Search for Quarks and Heavy Stable Particles Produced at 300 GeV*

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We report a search for quasistable particles with anomalous charge or large mass produced by the interaction of 300-GeV protons at the National Accelerator Laboratory. Analyses of energy losses in a counter telescope lead to cross-section limits of 10^{-35} cm^2 for particles with charges of $e/3$ and $2e/3$ and 5×10^{-31} cm^2 for charge-$4e/3$ particles. Time-of-flight measurements gave cross-section limits of about 10^{-31} cm^2 for the production of massive charged particles.

As new accelerators allow access to new regions of particle energy and intensity, particle searches can, and should, be extended to exploit the new conditions. The advent of operation of the National Accelerator Laboratory proton synchrotron, accelerating about 10^{12} protons per second to 300 GeV, then allows searches for anomalously charged particles such as quarks and searches for heavy quasistable particles which extend[1] to new mass limits and cross-section limits. We have now conducted searches for such particles produced in the interaction of 300-GeV protons with a wolfram target at an angle of 6.5 mrad from the direction of the incident proton beam.

Protons from the external beam of the accelerator were directed to a wolfram target in the meson experimental area. The apparatus used for our measurements was located 405 m downstream from the target in line with the proton beam in the horizontal plane and at an angle of 6.5 mrad downward from the proton beam in the vertical plane. This secondary beam from the target passed through collimators in galleries 210 and 330 m downstream from the target and through a magnet in the 210-m gallery. From the magnet to the apparatus gallery the path was evacuated.

We attempted to identify fractionally charged particles through analyses of their energy loss in passing through an eight-scintillator counter telescope where each element was composed of a 2.5-cm-thick plastic scintillator viewed through air light pipes by 5-cm-diam phototubes. The elements were 2.5 and 2.8 cm square, arranged in alternation, to reduce edge effects. 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 tube or to reduce the light through masks consisting of holes drilled in opaque material so that $\frac{1}{9}$ or $\frac{4}{9}$ of the light was transmitted. This feature allowed us to simulate the passage of particles with charges of $e/3$ and $2e/3$ for calibration purposes.

During the measurements made to detect the existence of particles with charges less than the electronic charge, the output of the telescope phototubes was split three ways and fed to two ranks of discriminators and to a pulse-height analog-to-digital converter. The thresholds of one set of discriminators (C_i) were set to 0.05 of the average loss, I_e, of a minimum-ionizing singly charged particle, while the other rank of discriminators (A_i) were set to thresholds of $0.75I_e$. A trigger indicating a possible particle with charge less than e (a quark candidate) was generated by a coincidence of all C_i ($i = 1, 2, \ldots, 8$) and the absence of a signal from any A_i; i.e., a trigger is generated when the pulse from each telescope element is larger than $0.05I_e$ and smaller than $0.75I_e$. The digitizer was then gated on, and the pulse heights from the eight counters were recorded on punched paper tape.

The search for particles with charge less than e was conducted in the direct beam with the magnet off. The proton intensity on the target was typically of the order of 2×10^{11} per pulse leading to an intensity of charged particles through our telescope of about 30 000 per pulse where the pulse rate was about 10 per minute. We ran for a period which gave us about 1.4×10^9 particles through the telescope and about 2000 triggers. The trigger rate was heavily correlated with the instantaneous particle rate through our counters. While the beam was emitted nominally over a period of nearly 0.5 sec, there was sometimes considerable structure and spikes of extremely high intensity. We presumed that these occasional spikes induced excessive current in our phototubes which led to voltage drops and then anomalously small pulse heights for singly charged particles. It is probable that most of our triggers resulted from such infrequent overloading of our counter system. Since the limitation on our results which followed from this effect was not more severe than that imposed by the statistical significance of the data, we chose not to modify our equipment to eliminate the problem.

Triggers which result from the passage of particles of definite charge through the telescope can be differentiated from most spurious triggers through examination of the pulse-height correlations in the eight counters. Relativistic particles with a charge of ae will give rise to a pulse height of about $a^2 I_e$ in each counter, while spurious triggers seem to arise from more nearly random pulse heights in the various counters. We then use a correlation function f^2 to discriminate between these classes of triggers, where

$$f^2(\bar{I}) = \frac{1}{8} \sum_{i=1,8} \frac{(I_i - \bar{I})^2}{\sigma_i^2},$$

where I_i is the pulse height in counter i, $\bar{I}$ is the average pulse height, and σ_i is the counter resolution at the pulse height $\bar{I}$. In this description the counter pulse heights are normalized to the same value of I_e. In order to determine the spectrum of values of f^2 for real particles, we investigated the spectrum of pulse heights and correlation functions f^2 for the passage of singly charged particles through the telescope with the $\frac{1}{9}$ and $\frac{4}{9}$ transmission masks in place. The diagram of Fig. 1 shows the distributions in pulse heights and correlation function using the masks which correspond to charges $e/3$ and $2e/3$, as well as the average pulse heights and correlation values for all the recorded events where f^2 was less than 8. Clearly there is only about one event which fulfills the criteria expected for the passage of an $e/3$ quark and one which corresponds to a charge-$2e/3$ quark where the background can be expected to contribute at this level. We then observe no quarks.

Although all accelerator quark searches result in limits on differential cross sections, it is useful, and has become a convention, to attempt to estimate a limit in terms of the total production cross section. To do this one must have recourse to a model of quark production which is not tied too closely to a particular view of the production process since we cannot be certain that we understand such processes. In particular, we are not at all confident that quarks will be produced at the high momentum postulated in searches using the "supermomentum" method[2] where magnets sweep out singly charged particles leaving quarks, with their smaller charges, to pass through detection systems. We therefore chose a method of measurement, using no magnetic fields, which is sensitive to a very wide range of production models. We assume that quarks are produced according to a recipe which provides an adequate fit to all other particle production processes:

$$d\sigma/dp^3 = C \exp(-Ax) \exp(-p_t^2/p_0^2),$$
$$x = p_L/p_m, \qquad (1)$$

where p_L and p_t are the longitudinal and transverse momenta of the particle in the center-of-mass system and p_m is the maximum momentum allowed kinematically. Here we consider A and p_0 as free parameters and investigate the proportion of the produced particles accepted by the telescope as a function of A and p_0. Upon calculation, we find that this acceptance is about 2.5×10^{-6} and does not vary more than a factor of 2 from this value as we vary the particle mass from 2 to 11 GeV/c^2, p_0 from to 2.0 GeV/c, and A from 2 to 12.

In order to determine cross sections, we use the formula of Sanford and Wang[3] to relate the number of charged particles passing through our telescope to the number of protons interacting in the target. These calculations lead to predictions of about 35 000 charged particles with momenta above 40 GeV/c per 10^{11} interactions in

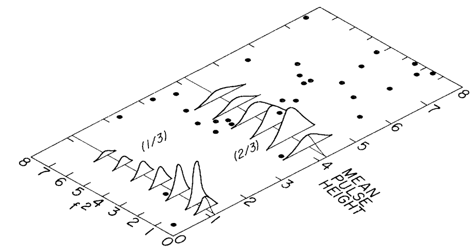

FIG. 1. The solid points show the pulse heights (in arbitrary units) and the pulse-height correlation numbers, f^2, for those events where $f^2 < 8$. The distributions in intensity of simulated quarks with charges of $e/3$ and $2e/3$ over such a plot are also shown by the three-dimensional representations.

the target. Later measurements, with the magnet powered, verified the general momentum dependence expected from the Sanford-Wang formulas and verified the calculated cutoff at 40 GeV/c induced by multiple scattering in the air and a counter in the 210-m gallery. If we take the inelastic proton cross section as 30×10^{-27} cm, the cross section which corresponds to one quark is then $(30\times10^{-27}\times3\times10^{4})/(10^{11}\times1.4\times10^{9}\times3\times10^{-6})\approx2\times10^{-36}$ cm^2. We conclude that it is unlikely that as many as three quarks of either charge $e/3$ or $2e/3$ should have been expected and, over all, it is unlikely that the cross section for the production of either charge $e/3$ quarks or $2e/3$ quarks is greater than 10^{-35} cm^2. The kinematic mass limit is about 12 GeV/c^2.

Even as three quarks may be much lighter than one quark, it is plausible that a two-quark compound may be lighter than one quark, and that any quarks produced in primary interactions may quickly decay to pions plus two-quark compounds.[4] Furthermore, the two-quark compounds may decay quickly through the weak interactions to the lightest member of their multiplet which will probably have a charge of $4e/3$ if the lowest two-quark multiplet is a sextet. Considering this possibility that an initial quark beam will quickly decay to charge $4e/3$ states, we conducted a search for such particles in a manner similar to that used in the searches for single quarks.

We conducted the search for charge $4e/3$ particles in a beam magnetically deflected by about 8 cm at our apparatus with the field adjusted so that we accepted particles with a charge of $+e$ and a momentum of 60 ± 20 GeV/c. Slow protons, with their large energy losses, were then eliminated. The energy loss measurements were made with the $\frac{4}{9}$ transmission masks in place. Calibration runs with the masks defined the pulse heights for charge-e particles as I_e, while calibration runs with the masks removed gave pulse heights equal to $2.25I_e$. Signals from charge-$4e/3$ particles, with I equal to $1.77I_e$, were successfully simulated by running without masks and with a lower voltage on the phototubes. During the searches for the anomalous particles, the discriminators C_i were set at $1.3I_e$ and the A_i were set at $2.4I_e$. Under these conditions, 16 000 triggers were recorded while 8×10^6 charged particles passed through the telescope. It seems probable that most triggers were initiated by hadrons which interacted in the first scintillator to produce several charged particles which passed through the other scintillators. There was no evidence of any contribution above background at $1.77I_e$ and then no evidence for production of charge-$4e/3$ particles. Again using the model of Sanford and Wang to relate the number of charged particles accepted to the number of interactions in the target, and using Eq. (1) to describe the production of the quark compounds, we conclude that our results suggest that the cross section for the production of particles with a charge of $4e/3$ is not greater than 5×10^{-31} cm^2. Again the results do not seem to be strongly dependent upon the particle mass or the parameters of Eq. (1).

The availability of the beam and our associated equipment presented us with an opportunity to make measurements of interest concerning the possibility that other heavy, quasistable particles might be produced in these high-energy interactions. We found it possible to make time-of-flight measurements over a path of 230 m from a 6-mm-thick scintillation counter mounted near the magnet to a 6-mm-thick counter, 12 mm square, set in our apparatus bay downstream. This counter was set in coincidence with a larger counter to reduce accidental backgrounds. This detector and the appropriate collimators were arranged such that the beam was deflected 15 cm giving the system a momentum resolution of about 10%. The downstream counters were placed behind two gas Cherenkov counters, each 3 m long filled with CO_2 at atmospheric pressure, set in anticoincidence with the scintillation counters. These Cherenkov counters reduced the background from mesons and protons by about a factor of 100. Under conditions such that the beam spill showed very little structure, chance coincidences of those particles which were not eliminated by the Cherenkov anticoincidence counters with triggers of the upstream counter resulted in a large background of apparently slow, massive, particles. However, if the beam was extracted from the accelerator while the rf cavities were excited, the extracted beam retained a sharp rf structure and appeared in bunches separated by about 18 nsec leaving a period of about 12 nsec quite free of background. We then chose to run under this beam condition at a series of momenta designed to maximize the possibility of detecting particles of masses between 3 and 11 GeV/c^2 with a charge of either sign. The graphs of Fig. 2 show the results of these searches at four different momenta and indicate that there is no evidence for the production of such massive particles. Over most of the range of mass, it is

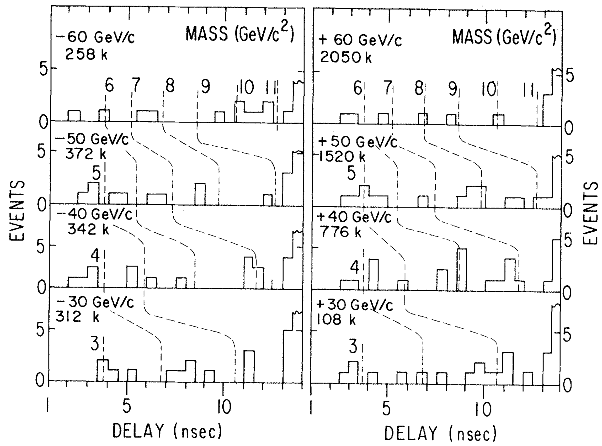

FIG. 2. The eight graphs show the result of time-of-flight measurements at various momenta. The dashed lines connect regions where the delay corresponds to similar particle masses. In the upper left corner of each graph is the nominal momentum of the beam and the number of particles passing through the apparatus.

possible to say that the flux of massive particles is not greater than 10^{-5} times the flux of light particles.

Unlike the results of the searches for particles with anomalous charge, the sensitivity of the searches for massive particles is quite model dependent. In these measurements, the velocities of the particles which might have time delays accessible to detection are less than the velocity of the collision center of mass in the laboratory system and the efficiency of detection is then likely to be small. Indeed, if such particles exist, we might well expect that most of the flux in the region covered by these measurements would result from the slowing down of the particles produced at high velocities through collisions with nucleons in the target. For these particular measurements, the target was wolfram and 15 cm long. In such a nucleus and in such a target the probability of a particle making several collisions is quite high, and we then believe that we would probably be sensitive to any appreciable production of massive particles with a lifetime greater than the time of about 200 nsec required for a particle to survive the passage down the beam. We estimate that we probably would see production of such particles if the cross section were greater than 10^{-31} cm^2.

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[1]For a general review of recent searches for quarks or other anomalously charged particles, see L. W. Jones, Physics Today 26, No. 5, 30 (1973).

[2]See, for example, Yu. M. Antipov *et al.*, Phys. Lett. 30B, 576 (1969).

[3]J. R. Sanford and C. L. Wang, Brookhaven National Laboratory Report No. 11299, 1967 (unpublished); C. L. Wang, Phys. Rev. D 7, 2609 (1973).

[4]H. Kasha, R. C. Larsen, L. B. Leipuner, and R. K. Adair, Phys. Rev. Lett. 20, 217 (1968); J. J. de Swart, Phys. Rev. Lett. 18, 618 (1967).