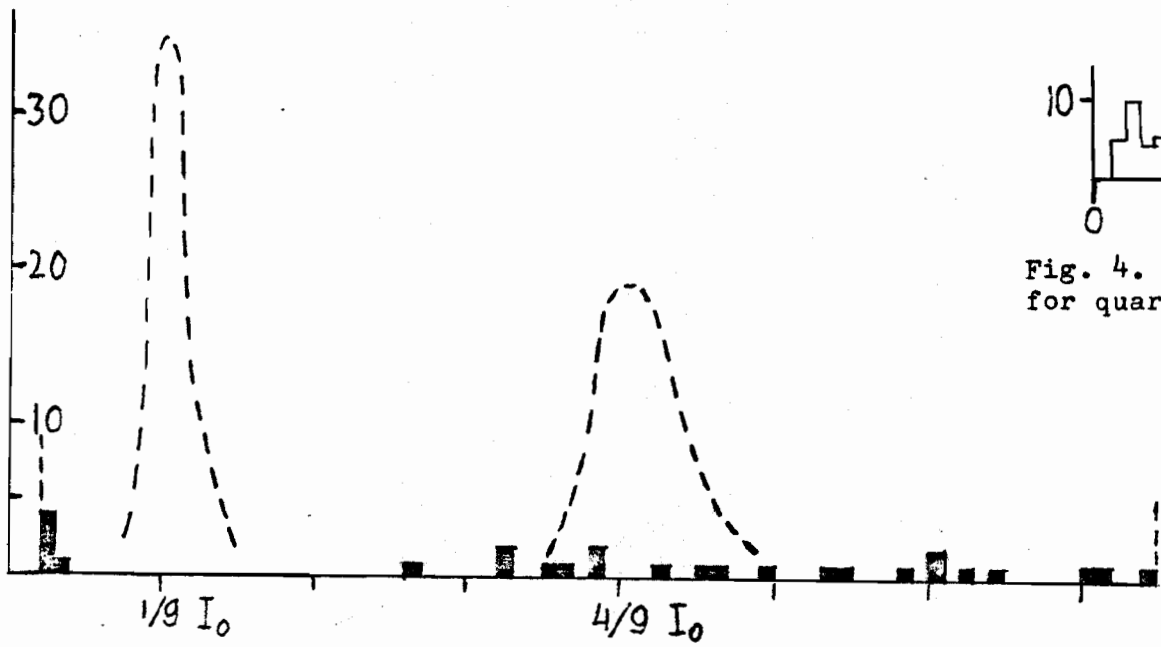



Fig.2. Distribution of the correlation function $f^2$ for simulated quarks.

4. Results and Conclusions. After the initial setting up, the accelerator was targeted to the Meson Area for about two weeks, during which the data were taken. During this period $1.15 \times 10^9$ particles traversed the telescope. The distribution of the average ionization

of quark candidates for which the correlation function was less or equal 8.0 is shown in Fig. 3. The $f^2$ distribution of the candidates is shown in Fig. 4.



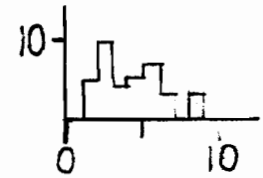




Fig. 4. $f^2$ distribution for quark candidates.

Fig. 3. Results of the quark search . The distribution represents the average pulse height in eight counters in terms of the minimum ionization of singly charged particles $I_o$. Events plotted have value of the correlation function $f^2 \leqslant 8$.
The dashed curves outline the signals expected from calibration runs for 100 quarks of each charge, (1/3)e and (2/3)e, passing through the telescope.

It can be seen that the $f^2$ distribution does not peak, and that the region of the (1/3)e quark shows no signal at all. There is uniform background at ionization loss values between $(3/9)I_o$ and the high end of the scale, and no peak is visible where the (2/3)e quark should show up; there is in fact less counts there than expected from the background average. The result is consistent therefore with seeing no quark candidates of either charge, or to an upper limit of 2.3 at 90% significance level.

To arrive at a limit on the quark production cross section we must recur to some plausible, if arbitrary, model. (The arbitrariness of such calculations should be borne in mind when comparing the various reported limits on quark production.) We shall assume that the

distribution of quarks is similar to that of other particles and is given by

$$dN/dp^3 = C \exp(-Ax) \exp(-(p_\perp/p_o)^2) \qquad (1)$$

where x is the Feynman variable ($x = p_\parallel^{CM}/p_{max}$) and $p_o$ is the characteristic transverse momentum. From this we could calculate the acceptance of our telescope to quarks produced in the target by 300 GeV protons. The result of this calculation is relatively insensitive (to about a factor of two) to the parameters of the model, for $p_o$ from 400 MeV/c to 2 GeV/c, values of A between 3 and 12, and quark masses between 3 and 12 GeV/$c^2$. The mass dependence of the aperture is shown in Fig. 5.

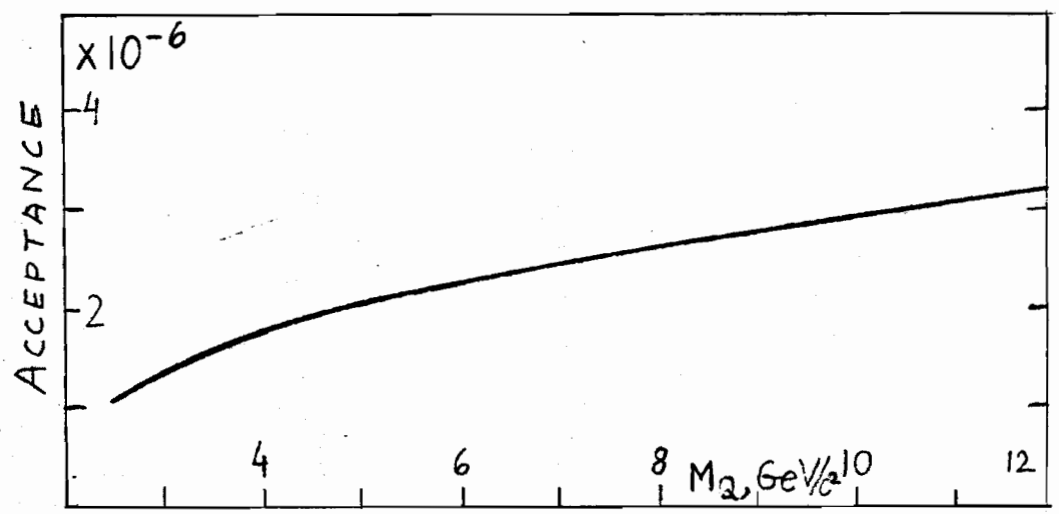



Fig. 5. Acceptance of the detector to quarks produced at the target as a function of the quark mass $M_Q$. The other parameters of the model (Eq.(1)) have been set to: A=8, $p_o = \sqrt{2 M_\pi M_Q}$, where $M_\pi$ is the pion mass.

To relate the observed upper limit at 90 % significance level of 2.3 quarks/$1.15 \times 10^9$ secondaries, we shall make use of the particle production calculations by Sanford and Wang [1] who predict 43 000 charged secondaries with energy greater than 40 GeV at 6.5 mr into the solid angle subtended by our telescope per $10^{11}$ protons of 300 GeV on the target. (Protons and pions with energy lower than 40 GeV were scattered out from our beam in its air-filled part.) Our detection of $1.15 \times 10^9$ secondaries corresponds then to $2.67 \times 10^{15}$ protons; if we take the inelastic proton cross section as $3 \times 10^{-26}$ cm² and the quark

acceptance of our telescope (from Fig.5) as $2.5 \times 10^{-6}$, we find the upper limit at 90% significance level of $2.3 \times 3 \times 10^{-26} / (2.67 \times 10^{15} \times 2.5 \times 10^{-6}) = 1.0 \times 10^{-35}\,cm^2$ for the quark production cross section.

It should be noted that we did not recur to the "supermomentum" method to lower the background. This method makes use of the fact that quarks with momentum p are deflected only 1/3 or 2/3 as much as singly charged particles of the same momentum. If one uses analyzing magnets magnets tuned for quarks of sufficiently high momentum, close to the kinematic limits for the reaction, singly charged particles are largely swept out of the beam. If the quarks, however, are produced in the center-of-mass system with rather low momenta, as predicted, e.g., by the thermodynamical theories of particle production, they may themselves be absent from the supermomentum beam.

5. Acknowledgements. This research has been carried out under the auspices of the United States Atomic Energy Commission.

Reference:

(1) J.R. Sanford and C.L. Wang, Brookhaven Reports BNL 11299 and BNL 11479; C.L. Wang, Isabelle Study, BNL 17522.