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EXPERIMENTAL PROPOSAL TO N.A.L. QUARK SEARCH

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An experiment is described which is designed to detect particles of anomalous charge which might be produced through the interaction of the proton beam with material. We plan to be able to detect positive and negative particles with a charge between 0.20 e and 0.85 e, as well as particles with charges greater than 1.20 e. We are sensitive to particles which are relativistic ($pc > cm^2$) and have a mean free path not mucn smaller than 10 grams of scintillator. We expect to be able to detect about one anomalous particle per 10^{10} singly charged particles passing through our apparatus for particles with a charge less than 0.75 and about one anomalous particle per 10^9 in other charge regions. While the experiment is motivated by the possibility that quarks with charges of 1.3 e and 2/3 e are produced, we feel that it is also essential that we be able to examine the production of quark compounds with charges of 4e/3, 5e/3, etc., as quarks might decay rapidly to these compounds. We would identify the quarks by their anomalous pulse height as observed in a series of scintillation counters in various charged beams. The apparatus is very simple and we propose to operate in a largly parasitic fashion in specific way to be defined in accordance with beams set up and used in other programs.

Physics Justification

The realistic quark model has been extraordinarily successful in accounting for the systematics of both the ground states and excited states of the hadrons; the model accounts very well for the leptonic decays of the hadrons; and, most recently, the quark model (as a parton model) has been able to qualitatively account for the small momentum transfer dependence of the form factors for the inelastic electron scattering from nucleons.

Searches for quarks produced in the beams of other accelerators[1] have not been successful. While differential cross sections, $d^2\sigma/dE\, d\Omega$ are always measured, many experimenters have used models of varying naivety to estimate total cross sections from their measurements. We report these cross sections without implying that we believe they are more than a very rough, and usually over optimistic, estimate of the limit on the total quark production cross section. These limits are then about 10^{-36} cm^2 for the production of quarks with mzsses up to about 4 GeV/c^2 with 30 GeV protons, and 10^{-39} cm^2 for the production of quarks with masses up to about 6 GeV/c^2 using 70 GeV protons.

Examination of the flux of cosmic rays[2] in the atmosphere concern the possible production of quarks of very high mass. However, the limited fluxes of primary protons restricts the sensitivity of the measurements. Roughly speaking, the cross section limits set by these observations is 10^{-34} $M^{3.4}$, where M, the mass of the quark, is measured in GeV/c^2. Ingenious measurements of quarks bound in matter[3] have placed much lower limits on the cross sections for the production of quarks, but these experiments usually rely on a chain of very plausible, but not completely convincing suppositions. As more of these valuable measurements accumulate, the negative evidence will be more reliable, but as of now, we do not believe that these experiments rule out the possibility that quarks are produced in nucleon-nucleon collisions at energies accessible at the N.A.L. with reasonably large cross sections.

Recently, two reports[4,5] have been published claiming to exhibit evidence for the discovery of quarks. In each case, the claims are not supported by the evidence presented and we discount the results.

In the face of the negative evidence for the production of quarks, can we still presume that it might be possible that free quarks exist and have not been detected. One might well expect that the success of the realistic quark model, would suggest that quarks would be produced through some kind of impact process and the cross section for the production of free quarks would be rather large; perhaps of the order of the square of the compton wave length of the quark. However, if the quark is very heavy, the binding energy of quarks compounded into hadrons is very large, the potential binding of the quarks must be very large and the forces between quarks must be very strong. This suggests that quarks are very strongly bound to some field, which (perhaps in second order) is coupled to such quark-antiquark compounds as mesons. Perhaps, then, this coupling is so strong that the quark can be considered to be in equilibrium with these field particles. In this case, a statistical model of quark production might be relevant[6] and such models predict very small cross sections for the productions of quarks. While we feel that such models are not easily reconcilable with the very successful realistic quark model of hadrons, we certainly do not understand such things very well, and we would be foolish to neglect the possibility that quarks exist but are produced only at very high energies and with very small cross sections.

The collision of 200 GeV protons with nucleons, results in a center of mass energy of about 20 GeV; sufficient to produce a pair of quarks with a mass of 9 GeV/c^2 as well as the two original nucleons. If we include fermi energy, or the possibility of hitting two or more nucleons simultaneously, the mass limit will be somewhat greater but we have no very reliable way to make very great extrapolations in this way. If the proton energy is 500 GeV in the laboratory, we could expect to be able to make quarks as heavy as 15 GeV/c^2. We expect to detect quarks with a considerable sensitivity so that if quarks are produced with cross sections as great as 10^{-39} cm^2, we should have a good chance of detecting them.

Experimental Design and Arrangement

Without knowing either the masses of the anomalous particles or their production mechanism, it is not possible to design an experiment which is optimum for all possibilities and it is foolish to attempt to design too singular an experiment following some specific prejudice as to the character of nature. At this point in our ignorances, we can presume that the mass of the quark may be as small as 4 GeV/c^2 and as large as we can produce with 500 GeV protons, about 14 GeV/c^2. We might presume, at one extreme, that the quarks are produced at rest in the center of mass system, or at the other extreme, that they are produced through a diffractive disruption of the proton where three quarks are freed and the total energy is approximately divided among the three quarks.

Table I lists some relevant quantities for three different proton energies where M_q(max) is the mass of the heaviest quark which can be produced in a nucleon-nucleon interaction where the energy of the incident nucleon is E_p; E_{min} is the energy of a 4 GeV/c^2 quark emitted at rest in the center-of-mass system and, if the hunt is restricted to quarks with a mass no smaller than this, is the smallest quark energy at which searches can conceivably be necessary; E_{max} is the maximum neergy necessary and E_{diff} is the mean energy of quarks produced in the diffractive disruption of the incident nucleon.

E_p	E_{cm}	M_q(max)	gamma$_{cm}$	E_{min}	E_{max}	E_{diff}
200	20	9	10	40	100	67
350	26	12	13.5	54	175	117
500	32	15	15.5	62	250	167

From the table, it seems desirable to make measurements at momenta as low as 50 GeV/c and as high as one half of the momentum of the initial proton. While it is likely that measurements of negative particles only is sufficient, there is some possibility that quarks could be missed by such a procedure. If the dominant production mechanism is the production of quark-antiquark pairs -- that is broken mesons -- there will be no important differentiation between positive and negative quarks and we could be confident that measurements of one sign would be sufficient (though the number of negative quarks of a specific absolute charge need not be the same as the number of positive quarks which are produced.) However, the diffractive disassociation mechanism would act so as to produce, initially, two quarks with a charge of +2e/3 and one with a charge of -2e/3. From the mass systematics of hadrons, it seems probable that the charge 2e/3 quark is lighter than the charge e/3 quarks and if the quarks are quite massive, it is plausible that the mass difference might be larger than a pion mass and the transition could be very fast leaving only positive quarks in the beam. Therefore, it is desirable to make some measurements in a positive beam though, in general, measurements in a negative beam allow somewhat more sensitive determinations since there will be no proton contamination in these beams.

Since the lightest anomalous state may not be a single quark but a set of two quarks and an anti-quark into which a quark might decay spontaneously and very quickly, it is desirable to cover this eventuality in our measurements. It is quite probable, that if such a state exists, the lowest mass member of the multiplet will be the member with the largest charge. Then it is important to search[7] for particles of charge 4/3, 5/3, and 7/3. We have looked for such states in cosmic rays with negative results.[8]

As we shall demonstrate, thc experimental apparatus we propose to use is extremely simple, insensitive to beam conditions and backgorund, and quite mobile. Further, the apparatus is such that a few hours of sporaidic running will result in valuable conclusions though, numerically more significant results will certainly be achieved with longer, steadier runs. As a result of these features of the experiment, we believe that we can run profitably during the very first tuning of the beam: indeed, during the first measurements of ejection. A most useful result can be obtained in less than ten hours of running where we would test the apparatus elsewhere. All possible measurements should be finished in less than 100 hours of running. While we make specific suggestions for beam areas below, in fact, we can run under quite different conditions as is convenient during the early test running.

Apparatus

The apparatus is exceedingly simple. We plan to measure the energy loss of the particles in scintillator, very much as we did in the first quark search at the AGS,[9] by registering the pulse heights in a number of scintillators when a particle passes through the scintillator. Since there is an appreciable statistical spread in the pulse heights from a single scintillator, not to mention the Landau effect which creates a bias towards larger pulse heights, it is necessary to examine the average of a number of scintillators so as to reliably exclude statistical fluctuations. We have found[10] that we can reduce the accidental background to a very small level -- about 10^{-9} -- by using suitable statistical criteria on the pulse heights from 8 counters where the scintillator is ½" thick, 4" wide and 8" long, viewed by a 2" photomultiplier. Typically, a trigger is initiated if all of the pulses are below, or above, certain levels. The trigger is used to initiate a measurement of the pulse heights of the eight counters which are then stored. At this time we believe that we would prefer to use A to D converters and record each interesting event on punched paper tape for later detailed analysis with a computer. In the past we have operated very successfully by simply photographing the pulses from the counters on an appropriately triggered oscilliscope. These methods are both simple and are logically equivalent. We would make a final decision based on logistic considerations. In either case, we would plan on supplying all of the apparatus.

The apparatus which we plan on using is light, simple, compact and mobile. We would plan on placing the detector (which is table top size) on one light cart and all of the electronics on another cart. This apparatus should be able to be in operation 30 minutes after being wheeled into position. Further, we can have the apparatus ready and tested in ten days after any notice. We would like to be available during the first test of the beam on the basis that we could almost certainly make useful measurements with little or no interference with the testing program and we would require a minimum of assistance from the laboratory as far as set up requirements. Indeed, we could probably operate with no extra assistance at all. Of course, later, when the experimental areas are ready, we would like to spend a little more time under various conditions, to be defined at that time, refining the first searches. As with our proposed searches during the first tests of the machine, we propose to then operate primarily in parasitic modes with other experiments.

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ADDENDUM TO EXPERIMENT #72

QUARK SEARCH

It appears now that we can suggest definite beams where we might conveniently conduct measurements designed to detect quarks. In particular: a) We would like to set up in a nominally neutral beam which looks at the target used for the diffracted ptoton beam and examine the charged reaction products which pass down that beam aperture. In this way we would be prepared to detect quarks produced by 200 GeV protons on the target. Soon after this measuremnt, b) we would like to set up in the "meson beam dump" area of the neutrino beam where we would hope to examine charged particles produced by 400 GeV protons for evidence of quarks. We would expect to run during the testing of the 300 GeV meson beam and then look for quarks with a magnetic rigidity equal to that of 300 GeV singly charged particles.

a) We would like to set up our apparatus at the end of the neutral beam #22, about 1350' from the target. This is the beam which, in the horizontal plane, is aligned with the incident proton beam and lies at an angle of 8.25 mr downwards in the vertical plane. Since the proton beam is directed downwards at an angle of about 1.75 mr, the production angle is then about 6.5 mr.

We believe that it would be quite desirable to have a small degree of momentum resolution and that such resolution could be achieved without untoward difficulty. The design proposed here, which is meant to be suggestive rather than definitive, would be satisfactory.

At the 350' gallery we would like to have a collimator with an aperture of the order of ½" x ½". In the 650' gallery, we would like to have an adjustable collimator set typically with jaws ¼" wide and ½" high. After the collimator we would place a small magnet with pole faces 2" wide and 30" long and a gap of 9/16". The magnet would be designed to reach fields of 8 kgauss without the necessity of water cooling. At the 1050' gallery we would have a collimator with an opening ½" wide and 1" high which is offset (left or right, whichever is more convenient) 3" from the beam center line. A beam must then be deflected about $6 \cdot 10^{-4}$ radians to pass through the slit. Such a beam will emerge from the tunnel at the 1350' point, where the detector is to sit, about 5" from the nominal beam center. The beam will then be near the edge of the 12" diameter pipe if the first two collimators are set exactly in the center of the beam area. Of course they can be set off-center slightly if this seems desirable and the final beam can emerge more nearly at the center of the tunnel. At any rate, the deflection will be quite sufficient to allow the very rough momentum resolution which is desirable, the sign of the beam will be defined, and the intense neutral beam will be intercepted by collimators. In order to achieve these results, multiple scattering of the beam must be reduced by filling the 12" tunnels with helium.

We would hope to use the beam while other work is proceeding in the associated beams. We may then have a problem in controlling the intensity. Our detection techniques are such as to limit us to fluxes of the order of 10^6 charged particles per second and the beam as suggested could well exceed this by as much as two orders of magnitude. If the jaws of the middle collimator (in the 650' gallery) are adjustable and can be closed to gaps such as 0.030" x 0.030" we would have sufficient flexibility to operate under a wide variety of conditions. It would be especially desirable if the collimator could be adjusted remotely.

We presume that there are limitations on the proton beam transport system which preclude directing a higher energy proton beam upon the target used in this area. Otherwise, this set up would be ideal for investigating the production of quarks by higher energy protons.

b) Presuming that 400 GeV protons are not likely to be available for use with beam #22, we would like to investigate the production of quarks by higher energy protons using a beam at the neutrino area. We would like to set up our apparatus at the end of the drift tube in the neutrino beam. It is our understanding that there is likely to be a period devoted to testing the 300 GeV meson beam in this area where the meson beam is obtained through the interaction of protons with energies greater than 400 GeV. We understand that the end of the drift tube will then be blocked by a temporary beam stop. We would like to sit behind a small hole in this beam stop and examine the charged particles passing through this hole.

Again we are likely to have too much flux for our instrumentation to handle. It would seem that even through a ¼" x ¼" hole, we might well expect to have 10^7 charged particles pass per pulse. We might need to run with the meson beam defocussed or otherwise reduced in some manner.

For either experiment, we can make a quite sensitive measurement of the quark flux in 24 hours of satisfactory running. In this time a q/(charged meson) ratio of 10^{-8} should be easily achieved and we can do an order of magnitude better with no great difficulty.